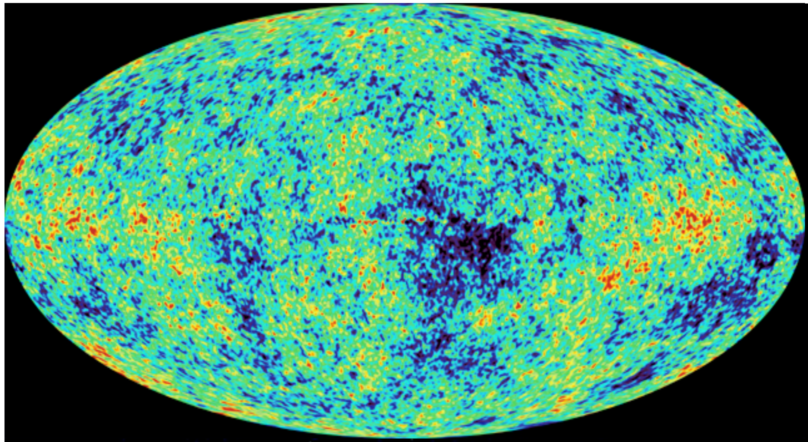
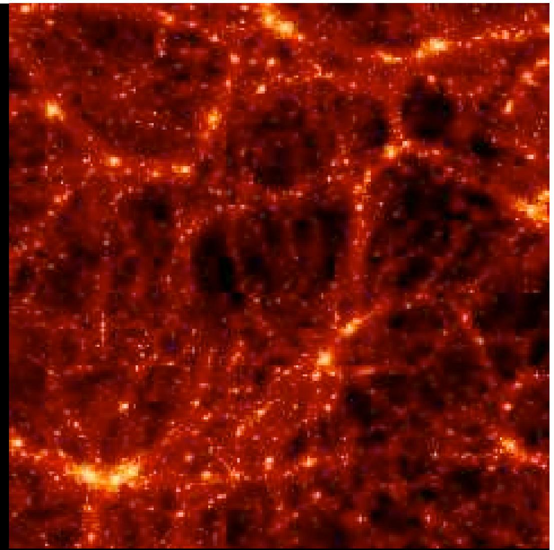
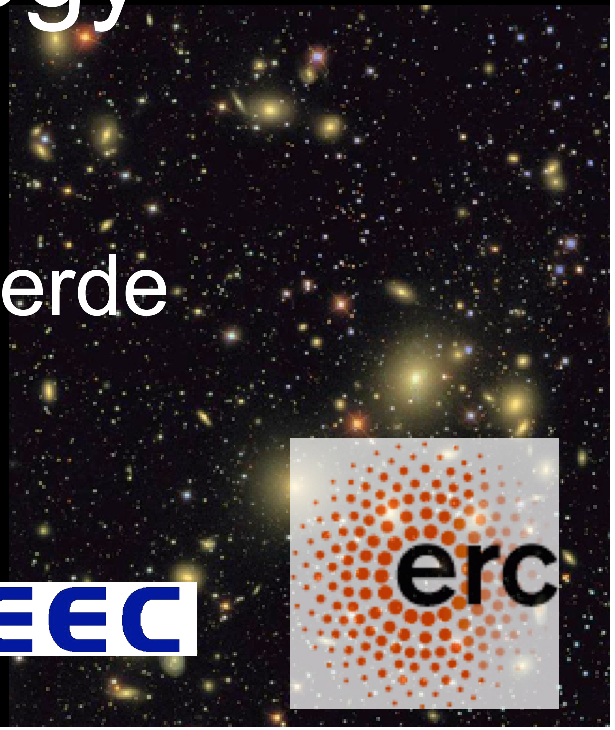




A taste of cosmology

Licia Verde

http://icc.ub.edu/~liciaverde



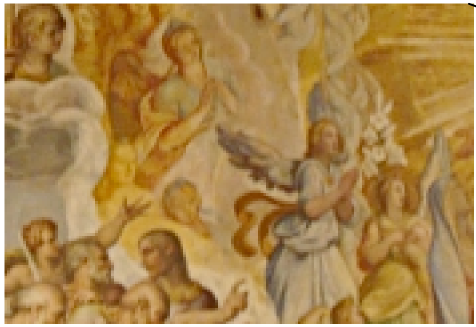
Institut de Ciències del Cosmos

OUTLINE

- The standard cosmological model
- The successes of cosmology over the past 10 years
- Cosmic Microwave Background
- Large-scale structure
- Inflation and outlook for the future

Lectures and additional material will appear at
http://icc.ub.edu/~liciaverde/CLASHEP.html

Outline 2



Last Judgment, Vasari, Florence Duomo

Successes of the Big Bang model

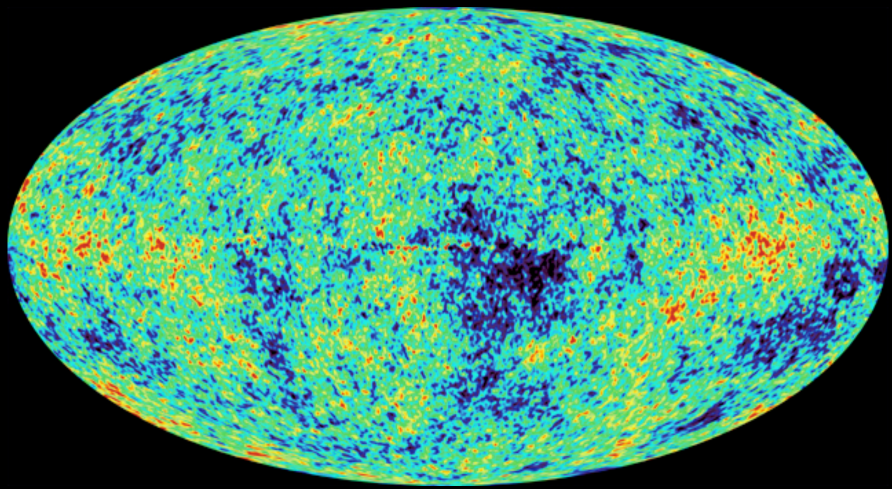
GR+cosmological principle

Hubble's law
CMB
Abundance of light elements

.. And problems

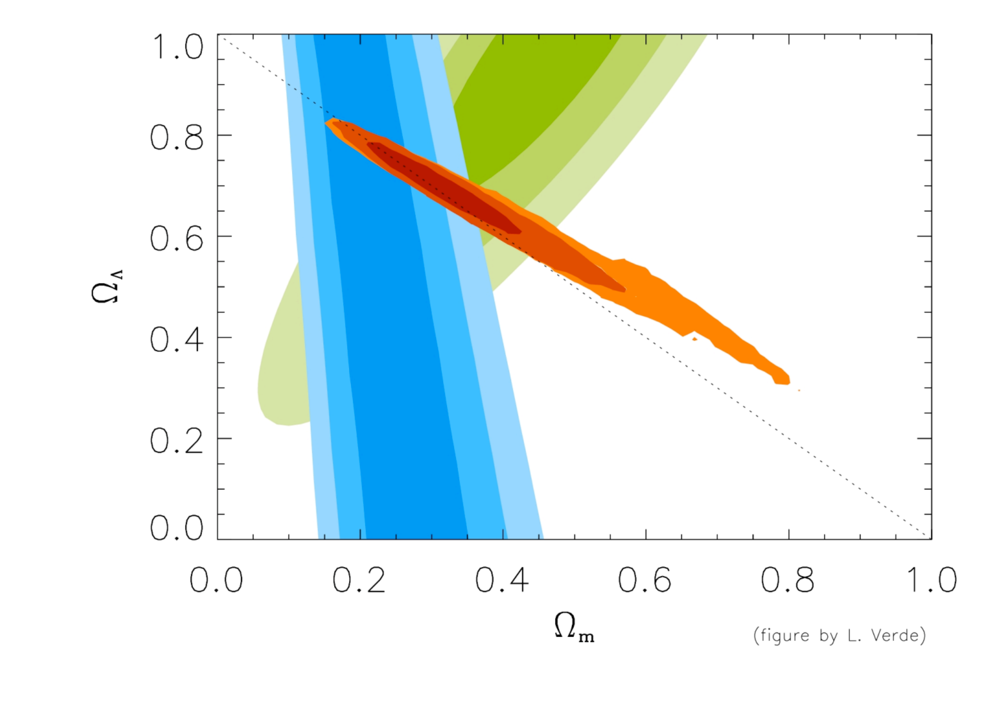
Flatness problem
Horizon problem
Monopole problem

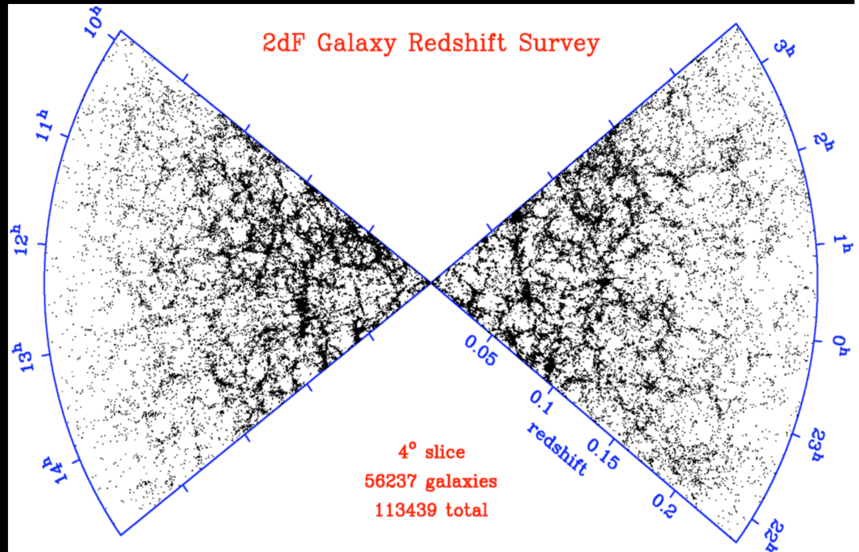
Origin of perturbations



Horizon problem

Flatness problem





Structure Problem

Very quickly you find that early on $|1-\Omega|<10^{-60}$

It is like balancing a pencil on its tip, coming back years later and still finding it balancing on its tip

The Horizon problem

Different type of Horizons in Cosmology

Since light travels at a final speed & Universe is expanding

PARTICLE HORIZON: Maximum comoving distance light can have propagated in ti to tf

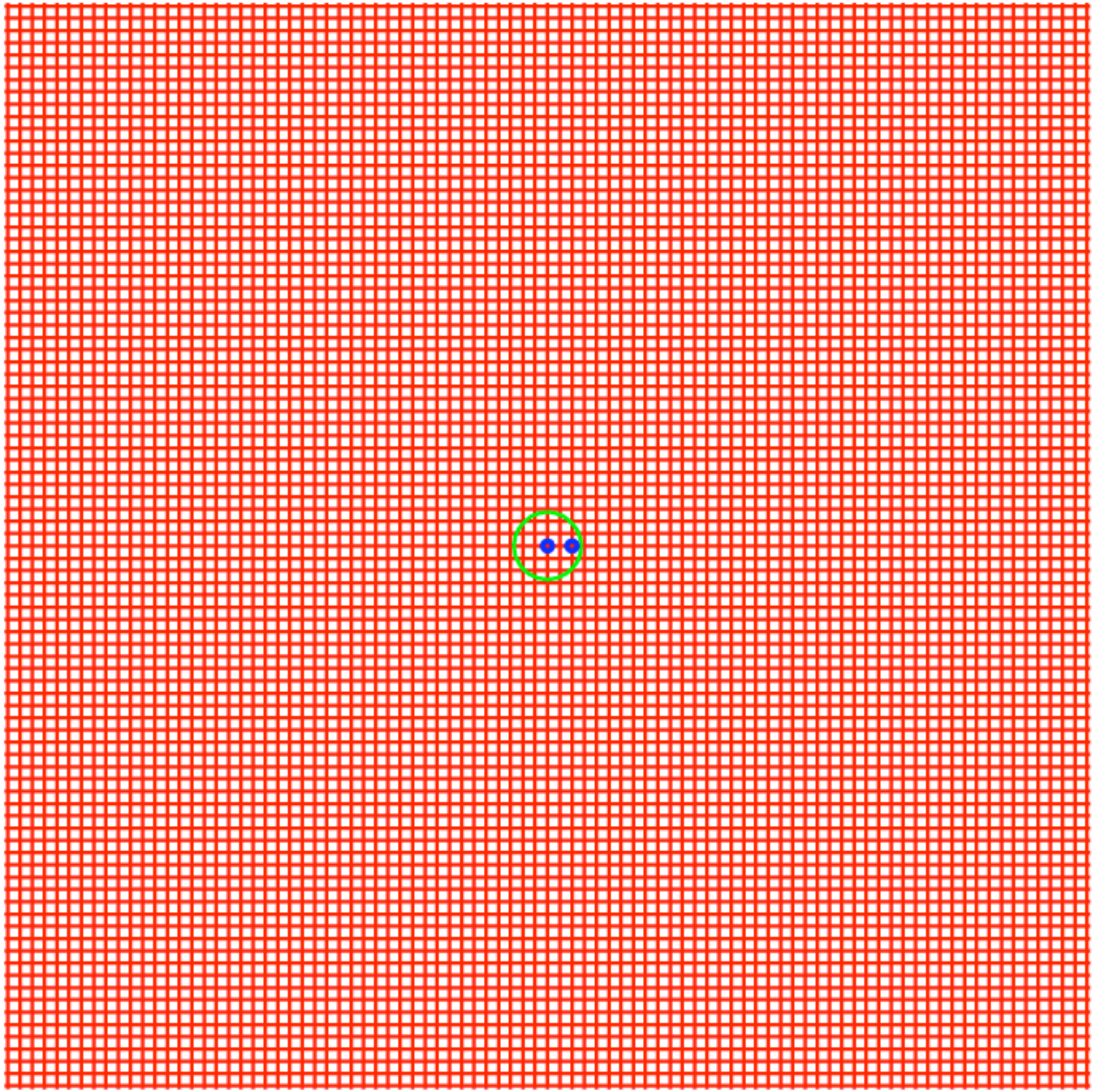
$$d_p(t) = \int_{t_i}^{t_f} \frac{dt}{a(t)}$$

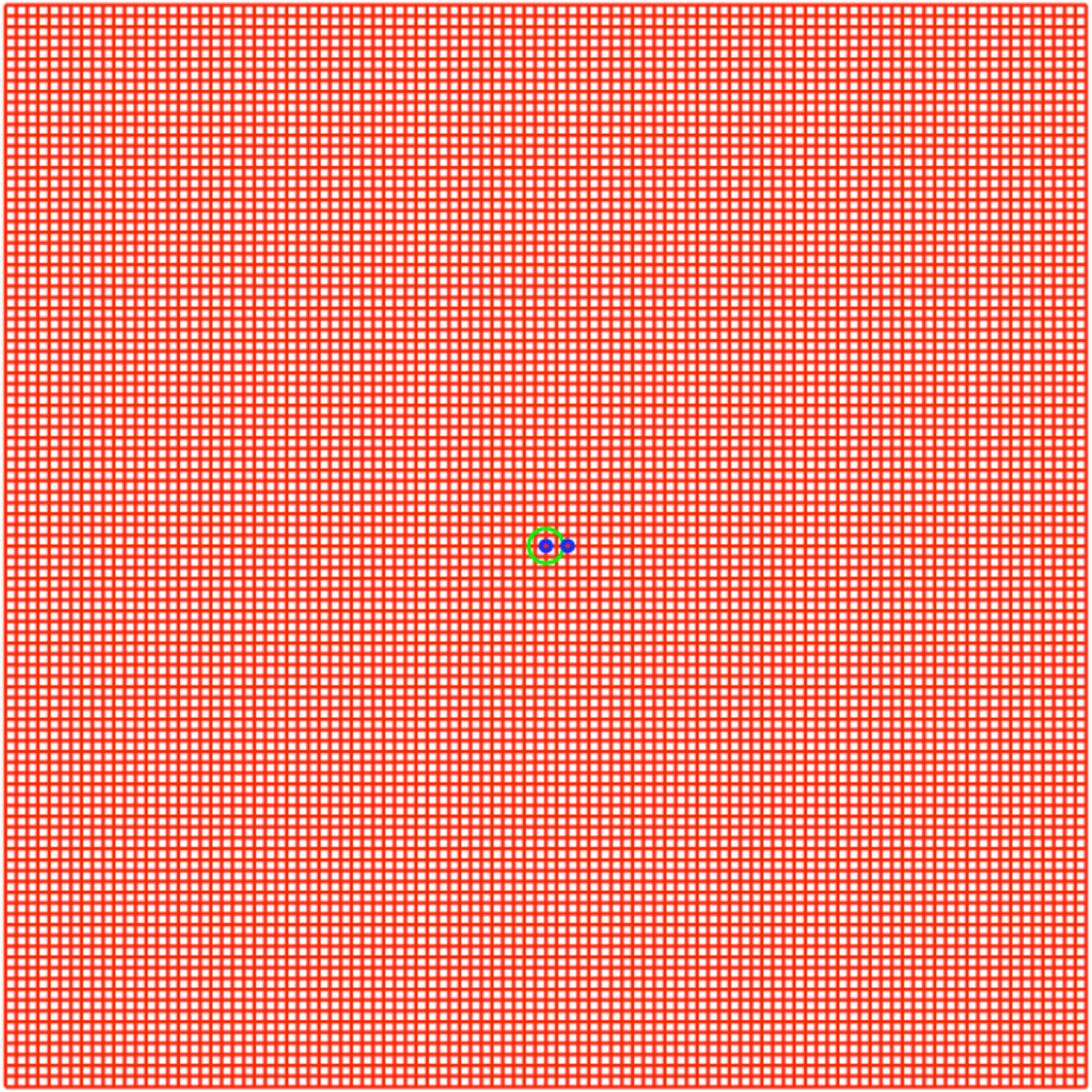
Accounts for all the past expansion history

Given the same dt, dp can be very different if a(t) is weird!

