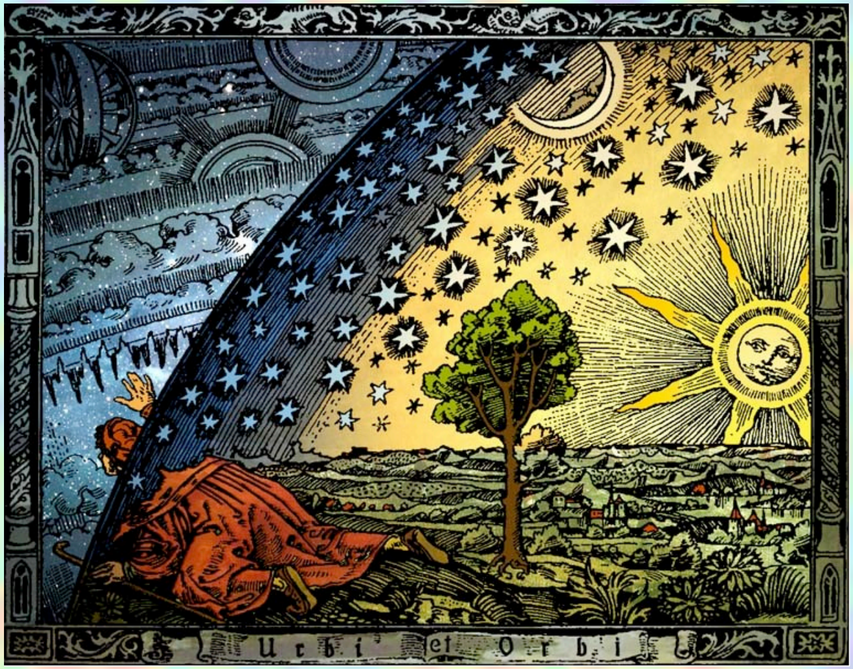
Observational cosmology and fundamental physics



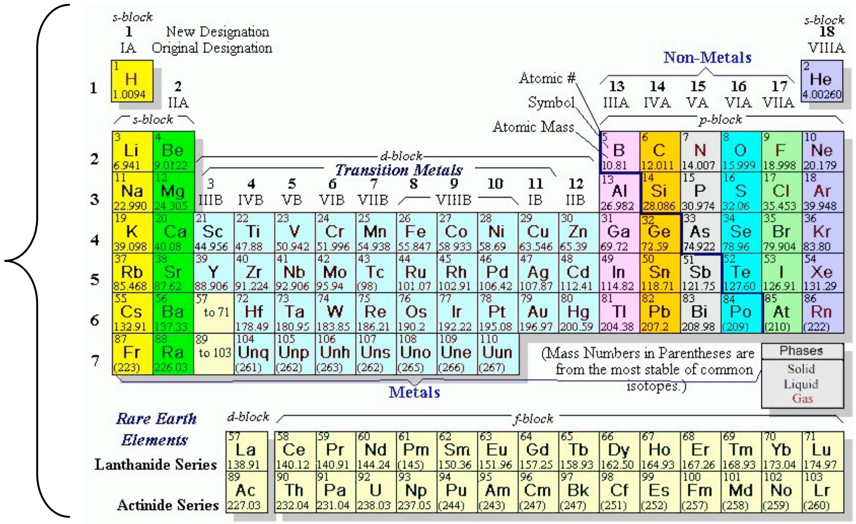
Licia Verde

Institute of space Sciences (ICE CSIC-IEEC) & ICREA

www.ice.csic.es/personal/verde

We (and all of chemistry) are a small minority in the Universe.

Courtesy of WMAP team



s-block

1 New Designation
IA Original Designation

Non-Metals

Atomic #
Symbol
Atomic Mass

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H 1.0094																	2 He 4.00260
2	3 Li 6.941	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.179
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.06	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.91	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 to 71	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.03	89 to 103	104 Unq (261)	105 Unp (262)	106 Unh (263)	107 Uns (262)	108 Uno (265)	109 Une (266)	110 Uun (267)								

s-block · *d-block* · *Transition Metals* · *p-block* · *s-block*

Metals

(Mass Numbers in Parentheses are from the most stable of common isotopes.)

Phases
Solid
Liquid
Gas

Rare Earth Elements · *d-block* · *f-block*

Lanthanide Series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide Series	89 Ac 227.03	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

We do not know what 96% of the Universe is !

Four important documents

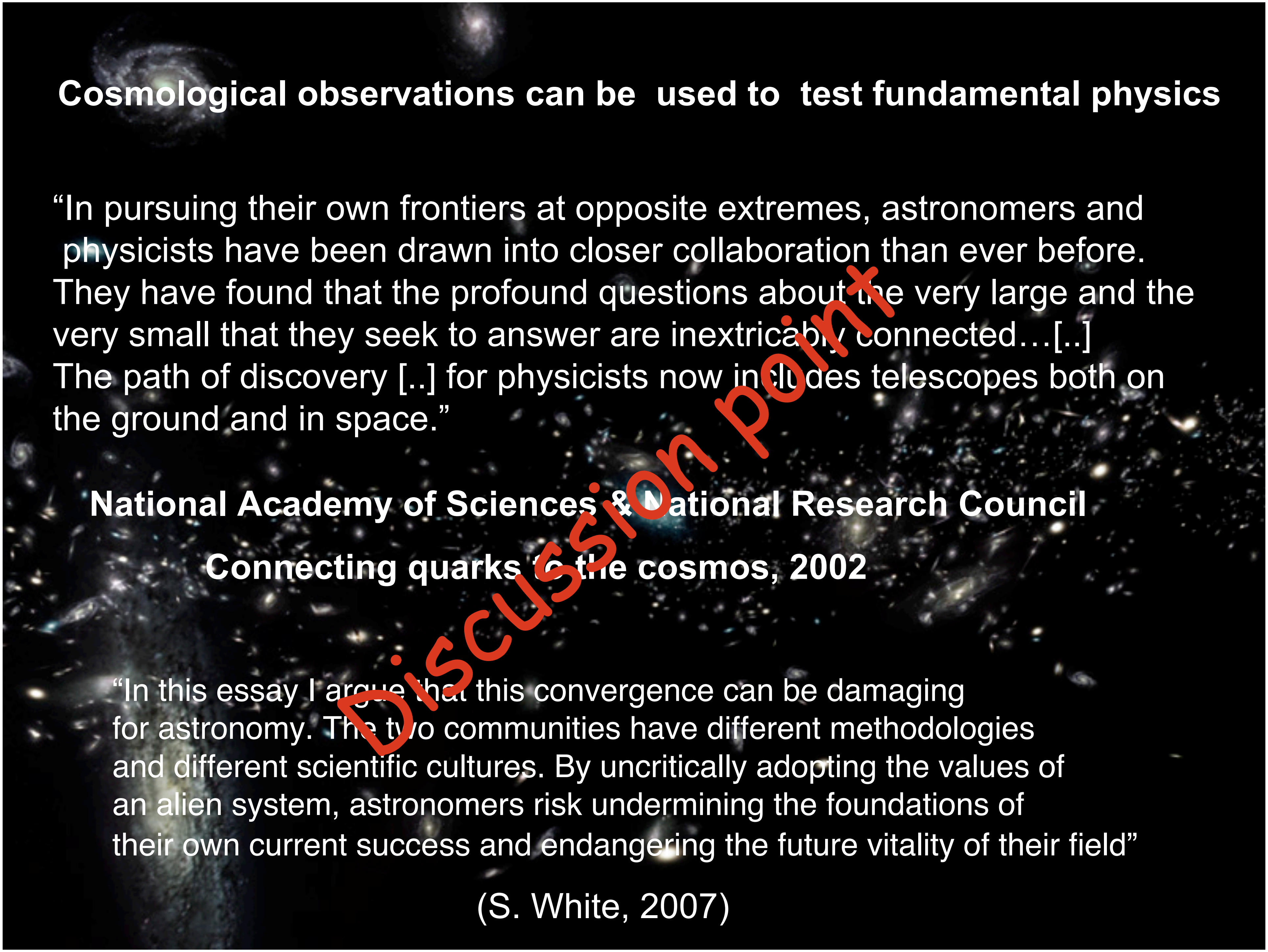
(will probably shape observational cosmology for the next 10 years)

“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)

“NASA's Beyond Einstein Program: An Architecture for Implementation”, NRC, http://www.nap.edu/catalog/12006.html



Cosmological observations can be used to test fundamental physics

"In pursuing their own frontiers at opposite extremes, astronomers and physicists have been drawn into closer collaboration than ever before. They have found that the profound questions about the very large and the very small that they seek to answer are inextricably connected…[..] The path of discovery [..] for physicists now includes telescopes both on the ground and in space."

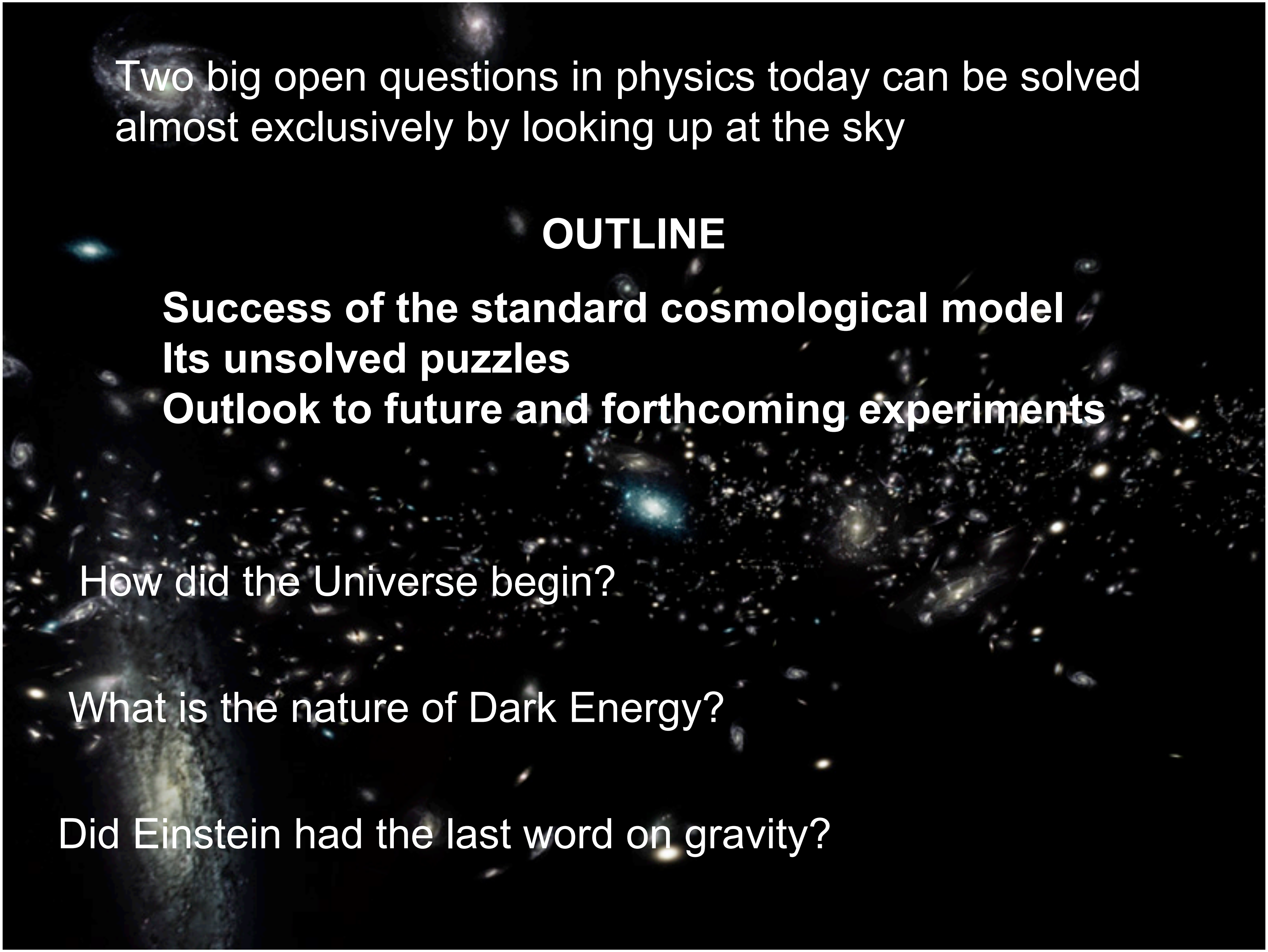
National Academy of Sciences & National Research Council

Connecting quarks to the cosmos, 2002

Discussion point

"In this essay I argue that this convergence can be damaging for astronomy. The two communities have different methodologies and different scientific cultures. By uncritically adopting the values of an alien system, astronomers risk undermining the foundations of their own current success and endangering the future vitality of their field"

(S. White, 2007)



Two big open questions in physics today can be solved almost exclusively by looking up at the sky

OUTLINE

Success of the standard cosmological model
Its unsolved puzzles
Outlook to future and forthcoming experiments

How did the Universe begin?

What is the nature of Dark Energy?

Did Einstein had the last word on gravity?

