Introduction to Cosmology
lecture 3

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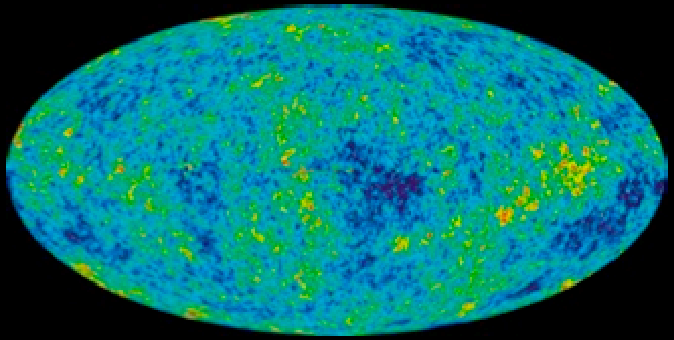
The era of precision cosmology:

LCDM: the “standard” model for cosmology

Few parameters describe the Universe composition and evolution

Homogenous background

Perturbations



$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$

A_s, n_s, r

- atoms 4%
- cold dark matter 23%
- dark energy 73%

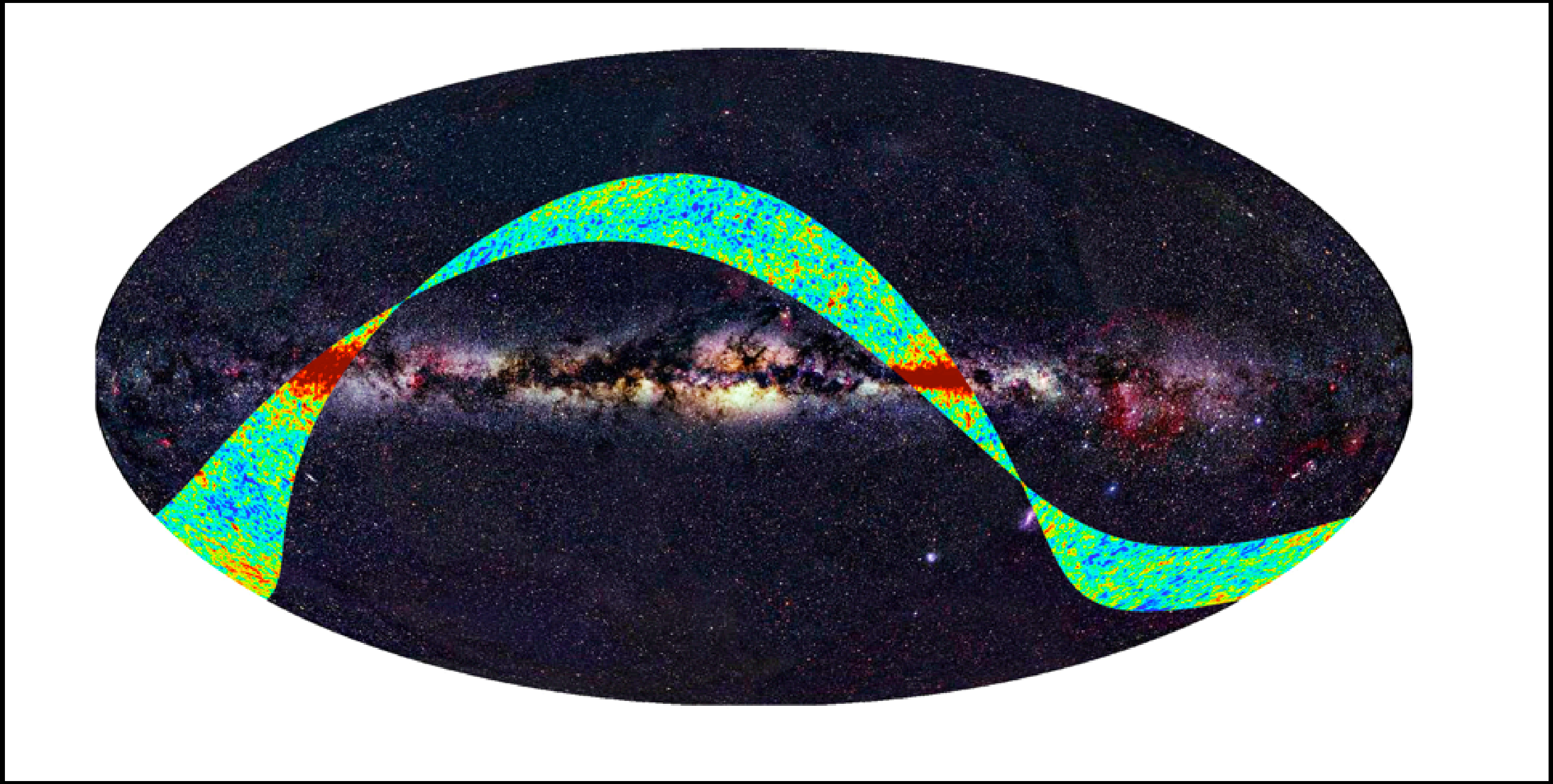
- nearly scale-invariant
- adiabatic
- Gaussian

Λ? CDM?

ORIGIN??

The future is here

Planck satellite successfully launched in May 2009!

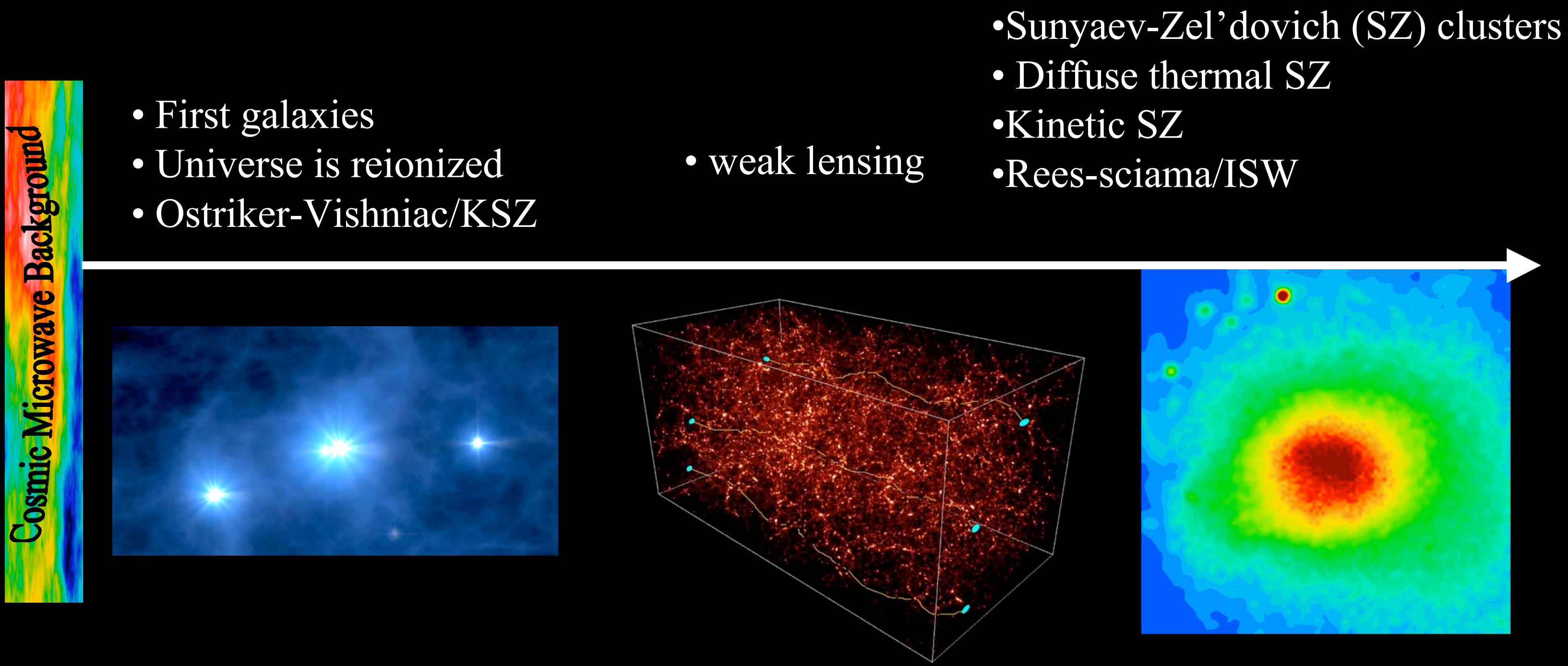


“PR” image

What next?

a) Beyond primary anisotropies

Use the CMB as a backlight to illuminate the growth of cosmological structure.



- First galaxies
- Universe is reionized
- Ostriker-Vishniac/KSZ

- weak lensing

- Sunyaev-Zel’dovich (SZ) clusters
- Diffuse thermal SZ
- Kinetic SZ
- Rees-sciama/ISW

Watch this space because experiments like e.g., South Pole Telescope or Atacama Cosmology Telescope are releasing data these days

What next?

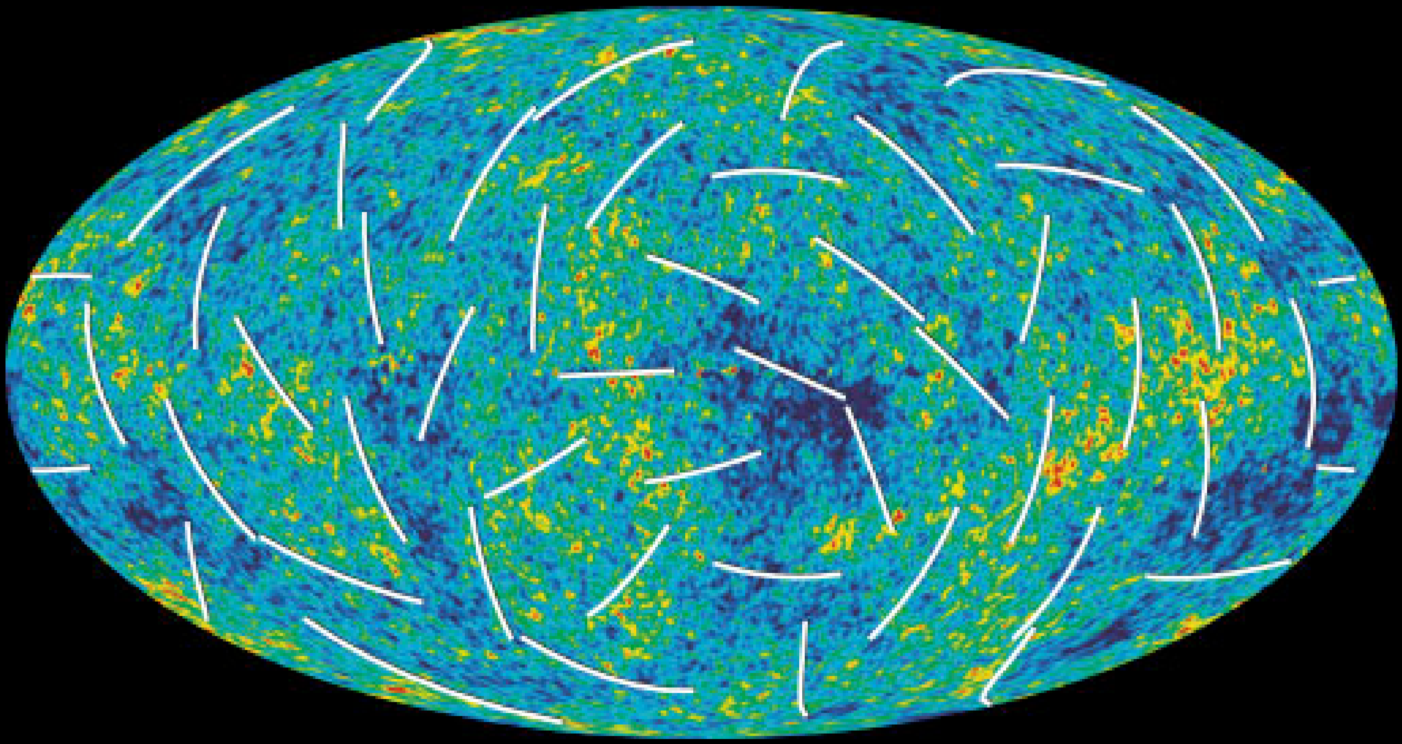
b)Polarization, the next frontier

Why measure CMB Polarization?

Directly measures dynamics in early universe

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

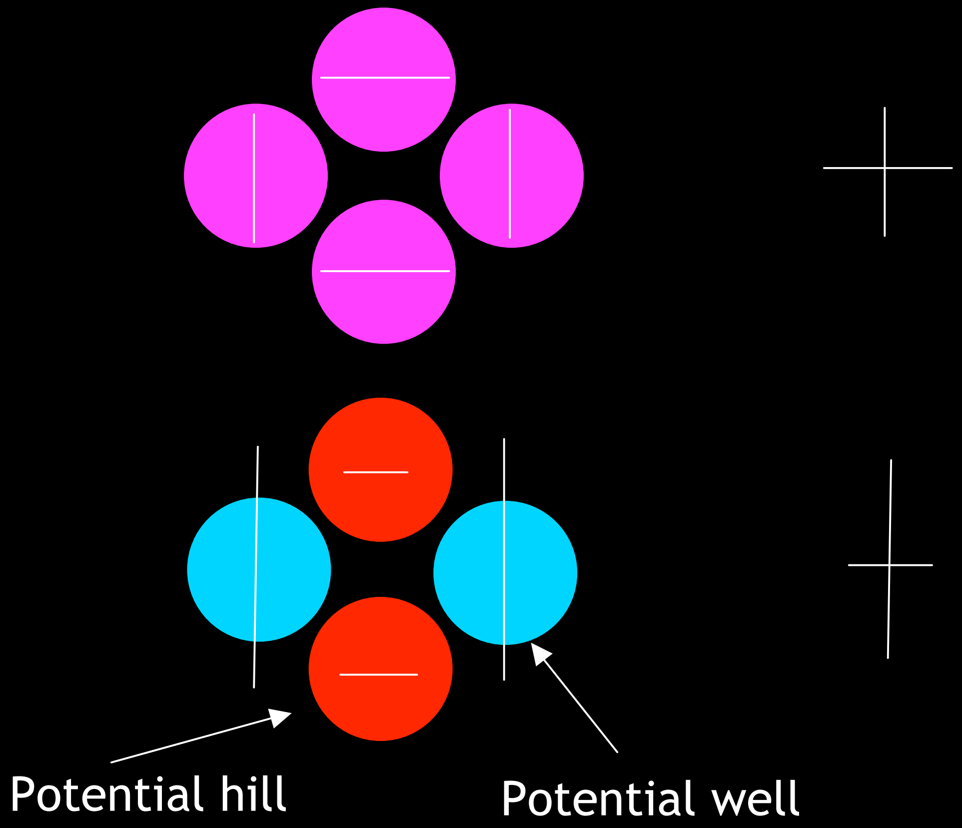
Future: “How did the Universe begin?”
Improve cosmological constraints
Eventually, perhaps, test the theory of inflation.

