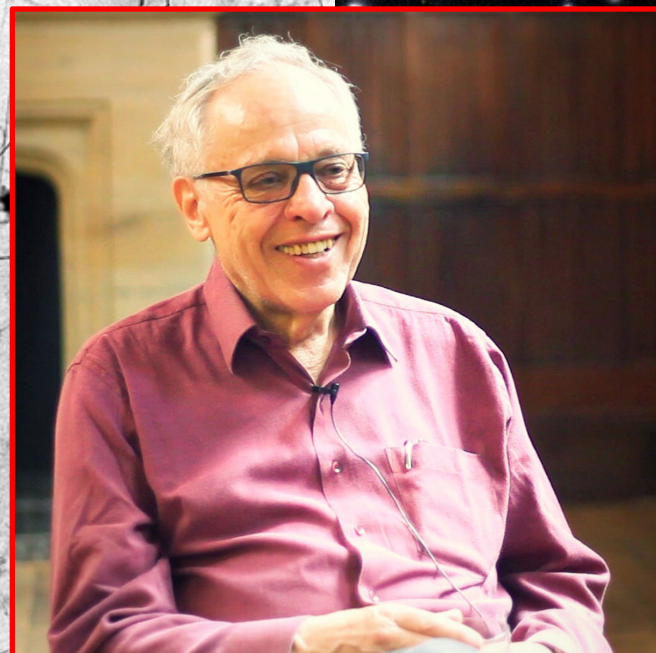
ΛCDM: More than we expected, less than we now want

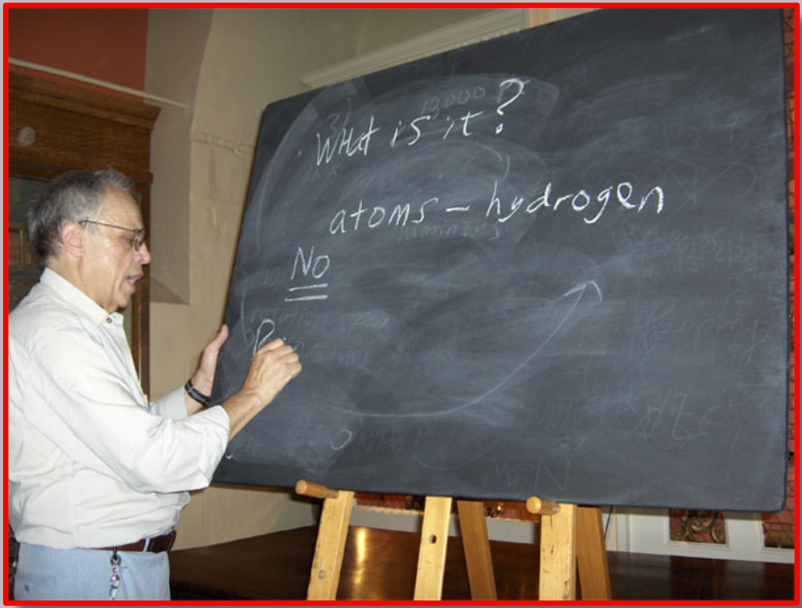


DARK MATTERS 11-13 December 2017
Joe Silk's 75th Birthday

Institut d'Astrophysique de Paris
13 December 2017

Joe Silk "word cloud"

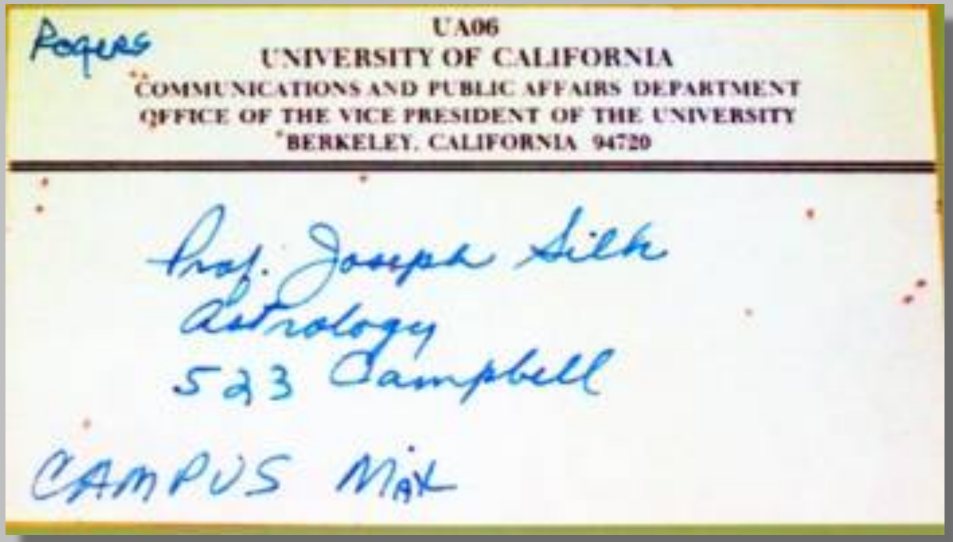
- Insightful
- Supportive
- Enthusiastic
- Thought leader
- Disruptive
- Daring & curious
- Entrepreneurial
- Not afraid to ask others to teach his class



- Makes others better
- Mentor & friend
- <u>Always a positive force</u>

Some favorite memories

- December 1980 (my JS t = 0): train ride with Silk family from NYC to Baltimore (10th Texas Symposium)
- Summer 1984: Cargese summer school
- CfPA UCBerkeley (1989 – 2001): Joe made UCBerkeley 2nd most important cosmology center
- Silk/Davis coin flip debate on Omega (1994?)



Favorite paper with Joe: now called, "Bartlett et al"

ARTICLES

The Case for a Hubble Constant of 30 km s^{-1} Mpc^{-1}

James G. Bartlett, Alain Blanchard, Joseph Silk, Michael S. Turner

Although recent determinations of the distance to the Virgo cluster based on Cepheid variable stars represent an important step in pinning down the Hubble constant, after 65 years a definitive determination of the Hubble constant still eludes cosmologists. At present, most of the observational determinations place the Hubble constant between 40 and 90 kilometers per second per megaparsec (km s^{-1} Mpc^{-1}). The case is made here for a Hubble constant that is even smaller than the lower bound of the accepted range on the basis of the great advantages, all theoretical in nature, of a Hubble constant of around 30 kilometers per second per megaparsec. Such a value for the Hubble cures all of the ills of the current theoretical orthodoxy, that is, a spatially flat universe composed predominantly of cold dark matter.

sistent with the ages of the oldest stars. Even in the case of an open universe, consistency requires the Hubble constant to be at the low end of the currently accepted range. For example, the age of the universe for a model with $\Omega_0 \approx 0.2$ and $H_0 \approx 70$ km s^{-1} Mpc^{-1} is only about 12 billion years. This all becomes more severe if the oldest stars formed at modest redshifts, say $z \sim 1$ to 2, as might be expected in the cold dark matter model, because it would require the addition of

J. G. Bartlett and A. Blanchard are with the Observatoire Astronomique de Strasbourg, Université Louis Pasteur, 11, rue de l'Université, 67000 Strasbourg, France. J. Silk is with the Departments of Astronomy and Physics and the Center for Particle Astrophysics, University of California, Berkeley, CA 94720, USA. M. S. Turner is with NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510–0500, and the Departments of Physics and of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637–1433, USA.

age of the universe are difficult, but recent values based on the ages of the oldest stars are uncomfortably high, 15 ± 3 billion years (7), when compared to the expansion age unless the Hubble constant is low.

If the universe is flat and the Hubble constant is at the lower extreme of the currently accepted range, then the expansion age is barely long enough to be con-

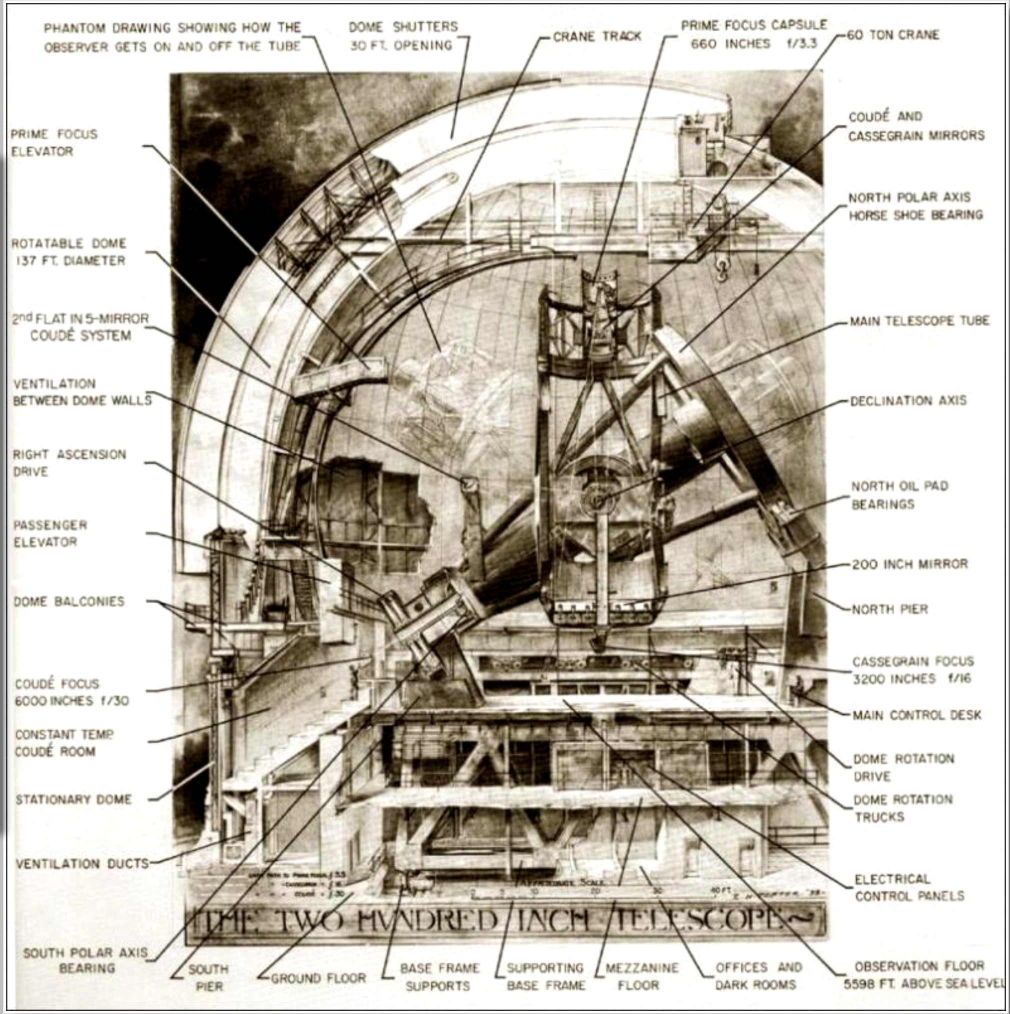
Cosmology circa 1970

Joe Silk at IOA with Rees, Hawking, Steigman, …

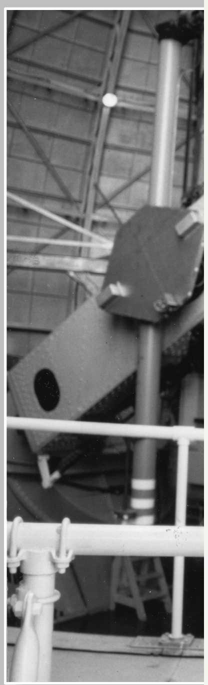
- High redshift: $z \sim 0$.few, highest $z_{QSO} \sim 2$
- Total redshifts measured: less than 1000
- CMB discovered, spectrum not well established
- H_0 precisely known (±5%), but not accurately known (factor of 2x spread)
- Consensus: $\Omega_0 \sim 0.1$ and $t_0 \sim 10$ to 20 Gyr
- Dark matter still a Princeton (Ostriker/Peebles) and Caltech (Zwicky) thing, particle dark matter even further away
- Recent birth of relativistic astrophysics (1963)
  - Quasars, neutron stars, CMB, and the Kerr metric recently discovered; 1st Texas Symposium
- Province of 30 astronomers led by Allan Sandage

The search for two numbers (H_0 and q_0)

Allan Sandage,
Hubble's "student"