HUBBLE HORIZON: c/H or c/t0.
For normal expansion histories dp ~ c/H
For weird ones BEWARE!

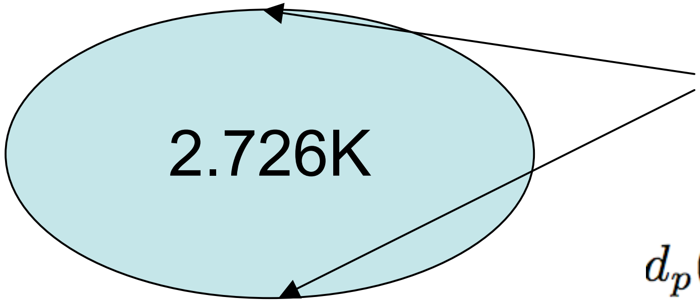
$$\frac{c}{H}$$





The Horizon problem

The universe is homogeneous and isotropic on large scales



Consider 2 antipodal points they are separated by $2d_H$~30000 Mpc

$$d_p(t_0) = c\int_{t_{cmb}}^{t_0} \frac{dt}{a(t)} \sim d_H(t_0);\;\; t_{cmb} << t_0$$

What was the Hubble radius (horizon) back then?

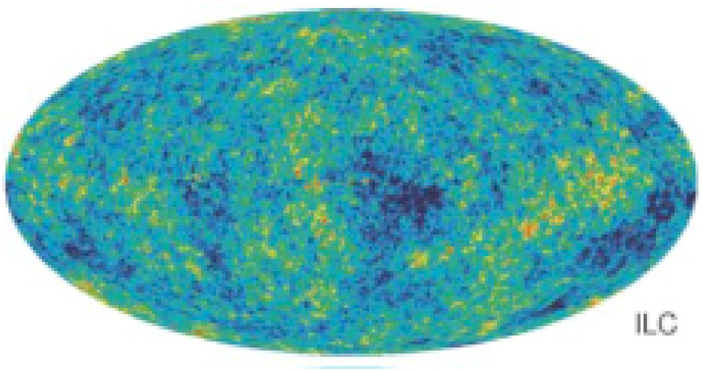
$$H(z)^2 \sim H_0^2\Omega_{m,0}(1+z)^3 \longrightarrow \frac{c}{H_{z=1000}} \simeq 0.2Mpc$$

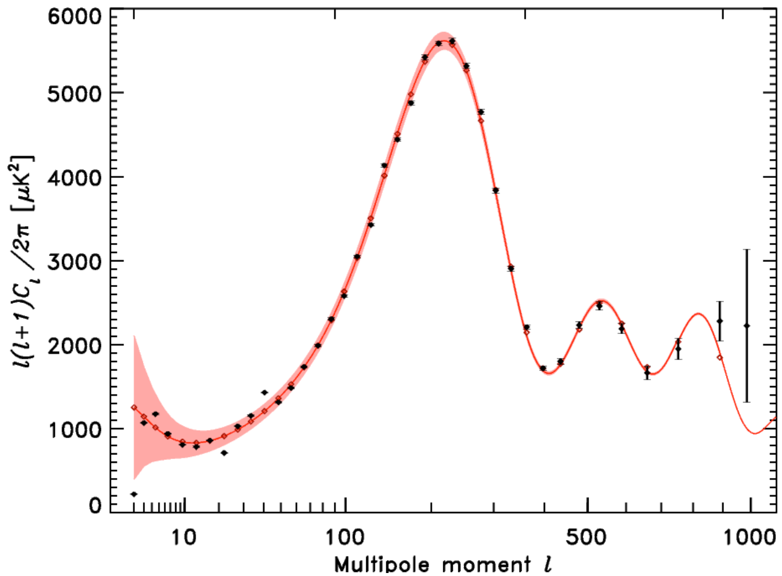
Only points at ~0.2 Mpc could have "talked"

Small aside

$$\theta_H(z_{CMB}) = \frac{d_H}{d_A} = \frac{d_H}{d_p/(1+z)} \sim 1^\circ$$

c_s ~c





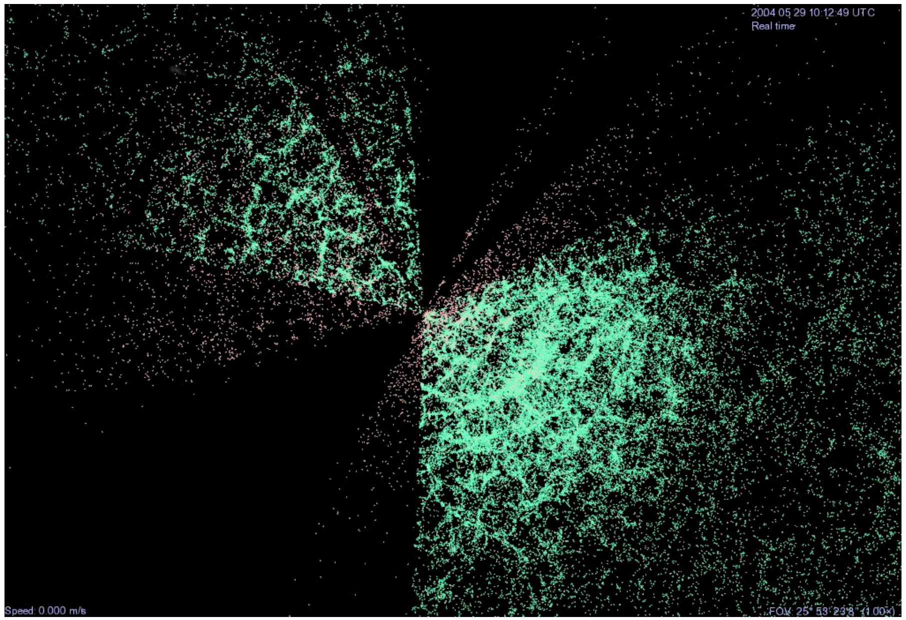
Compare with the size of the CMB spots!

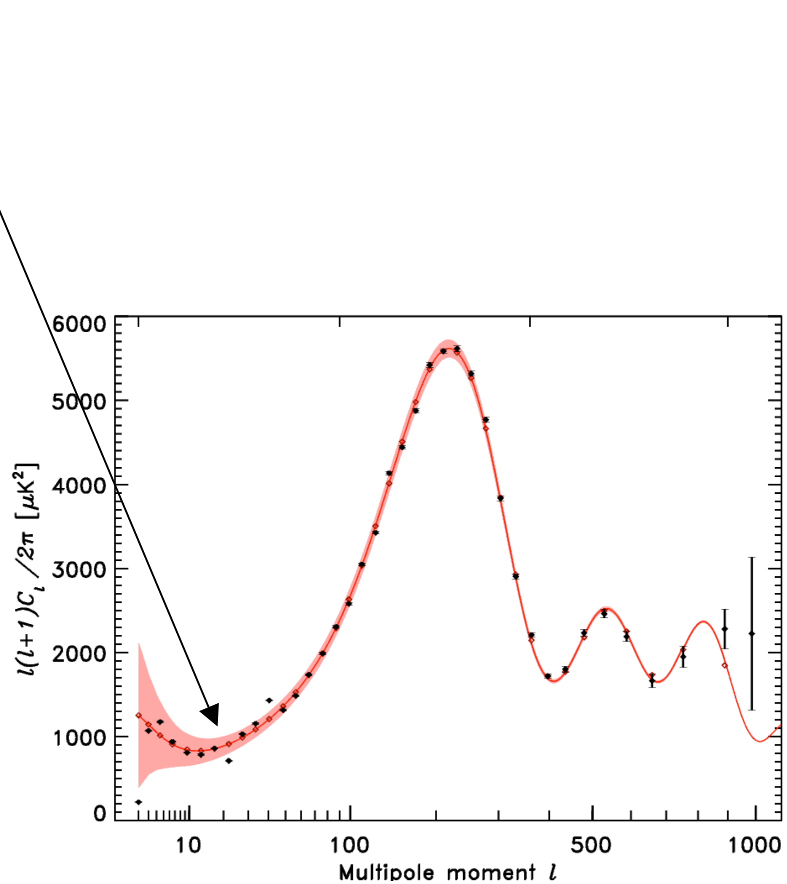
The last scattering surface can be divided in 40000 patches of degree size I.e. 40000 “horizons”….

How could they all be at 2.726K?

Imagine 40000 students taking an exam, and all returning THE SAME exam down to the commas…

And where the heck these perturbations come from?



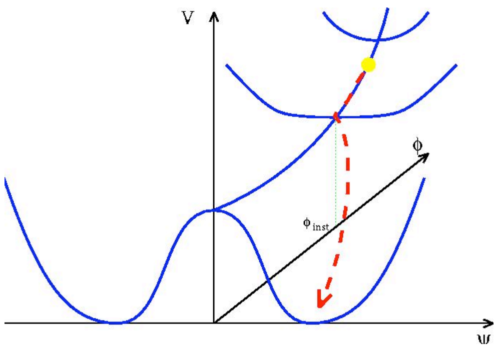


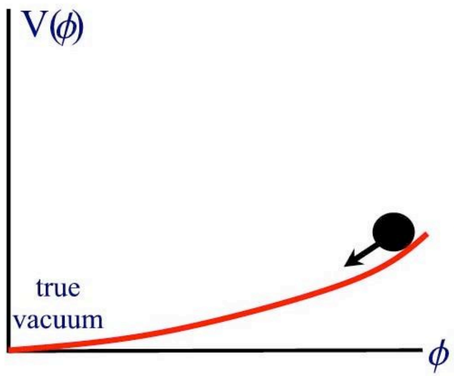
INFLATION to the rescue

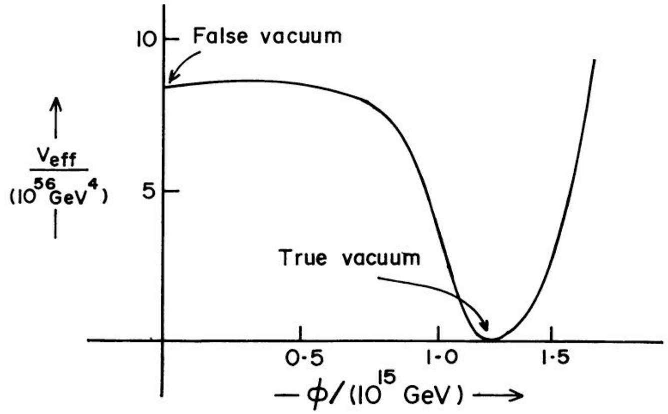
Started in the 1980 with A. Guth, active research area.
Still a "paradigm" not a proven fact…

Postulate a period of accelerated expansion
at the very beginning!
Something like a cosmological constant

Different scenarios, particle-physics motivated (?)







Any weirdness like monopole

Would be diluted away!

Inflation solves the Flatness problem

Something like a Λ

$$H = const\,; \quad a \sim \exp(H_I t)$$

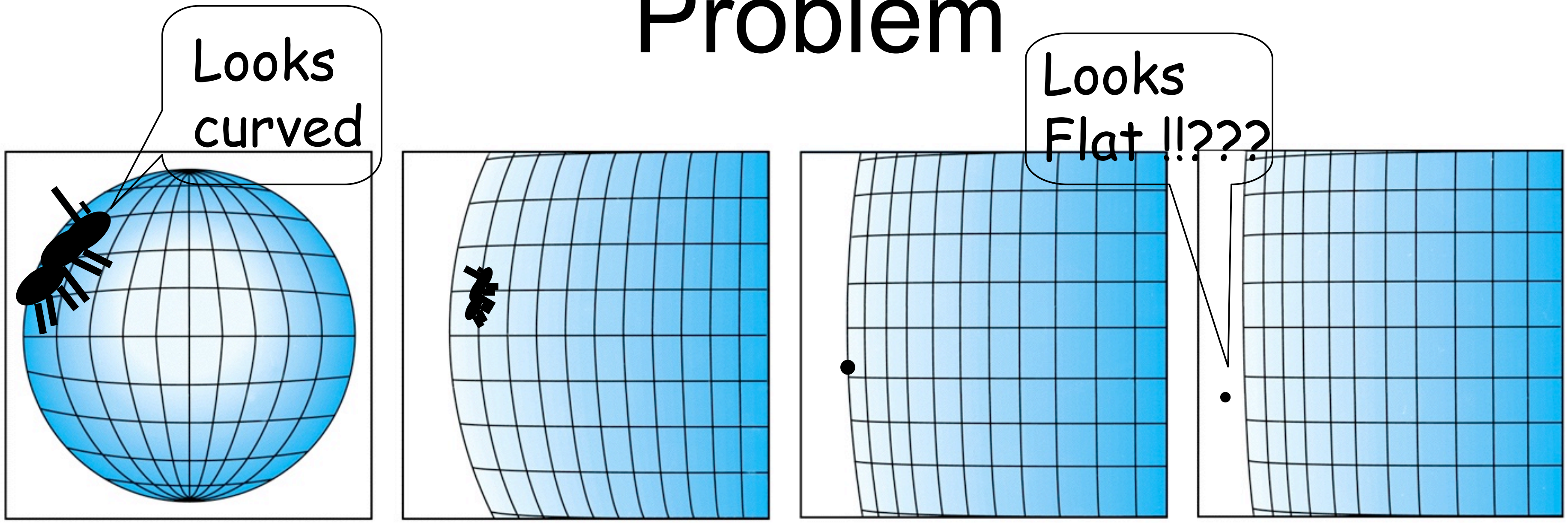
$$1 - \Omega(t) = \frac{c^2}{R_0^2 a^2 H^2}$$

$$\frac{a(t_f)}{a(t_i)} = e^N \quad N = H_i(t_f - t_i) \quad \mathrm{number\ \ of\ \ e-foldings}$$

$$|1 - \Omega(t_f)| = \exp(-2N)|1 - \Omega(t_i)|$$

For N~100 NOT BAD!

Inflation Solves the Flatness Problem



What made the Universe so flat?

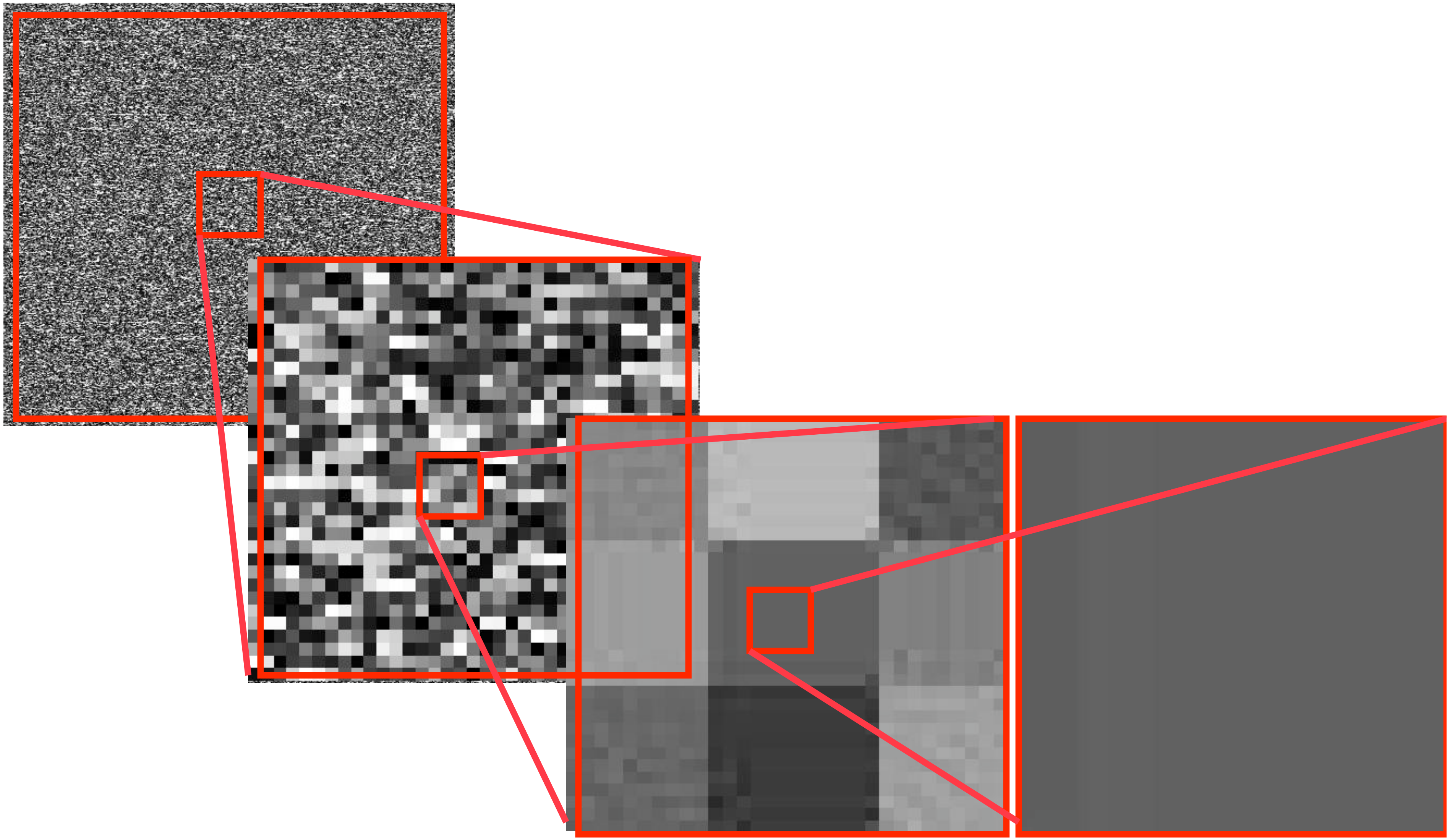
What made the Universe so big?