Testing fundamental physics by looking up at the sky is not new

The interplay between astrophysics and fundamental physics has already produced spectacular findings (e.g. the solar neutrino problem)

Cosmology has entered the precision era very recently

Cosmological data* can be used to test fundamental physics

4 Areas

Dark matter

Neutrinos

Inflation

Dark energy

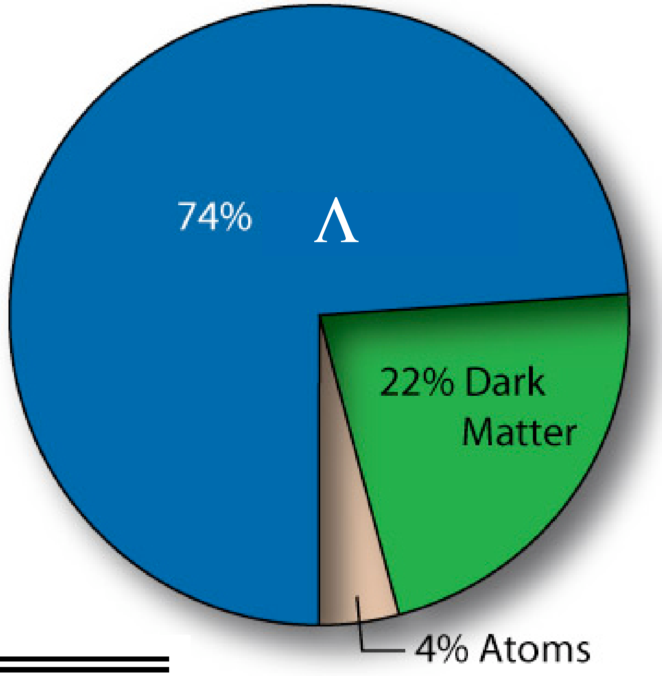
*For now, CMB is the cleanest probe we have

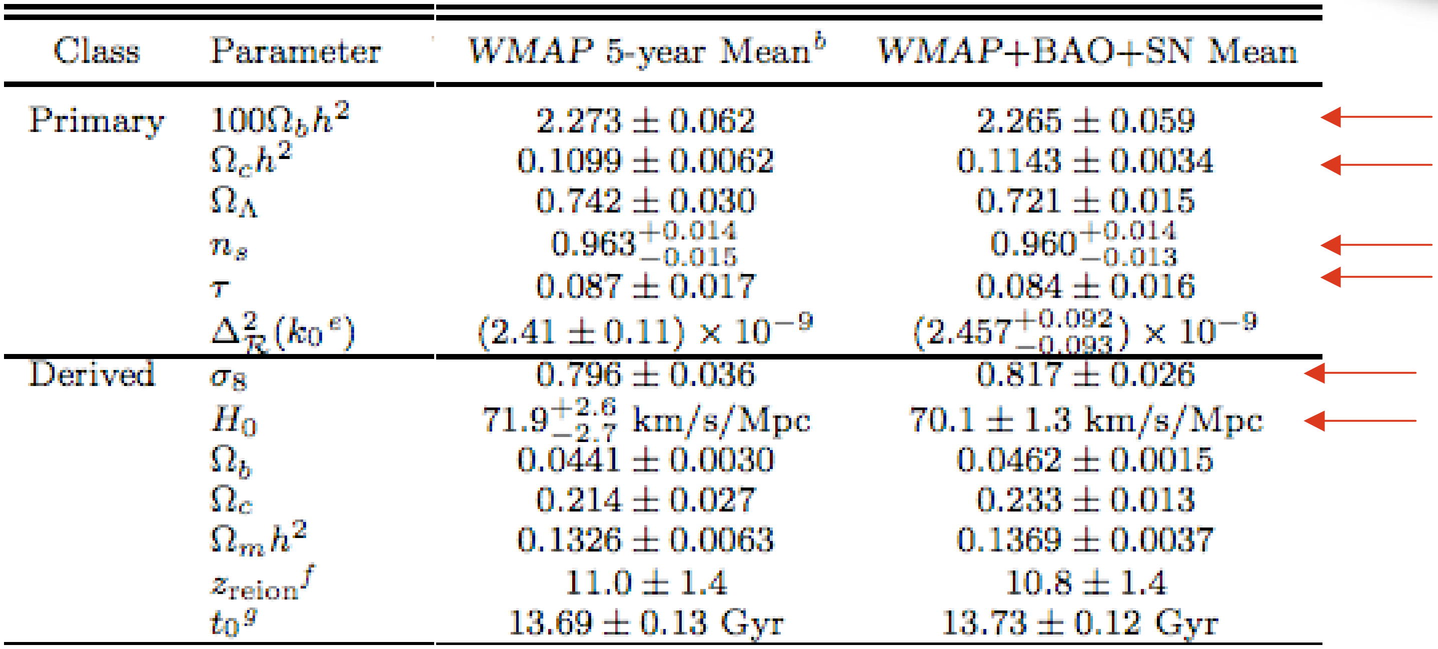
The standard cosmological model
ΛCDM model

Spatially flat Universe

Power-law, primordial power spectrum

Only 6 parameters: WMAP5yr analysis

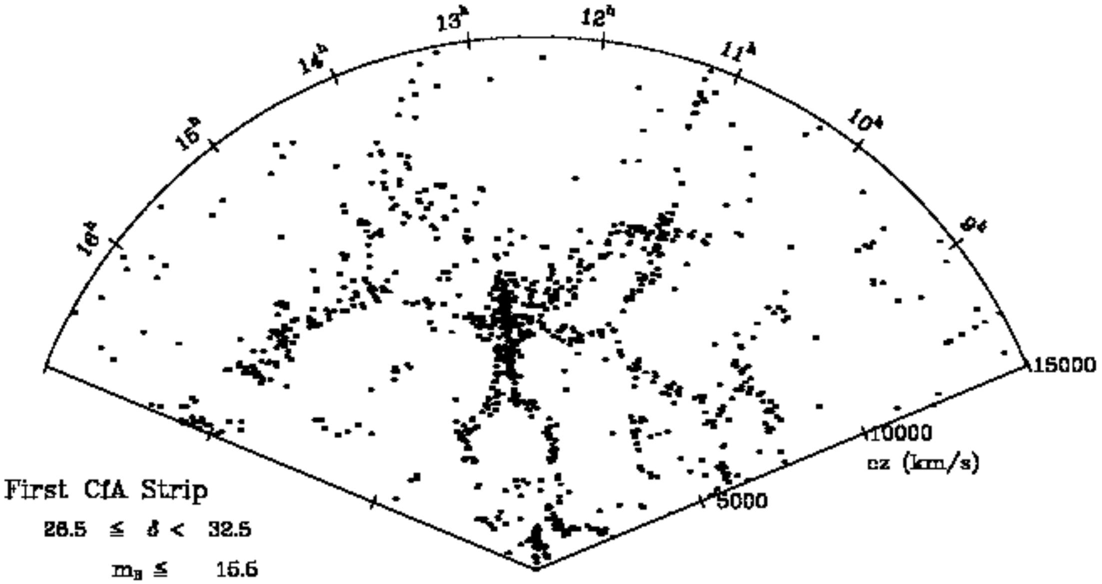




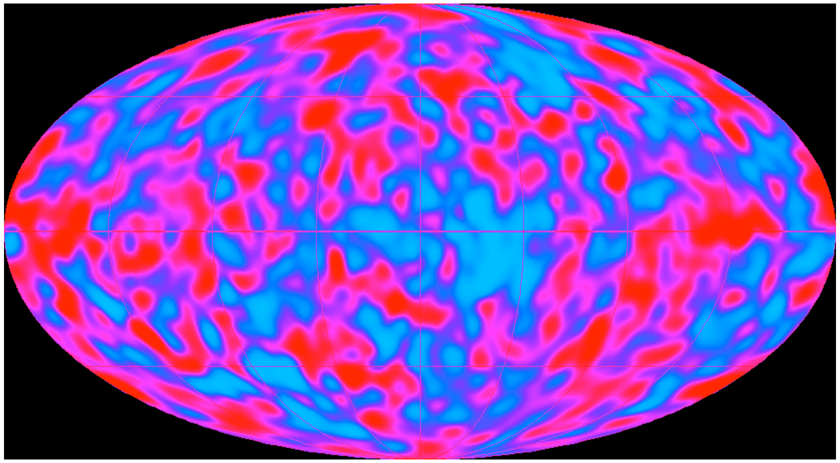
Class	Parameter	WMAP 5-year Mean[b]	WMAP+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.742 ± 0.030	0.721 ± 0.015
	n_s	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.796 ± 0.036	0.817 ± 0.026
	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

Not NEW!

State of the art of data then…



~14 Gyr
(a posteriori information)



(DMR)COBE

CMB

380000 yr
(a posteriori information)

Fast forward a decade or so

Avalanche of data:

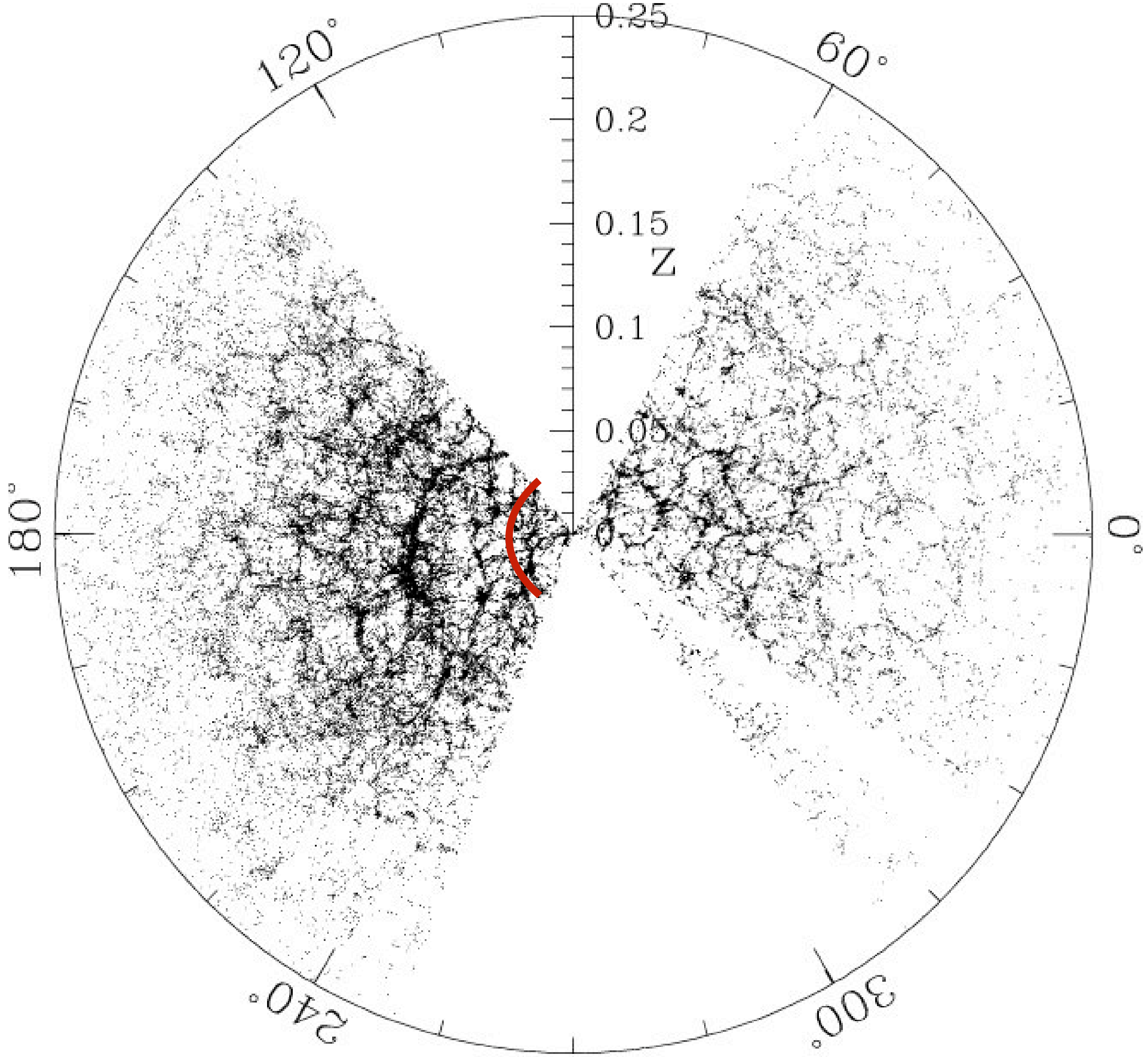
Toco
Maxima
Boomerang
Archeops
CBI
VSA
ACBAR

+Supernovae

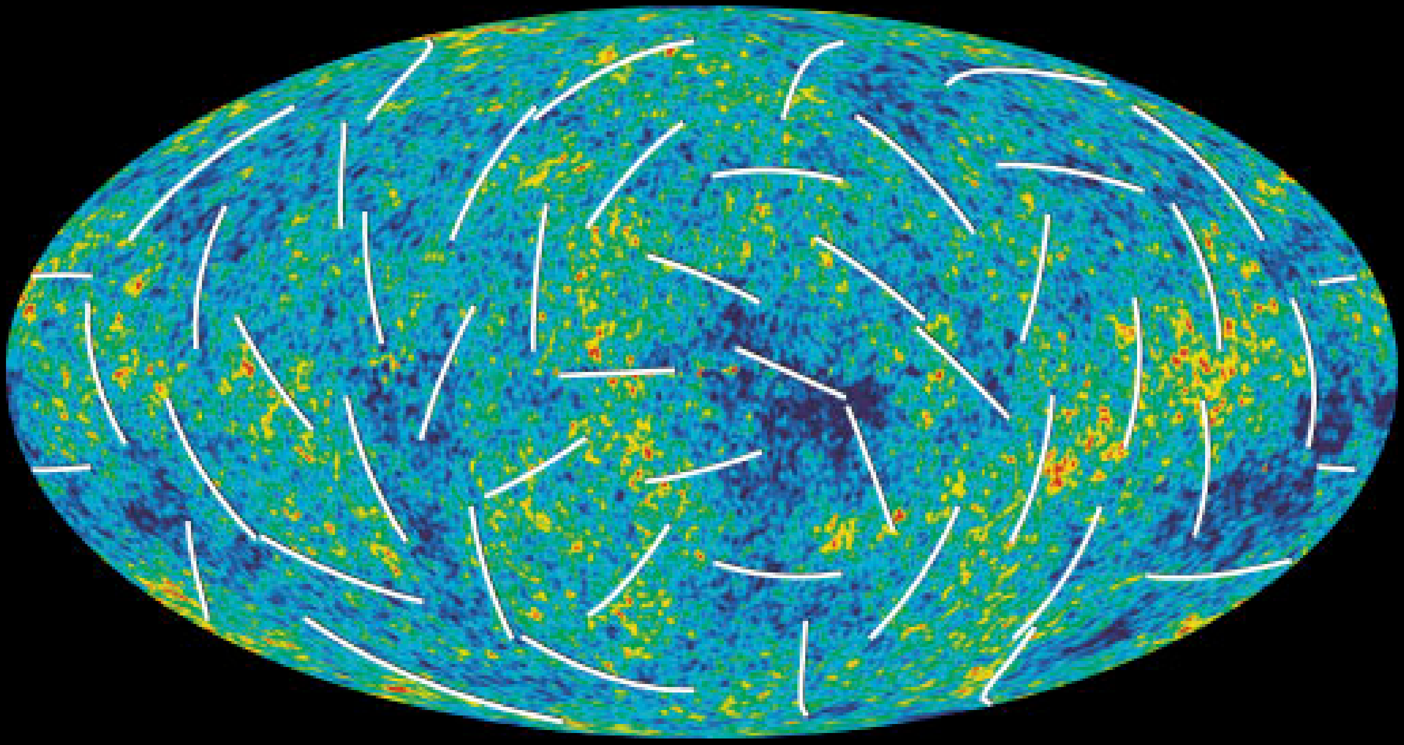
Las campanas
PSCz
SDSS
2dF
2MASS

Weak lensing (emerging technique)