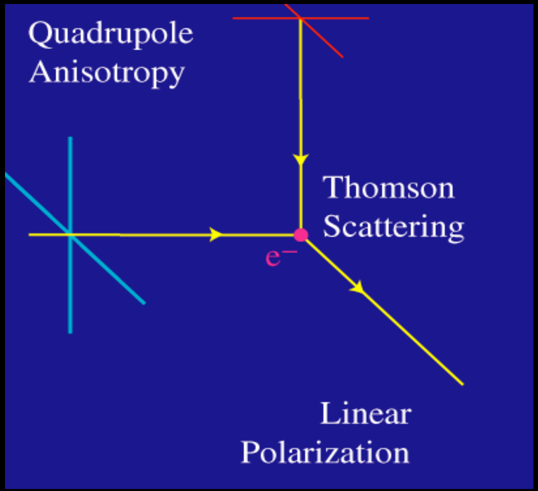


New in 2006

Generation of CMB polarization

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





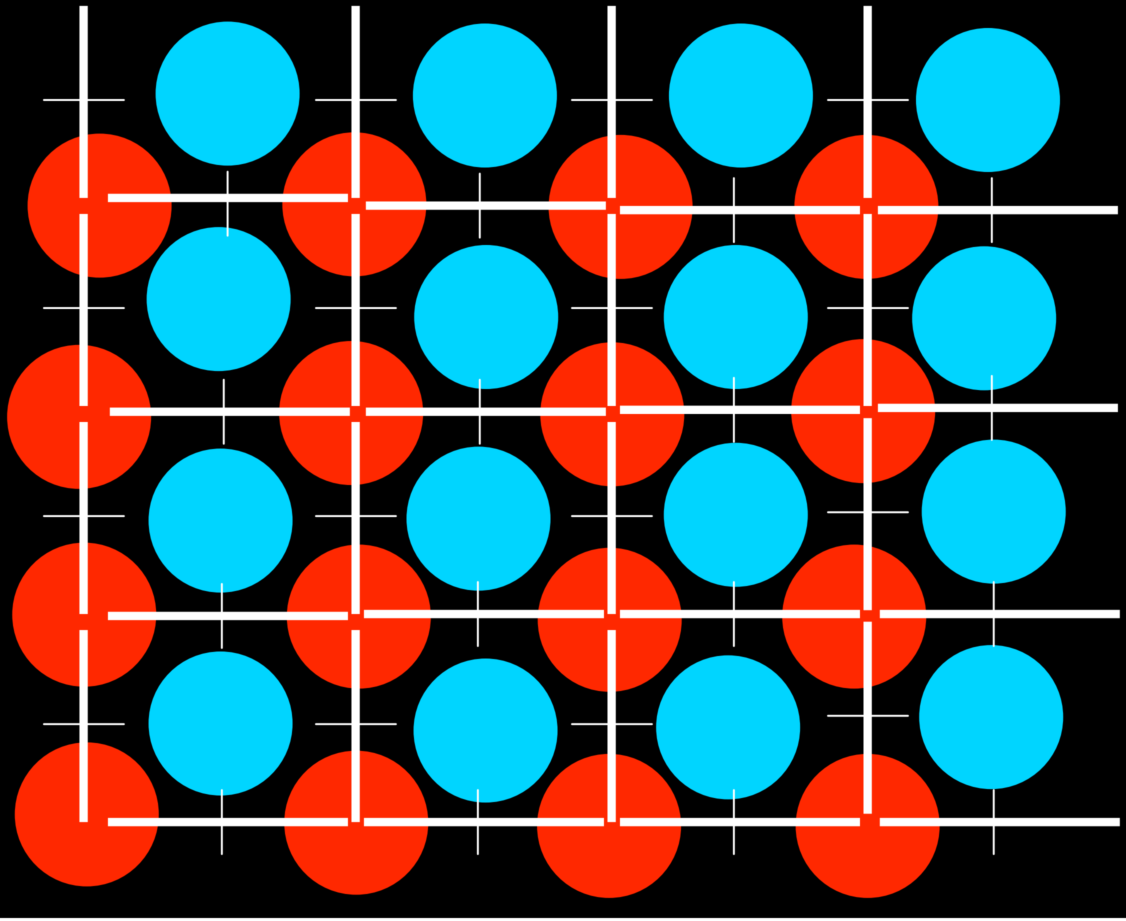
From Wayne Hu


At the last scattering surface


At the end of the dark ages (reionization)

Polarization for density perturbation

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

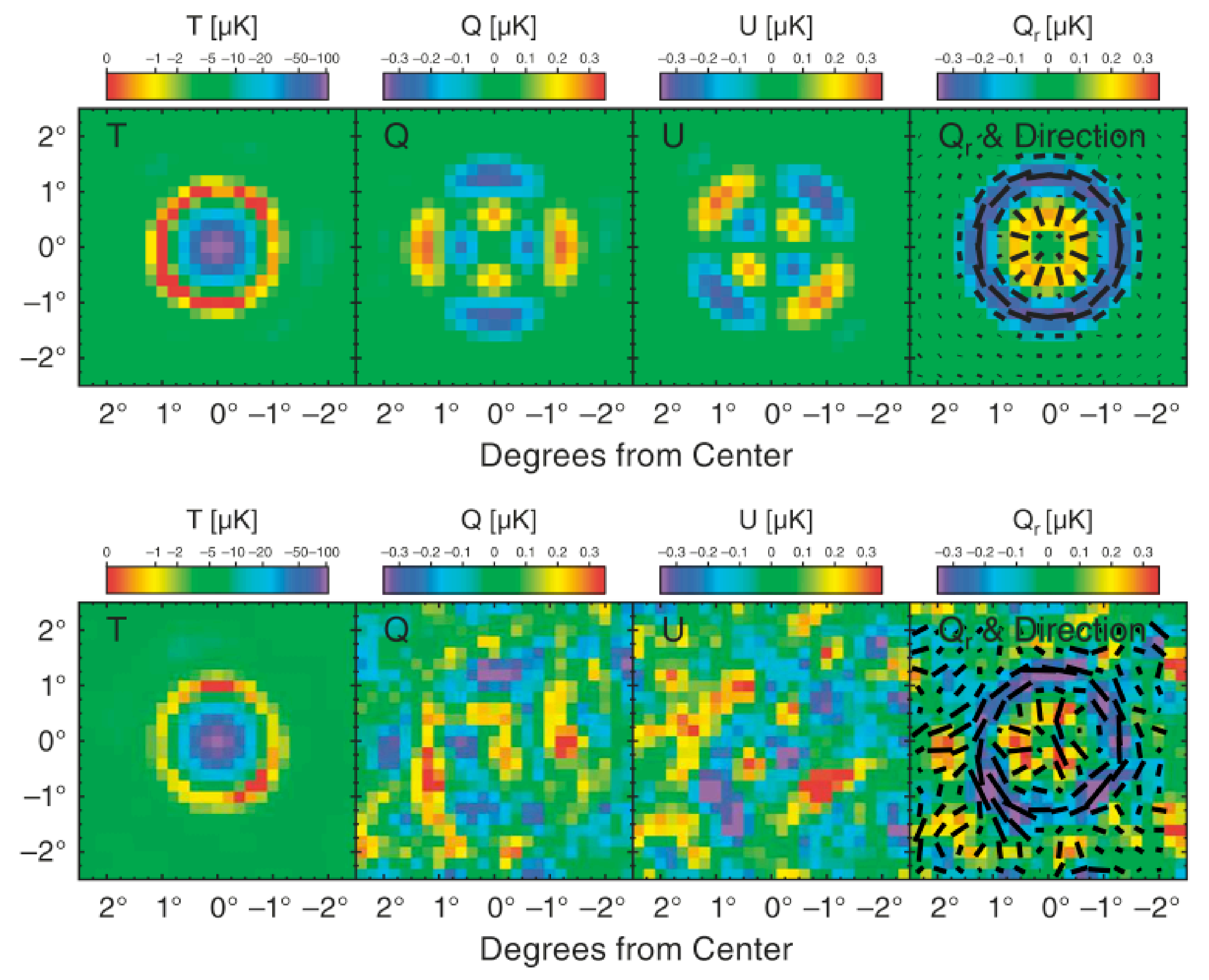


And it has been seen!

Komatsu, WMAP7yrs team (2010)

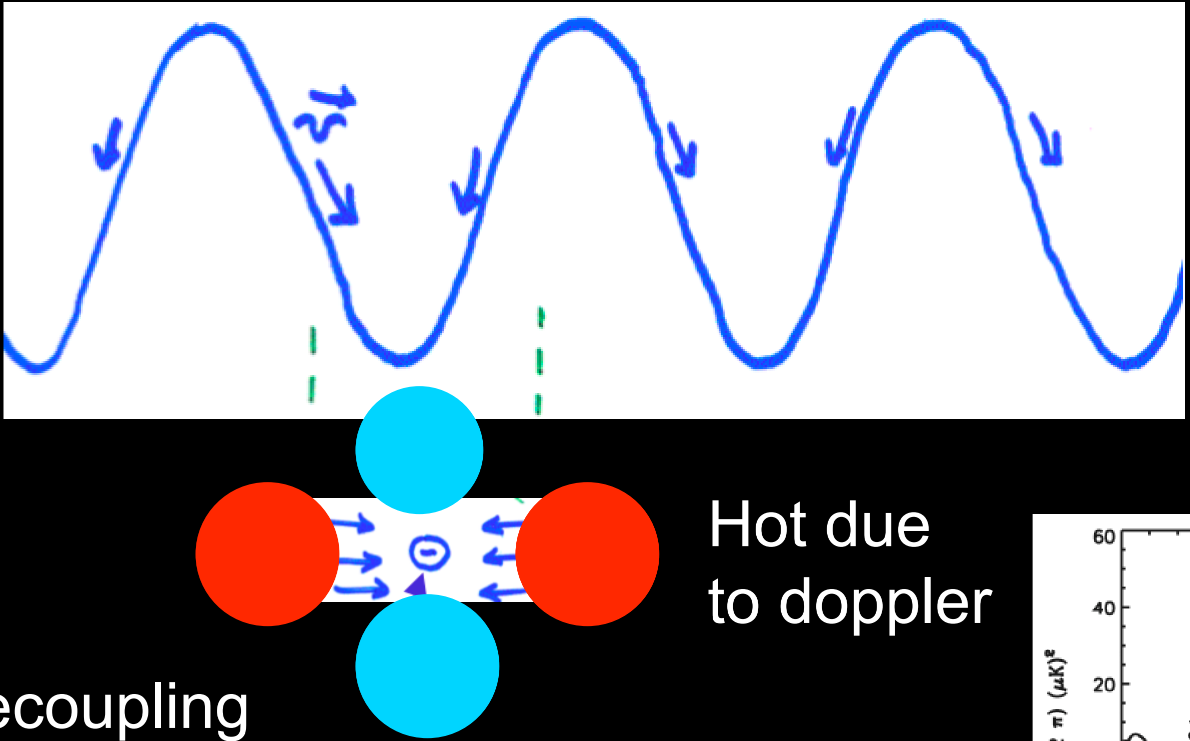
Theory prediction

Observed



Super-horizon perturbations: Large-scale TE anti correlation

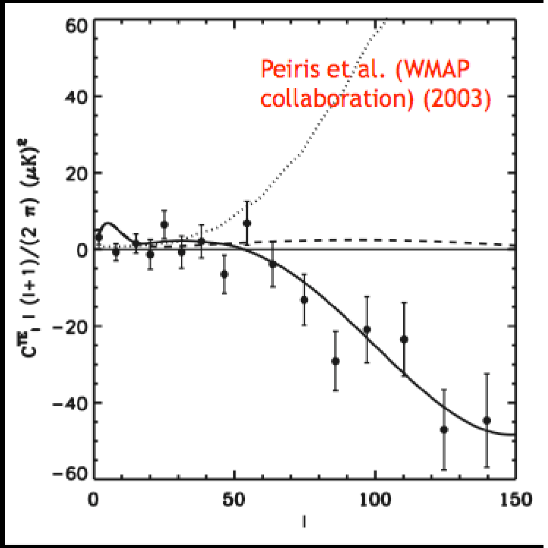
Density mode



Velocities (hot to cold)

Hot due to doppler

During decoupling

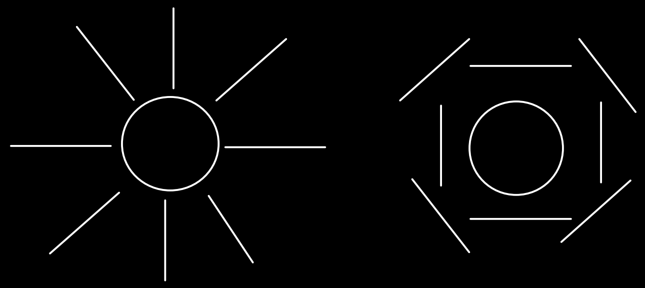


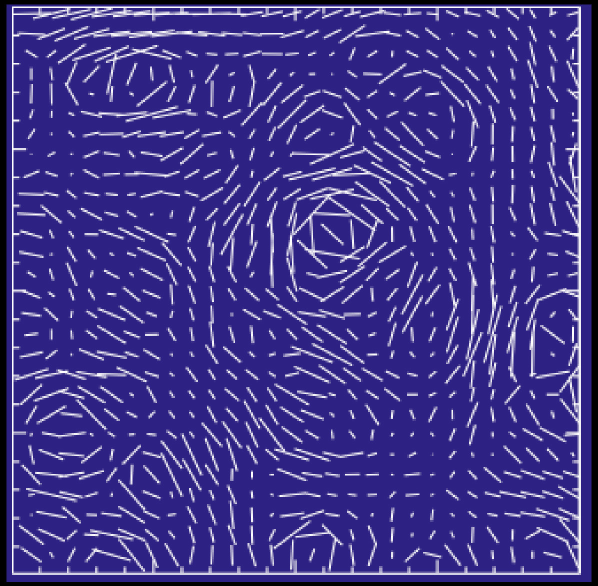
Peiris et al. (WMAP collaboration) (2003)

Gravity waves (tensor) are different…

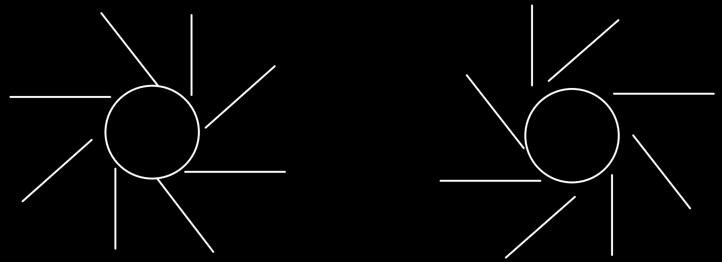
E and B modes polarization

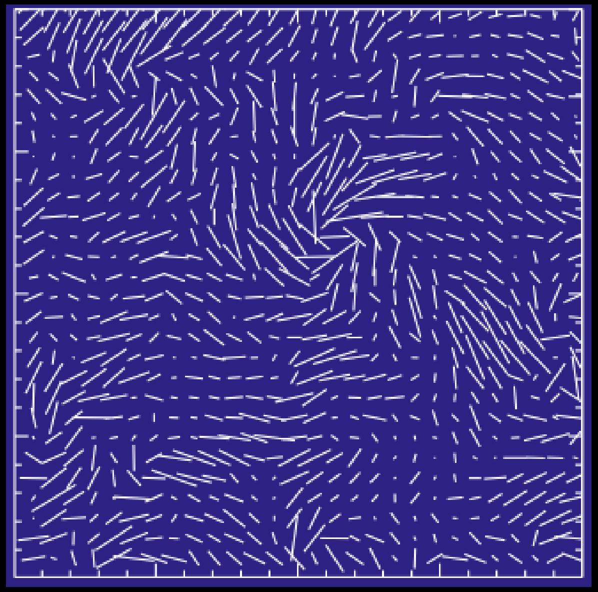
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes



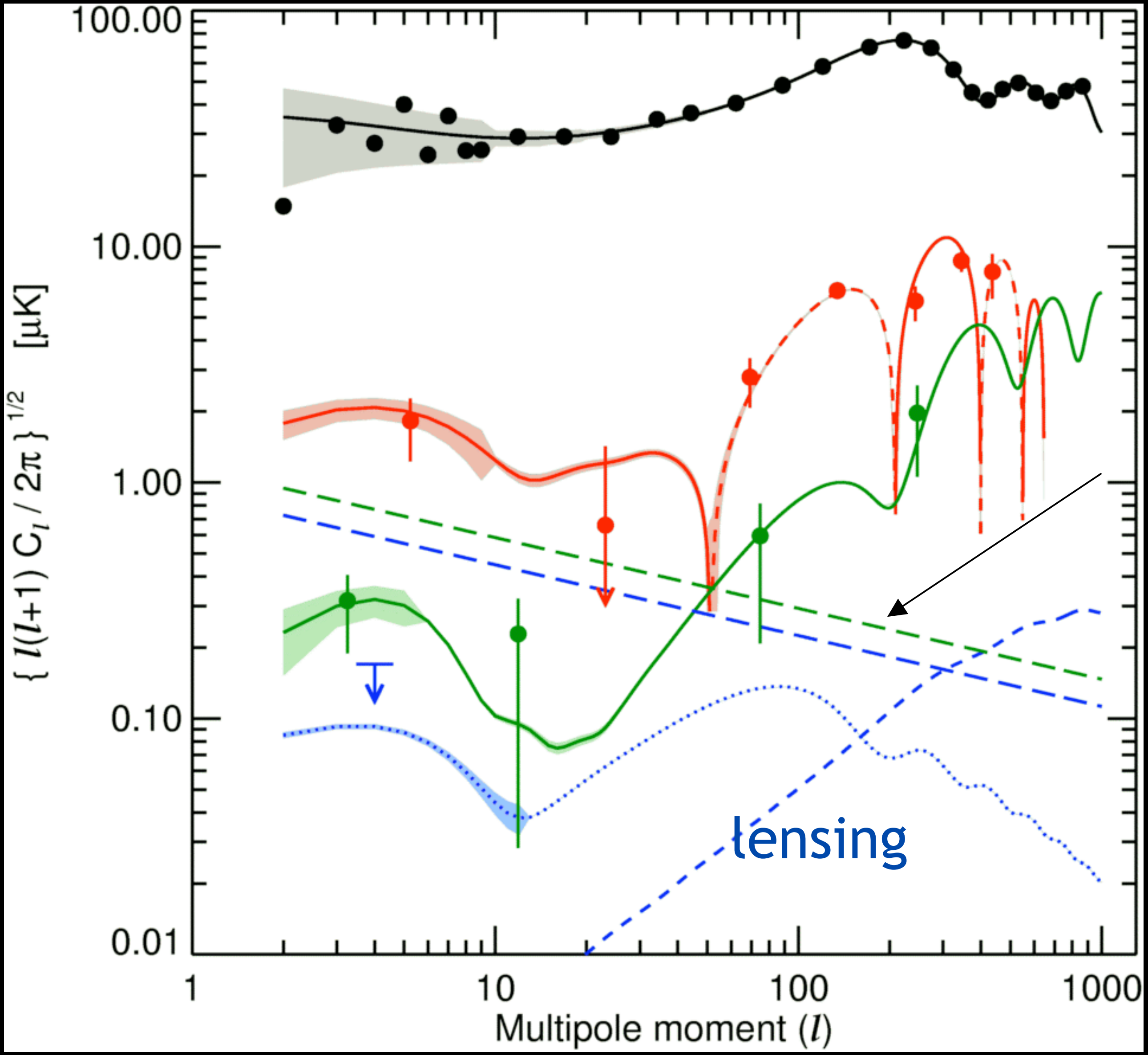


Smoking gun of inflation
holy grail for future CMB experiments

Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

We happen to live in a galaxy!

State of the art today



Foregrounds after cut

r=
tensor-to-scalar
ratio

Line is for r=0.3

Why polarization?

Temperature
(and E-modes) ↔ Shape of the inflation potential

Energy Scale of Inflation (Height of the potential)

B-modes are needed!   Tensor to scalar ratio, r

- Current limit $r_{\mathrm{CMB}} < 0.2$. “Realistically” observable: $r_{\mathrm{CMB}} \geq 0.01$

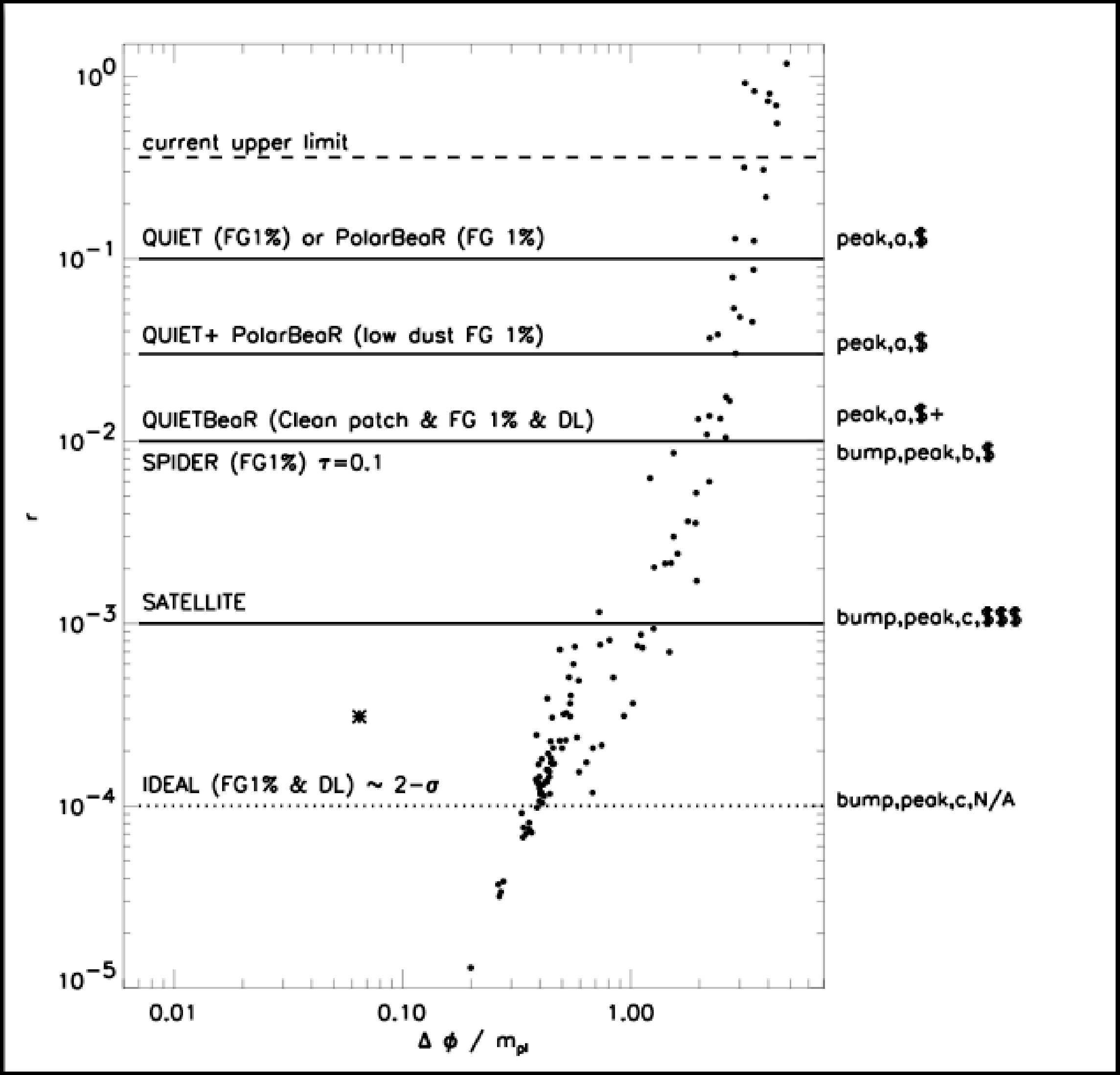
- Measurement gives two critical pieces of info:
  - energy scale of inflation: $V^{1/4} \sim \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4} 10^{16}\ \mathrm{GeV}$
  - super-Planckian field variation: $\frac{\Delta\phi}{M_{\mathrm{Pl}}} > \mathcal{O}(1) \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/2}$

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

Prospects for B Modes measurements



TeV

$3.2x10^{13}$

$1.7x10^{13}$

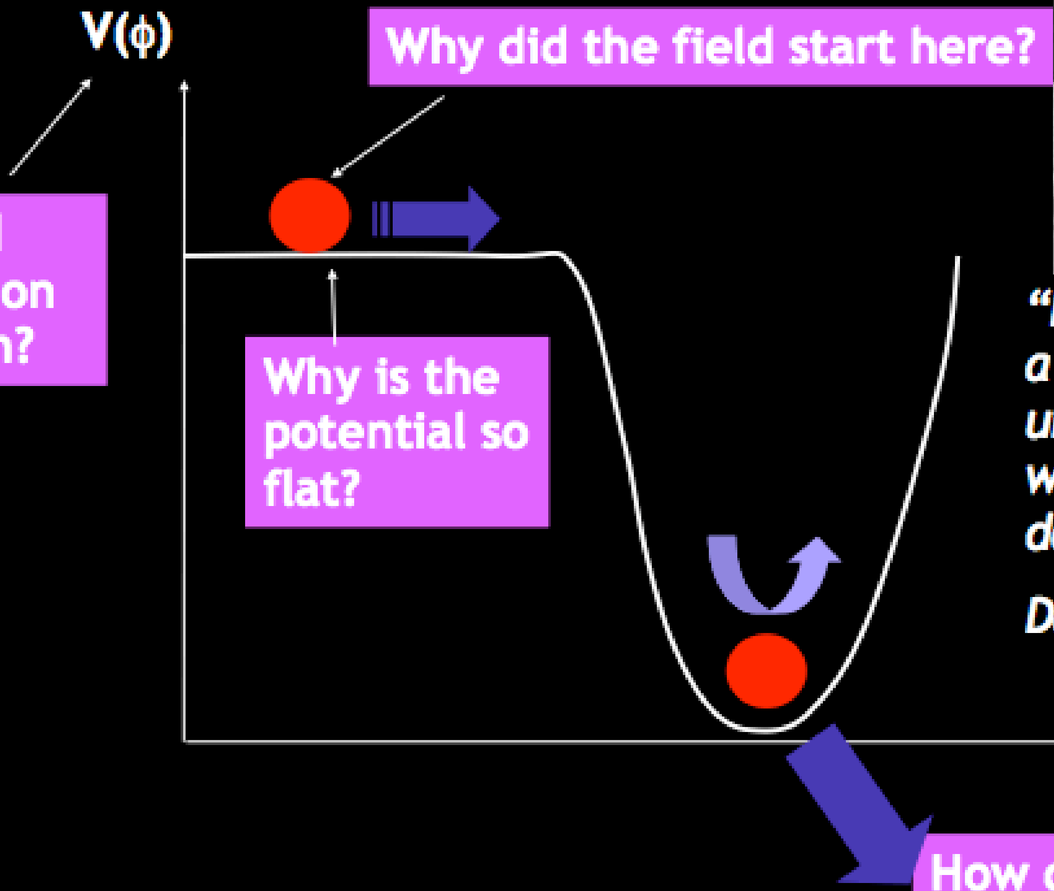
$9.7x10^{12}$

$5.5x10^{12}$

$3.\ x10^{12}$

Limitations: Foregrounds, lensing

Inflation: Theoretical Front



Where did this function come from?

Why did the field start here?

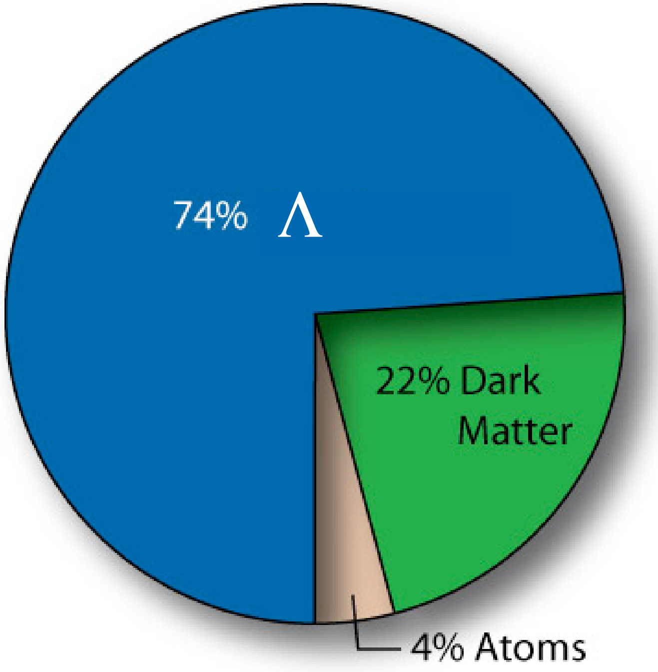
Why is the potential so flat?

How do we convert the field energy completely into particles?

"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

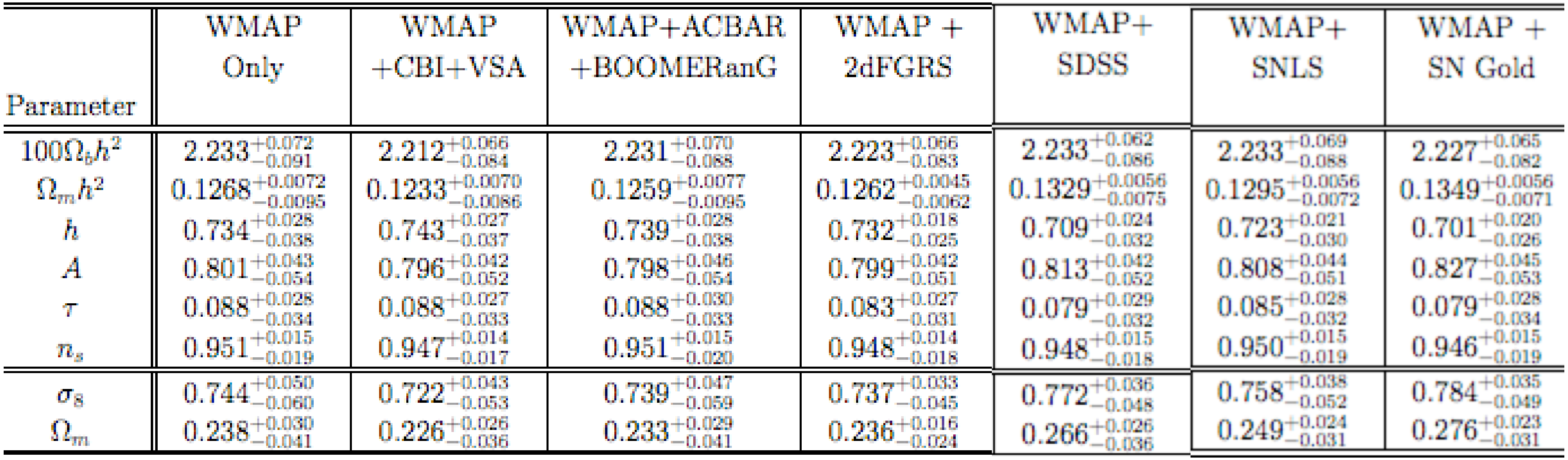
The standard cosmological model
ΛCDM model