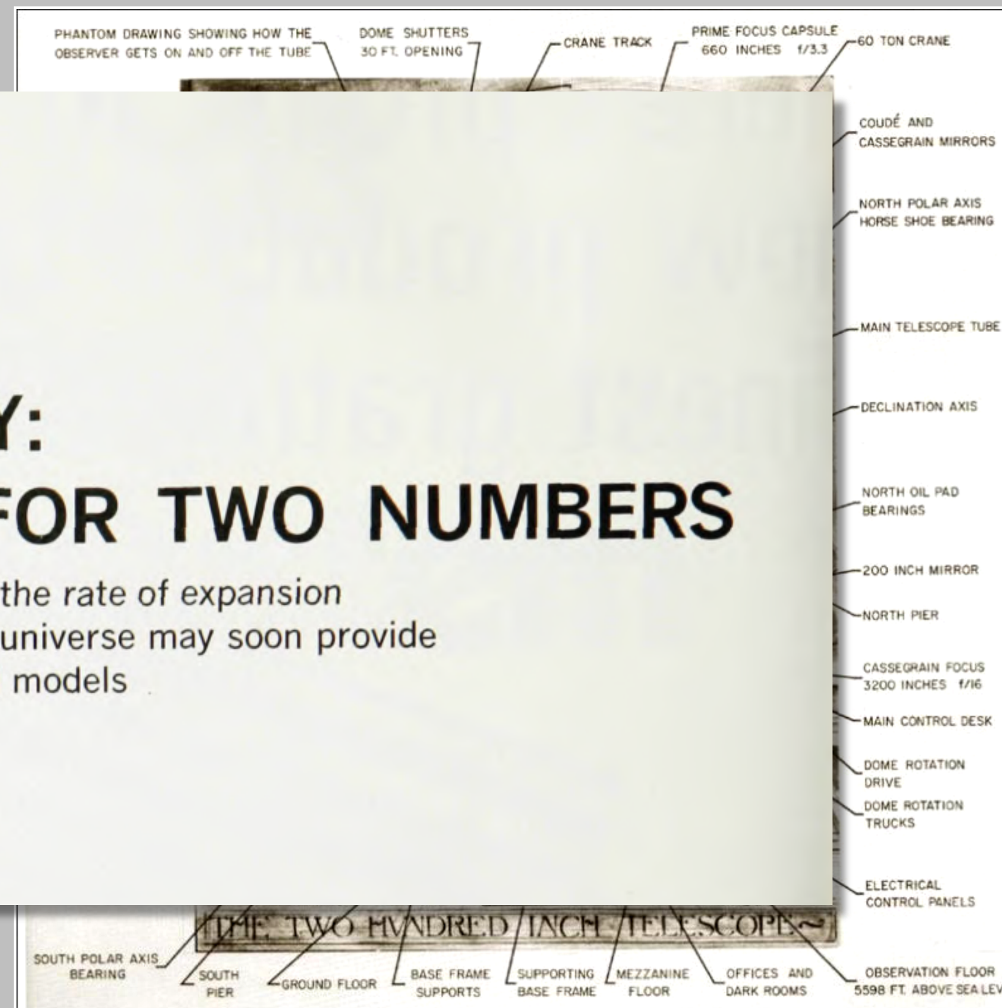
The search for two numbers (H_0 and q_0)



COSMOLOGY: A SEARCH FOR TWO NUMBERS

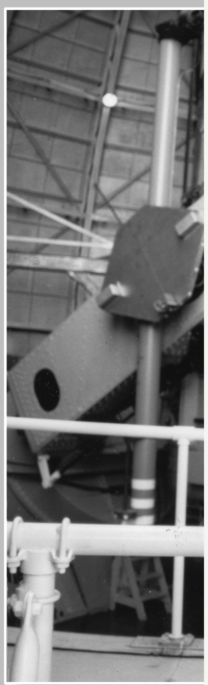
Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

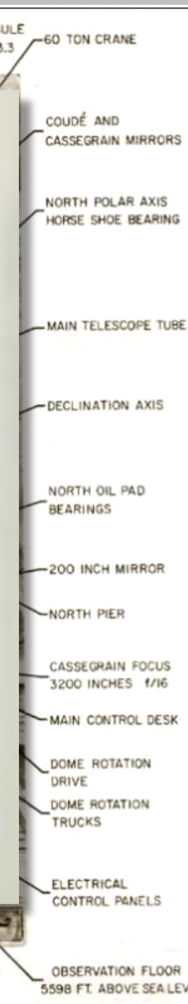
ALLAN R. SANDAGE

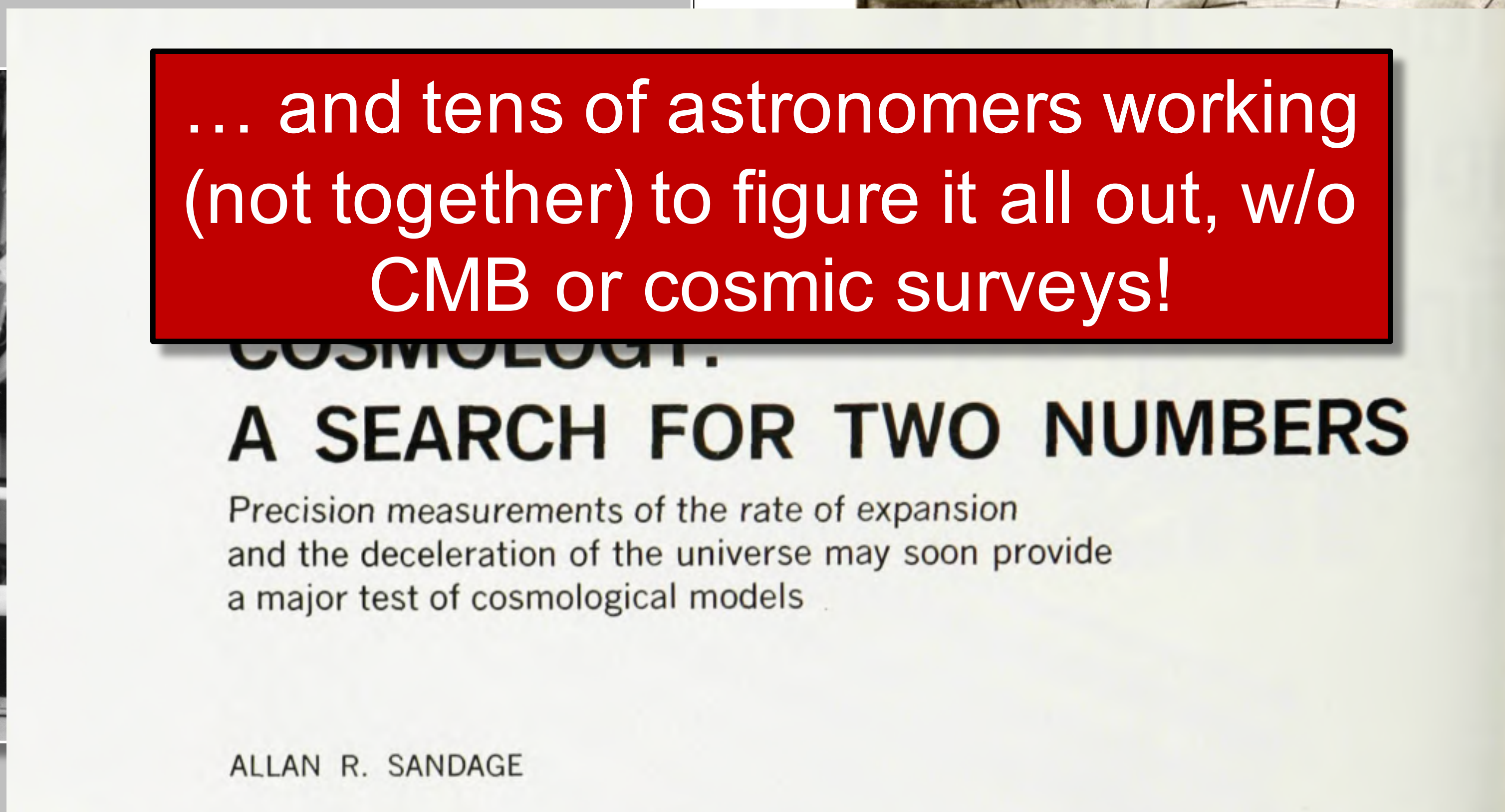


Allan Sandage, Hubble's "student"

The search for two numbers (H_0 and q_0)







A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

ALLAN R. SANDAGE

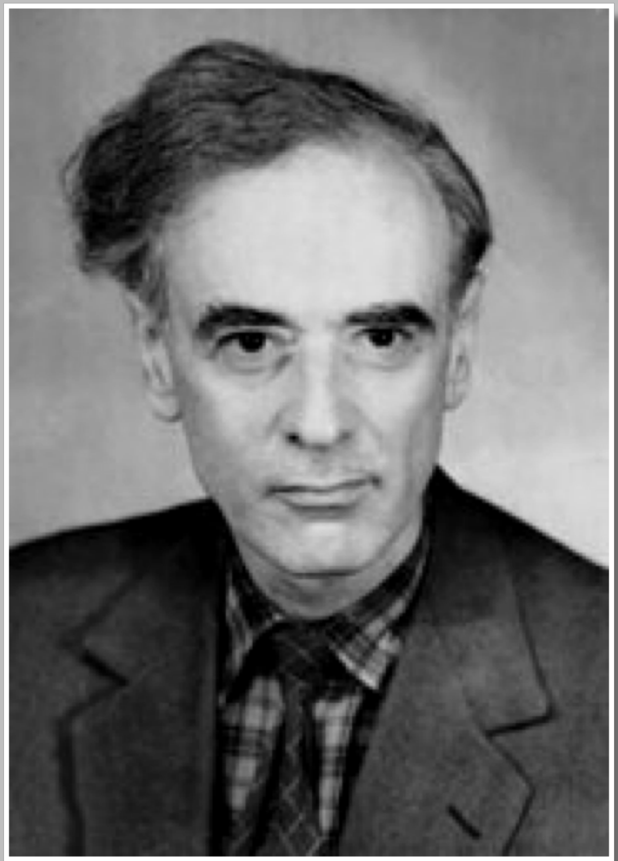
… and tens of astronomers working (not together) to figure it all out, w/o CMB or cosmic surveys!

Allan Sandage, Hubble's "student"

Cosmology circa 1970s: Big Questions

- Spectrum of fluctuations (not origin)
- Adiabatic or isothermal/top down or bottom up
- Epoch of galaxy formation z = 10 or 100?
- CMB fluctuation amplitude expected (10^{-3})
- Gravitational instability – probably (other ideas)
- H_0 = 50, 100??
- Two guide books
  - Peebles' *Physical Cosmology* (for astronomers)
  - Weinberg's *Gravitation and Cosmology* (for physicists)

Landau on Cosmologists



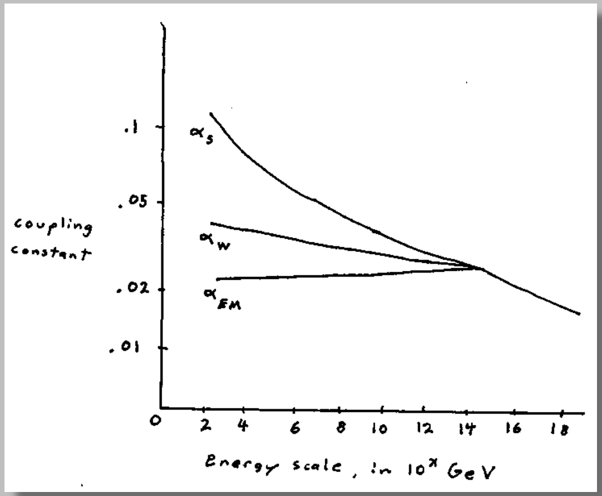
Often in Error,
Never in Doubt!

The Fall of “The Hadron Wall”

The Fall of “The Hadron Wall”

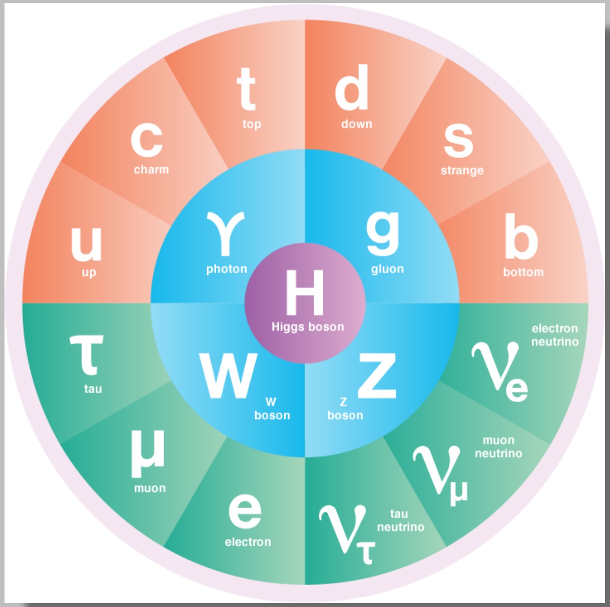
The 1980 revolution

Deep connections between quarks with the cosmos revealed



Lots of ideas: go-go junk bond days of early Universe cosmology

- Grand unification
- Baryogenesis
- Cosmic strings
- Cosmic inflation
- Dark matter
- Dark energy
- String theory
- Multiverse!



simmer for 20 years,

add data, and voila!

