Concluding Talk

The Spacetime Odyssey Continues

celebrating the accomplishments and identifying the challenges

2 to 5 June 2015

Stockholm, Sweden

Michael S. Turner

Kavli Institute for Cosmological Physics

The University of Chicago

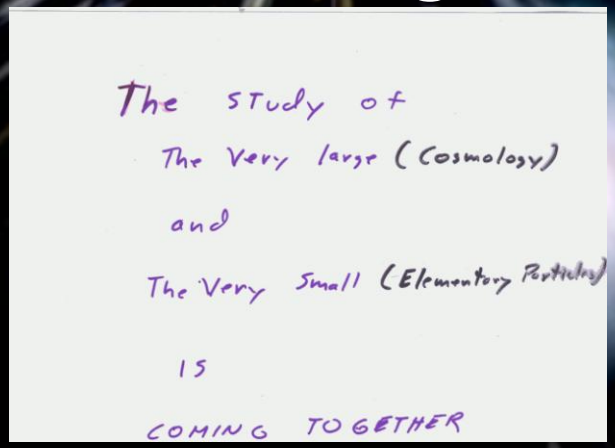
Concluding talks

- Definition
  - |Summary> = coherent sum of what was said + what I heard + what should have been said + my opinions
  - What you hear: $|\text{Summary}|^2 \approx |\text{what should have been said}|^2 + |\text{my opinions}|^2$
- Dangerous job
  - Thorlacius/Silk/Aprile/Turner → Silk/Aprile/Turner → Aprile/Wilczek/Silk/Turner → Aprile/Wilczek/Turner → Turner (survival of the fittest?)

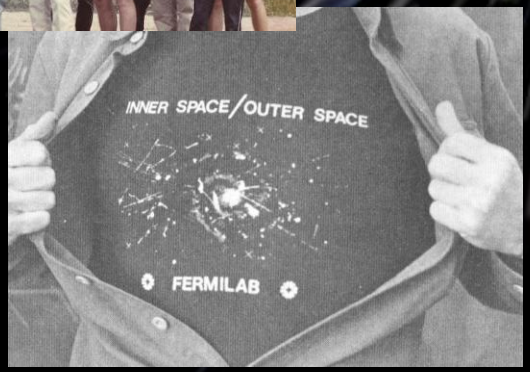
  … right up there with being #2 at Al-Qaida (7 killed since 2006!)

Big ideas (quarks and the cosmos) and powerful instruments (accelerators & telescopes) have pushed both fields forward shoulder to shoulder

Golden Age??



Circa 1984 (when Katie was finishing her thesis)



- Observational cosmology summary: $H_0 = 50 \pm 1$ or 100 ± 1; $\Omega_0 = \Omega_M \sim 0.1$; CMB: dipole + $\delta T/T < 10^{-4}$
- HST 6 years from launch
- Birth of modern inflationary paradigm
- HDM falling and CDM rising with axion as first CDM candidate
- SUSY DM coming soon


Celebrating the accomplishments
we've come a long way

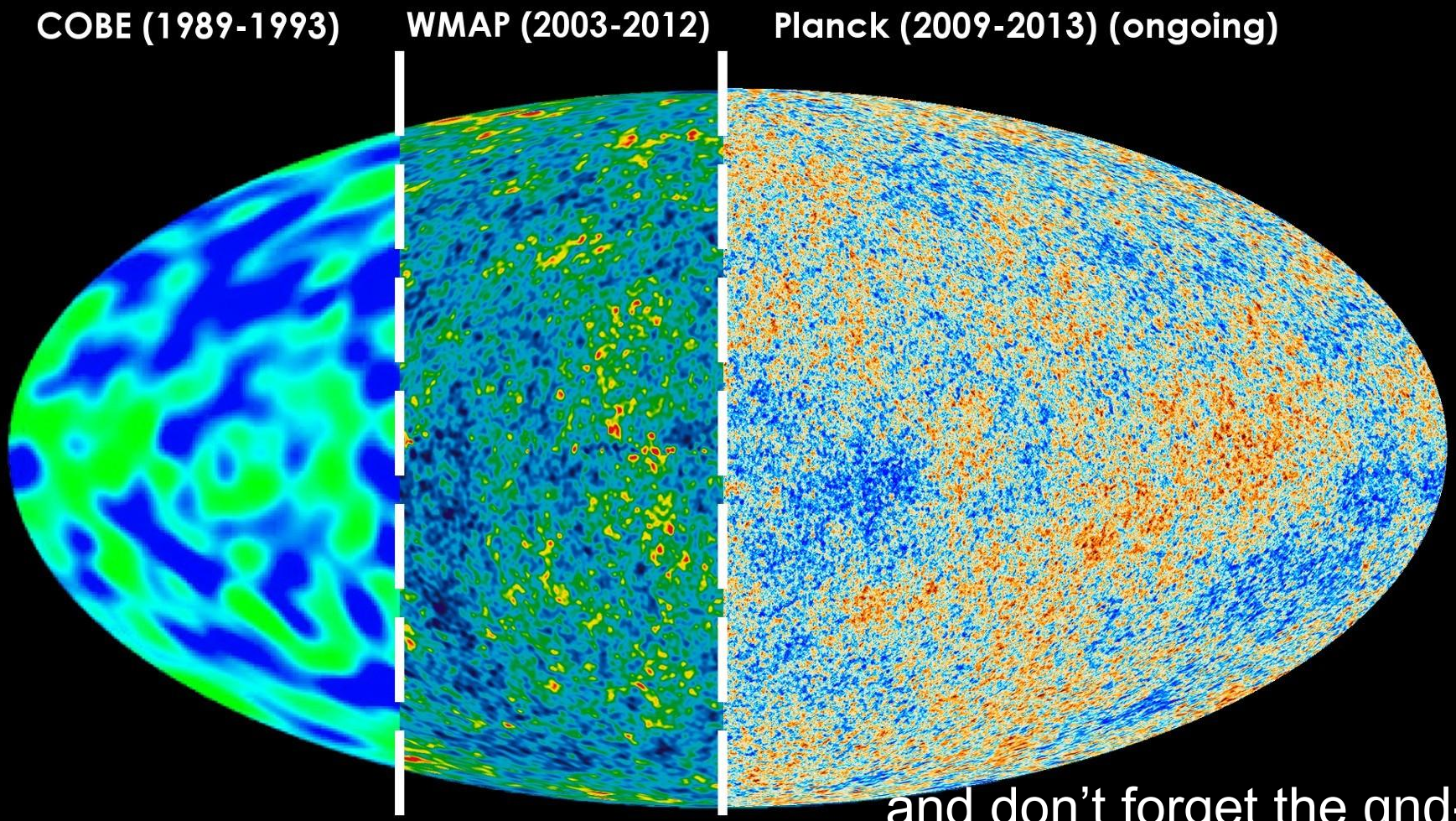
Consensus Cosmology

precision, accuracy, full accounting and consistency

- From quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision cosmological parameters
  - $\Omega_0 = 1.005 \pm 0.005$ (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 all data, laboratory and cosmological!