Spatially flat Universe

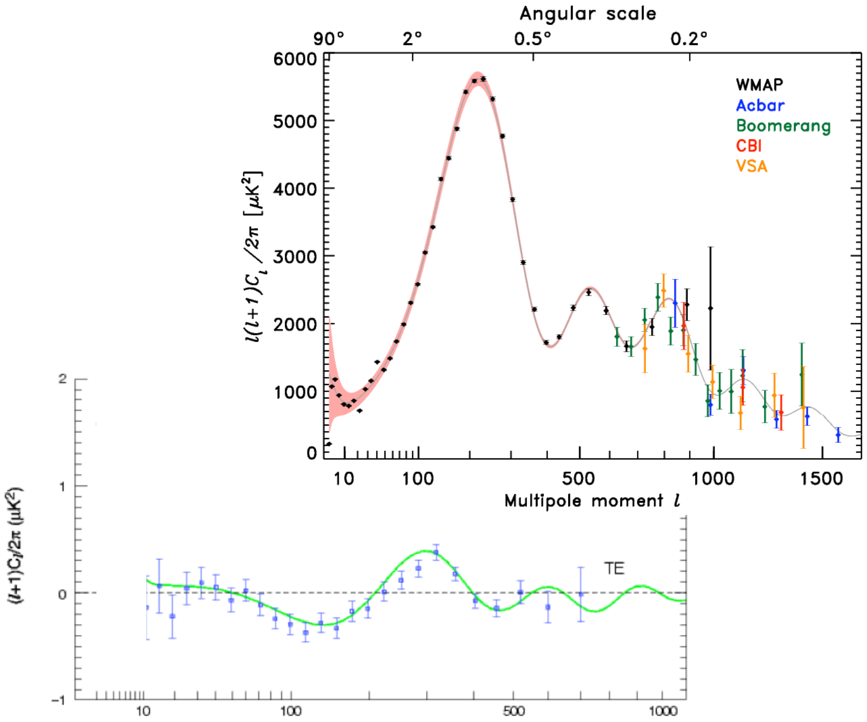
Power-law, primordial power spectrum

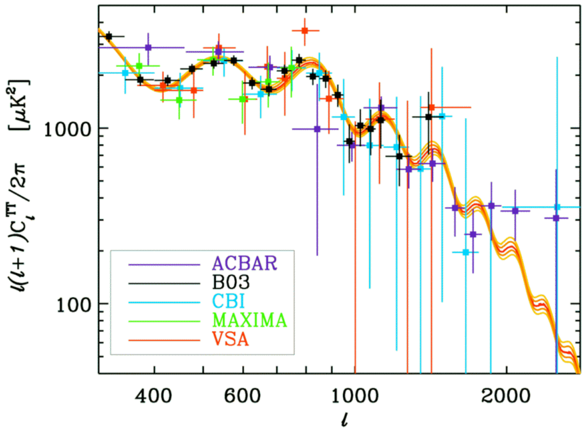
Only 6 parameters

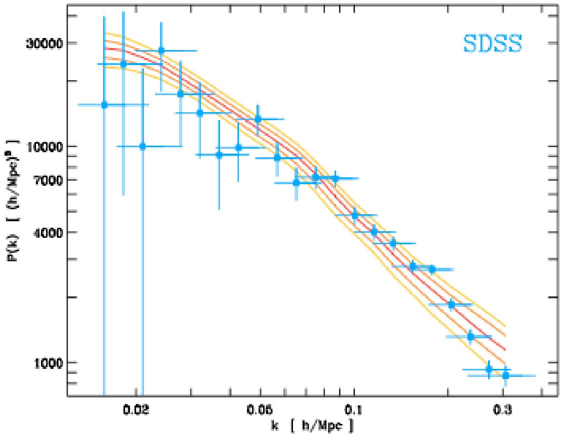


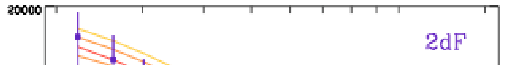
Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS	WMAP+ SDSS	WMAP+ SNLS	WMAP + SN Gold
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.212^{+0.066}_{-0.084}$	$2.231^{+0.070}_{-0.088}$	$2.223^{+0.066}_{-0.083}$	$2.233^{+0.062}_{-0.086}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$
$\Omega_m h^2$	$0.1268^{+0.0072}_{-0.0095}$	$0.1233^{+0.0070}_{-0.0086}$	$0.1259^{+0.0077}_{-0.0095}$	$0.1262^{+0.0045}_{-0.0062}$	$0.1329^{+0.0056}_{-0.0075}$	$0.1295^{+0.0056}_{-0.0072}$	$0.1349^{+0.0056}_{-0.0071}$
h	$0.734^{+0.028}_{-0.038}$	$0.743^{+0.027}_{-0.037}$	$0.739^{+0.028}_{-0.038}$	$0.732^{+0.018}_{-0.025}$	$0.709^{+0.024}_{-0.032}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$
A	$0.801^{+0.043}_{-0.054}$	$0.796^{+0.042}_{-0.052}$	$0.798^{+0.046}_{-0.054}$	$0.799^{+0.042}_{-0.051}$	$0.813^{+0.042}_{-0.052}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$
τ	$0.088^{+0.028}_{-0.034}$	$0.088^{+0.027}_{-0.033}$	$0.088^{+0.030}_{-0.033}$	$0.083^{+0.027}_{-0.031}$	$0.079^{+0.029}_{-0.032}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.951^{+0.015}_{-0.020}$	$0.948^{+0.014}_{-0.018}$	$0.948^{+0.015}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.043}_{-0.053}$	$0.739^{+0.047}_{-0.059}$	$0.737^{+0.033}_{-0.045}$	$0.772^{+0.036}_{-0.048}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$
Ω_m	$0.238^{+0.030}_{-0.041}$	$0.226^{+0.026}_{-0.036}$	$0.233^{+0.029}_{-0.041}$	$0.236^{+0.016}_{-0.024}$	$0.266^{+0.026}_{-0.036}$	$0.249^{+0.024}_{-0.031}$	$0.276^{+0.023}_{-0.031}$

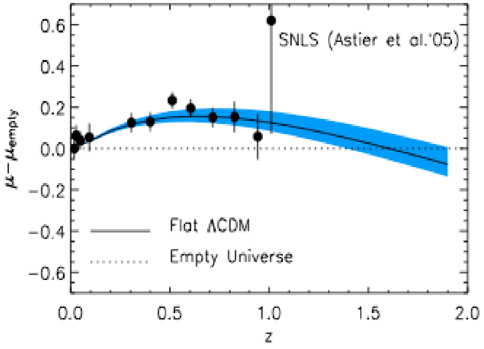
Success of the standard cosmological model:

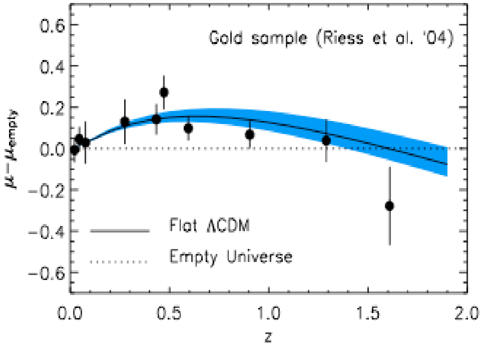












Aside

Cosmic Variance: Homogeneity and uniformity.

Statistical properties

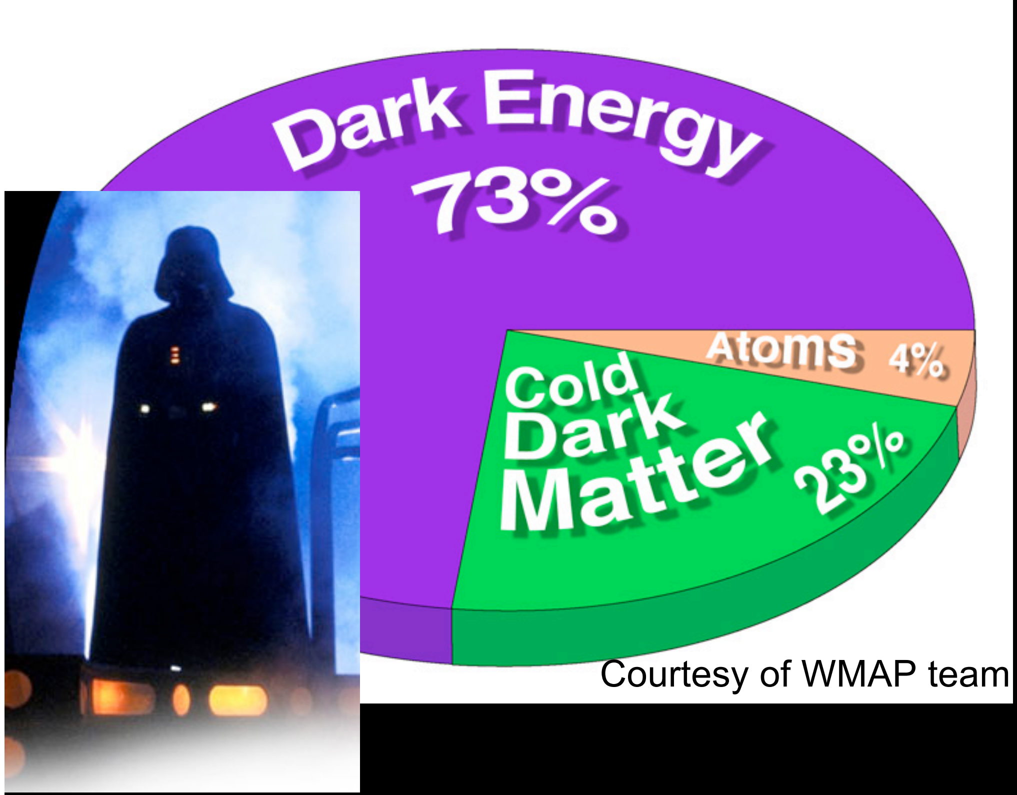
Visible Universe (think of inflation)

It is only possible to observe part of the Universe at one particular time, so it is difficult to make statistical statements about cosmology on the scale of the entire universe, as the number of independent observations (sample size) is finite.

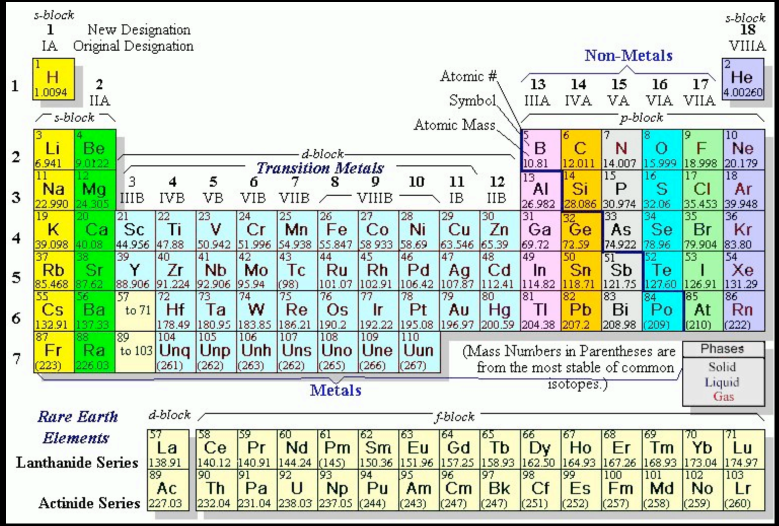
Fundamental limit: “Cosmic variance-dominated” measurement

Legacy power of forthcoming surveys

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



Courtesy of WMAP team



s-block

1 New Designation

IA Original Designation

Atomic #

Symbol

Atomic Mass

Non-Metals

d-block

Transition Metals

p-block

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	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)								

Metals

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

Phases

Solid

Liquid

Gas

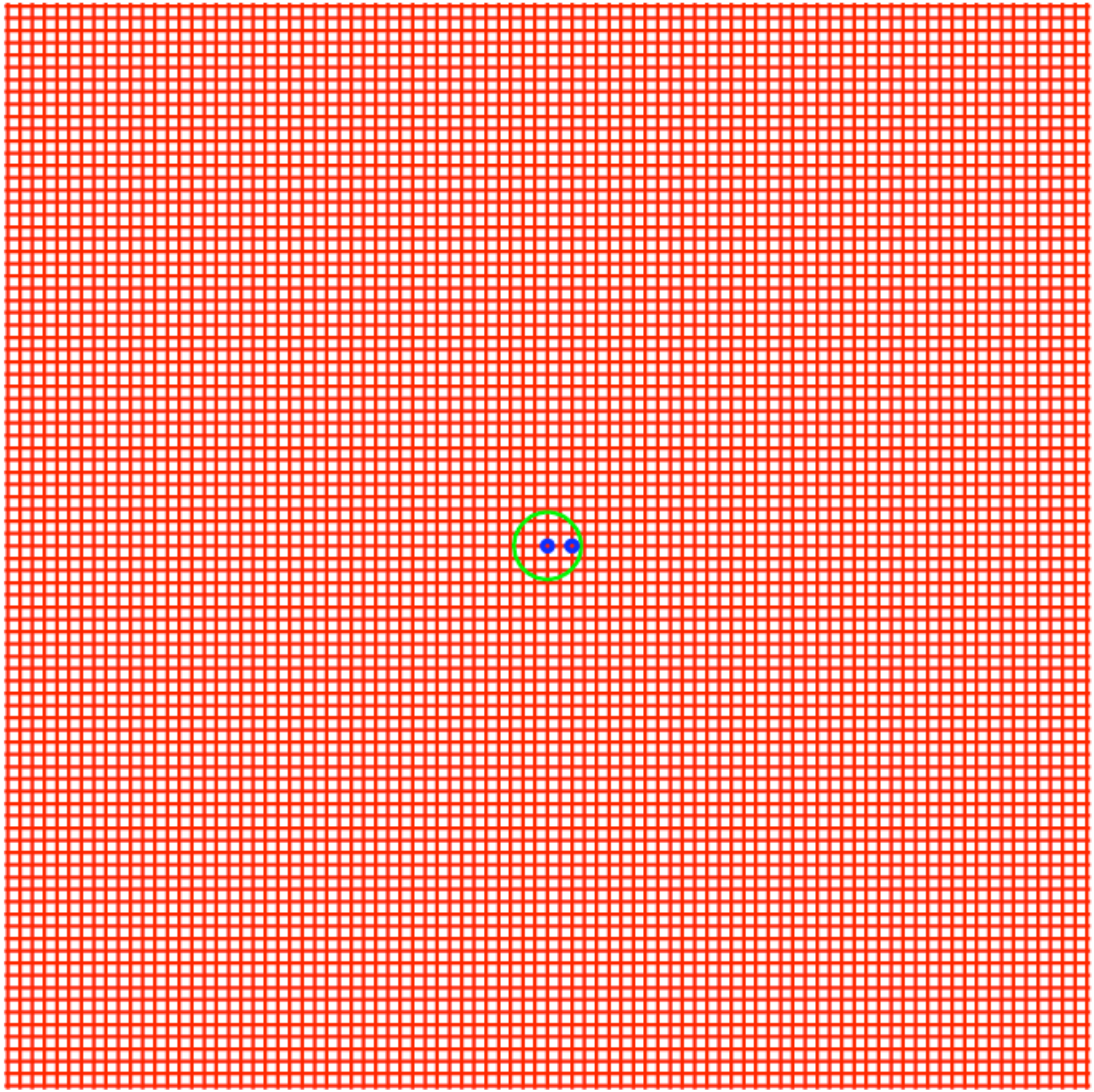
Rare Earth Elements

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 !