State of the art of data now…



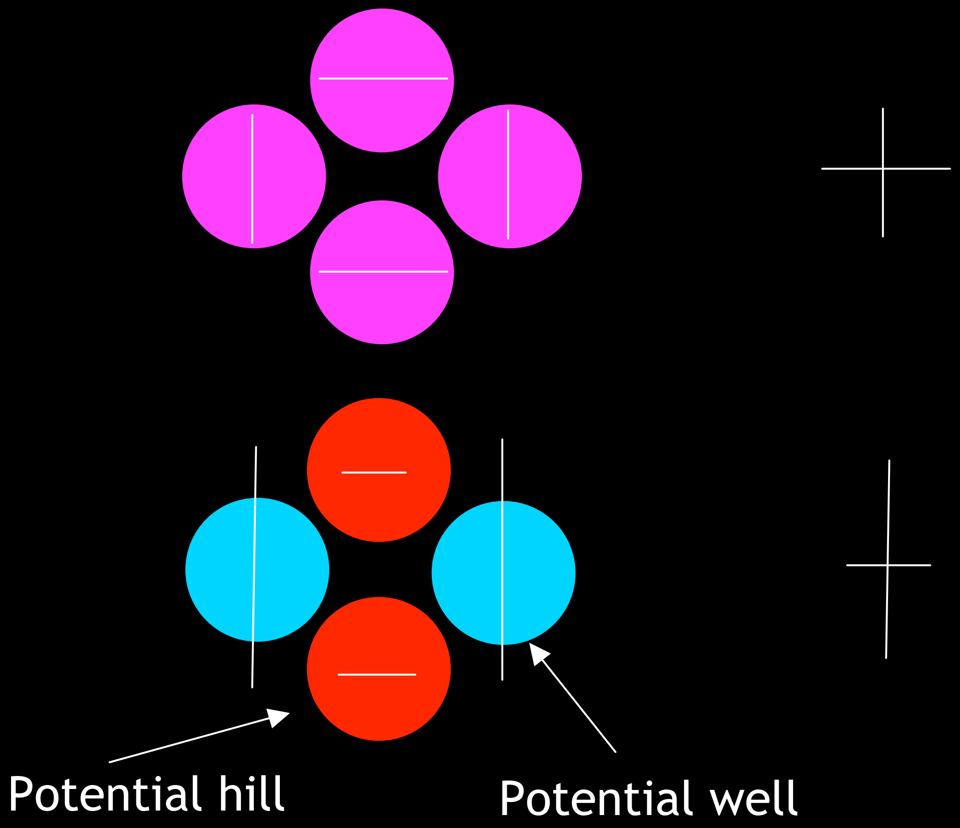
State of the art of data now…

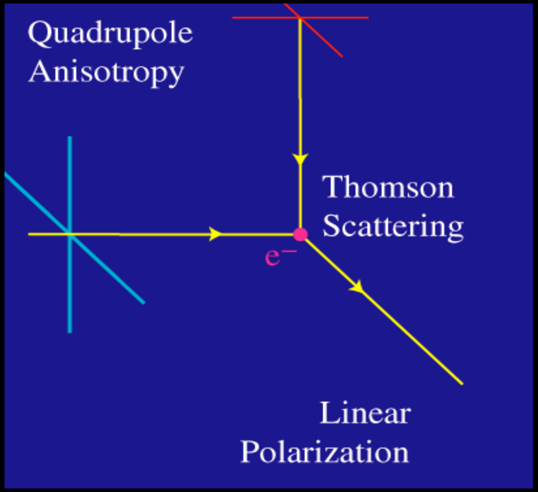


New in 2006

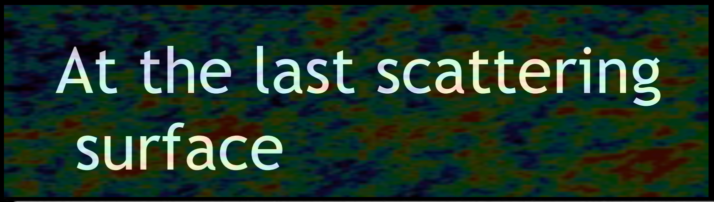
Generation of CMB polarization

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





From Wayne Hu

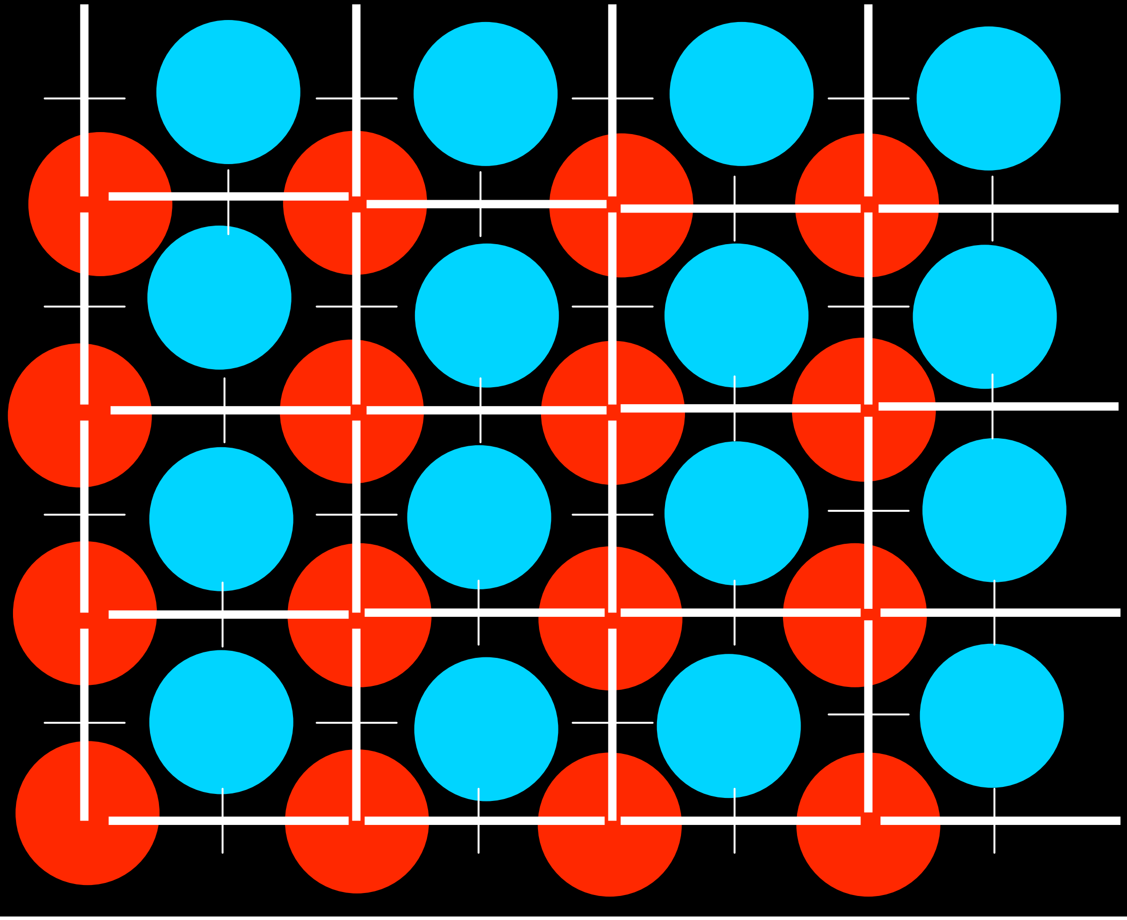


At the last scattering surface

At the end of the dark ages (reionization)

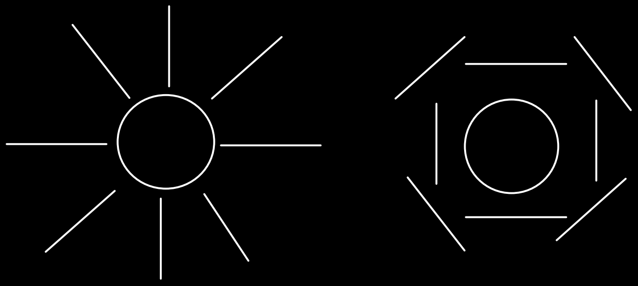
Polarization for density perturbation

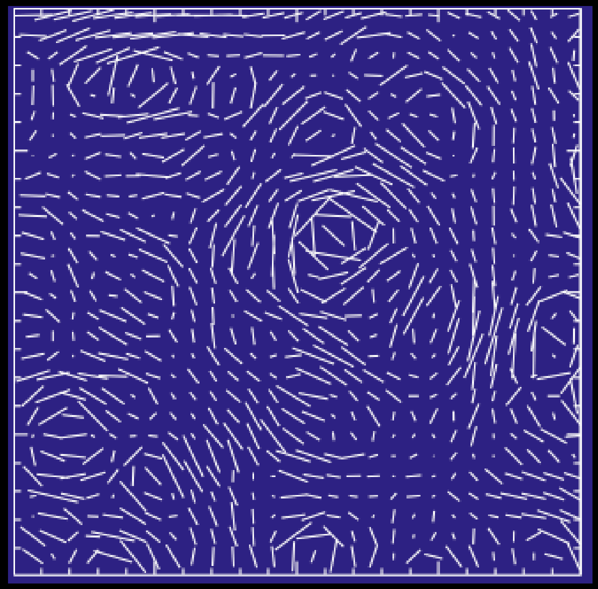
- Radial (tangential) pattern around hot (cold) spots.



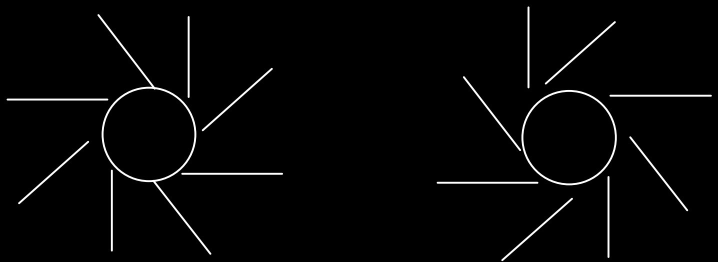
E and B modes polarization

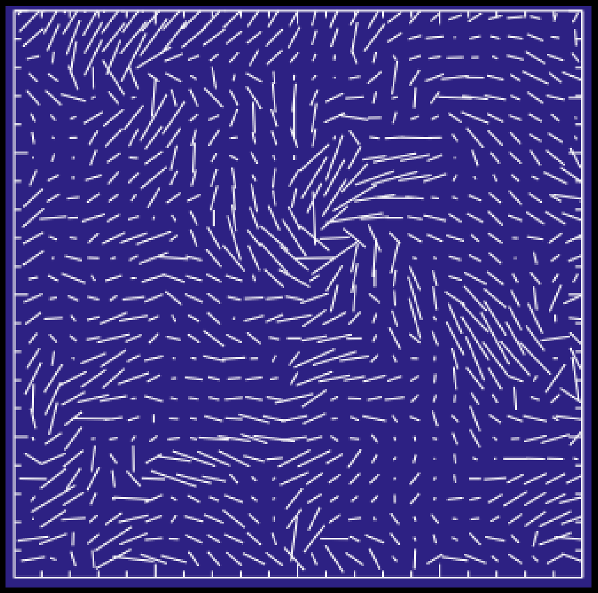
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes (tensor-to scalar ratio r)





Smoking gun of inflation, holy grail for CMB…

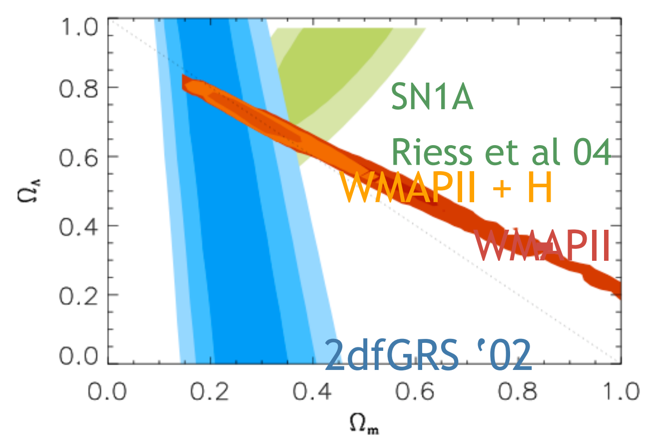
Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

Origins of primordial fluctuations: Clues

- Flat universe:

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

Ω_K



- Gaussianity:?

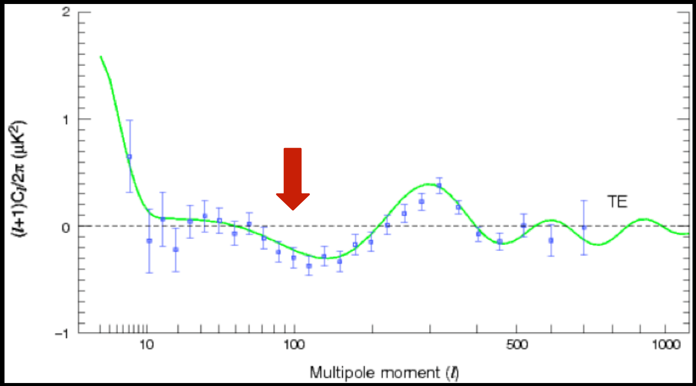
- Power Spectrum spectral index nearly scale-invariant:

n_s

WMAP	WMAP+CMB	WMAP+LSS
$0.963^{+0.014}_{-0.015}$	0.960 ± 0.014	$0.960^{+0.014}_{-0.013}$

- Adiabatic initial conditions

- Superhorizon fluctuations (TE anticorrelations)



Observations Consistent with Simplest Inflationary Models

How about Non-gaussianity?

$$\Phi(\mathbf{r}) = \Phi_L(\mathbf{r}) + f_{\rm NL}\left(\Phi_L^2(\mathbf{r}) - \langle\Phi_L^2(\mathbf{r})\rangle\right)$$

Up to WMAP3 • $-54 < f_{NL} < 114$

Yadev&Wandelt '07
(on WMAP3)

$f_{\rm NL} = 83.5 \pm 27$

"detection"

Komatsu et al
(WMAP5)

V+W	$K\dot{Q}85$	600	68 ± 31
V+W	$KQ85$	700	67 ± 31
V+W	$K\dot{Q}75$	600	61 ± 36
V+W	$KQ75$	700	58 ± 36

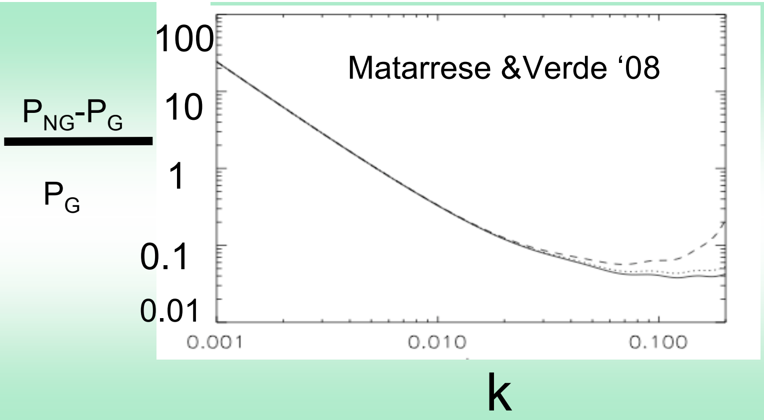
"hint"

They agree, but see Minkowski functionals!!!

