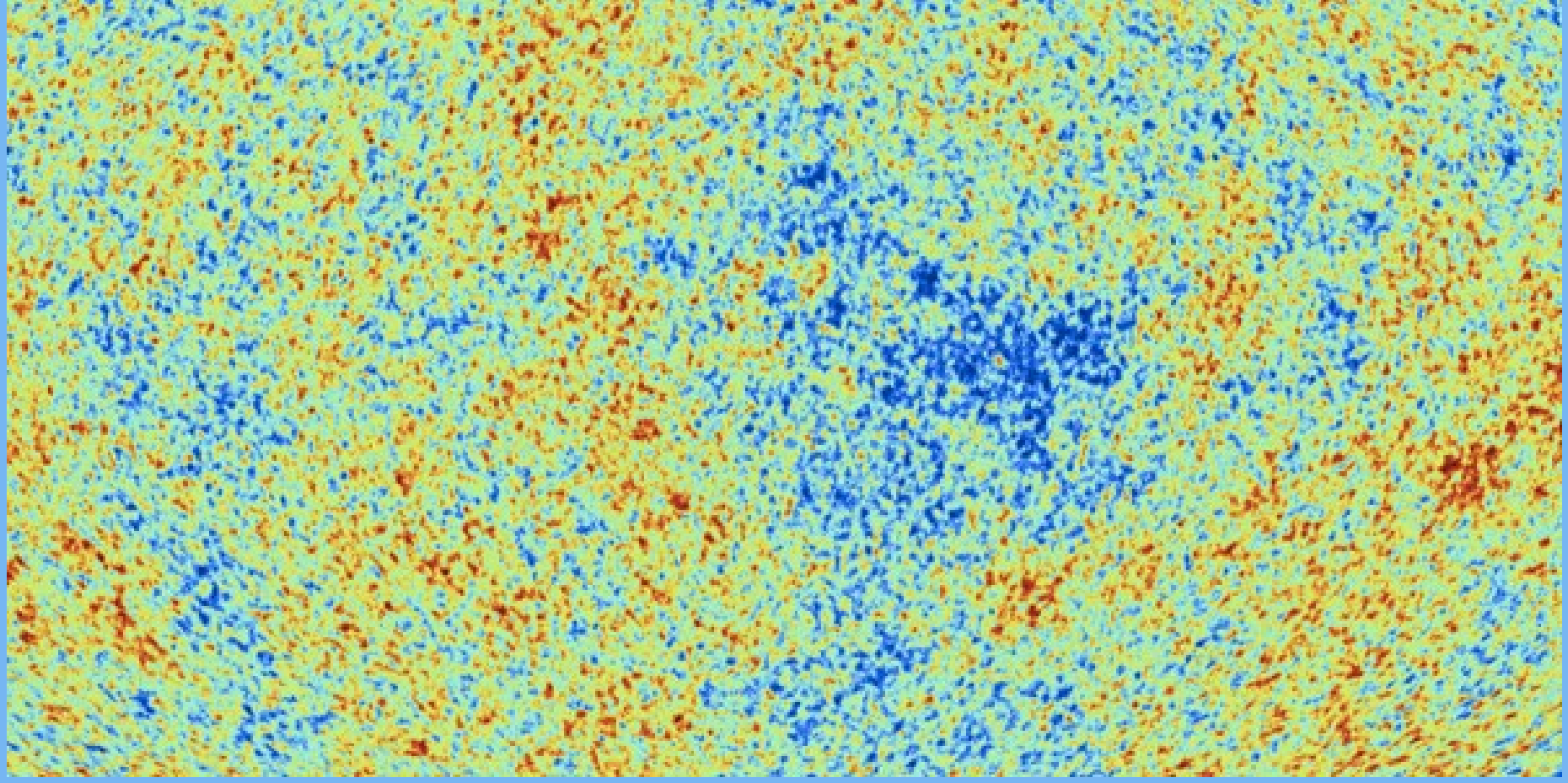


Can LCDM survive another decade?

Marc Kamionkowski
Johns Hopkins University
KICC@10, Cambridge

Can the Civil Service survive Brexit?

Follow

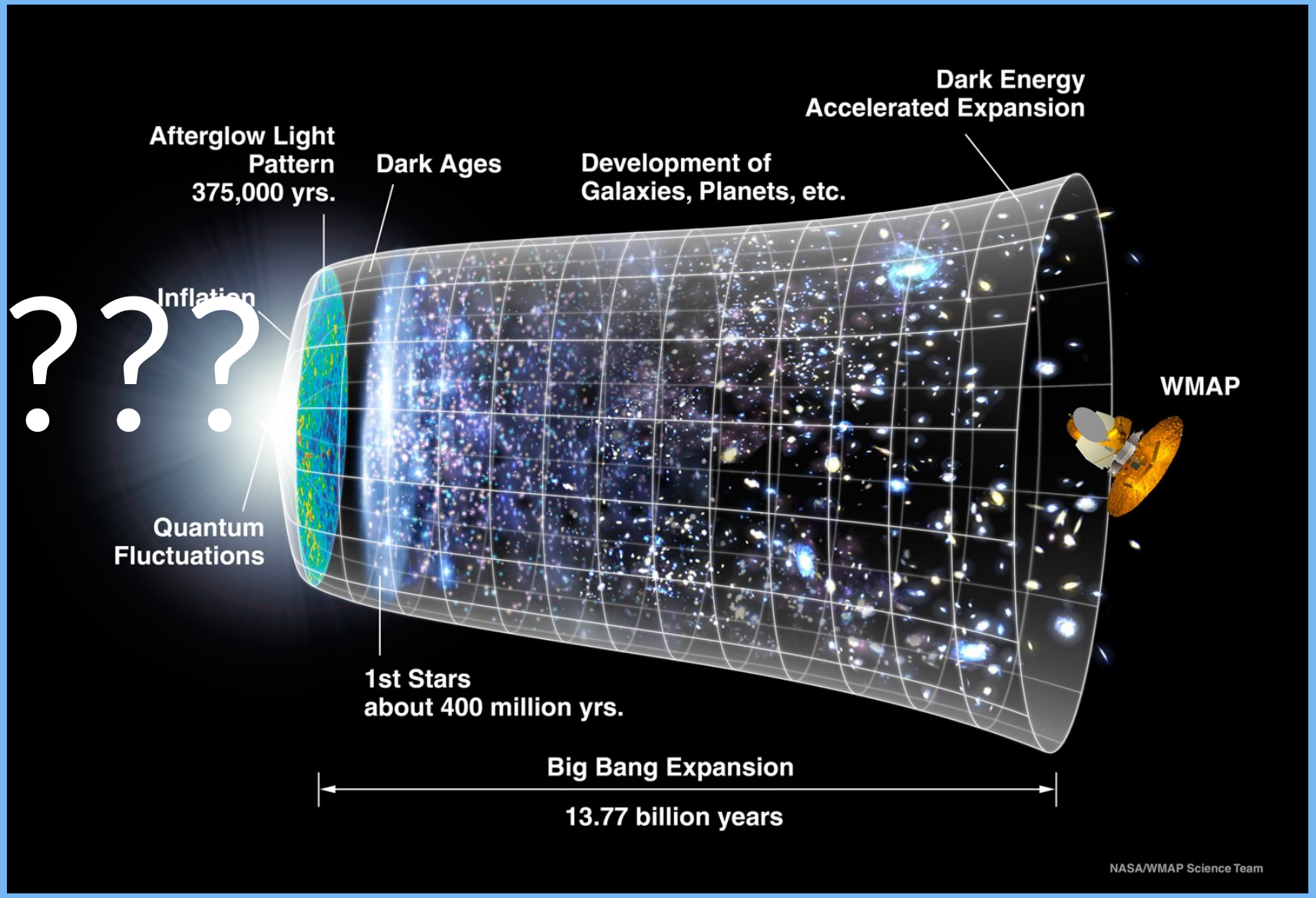
PHILIP JOHNSTON

9 JULY 2019 • 9:30PM

Can Sino-US relations survive calls for more scrutiny of Chinese investment in America?

Will the United States Survive Until 2022?

Property Rebate – Can The Standard Model Survive?


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
???
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

ΛCDM & Galaxies (AST80006)

Primordial Photon-Baryonic Fluid at Recombination Era

Early universe filled with hot dense plasma of p, e and γ. Wilkinson Microwave Anisotropy Probe Cosmic Microwave Background data shown. CMB shows the oldest light of the universe from recombination epoch when electrons combined with protons to form H atoms. Photons no longer interacted with neutral atoms, universe became transparent. Matter decoupled from radiation. Due to universe expansion, high-energy radiation was redshifted to microwave range.

z~1089 (379 kyr)

DARK AGES

Era from recombination until first stars are born

HIERARCHICAL CLUSTERING

Larger structures are formed through the continuous merging of smaller structures, due to the CDM at negligible velocity that gravitationally clumps together (Blumental, Faber, Primack, Rees 1984). Average mass of galaxies increases with decreasing redshift. Matter from IGM condenses to galaxies.

Pair-Instability SNe (PISNe)

e- and e+ pairs produced within high-T core, annihilate this reduces pressure, then core-collapse model. PISNe produce heavier elements via nucleosynthesis.

Population III Stars, Globular Clusters and Ultra-Compact Dwarf Galaxies (Drinkwater et al. 2014)

Heisenberg uncertainty principle dictates density fluctuations in primordial fluid out of which first stars and spheroidal components of galaxies are born. Fluctuations larger than the M_J (Jeans Mass) became denser as gravity wins over pressure, and smaller than M_J have smoothed out. M_J at recombination era is comparable to mass of typical GC. Thermal instability: as gas is not perfect sphere it fragments when collapsing, forming complex objects instead of BHs.

First stars have initiated reionization epoch, ionizing neutral H in IGM.

z~60–20 (50-200 Myr) (Zackrisson et al. 2015)

~1–1000 $M_\odot$, Stars

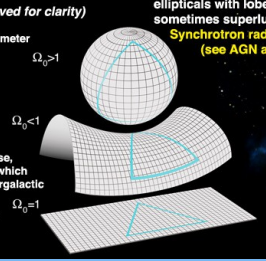
~5 x 10^5 $M_\odot$, Globular Clusters

Λ from CMB

CMB Shows Flat Universe *(Subscripts removed for clarity)*

From 1° spot size of CMB, it is concluded:

Ω0 = ρ0/ρc = 1±2%, where Ω0 is mass density parameter of the universe, ρ0 is combined average mass density (including DM), and ρc is critical density of the universe (at ρ0>ρc the universe is spherical, K>0, closed; at ρ0=ρc it is flat, K=0; at ρ0<ρc it is hyperbolic, K<0, open.)



From cluster dynamics and T of intracluster medium it was measured:

Ωm = ρm/ρc = 0.24 for all types of matter in universe, including DM. Baryonic matter is ~4–5%, ~50% of which is in stars, hot and cold gas, rest in Warm-Hot Intergalactic Medium (WHIM). While radiation energy Ωrad is negligible, Ωm alone does not explain Ω0=1. Thus, remaining ΩΛ = Ω0-Ωrad-Ωm = 0.76.

76% of energy in our universe is dark.

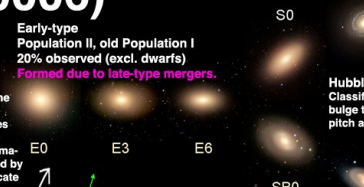
~10^8–10^{13} $M_\odot$ D~1–250 kpc

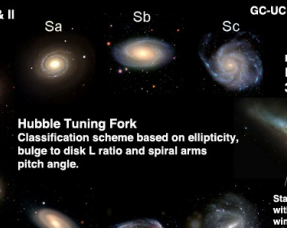
Normal Galaxies Are Active

After AGN becomes quescent the galaxy turns "normal". The understanding is that all galaxies are active but dormant and experience quasar bursts. Gamma-ray Fermi bubbles of gas inflated by jets from accreting BH jets indicate activity.

Late-type Populations I & II
77% observed

Early-type
Population II, old Population I
20% observed (excl. dwarfs)
Formed due to late-type mergers.





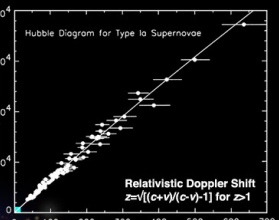
Hubble Tuning Fork
Classification scheme based on ellipticity, bulge to disk L ratio and spiral arms pitch angle.

mostly Population I
3% observed

Starburst M82 shown with superwinds - stellar winds from OB stars blowing H away.

[1] H I atoms in intergalactic medium (IGM) result in Lyman-α forest absorption.

GC-UCD-E$_{galaxy}$ Mass/Metallicity Continuum (Wehner & Harris 2007)



Expanding Universe - Hubble Law

All galaxies are red shifted and their recessional velocities are related to distances, as type Ia SNe have shown:

$v = H_0 d$, where H_0 is Hubble's constant $H_0 = v/d = 73.2$ km/s/Mpc.