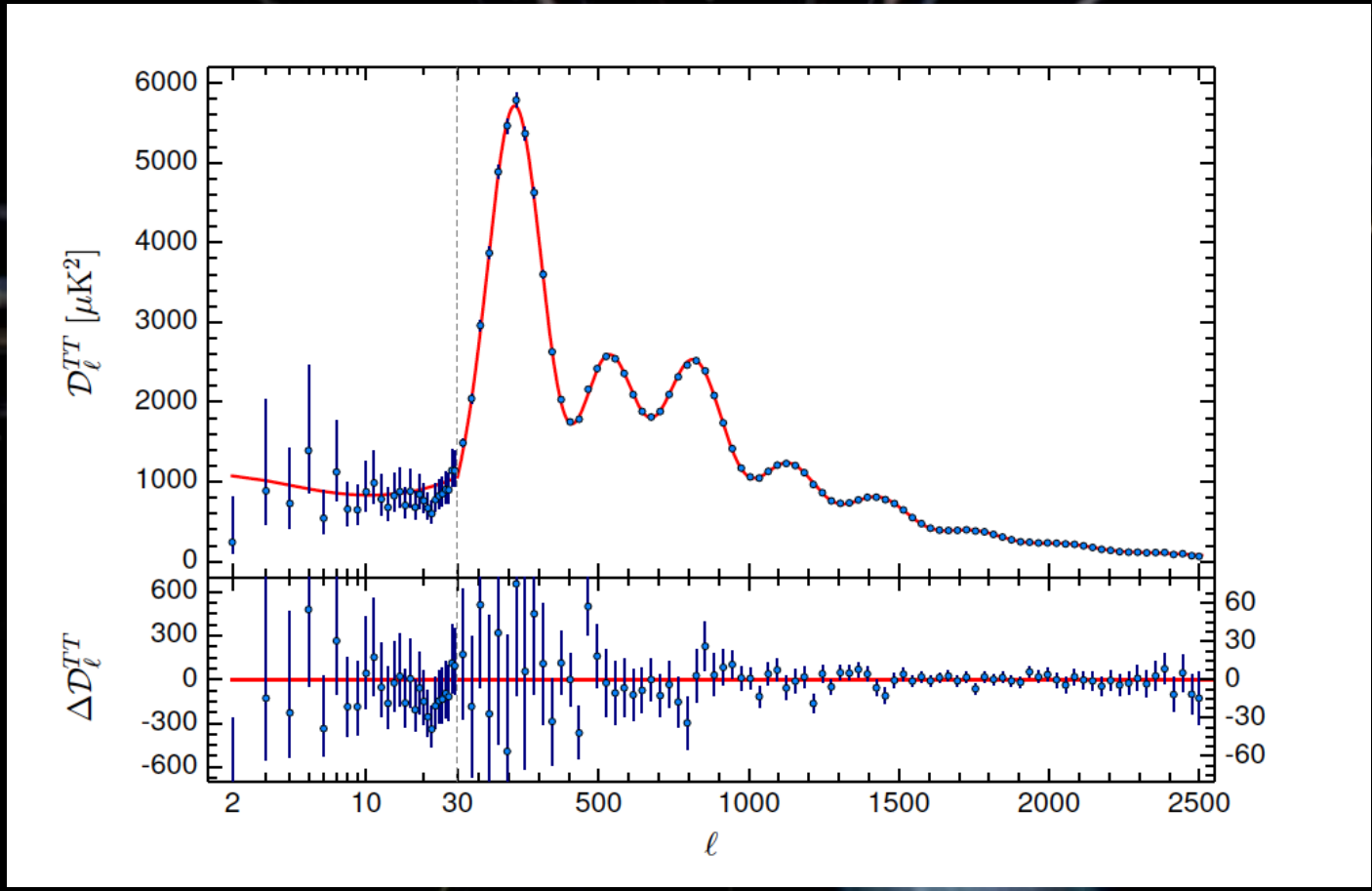
The Universe circa 380,000 yrs



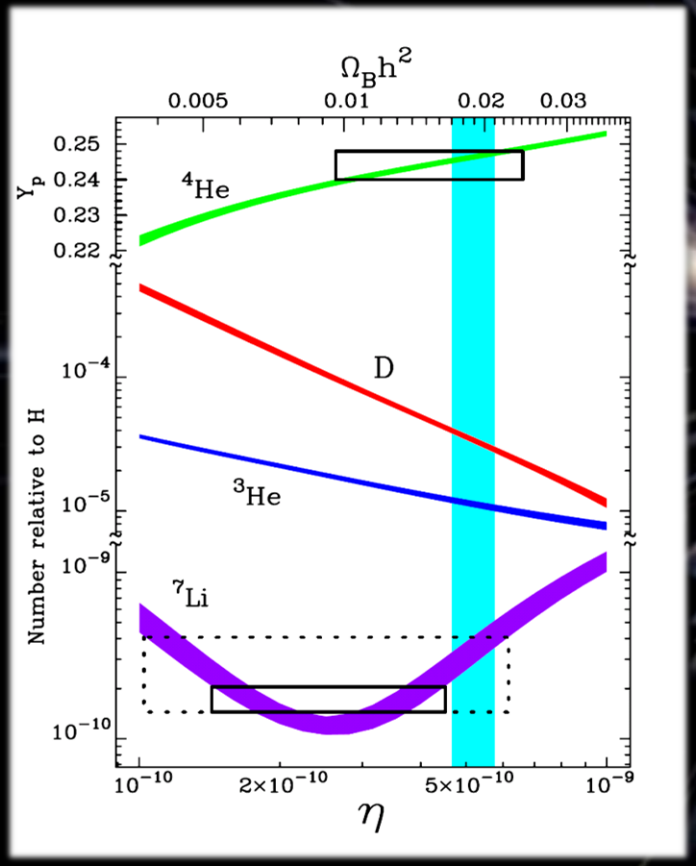
and don't forget the gnd-based experiments: ACT, Boomerang, DASI, SPT, …

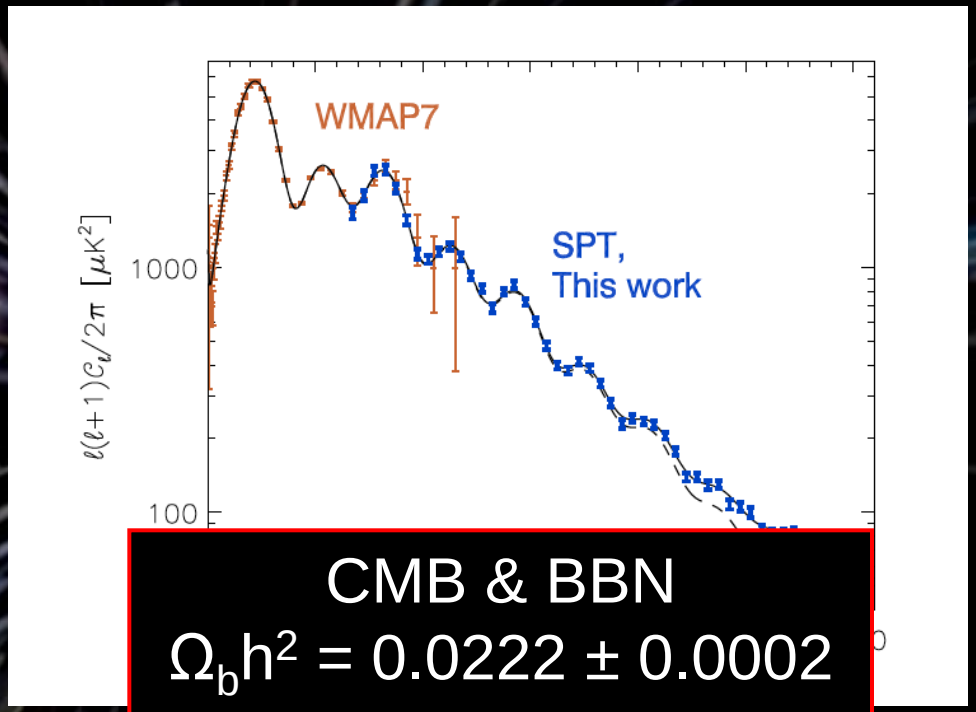
Planck Power Spectrum

a thing of beauty!



Airtight Evidence for Nonbaryonic Dark Matter





CMB & BBN

$\Omega_b h^2 = 0.0222 \pm 0.0002$

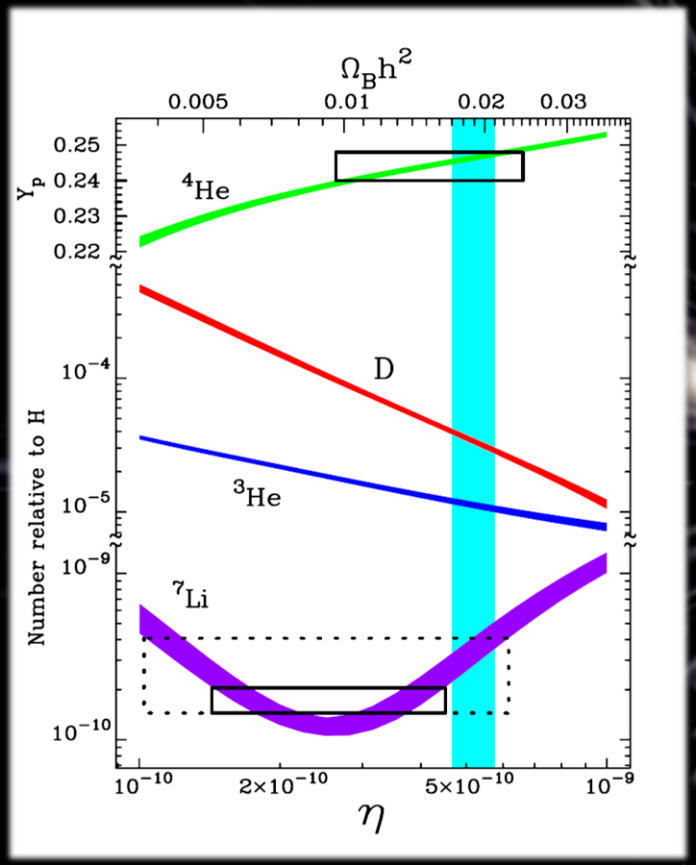
vs.