Accelerating Universe: the evidences

Age of the Universe+Ho (1998)

Supernovae 1A (1998)

Flatness + low density (2000)
(e.g., Boomerang + galaxies)

Structure growth

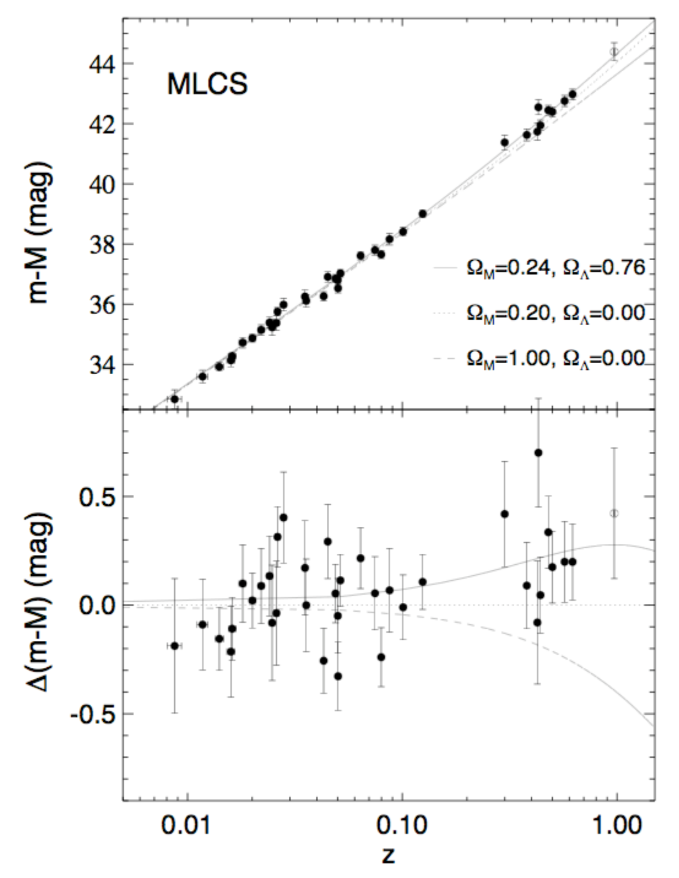
Gravitational lensing

Galaxy clusters number counts

ISW

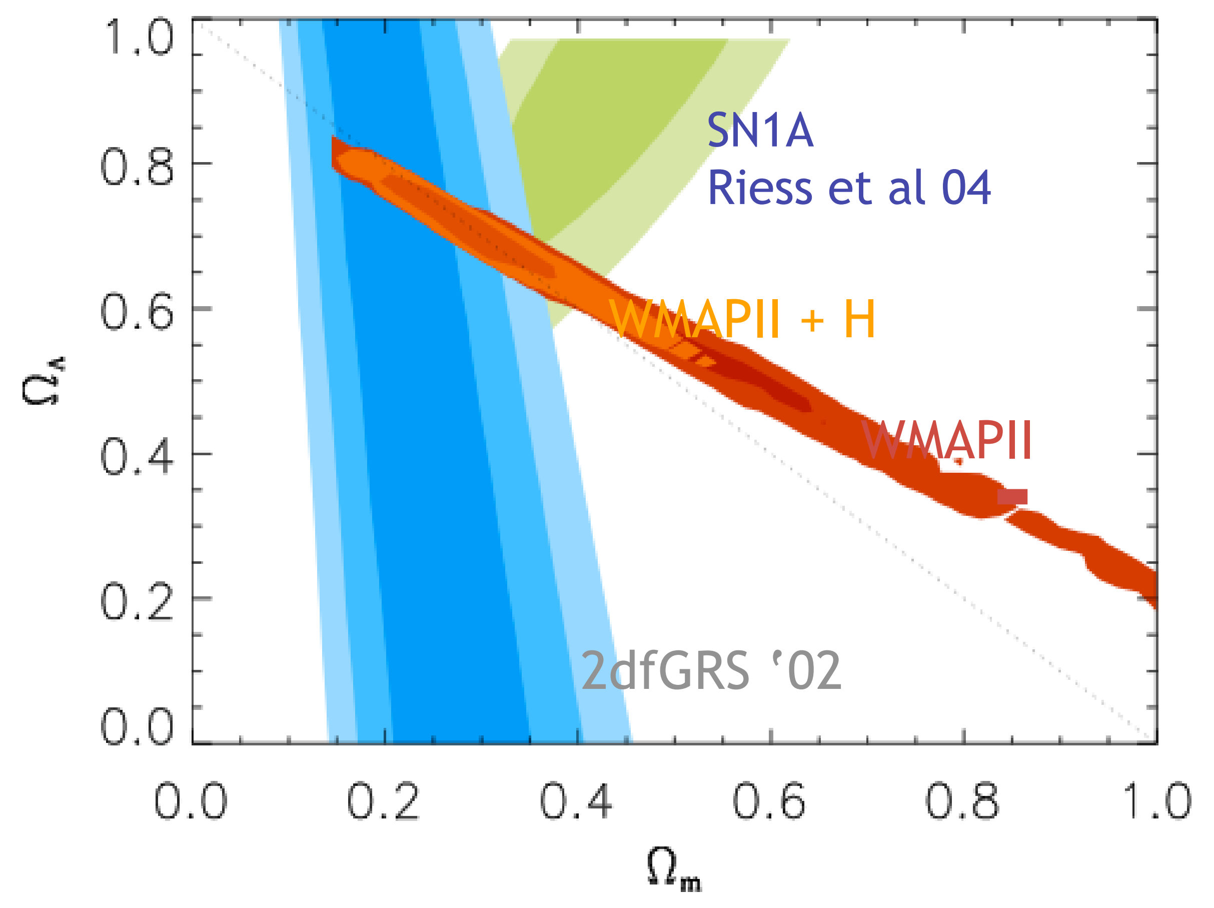
H(z)

Etc…



SNe back in 1998
(Permutter & Riess 1998)

Observational status:



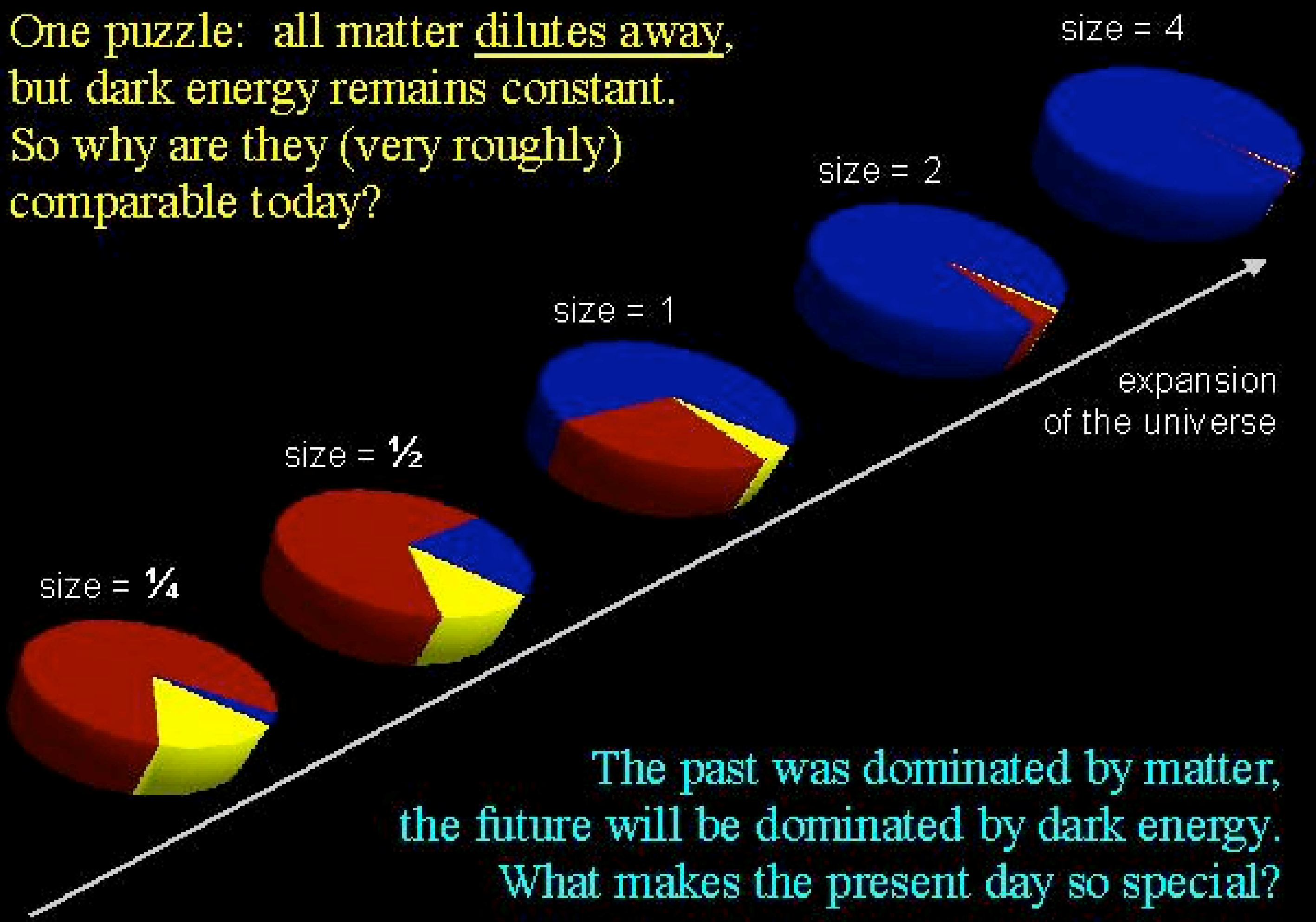
Einstein’s Equations

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda\,g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Interpretation in terms of vacuum energy

The “why now” problem

One puzzle: all matter dilutes away, but dark energy remains constant. So why are they (very roughly) comparable today?

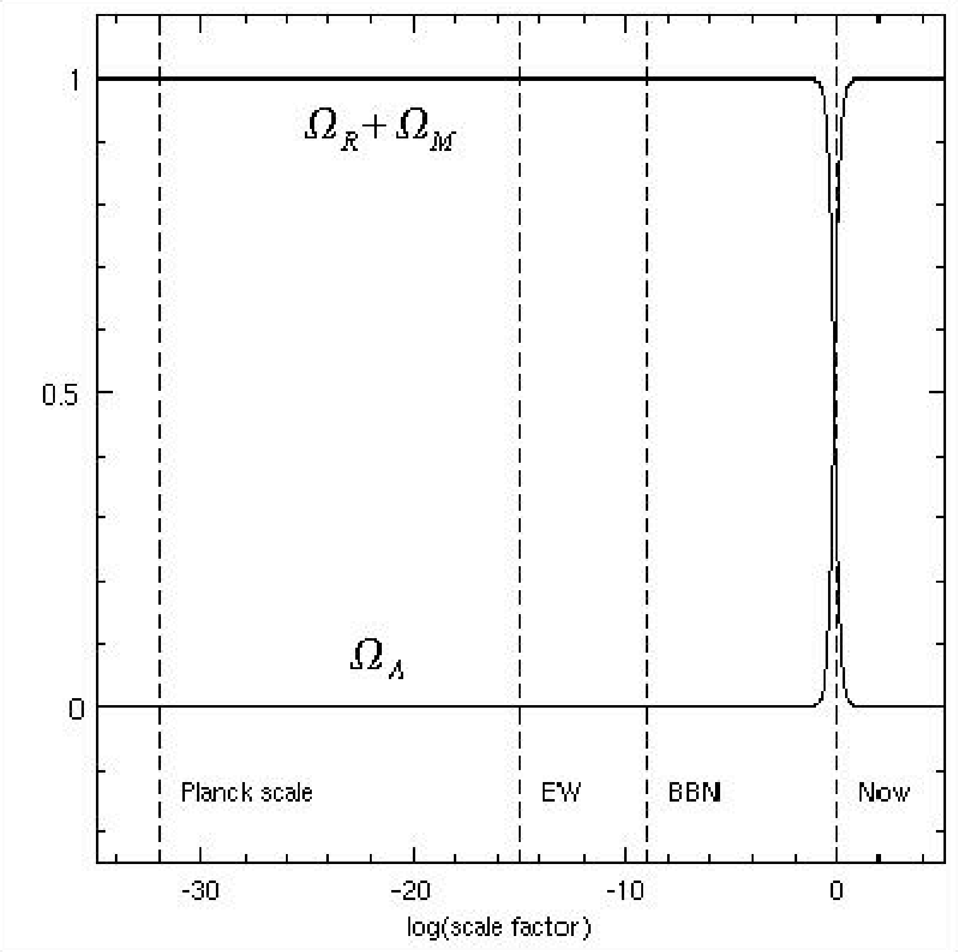


The past was dominated by matter,
the future will be dominated by dark energy.
What makes the present day so special?

Slide courtesy of S. Carroll

And it's moving quickly:

$$\boxed{\frac{\Omega_\Lambda}{\Omega_M} \sim a^3}$$



The CC problem

QFT predict a huge cosmological constant from the energy of the quantum vacuum.

If the universe is described by an effective local quantum field theory down to the Planck scale, then we would expect a cosmological constant of the order of Mpl^4.

$$\rho_{DE}^{(theory)} = 10^{120} \rho_{DE}^{(obs)}$$

What cancels it out (almost but not completely)?
Fine tuning? Dynamical?

Preposterous Universe!

Compare DE with other major discoveries in physics

★ Constancy of the speed of light (1887)

★ Discovery of the μ-particle (1936)

★ Discovery of the Ω^- baryon (1964)

★ Cosmic Backgroud Radiation (1965)

★ W and Z bosons (1983)

☆ Higgs particle ?? (2010/2012 ??)

Courtesy of A. Casas

Compare DE with other major discoveries in physics

★ Constancy of the speed of light (1887)

★ Discovery of the μ-particle (1936)

★ Dark Energy

★ Discovery of the Ω^- baryon (1964)

★ Cosmic Backgroud Radiation (1965)

★ W and Z bosons (1983)

☆ Higgs particle ?? (2010/2012 ??)

Courtesy of A. Casas

Michelson & Morley result was against the theoretical expectations (theory of aether)

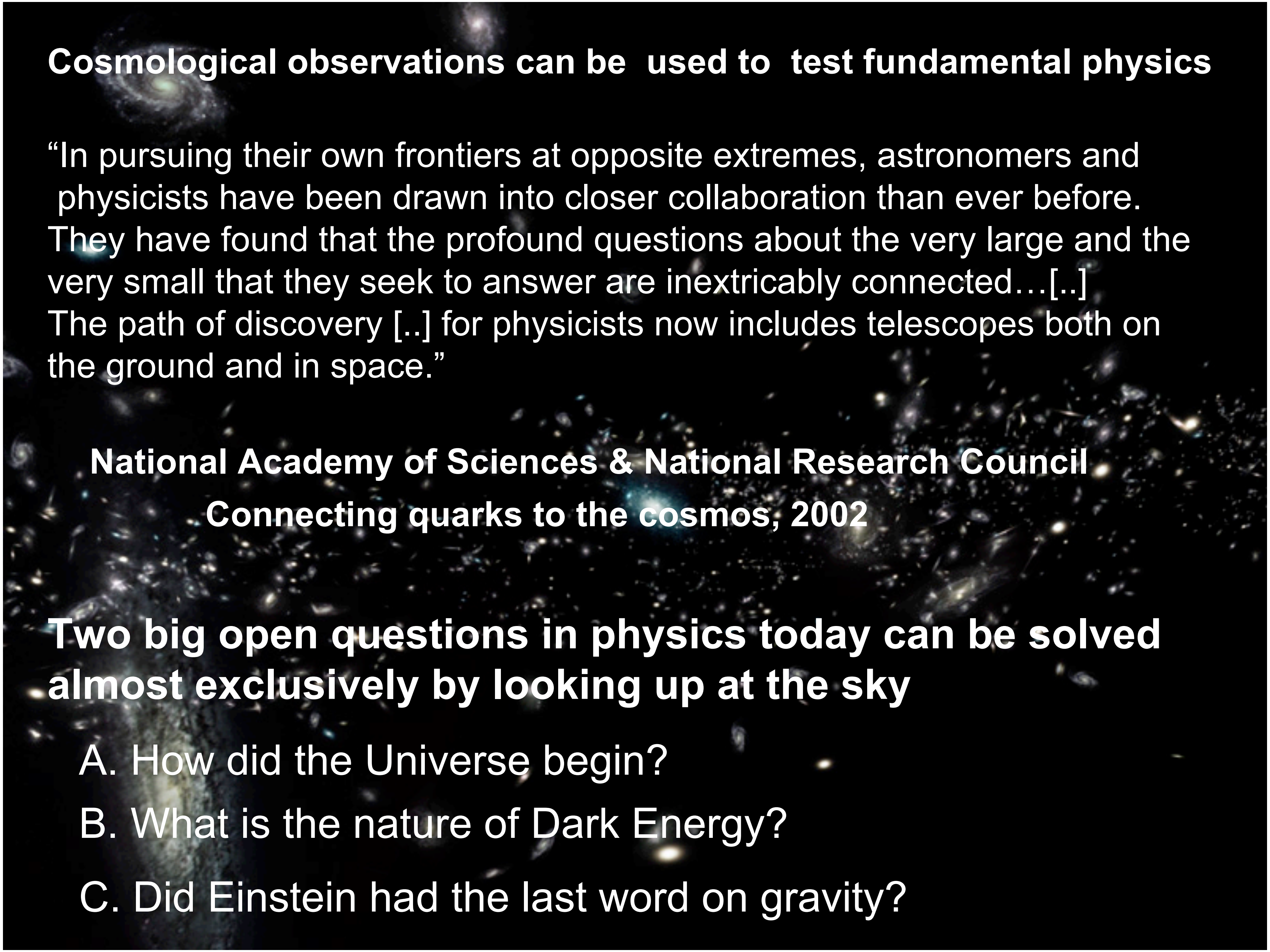
Nobody expected the muon **Who ordered the muon?** **(I.I. Rabi)**
but it does not challenge the theoretical framework

The DE discovery is also against the theoretical expectations

It likely requires a radical change in our pre-conceptions

A continuation of the cosmological constant problem: why is Λ that small???