Look beyond CMB

Promising: large scale clustering

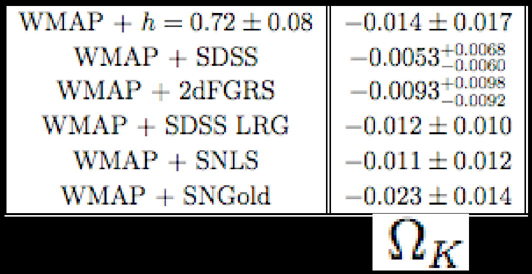
$$P_{\rm halo}(k,z) = \frac{\delta_c^2(z)}{\sigma_R^4 D^2(z)} P_{\delta\delta}(k,z)\left[1 + 4 f_{nl}\delta_c(z)\frac{\mathcal{F}_R(k)}{\mathcal{M}_R(k)}\right]$$



Matarrese &Verde '08

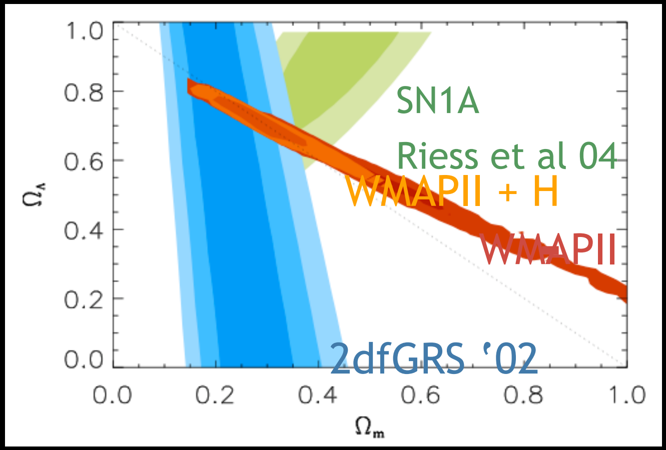
Origins of primordial fluctuations: Clues

- Flat universe:



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

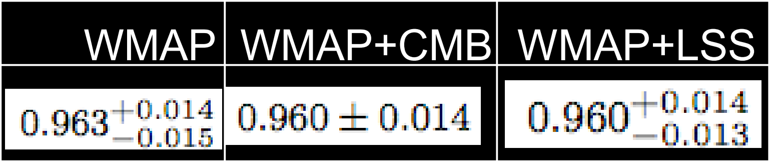
Ω_K



- Gaussianity:?

- Power Spectrum spectral index nearly scale-invariant:

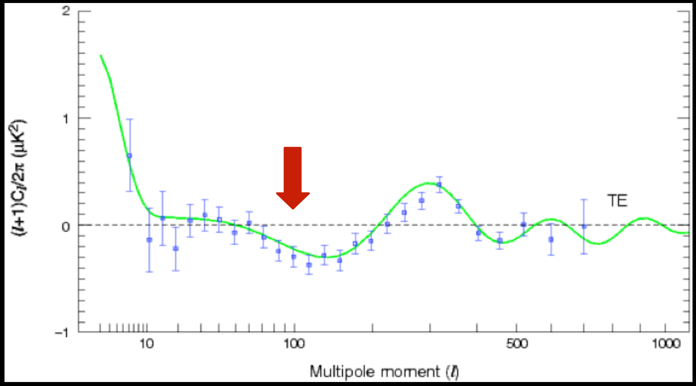
n_s



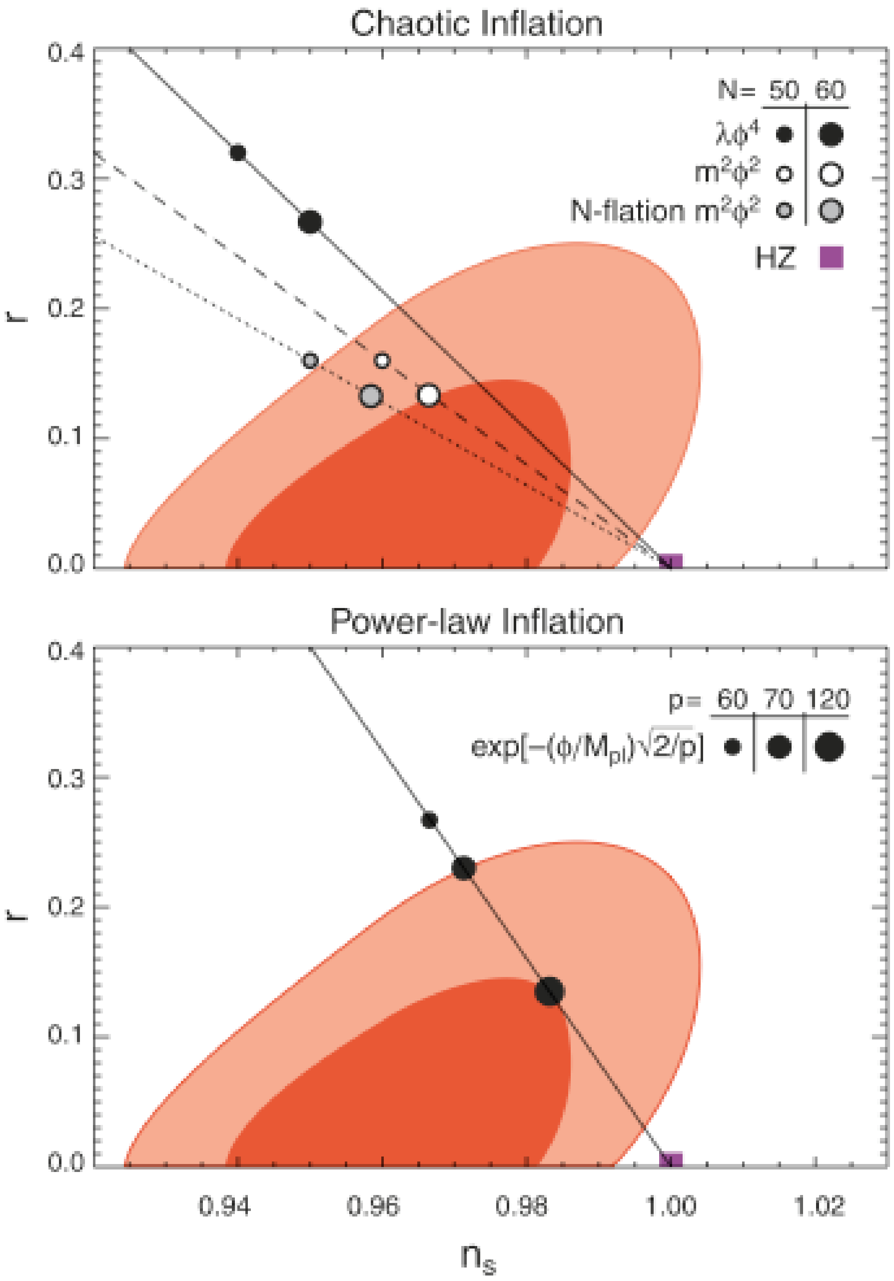
WMAP	WMAP+CMB	WMAP+LSS
$0.963^{+0.014}_{-0.015}$	0.960 ± 0.014	$0.960^{+0.014}_{-0.013}$

- Adiabatic initial conditions

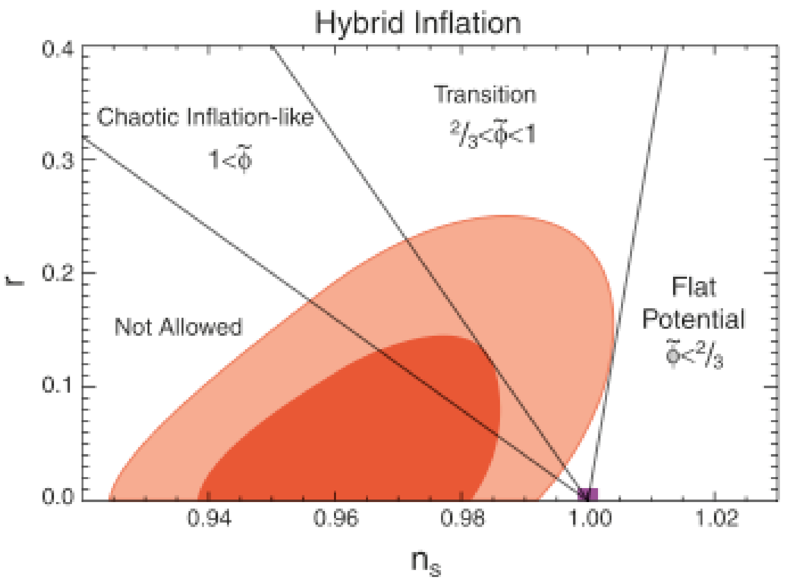
- Superhorizon fluctuations (TE anticorrelations)



Observations Consistent with Simplest Inflationary Models



Specific inflationary models are being critically tested



Komatsu et al 08

Seeing (indirectly) z>>1100

Hot issue!

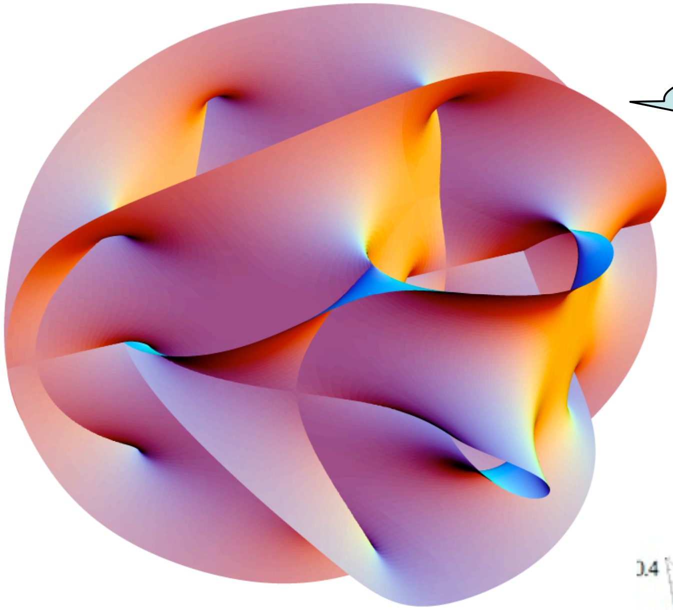
Information about the shape of the inflaton potential is enclosed in the shape and amplitude of the primordial power spectrum of the perturbations.

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.

Example: Balasubramanian,Berglund, Jimenez, Simon, LV

Topology from Cosmology

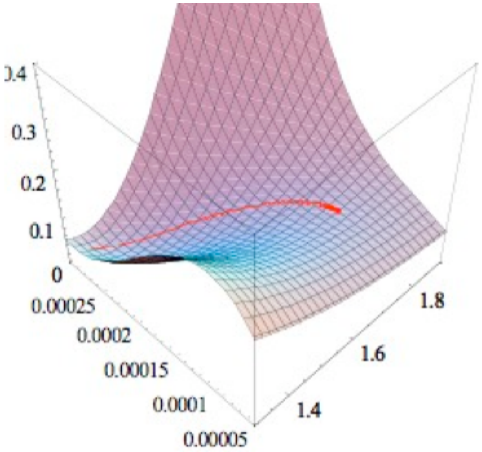


Calabi-Yau compactification

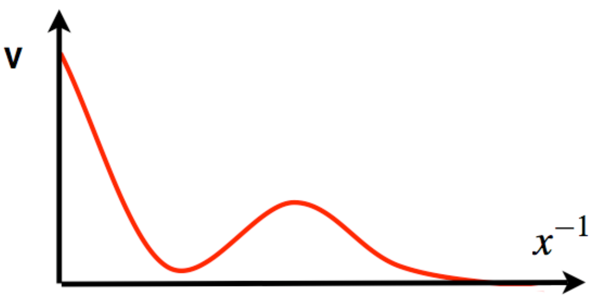
String theory lives if 10 or 11 D

We only see 4

Scalar fields ⇨ inflation?