CMB/SDSS

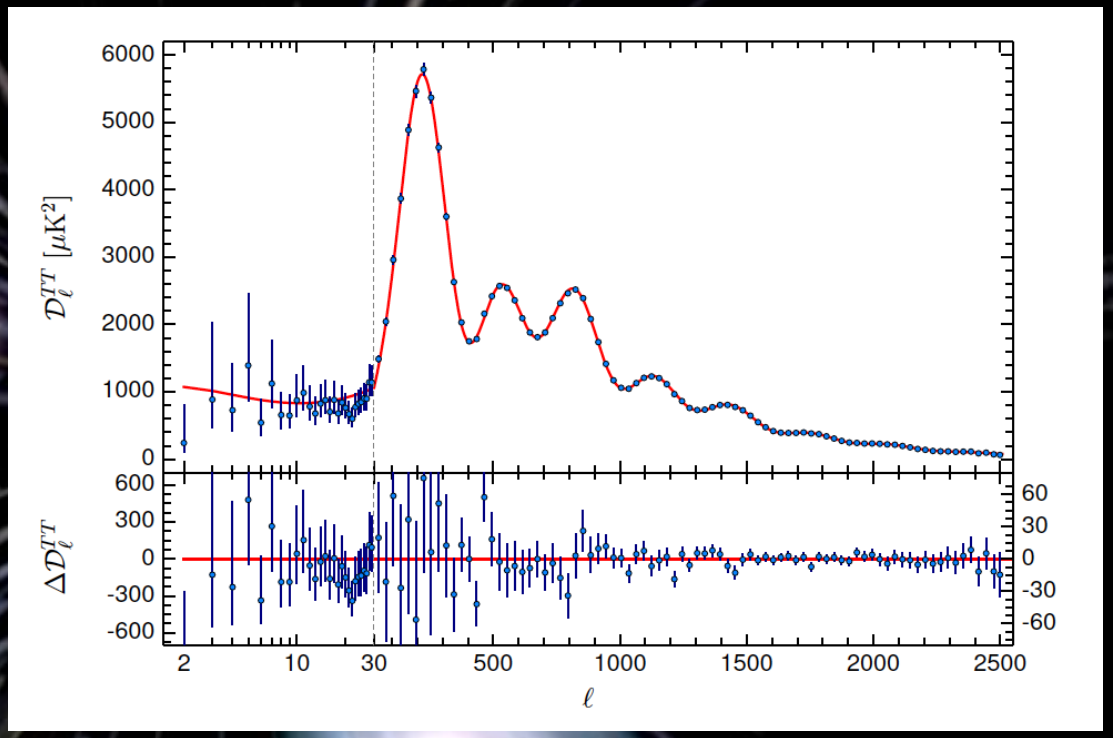
$\Omega_M h^2 = 0.142 \pm 0.0013$

40+σ discrepancy

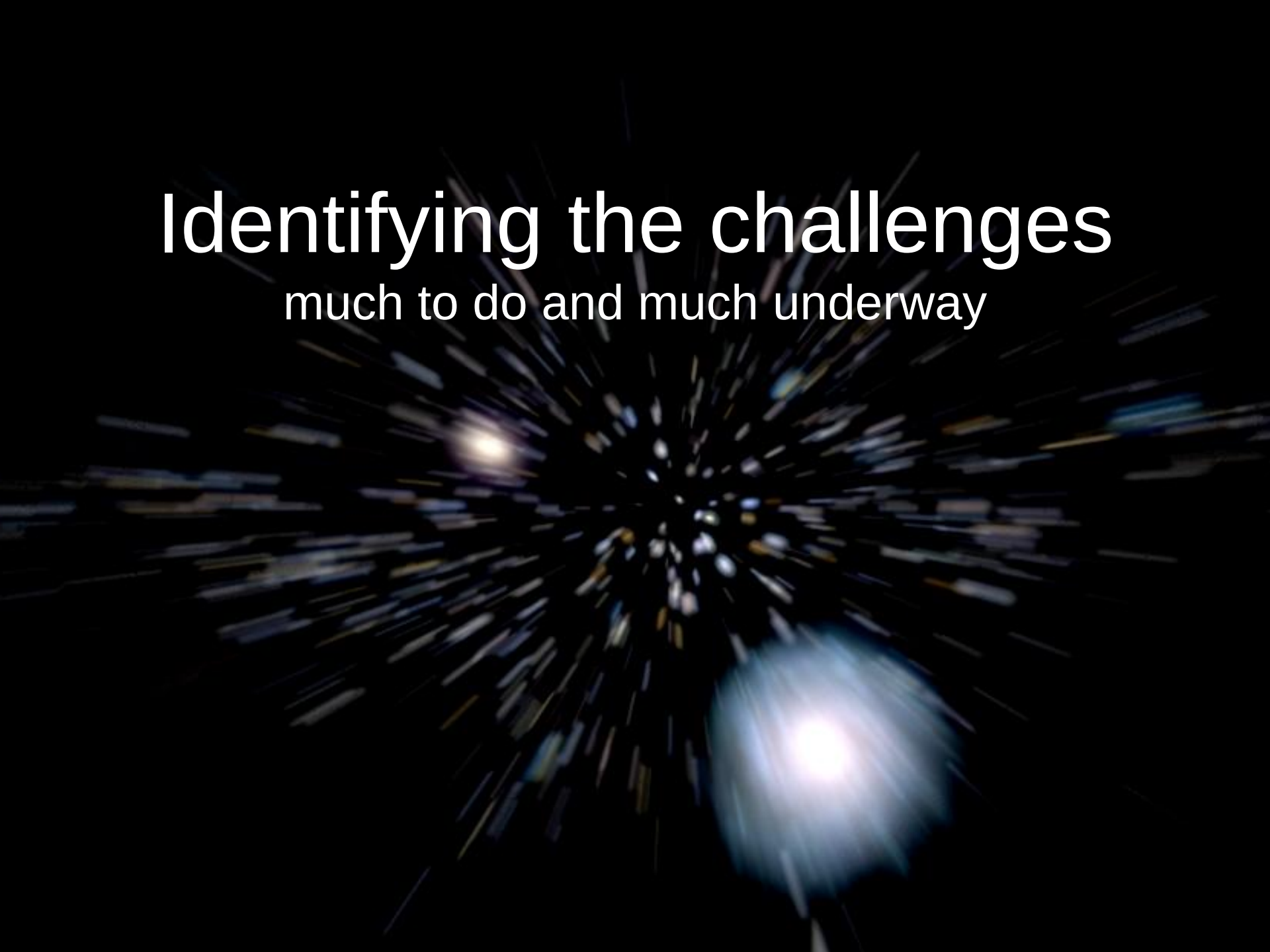
Cosmic consistency



D/H + Nuclear physics at t ~ 1 sec → $\Omega_b h^2 = 0.022 \pm 0.002$



CMB + Gravity driven acoustic oscillations at t = 380,000 yrs → $\Omega_b h^2 = 0.0222 \pm 0.0002$


Identifying the challenges
much to do and much underway

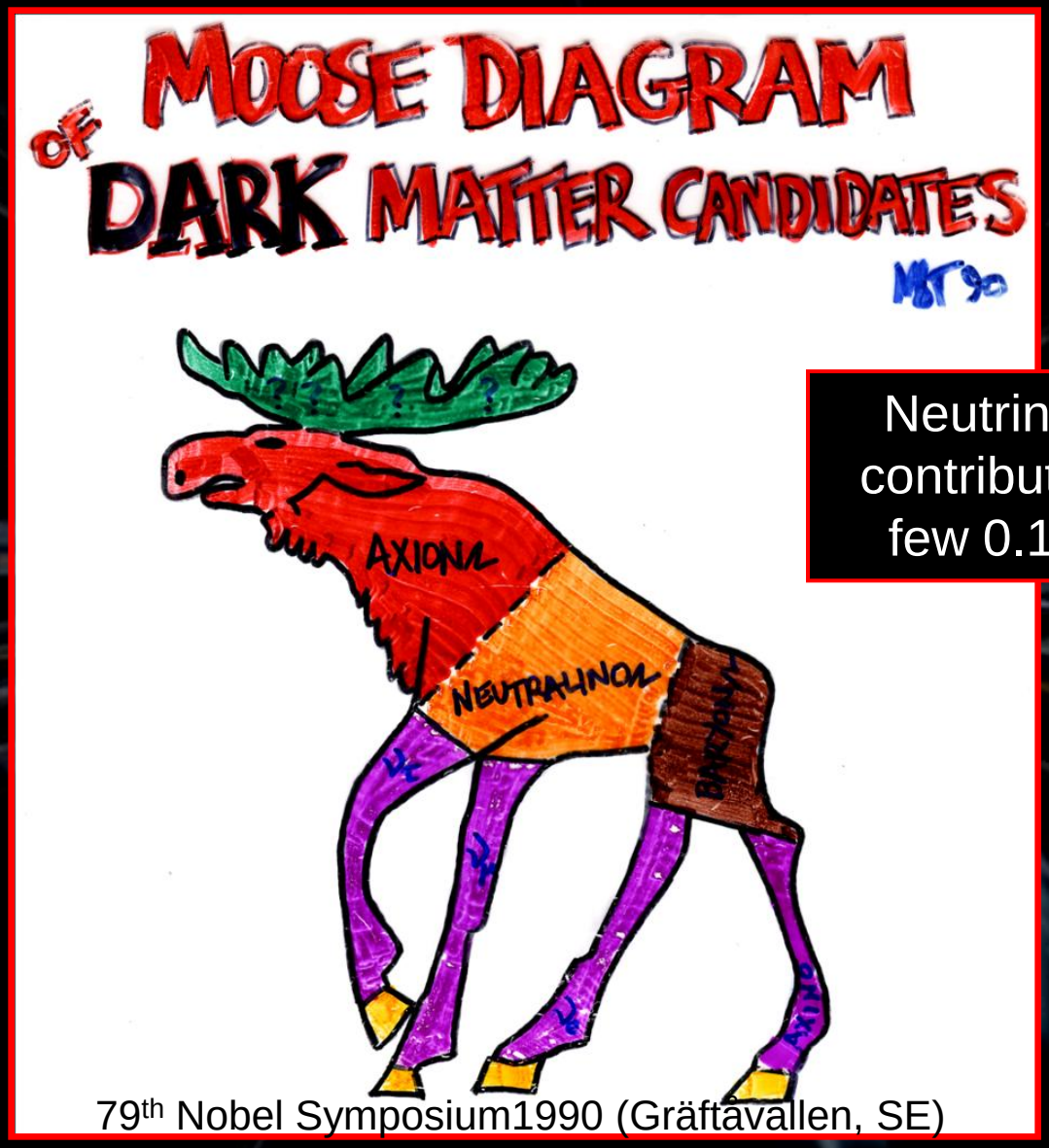
Consensus Cosmology

Rests upon three mysterious pillars

All implicate new physics!