Red shift z is related to distance: $z=v/c$ (for low v), $z=(\lambda-\lambda_{rest})/\lambda_{rest}$.

Reciprocal $T_0=d/H_0 d=1/H_0$~13.4 Gyr is Hubble time since BB.

Λ from SNe, H_0?

Accelerating Universe

High-z SNe teams (Schmidt; Perlmutter 1998) show that recessional velocities were lower in the past and that H_0 was lower. This means the universe expansion rate is increasing, fueled by repulsive dark energy.

Problems:

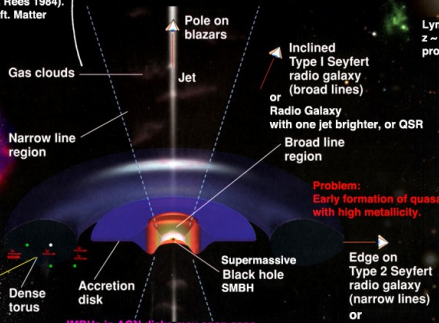
I. Varying L of type I SNe (Milne et al. 2014)

II. We can be living in underdense void explaining dim SNe.

III. Big SNe DB: evidence is only marginal (Nielsen et al. 2016)

Synchrotron Radiation

e$^-$ spiral along magnetic fields due to rotating black hole and emit polarized photons in plane perpendicular to magnetic field.



Megamasers
e$^-$ in AGN torus molecules absorb rad-n, get pumped up and emit at microwave as H_2O, H_2CO or CH masers when properly stimulated

Active Galactic Nuclei (AGN)

The first engines of AGN. BHs due to GX mergers. At z > 6 Gunn-Peterson troughs (absorption in QSR spectra due to neutral H in IGM) disappear due to reionization.

z~10 (0.5 Gyr)

z~6.4–0.1 Era of Quasars, ρ_{peak} z~2.2

The AGN Paradigm

All active galaxies can be explained by a single model with accreting supermassive black hole, depending on the line of sight to the object.

BL - Broad Emission Lines (high-*v* BLR)
NL - Narrow Emission Lines
WR - Weak Radio Emission, SR - Strong Radio Emission
X - X-Ray Emission, V - Variable
P - Polarization (Synchrotron Emission)
H - Host Galaxy is Observed

Seyfert Galaxies:

```
TYPE 1 SEYFERT: BL NL WR X V P H
TYPE 2 SEYFERT:    NL WR X    H
```

Radio Galaxies:

```
BLRG          :BL NL WR   V P H
NLRG          :BL NL SR   V P H
```

Quasars, ~10^{11}-10^{12} $L_\odot$:

```
RADIO-LOUD QSR: BL NL SR   V
RADIO-QUIET QSO:BL NL WR   V
```

Blazars:

```
BLAZAR (BL LAC):      SR   V P
OVV QUASAR:        BL NL SR   V P
```

OVV - Optically Violently Variable, more L.
Radio-loud - with radio jets/lobes.
ULIRGs (Ultra-L IR Galaxies) are probably dust-enshrouded quasars.
LINERs (Low-ionization nuclear emission line) galaxies are similar to low-LType 2 Seyferts with starburst phenomena or H II emission.
Approx 1/2 of all spiral galaxies are LINERs.

High-L nuclei Seyfert

Radio galaxies are ellipticals with lobes/jets sometimes superluminal
Synchrotron radiation (see AGN above)

Lyman Alpha Blob LAB-1
z ~ 3.1 gas blob in SSA-22 protocluster of galaxies

Cold Dark Matter Features

I. Cold (non-relativistic velocities << c), Hot wouldn't clump gravitationally due to velocity.
II. Non-baryonic (not p or n)
III. Dissipationless (cannot cool by radiating photons)
IV. Collisionless (DM interacts only through gravity and, possibly, weak force; does not feel force of fluid resistance unlike X-ray gas - see Bullet cluster after collision.)

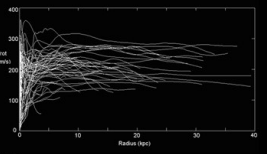
Earth
Solar system and Earth formed at ~9 Gyr

X-Ray Emission
Hot Intracluster Medium (or Intergalactic Medium - IGM) gas ejected due to galactic mergers

z~2 (3.3 Gyr)
~10^{14}–10^{15} $M_\odot$, D~2–10 Mpc

Galaxy Clusters

Rich galaxy clusters have 50–1000 galaxies. Galaxy groups have less than 50 galaxies. (Bullet Cluster shown, blue - mass distribution, red - X-ray gas.)



Superclusters, Walls and Voids

Gravitationally bound but still not in equilibrium. Laniakea shown. Definition is still debated.

z~1 (6 Gyr)
~10^{15}–10^{17} $M_\odot$, D~10-100 Mpc

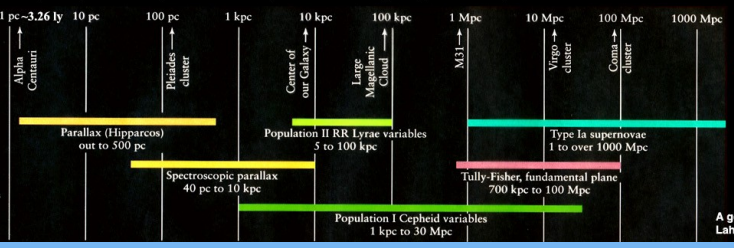
Cold Dark Matter

Dark Matter Evidence

I. Flat rotation curves indicate extended halos of DM in galaxies.
II. Gravitational lensing allows to reconstruct mass of the lensing galaxy, indicating large amounts of DM.
III. High M/L ratios of galaxies indicate DM (with dynamical M derived from stellar dynamics using Newton's form of Kepler's 3rd Law or virial theorem - relationship between kinetic and gravitational potential energy (Zwicky 1937), and L from apparent magnitude and distance).
IV. Large-scale clustering of galaxies.

Distance Ladder

Variety of inter-calibrated techniques to estimate distances. Tully-Fisher relates 21 cm H emission line width to L of a spiral galaxy. Type Ia SNe have $M_v \approx -19.3\pm0.03$ at peak. Core collapse SNe L can be determined from ejecta velocities and T with 15-25% accuracy. P/L relations exist for variable stars. Spectroscopic parallax uses width of spectrum lines to estimate star's luminosity class; fitting to H-R diagram allows to estimate L and d. Ladder-independent techniques: Maser rotation, time delay in gravitational lensing due to path length difference. (Carroll & Ostlie 2008, Freedman et al. 2014). RR Lyr have same M_v=0.69.



Λ, other evidence

Why Dark Energy?

I. Distribution of galaxy clusters (knots turning into galaxy clusters) are modelled better with Λ (Kofman, Starobinskii) or standard CDM inflation model (Maddox et al. 1990).

II. Nucleosynthesis constraint and standard CDM inflationary model (Ω_m=1) predict less baryonic mass in galaxy clusters than observed (White at al. 1993)

III. Galaxy clusters mass increases with time (as z approaches 0) faster than due to the gravitational clumping alone.

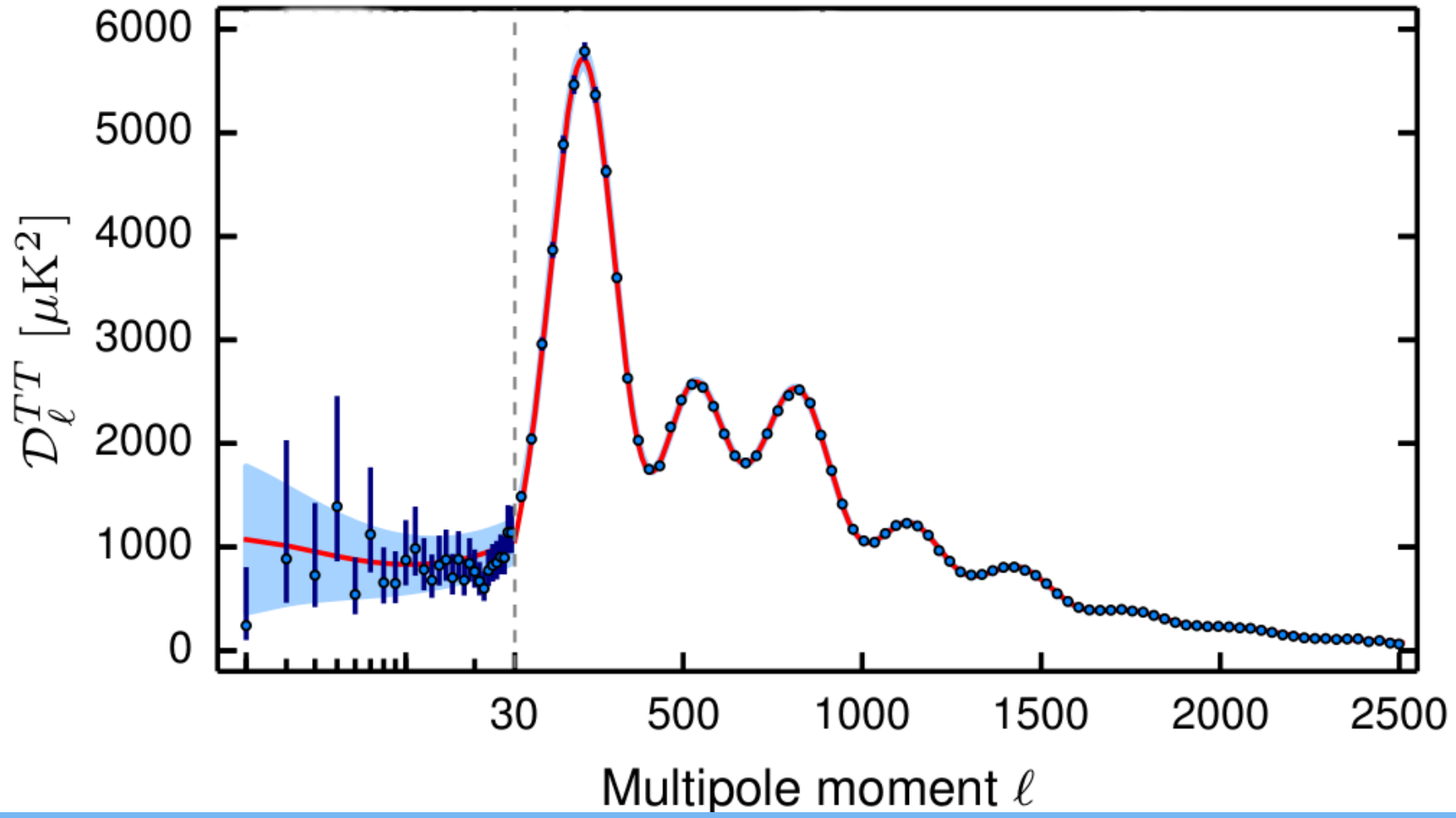
Possible explanations:

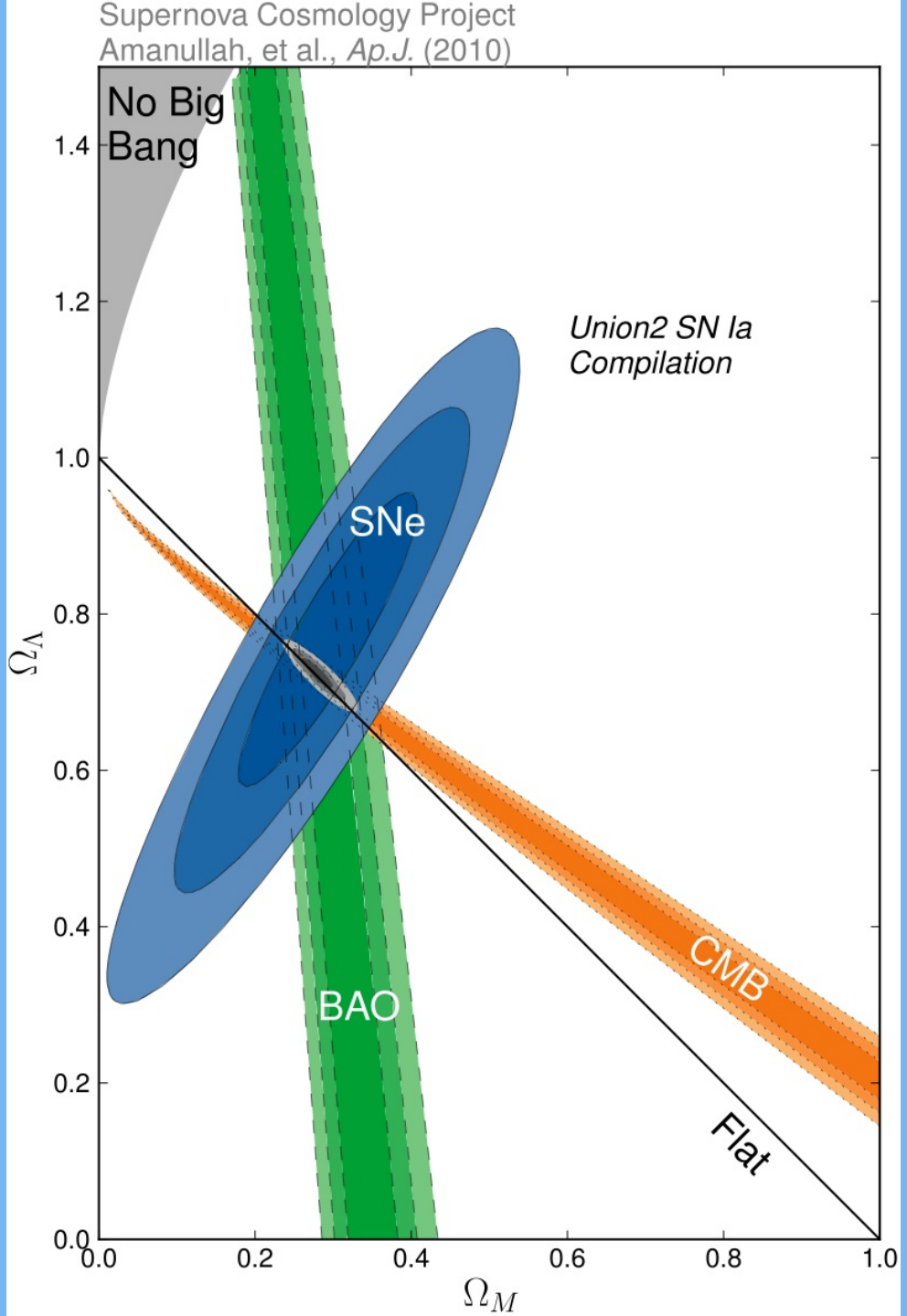
Dark energy is the energy of empty space (vacuum energy) from virtual pairs of particles/antiparticles (e/e$^+$) appearing and annihilating spontaneously and providing repulsive force (e.g. Casimir effect).