ΛCDM …

describes the Universe from a tiny fraction of second when galaxies and larger structures were just quantum fluctuations to hot, lumpy quark soup, from quark soup to neutrons, protons and then light nuclei, from ionized matter to atoms and photon last scattering, and from lumpy dark matter to stars, galaxies and large scale structure, 13.8 billion years later

Key features of ΛCDM

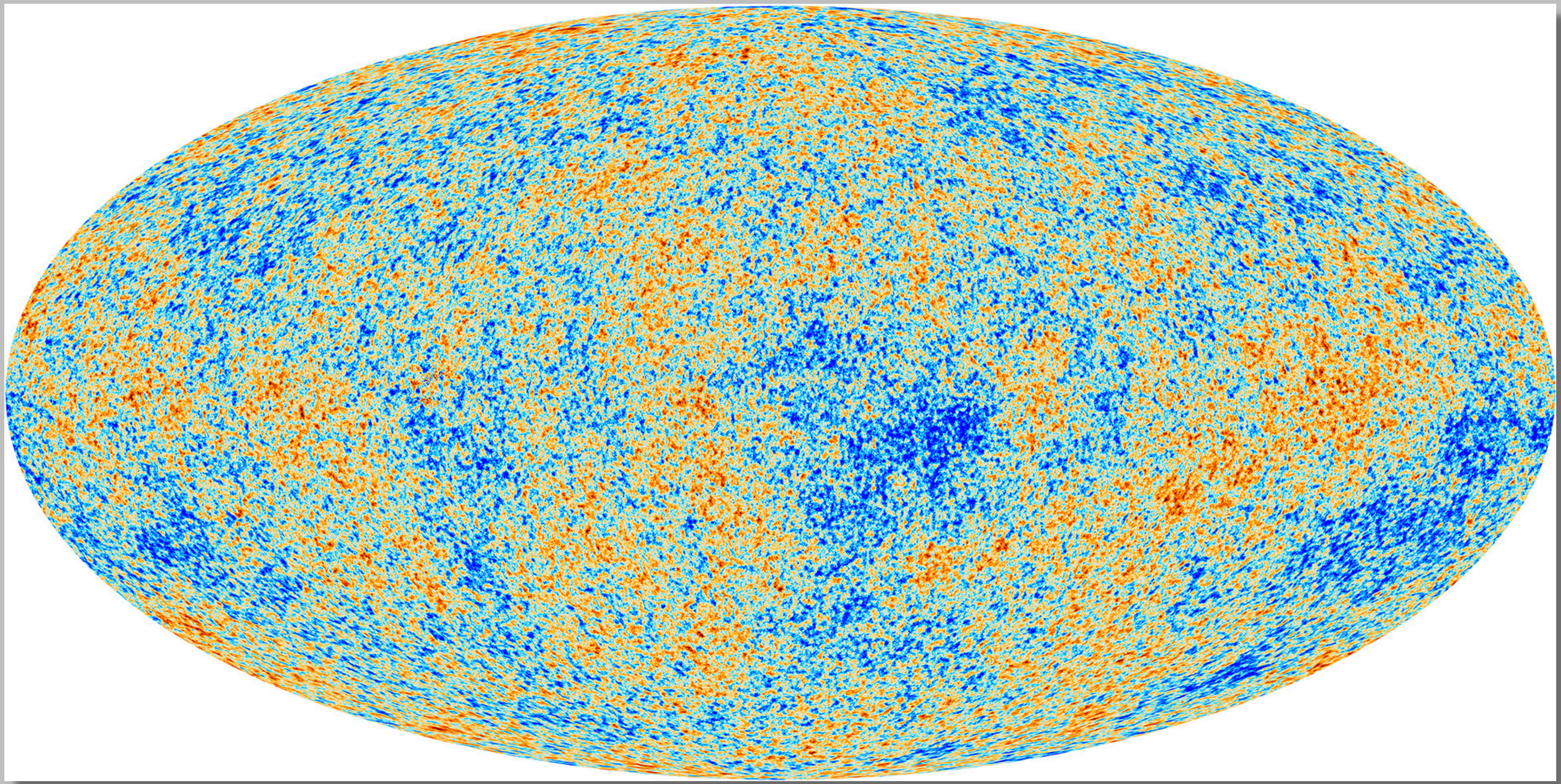
- A very early burst of tremendous expansion – **<u>Inflation</u>** – explains our smooth, flat Universe with seeds for galaxies grown from quantum fluctuations

- Ordinary matter (baryons) arises from a baryon asymmetry produced after inflation through **<u>Baryogenesis</u>**

- The gravity of slowly-moving **<u>Dark Matter</u>** particles (CDM) holds all cosmic structures together

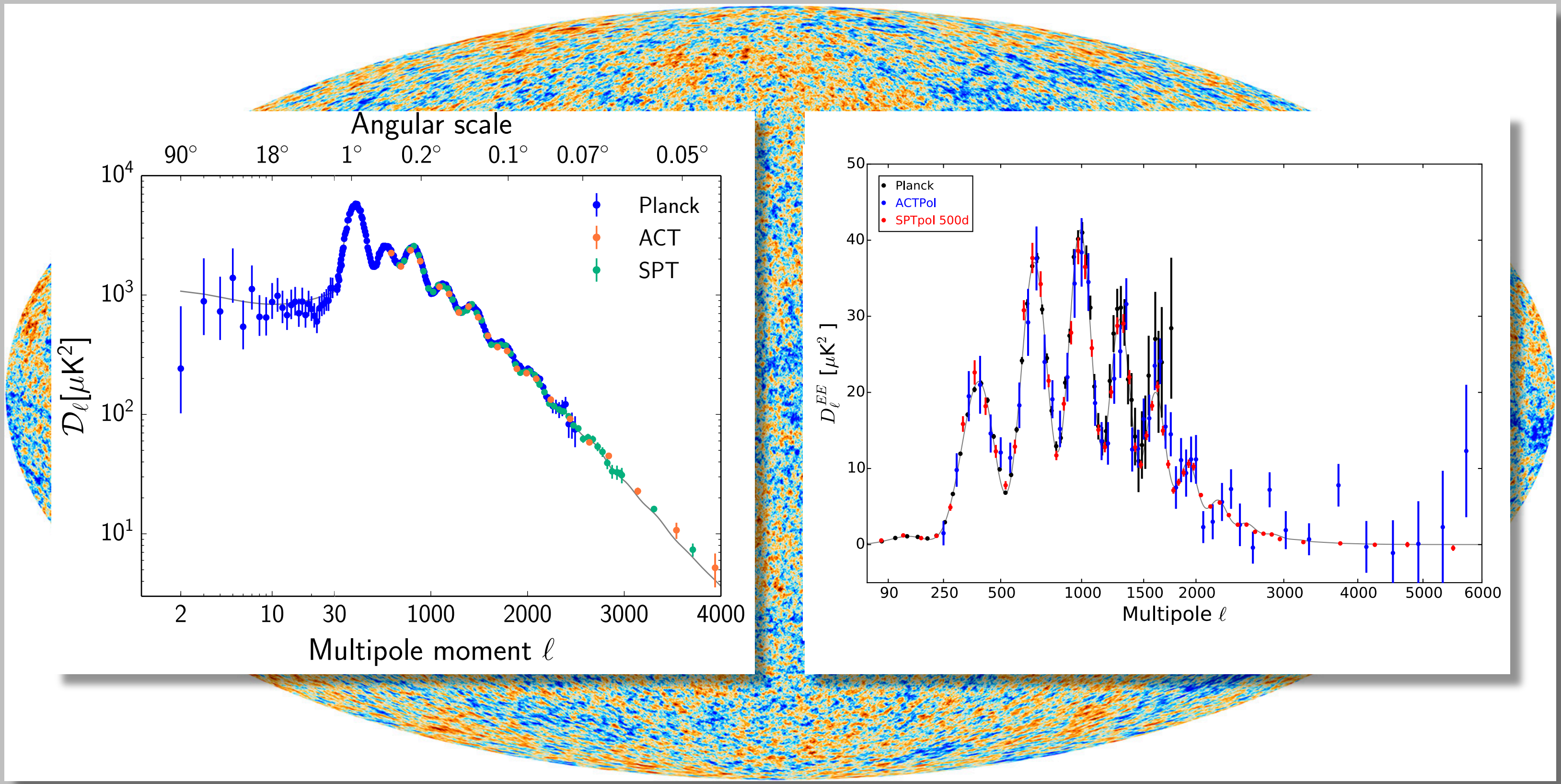
- The repulsive gravity of **<u>Dark Energy</u>** explains cosmic acceleration and Λ (quantum vacuum energy) is the default dark energy candidate

The remarkable ΛCDM paradigm



6 numbers describe the Universe from
the big bang and quantum fluctuations until today

The remarkable ΛCDM paradigm



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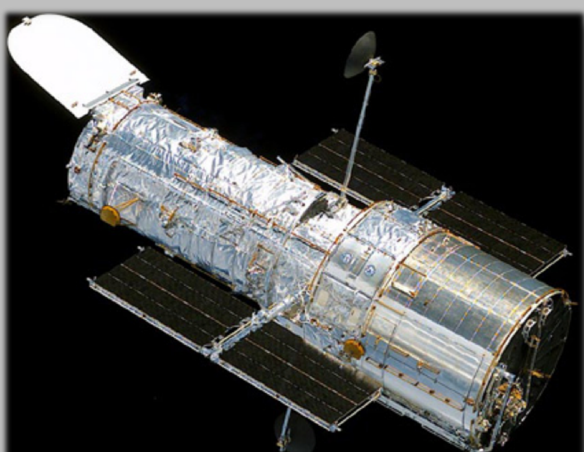
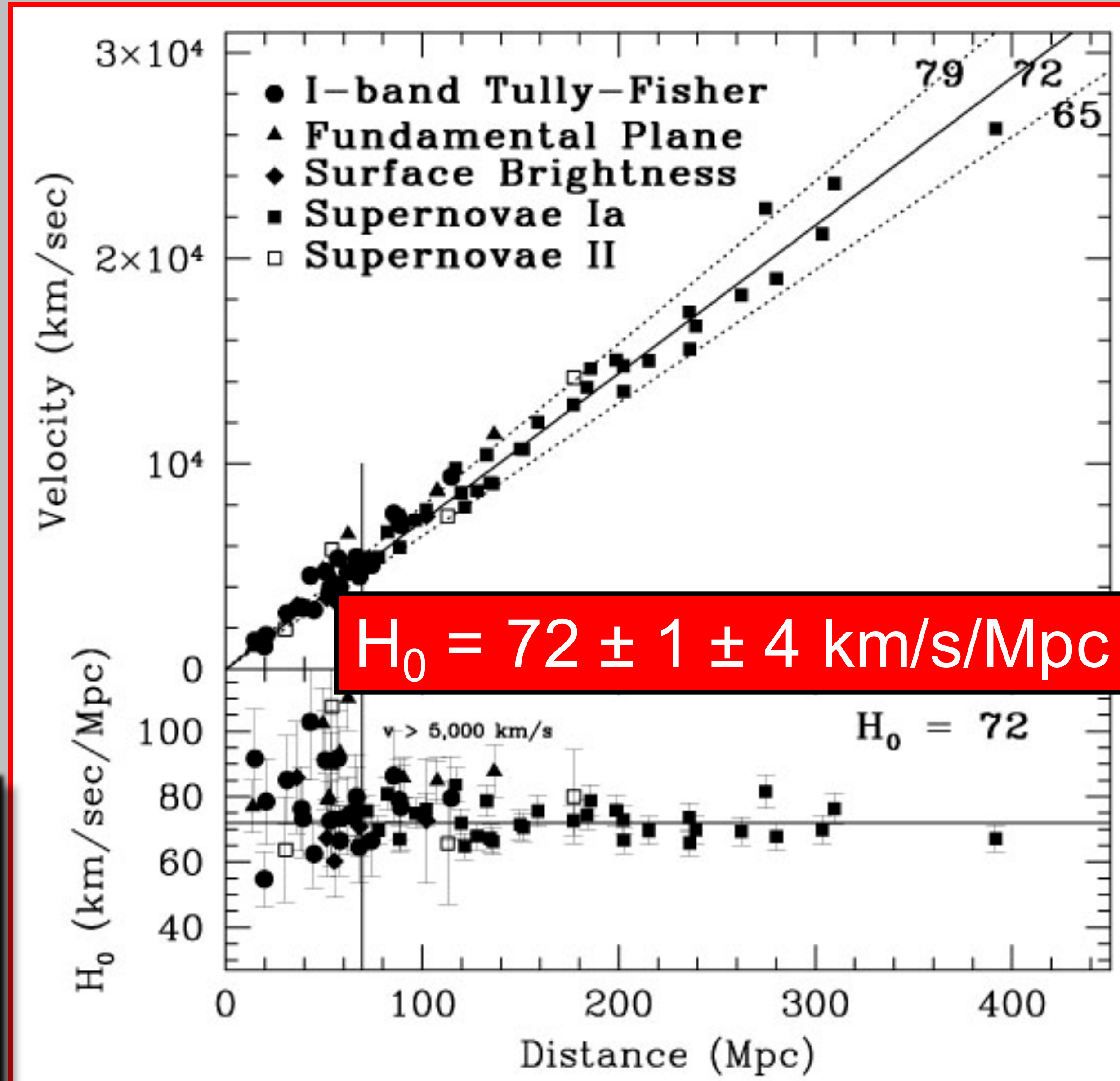
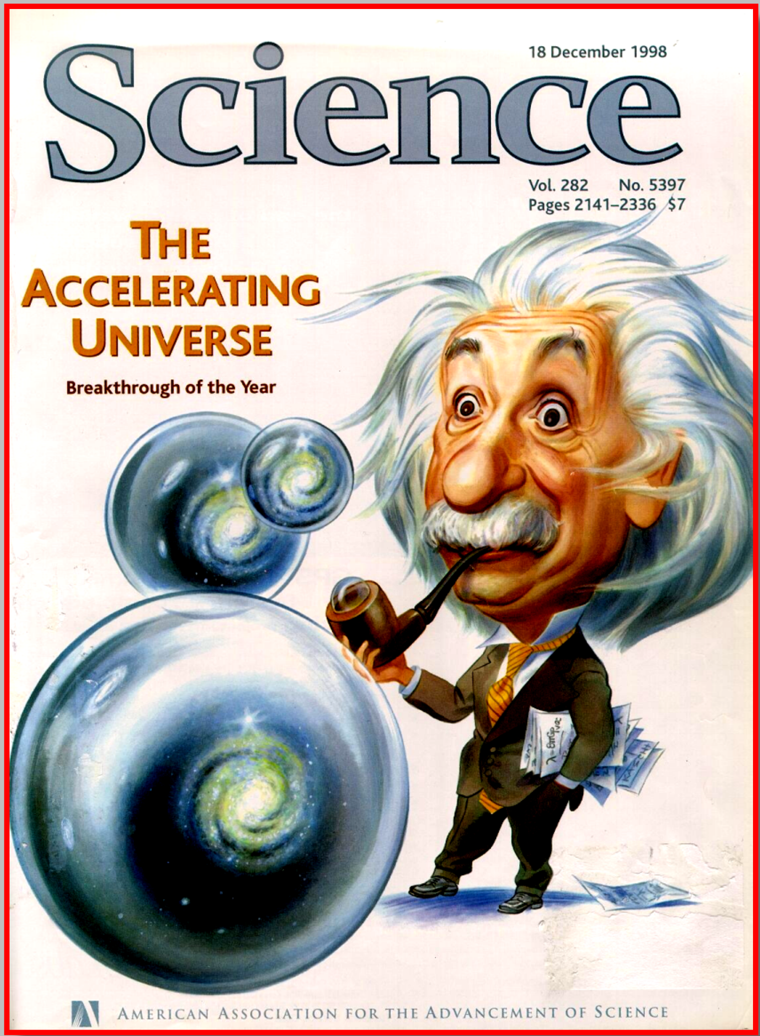