Courtesy of A. Casas



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

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

A. How did the Universe begin?

B. What is the nature of Dark Energy?

C. Did Einstein had the last word on gravity?

The Challenges

Challenge n1: If it’s Λ why is it that small?

On this issue astronomers have done their work already (I.e. Λ is non zero)
Now it is the job of theoretical physicists

Challenge n2: is it dynamical?

Astronomers: go measure it!

Theoretical physicists: which parameterization?

Challenge n3: are we sure we know gravity?

Dynamical? What do you mean?

Think of inflation…. Or a slowly rolling scalar field…

$$p = \frac{1}{2}\underset{\uparrow}{\dot{\phi}^2} - \underset{\uparrow}{V(\phi)} \qquad \rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

K.E. P.E.

$$\dot{\rho} + 3H(\rho + p) = 0$$ continuity

$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

$$w = \frac{p}{\rho} \longrightarrow a(t)$$

Challenge n2: is it dynamical?

Theoretical physicists: which parameterization?

To give you a flavor, assume it is a slowly rolling potential and think about inflation

$$\varepsilon_1 = -\frac{\dot{H}}{H^2} = 1 - \frac{\ddot{a}}{a} H^{-2} = \frac{dH}{dz}\frac{(1+z)}{H}$$

Similar to horizon flow parameters

$$V(z) = (3 - \varepsilon_1)\frac{H^2}{\kappa} - \frac{1}{2}\rho_m$$

H(z)

$\dot{H}(z)$

$$K(z) = \varepsilon_1 \frac{H^2}{\kappa} - \frac{1}{2}\rho_m$$

Just integrate to get ϕ(z)

But f you have a parameterization (or a model)

$$3H^2(z) - \frac{1}{2}(1+z)\frac{dH^2(z)}{dz} = \kappa\left(V(\alpha_i,\, z) + \frac{1}{2}\rho_m(z)\right) \equiv g(\alpha_i,\, z)$$

Can be integrated analytically!

Challenge n2: is it dynamical?

Astronomers: go measure it!

CMB (only secondary anisotropies will now help: ACT, SPT, APEX, etc…)

SNe (SLNS, ESSENCE, SNAP, LSST, SDSSII, etc.)

Gravitational Lensing (DES, Panstarr, LSST, DUNE,…)

Galaxy Clusters (ACT, SPT, APEX…)

BAO… (DES, WFMOS, VISTA, AAO, BOSS, ADEPT, SPACE…)

And the acronyms keep coming….

Data challenge

"exponential world"

Systematics challenge.

"controlled errors are more important than how small they are"

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

Leading observational techniques to go after dark energy

Supernovae (expansion history)

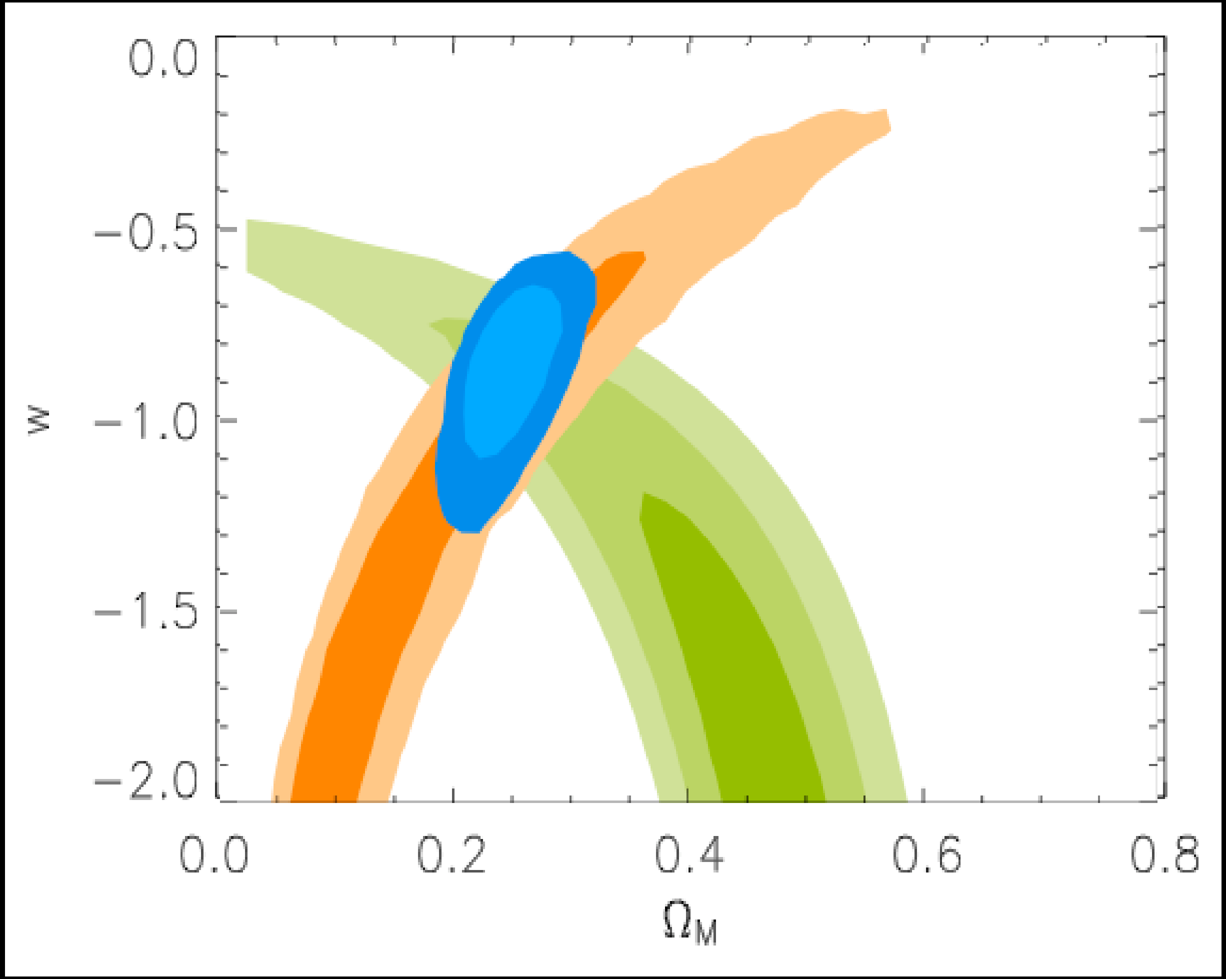
Galaxy clusters number counts (mostly growth of structure)

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

Dark energy so far…



2dfGRS

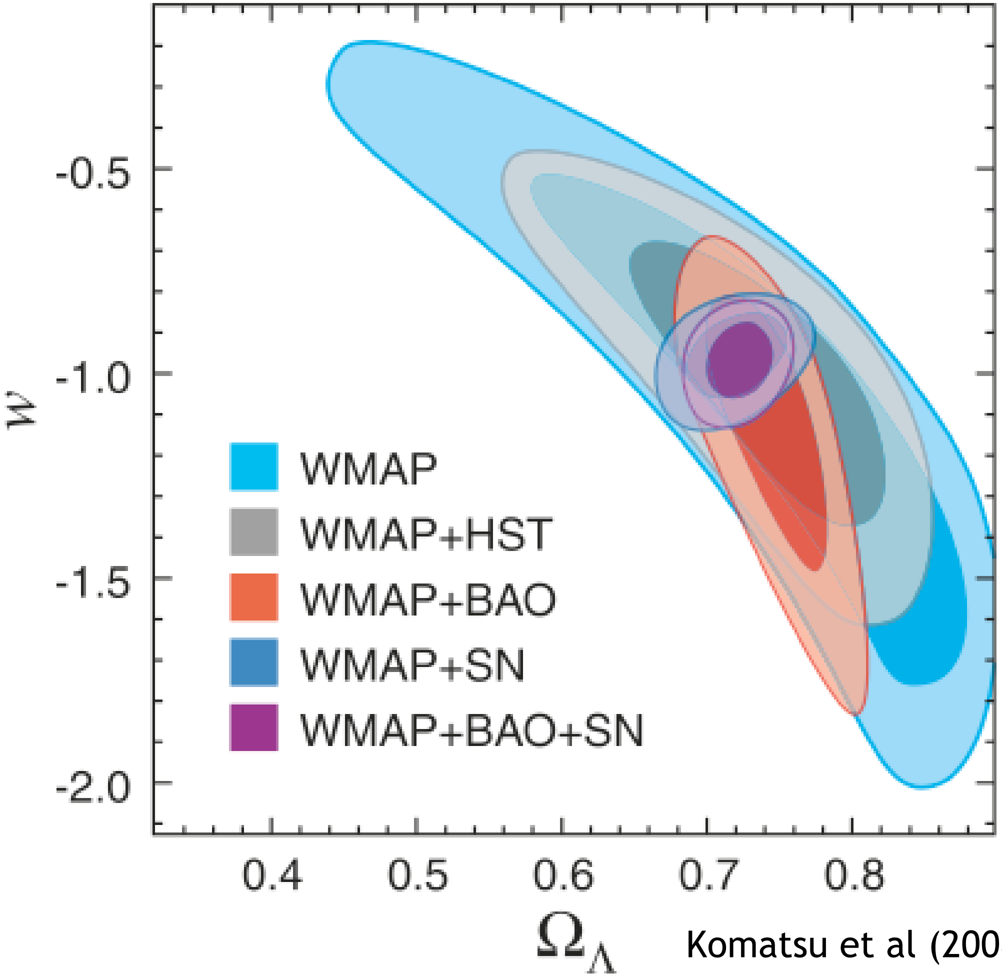
H prior

WMAPII

SN

(With DE clustering)

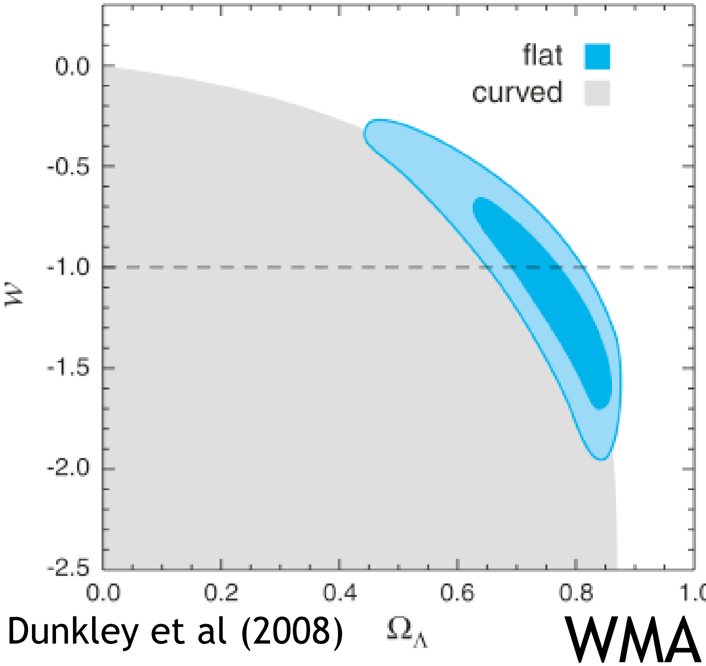
Dark energy



Komatsu et al (2008)

WMAP5

Why so weak dark energy constraints from CMB?



Dunkley et al (2008)

WMAP5

We have seen that sto reconstruct dark energy non parametrically,

$\dot{H}(z)$ is needed

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. more than one snapshot of the Universe)

Several options....

weak dark energy constraints from CMB?

A BUT The CMB encloses information about the growth of foreground structures: secondary CMB!

- Integrated Sachs Wolfe effect
- Secondary effects: Sunyaev Zeldovich(SZ), Kintetic SZ, Rees-Sciama, Lensing.

B **What if one could see the peaks pattern also at lower redshifts?** (and get other things for free)

C … resort to other probes

We test inflation by looking at the perturbations it generated

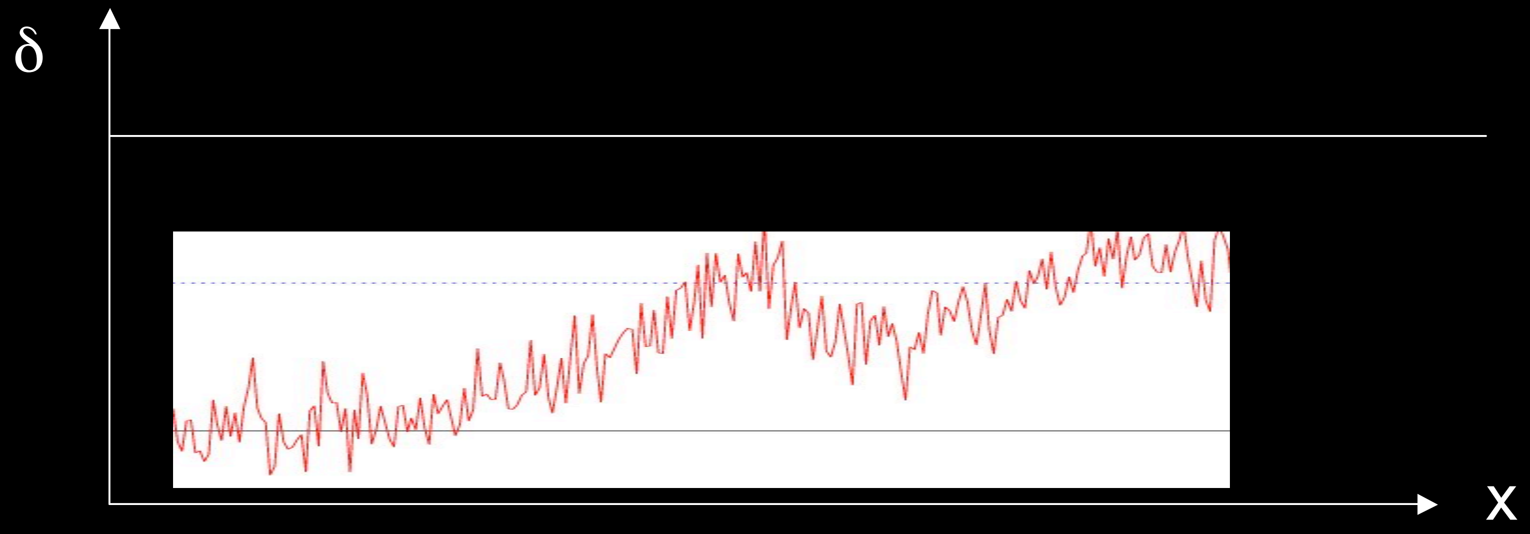
We can test about 10 efoldings by looking at cosmological structures
Despite Inflation happening 13.7 billion years ago and dark energy happening today, we seem to know much less about DE: we cannot see its perturbations and we can only see ~2 efoldings.
But we can follow the (recent) expansion history and the growth of cosmological structures

We test dark energy by looking at the expansion history (encoded also in the growth of cosmic structures)

Galaxy clusters number counts

Galaxy clusters are rare events:
P(M,z) oc $\exp(-\delta^2/\sigma(M,z)^2)$

In here there is the growth of structure



Beware of systematics! “What’s the mass of that cluster?”