Problems:

Vacuum energy is orders of magnitudes larger than observations permit.

A good overview of ΛCDM is available from Calder & Lahav (2010), "Dark energy: how the paradigm shifted"


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
30
500
1000
1500
2000
2500
Multipole moment ℓ


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

6 parameters: amazing!

- Dark-matter density
- Baryon density
- vacuum-energy density
- Fluctuation amplitude
- Fluctuation spectral index
- Reionization optical depth

Can LCDM survive another decade?

Cosmic…..

Controversy?

Tension?

Anomaly?

Stress?

Discrepancy?

Disparity?

Inconsistency?

Problem?

Crisis?

Dwarf galaxies?

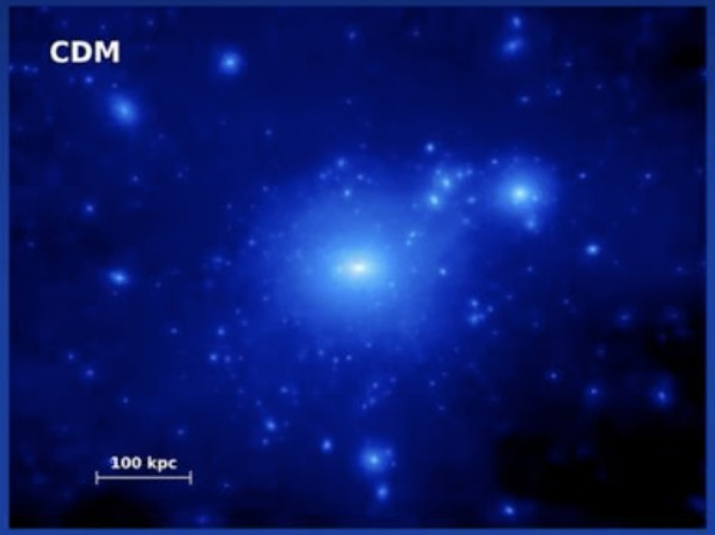
Study plunges standard Theory of Cosmology into Crisis

New insights into Milky Way satellite galaxies raise awkward questions for cosmologists

Missing satellite problem?

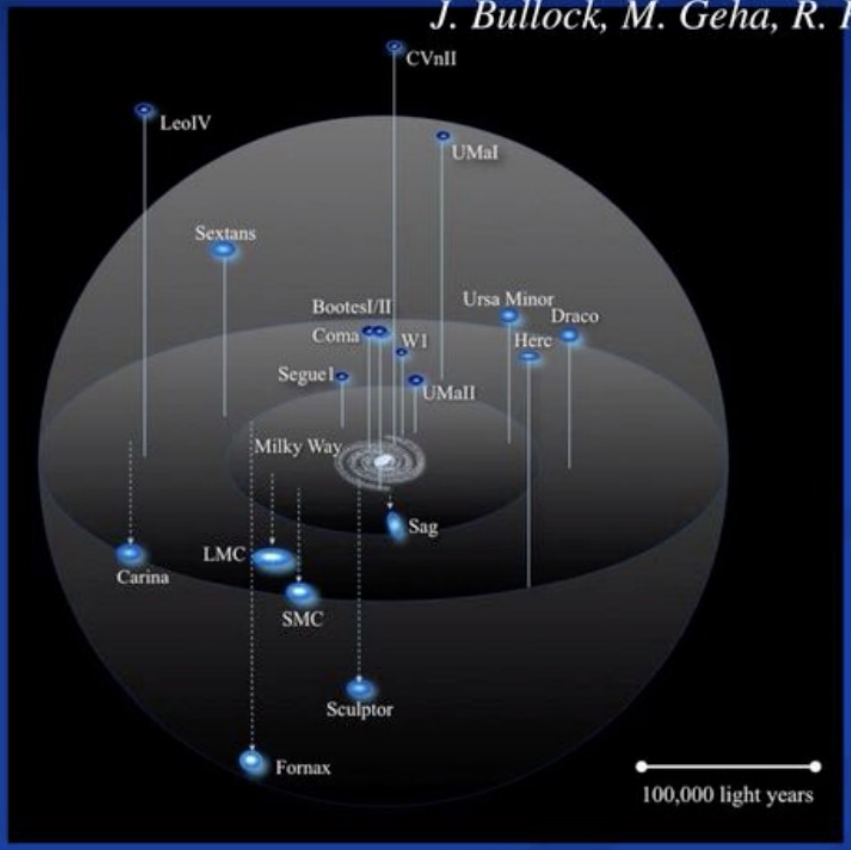
Too big to fail problem?

Missing satellite problem



Durham University

J. Bullock, M. Geha, R. Powell



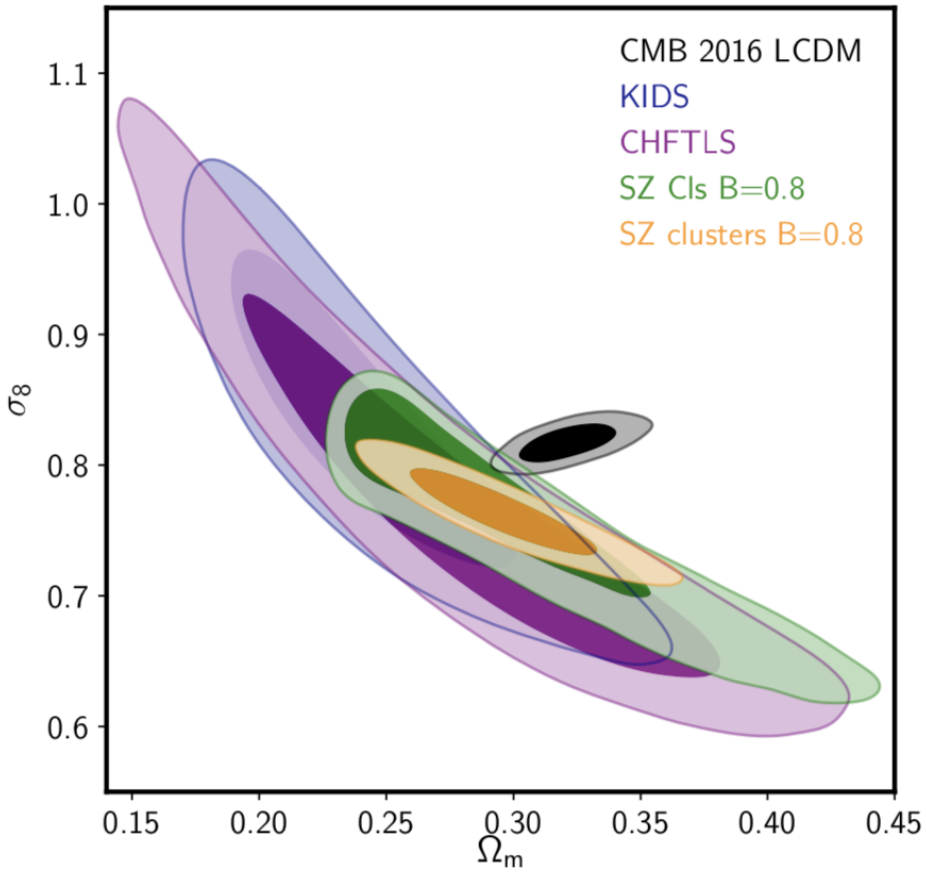
- Dwarf satellites of Milky way are ideal for DM research

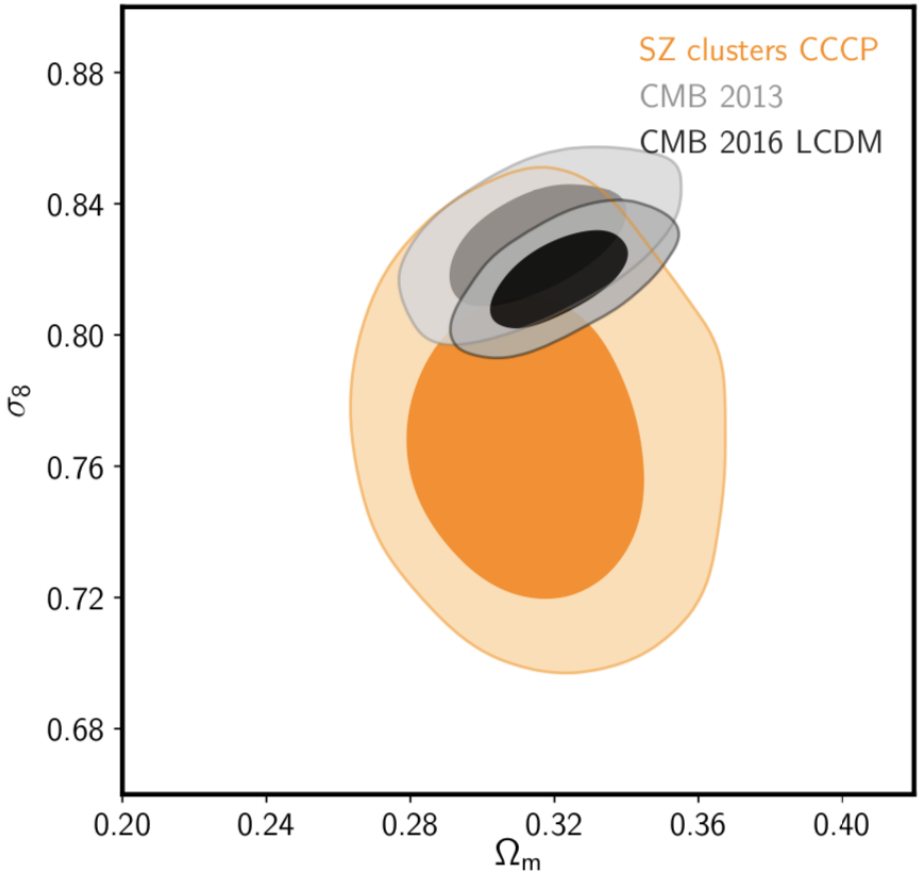
σ_8 Problem

On the tension between Large Scale Structures and Cosmic Microwave Background

Marian Douspis, Laura Salvati, Nabila Aghanim

Primordial fluctuation amplitudes inferred from CMB and from the galaxy distribution disagree??