H$_0$ = 72 ± 1 ± 4 km/s/Mpc
I−band Tully−Fisher
Fundamental Plane
Surface Brightness
Supernovae Ia
Supernovae II
79
72
65
3×10⁴
2×10⁴
10⁴
0
Velocity (km/sec)
v > 5,000 km/s
H$_0$ = 72
100
80
60
40
H$_0$ (km/sec/Mpc)
0
100
200
300
400
Distance (Mpc)

$q_0 = -0.54 \pm 0.05$ – speeding up, not slowing down



ΛCDM: today's big picture

precision, accuracy, full accounting and consistency

- From quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe, inflationary beginning
- Atoms, exotic dark matter & dark energy
- Precision cosmological parameters
  - $T_0 = 2.7255 \pm 0.0006$ K
  - $\Omega_0 = 1.005 \pm 0.005$ (uncurved = flat)
  - $\Omega_M = 0.315 \pm 0.01$
  - $\Omega_B = 0.048 \pm 0.001$
  - $\Omega_{DE} = 0.685 \pm 0.01$
  - $H_0 = 67^* \pm 0.5$ km/s/Mpc
  - $t_0 = 13.80 \pm 0.02$ Gyr
  - $n_s = 0.965 \pm 0.005$
  - $N_\nu = 3.0 \pm 0.33$

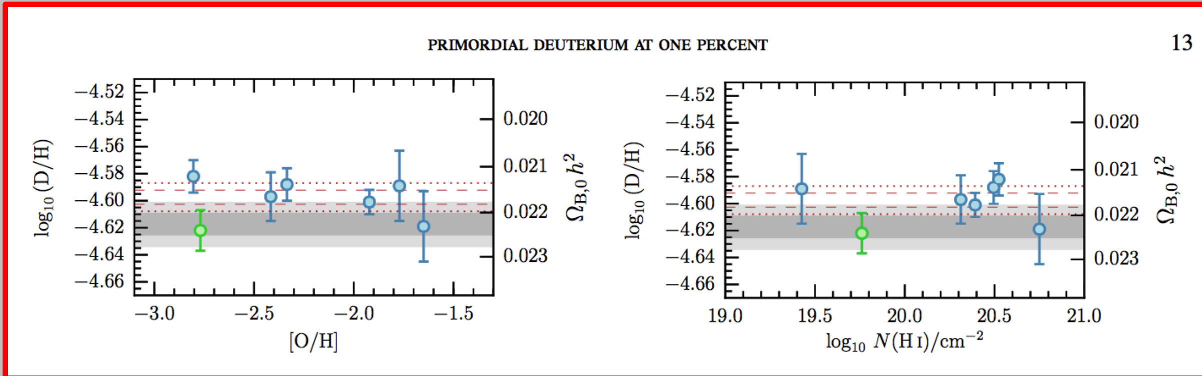
Consistent with immense body of high-quality data!

Precision Cosmology!

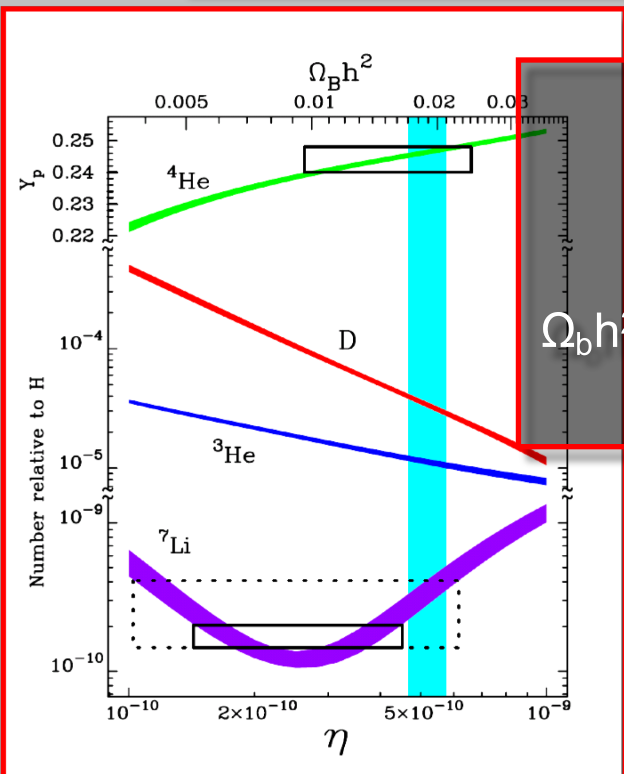
Precision Cosmology is Hard

Accurate Cosmology is even Harder!

Precision and accurate cosmology!



arXiv:1710.11129



CMB (first to second peak)

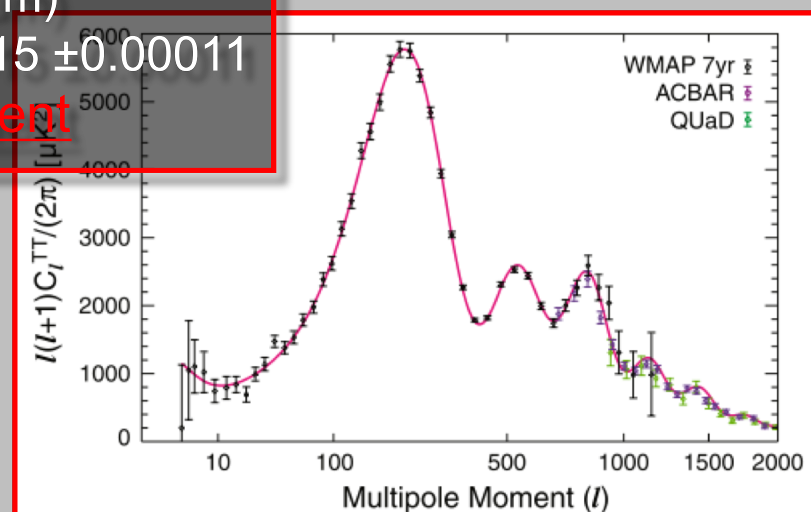
$\Omega_b h^2 = 0.02226 \pm 0.00023$

vs.

BBN (Deuterium)

$\Omega_b h^2 = 0.02166 \pm 0.00015 \pm 0.00011$

2.5% agreement



Airtight Evidence for Nonbaryonic Dark Matter

CMB & BBN

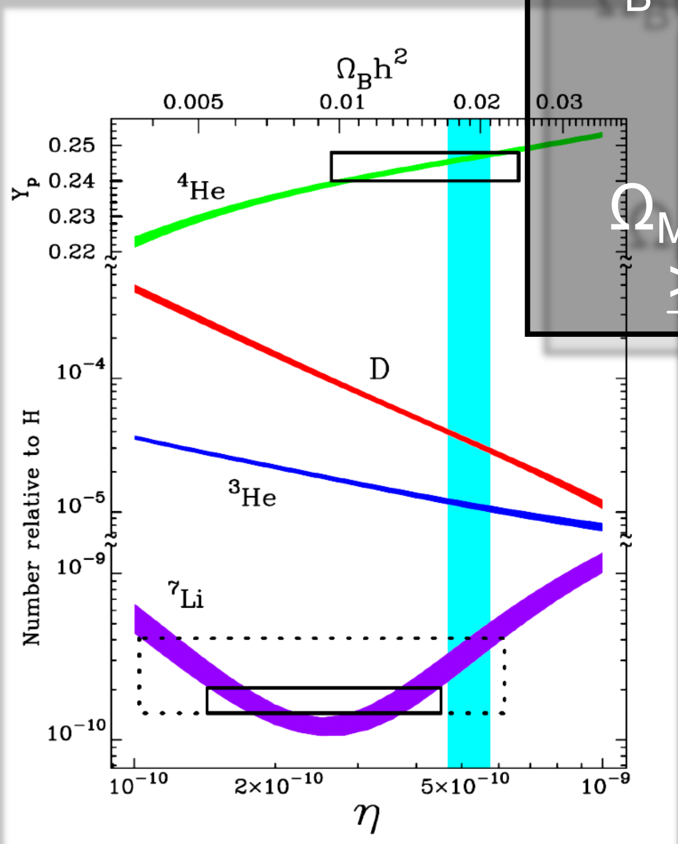
$\Omega_B h^2 = 0.02166 \pm 0.0002$

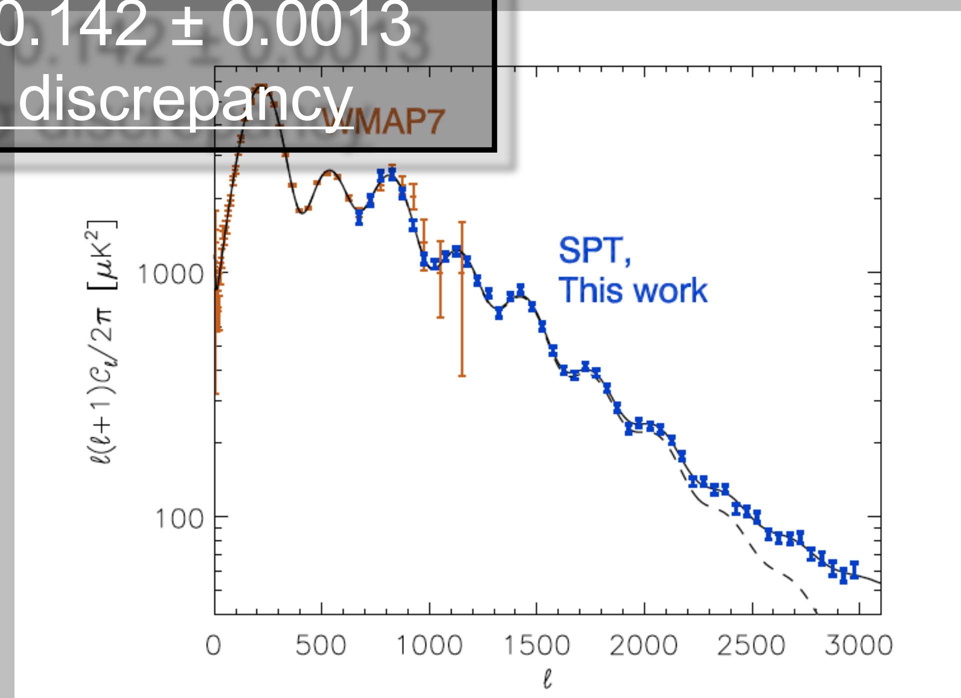
vs.