Full Court Press!!

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

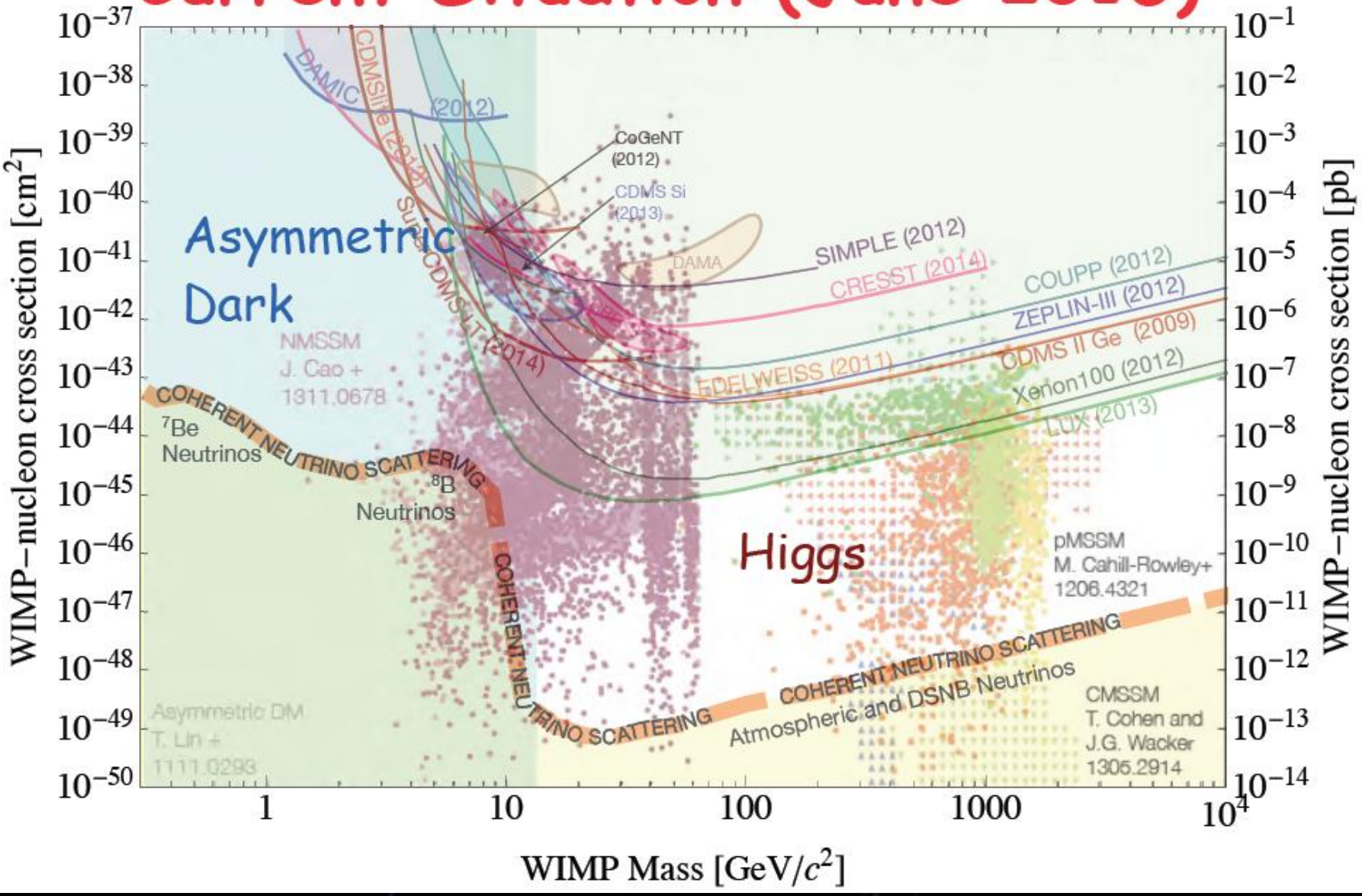


Neutrinos contribute a few 0.1%

79th Nobel Symposium1990 (Gräftåvallen, SE)

Direct Detection

Current Situation (June 2015)



Lots of intriguing hints

- Puzzles to resolve: Pamela/AMS, “the Hooperon”, DAMA/Libra, how much do neutrinos contribute? (cosmology seems to have the best shot)
- Importance of complementarity
  - Backgrounds: indirect (astrophysical), direct (radioactivity) & accelerator (SM/new physics)
  - Triple signature to convince the skeptic
- Time for new ideas? Cast the net more broadly? (Ugh, I hate the dark sector)

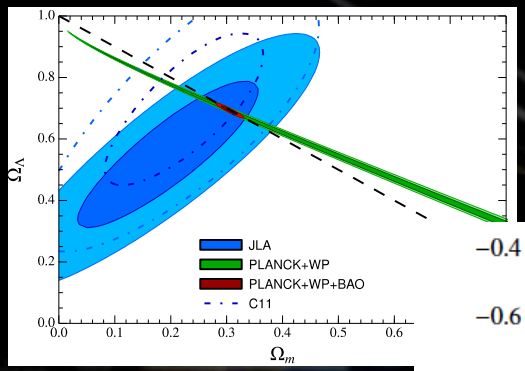
DARK ENERGY

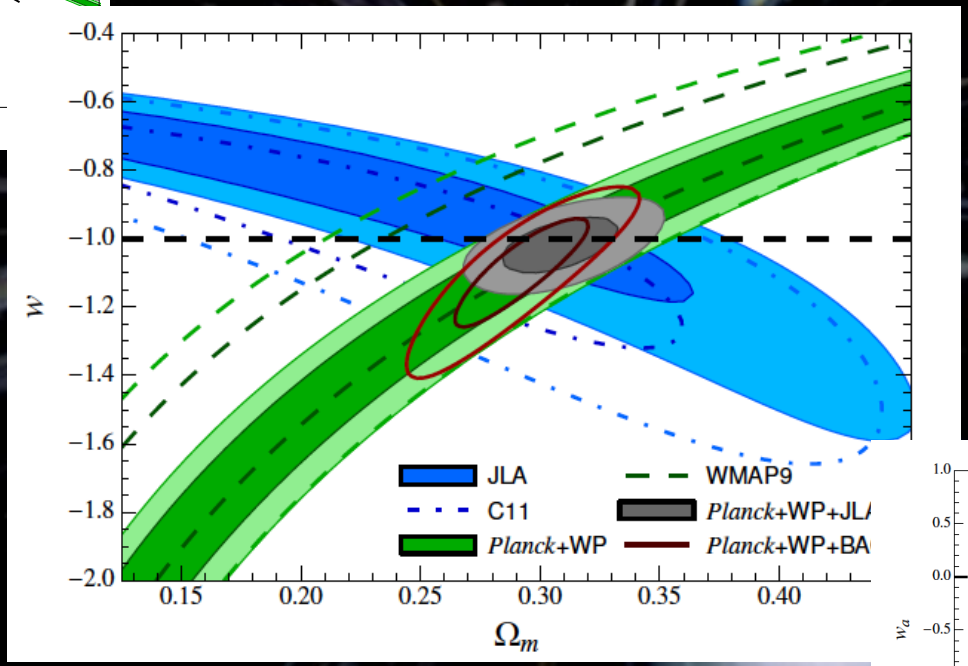
MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

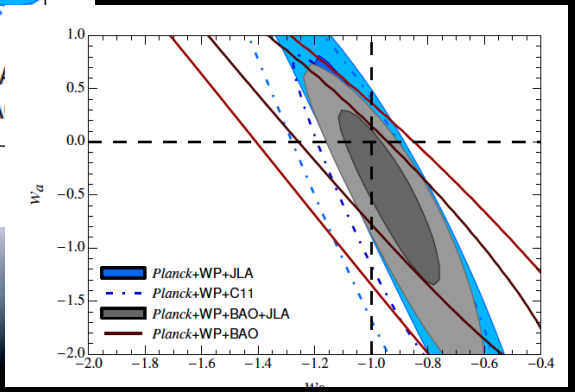
So why does the solution look so simple? Λ

Wow!