CMB 2016 LCDM
KIDS
CHFTLS
SZ Cls B=0.8
SZ clusters B=0.8
1.1
1.0
0.9
0.8
0.7
0.6
σ_8
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Ω_m


SZ clusters CCCP
CMB 2013
CMB 2016 LCDM
0.88
0.84
0.80
0.76
0.72
0.68
σ_8
0.20
0.24
0.28
0.32
0.36
0.40
Ω_m

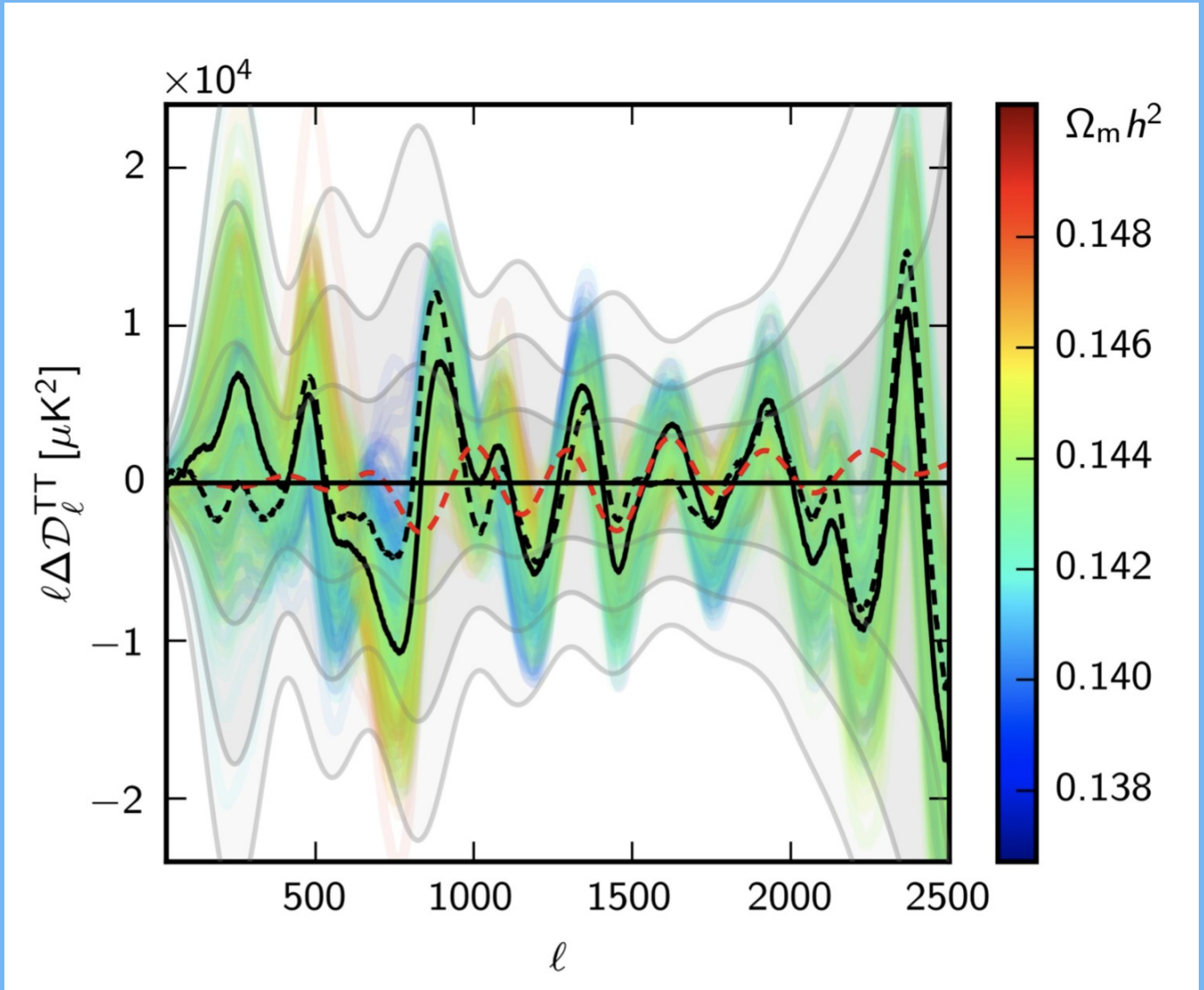
CMB Anomalies after Planck

Dominik J. Schwarz, Craig J. Copi, Dragan Huterer, Glenn D. Starkman

(Submitted on 27 Oct 2015)

Several unexpected features have been observed in the microwave sky at large angular scales, both by WMAP an by Planck. Among those features is a lack of both variance and correlation on the largest angular scales, alignment of the lowest multipole moments with one another and with the motion and geometry of the Solar System, a hemispherical power asymmetry or dipolar power modulation, a preference for odd parity modes and an unexpectedly large cold spot in the Southern hemisphere. The individual p-values of the significance of these features are in the per mille to per cent level, when compared to the expectations of the best-fit inflationary ΛCDM model. Some pairs of those features are demonstrably uncorrelated, increasing their combined statistical significance and indicating a significant detection of CMB features at angular scales larger than a few degrees on top of the standard model. Despite numerous detailed investigations, we still lack a clear understanding of these large-scale features, which seem to imply a violation of statistical isotropy and scale invariance of inflationary perturbations. In this contribution we present a critical analysis of our current understanding and discuss several ideas of how to make further progress.

Lensing anomaly?
More smoothing of peaks than expected?



APS NEWS

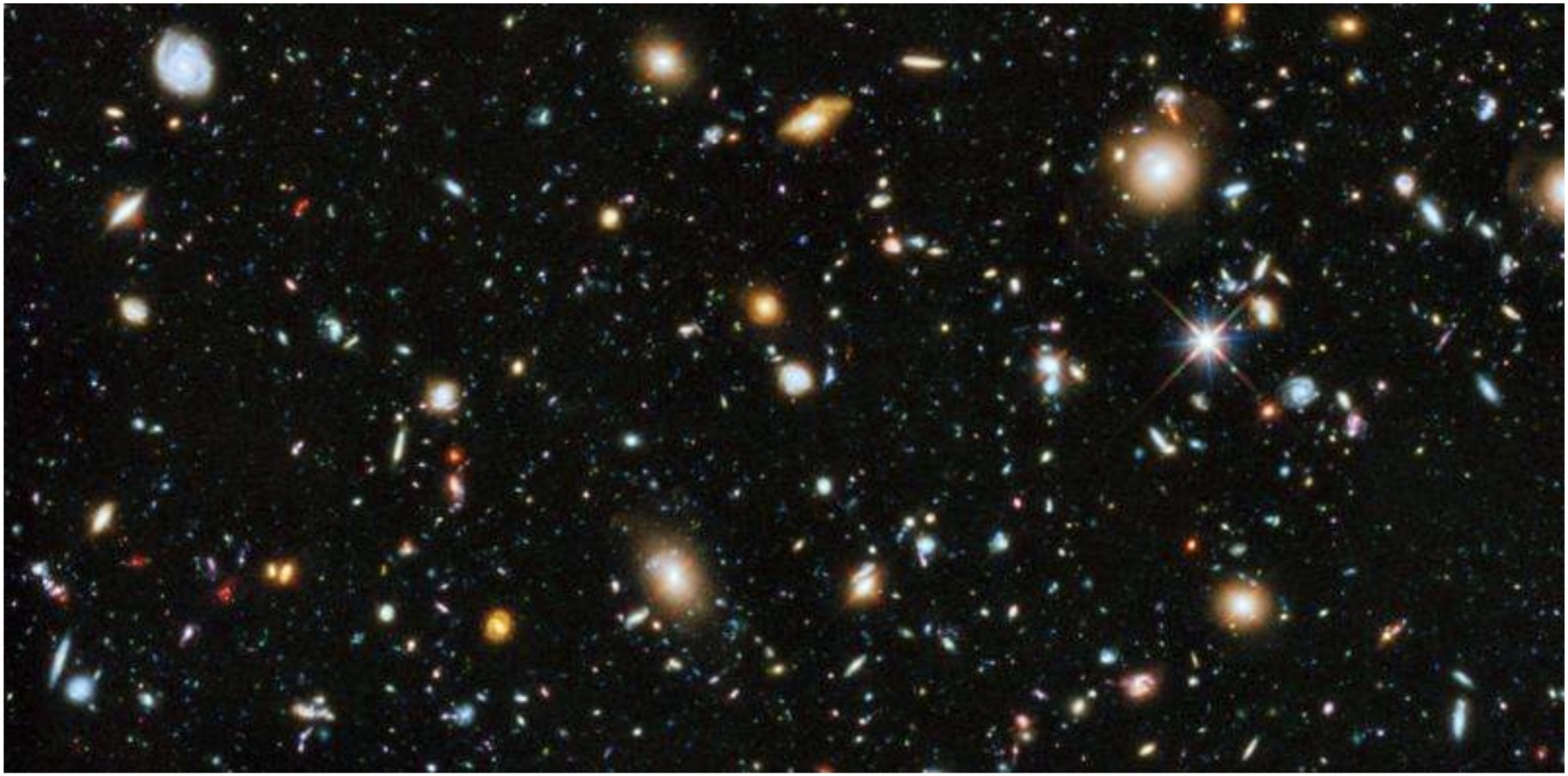
APS News

May 2018 (Volume 27, Number 5)

Hubble Trouble: A Crisis in Cosmology?

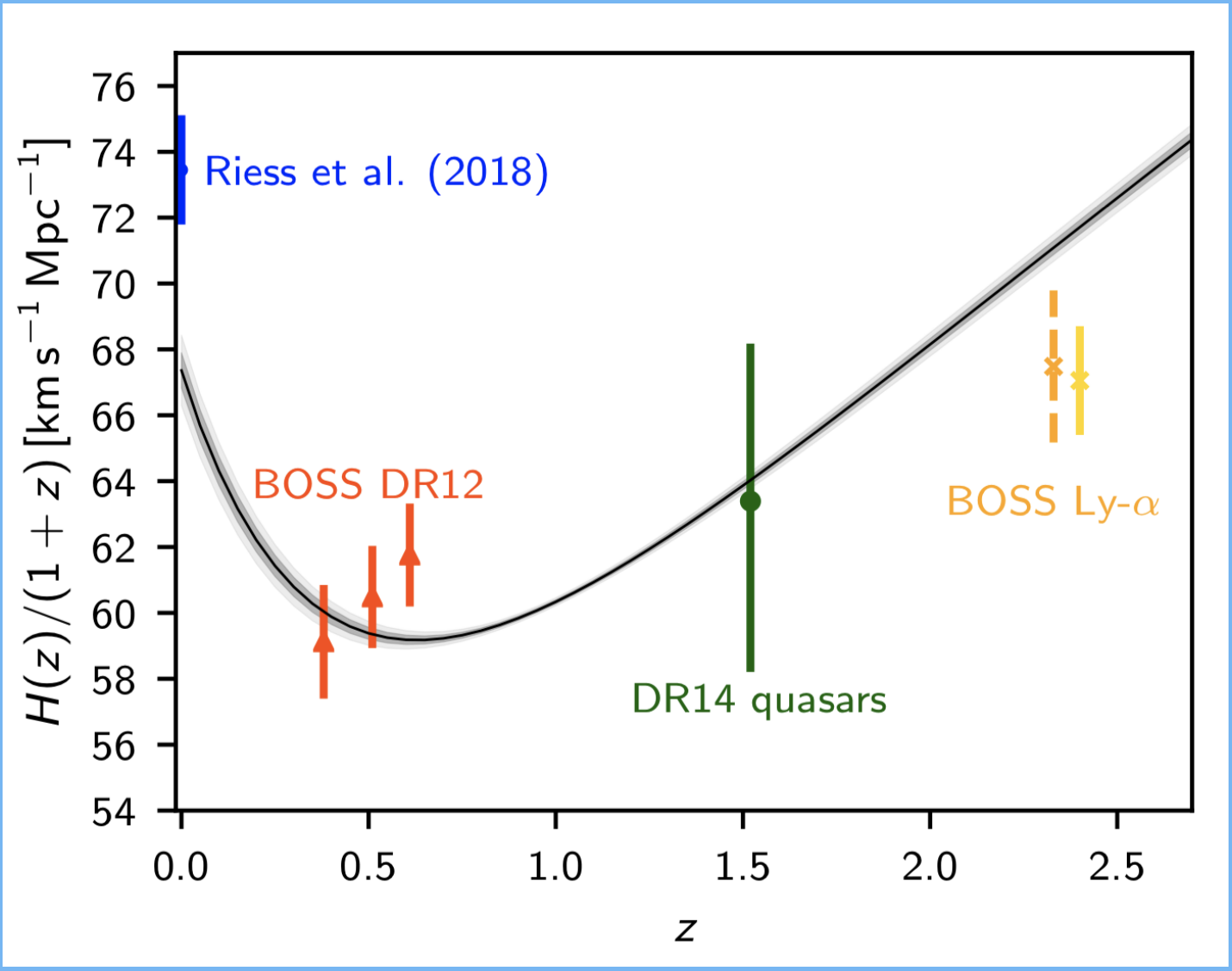
Cosmology is in crisis – but not for the reason you may think