CMB/SDSS

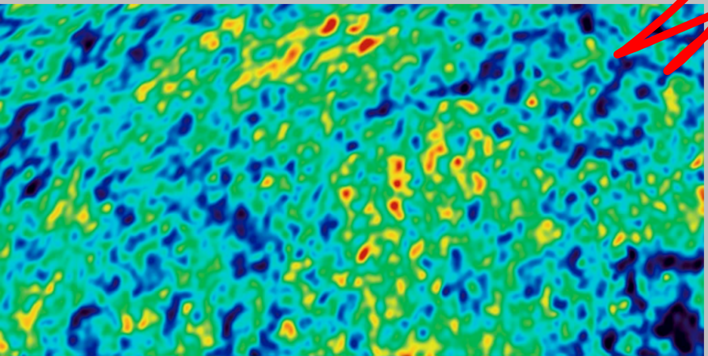
$\Omega_M h^2 = 0.142 \pm 0.0013$

<u>> 50σ discrepancy</u>





The Largest Things in the Universe Began from Subatomic Quantum Fluctuations!

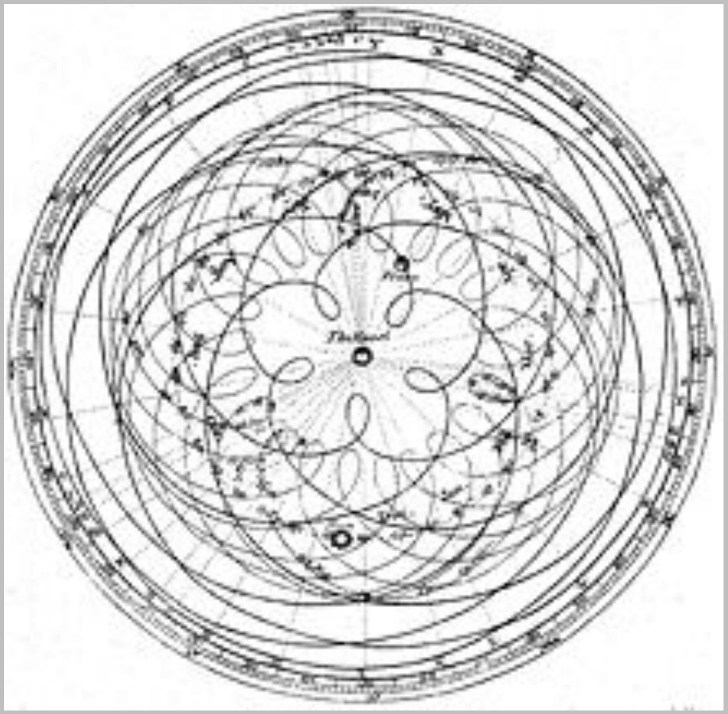


ΛCDM has revealed new physics

- The repulsive gravity of **Dark Energy** explains cosmic acceleration and Λ (quantum vacuum energy) is the default dark energy candidate
- A very early burst of tremendous expansion – **Inflation** – explains our smooth, flat Universe with seeds for galaxies grown from quantum fluctuations
- The gravity of slowly-moving **Dark Matter** particles (CDM) holds all cosmic structures together
- **Baryogenesis** leads to the creation of atoms

ΛCDM is *not* good enough for some

- ΛCDM may be good enough for astrophysical cosmologists (e.g., Ostriker, Silk?, Peebles?)
- Λ is still the most profound mystery in all of science
- No standard model – let alone fundamental model – of inflation
- So what is the name of the dark matter particle?
- New physics or just epicycles to create a best fit Universe
- **Not good enough for the “fundamental cosmologists”**



Astrophysical cosmology questions

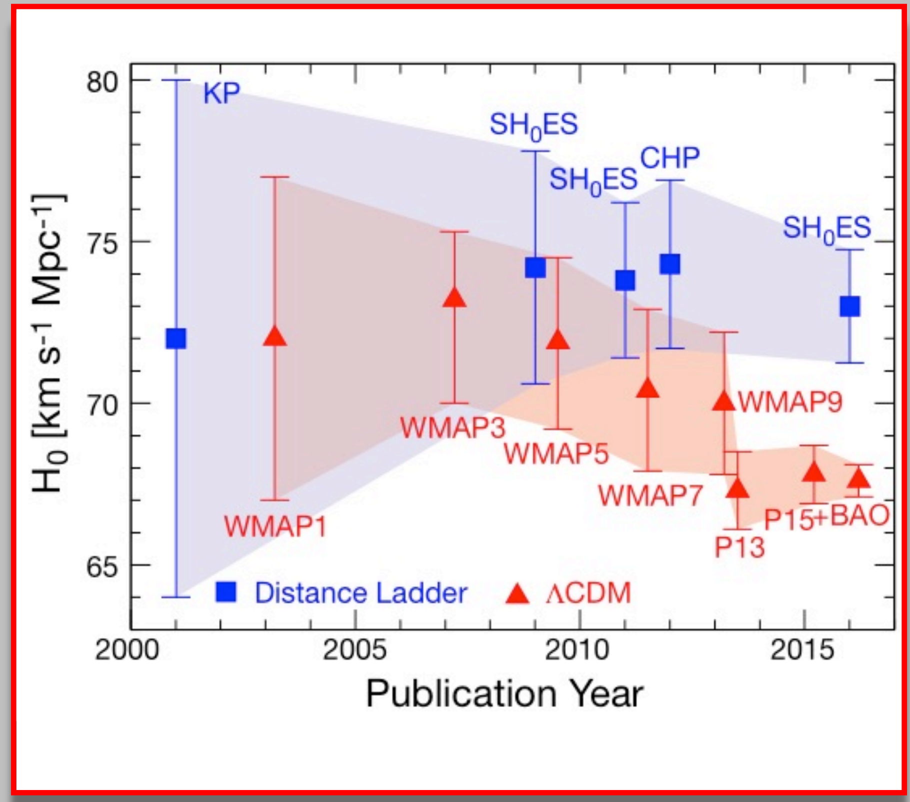
- CDM: out of lives? not all the truth? DM tuning?
- Star formation, magic masses, IMF, and the story of our creation from lumpy gas
- The empty voids (for Jim)
- *Milgrom Miracle: need for dark matter occurs at fixed acceleration $a \sim cH_0$*
  - NB: Hoyle miracle (CMB ~ starlight) not yet explained

Moving forward in the age of precision cosmology

- Disruption
  - H_0 portal
  - Cosmic Acceleration (growth of structure)
- Discovery
  - B-modes of inflation
  - Dark matter
- And on to bigger mysteries ahead!

The H_0 portal: disruption and discovery?

- 3.4σ discrepancy between direct measures and CMB measurements that *<u>assume</u>* ΛCDM
- *If b*oth values are right – ΛCDM disrupted! + discovery



The H_0 portal: disruption and discovery?

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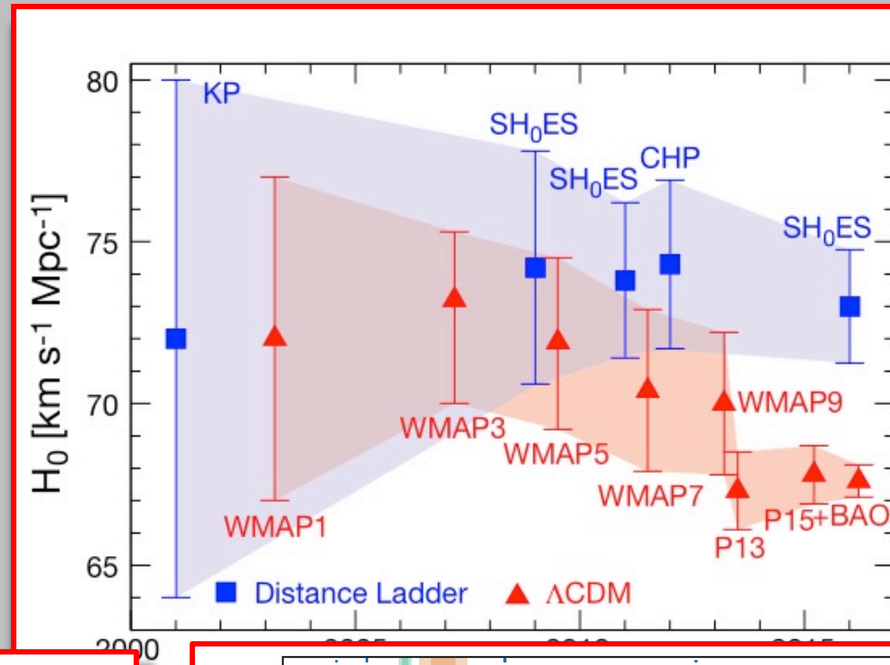


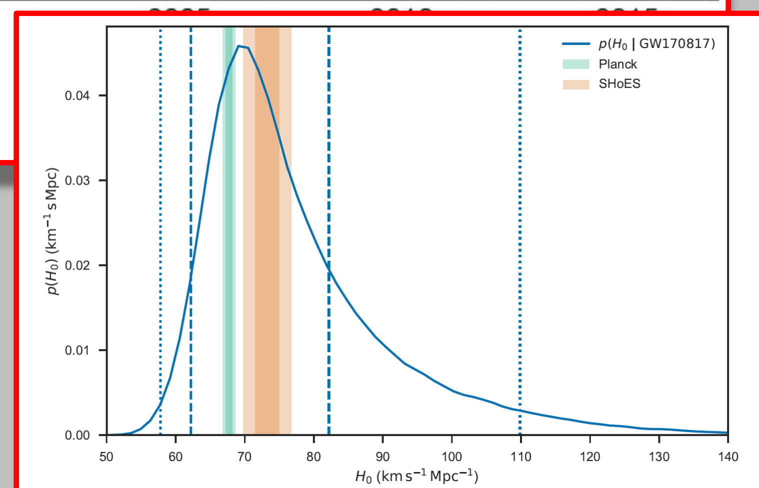
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]

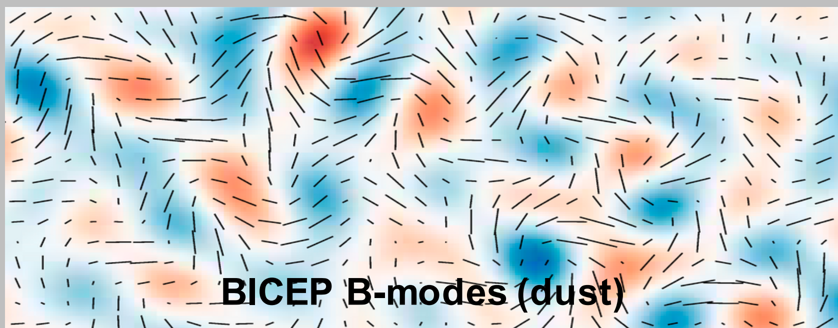
(LIGO Scientific Collaboration and Virgo Collaboration)

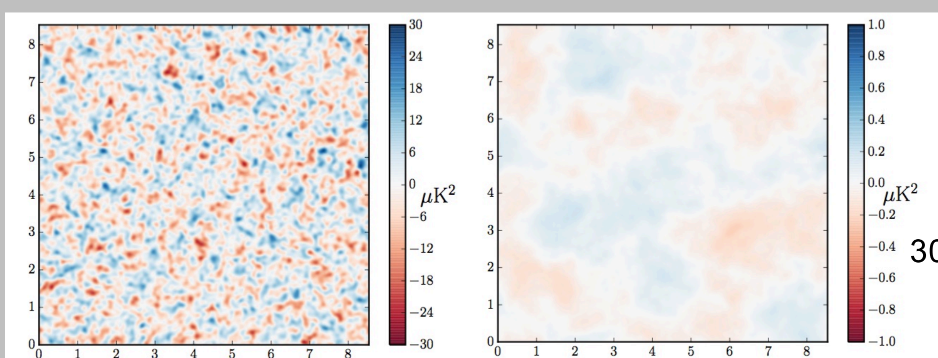
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

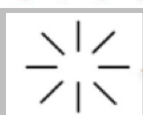
On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.



