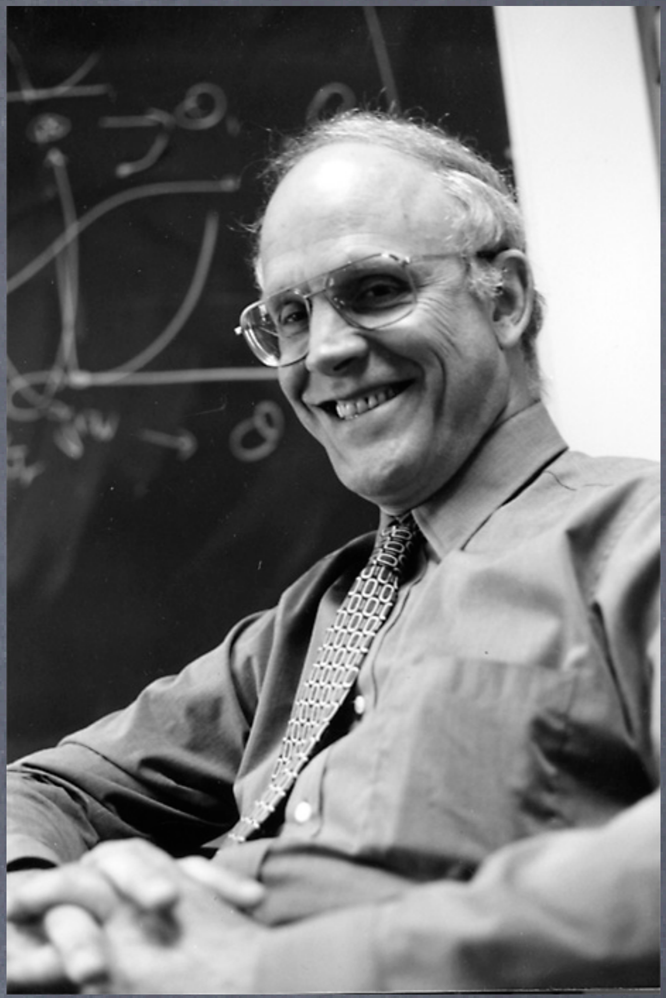
Probing the Origins of the Cosmos

Justin Khoury (Penn)

David Gross introducing a cosmologist colloquium speaker in the mid-90's...



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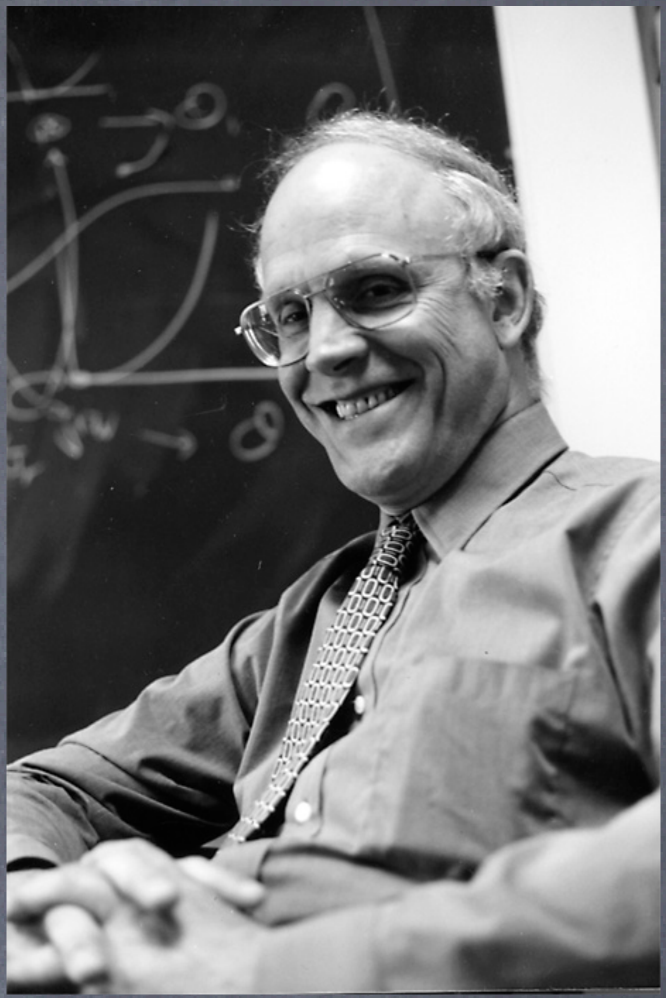

"Cosmologists are very much like us, particle physicists.

We have our standard model, they have their standard model.

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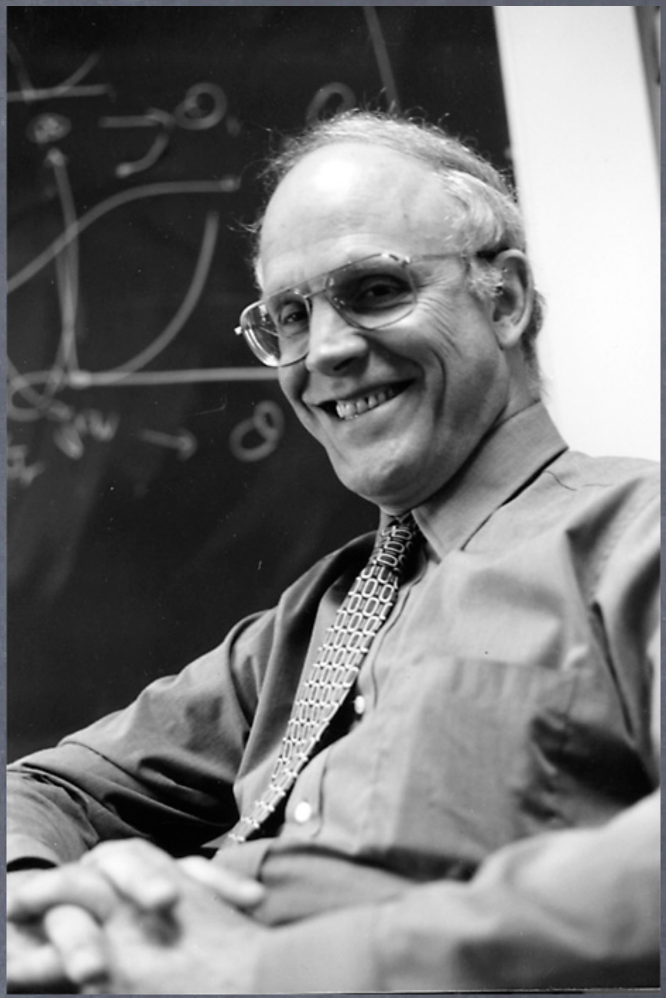
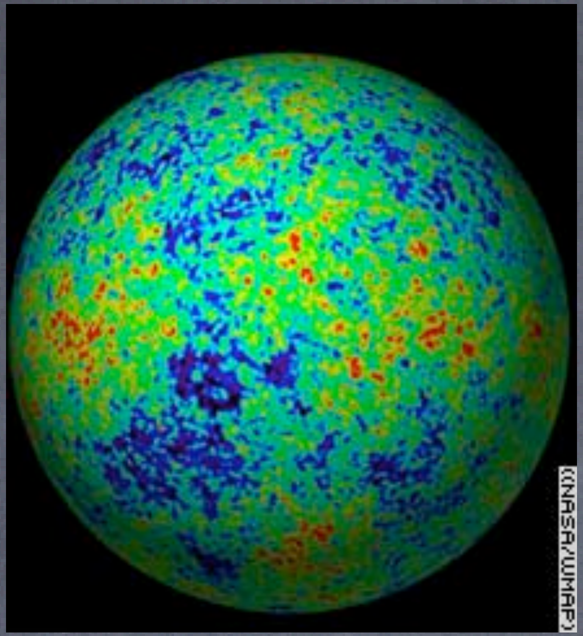


"Cosmologists are very much like us, particle physicists.

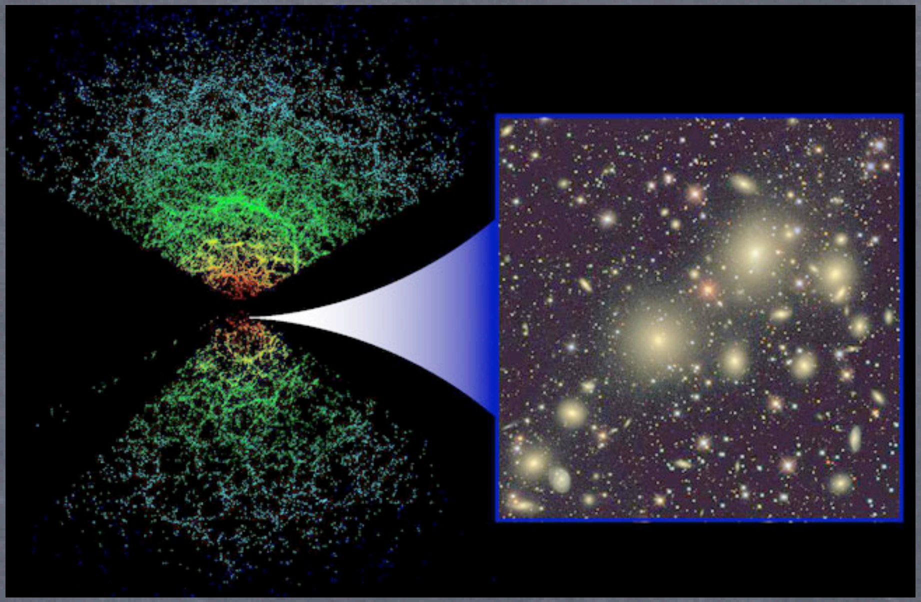
We have our standard model, they have their standard model.