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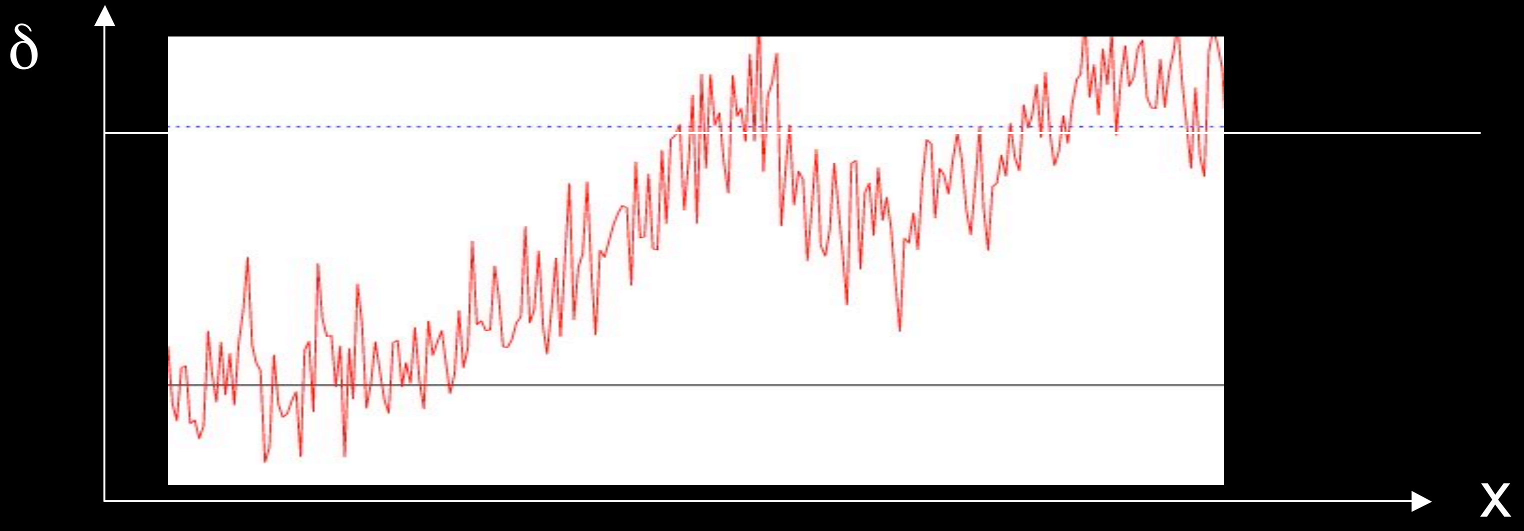

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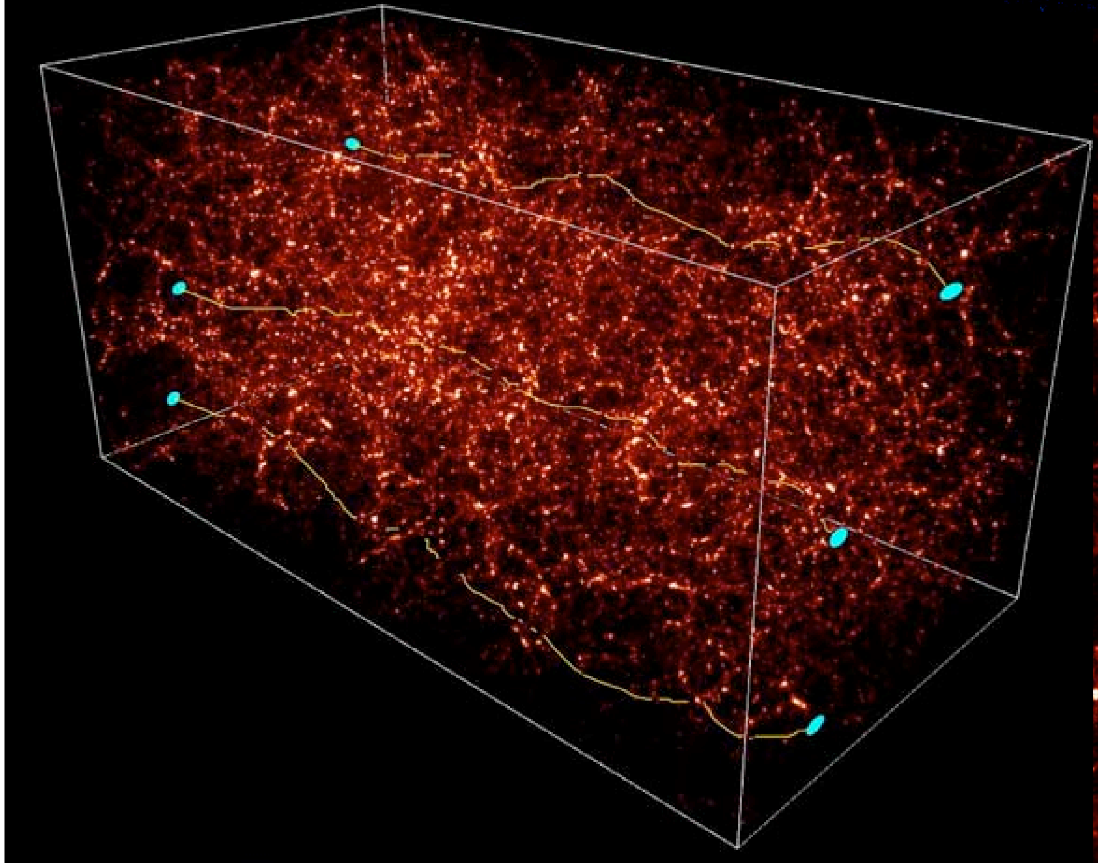
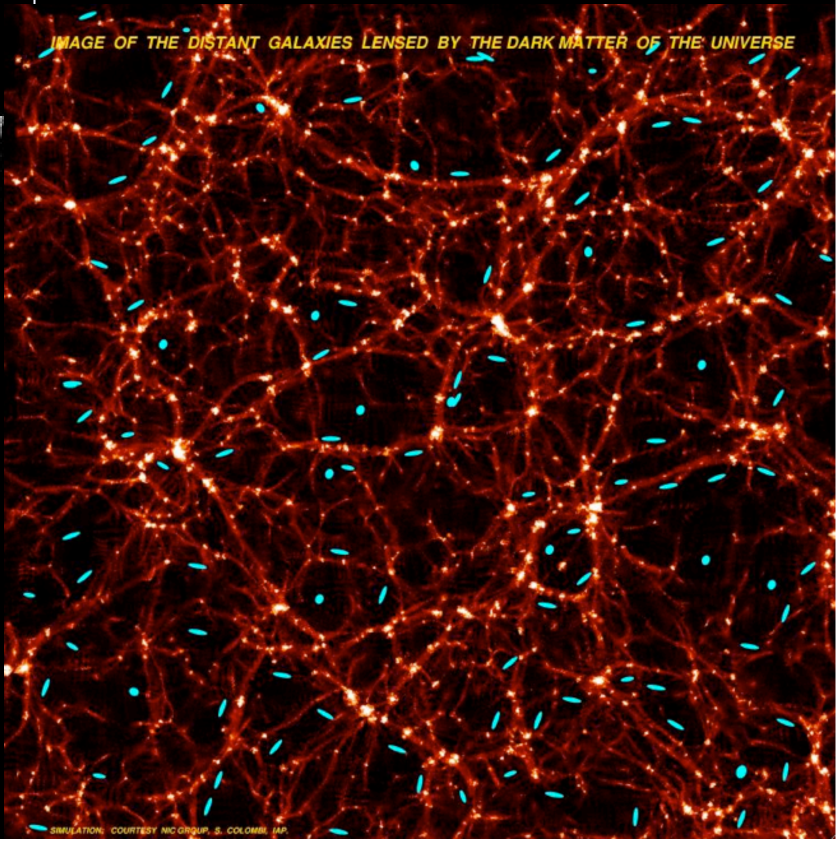
Weak lensing





weak dark energy constraints from CMB?

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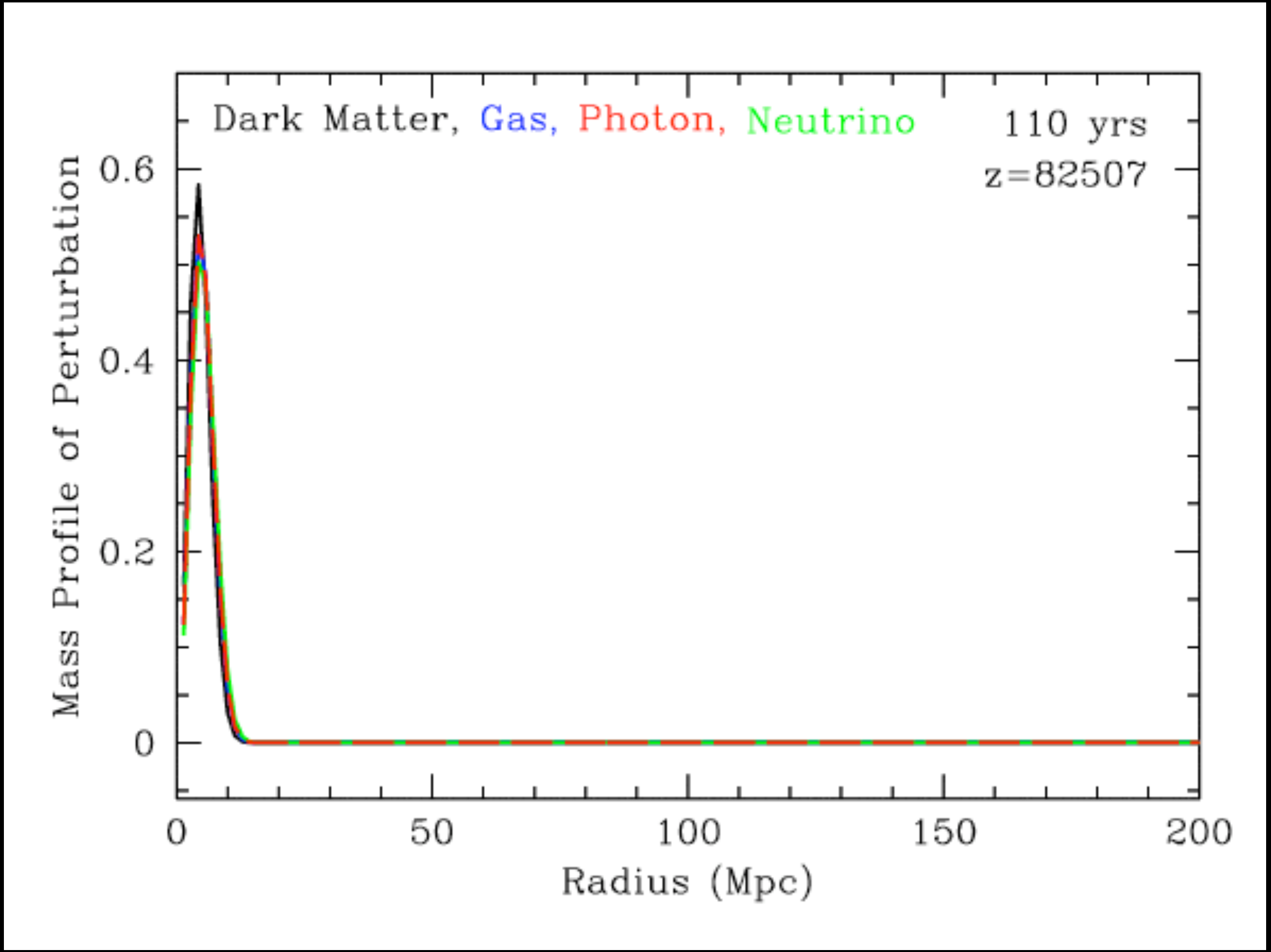
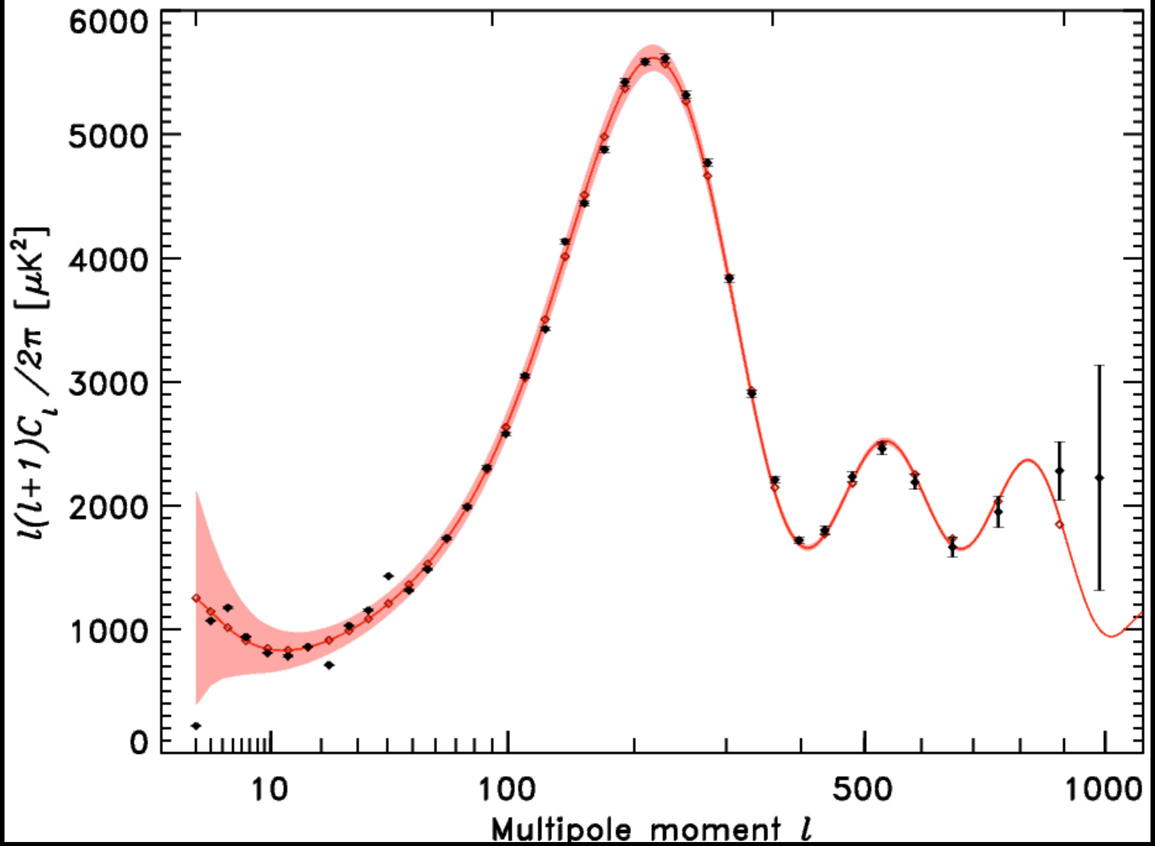
Baryonic Acoustic Oscillations