Discover the epoch of inflation with B-mode polarization







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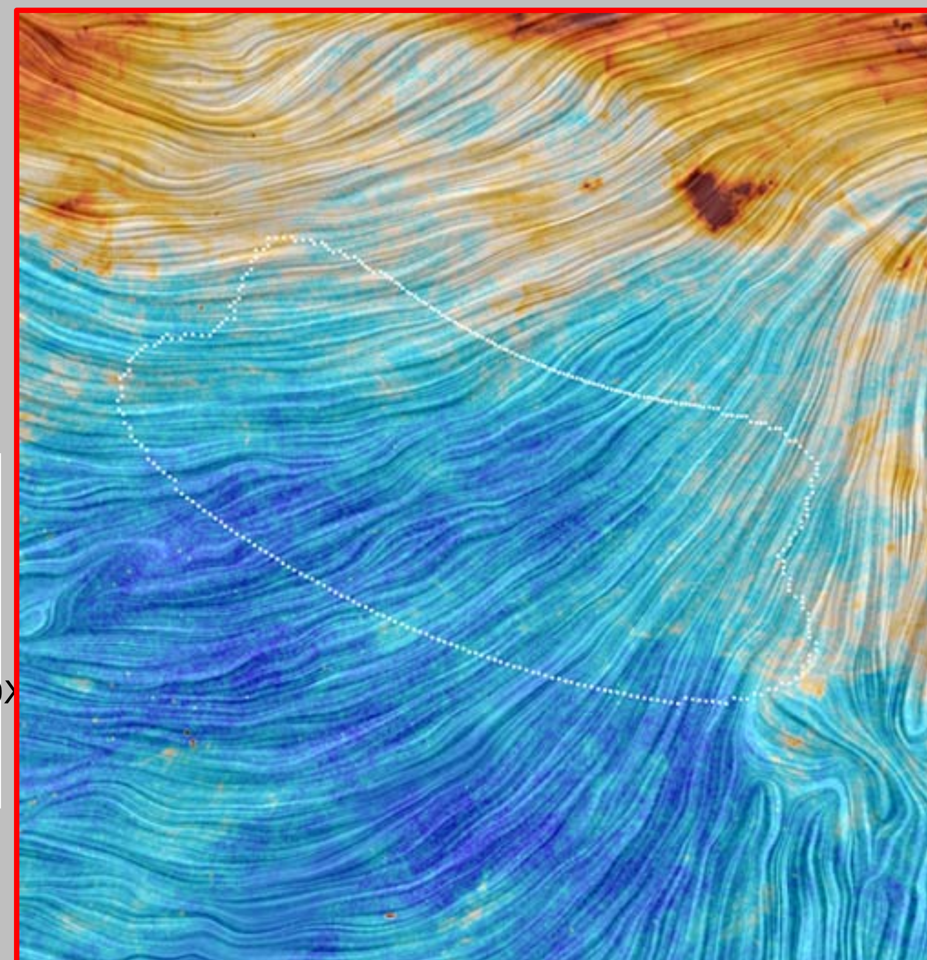


When all the "dust" settled: BICEP2/Keck/Planck joint analysis

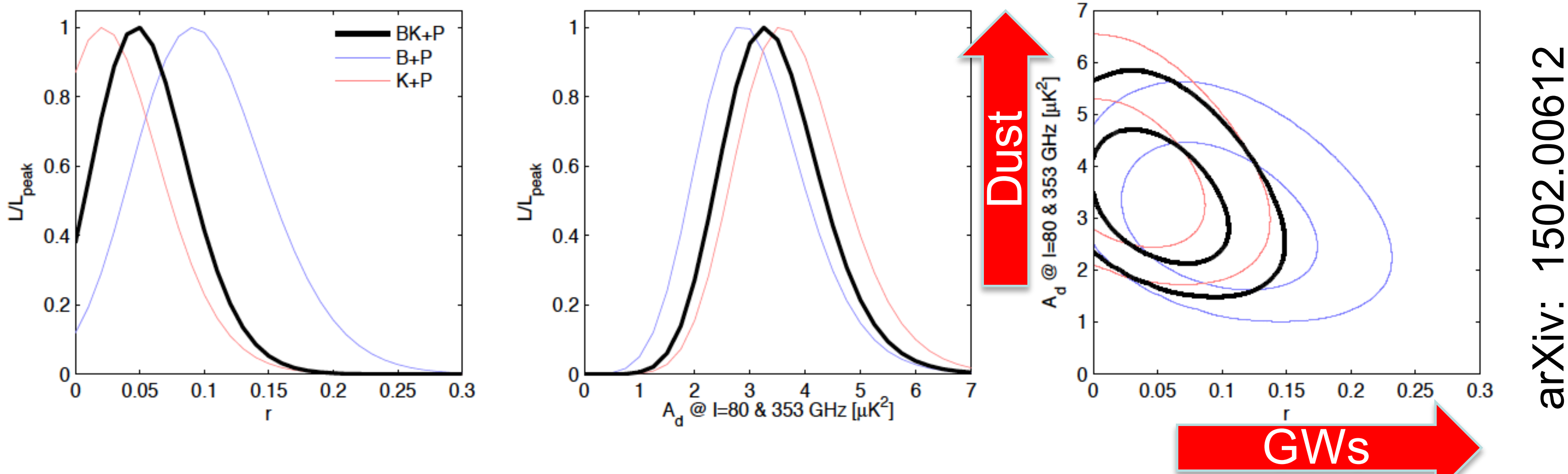
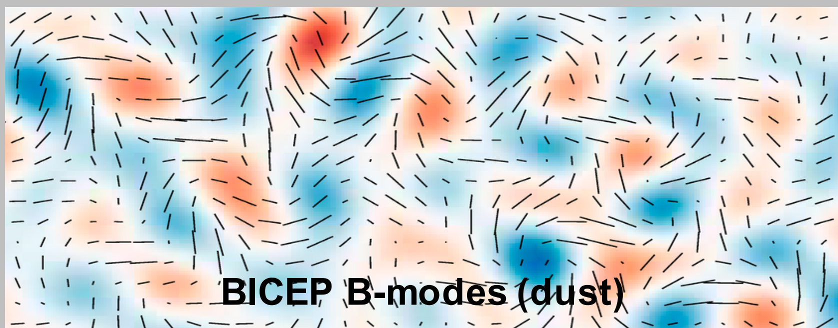


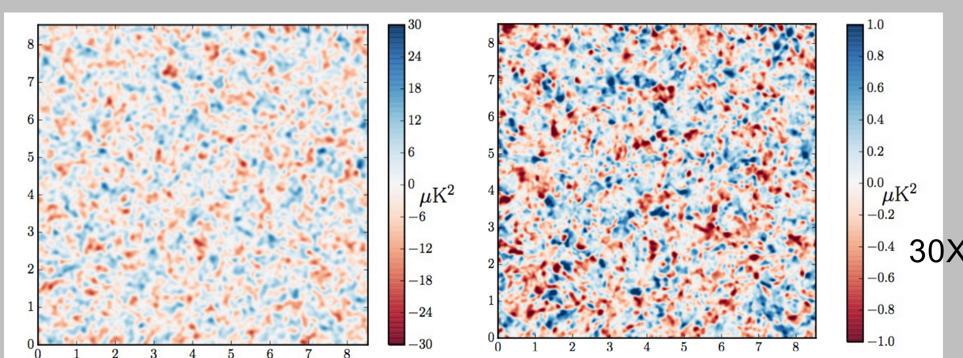
FIG. 6. Likelihood results from a basic lensed-ΛCDM+r+dust model, fitting BB auto- and cross-spectra taken between maps at 150 GHz, 217, and 353 GHz. The 217 and 353 GHz maps come from *Planck*. The primary results (heavy black) use the 150 GHz combined maps from BICEP2/*Keck*. Alternate curves (light blue and red) show how the results vary when the BICEP2 and *Keck Array* only maps are used. In all cases a Gaussian prior is placed on the dust frequency spectrum parameter $\beta_d = 1.59 \pm 0.11$. In the right panel the two dimensional contours enclose 68% and 95% of the total likelihood.

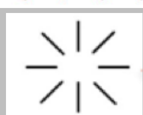
B-modes detected! Dust detected at > 3σ

Evidence for something else (GWs)?

Discover the epoch of inflation with B-mode polarization







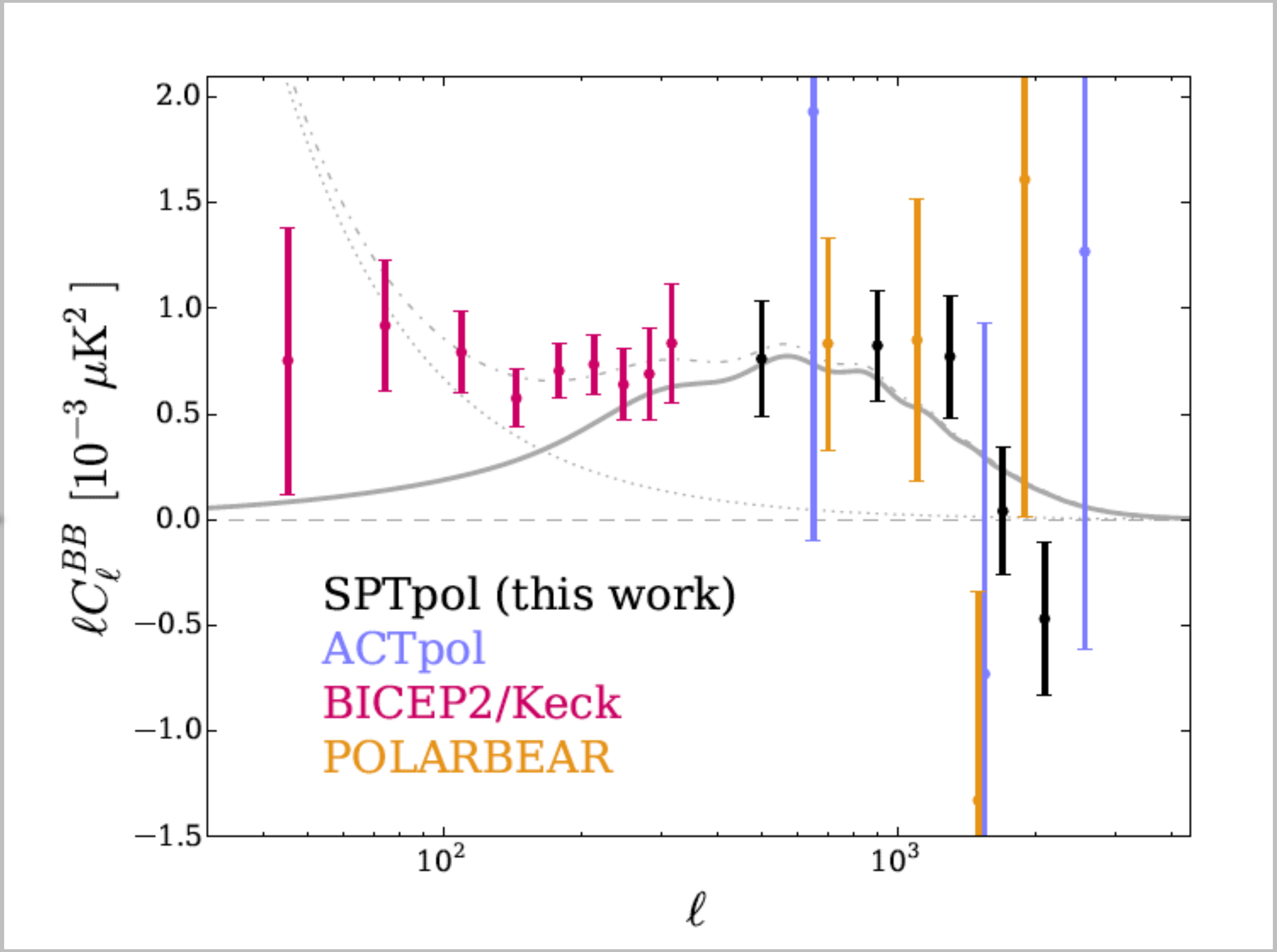
Lensing “turns” E into B

- Combine SPT with BICEP/Keck and other CMB experiments
- “De-lens” (neutrino mass is a by-product!)
- Discovery potential:
  - Inflationary B-modes
  - Neutrino mas
  - New particle species