w = -1.018 ± 0.06

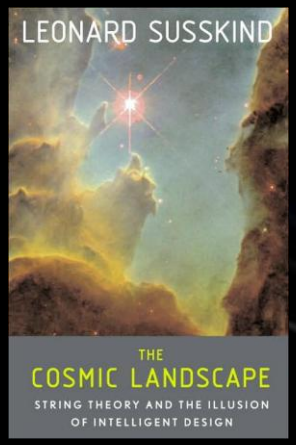






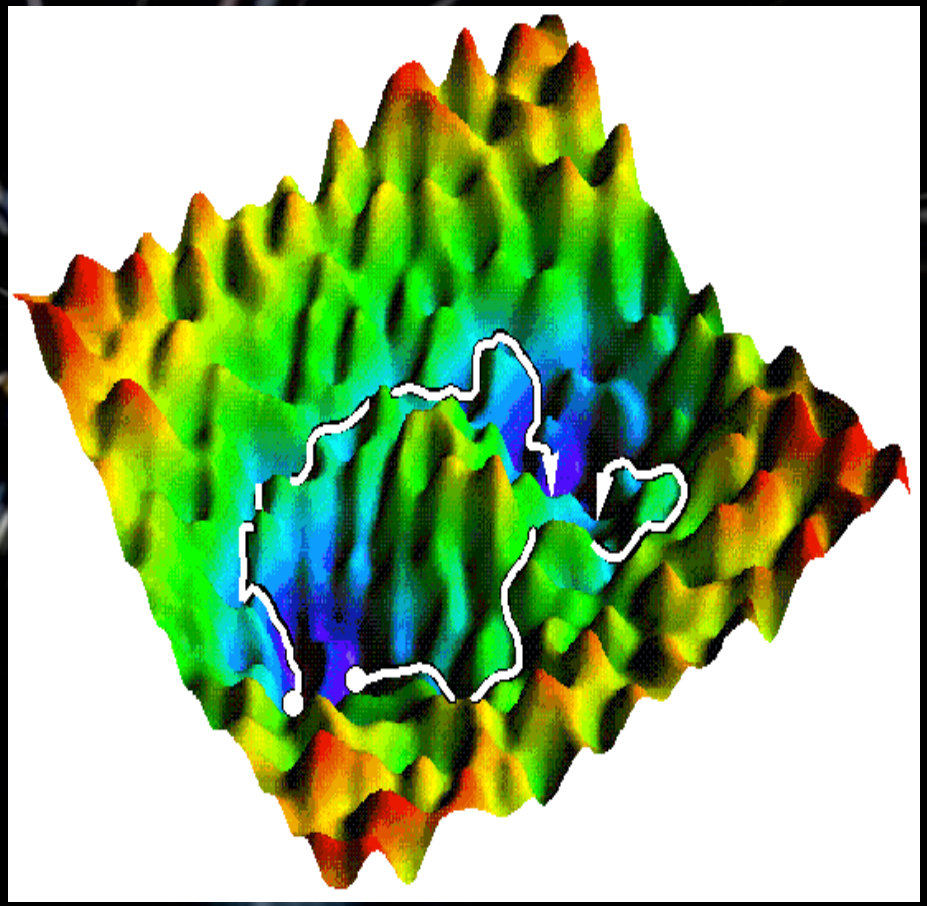
Betoule et al (1401.4064) Joint Lightcurve Analysis

H.L. Mencken: “For every complex problem, there is a solution that is simple, elegant and wrong!”

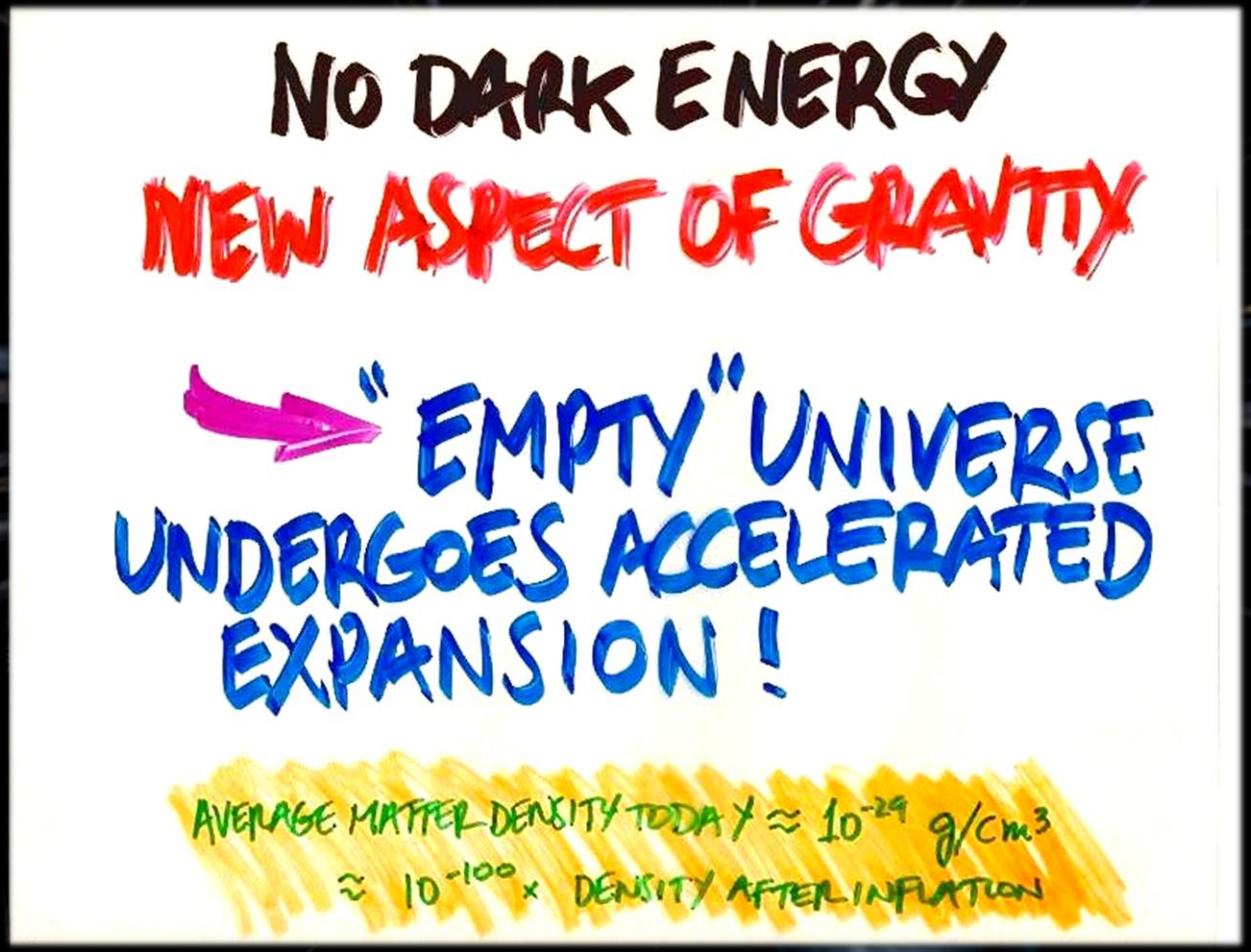


The Extravagant Solution

- 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?



New grand principle?



Two big questions

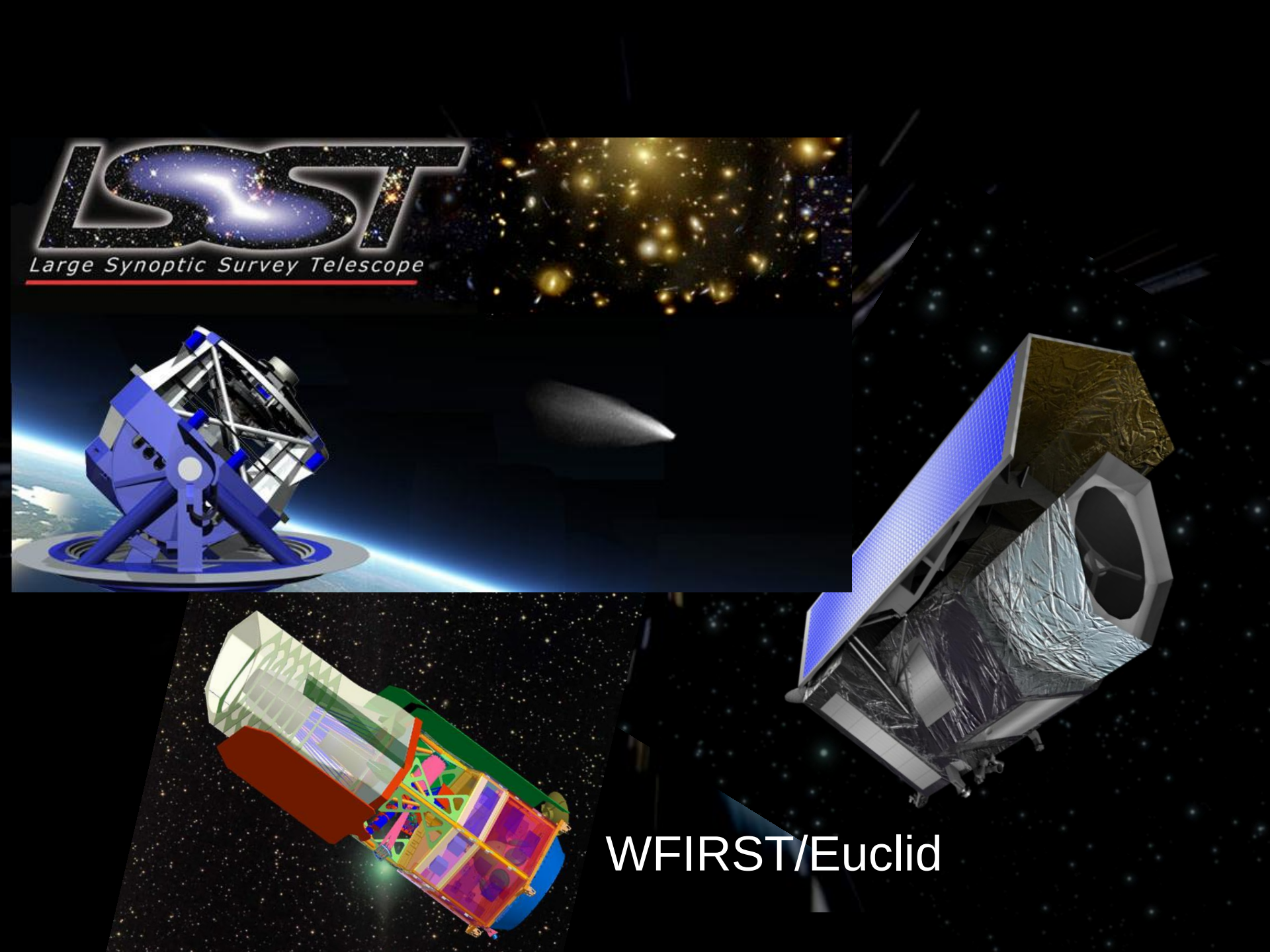
1. Does dark energy vary with time?