What made the universe so uniform?

What seeded the galaxies?

Why is the Universe so uniform?

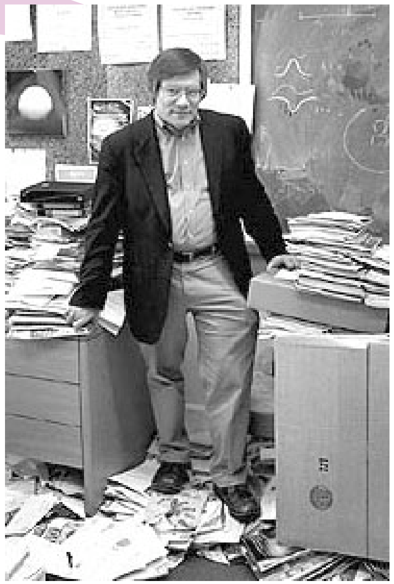
Inflation solves that



Inflation solves the Horizon problem

In an accelerated expansion the particle horizon
and the Hubble horizon can be VERY DIFFERENT

Given the same dt, dp can be very different if a(t) is weird!



As an added bonus:

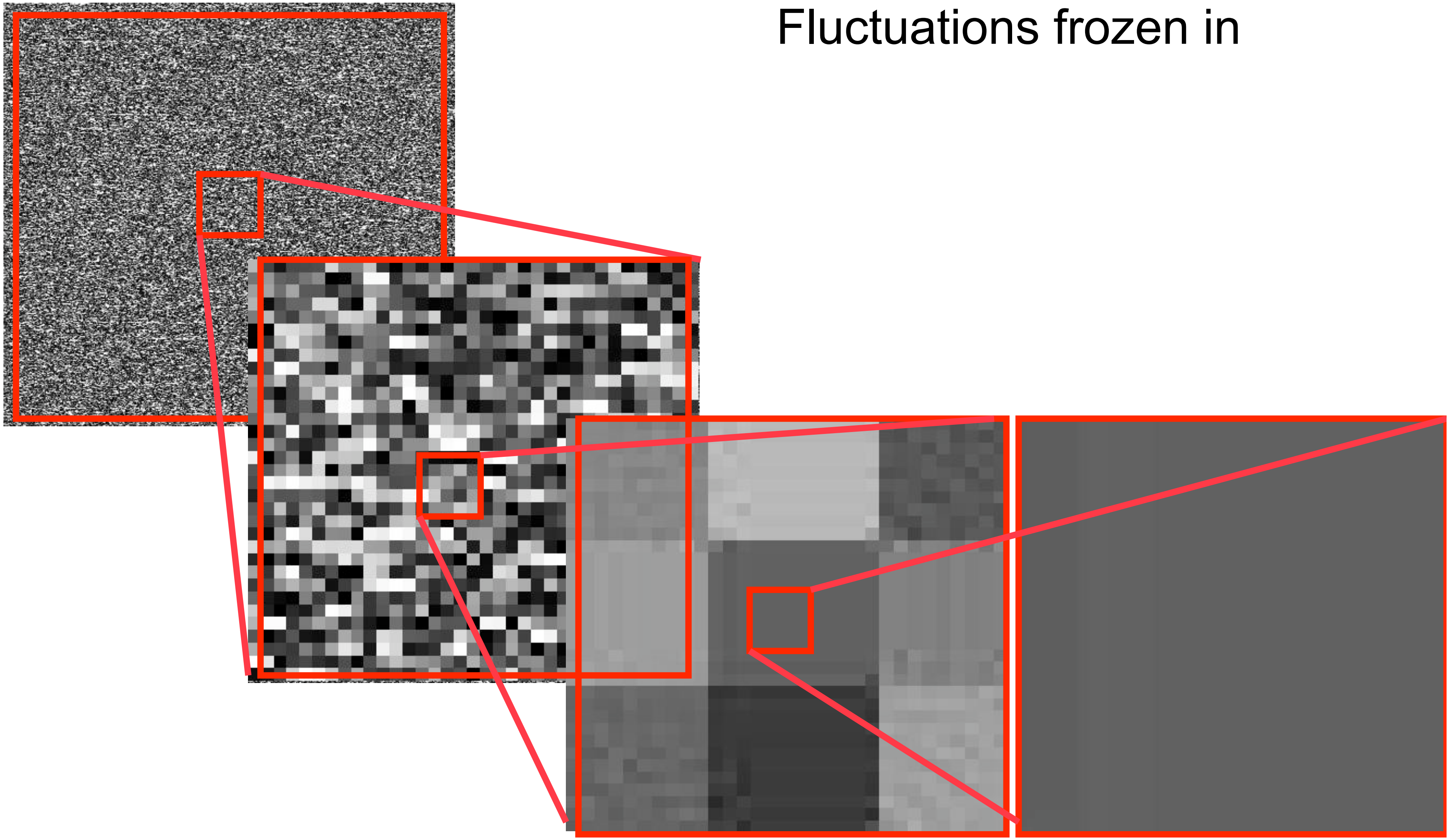
Inflation generates Gaussian perturbations:
quantum fluctuations stretched to become classical
by the expansion. The mechanism is similar to Hawkings
radiation. (The event horizon being the complementary
concept to the particle horizon…)

Turns out that the power spectrum of these perturbations will be
a power law: different model of inflation predict slightly different
power laws, but all close to “scale invariant”..

Perturbations outside the Horizon?

Inflation solves that

Fluctuations frozen in



CAN THIS BE TESTED?

flatness 

Power law primordial power spectrum 

Can even hope to distinguish specific models

Super horizon fluctuations (polarization)  Coming next

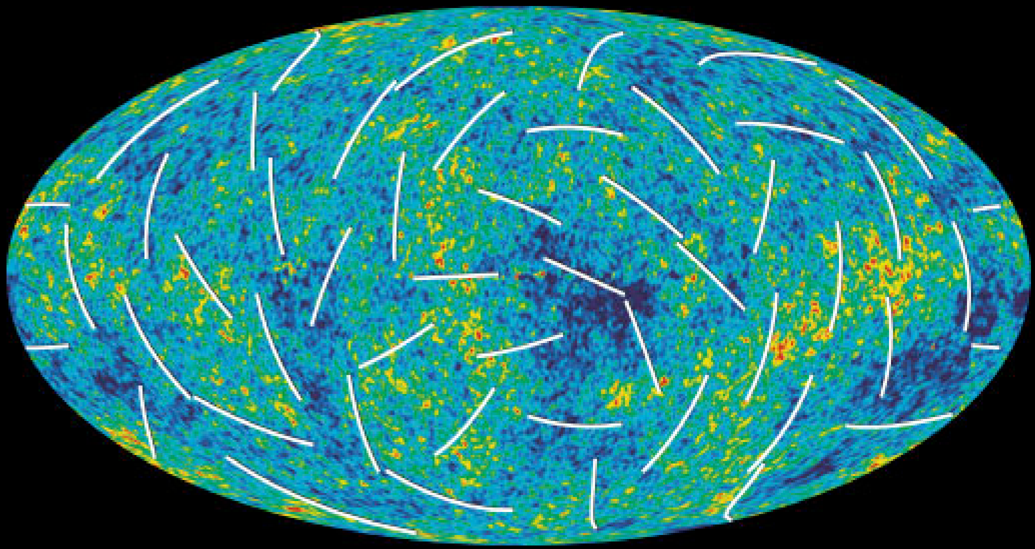
gaussianity 

Can even hope to distinguish specific models

Stochastic background of gravity waves
(polarization)

There's more!

Polarization

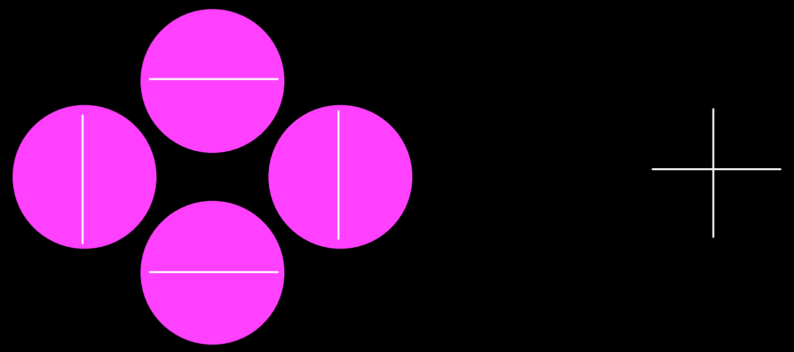


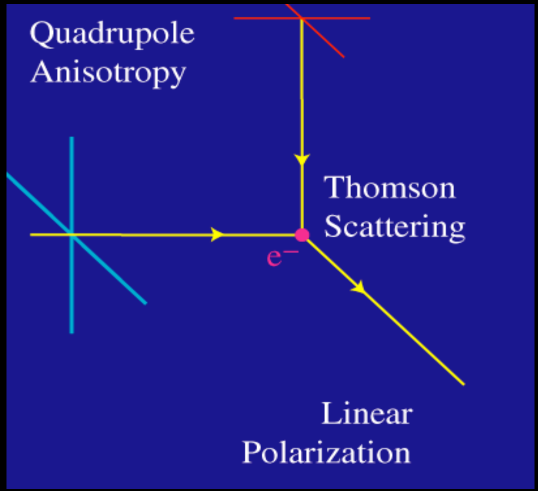
WMAP (2006)

First detected by DASI in 2002

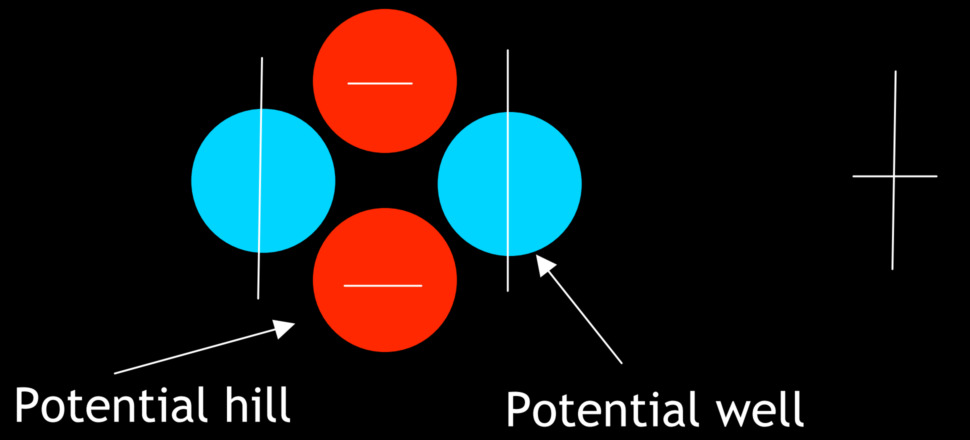
Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.





From Wayne Hu

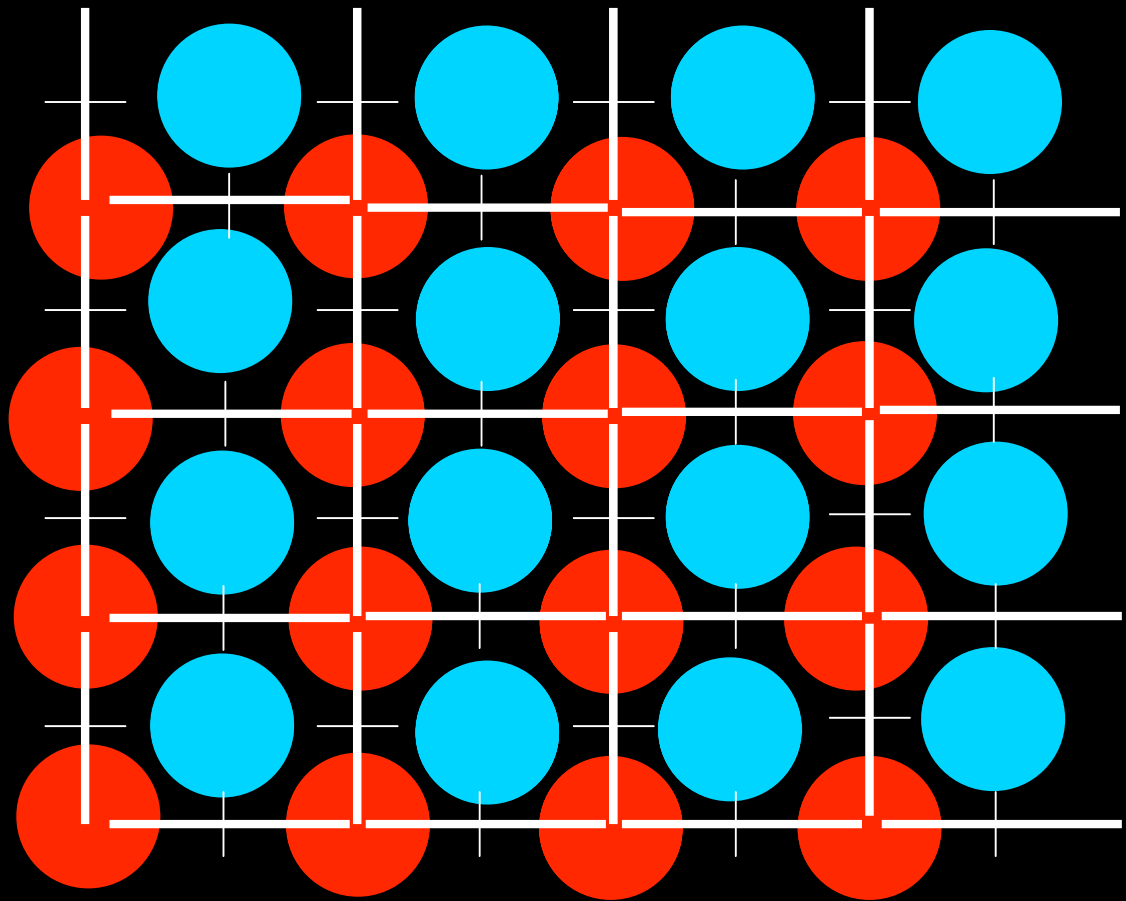


YES, there is also reionization

Rees 68, Coulson et al '94
….. Hu& White 97(pedagogical)

Polarization for density perturbation

- Radial (tangential) pattern around hot (cold) spots.