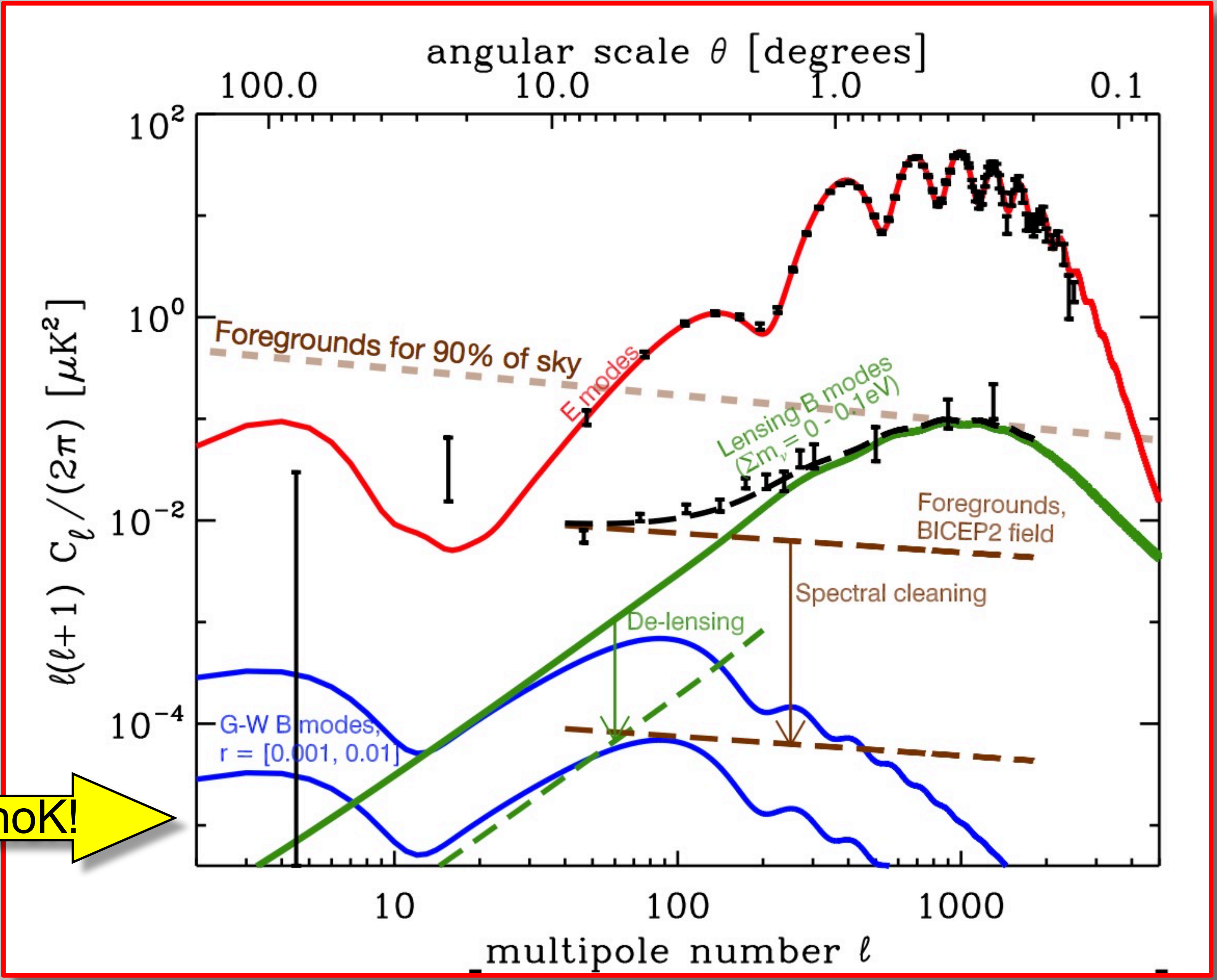
Where we are on B-modes

l ~ 30 to 100 dust, l ~ 1000 lensing

30 nanoK!



CMB S4



3 nanoK!

Full Court Press!!

- Produce at LHC
- Detect particles in our halo
- Detect annihilation products

Dark matter

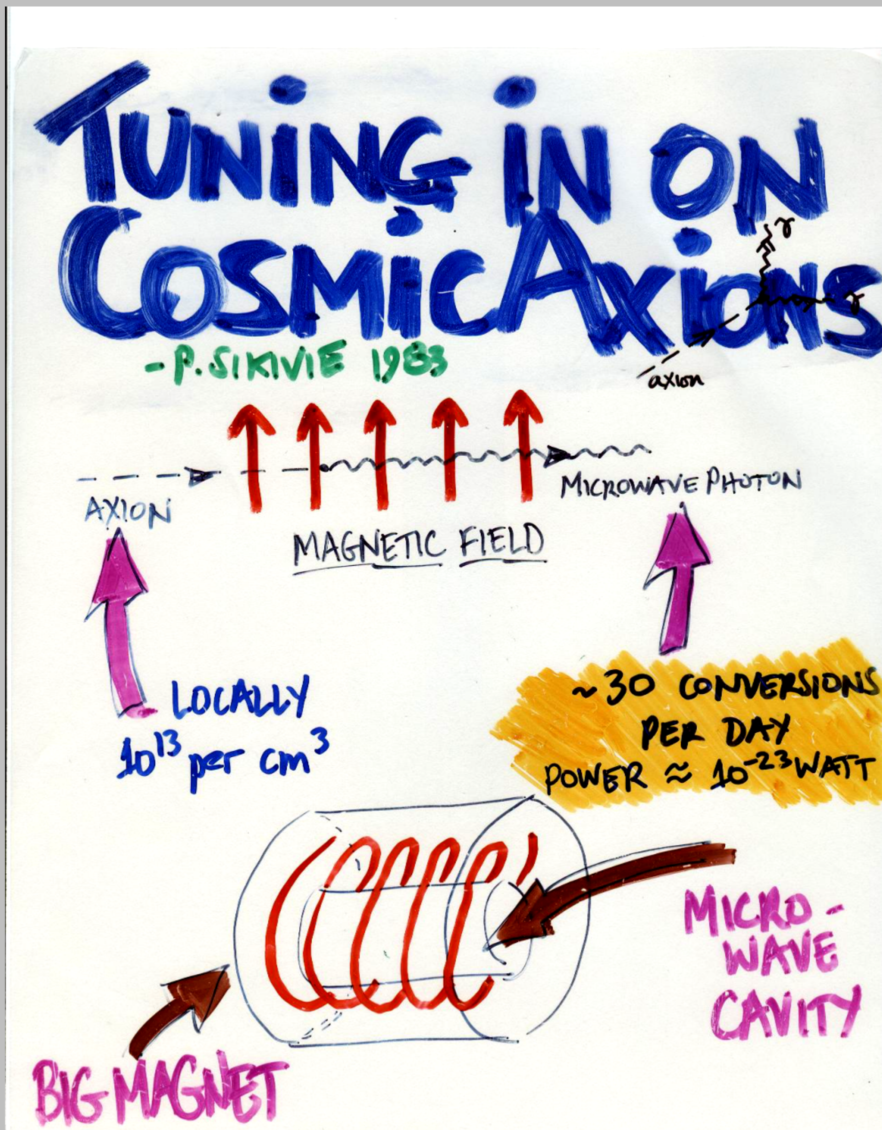
The story be more complicated:

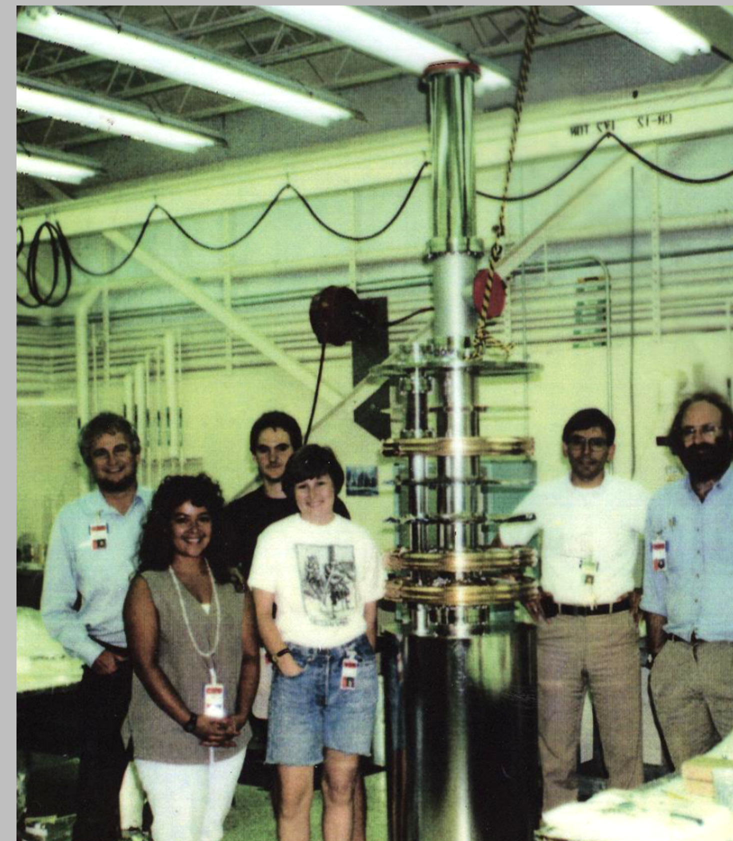
Many different kinds of dark matter

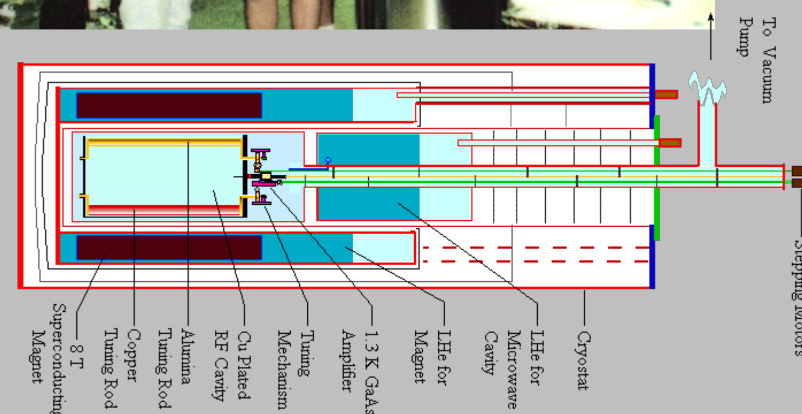
<u>A whole dark world waiting to be discovered!</u>

NB: I liked JEllis' constrained creativity

Detecting Cosmic Axions







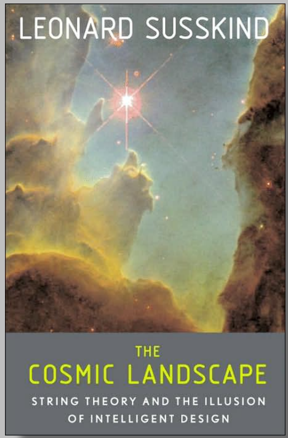
Why isn't lambda good enough?

Short answer: no good theory for it!