We know our parameters with 1% uncertainty, they know their parameters with 100% uncertainty!"

Cosmology has been flooded by a wealth of data...



CMB

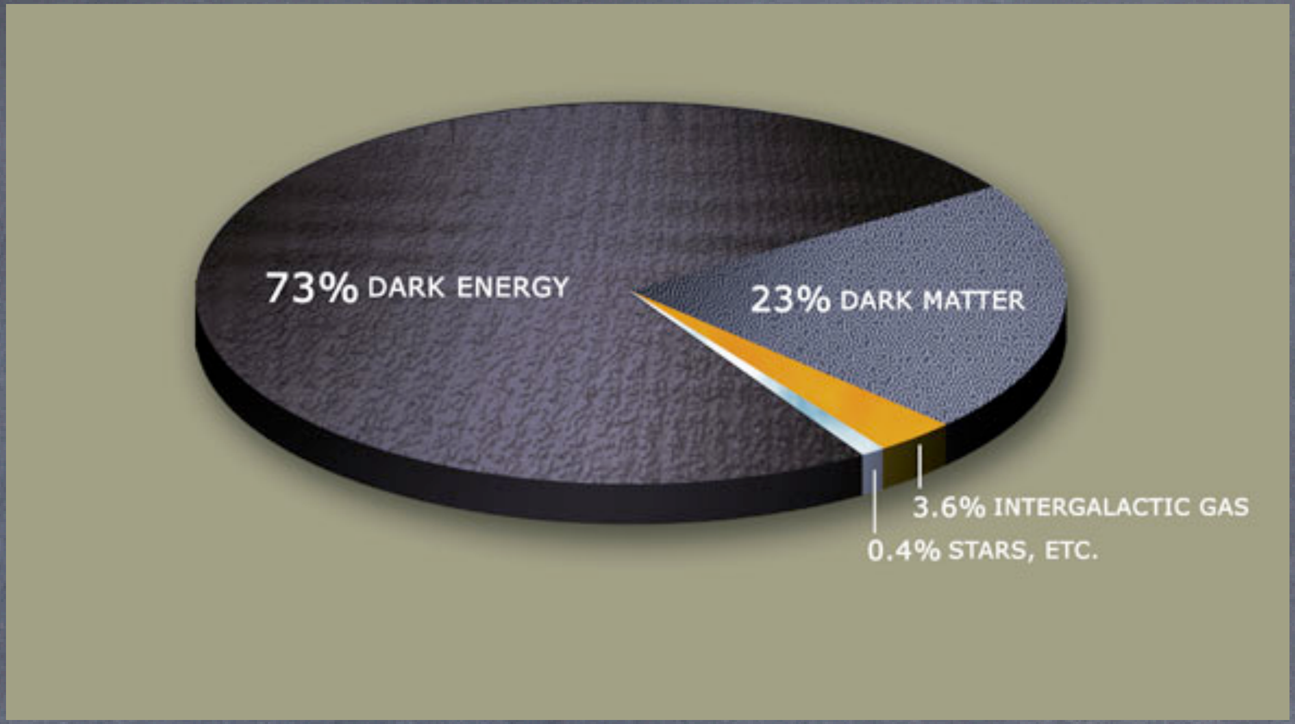


Galaxy surveys

Gravitational lensing

Type Ia supernovae

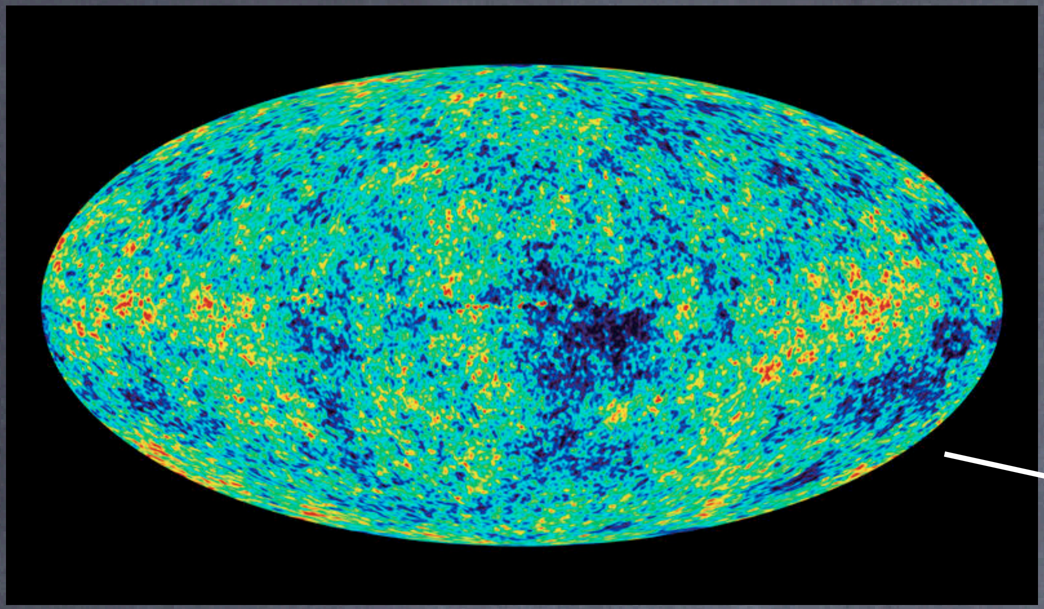
All of this data thus far gives a consistent picture of our universe

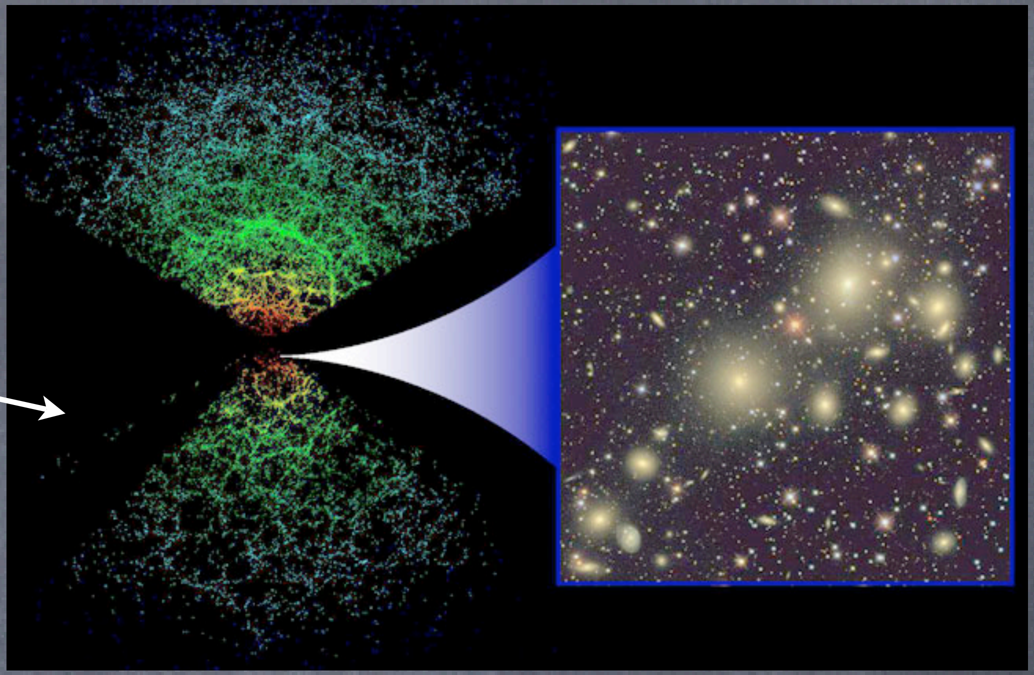


$$\Omega_{\rm b}h^2 = 0.02273 \pm 0.00062\ ; \qquad \Omega_c h^2 = 0.1099 \pm 0.0062\ ;$$
$$\Omega_\Lambda = 0.742 \pm 0.030\ ; \qquad n_s = 0.963 \pm 0.015\ ;$$
$$\sigma_8 = 0.796 \pm 0.036\ ; \qquad \tau = 0.087 \pm 0.017$$

Thus cosmology has emerged as a powerful tool for testing fundamental theories of particle physics

Where we come from...