   w and friends

1. Does general relativity self consistently describe accelerated expansion?

   Growth of structure …

Dark Energy Survey


LSST
Large Synoptic Survey Telescope
WFIRST/Euclid

Serious testing of Inflation has *begun*

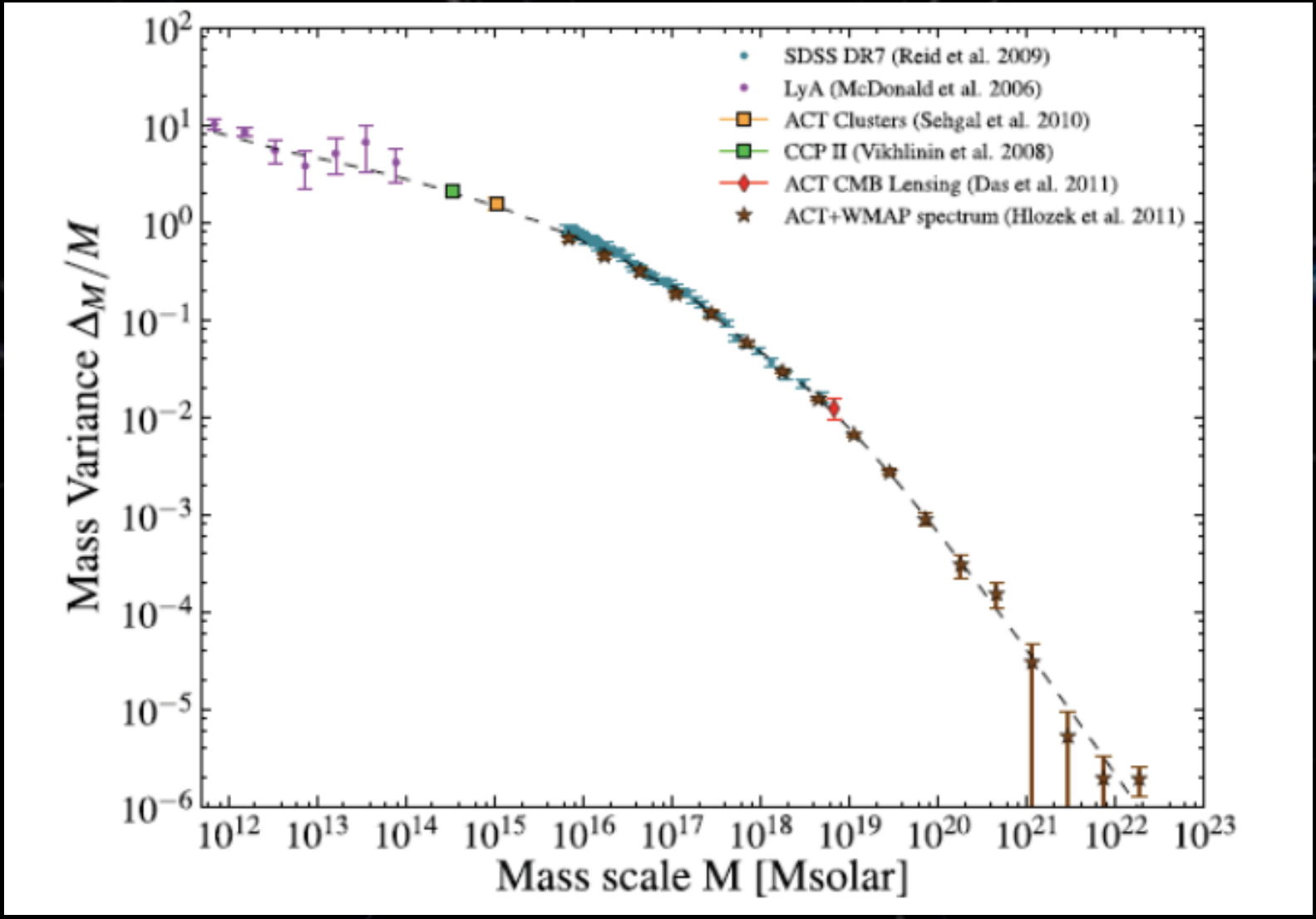
Key Predictions

- ✓ Flat Universe
- ✓ *Almost* scale-invariant, Gaussian perturbations:
  $|(n-1)| \sim 0.1$ and $|dn/d\ln k| \sim 0.001$
- Gravity waves: spectrum, but not amplitude
- ✓ Cold Dark Matter Scenario

Key Results

- $\Omega_0 = 1.00 \pm 0.006$
- $n = 0.965 \pm 0.005$; $dn/d\ln k = -0.002 \pm 0.013$; no evidence for nonGaussianity
- $r < 0.10$ (95% cl)

Success of CDM (from Spergel)