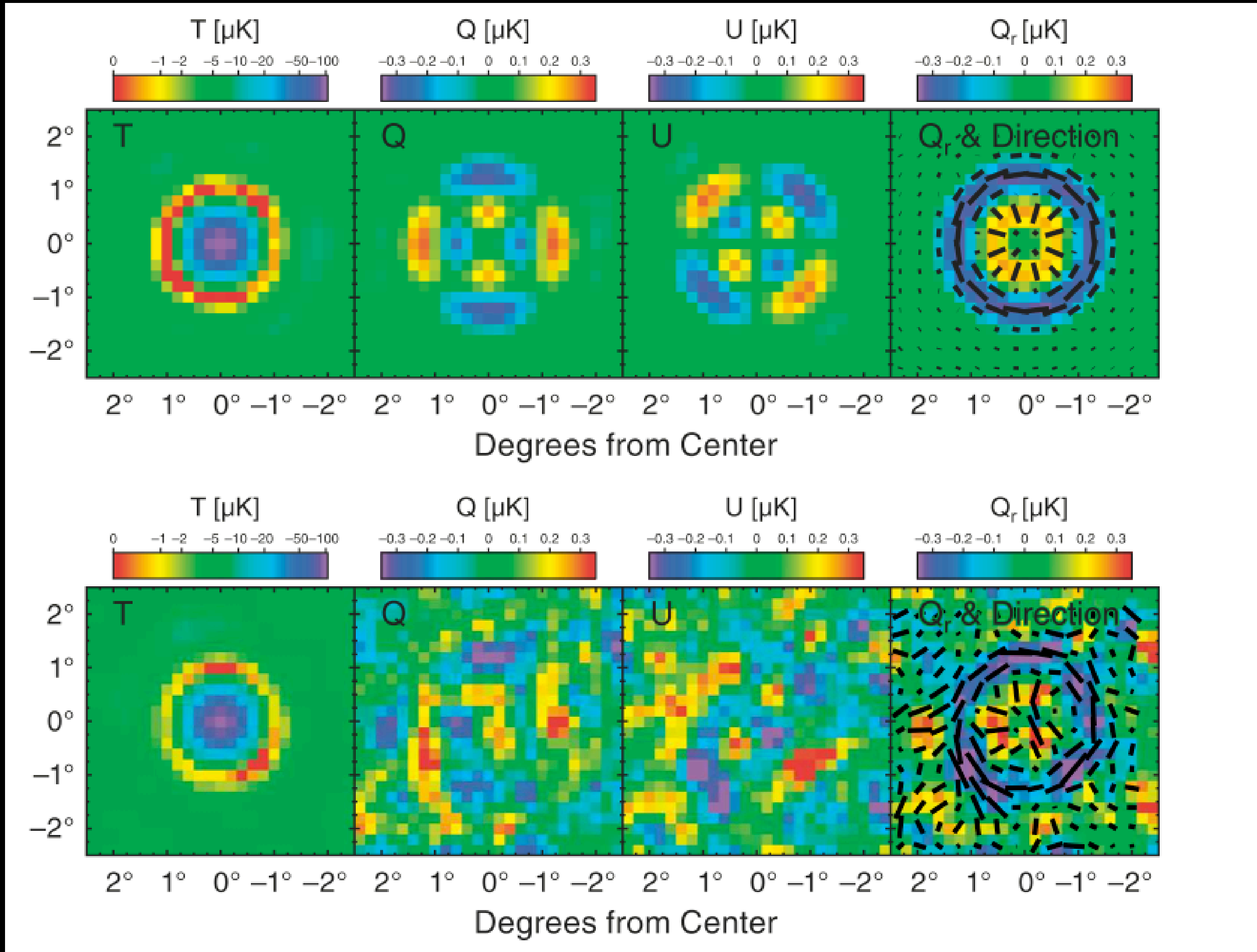


And it has been seen!

Komatsu, WMAP7yrs team (2010)

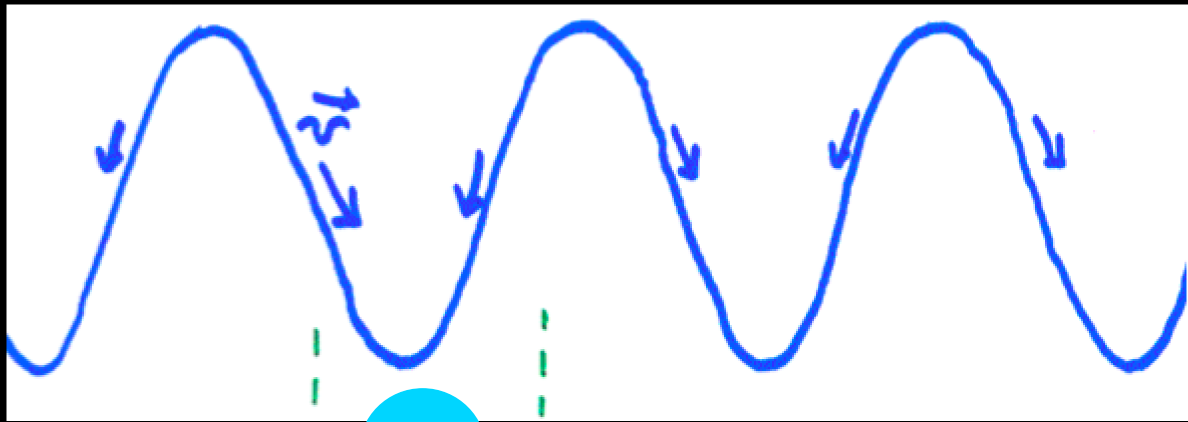
Theory prediction

Observed

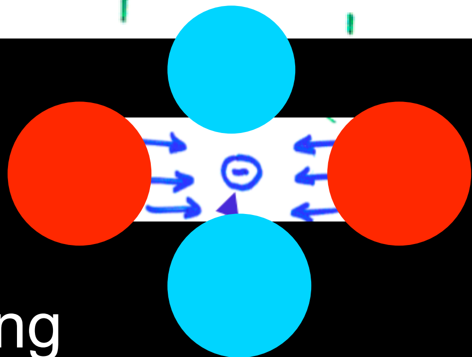


Large-scale TE anti correlation

Density mode



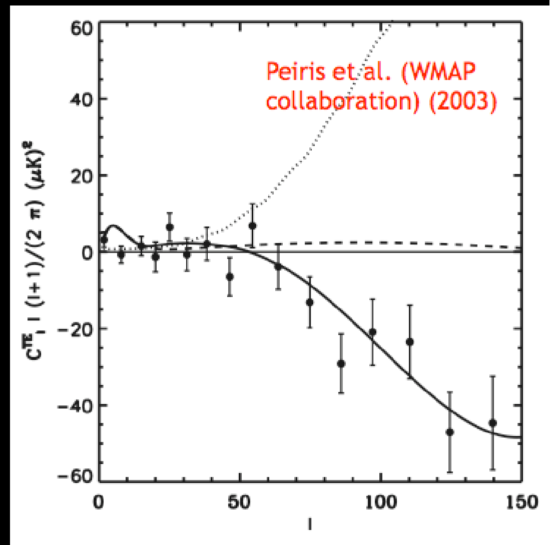
Velocities (hot to cold)



Hot due to doppler

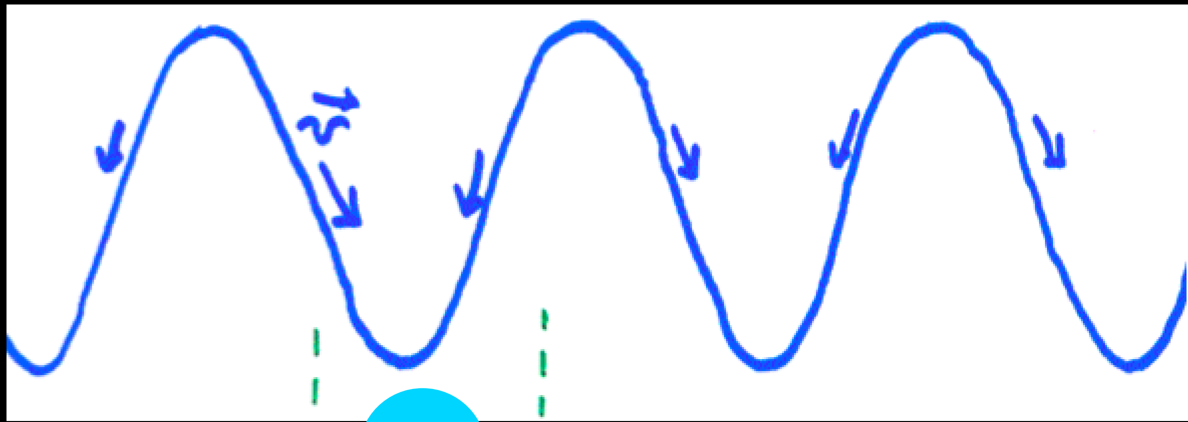
During decoupling

And it has been seen (2003)

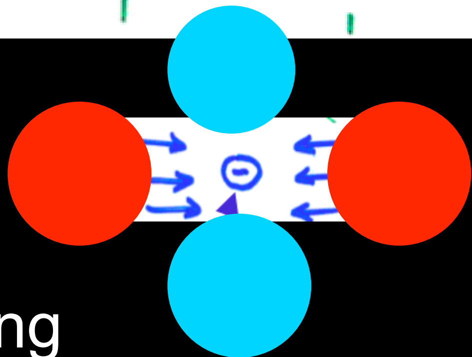


Large-scale TE anti correlation

Density mode

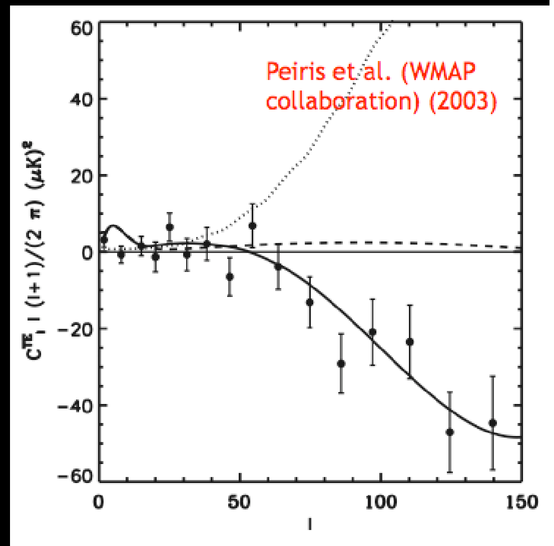


Velocities (hot to cold)



Hot due to doppler

During decoupling



Gravity waves (tensor) are different…

Gravity waves stretch space…

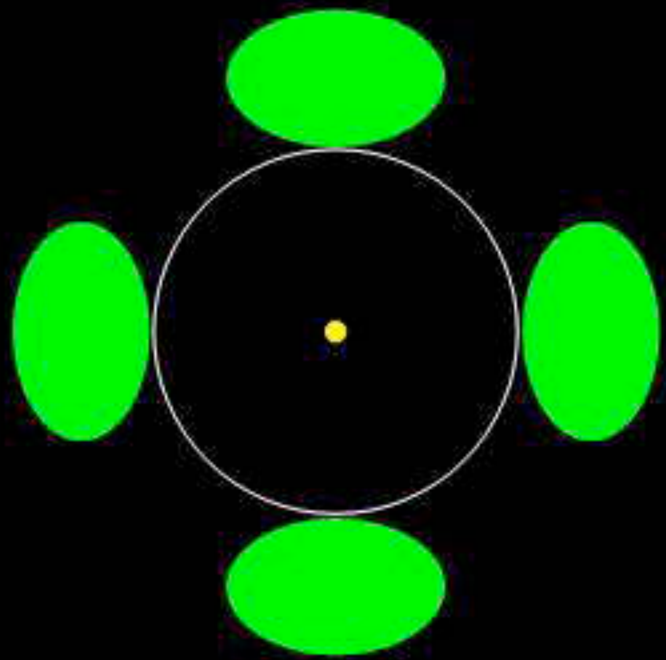
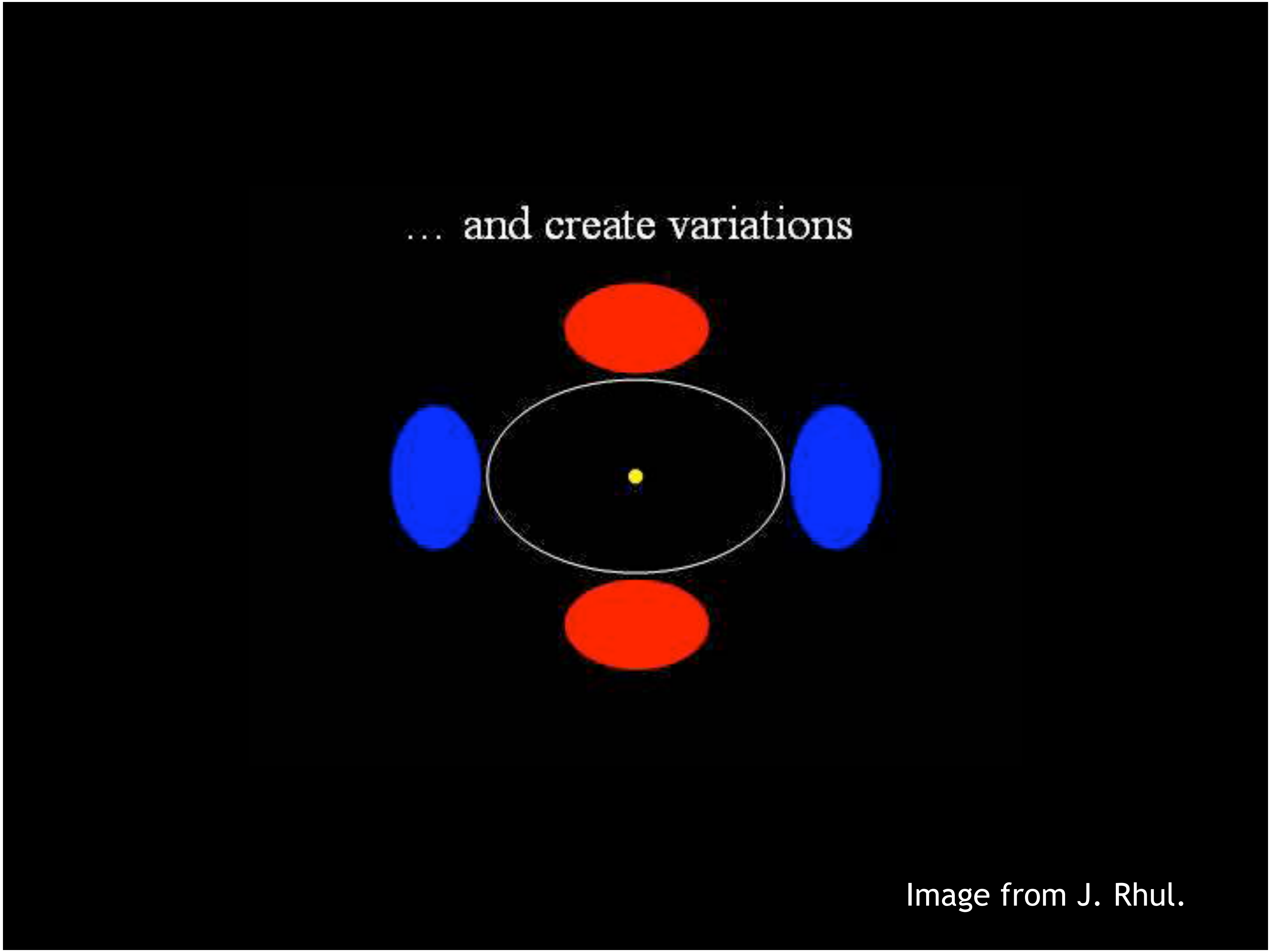
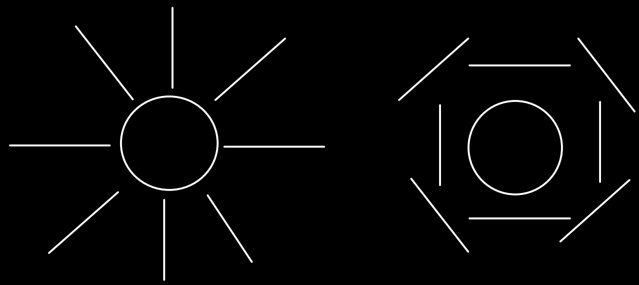


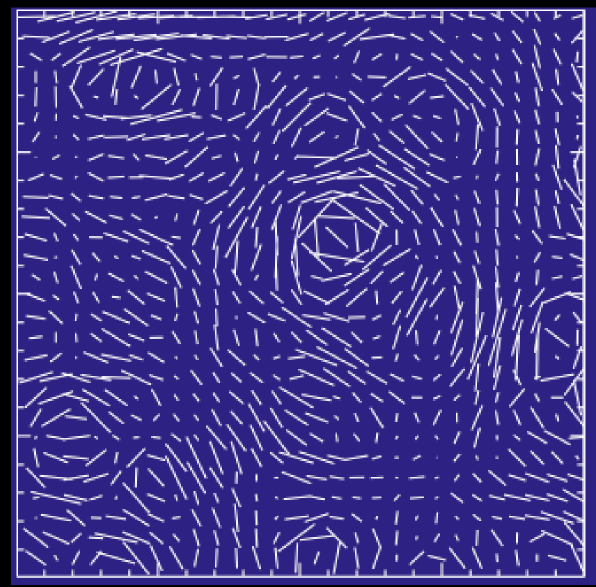
Image from J. Rhul.


… and create variations
Image from J. Rhul.