Large-scale structures in our universe have evolved, through gravitational instability, from primordial density perturbations that were

- Nearly Gaussian
- Linear
- Adiabatic
- Nearly scale-invariant

Inflation

Alan Guth's Notebook

EV ⑤

Dec 7, 1979

SPECTACULAR REALIZATION:

This kind of supercooling can explain why the universe today is so incredibly flat — and therefore ~~[illegible]~~ resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

Let me first rederive the Dicke paradox. He relies on the empirical fact the the deacceleration parameter today q_0 is of order 1.

$$q_0 \equiv - \ddot{R} \frac{R}{\dot{R}^2}$$

Use the eqs of motion

$$3\ddot{R} = -4\pi G (\rho + 3p) R$$

$$\dot{R}^2 + k = \frac{8\pi G}{3} \rho R^2 .$$

so

$$q_0 = \frac{\frac{1}{2}(1 + 3p/\rho)}{1 - \frac{3 k M_P^2}{8\pi \rho R^2}}$$

Inflationary Zoo

Old Inflation

k-Inflation

Chaotic Inflation

Natural Inflation

New Inflation

Extended Inflation

N-flation

Hybrid Inflation

Hyper-Extended Inflation

Pseudo-Natural Inflation

A-term Inflation

Roulette Inflation

D-term Inflation

Extra-Natural Inflation

Ghost inflation

DBI Inflation

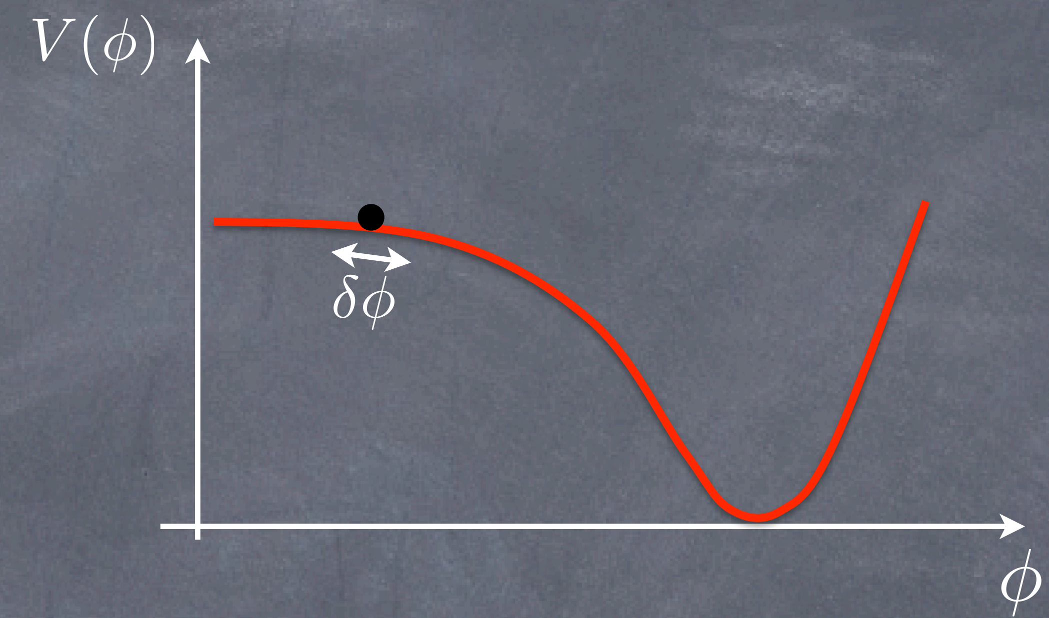
F-term Inflation

Classes of Models

- Slow-roll, “single-field” models

  New Inflation, Chaotic, Hybrid...

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi)$$



- Background clock also acts as progenitor of density perturbations

- Flat potential => field pertns are weakly coupled

- Fast-roll models

  k- or DBI Inflation, Ghost Inflation

$$\mathcal{L}_{\rm DBI} = -M^4\sqrt{1+\frac{(\partial\phi)^2}{M^4}} + M^4 - V(\phi)$$

Silverstein and Tong (2004)

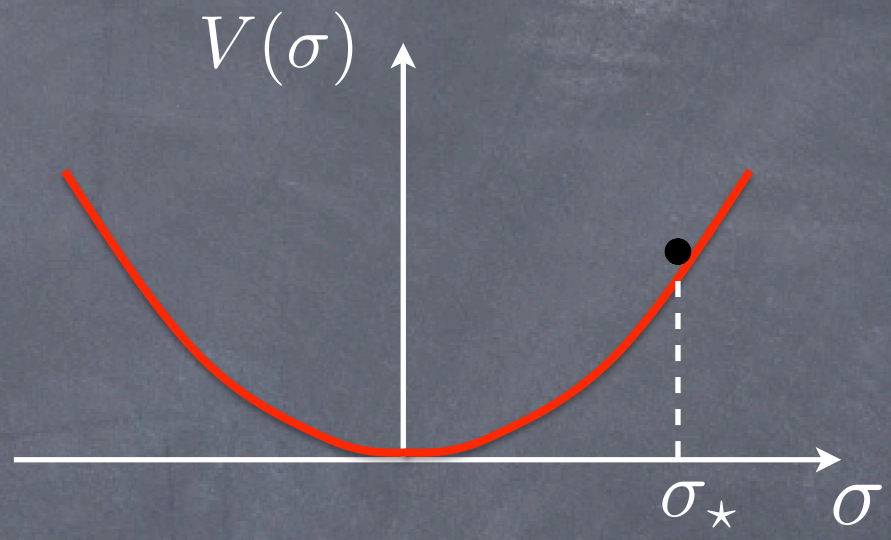
- Field need <u>not</u> be slowly rolling

- Perturbations NOT weakly coupled

Multi-field models

Curvaton model, Modulated reheating

- Progenitor of density pertns is a separate light field σ



- Because σ is light during inflation, its fluctuations acquire a scale-inv spectrum

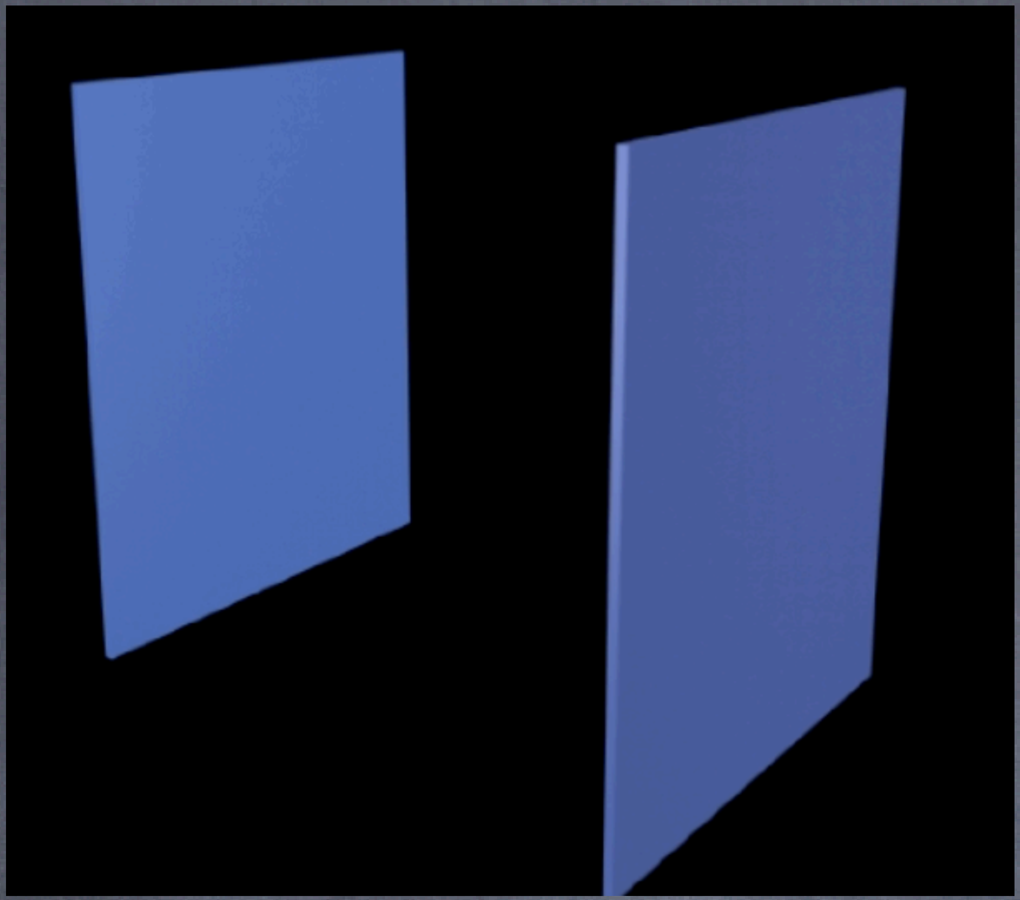
$$\delta\sigma \sim H$$

- After inflation, $\delta\sigma$ can be converted into $\delta T/T$

Lyth and Wands (2002)
Dvali, Gruzinov and Zaldarriaga (2003)

The Ekpyrotic Universe

1.