Samuel Meehan, URC, April 2007

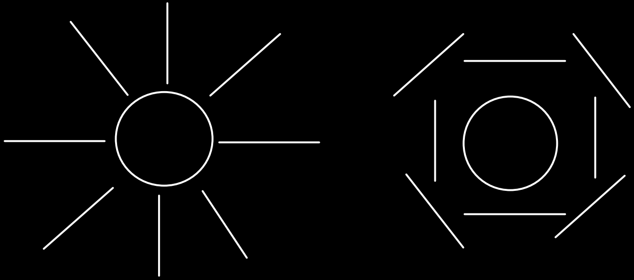


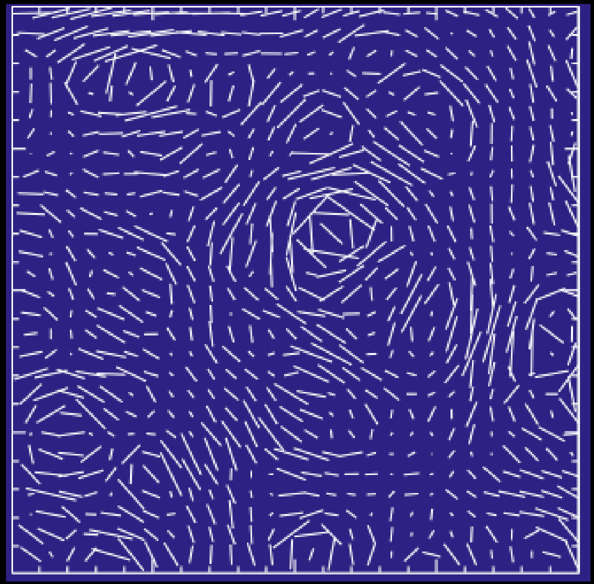
Not all effective field theories are consistent with string theory

String theory consistent models can be **falsified** using Cosmological observations, following our arguments or generalizations of them

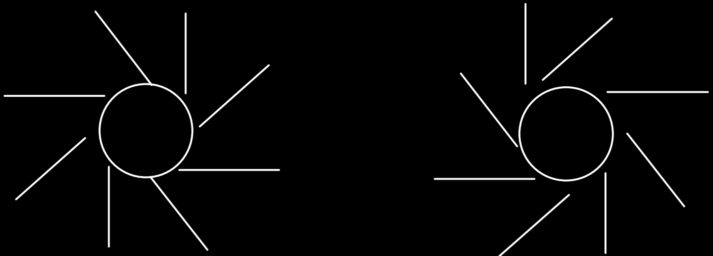
E and B modes polarization

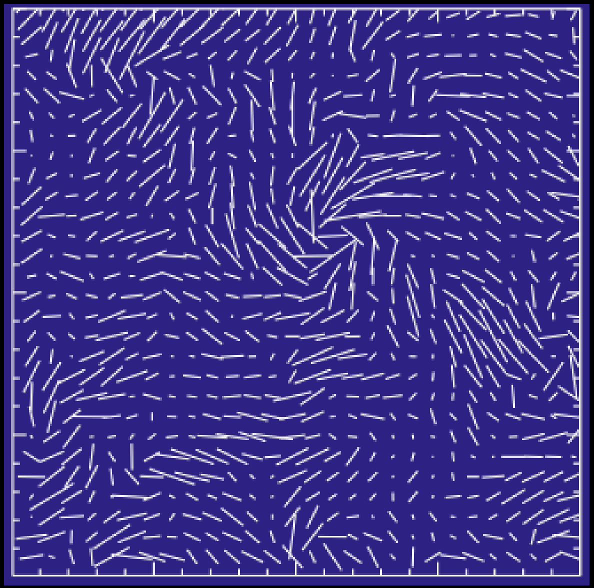
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes (tensor-to scalar ratio r)





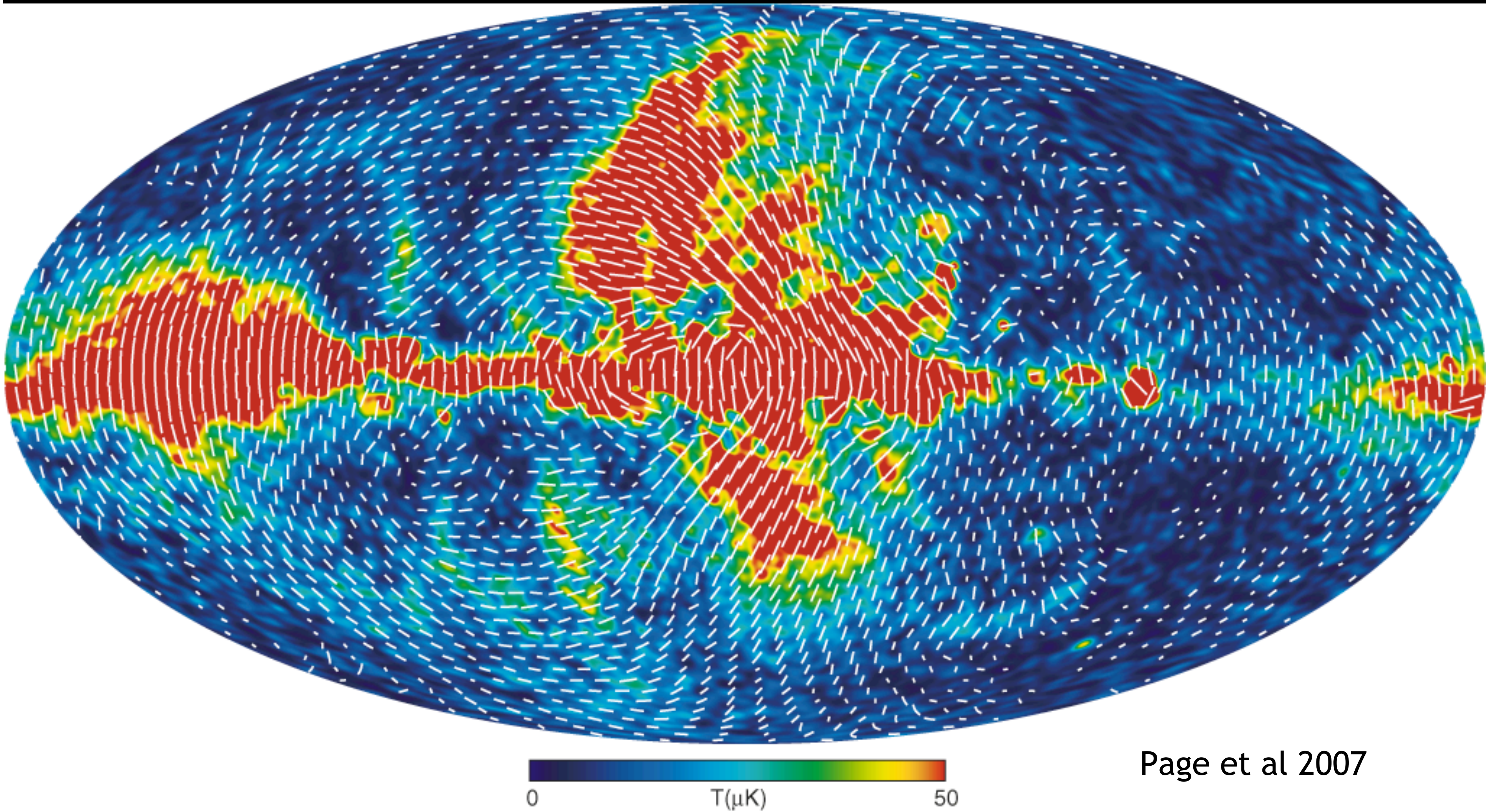
Smoking gun of inflation, holy grail for CMB…

Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

We happen to live in a galaxy!

K Band (23 GHz)

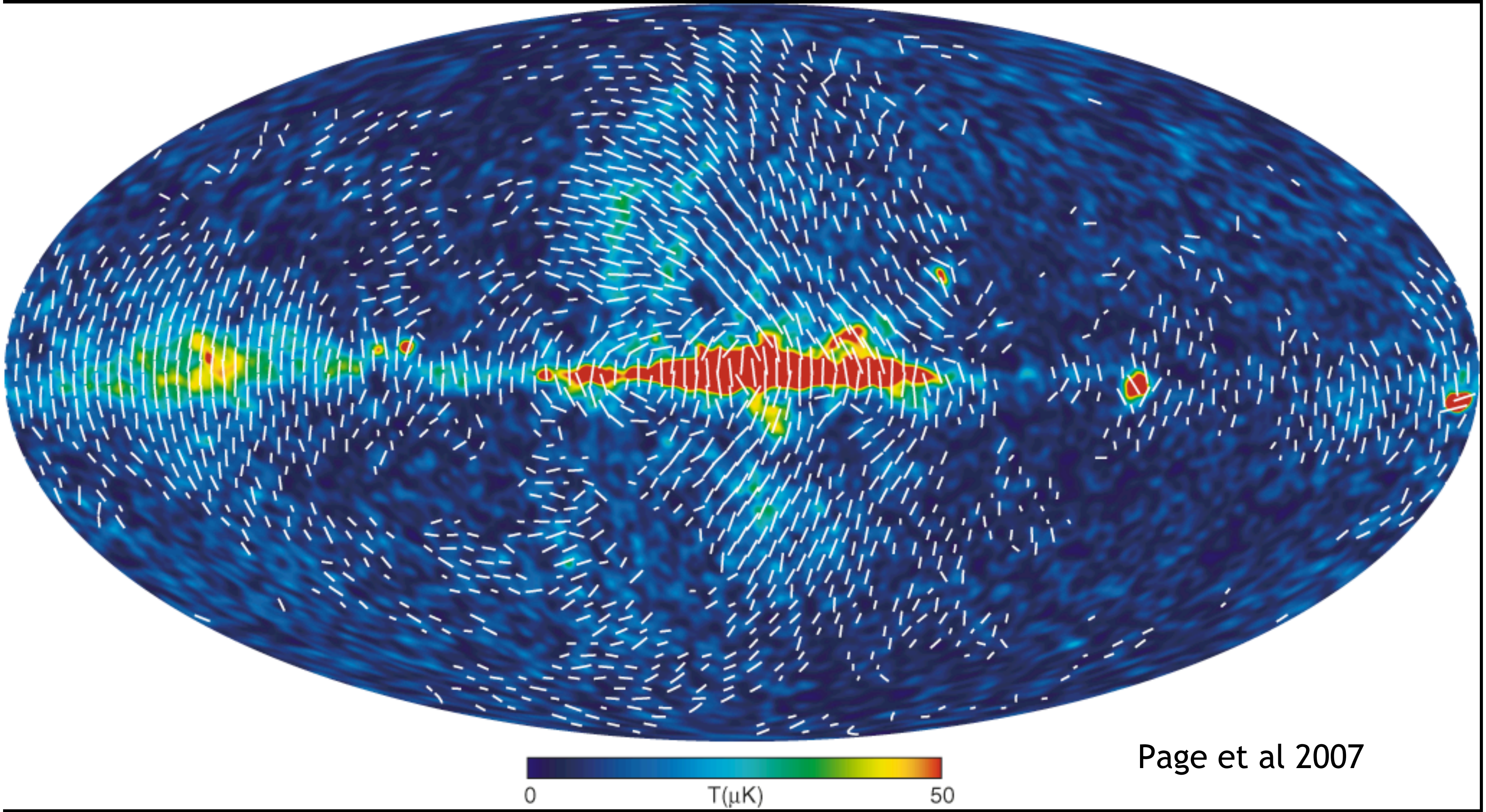
Dominated by synchrotron; Note that polarization direction is perpendicular to the magnetic field lines.



Page et al 2007

Ka Band (33 GHz)

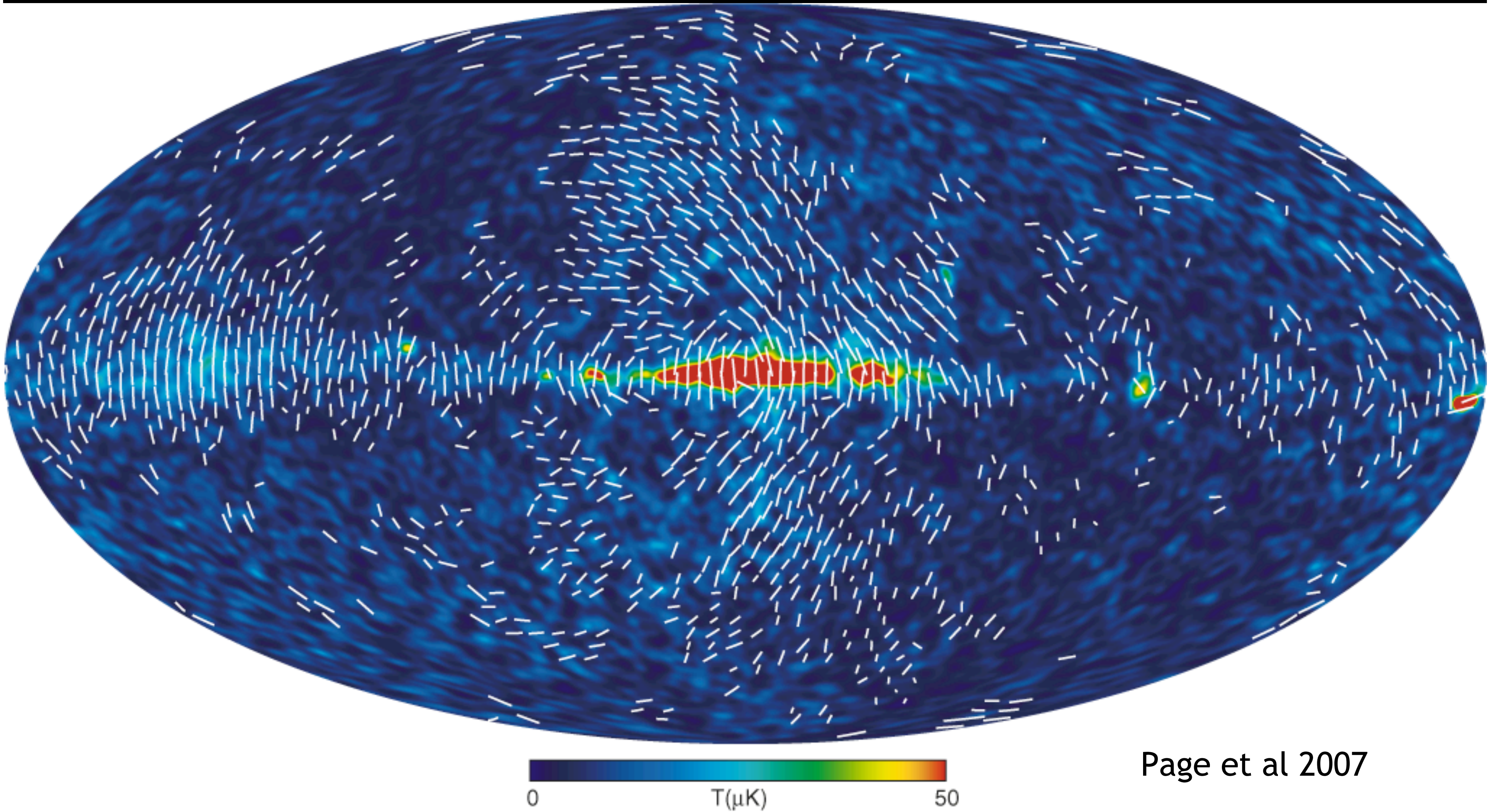
Synchrotron decreases as $n^{-3.2}$ from K to Ka band.