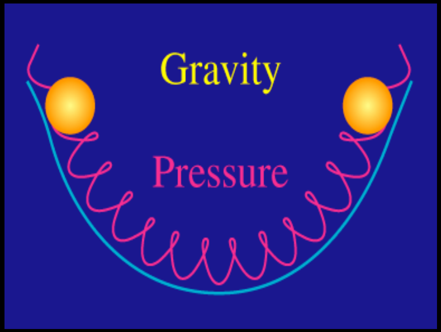


Evolution of a single
perturbation,
Imagine a superposition

For those of you who think in Real space

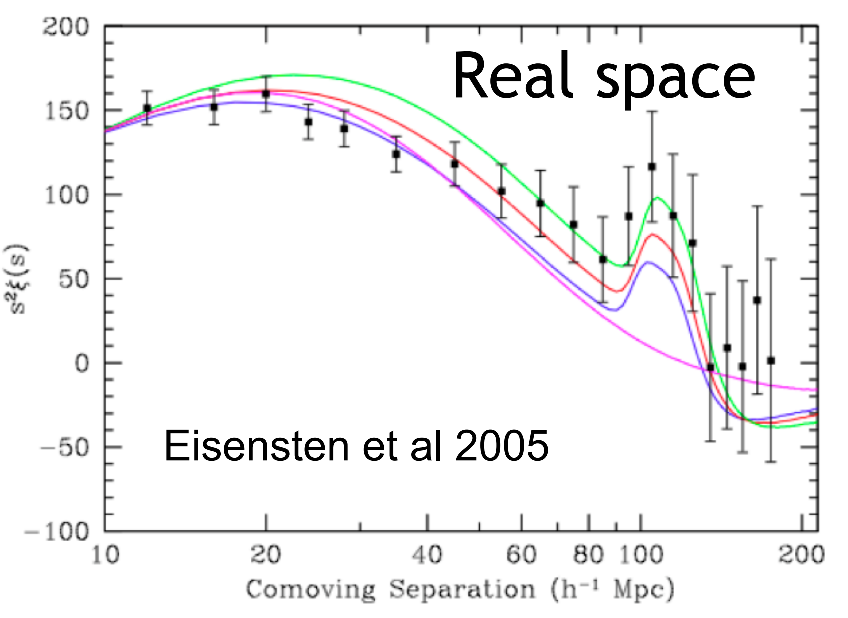
Courtesy of D. Eisenstein





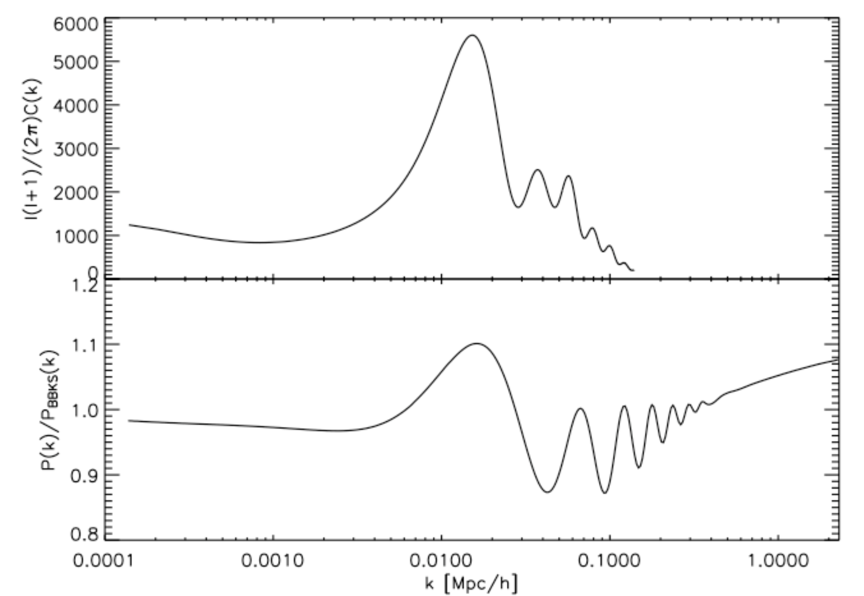
If baryons are ~1/6 of the dark matter these baryonic oscillations should leave some imprint in the dark matter distribution

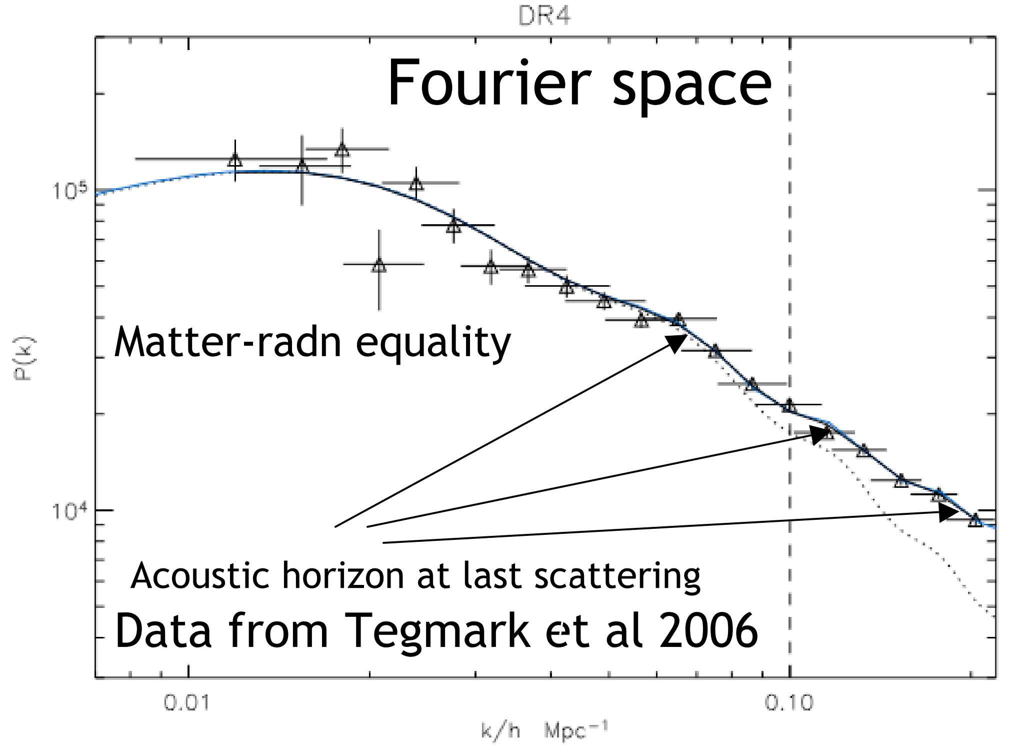
Fore those of you who think in Fourier space



Real space

Eisensten et al 2005



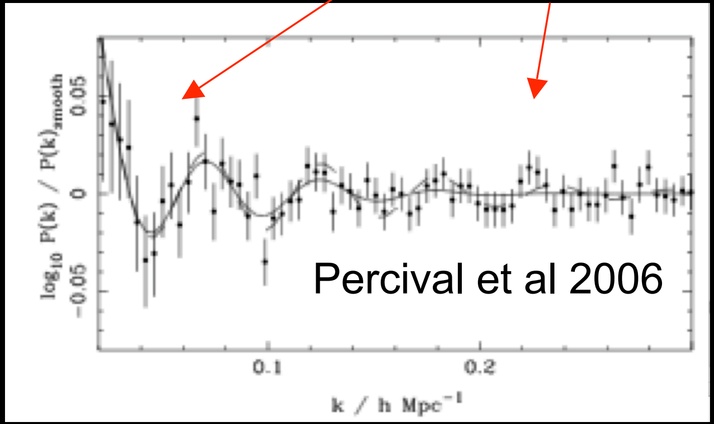


Fourier space

Matter-radn equality

Acoustic horizon at last scattering

Data from Tegmark et al 2006



Percival et al 2006

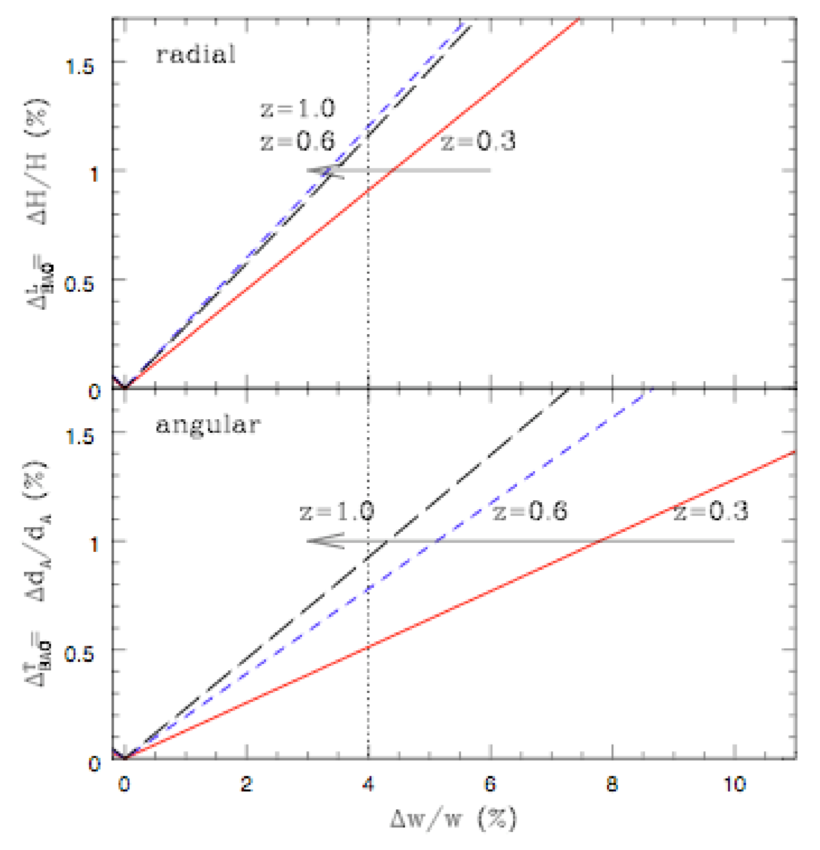
Divided by a smooth P(k)

Robust and insensitive to many systematics

2 measurements in one?

Challenge: scale of interest ~100 Mpc/h: large volumes!

Feature: measure BOTH dA and H(z) from 3D clustering



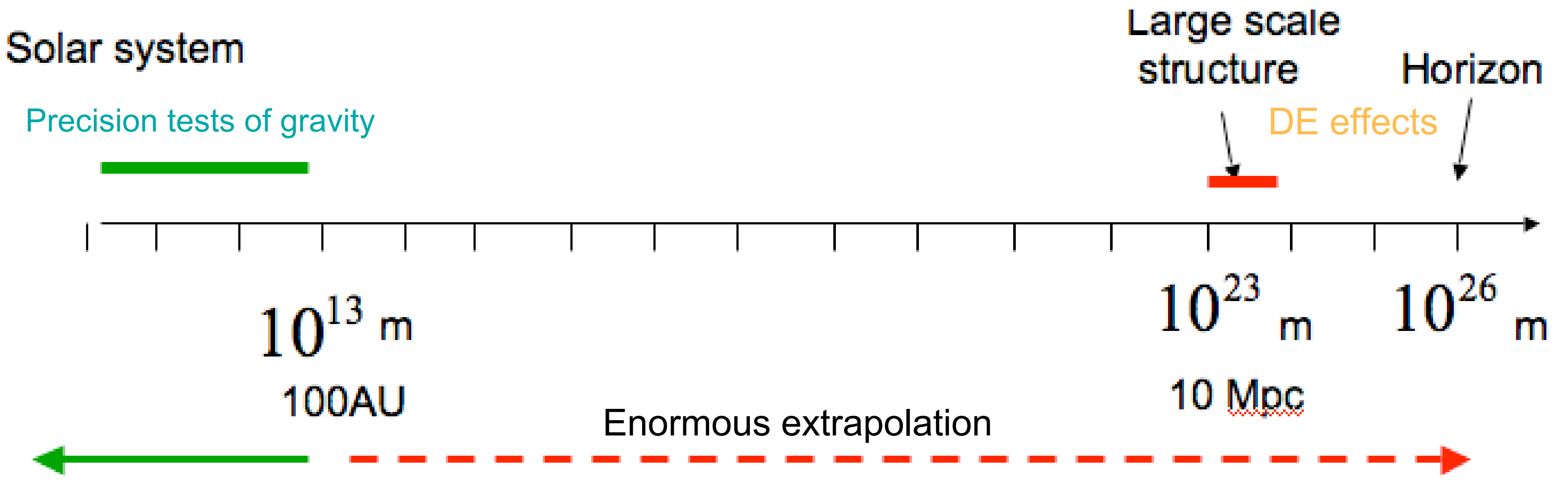
Line of sight (radial)

$$dr(z) = \frac{c}{H(z)} dz$$

Plane of the sky (angular)

$$d_A(z) = \frac{c}{1+z} \int_0^z \frac{dz'}{H(z')}$$

A few words about challenge n 3….



Solar system

Precision tests of gravity

Large scale structure

Horizon

DE effects

10^{13} m

100AU

10^{23} m

10 Mpc

10^{26} m

Enormous extrapolation

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

The same data for challenge n 2 will do here

In general, this degeneracy is lifted when considering the growth of structure

Early/vs late-time observables will also help

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)
Can always map an a(t) to a w(z)…

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!

COMPLEMENTARITY IS THE KEY!

The questions we want to ask:

Is it a cosmological constant?
A rolling scalar field? A fluid?
Is it a w= -1? w(z)?

Is it a breakdown of GR at horizon scales?

Backreaction…

Example:

Measurements of the growth of cosmological structures will help to disentangle the two cases.

Things could be "going wrong" in other ways

For not mentioning: control of systematics!

Summary: Much ado about nothing

The standard cosmological model is extremely successful, but….

Observations indicate that nothing weighs something (but much less than expected) and make the universe accelerate (other options are still Possible, inhomogeneities, gravity, but the result must "look like Λ").

What would it take to discriminate? discuss

Heroic observational effort is on going
(we'll learn not only about dark energy from it)

We HAVE TO ask: "how interesting it is really to add yet another significant figure to Λ or w ?" discuss

My personal view: The answer lies in the interface between Astronomy and Theoretical physics, if we take the "**Accelerating universe challenge**", there is no other way.

Challenges of the accelerating universe:

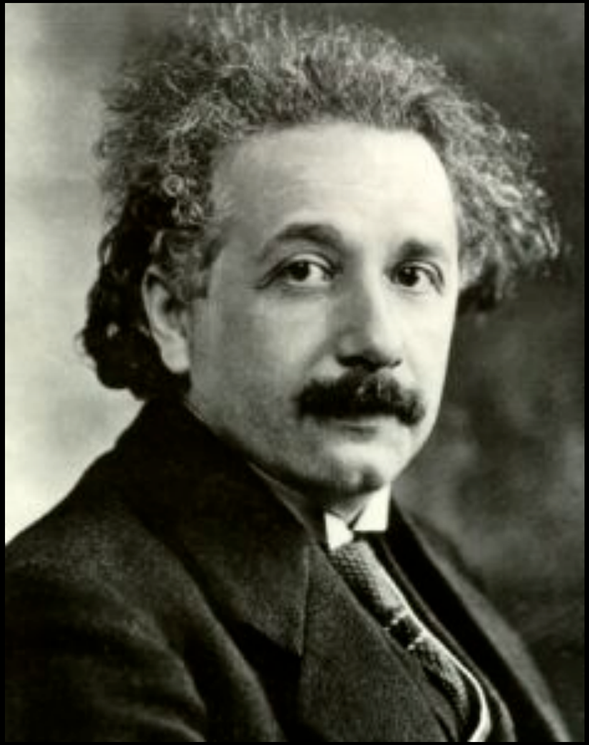
Zero-th order challenge: create a new culture of particle physicists and astronomers working together, theorists and experimentalists

First_order challenge: If it is Λ why is it so small?
On this issue astronomers have done their work already (I.e. Λ is non zero)
Now it is the job of theoretical physicists.

Second order challenge: is it dynamical? and if so how does it evolve?

Third order challenge: “could we have been wrong all along?”
did Einstein had the last word on gravity? Or FRW on the metric?

The data challenge: Avalanche of data coming soon
The systematics challenge: systematic errors in many cases will be the limit



“In the middle of difficulty lies opportunity" ---

A. Einstein

END