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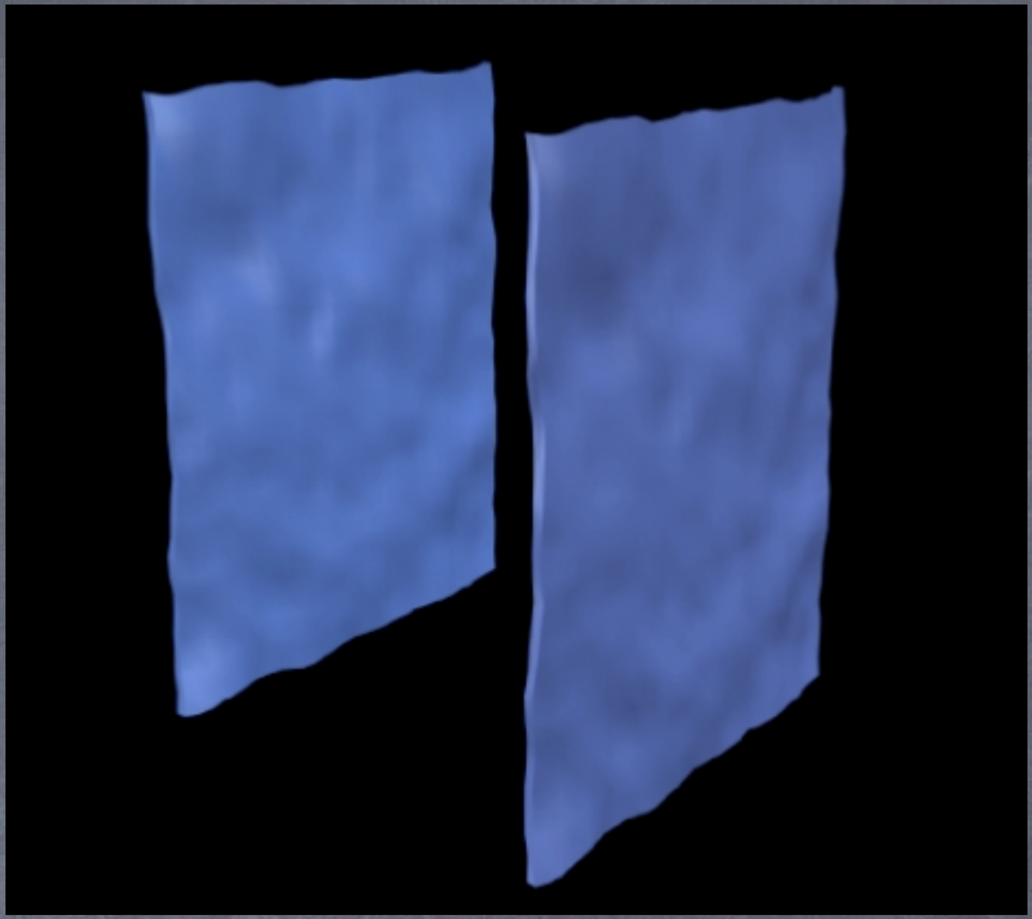

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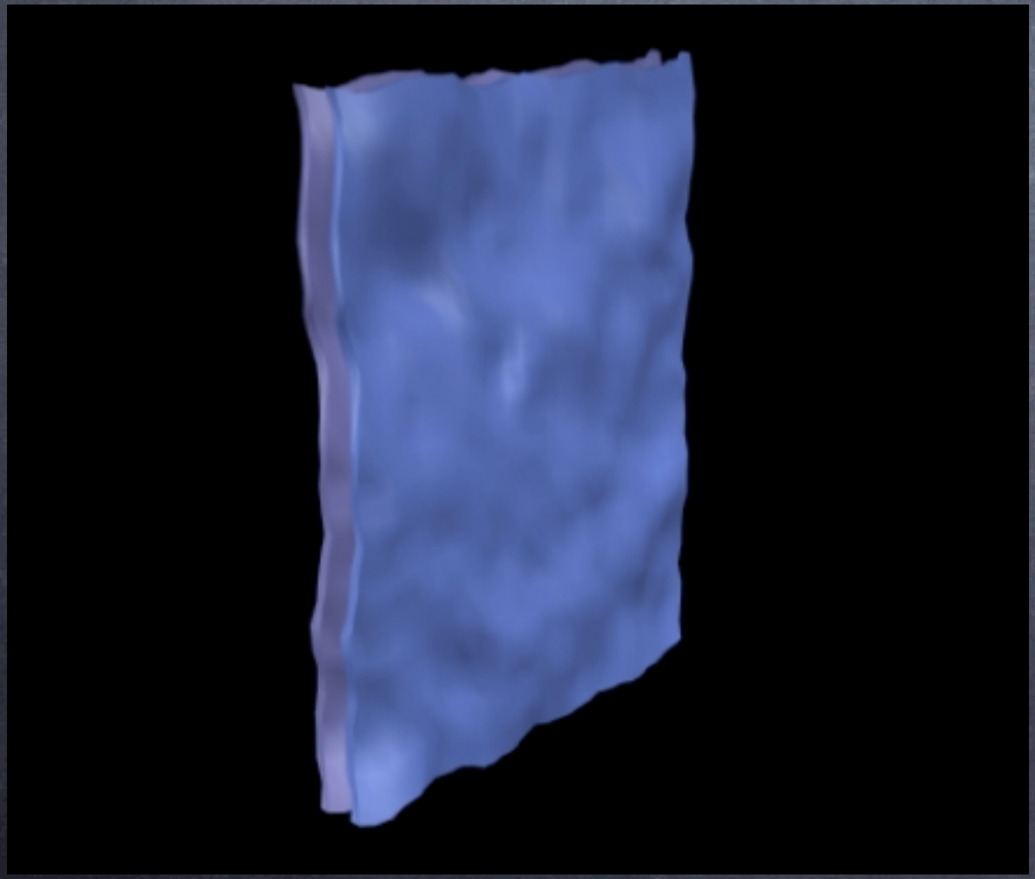

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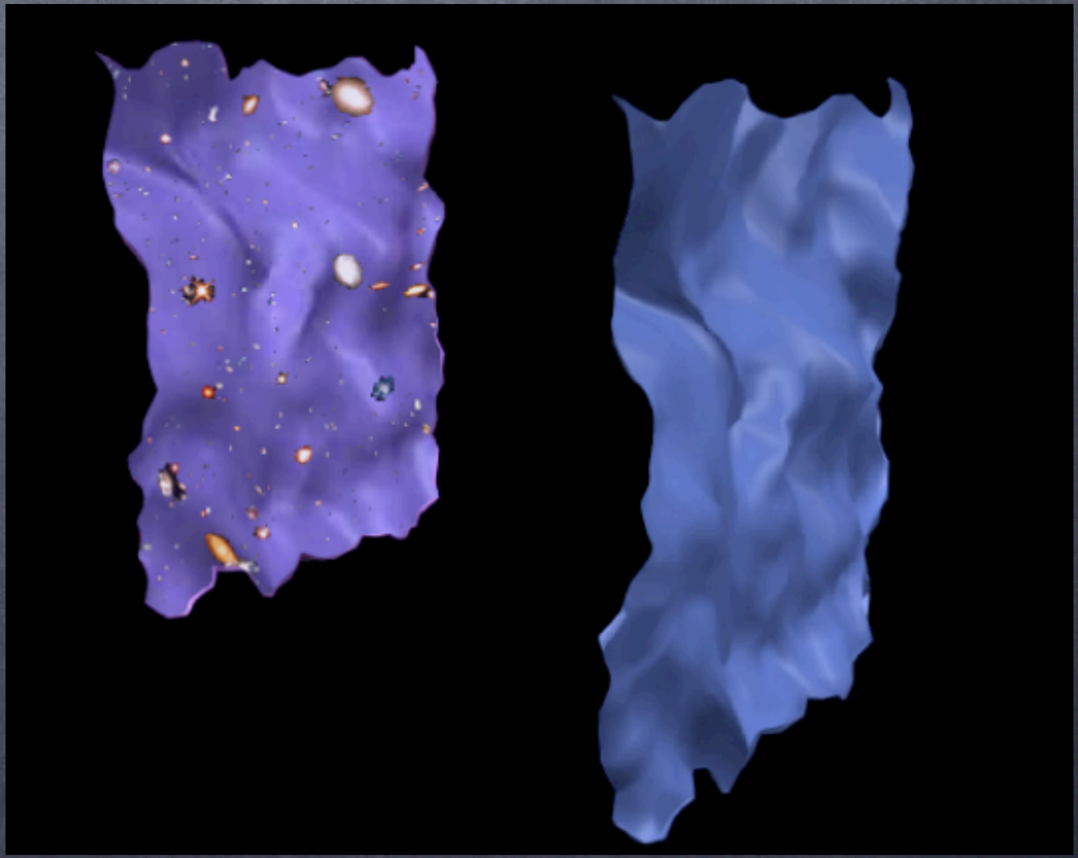