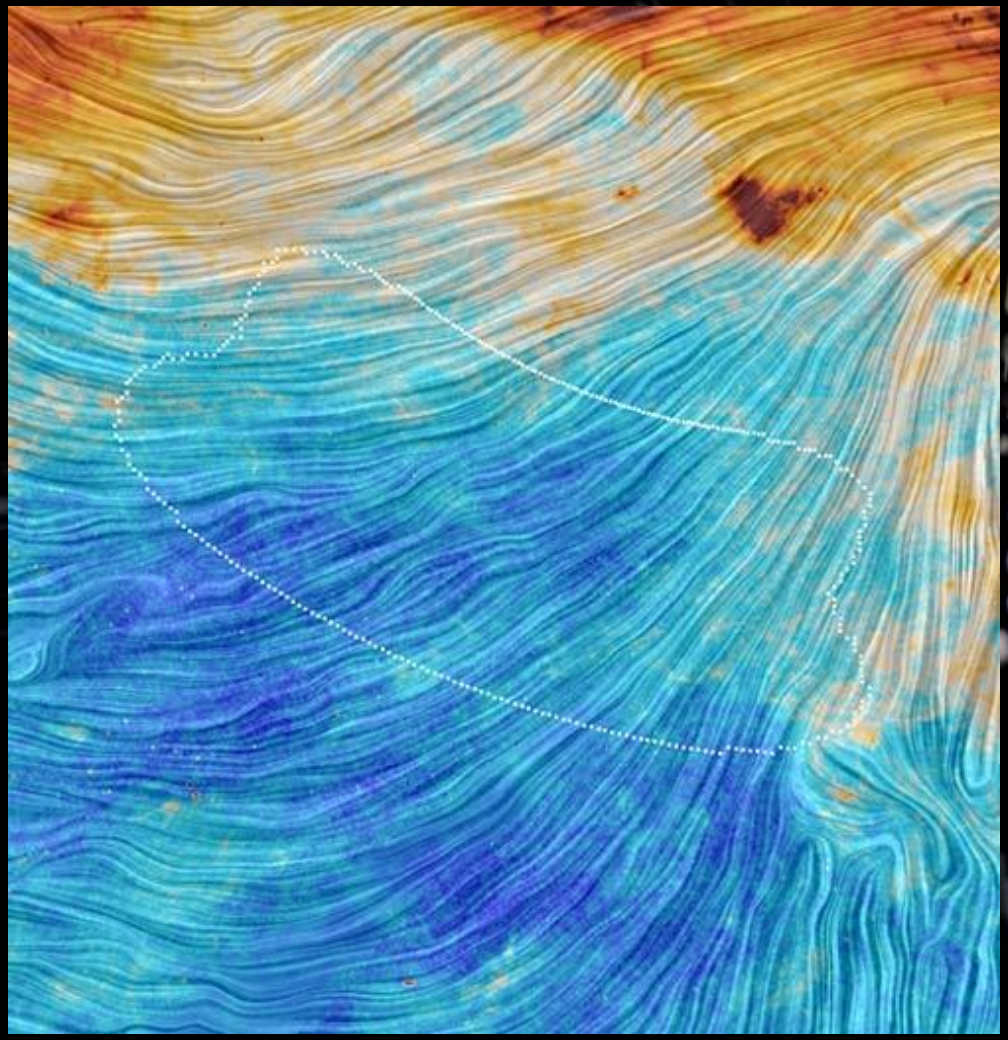

WILD
GOOSE
CHASE

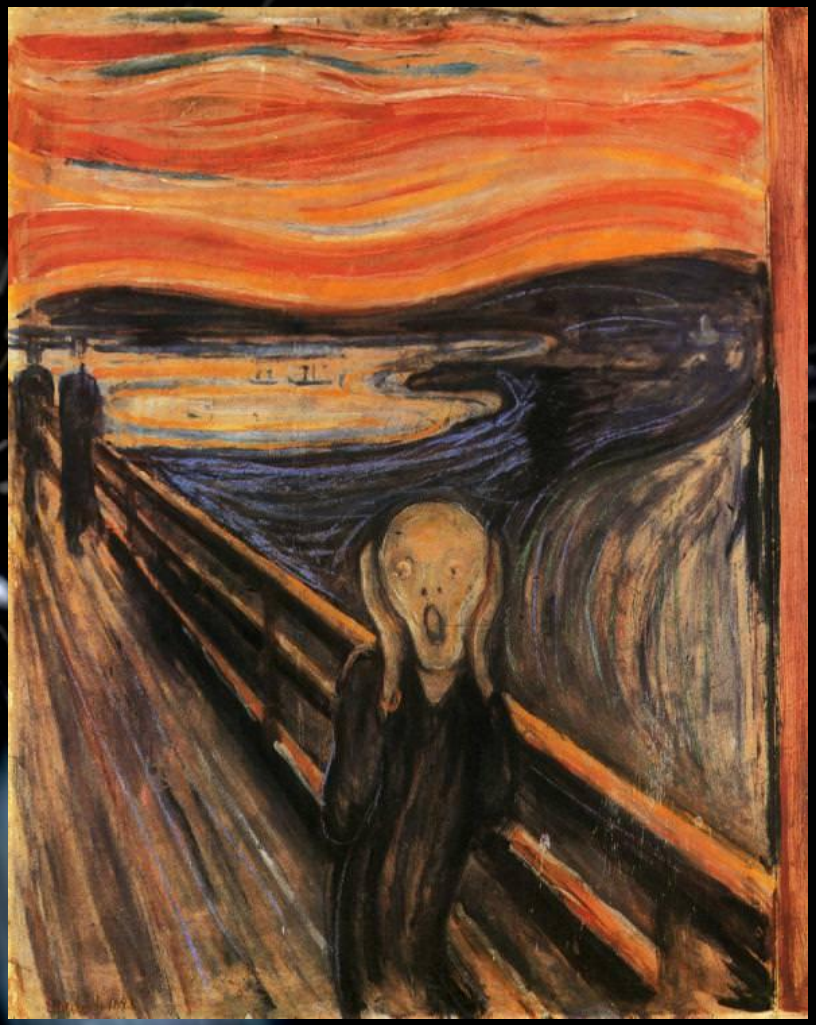
B-modes detected!
17 March 2014/BICEP2

Most exciting interpretation

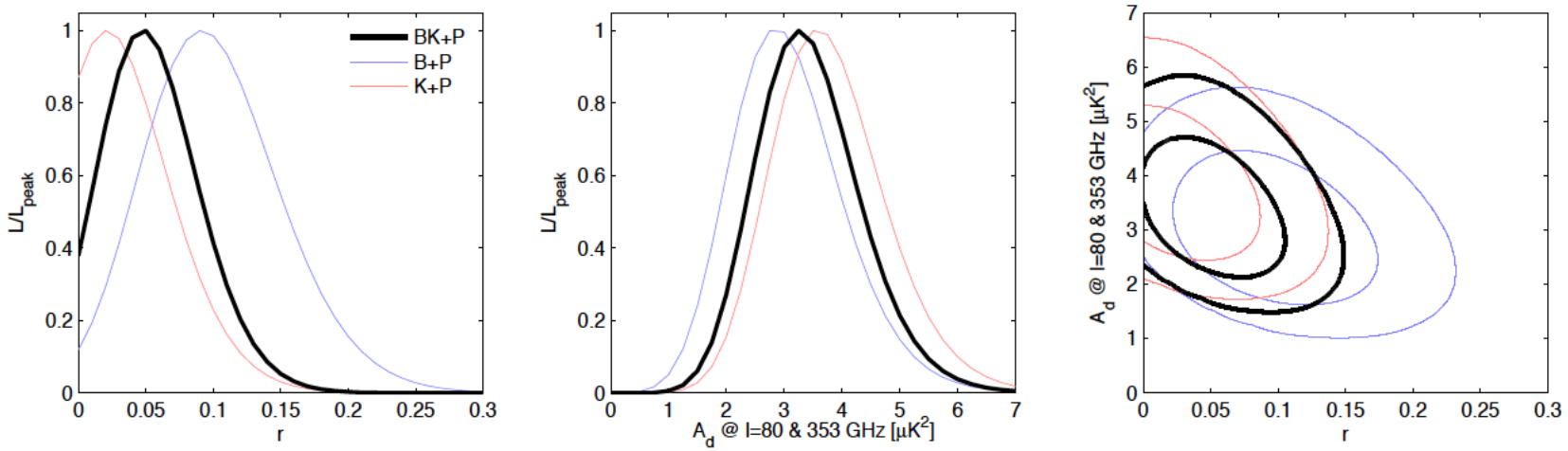
- Smokin' gun for inflation
  - r = tensors/scalars = $0.2^{+0.07}_{-0.05}$
- The when and clues about how 10^{-38} sec
  - 10^{-38} sec
  - Energy scale of 2×10^{16} GeV = 10^{12} x LHC
  - "Planck scale physics":
    - $\Delta\varphi \sim m_{pl}$
    - $V \sim (2 \times 10^{16}\ \text{GeV})^4$, $V' \sim 1.2V/m_{pl}$, $V'' \sim 0.6V/m_{pl}^2$
- Remember, "extraordinary results require extraordinary evidence" … Carl Sagan

The bane of astronomy: dust





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



arXiv: 1502.00612

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.

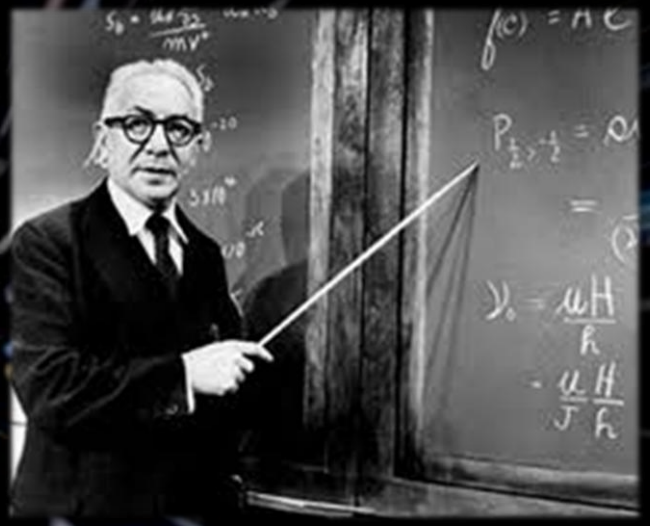
B-modes detected! Dust detected at > 3σ
Evidence for something else (GWs)

Grand challenges and big surprises

plenty to motivate the most talented

The Complicated Universe

- Atoms only: 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
- + ??: 20??



I.I. Rabi: Who ordered that?
Origin of dimensionless ratios?
More relics?

Modern Physics Letters A, Vol. 2, No. 1 (1987) 1–7

WHY SHOULD BARYONS AND EXOTIC RELIC PARTICLES HAVE COMPARABLE DENSITIES?