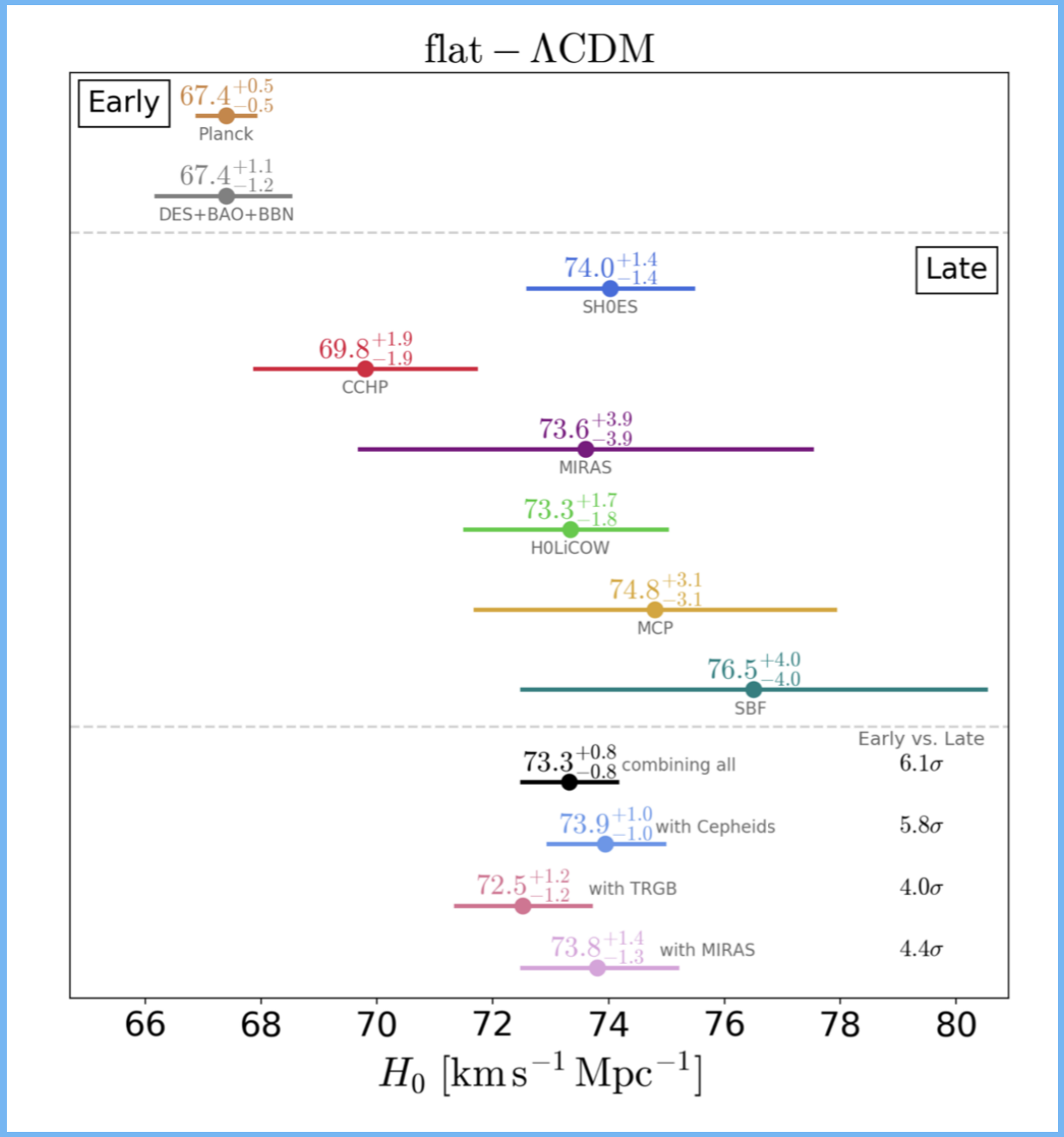
by Thomas Kitching, Ucl, The Conversation



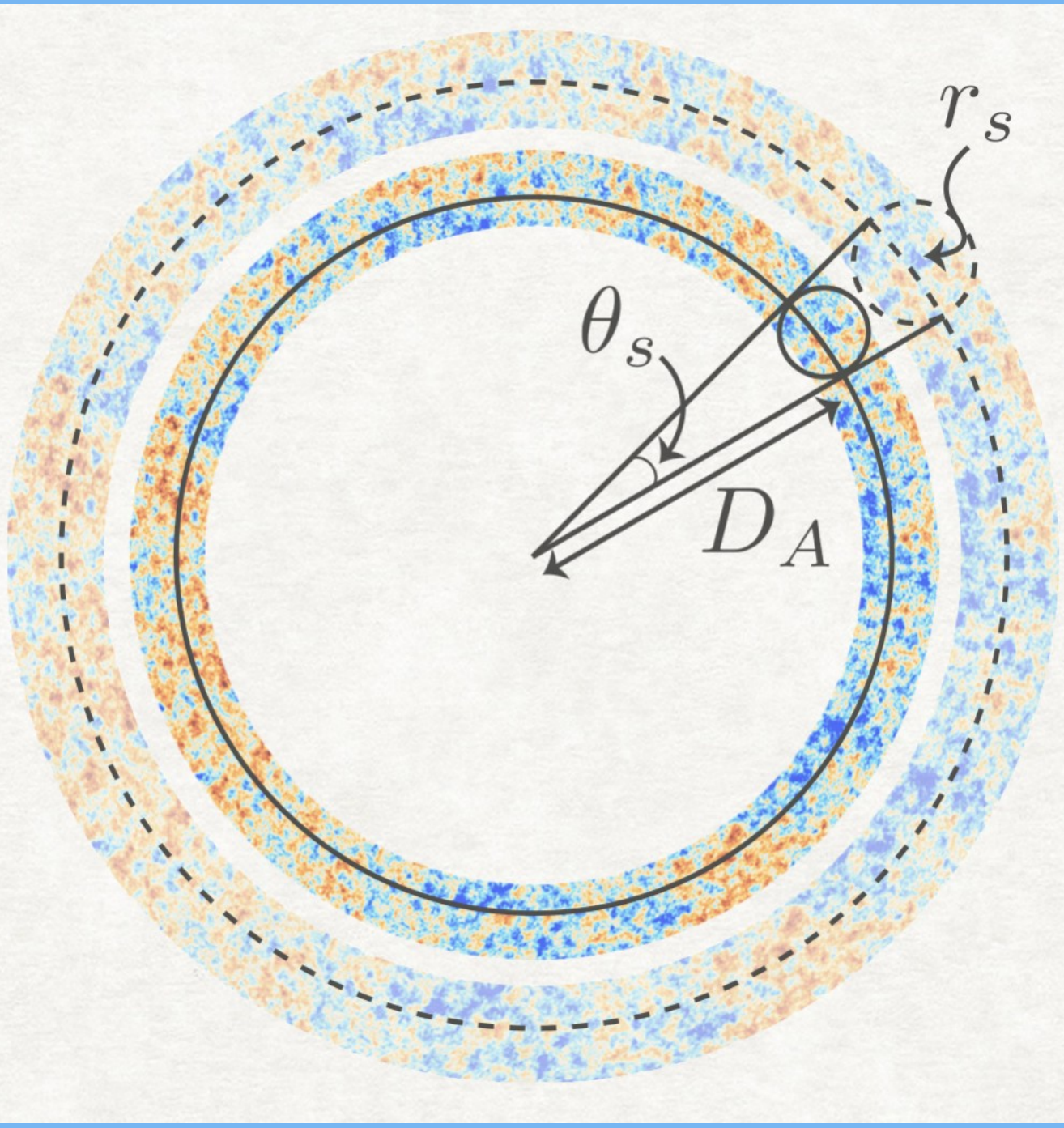
Our tendency to see what we want to see is the biggest threat to cosmology. Credit: NASA/wikimedia

Hubble tension





Verde, Treu, & Riess 2019


r_s
θ_s
D_A

Late-time solutions

- Modify late-time expansion history to reduce comoving distance to surface of last scatter
- E.g., phantom energy ($w<-1$)
- Induce inconsistency with BAO

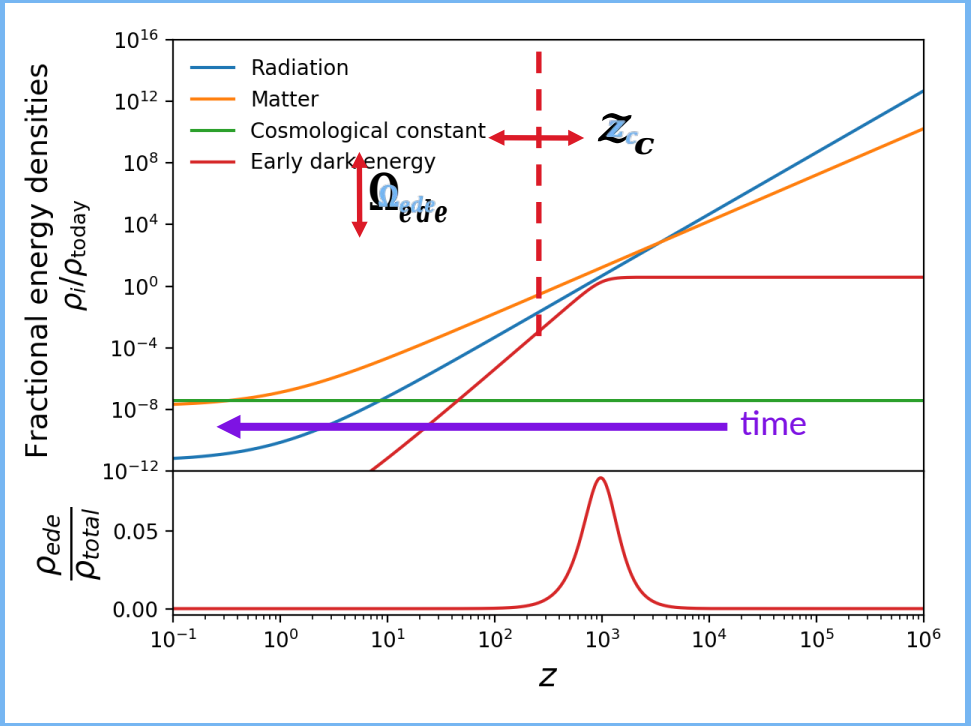
Early-time solution

- Reduce sound horizon
- Does not mess with BAO
- E.g., increase N_{eff} (but induces tension with small-scale CMB)

Early Dark Energy

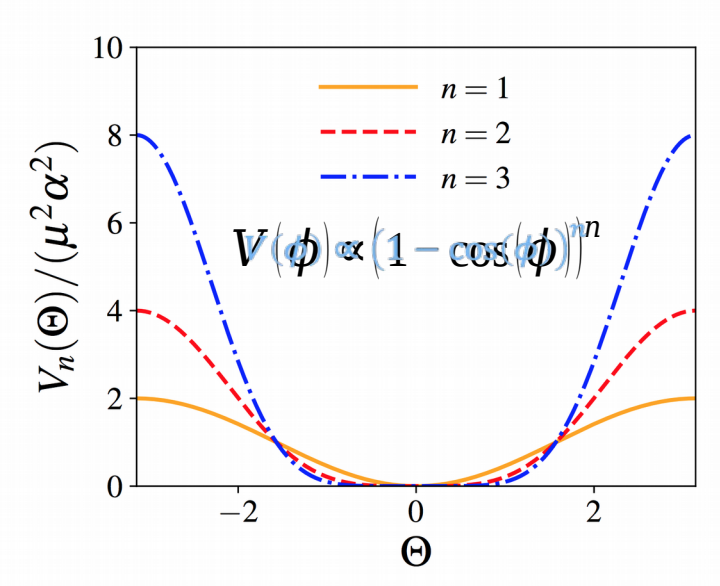
(Karwal,MK 2016; Poulin, Smith, Karwal, MK 2018; Agrawal et al. 2019; Lin et al. 2019)

Behaves like cosmological constant before recombination and then redshifts away faster than radiation