Page et al 2007

Q Band (41 GHz)

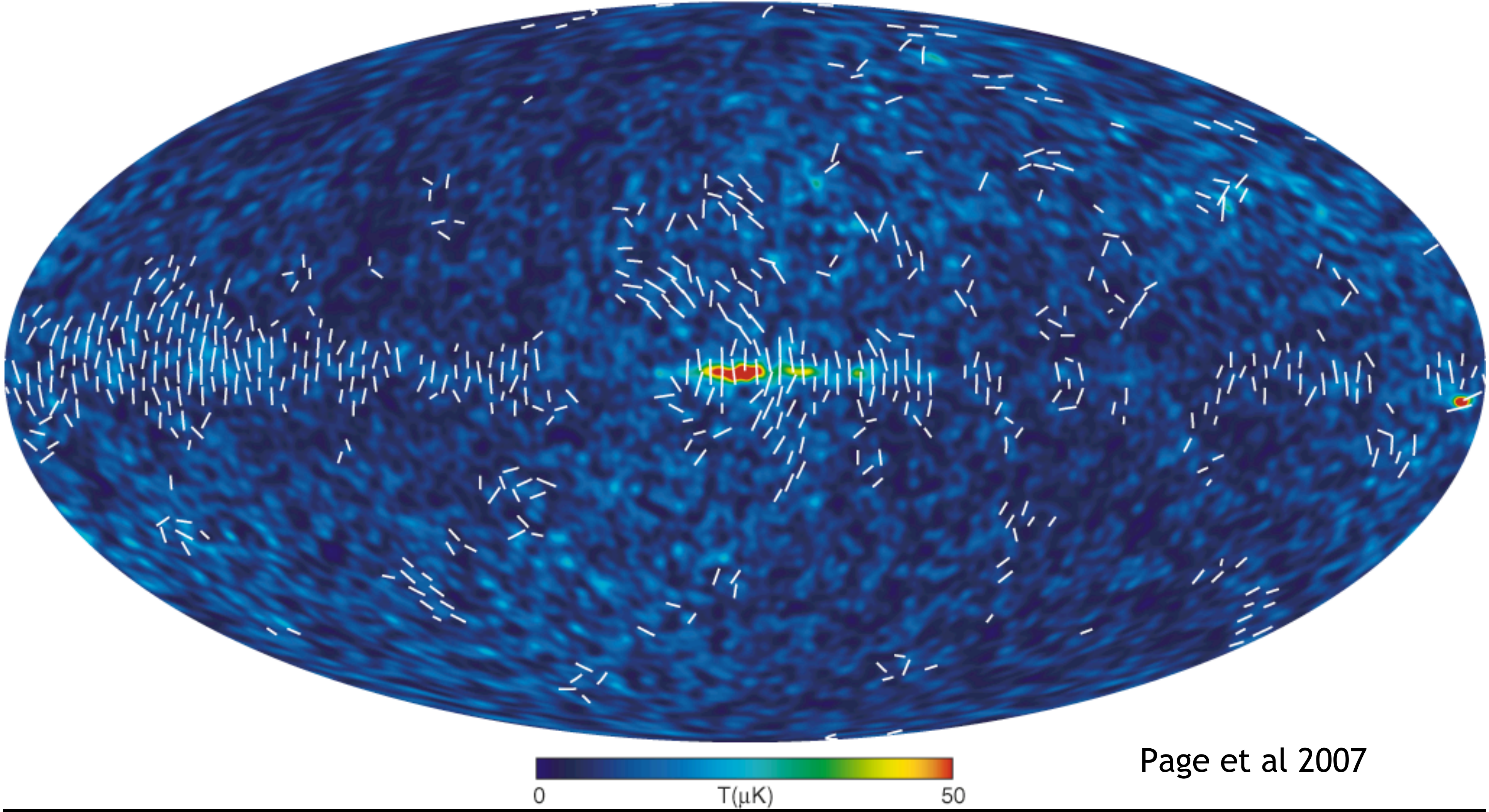
We still see significant polarized synchrotron in Q.



Page et al 2007

V Band (61 GHz)

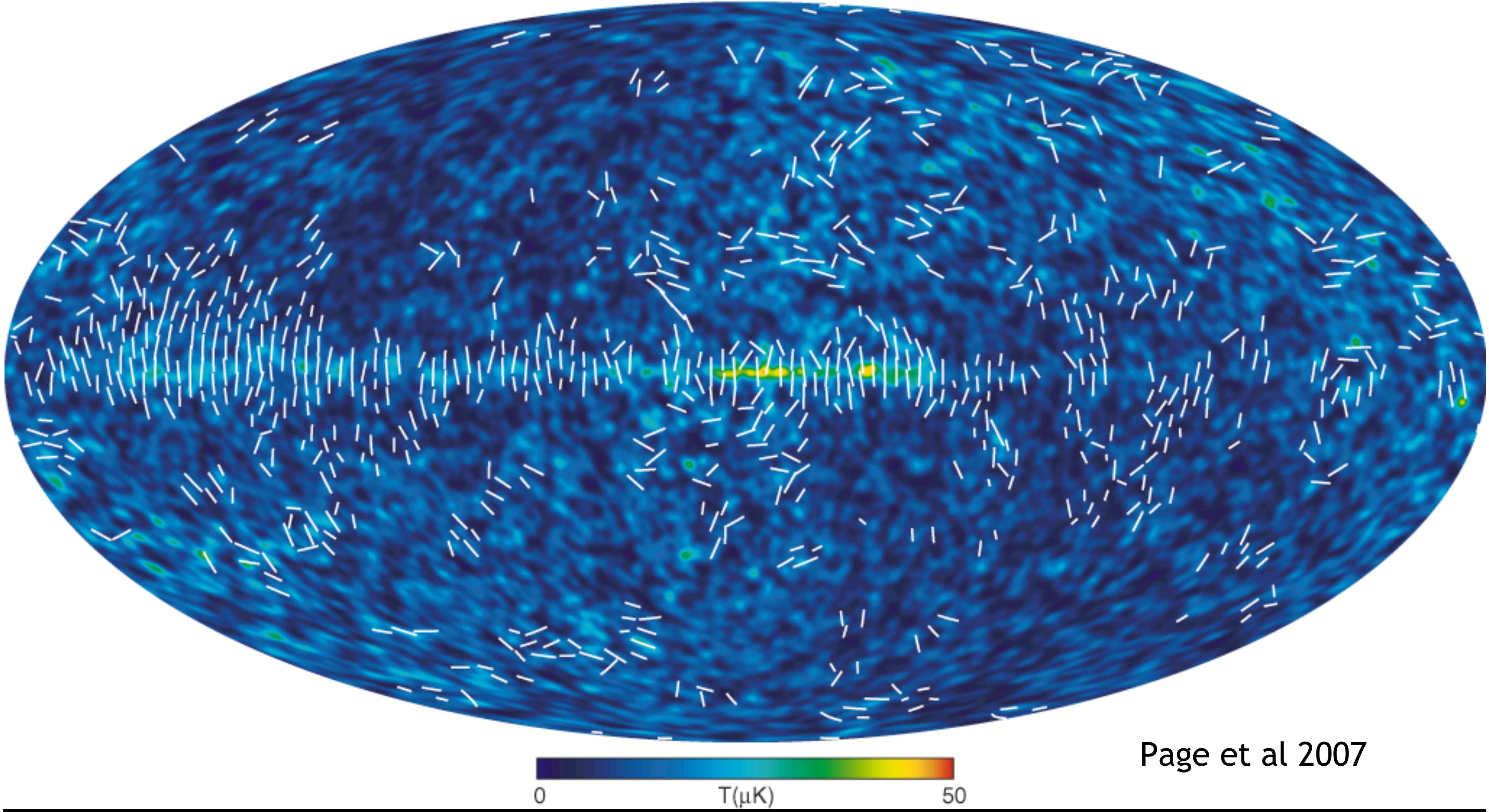
The polarized foreground emission is also smallest in V band.
We can also see that noise is larger on the ecliptic plane.



Page et al 2007

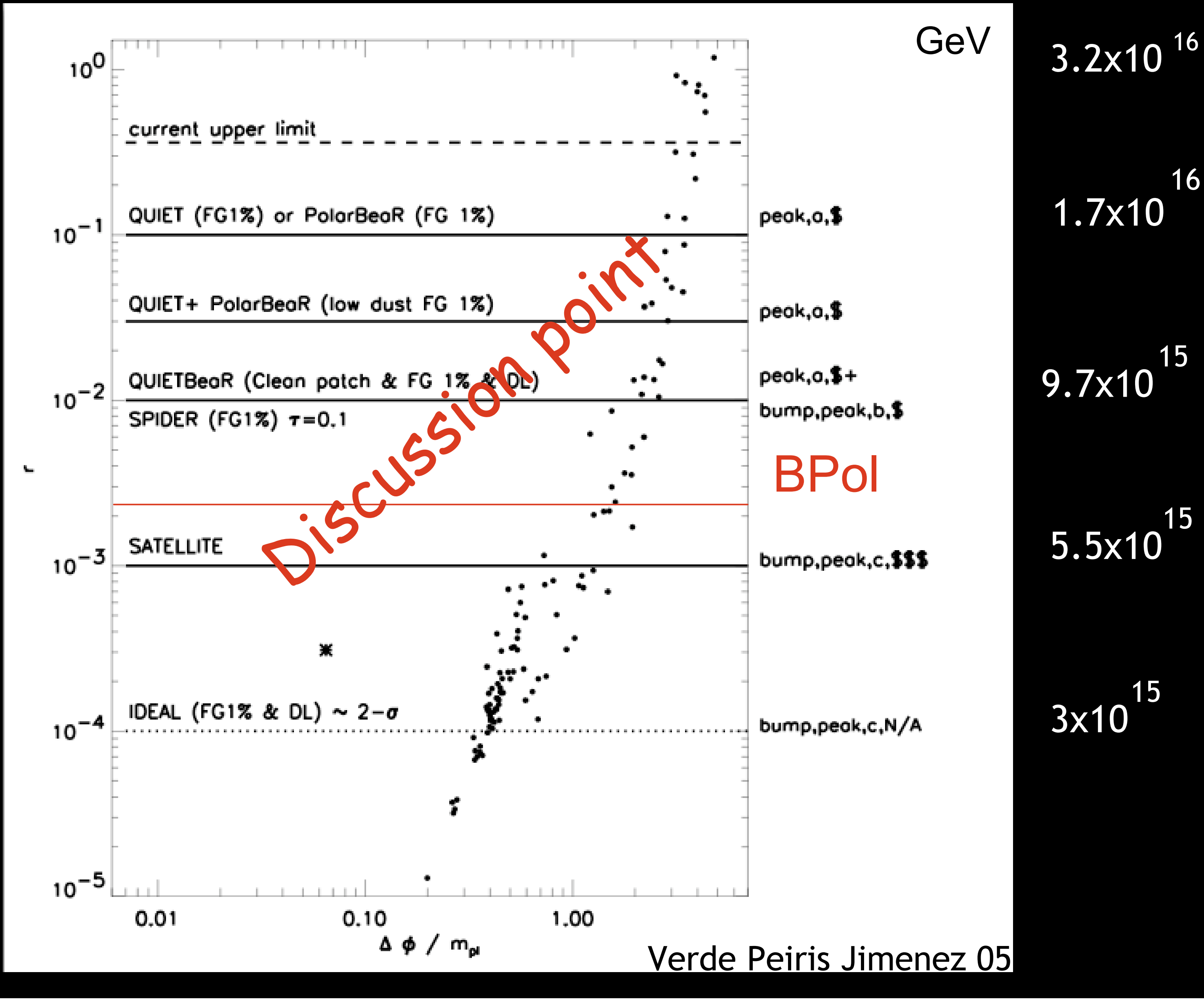
W Band (94 GHz)

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



Page et al 2007

The next frontier: gravity waves

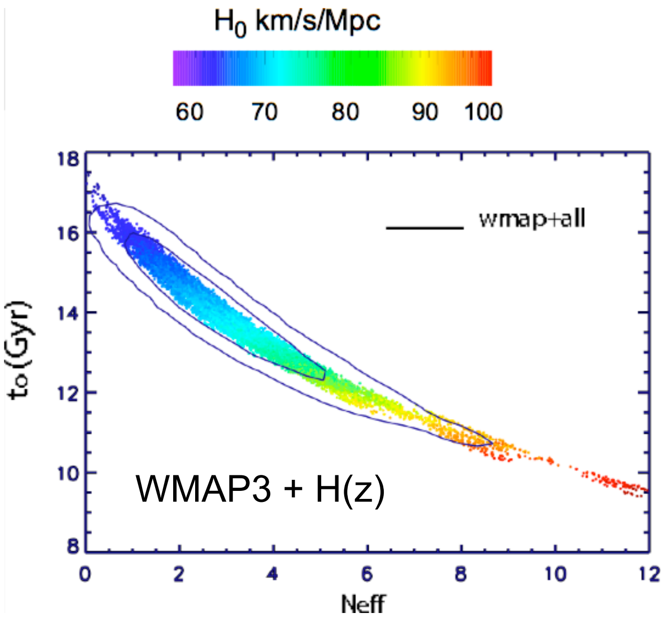


Discussion point

Verde Peiris Jimenez 05

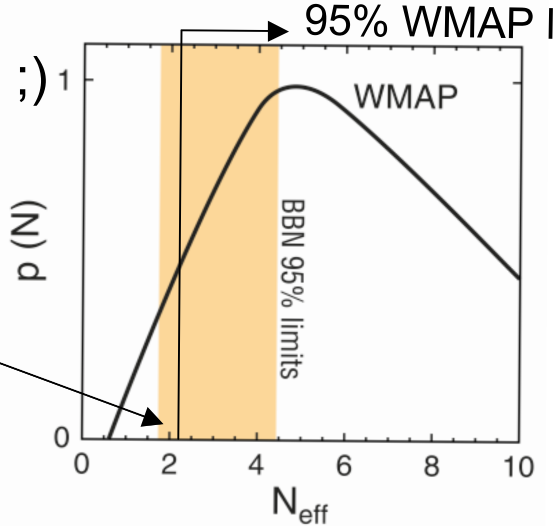
Neutrinos

De bernardis et al 08:
detection of neutrino background
$N_{\rm eff} > 1.8$ at better than 99% confidence



WMAP5 confirms ;)
from CMB alone

(Dunkley et al 08)



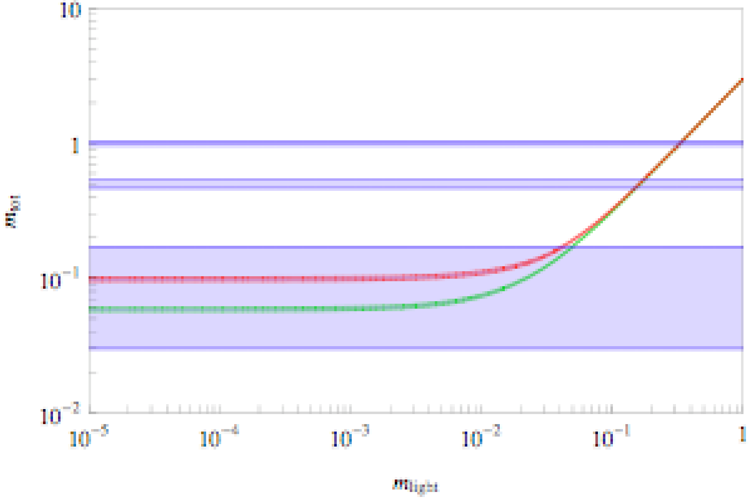
95% WMAP limit

2.3

Future cosmological data
may reach $\Delta m_\nu \sim 0.1$eV

to discriminate direct/inverse
hierarchy

e.g., Fernandez-Martinez, Mena in prep.