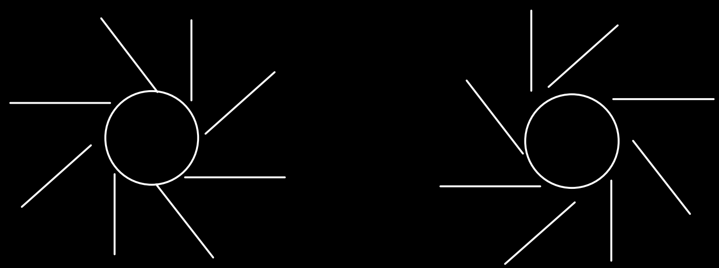
E and B modes polarization

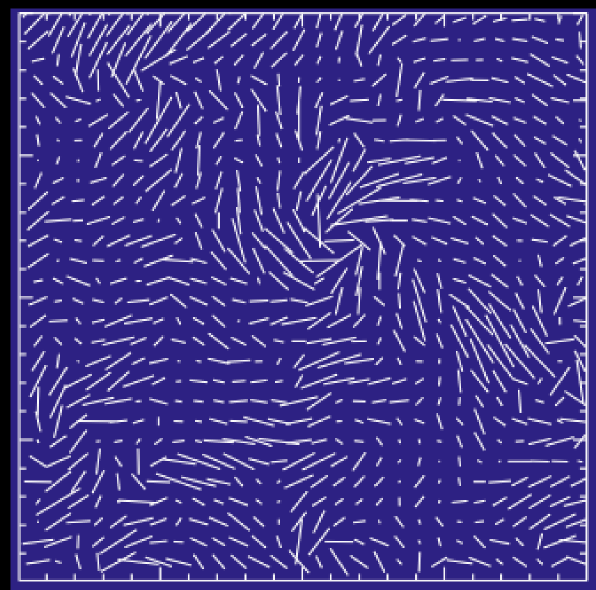
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes





Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

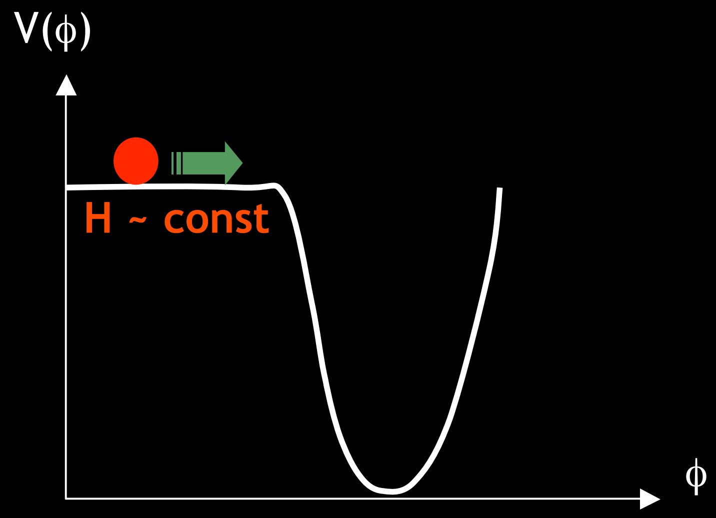
Seeing (indirectly) z>>1100

Information about the shape of the inflaton potential is enclosed in the shape and amplitude of the primordial power spectrum of the perturbations.

Information about the energy scale of inflation (the height of the potential) can be obtained by the addition of B modes polarization amplitude.

In general the observational constraints of Nefold>50 requires the potential to be flat (not every scalar field can be the inflaton). But **detailed measurements of the shape of the power spectrum can rule in or out different potentials**. For example: Kahler inflation towards the KKLT minimum, or for multi-field other minima.

The inflationary solution



Accelerated expansion…

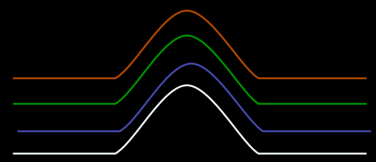
Factor 10^{26} in less than 10^{-34} s

Solves cosmological problems (Horizon, flatness).

Cosmological perturbations arise from quantum fluctuations, evolve classically.

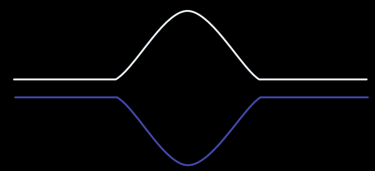
Guth (1981), Linde (1982), Albrecht & Steinhardt (1982), Sato (1981), Mukhanov & Chibisov (1981), Hawking (1982), Guth & Pi (1982), Starobinsky (1982), J. Bardeen, P.J. Steinhardt, M. Turner (1983), Mukhanov et al. 1992), Parker (1969), Birrell and Davies (1982)…

Perturbations: adiabatic



Photons
Neutrinos
Baryons(+electrons)
Dark matter
(dark energy negligible early on)

(isocurvature



)

Tensor
(gravitational waves)

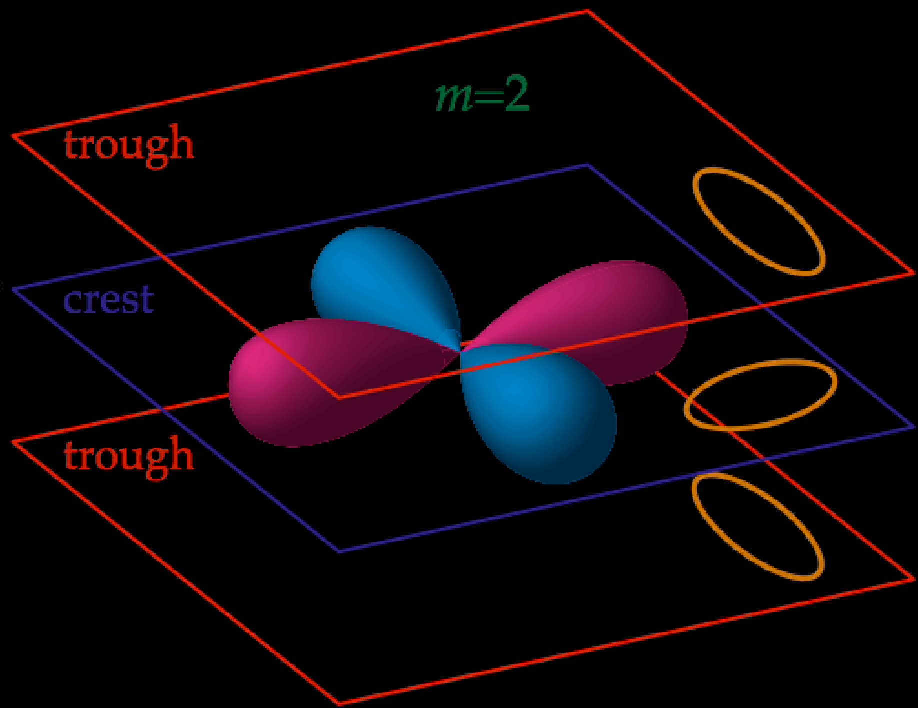
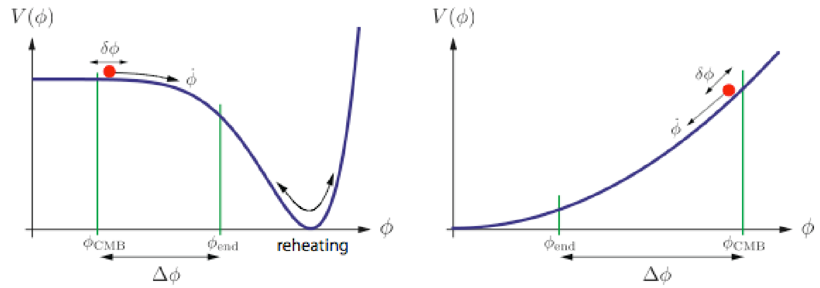


Fig. From W. Hu.

Inflationary cosmology

Friedmann equations, a is scale factor



$$H^2 = \left(\frac{\dot a}{a}\right)^2 = \frac{1}{3M_{pl}^2}\rho\,, = \frac{1}{3M_{pl}^2}\left(\frac{1}{2}\dot\phi^2 + V(\phi)\right)$$

$$\dot H + H^2 = \frac{\ddot a}{a} = -\frac{1}{6M_{pl}^2}(\rho + 3p) = -\frac{1}{3M_{pl}^2}\left(\dot\phi^2 - V(\phi)\right)$$

$$\ddot\phi + 3H\dot\phi + V'(\phi) = 0\,.$$

Single field slow roll inflation:
the simplest example

Inflate: $V \gg \dot\phi^2$. $\quad a(t) \approx a(0)e^{Ht}\,, \qquad H \approx \text{const}\,.$

Sustain it $|\ddot\phi| \ll |V'|$.

Process must terminate somehow

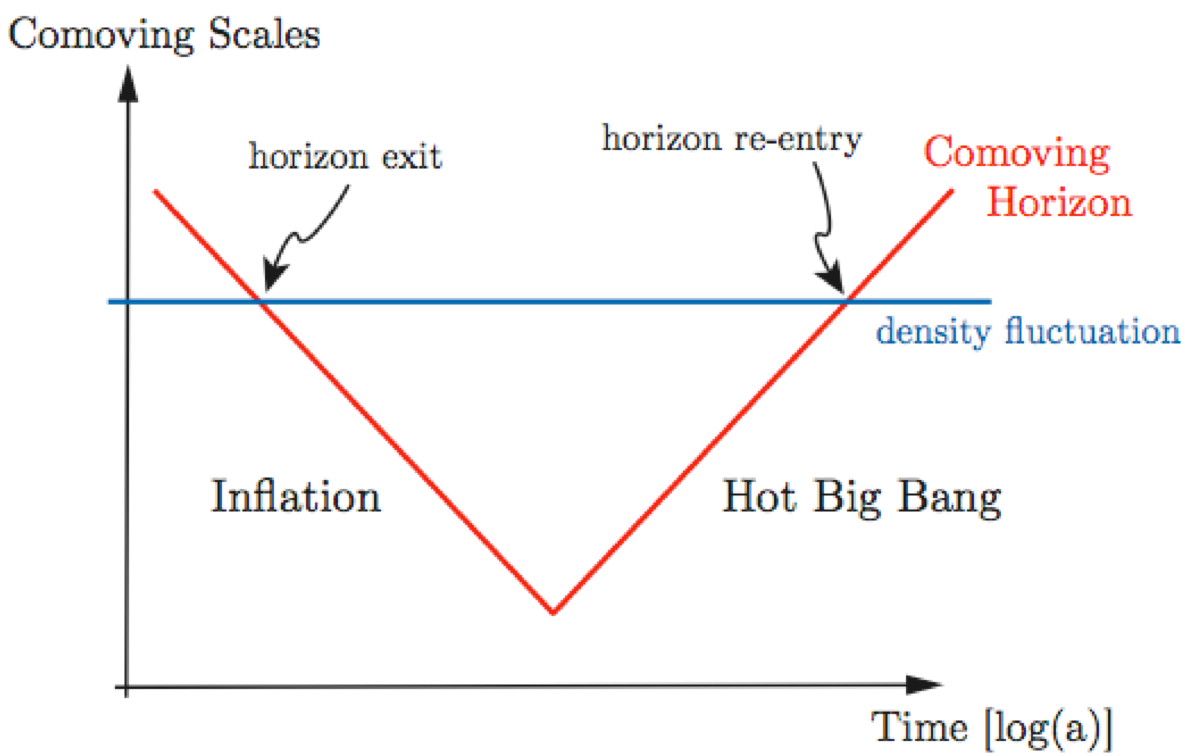
Restrictions in the form of the inflaton potential V:
SLOW ROLL PARAMETERS

$$\epsilon \equiv -\frac{\dot H}{H^2} = \frac{M_{pl}^2}{2}\frac{\dot\phi^2}{H^2} \approx \frac{M_{pl}^2}{2}\left(\frac{V'}{V}\right)^2, \qquad |\eta| \approx M_{pl}^2\left|\frac{V''}{V}\right|$$

Inflationary cosmology

Physical wavelength of fluctuations is stretched by expansion
The physical horizon is time dependent

Physical wavelengths grow faster than the horizon



Origin of structure

Quantum fluctuations get stretched to become classical

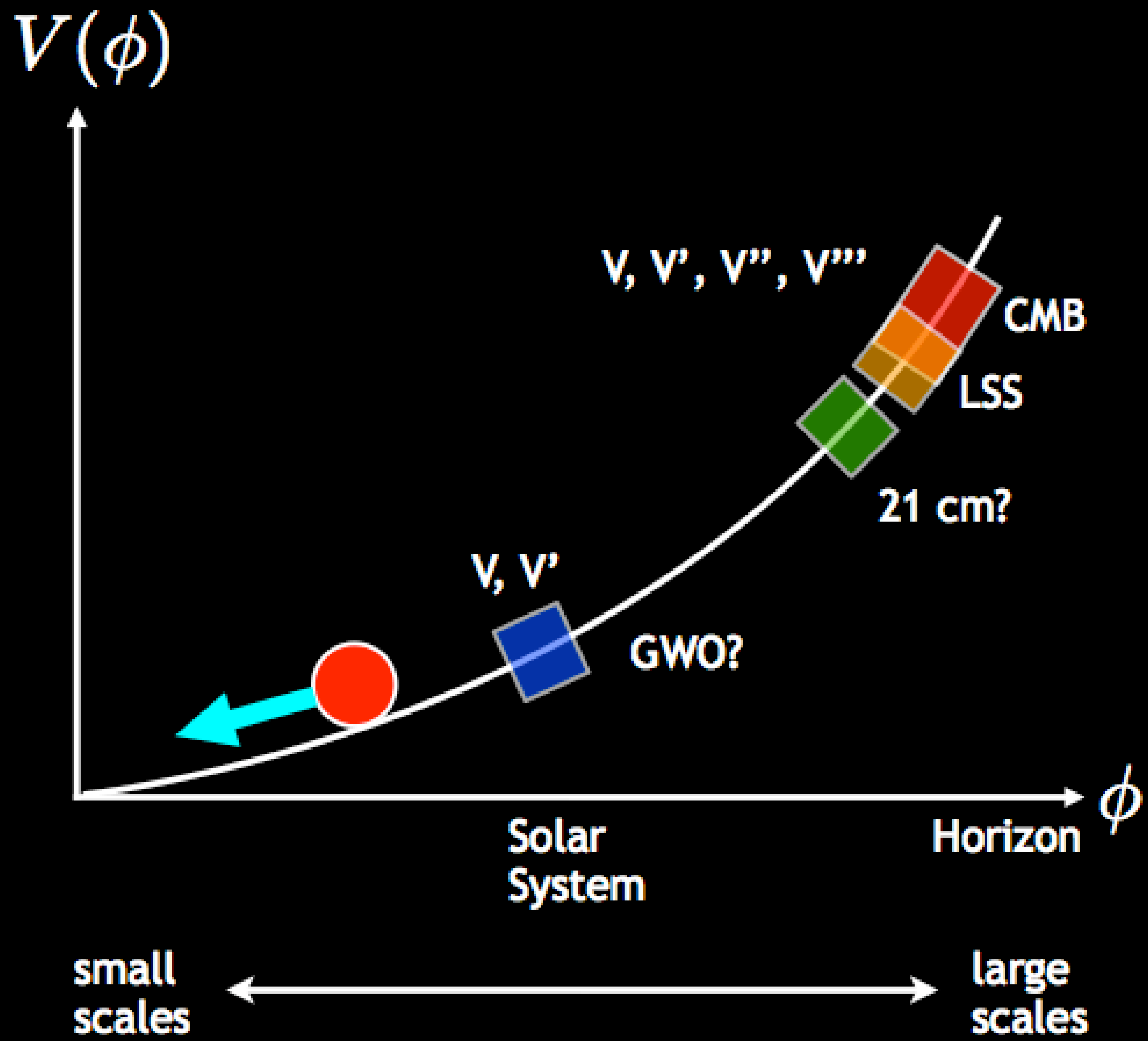
and "super-horizon" because of the accelerated expansion

But the spacing of the fluctuations
(their power as a function of scale)
depend on how fast they exited the horizon (H)

Which in turns depend on the inflaton potential

The shape of the primordial power spectrum
encloses information on the shape of the inflaton potential!