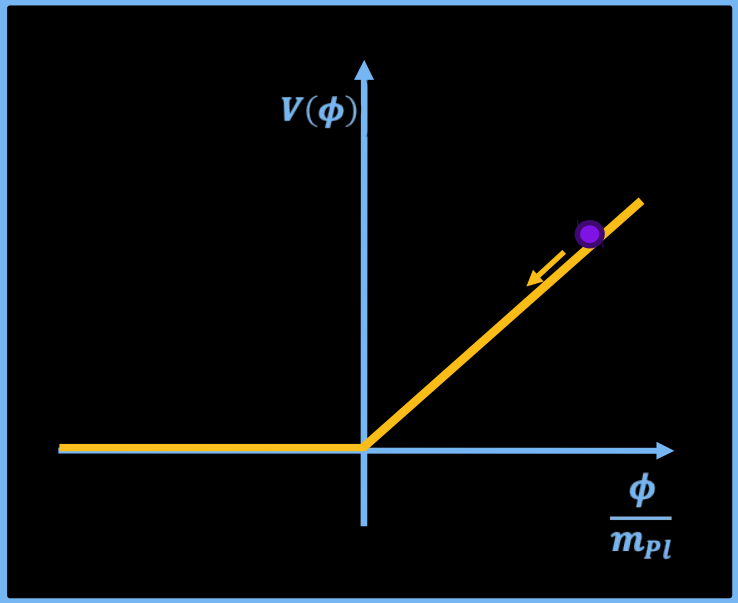
Scalar field EDE

Ultra-light axion (ULA) potential



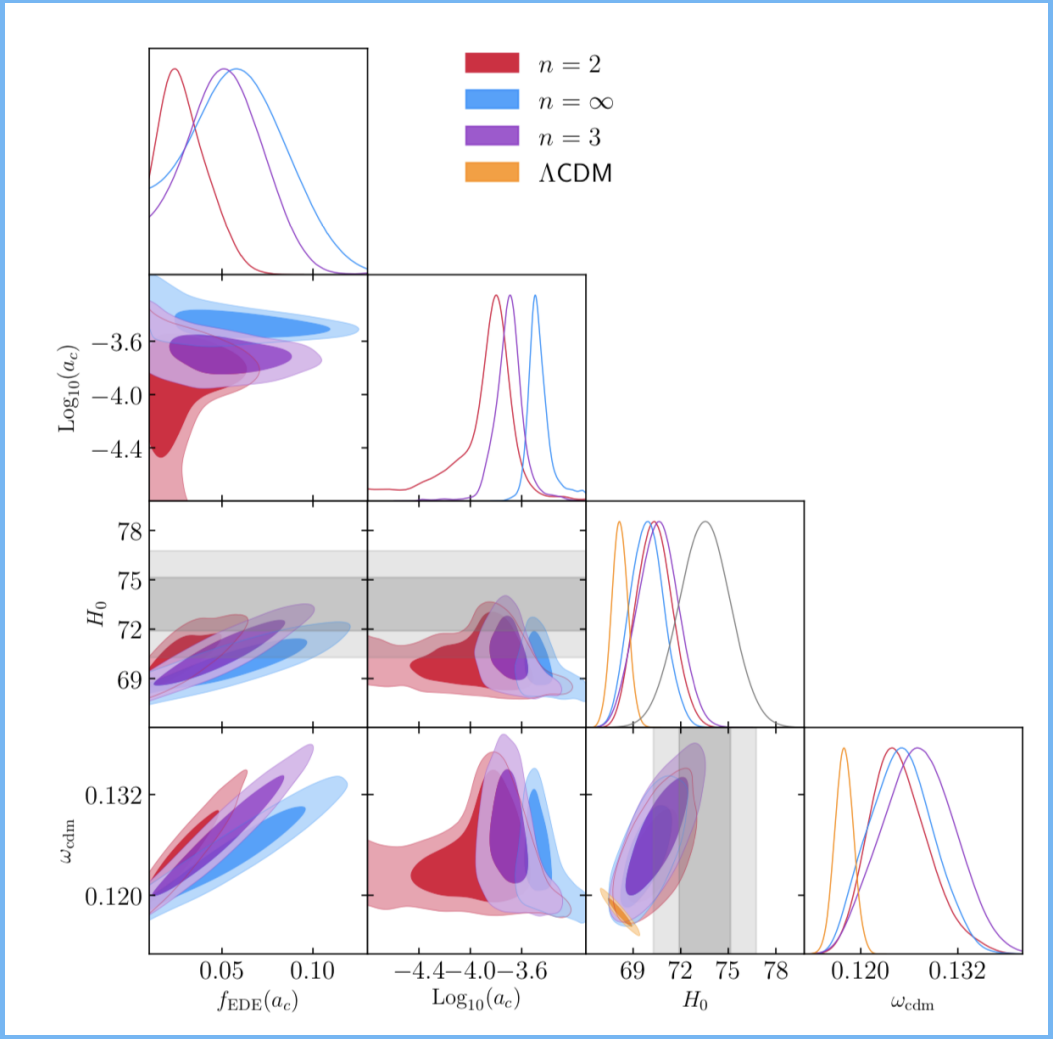
MK, Pradler, Walker 2014;
Poulin, Smith, Grin, Karwal, MK [arxiv:1806.10608]

Linear potential

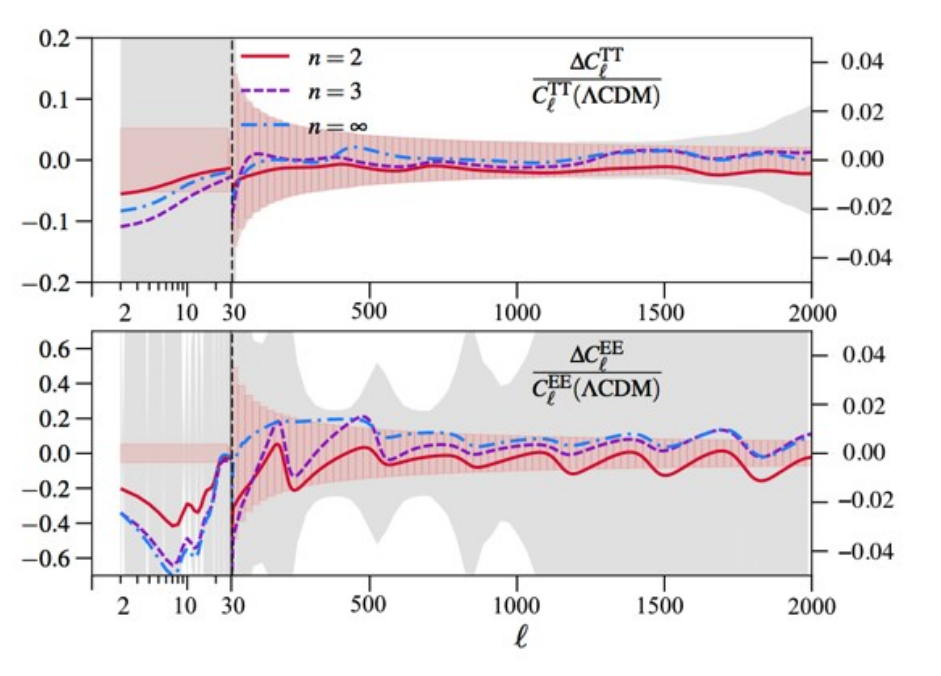


Poulin, Smith, Karwal, MK 2018

EDE fits CMB++ with higher H_0



Testable with future small-scale CMB polarization

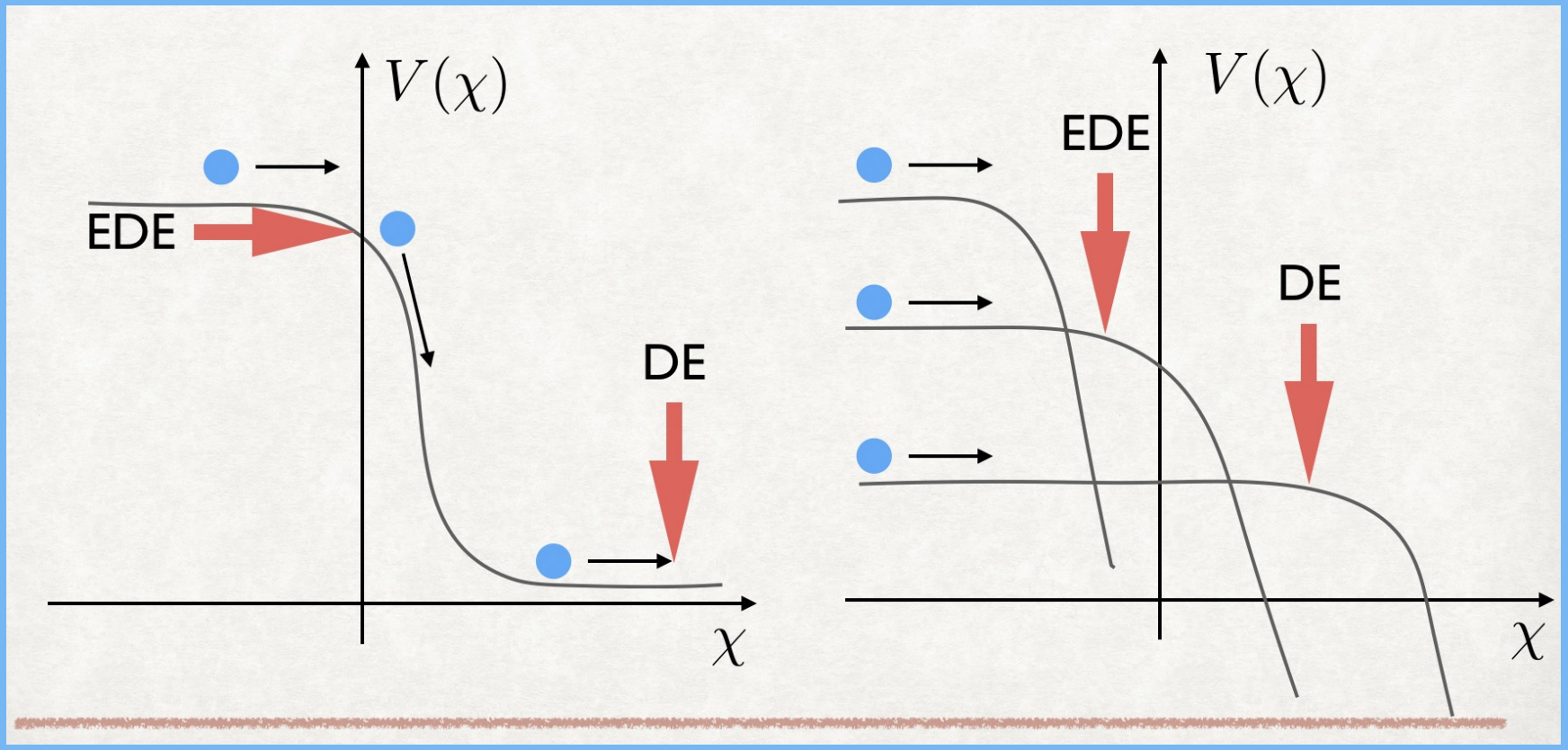


Poulin et al [1811.04083]

Recurring periods of DE domination?

e.g. Dodelson et al, astro-ph/0002360, Griest, astro-ph/0202052, MK, Pradler, Walker, 1409.0549

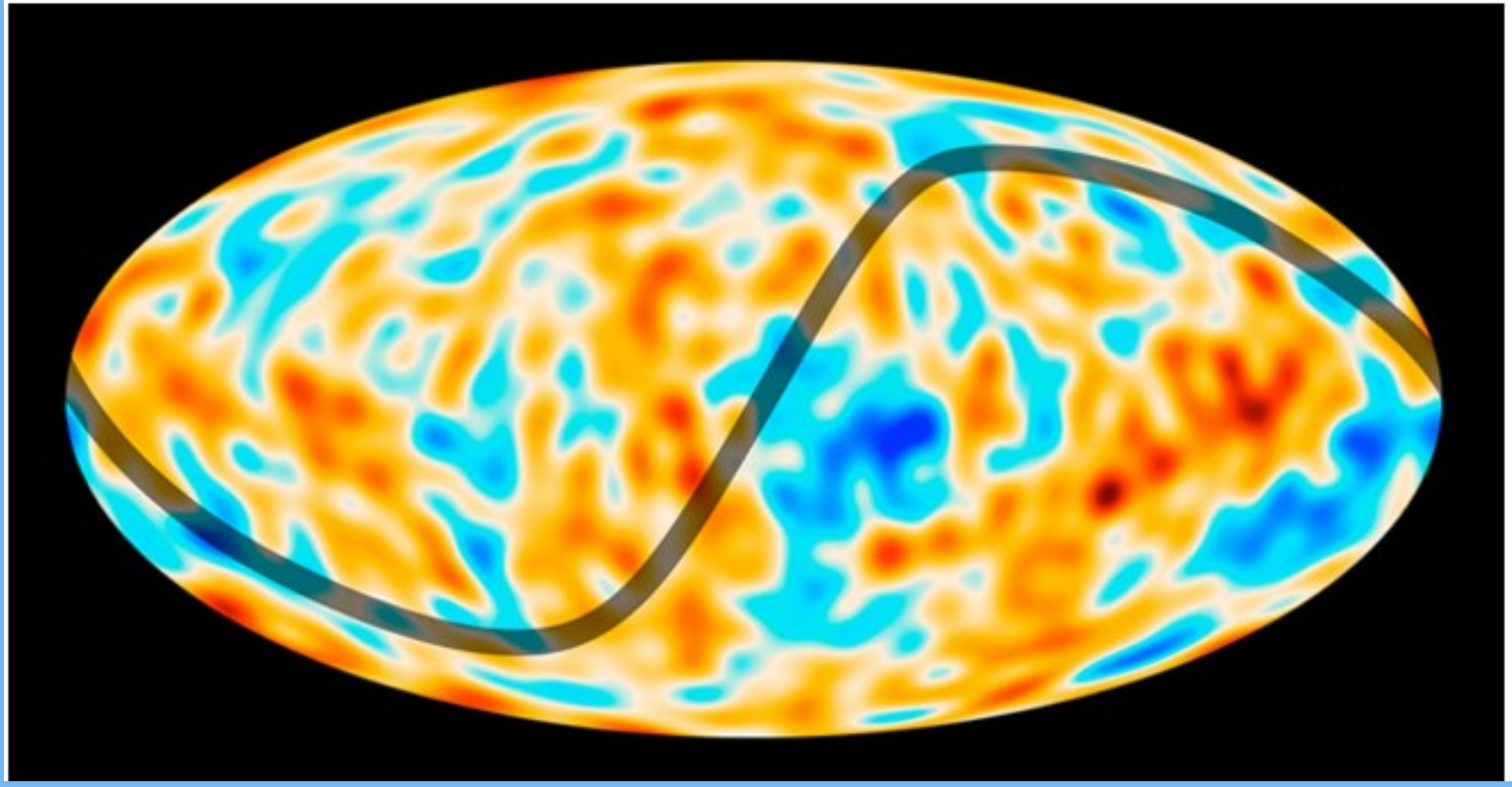
Oscillating dark energy? String axiverse?