DARK ENERGY

THE SYMPTOMS

Or OBSERVATIONAL EFFECTS of DARK ENERGY

Recession velocity vs brightness of standard candles: dL(z)

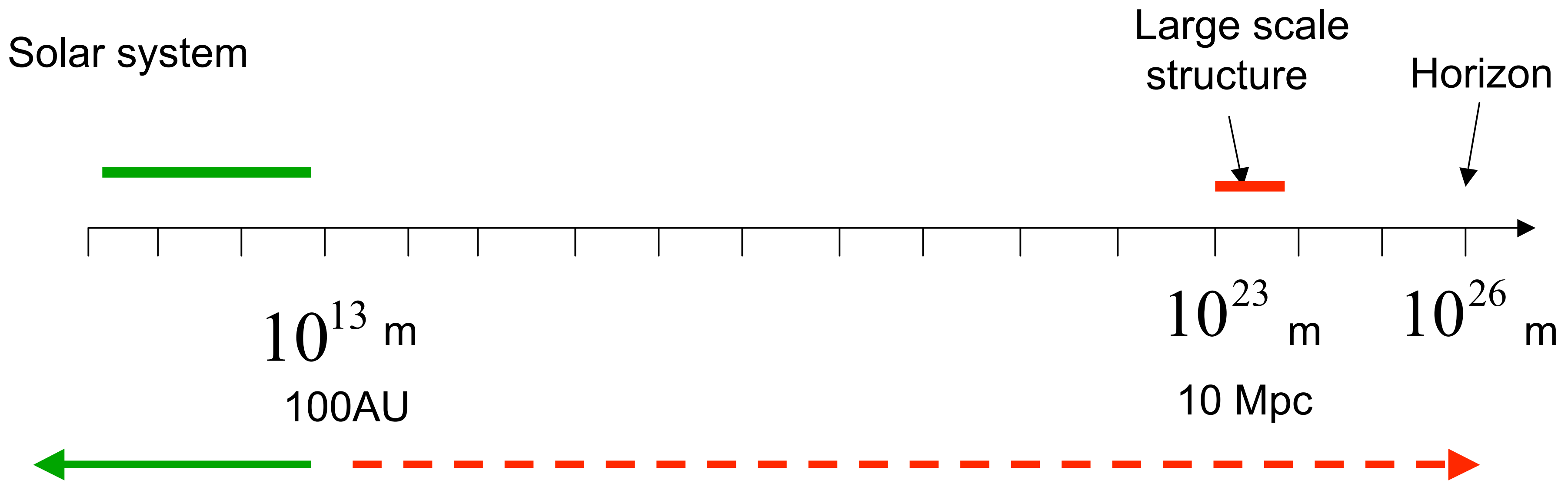
CMB acoustic peaks: Da to last scattering

LSS: $\left\{ \begin{array}{l} \text{Da to } z_{survey} \\ \text{perturbations amplitude today, to be compared with CMB} \\ \text{Perturbation amplitude at } z_{survey} \end{array} \right.$

Something on large scales?

Dark energy shows its effects on scales comparable to the horizon… 10^{26} m

Precision test of the law of gravity have been carried out on scales< 10^{13} m



Solar system

Large scale structure

Horizon

10^{13} m

100AU

10^{23} m

10 Mpc

10^{26} m

An enormous extrapolation is required

HOW TO MAKE A DIAGNOSIS?

Any modification of gravity of the form of f(R) can be written as a quintessence model for a(t)

This degeneracy is lifted when considering the growth of structure

Effort in determining what the growth of structure is in a given Dark Energy model!

combination of approaches!

Leading observational techniques to go after dark energy

Supernovae	(expansion history)
Galaxy clusters number counts	(mostly growth of structure)
Weak Lensing	(growth of structure and expansion history)
Baryonic Acoustic Oscillations (BAO)	(expansion history)

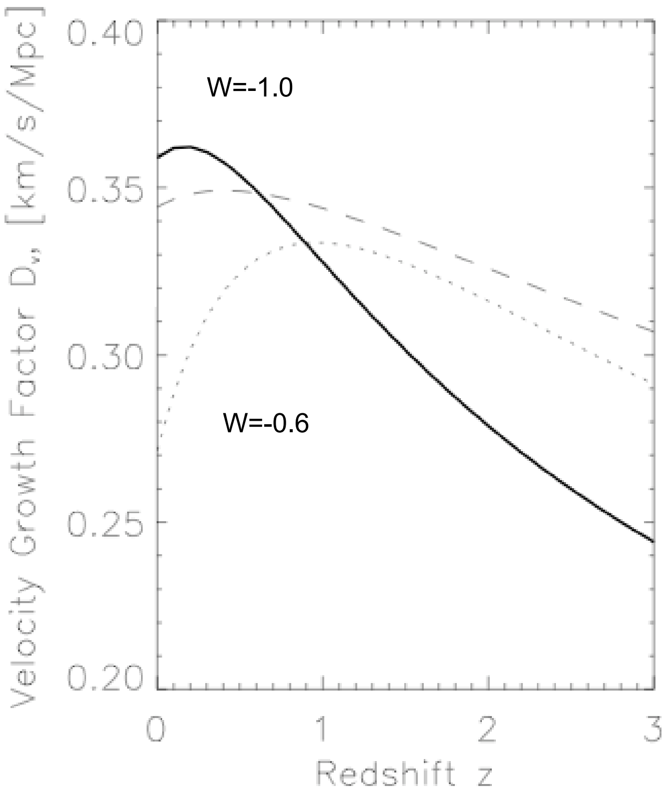
Q: A combination of techniques will be best for
at least two reasons

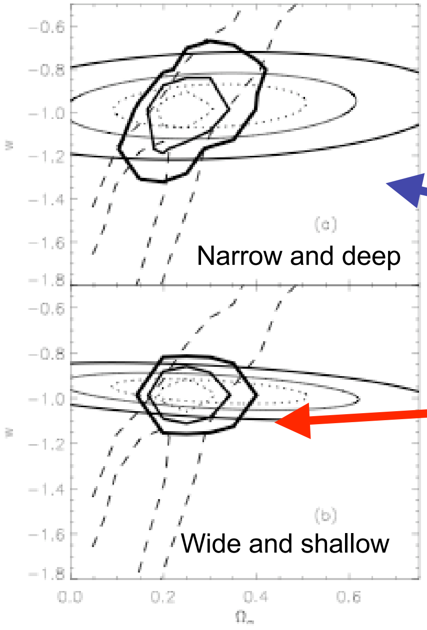
Velocities: (Hernandez-Monteagudo, Verde, RJ, Spergel 2005)

The peculiar velocity field is sensitive to the onset of the late acceleration of the Universe.

Recall that KSZ $\delta T_{kSZ} \propto n_e \mathbf{v_e} \cdot \mathbf{n}$

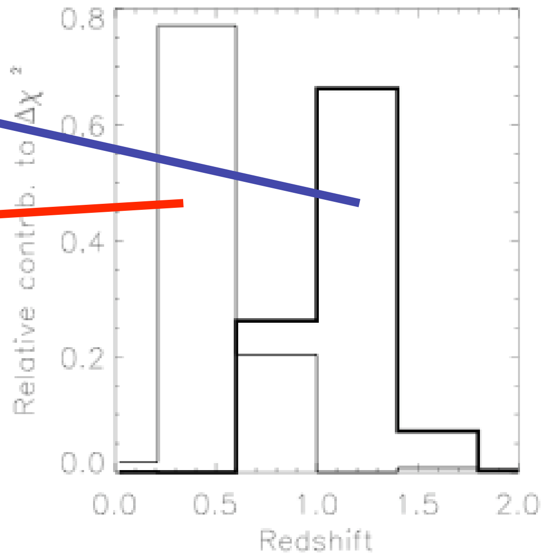
$$P_{vv}(k) = \left(H(z)\left|\frac{dD_\delta}{dz}\right|\right)^2 \frac{P_m(k)}{k^2} = \mathcal{D}_v^2 \frac{P_m(k)}{k^2},$$





Narrow and deep

Wide and shallow

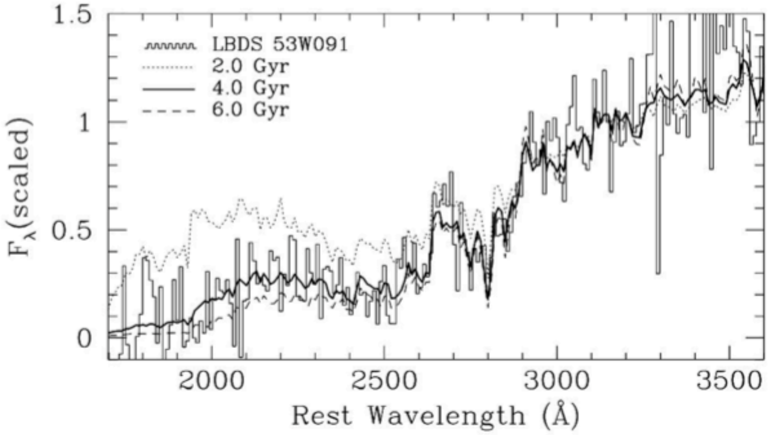


Cosmic clocks: *with D. Stern, M. Kamionkowski, R. Jimenez, T. Treu*

Standard Clock

early-type galaxies

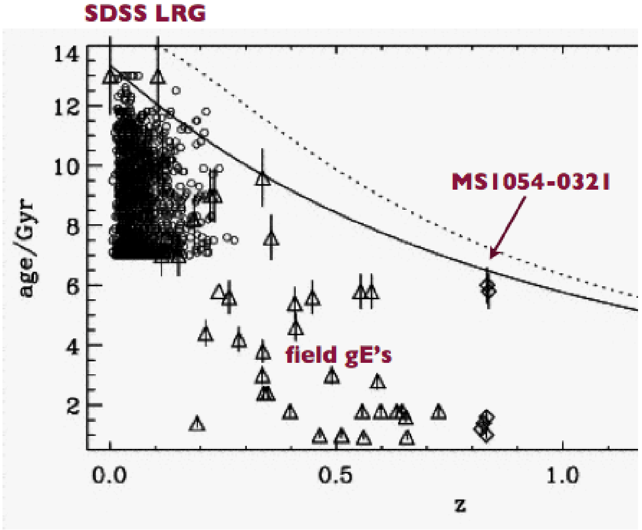
measuring age of stellar population

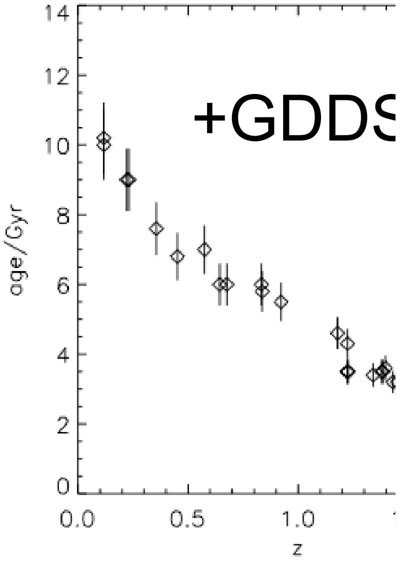


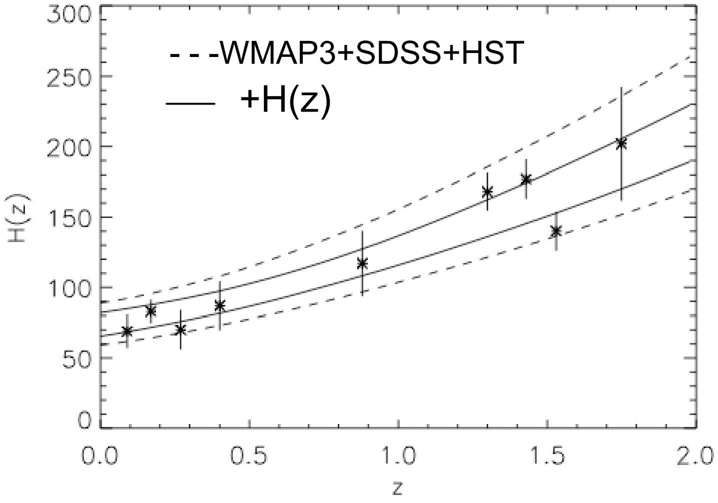
best fit age:
3.5 Gyr (at z=1.552)

Spinrad, Dey, Stern et al. (1997; ApJ, 484, 581)

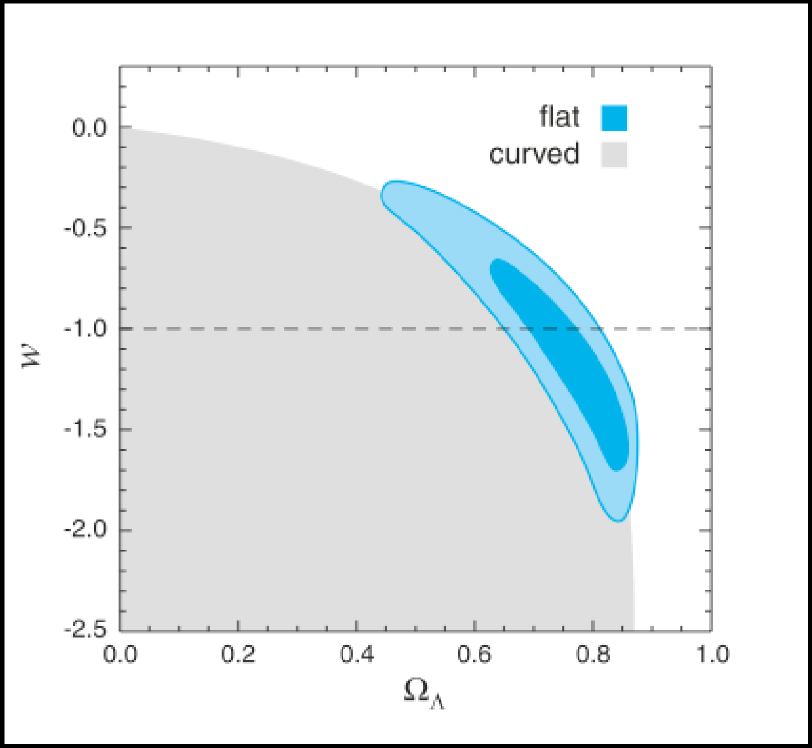
a worked example







Why so weak dark energy constraints from CMB?