Motivations

How to explain flatness, homogeneity and isotropy?

$$3H^2 = \frac{C_{\rm dust}}{a^3} + \frac{C_{\rm radn}}{a^4} + \frac{K}{a^2} + \frac{C}{a^6} + \ldots + \frac{C_\phi}{a^{3(1+w)}}$$

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* Expanding case:
  - curvature is most dangerous
  - need $w < -1/3$ (inflation)
  - inflation is an attractor

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Scale-invariant $\delta\rho/\rho$ further requires $w \approx -1$

or

$w \gg 1$

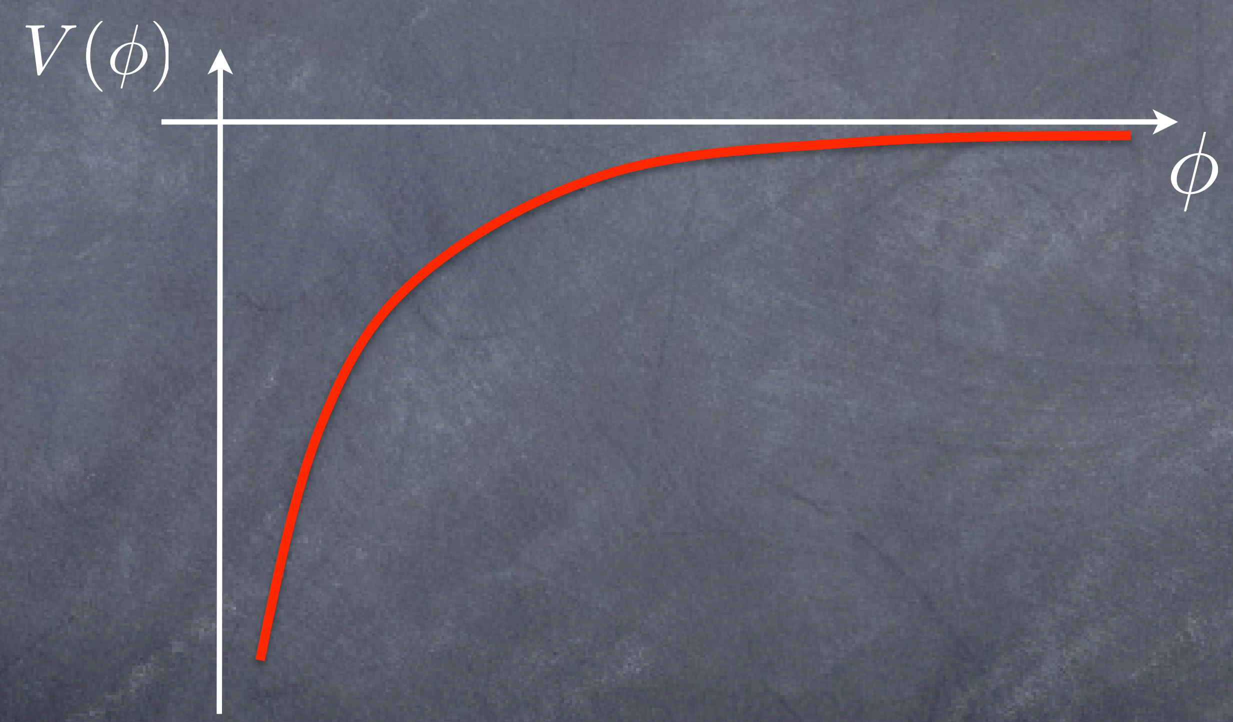
Ekpyrotic Dynamics

Khoury, Ovrut, Steinhardt and Turok (2001)

Before the big bang, universe underwent a long phase of slow contraction

(Spiritually the opposite of inflation)

Phase of $w \gg 1$ driven by scalar field with steep and negative potential



Leads to slow contraction: $a(t) \sim (-t)^{2\epsilon}$ where $\epsilon \ll 1$

“Dual” mechanisms for generating perturbations

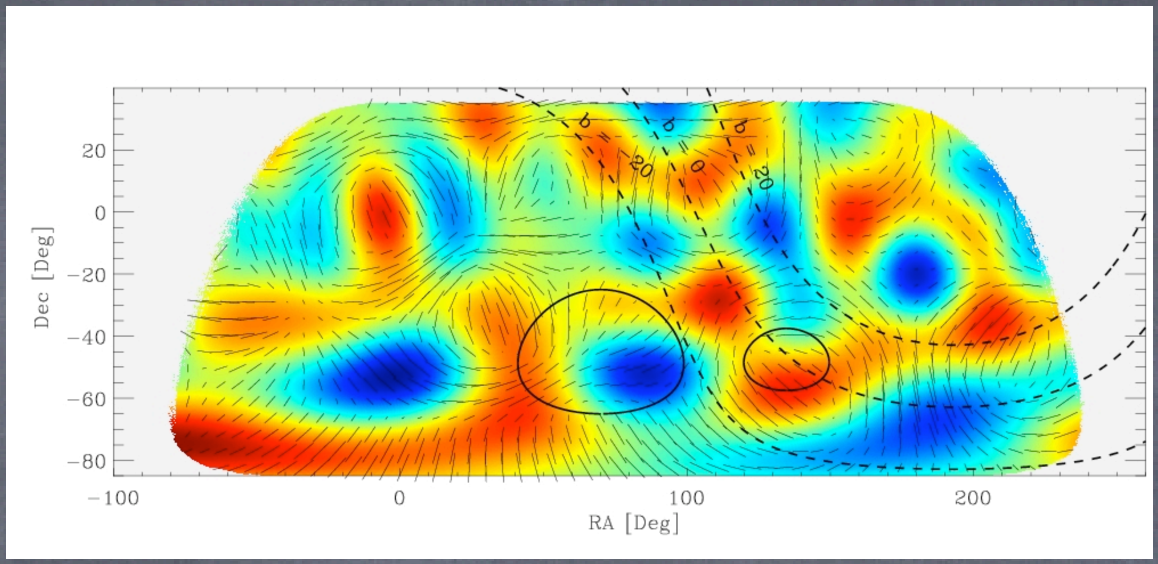
- Inflation: $a(t)$ grows rapidly, while H is nearly const.

- Ekpyrotic: $a(t)$ is nearly const., while $|H|$ grows rapidly

$\Longrightarrow$ degenerate predictions for power spectrum

Khoury, Steinhardt & Turok, PRL (2003)

But gravitational wave signature



- Inflation: - Rapid background expansion
  - All light fields are excited, including gravitational waves