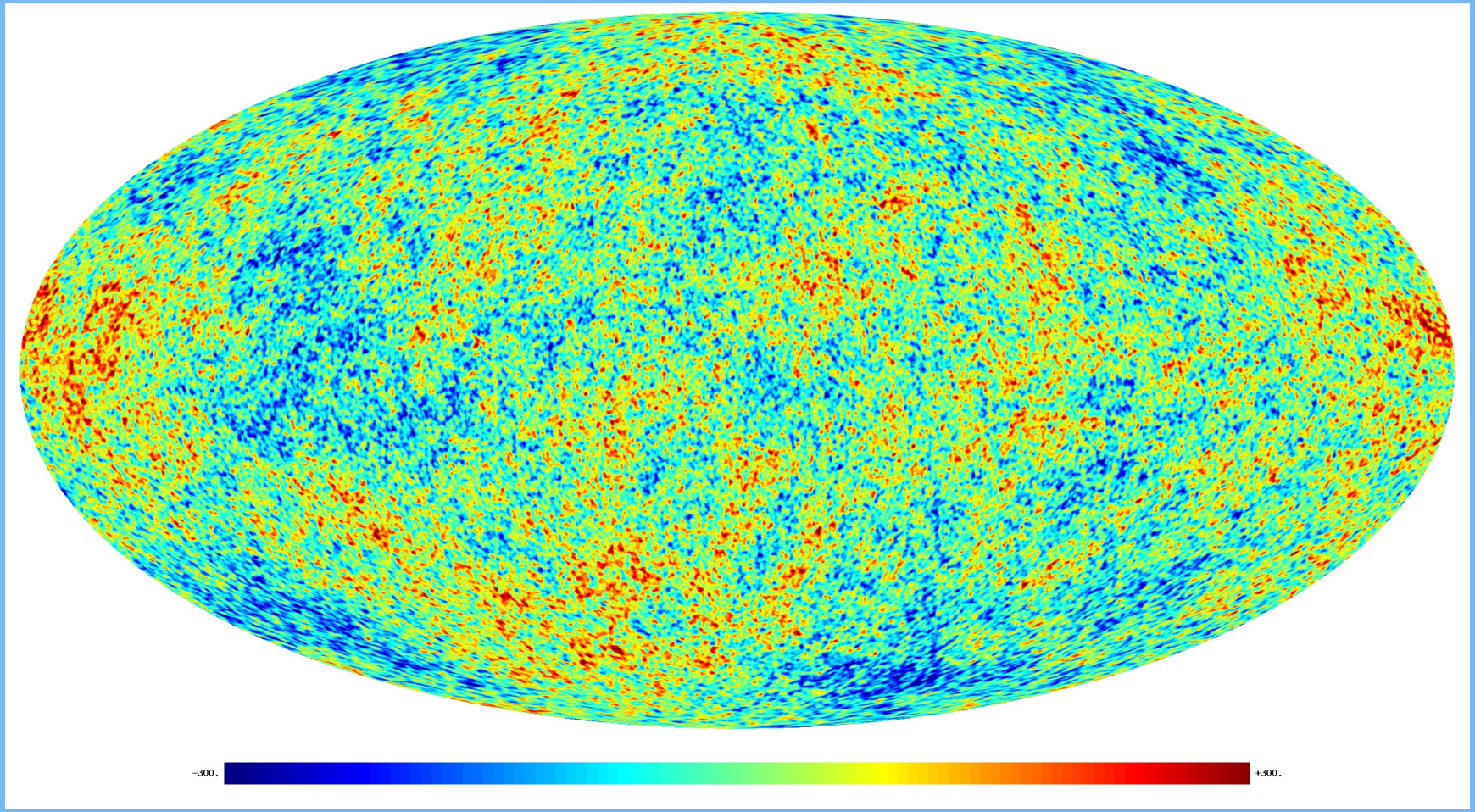
Power Dipole?

Lopsided Map of the Cosmos Offers New Clues to the Universe's Origins

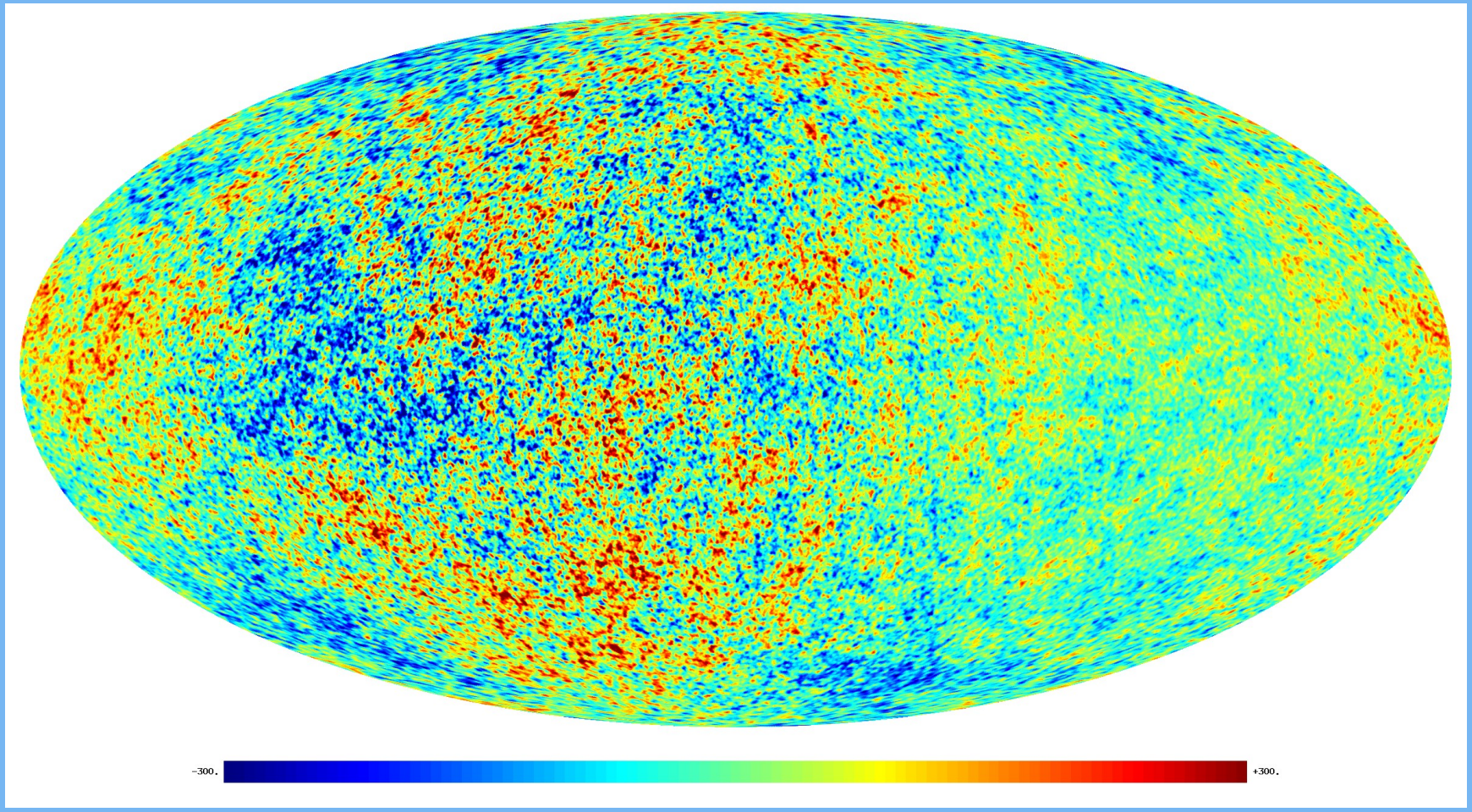
BY NATALIE WOLCHOVER, SIMONS SCIENCE NEWS 06.25.13 1:29 PM