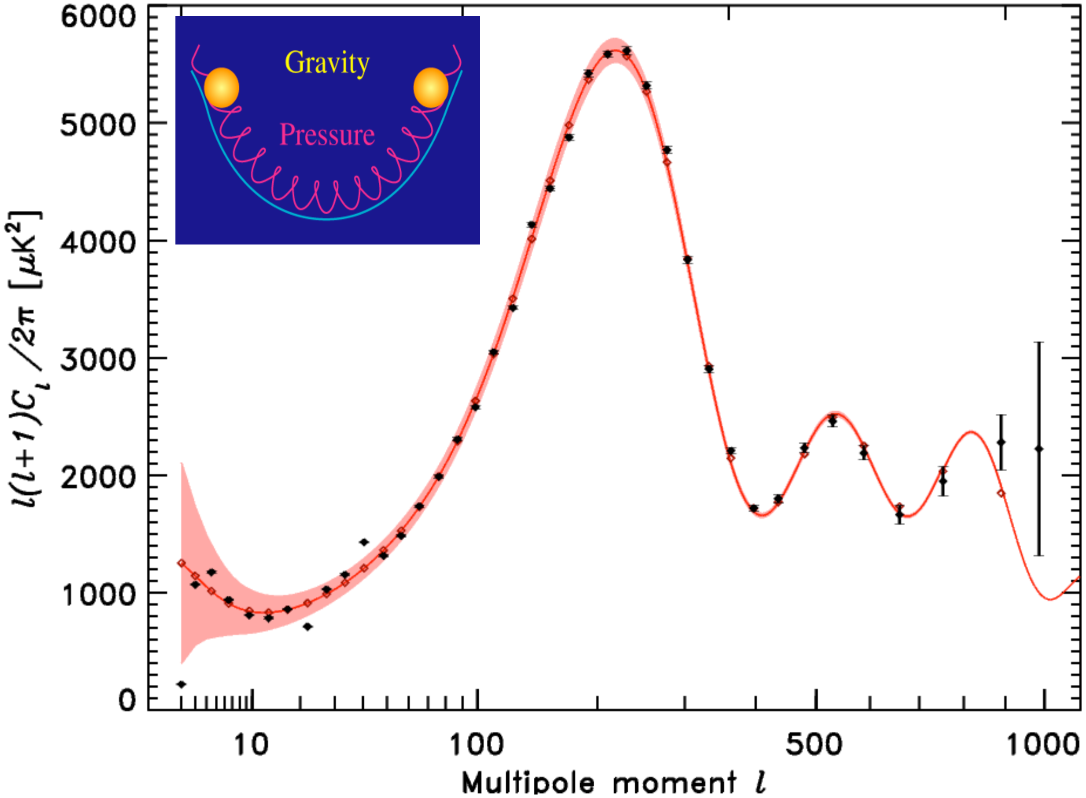


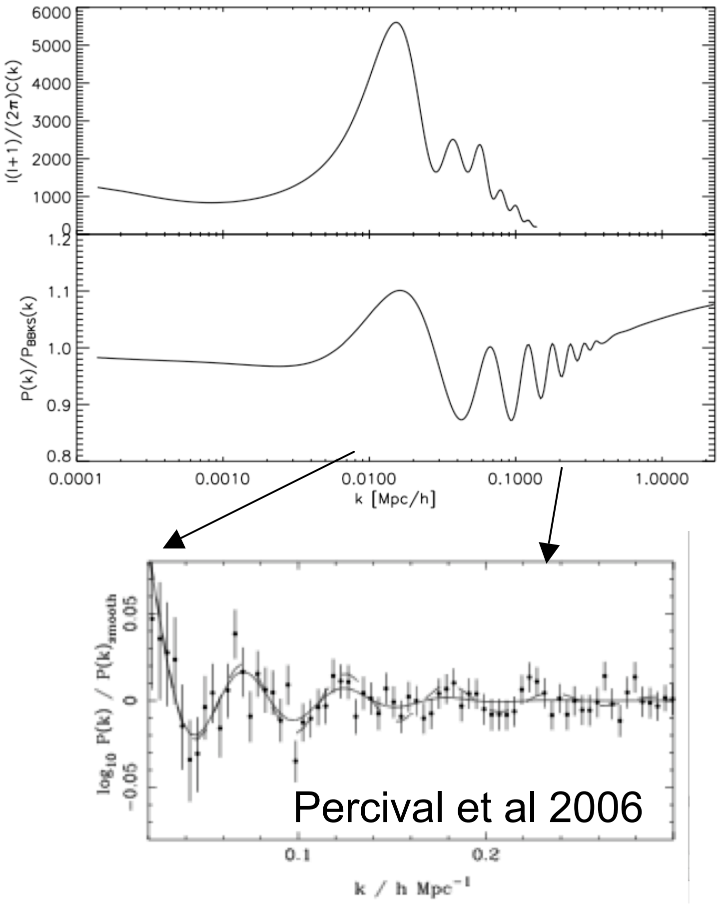
The limitation of the CMB in constraining dark energy is that the CMB is located at z=1090.

We need to look at the expansion history (I.e. at least two snapshots of the Universe)

What if one could see the peaks pattern also at lower redshifts?

For those of you who think in Fourier space





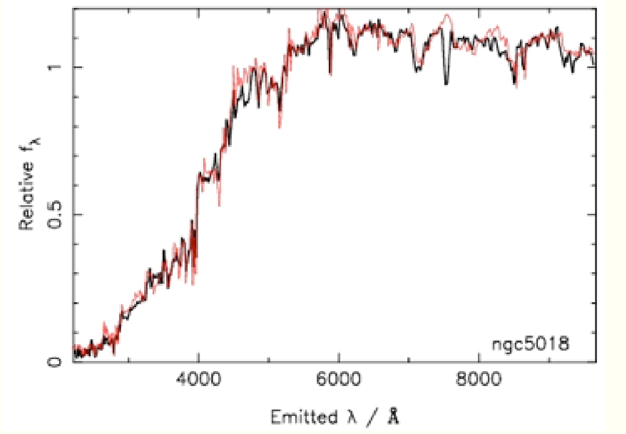
Percival et al 2006

If baryons are ~1/6 of the dark matter these baryonic oscillations should leave some imprint in the dark matter distribution

Spectroscopy or photometry?

AAOmega 600K galaxies, z~1 (10% error on w)

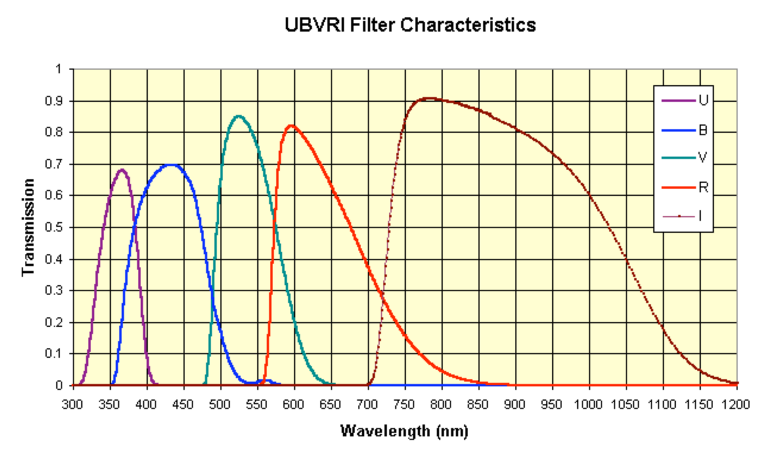
WFMOS several million galaxies >2012



VISTA, DES, LSST

Degrade information in the z direction but is faster & can cover more sky

Could do weak lensing almost for free



The debate is still open!

PAU

http://www.ice.csic.es/research/PAU/PAU-welcome.html

Close collaboration between particle physicists (theorists and experimentalists) and astrophysicists (theorists and observers)

Awarded consolider-ingenio 2010, E. Fernandez, PI

“Hybrid” technique: narrow band photometry (the best of both worlds?)

Survey ~10000 deg^2 $0.1<z<1.0$, ~14M LRG galaxies, 100’s M total

Likely: dedicated telescope. New camera (~40 narrow band filters)

Measures both H(z) and Da

Instituto de fisica de alta energias (IFAE-Barcelona)
Instituto de ciencias del Espacio (ICE-Barcelona)
Instituto astrofisico de Andalucia (IAA-Granada)
Instituto de fisica teorica (IFT-Madrid)
Centro de investigaciones[…] (CIEMAT-Madrid)
Instituto de fisica corpuscolar (IFIC -Valencia)
Puerto de informacion Cientifica(PIC-Barcelona)

Conclusions

The standard cosmological model is extremely successful, but leaves us with 2 fundamental problems:

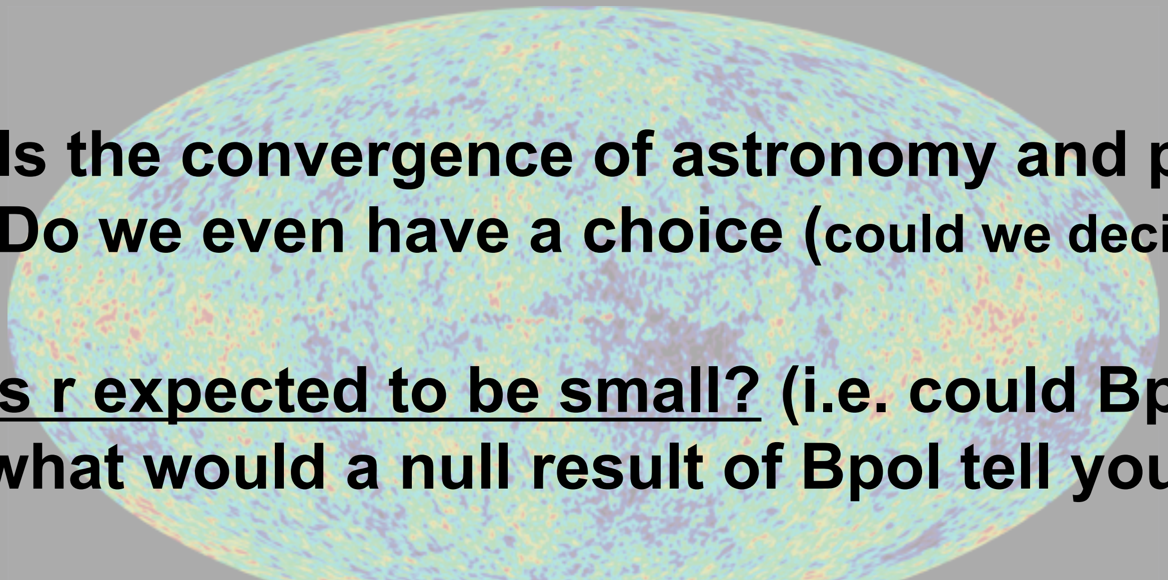
-Nothing weighs something (and gives accelerated expansion,
- but not as much as "naively" expected)
-Is our theory of gravity and particles correct or complete?
-Something like that may have happened before (inflation)
-Is the physics related? And what is it?
-Has inflation acted as a magnifying glass and microscopic effects left their signature in the sky?

Expect an avalanche of data (PAU will add > 10Tb)
(and of acronyms!)

LSST SNAP PAU Pan-Starr BPol BOSS WFMOS DES
JDEM ADEPT DUNE CMBPol QUIET Spider

Cosmology is far from "solved"….

Discussion points



Is the convergence of astronomy and physics, “damaging”? Do we even have a choice (could we decide not to “converge”)?

Is r expected to be small? (i.e. could Bpol give a null result? what would a null result of Bpol tell you?)

Is w “expected” to be not -1? (i.e. what could we reasonably learn from a dark energy experiment? What is the criterion for “success”?)

Is it even something with a w? (see point 1)

(here astro-types have done their job)

This is an effort from the entire community

The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence

Organizers:

Marc Kamionkowski (Caltech, USA) Carlos Martins (CAUP, Porto, Portugal)
Alessandro Melchiorri (University of Rome La Sapienza") Antonello Polosa (INFN, Rome) Licia Verde
(ICE/CSIC Barcelona, Spain)

Period: from 19-01-2009 to 13-03-2009

Deadline: 30-06-2008

Note: Later applications will be also considered

Abstract

The success of the standard cosmological model has many puzzling consequences and raises several key questions which are far from being answered. The observation of dark energy demonstrates that our well established theories of particles and gravity are incomplete if not incorrect. What makes up the dark side of the universe? What created the primordial fluctuations? Is gravity purely geometry as envisaged by Einstein, or is there more to it (such as scalar partners and extra dimensions)? An unprecedented experimental effort is currently being devoted to address these grand-challenge questions in cosmology. This is an intrinsically inter-disciplinary issue that will inevitably be at the forefront of research in astrophysics and fundamental physics in the coming decades.

Topics

- Dark energy
- Dark matter
- Inflation
- Gravity