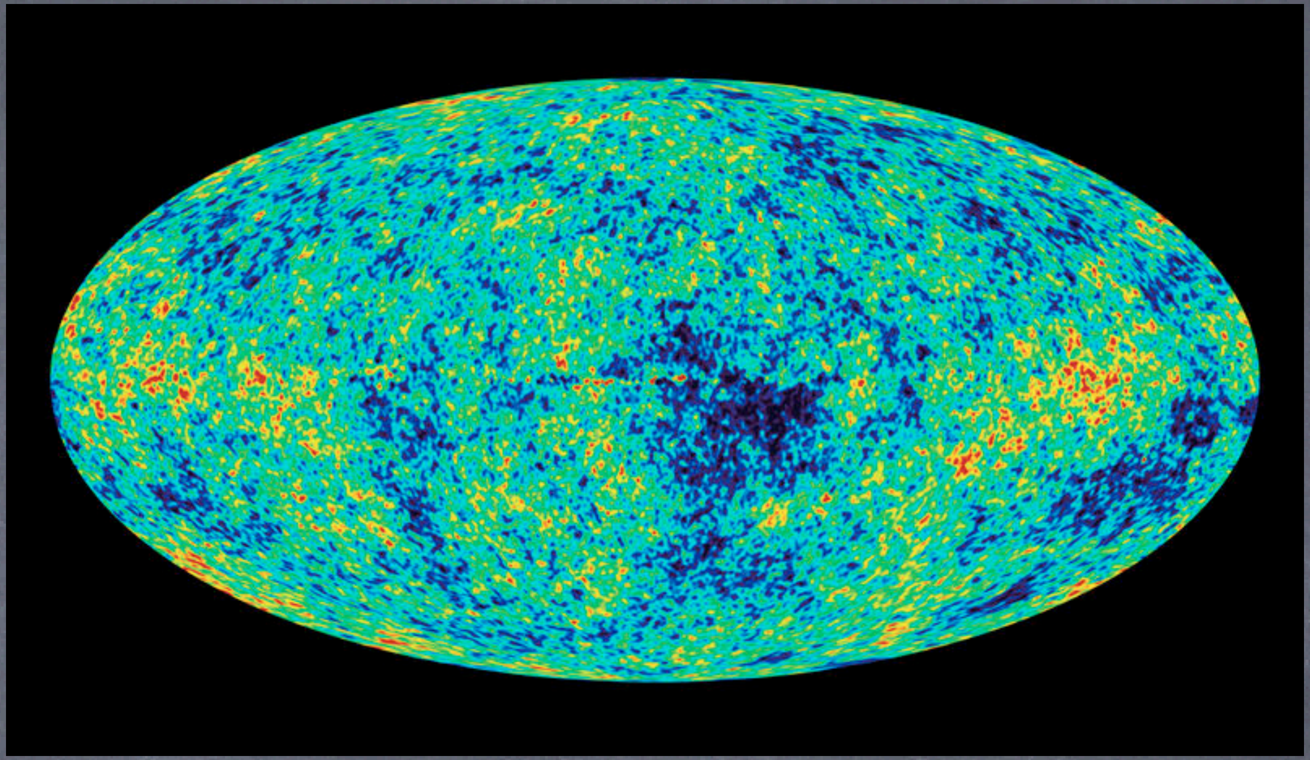
  $\Longrightarrow$ scale invariant GWs

- Ekpyrotic: - Slow contraction
  - Gravitational waves not appreciably excited

Detection of primordial GWs, e.g. through CMB polarization, would rule out ekpyrosis.

Non-Gaussianity

3 sources of Non-Gaussianity



- Particle physics theory $\mathcal{L}[\phi]$

$$\Longrightarrow \langle \delta\phi \, \delta\phi \rangle \, , \langle \delta\phi \, \delta\phi \, \delta\phi \rangle \, , \ldots$$

- Conversion to gravitational field (metric perturbation)

$$\zeta = c_1 \delta\phi + c_2 \delta\phi^2 + \ldots$$

$$\Longrightarrow \langle \zeta \, \zeta \, \zeta \rangle = c_1 \langle \delta\phi \, \delta\phi \, \delta\phi \rangle + c_2 \langle \delta\phi \, \delta\phi \rangle \langle \delta\phi \, \delta\phi \rangle$$

- Transfer function to temperature fluctuations

$$\langle \zeta \, \zeta \rangle \, , \langle \zeta \, \zeta \, \zeta \rangle \, \ldots \Longrightarrow \langle \delta T \, \delta T \rangle \, , \langle \delta T \, \delta T \, \delta T \rangle \ldots$$

Quantifying NG

Bond & Salopek (1990)
Komatsu & Spergel (2001)

$$\zeta(x) = \zeta_g(x) + \frac{3}{5} f_{\rm NL} \zeta_g^2(x)$$

where ζ_g is a Gaussian random field

This leads to a 3-pt function of the form

$$\langle \zeta\, \zeta\, \zeta \rangle \sim f_{\rm NL} \langle \zeta_g\, \zeta_g \rangle^2$$

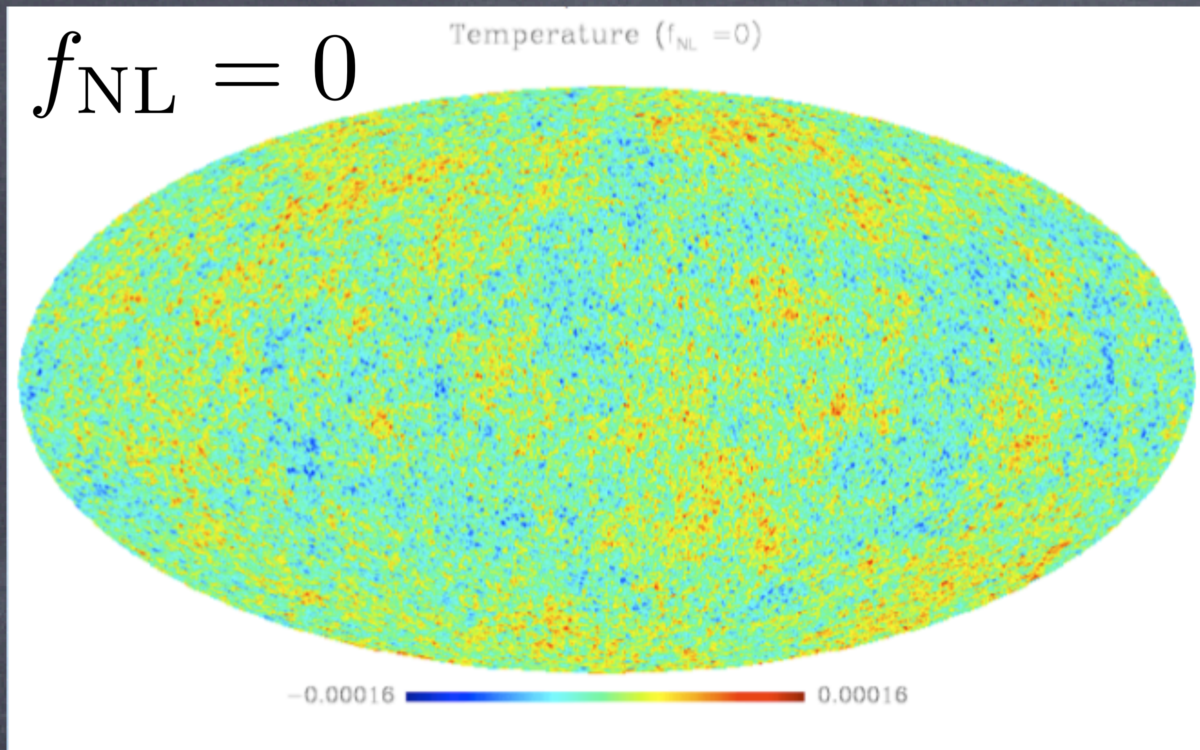
How skewed?

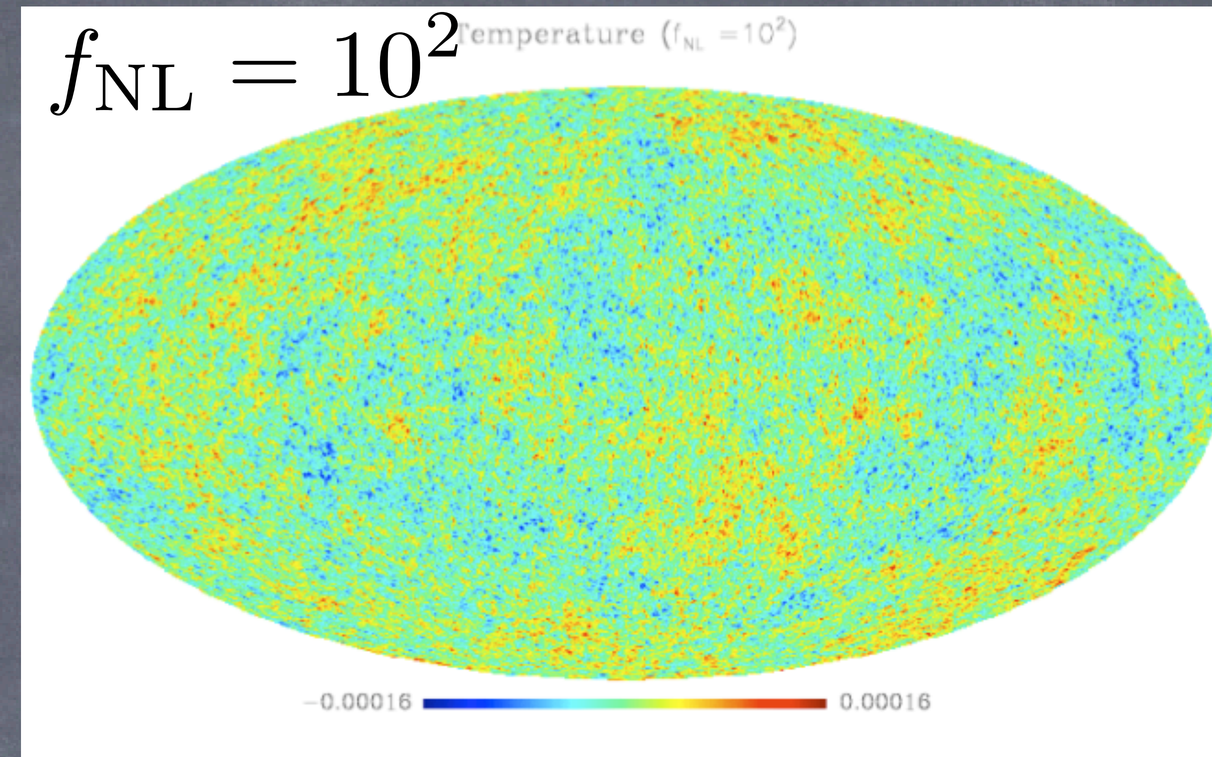
$$\frac{\langle \zeta\, \zeta\, \zeta \rangle}{\langle \zeta\, \zeta \rangle^{3/2}} \sim 10^{-5} f_{\rm NL}$$