Isotropic power



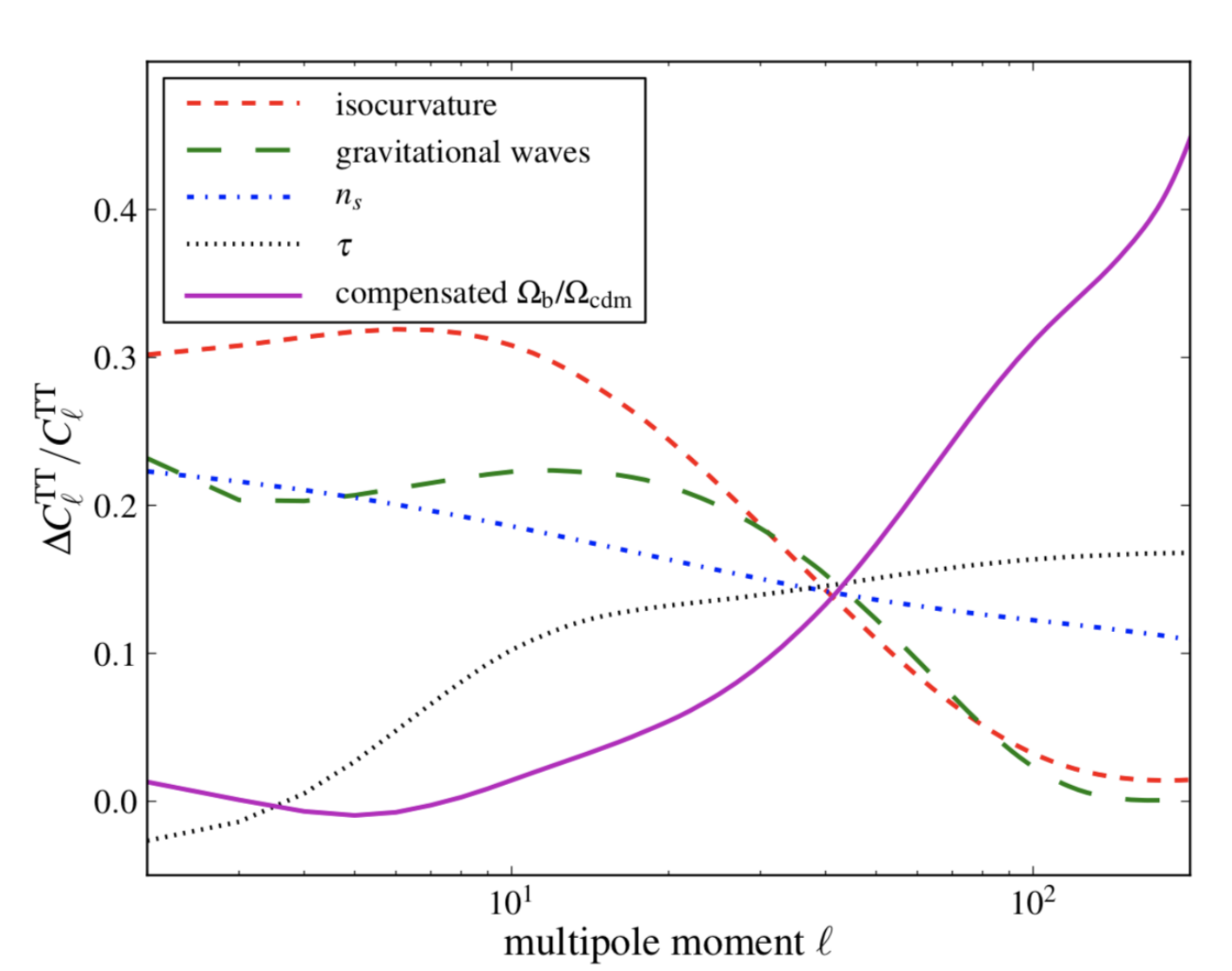
A power dipole



Two options

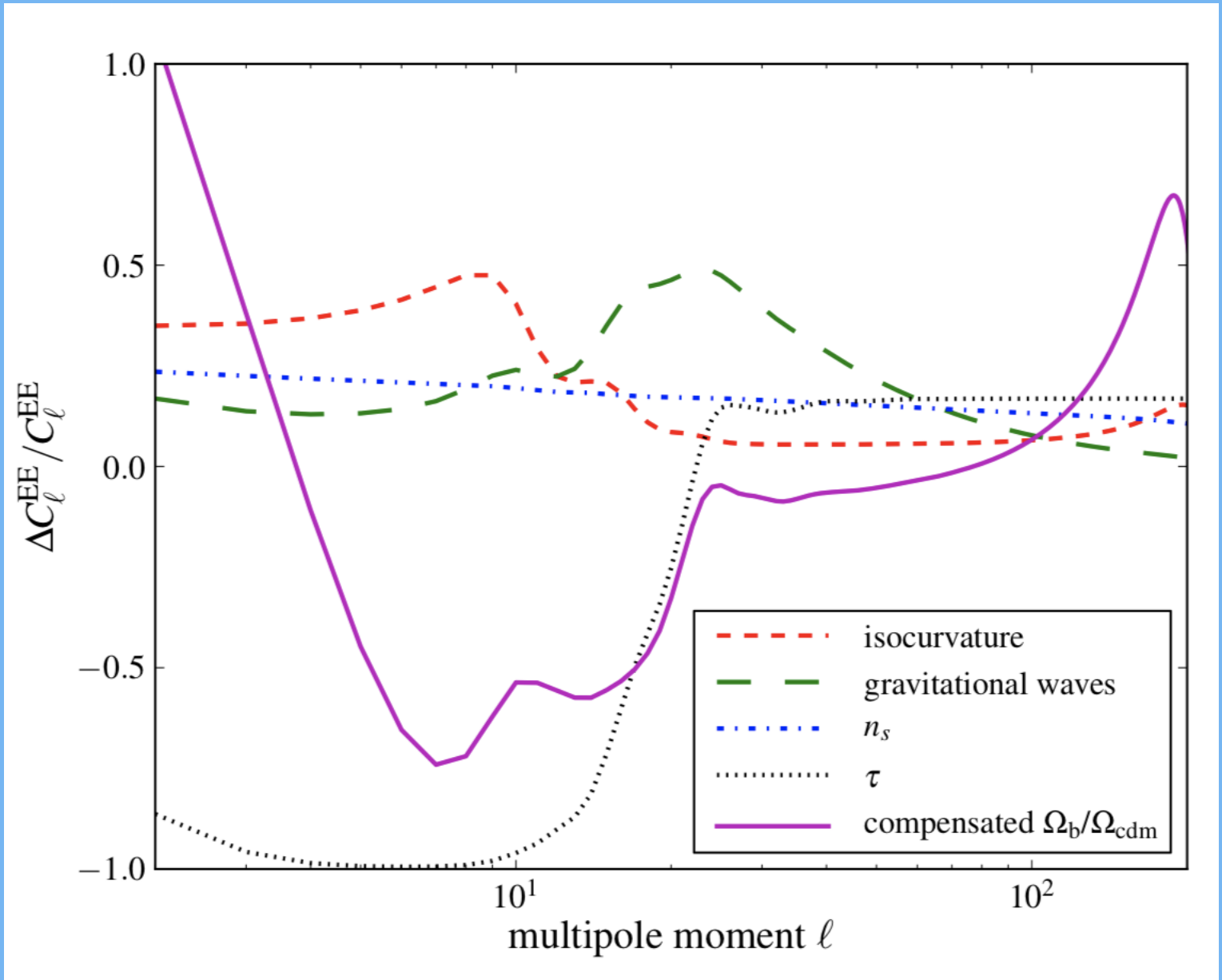
- Modulate density-perturbation amplitude; not easy, but can be done with isocurvature
  (Erickcek, MK, Carroll 2008; Erickcek, Hirata, MK 2009)
- Modulate parameters that map density perturbation to temperature fluctuation
  (Dai, Jeong, MK, Chluba 2013)

”Models” that fit l<60 asymmetry

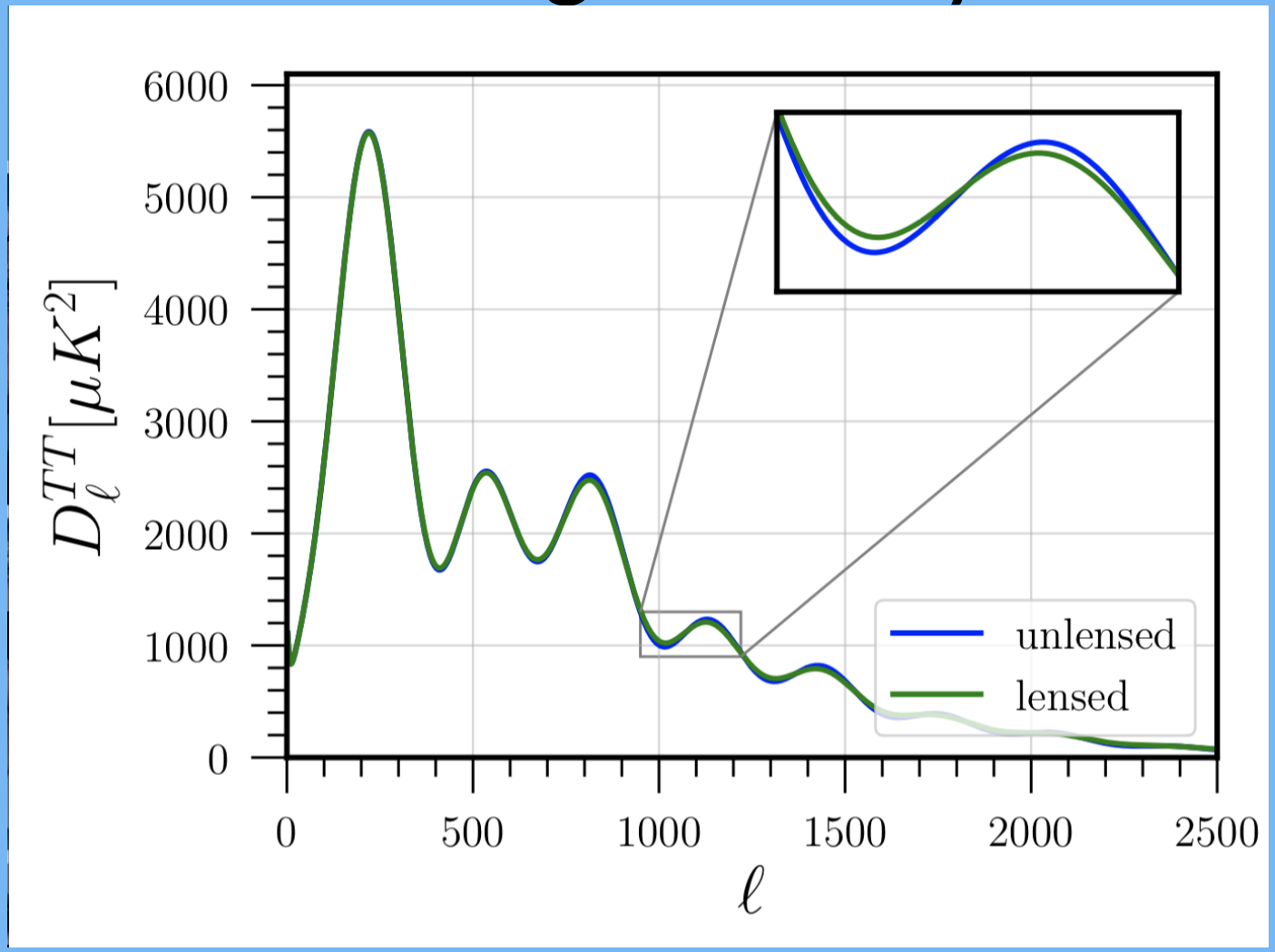


Dai et al 2013

Can be distinguished by polarization



Lensing anomaly?



Can try to explain with wiggles in primordial P(k), but not easy to come by in inflation (Domenech, MK 1905.04323)

Even if we chalk it all up to systematics…..

can LCDM survive another decade?

Can LCDM survive another decade?

- Probably

Can LCDM survive indefinitely?

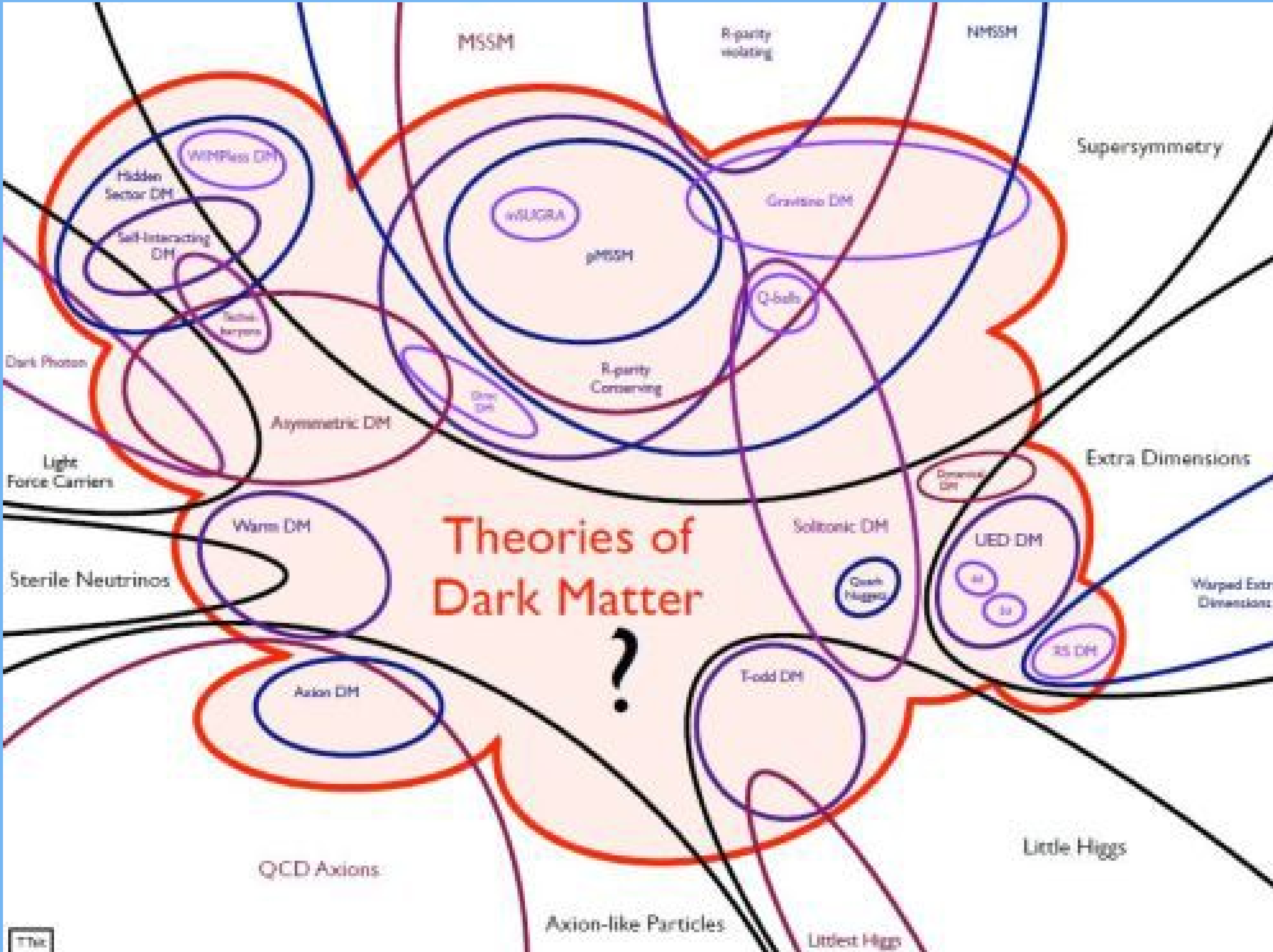
- Absolutely not

LCDM

a real theory

What is dark matter?

- WIMPs?
- Axions?
- Ultra-low-mass fields (fuzzy)?
- Primordial black holes



MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
R-parity
Conserving
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Warm DM
Theories of
Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Warped Extra
Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs

Dark-matter candidates

Why does the vacuum weigh?

- Quintessence?
- Alternative gravity
  - f(R)?
  - Gauss-bonet?
  - Massive?
  - Braneworlds?
- Strange neutrino interactions?
- Phantom energy?
- Landscape?
- Or is that just the way it is?

Why are there baryons?

What is the physics responsible for inflation?

- Natural, chaotic, supersymmetric, supergravity, axion, hilltop, SSB, multi-field, supernatural, new, old, ghost, helical-phase, quintessential, galileon, quartic, locked, stochastic, solid, k-flation, power-law, eternal, inflection-point, Higgs, warm, WIMPflation, two-field, critical-Higgs, gaugeflation, BSI, Gauss-Bonnet, Brans-Dicke, f(R), Starobinsky, attractor, ALP, brane,

How to Deal with STRESS AND TENSION

Cosmological consistency

- independent measurements and analyses
- Complementary measurements and cross-checks
- Precise questions and answers
- (testable) physical models for anomalies