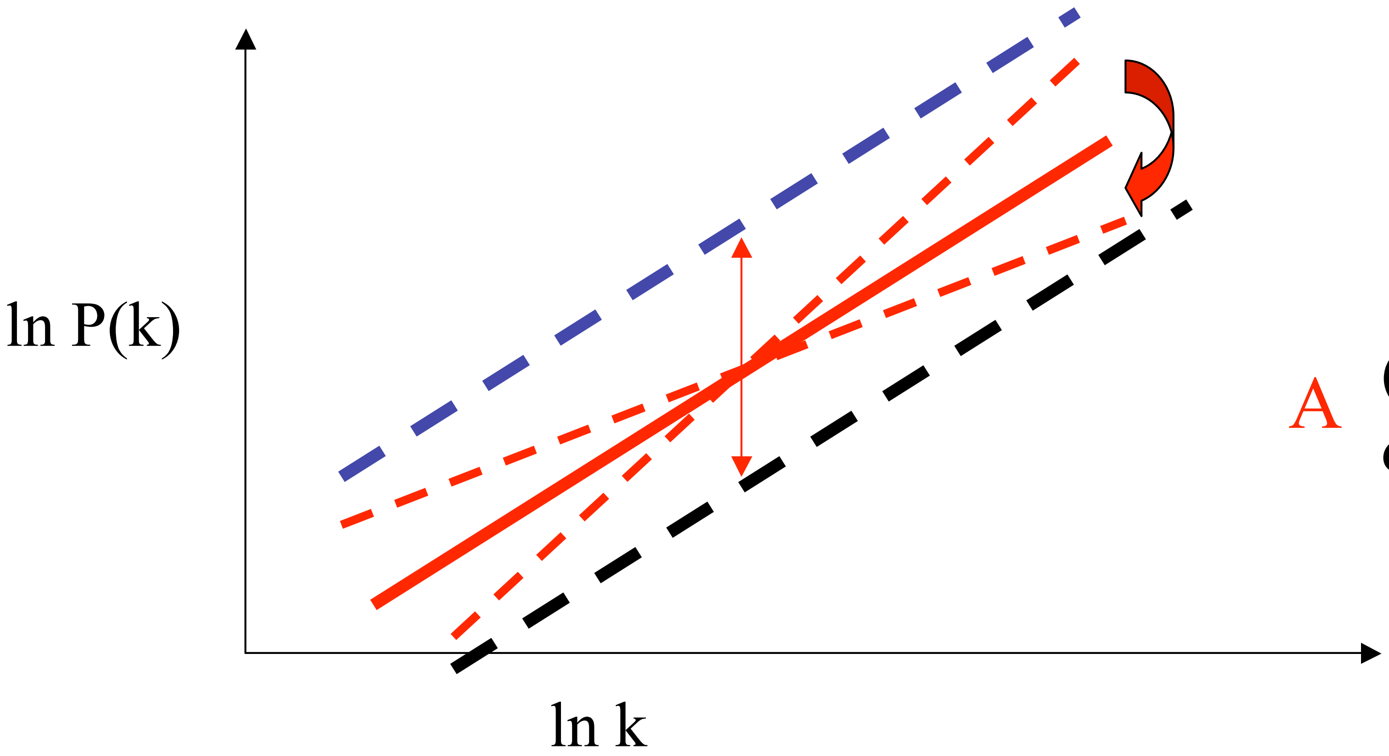
Fingerprints of the early universe



Primordial power spectrum= $A\ k^n$

Amplitude of the power law

slope



A (convention dependent)

Equal power per log k, n=1, scale invariant

Slow roll predictions

$$P_s(k) = \frac{1}{24\pi^2 M_{\rm pl}^4} \frac{V}{\epsilon}\bigg|_{k=aH}, \qquad n_s - 1 = 2\eta - 6\epsilon\,,$$

$\varepsilon \propto V'/V$

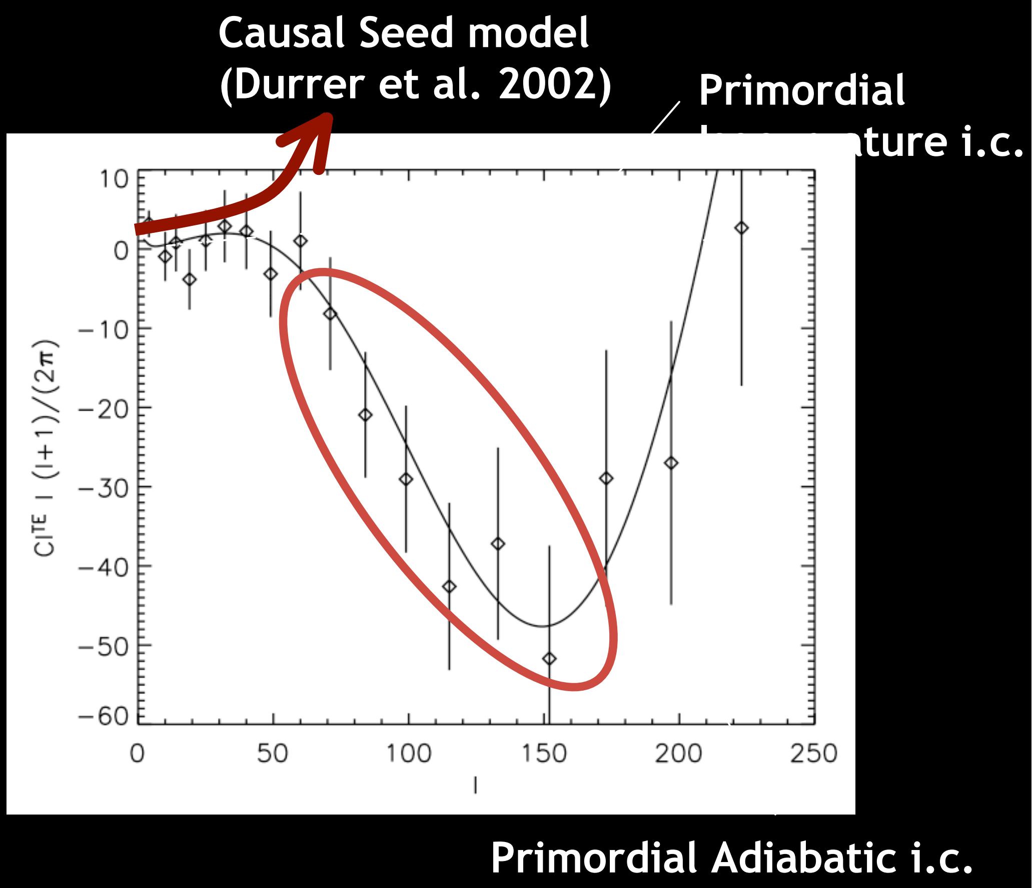
$$P_t(k) = \frac{2}{3\pi^2} \frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}, \qquad n_t = -2\epsilon\,, \qquad r = 16\epsilon\,.$$

$$V(\phi) = V|_\star + V'|_\star (\phi - \phi_\star) + \frac{1}{2} V''|_\star (\phi - \phi_\star)^2 + \frac{1}{3!} V'''|_\star (\phi - \phi_\star)^3 + \cdots$$

Other models, of course

CMB Consistent with Simplest Inflationary Models

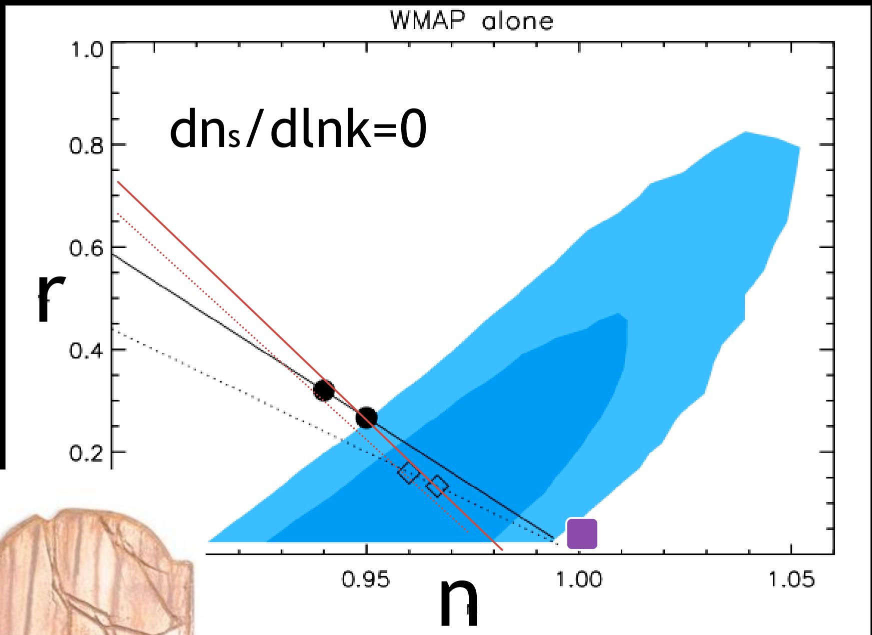
- Flat universe:
  $\Omega_{tot} = 1.0052 \pm 0.0064$
  (with SN and BAO)
- Gaussianity: $-9 < f_{NL} < 111$
- Power Spectrum spectral index nearly scale-invariant:
  $n_s = 0.97 \pm 0.01$
- Adiabatic initial conditions
- Superhorizon fluctuations
  (TE anticorrelations)

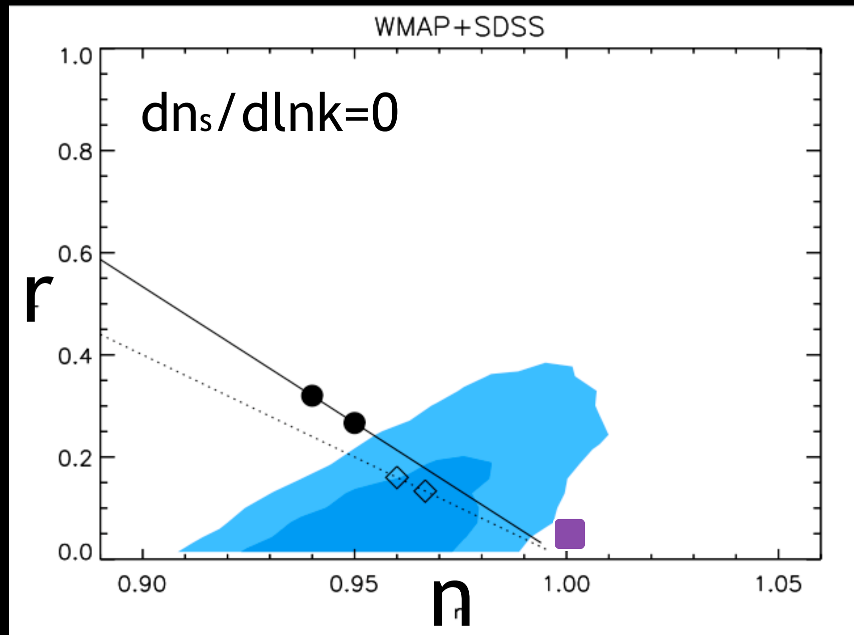


Hu & Sujiyama 1995
Zaldarriaga & Harari 1995
Spergel & Zaldarriaga 1997
Peiris et al 2003

Still testing basic aspects of inflationary mechanism rather than specific implementations

Specific models critically tested





Models like $V(\phi)\sim\phi^p$

○ p=4 ◆ p=2 For 50 and 60 e-foldings

■ HZ

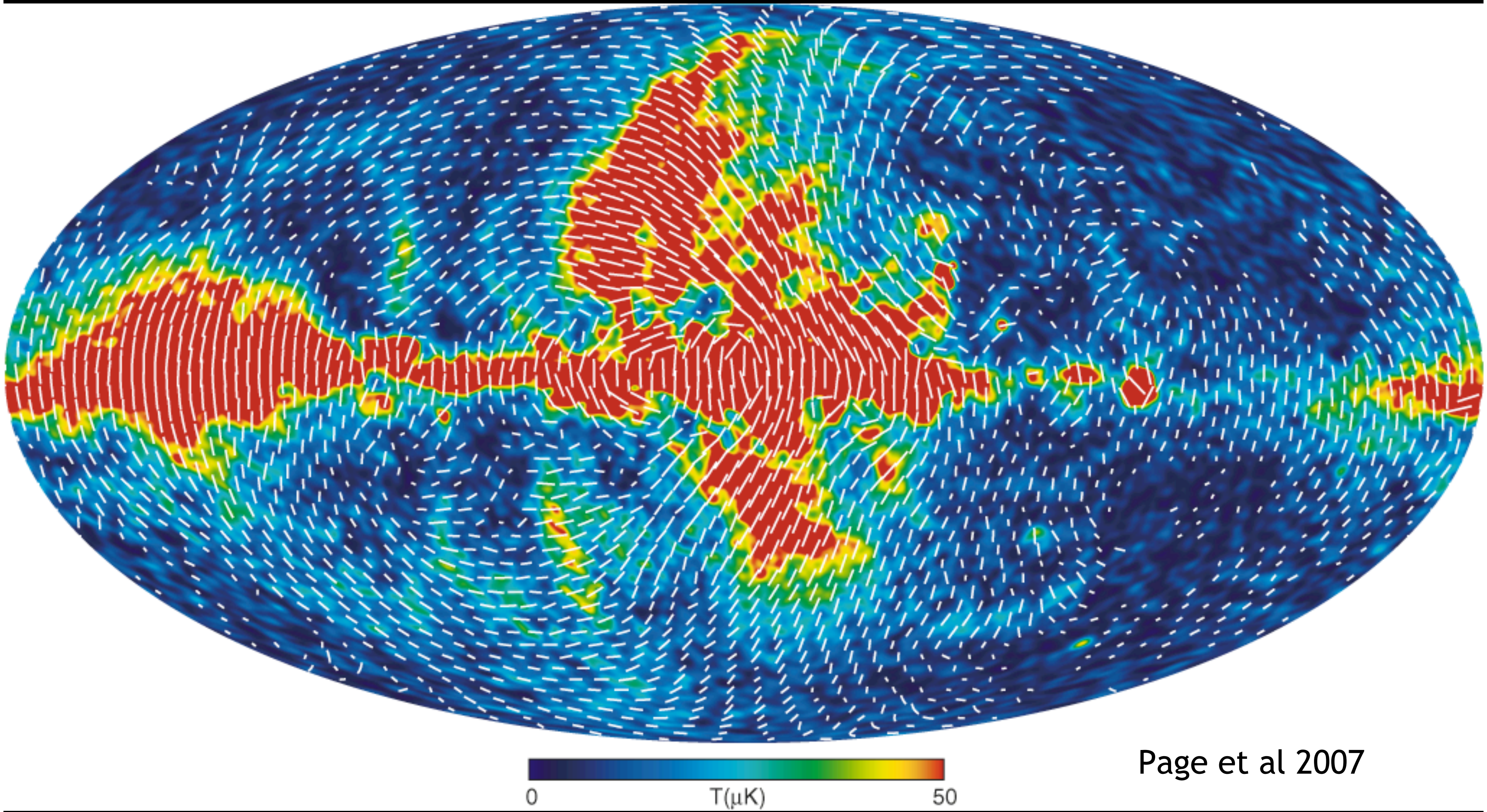
——— p fix, Ne varies

——— p varies, Ne fix

We happen to live in a galaxy!

K Band (23 GHz)

Dominated by synchrotron; Note that polarization direction is perpendicular to the magnetic field lines.



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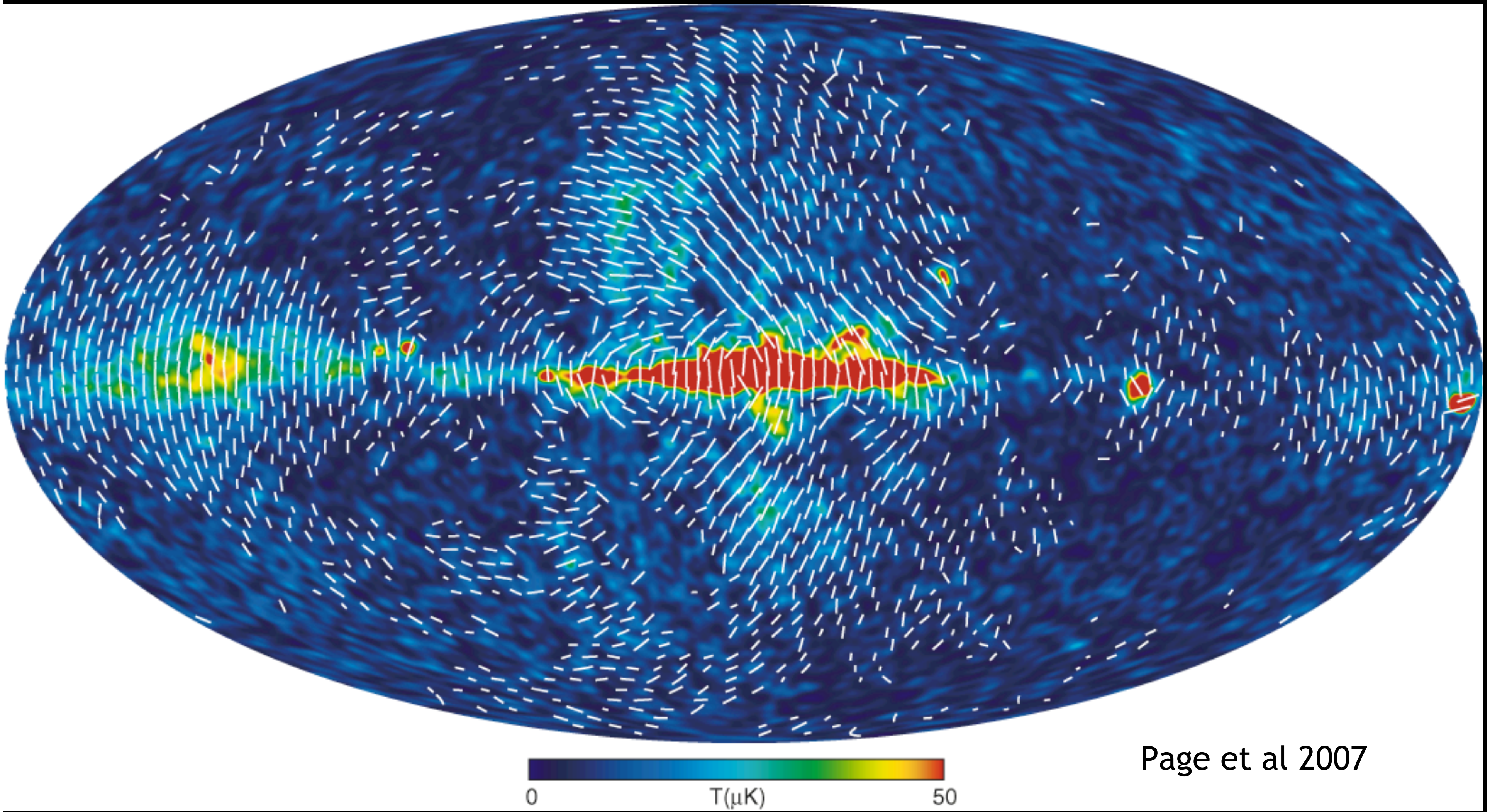
Ka Band (33 GHz)

Synchrotron decreases as $n^{-3.2}$ from K to Ka band.