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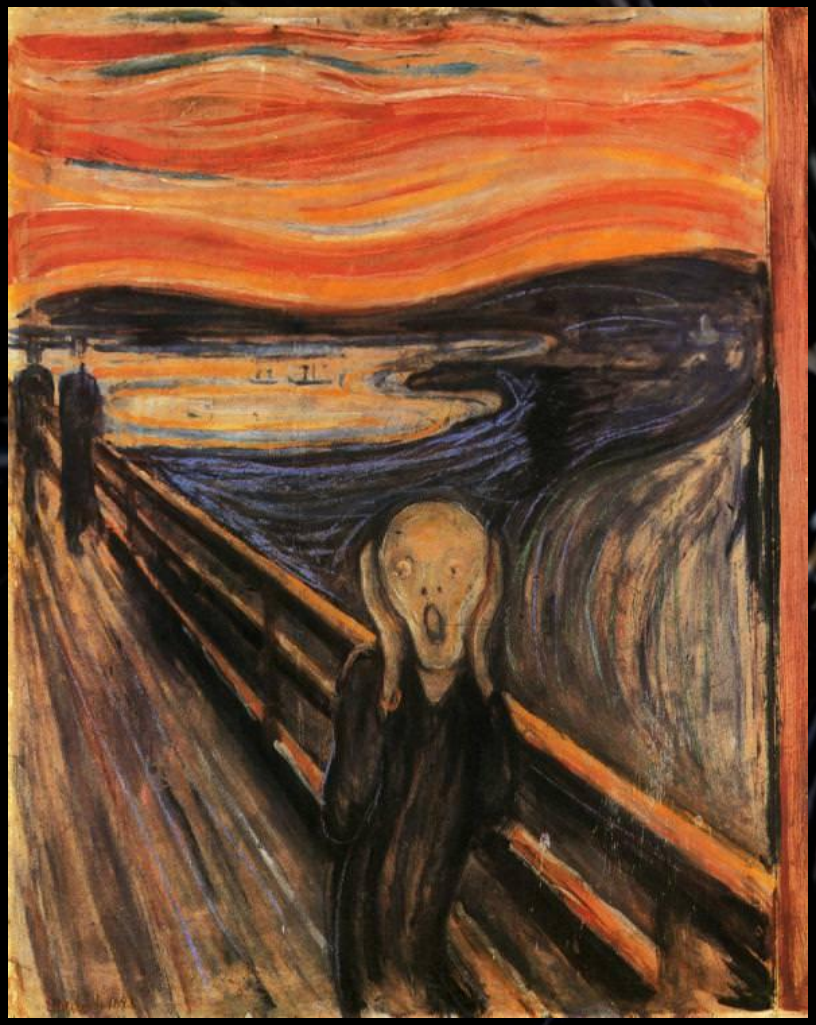
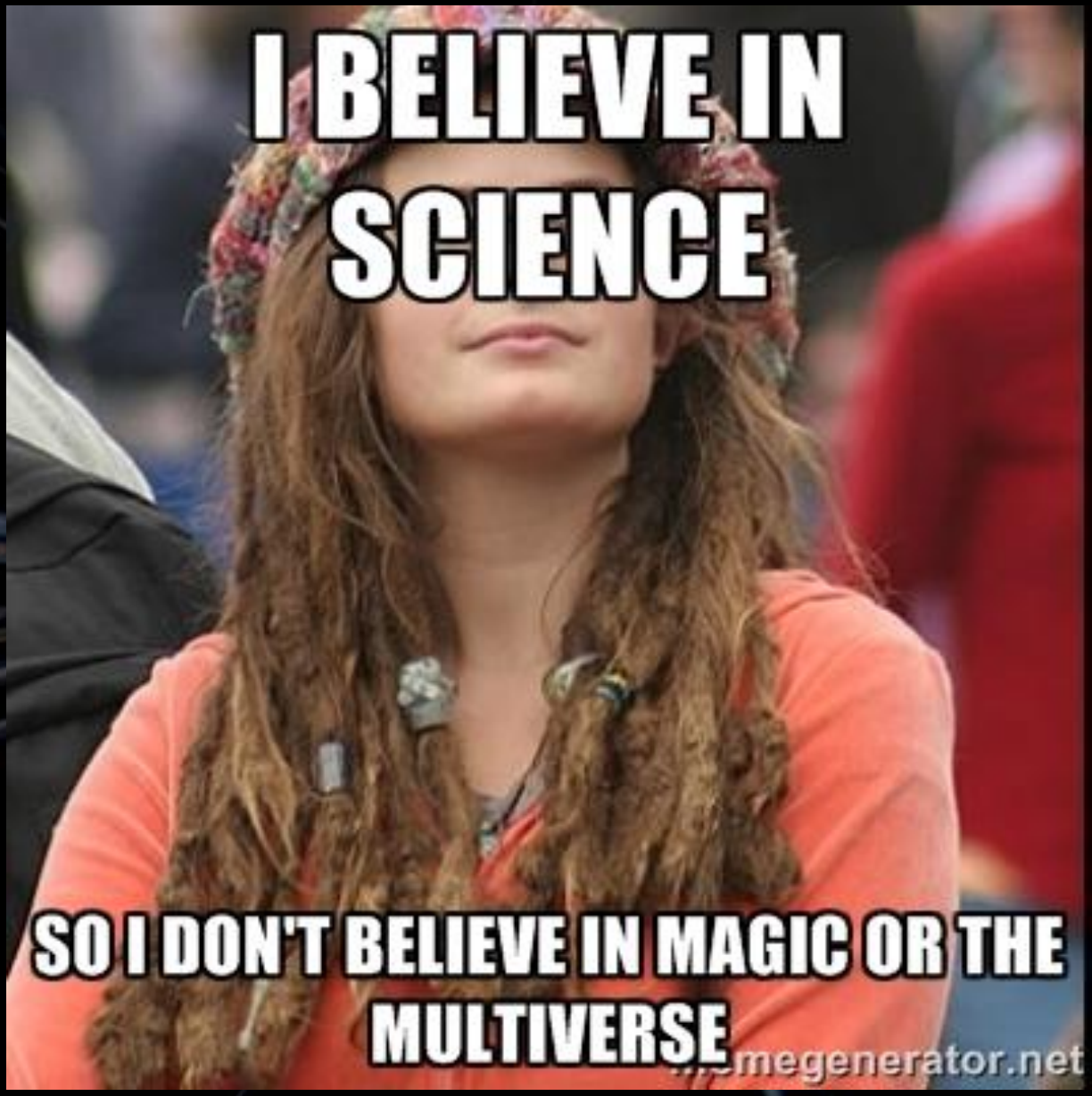
Received 23 December 1986

Observations suggest that the mass density of the Universe is dominated, not by ordinary matter, but by exotic particles which are a relic of the Big Bang. In this case, a new dimensionless cosmological ratio arises, the ratio of the mass density in ordinary matter to that in exotic matter, whose value is about 0.1. *A priori*, it might seem remarkable that this ratio should be so close to unity. However, we point out that, for many exotic dark matter candidates, the ratio is related to the fundamental scales of particle physics. A value of order unity arises naturally provided rather simple relationships exist between these scales. If the exotic particles are of a kind whose relic abundance is determined by annihilations (e.g., the photino or a heavy neutrino), then the required relationship is already satisfied for independent, cosmological reasons.

What to do about the multiverse



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


I BELIEVE IN SCIENCE
SO I DON'T BELIEVE IN MAGIC OR THE MULTIVERSE
memegenerator.net

More grand challenges

- Origin of ordinary matter (baryo/leptogenesis)
- “Completion of inflation” (Landau-Ginzburg → BCS) and/or development of a worthy competitor
- Experimental
  - 21(1 + z)cm science: next CMB?
  - More from the CMB than multipoles?
  - SUSY or something better at LHC
  - Cosmic neutrinos (never forget neutrinos!)

Game changing idea, but not time for a coronation

- No fundamental theory
- Does not address initial singularity or initial conditions
- Does not address cosmological constant problem
- Like “duct tape”, very useful but …
  - Only postpones appearance of inhomogeneity
  - not all initial conditions inflate
- Unsettling, uncertain predictions: eternal inflation; multiverse;

SPACE-TIME GEOMETRY

our initial geometry

smooth, small ripples

15 Gyr

10^{-43} sec

generic initial geometry

NOT LOGICAL INCONSISTENCY !

DILEMMA OF INITIAL DATA (WHY SO SPECIAL ?)

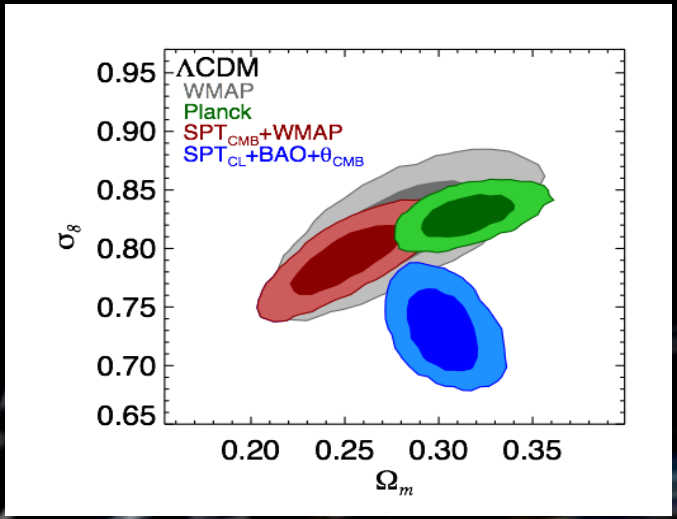
Crack in the cosmic egg?

... which we have been waiting for?!#

- CDM anomalies
  - on small scales
  - ➔ SIDM? WDM? MDM?WMD?
- CMB anomalies
  - $H_0/\sigma_8/N_v$
  - Low ell
- Time varying constants, dark flows, …

Theorem: real cracks get bigger – not smaller – with time! (2nd law)

"Planck/WMAP" H_0 trade space



Cluster abundance exponentially sensitive to σ_8

- Planck: "low" H_0, high σ_8 & $N_\nu = 3$
  (→ Planck predicts 3X clusters SPT observes)

- WMAP: "consensus H_0", "right number of clusters" & $N_\nu = 3.8$

Cosmological death spiral?

- Continued success of ΛCDM, no discovery of DM or understanding of DE
  - akin to success of SM or Ptolemy
  - continued overemphasis on the multiverse
- A personal observation
  - 1980s: lots of powerful, new ideas & little data
  - 2000s: lots of data & fewer powerful, new ideas (related to lots of data?)

I am bullish on the future!

The mysteries of cosmology and of particle physics are inextricably tied together

The combined tools and intellectual capital will push both fields forward

The best is yet to come!

Thanks to our hostess with the mostest for the meeting with the mostest! And bon voyage on your journey with Nordita