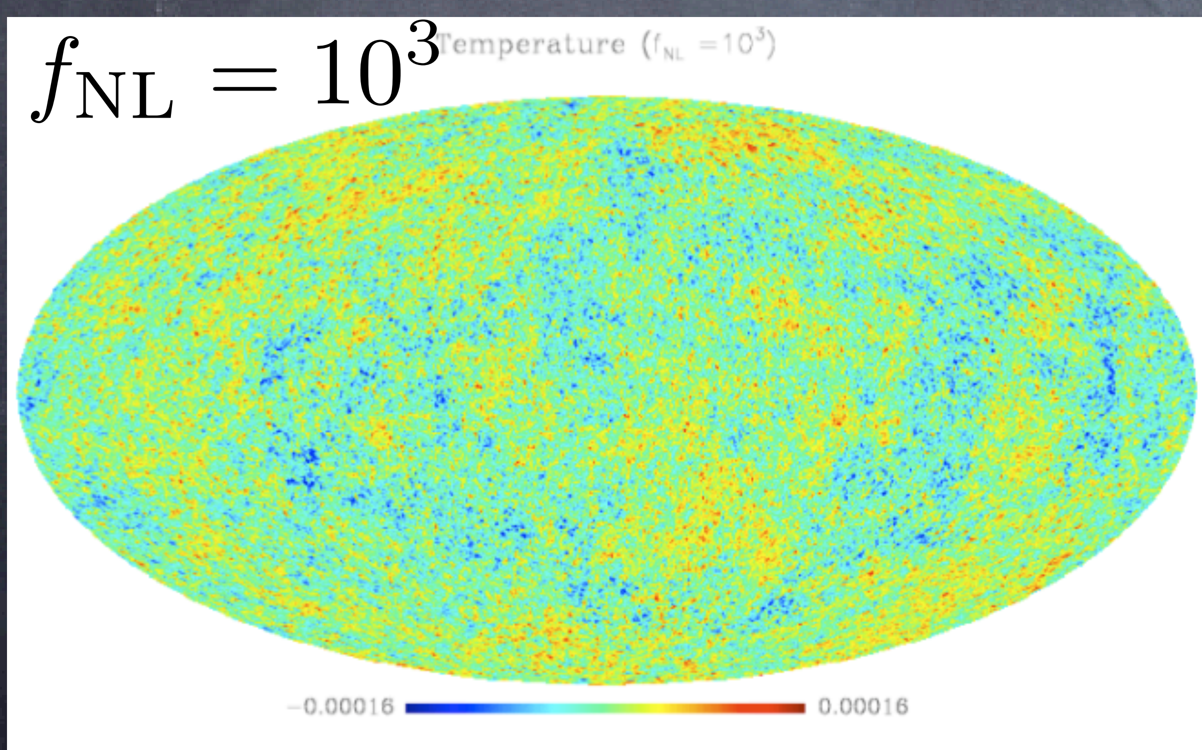
Hence perturbation theory breaks down for $f_{\rm NL} \sim 10^5$

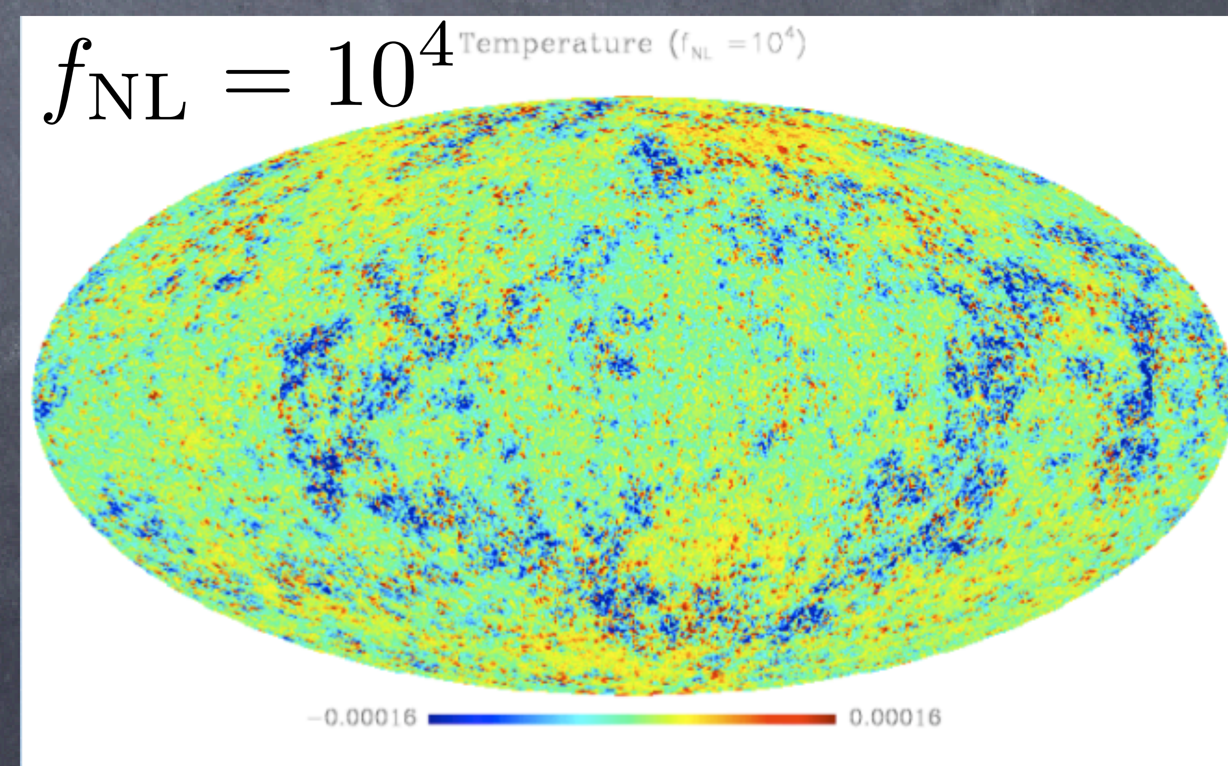
Liguori et al. (2007)

$$\zeta(x) = \zeta_g(x) + \frac{3}{5} f_{\rm NL} \zeta_g^2(x)$$









Shape of Non-Gaussianity

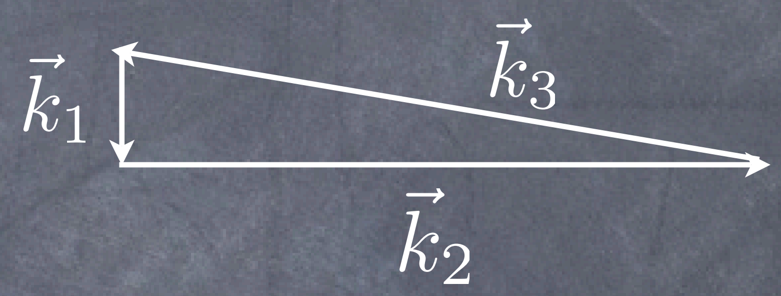
Babich, Creminelli & Zaldarriaga, JCAP (2004)

- "Local" shape: $$\zeta(x) = \zeta_g(x) + \frac{3}{5} f_{\rm NL} \zeta_g^2(x)$$

  - In momentum space, the amplitude peaks for $|\vec{k}_1| \ll |\vec{k}_2|, |\vec{k}_3|$

  - Non-linearities develop at long wavelengths

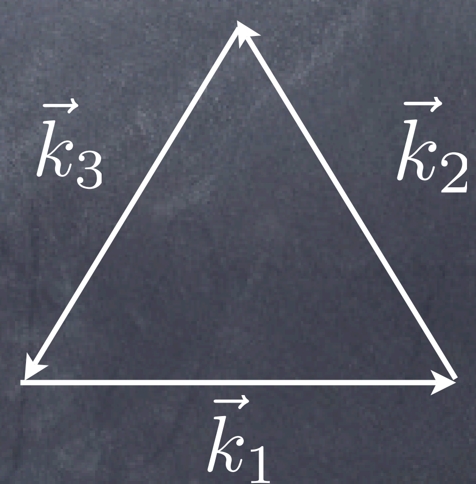
  - e.g. Separate-progenitor models



- Equilateral shape:

  - For fast-roll models, non-linearities come from derivative interactions

  - NG peaks for $|\vec{k}_1| \sim |\vec{k}_2| \sim |\vec{k}_3|$



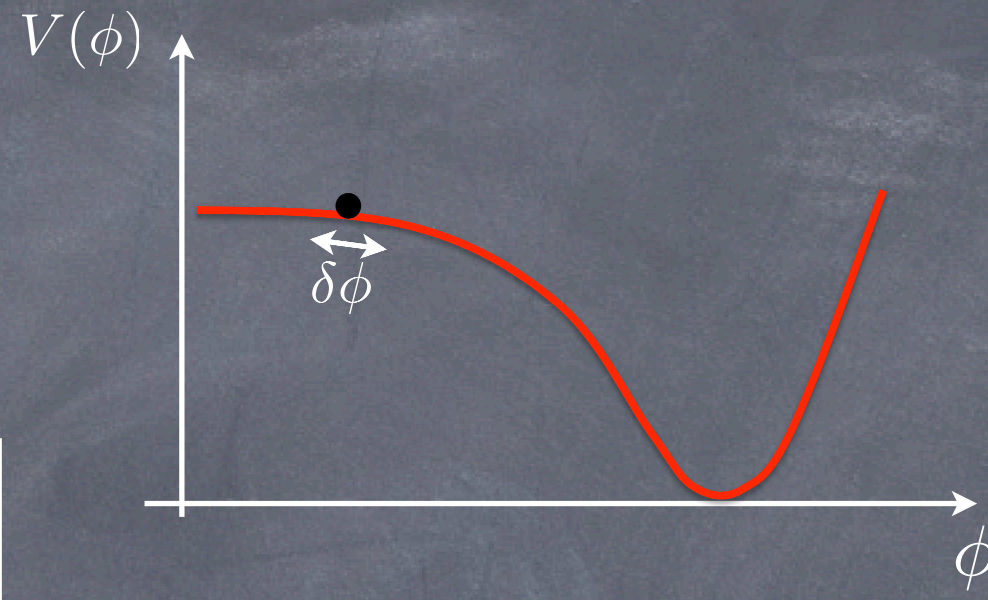
What models predict

- Slow-roll, "single-field" models:

  Field pertns are weakly coupled

$$\Longrightarrow \quad \boxed{f_{\rm NL} \sim \mathcal{O}(\epsilon_{\rm inf}, \eta_{\rm inf})}$$

Maldacena (2002)

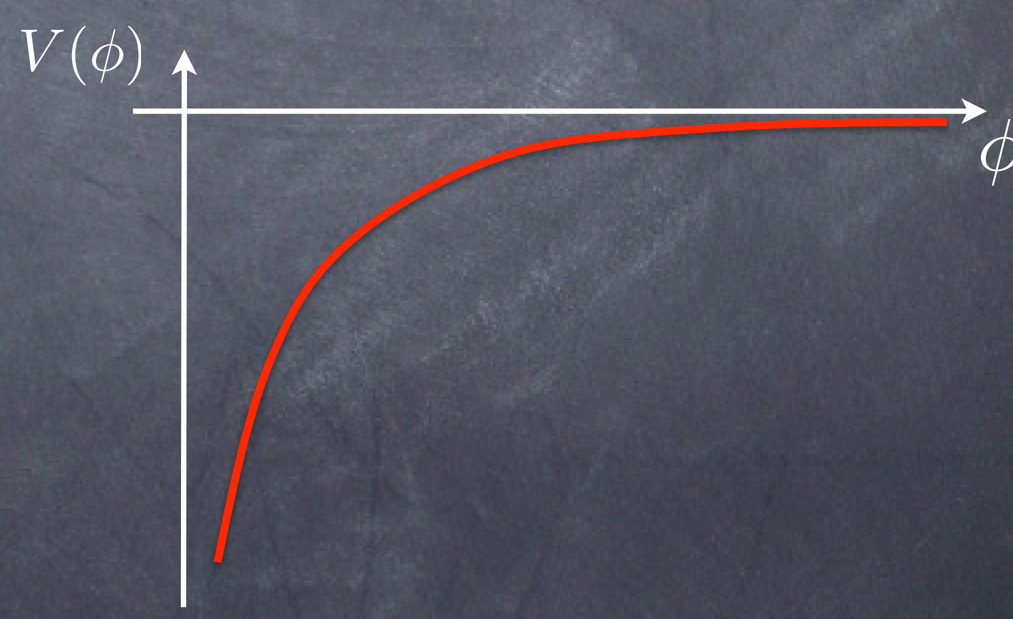


- Ekpyrotic Non-Gaussianity

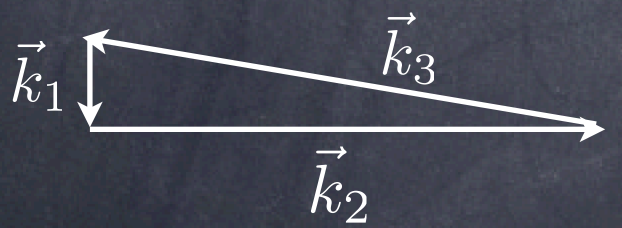
Buchbinder, Khoury & Ovrut, PRL (2008)
Koyama et al.; Lehners & Steinhardt (2008)

  - Here potential is steep

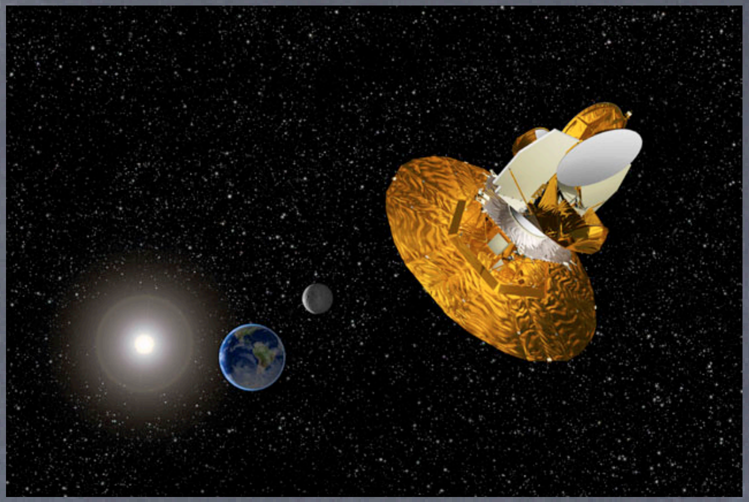
$$\Longrightarrow \quad \boxed{f_{\rm NL} \sim \frac{1}{\epsilon}}$$



  - Shape is local



Observations

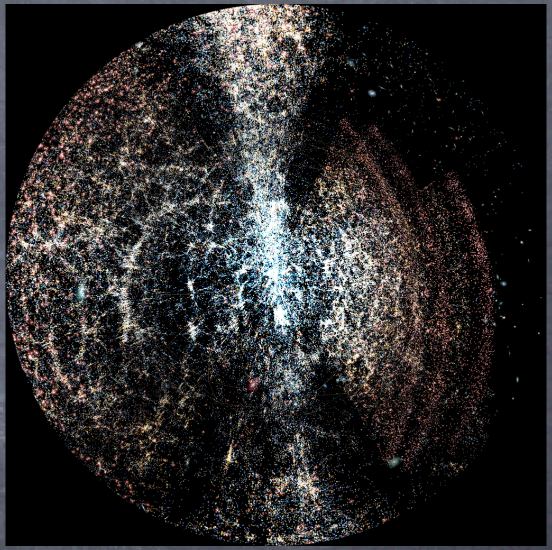


- WMAP 5-yr: $-4 < f_{\rm NL} < 80$

  Senatore et al. (2009)

- WMAP 3-yr: $27 < f_{\rm NL} < 147$

  Yadav & Wandelt (2008)



- Galaxy surveys $-29 < f_{\rm NL} < 69$

  Slozar et al. (2008)

- Planck $|\Delta f_{\rm NL}| \sim 5 - 10$

- Futuristic 21cm $|\Delta f_{\rm NL}| < 1$

  Cooray (2006)
  Pillepich et al. (2006)

Conclusions

- CMB observations have firmly established that density perturbations were already present on the largest scales at recombination

- Inflationary and ekpyrotic models fall into broad classes with distinguishable predictions

- Will be tested through key observables:
    - Primordial gravitational waves
    - Deviations from Gaussianity

What about the bounce?

- Can generate a non-singular bounce, without introducing instabilities or other pathologies

Creminelli, Luty, Nicolis and Senatore (2006)

- Can successfully merge the ekpyrotic phase with the subsequent bounce phase

Buchbinder, JK and Ovrut (2007)
Creminelli & Senatore (2007)

- Perturbations go through the bounce unscathed and emerge in the hot big bang phase with a scale-invariant spectrum