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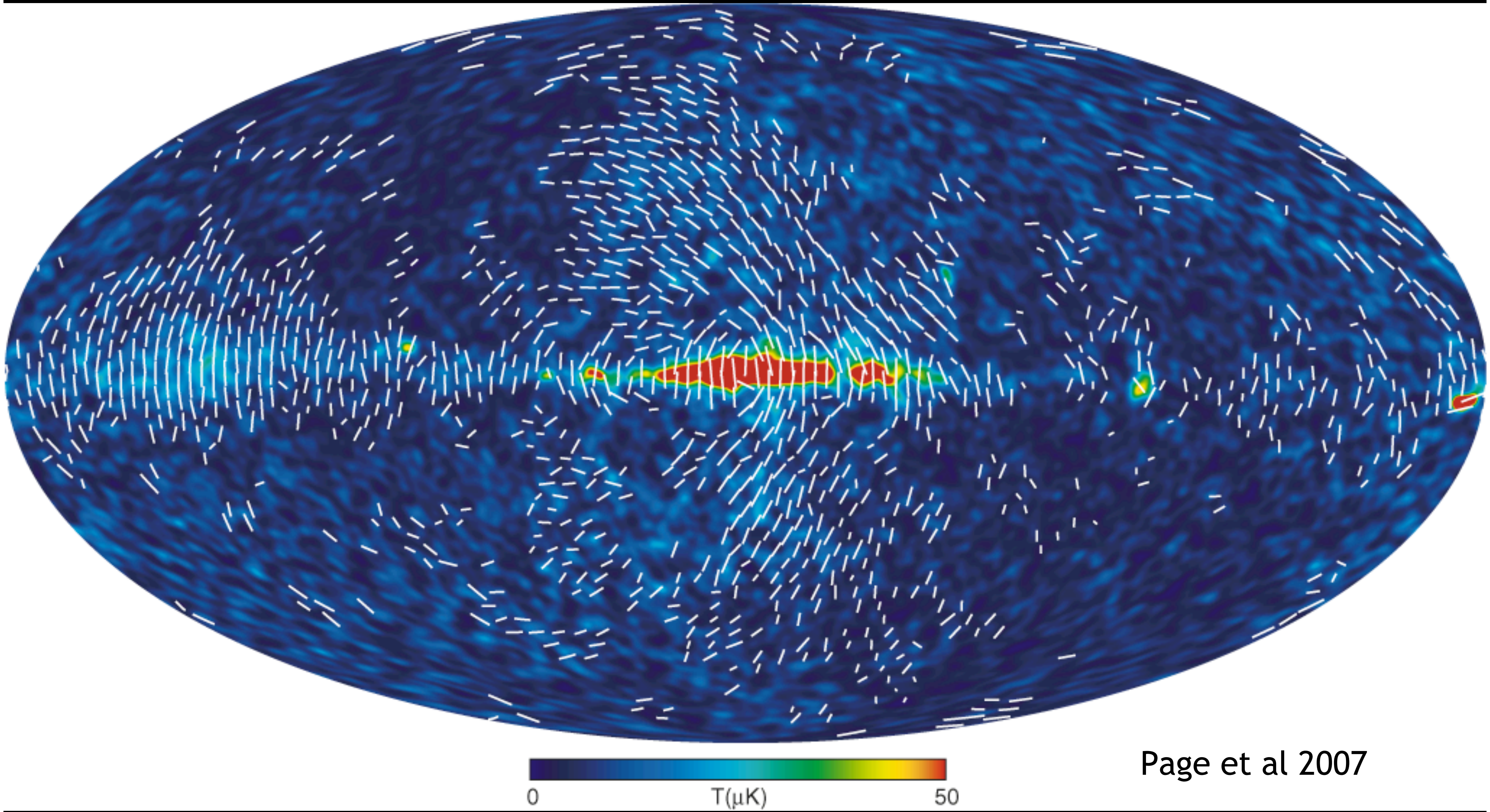
Q Band (41 GHz)

We still see significant polarized synchrotron in Q.



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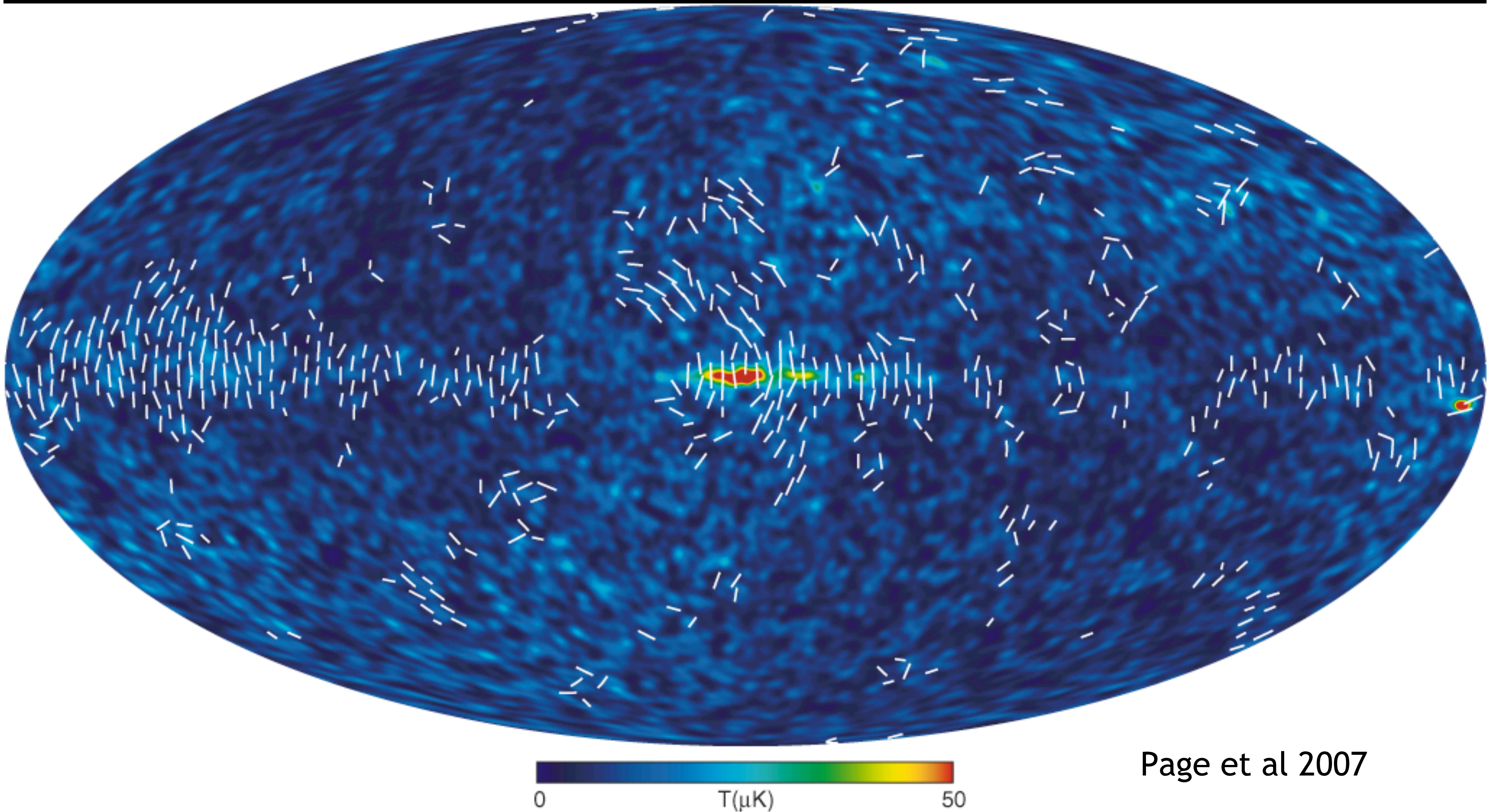
V Band (61 GHz)

The polarized foreground emission is also smallest in V band.
We can also see that noise is larger on the ecliptic plane.



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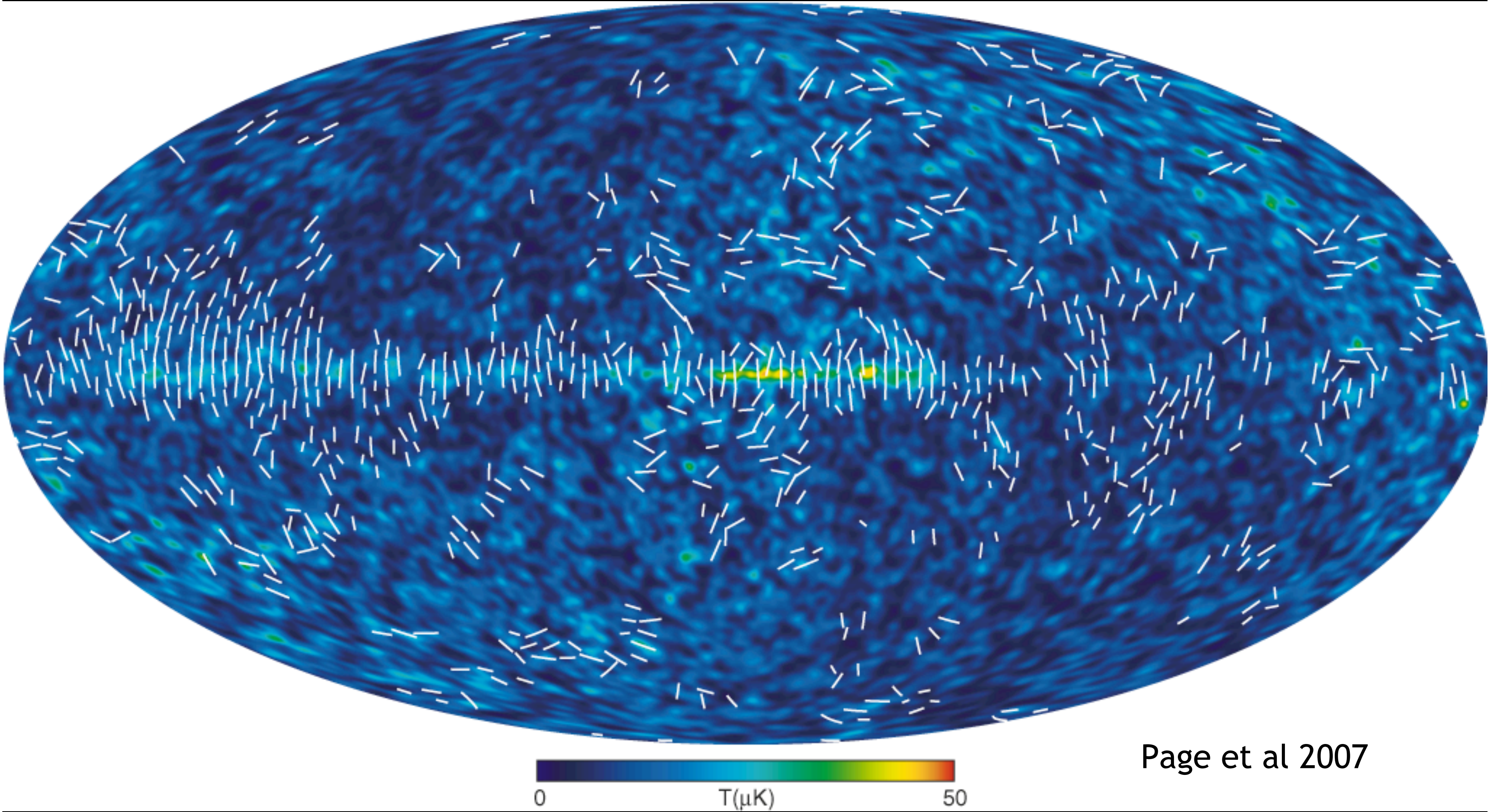
W Band (94 GHz)

While synchrotron is the smallest in W, polarized dust (hard to see by eye) may contaminate in W band more than in V band.