Λ is equivalent to vacuum energy & quantum zero-point energy diverges:

$$\Omega_\Lambda \sim (E_{cutoff}/10^{-4}\ \mathrm{eV})^4$$

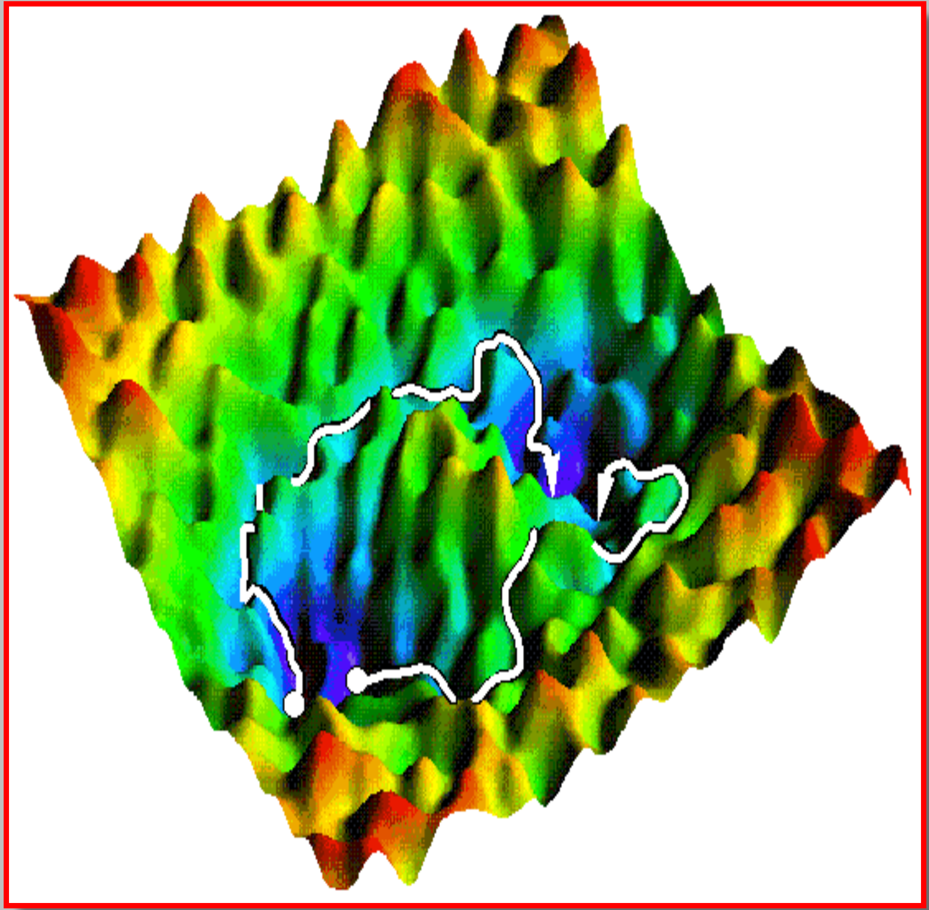
cf, Martin White's talk on measuring growth of structure – new test of dark energy/GR



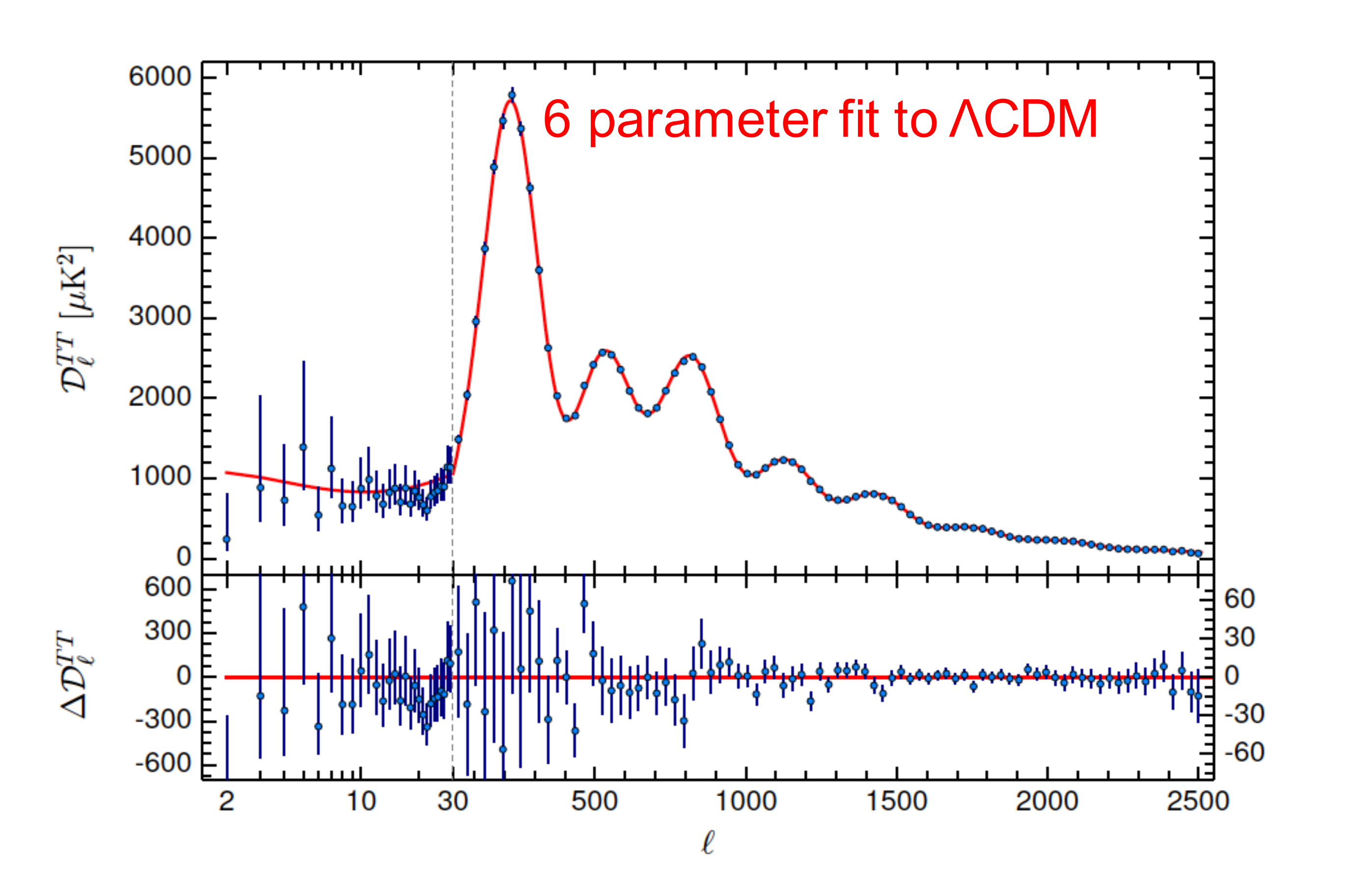
The Extravagant Universe

"the best left-coast solution"

- M-theory → 10^{500} vacua
- $\rho_{vac} \sim O(m_{Pl}^{4}) \pm O(m_{Pl}^{4})$
- Universe has a multiverse structure & we were lucky (narcissistic principle)
- Testable?



La dent (l ~ 20 to 40): disruption or discovery?

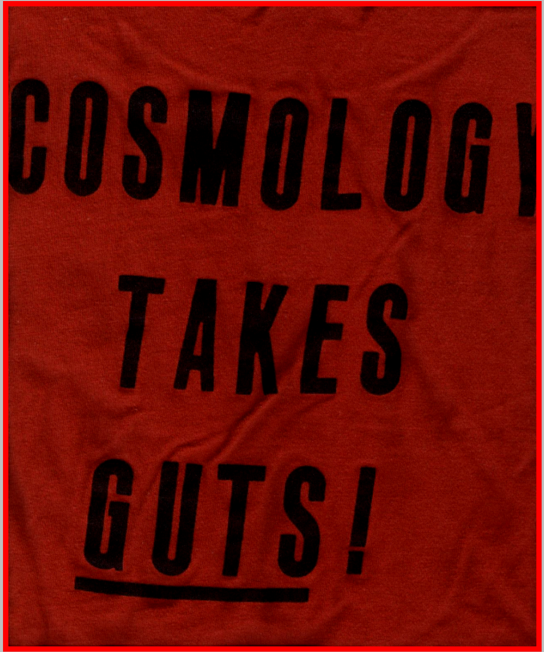


Inflation: Game changing idea, but not time for a coronation

- No fundamental theory
- Initial singularity, initial conditions
- Cosmological constant problem
- Like “duct tape”, very useful but …
  - Only postpones appearance of inhomogeneity
  - not all initial conditions inflate
- Unsettling, uncertain predictions: eternal inflation and *the multiverse*

Sakharov Conditions for Baryogenesis (1967)

?Famous April's Fools Seminar?



- Baryon number violation
- CP violation
- Departure from Thermal Equilibrium

May not take GUTs: Lepto/baryogenesis

Sakharov Conditions for Baryogenesis (1967)

?Famous April's Fools Seminar?

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

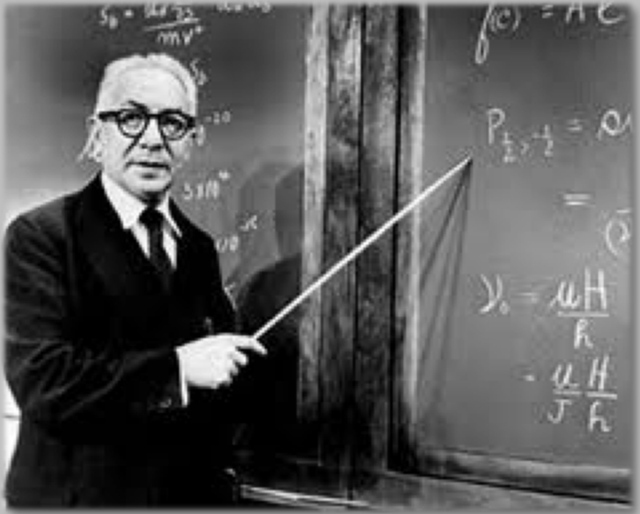
НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

The Complicated Universe

- Atoms : Democritus to 1964
- + photons: 1964
- + neutrinos (e, μ): 1967
- + exotic dark matter: 1981
- + CDM: 1983/4
- + massive neutrinos: 1998
- + dark energy: 1998
- + τ neutrino: 2000
- Done? Not likely!
- Why is $\Omega_{CDM}/\Omega_B \approx 5$?

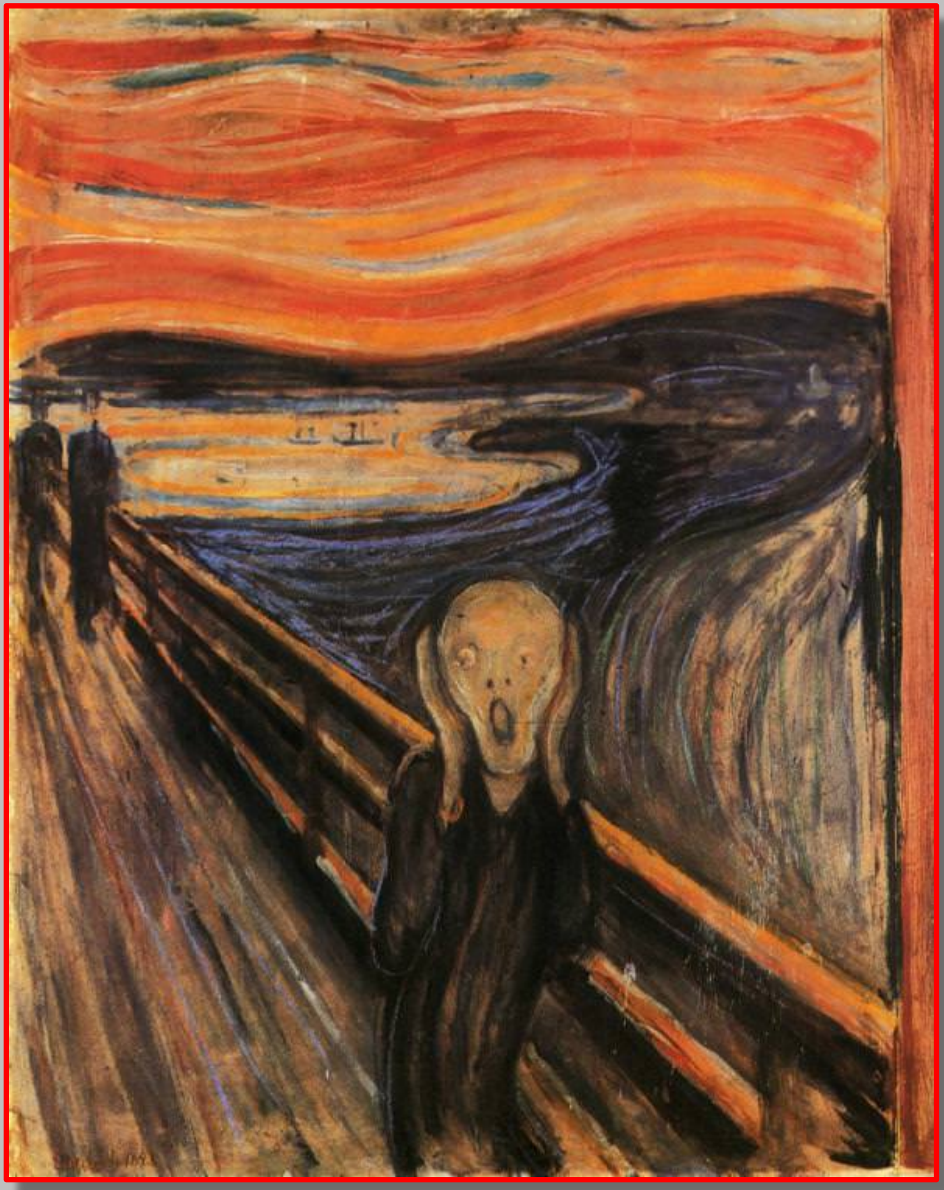


I.I. Rabi
Who ordered that?

How much room for more:

- UR: $\sim 0.2\rho_{CMB}$
- NR: $\sim 0.1\rho_{crit}$
- Other leftovers: ??

What to do about the multiverse



- Most important discovery since Copernicus?
- Is it science? (not falsifiable?)
- Many true believers (left coast) and not enough doubters

Exciting times ahead for both fundamental cosmologists and astrophysical cosmologists; plenty to do.

One thing is sure: Joe will be there leading us on. Happy Birthday Joe!