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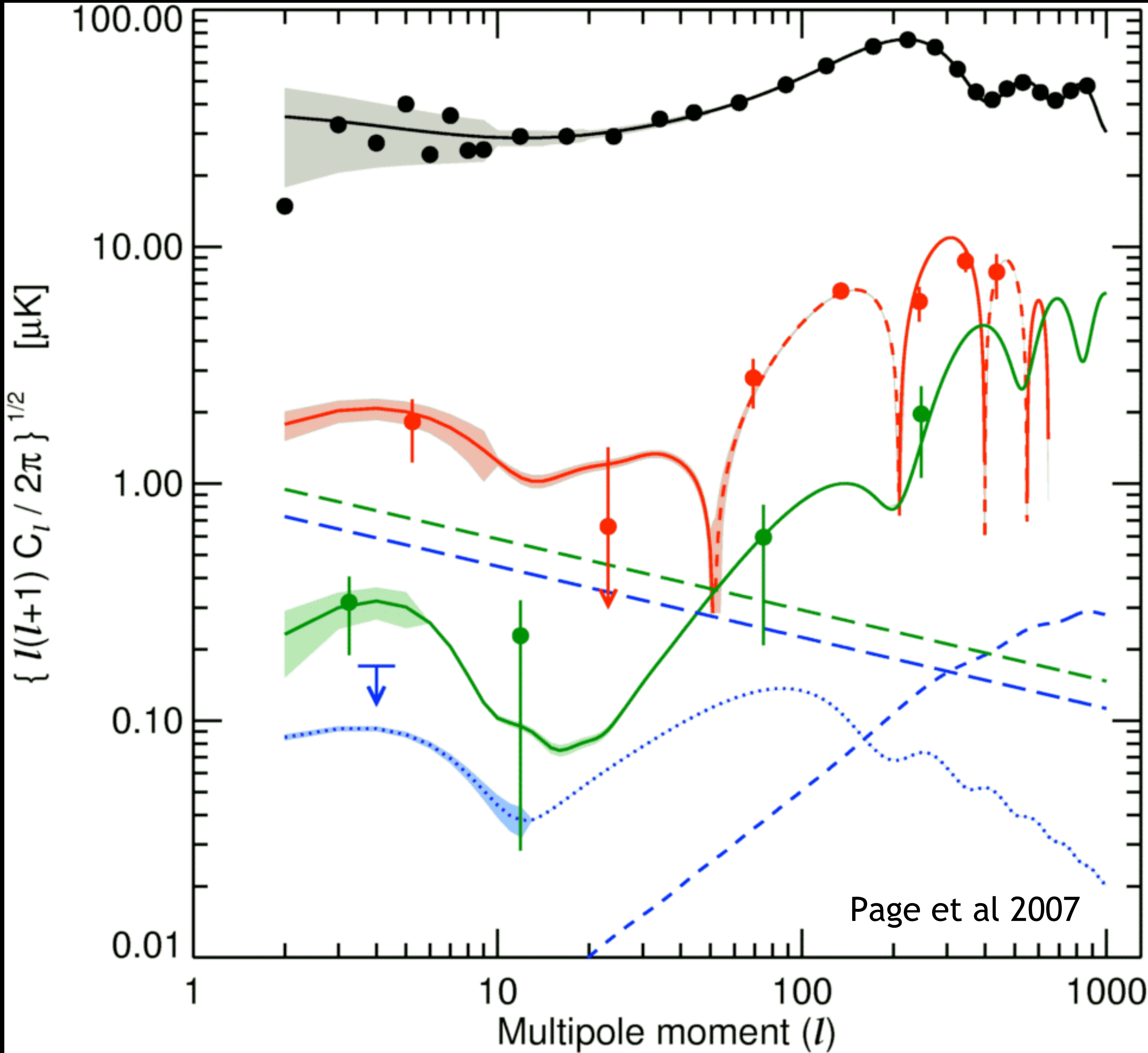
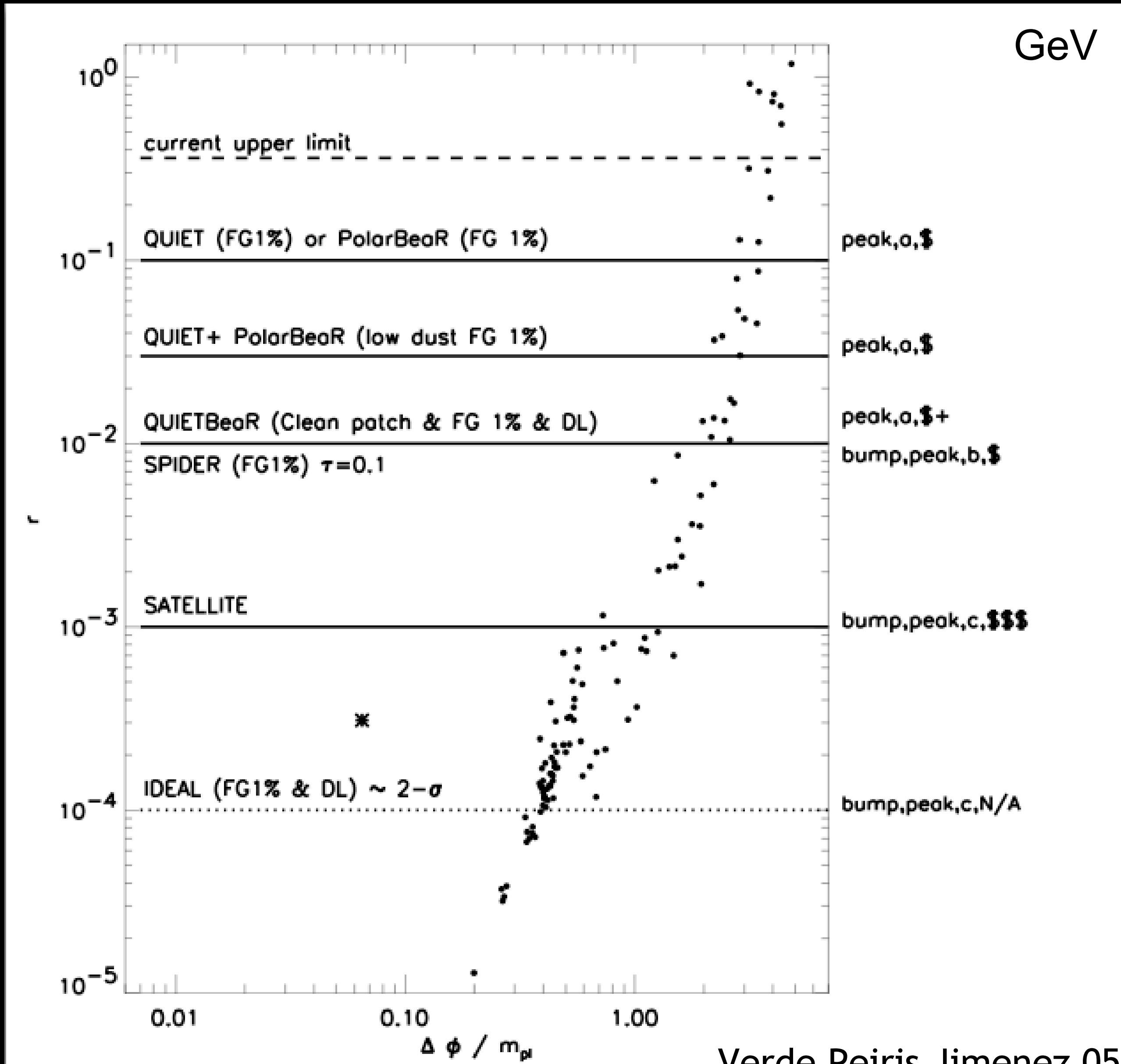


100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
{ l(l+1) C_l / 2π }^{1/2} [μK]
Page et al 2007

The next frontier: gravity waves



Verde Peiris Jimenez 05

Tev

3.2×10^{16}

1.7×10^{16}

9.7×10^{15}

5.5×10^{15}

3×10^{15}

Windows into the primordial Universe

Recombination	380000 yrs	Atomic physics/GR
Nucleosynthesis	3 minutes	Nuclear phyiscs
LHC		TeV energies
inflation	10^{-30} s (?)	GUT?

Big BANG

What next?

Polarization, the next frontier

Why measure CMB Polarization?

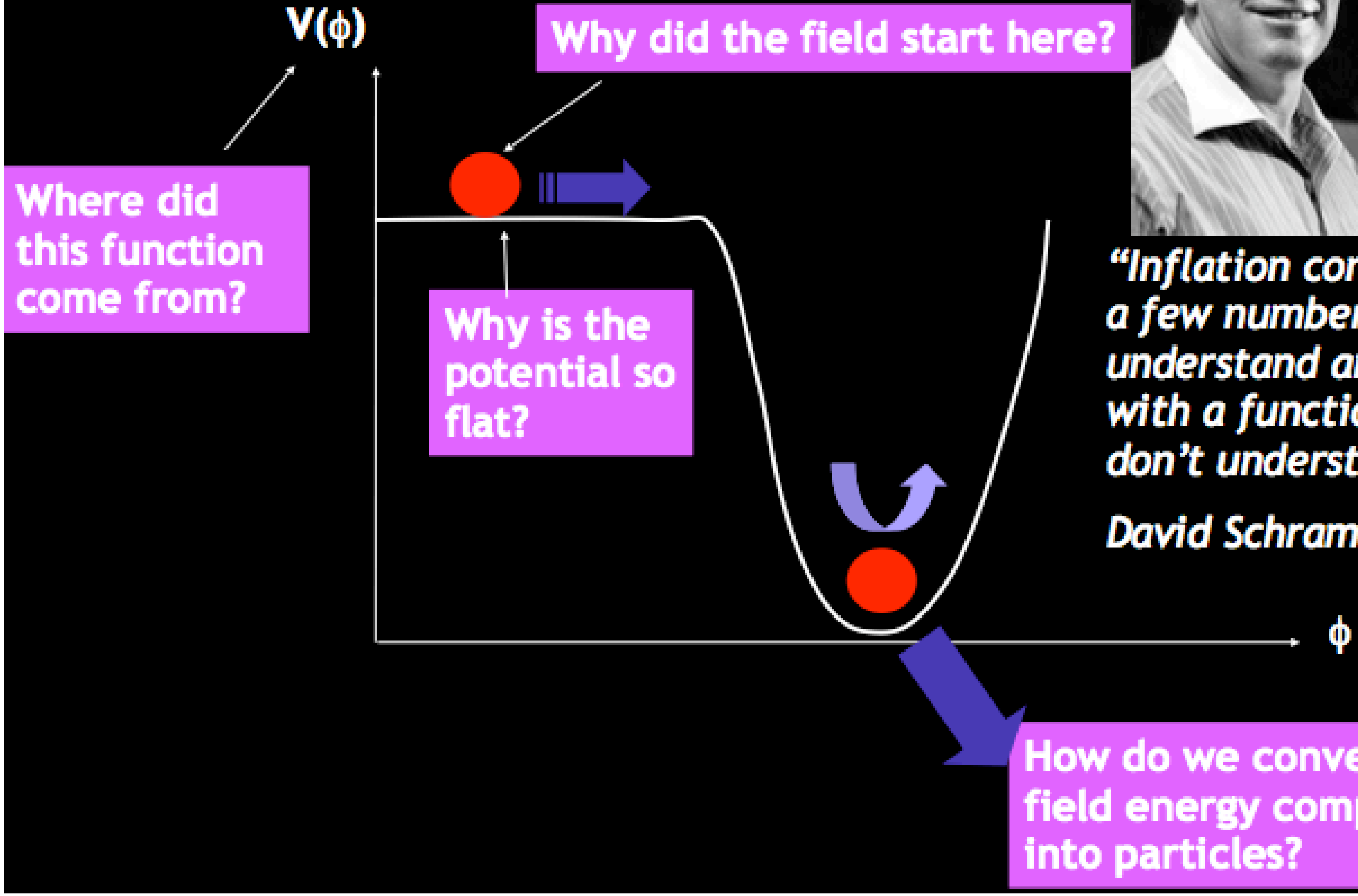
Directly measures dynamics in early universe

So far:
Critical test of the underlying theoretical framework for cosmology

Future: “How did the Universe begin?”
Improve cosmological constraints
Eventually, perhaps, test the theory of inflation.

Plans for the ultimate primary polarization CMB experiment
(CM)BPol

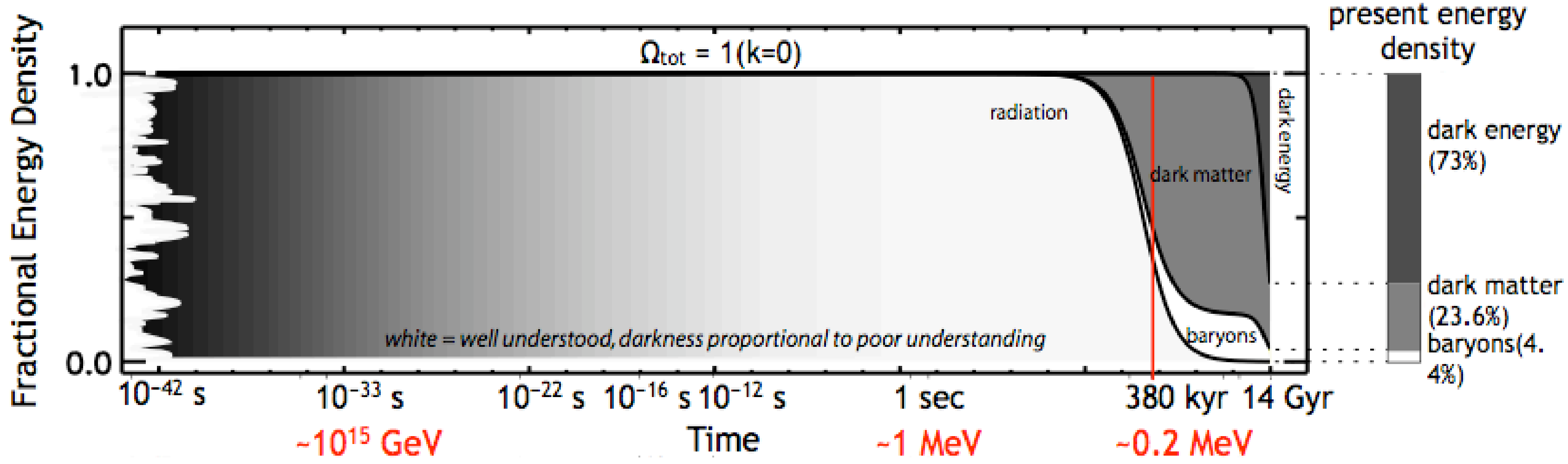
Inflation: Theoretical Front



"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

David Schramm 1945 -1997

Cosmic History / Cosmic Mystery



Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

Generation of primordial perturbations

Cosmic Microwave Background Emitted carries signature of acoustic oscillations and potentially primordial gravitational waves

non-linear growth of perturbations: signature on CMB through weak gravitational lensing

McMahon adapted by Peiris

Three important documents

(will probably shape observational cosmology for the next 10 years)

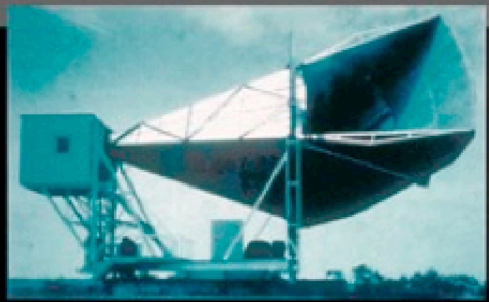
"Task force on CMB research" report
(to advise DoE, NSF, NASA):
Bock et al. 2006 (arXiv:astro-ph/0604101)

"The dark energy task force report"
(to advise DoE, NSF, NASA):
Albrecht et al. 2006 (arXiv:astro-ph/0609591)

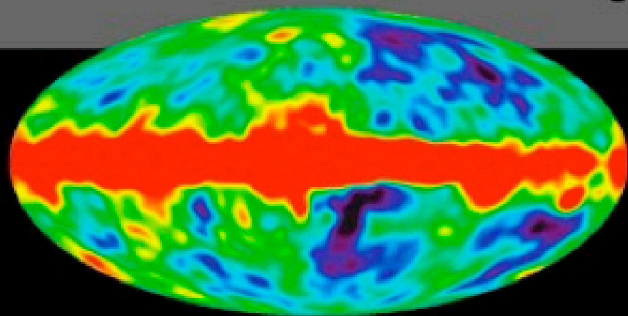
"The report by the ESA-ESO Working Group on Fundamental Cosmology"
Peacock et al 2006 (astro-ph/0610906)

History of CMB temperature measurements

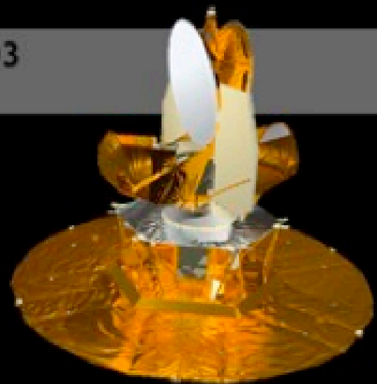
1965 — Penzias and Wilson

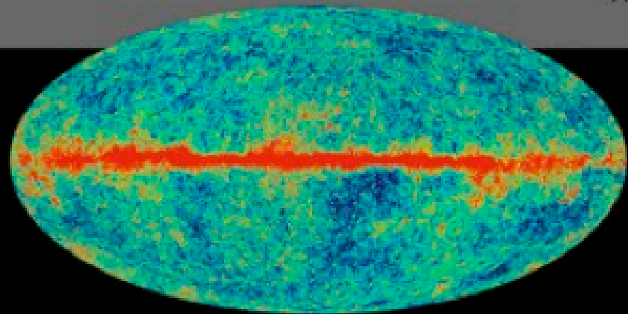


1992 — COBE



2003 — WMAP



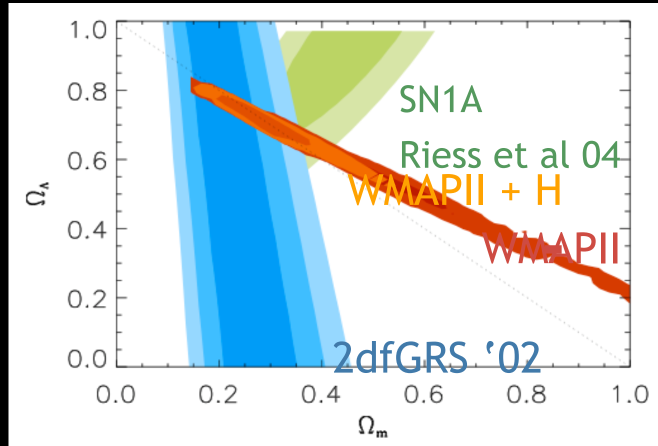


TOCO (1998) BOOMERANG (1998, 2003) MAXIMA (2000)
ARCHEOPS (2002) CBI (2002) ACBAR (2002) VSA (2002)

Origins of primordial fluctuations: Clues

- Flat universe:

	Ω_K
WMAP + $h = 0.72 \pm 0.08$	-0.014 ± 0.017
WMAP + SDSS	$-0.0053^{+0.0068}_{-0.0060}$
WMAP + 2dFGRS	$-0.0093^{+0.0098}_{-0.0092}$
WMAP + SDSS LRG	-0.012 ± 0.010
WMAP + SNLS	-0.011 ± 0.012
WMAP + SNGold	-0.023 ± 0.014



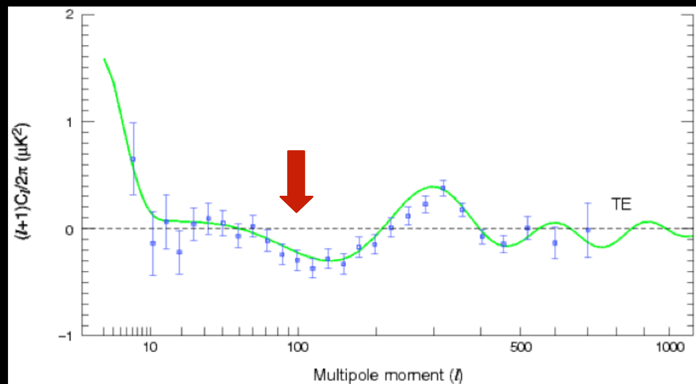
- Gaussianity: $-54 < f_{NL} < 114$

- Power Spectrum spectral index nearly scale-invariant:

	WMAP	WMAP+CMB	WMAP+LSS
n_s	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.948^{+0.014}_{-0.018}$

- Adiabatic initial conditions

- Superhorizon fluctuations (TE anticorrelations)



Observations Consistent with Simplest Inflationary Models