THE FUTURE OF COSMOLOGICAL PHYSICS

2015/10/07
MIKE TURNER
THE BIG PICTURE
WENDY FREEDMAN
OBSEVATIONAL COSMOLOGY
JOHN CARLSTROM
COSMIC MICROWAVE BACKGROUND
ANGELA OLinto
ULTRA-HIGH ENERGY PARTICLES

2016/1/06
ROCKY KOLB
DARK MATTER
WAYNE HU
DARK ENERGY

2016/3/30
JOSH FRIEMAN
COSMIC SURVEYS
ANDREY KRAVTSOV
STRUCTURE FORMATION

2016/6/01
SCOTT DODELSON
COSMIC CODA

Chicago scientists brought together the fields of particle physics and cosmology. This union of the very big and the very small now underpins both disciplines. A series of special Kavli Institute for Cosmological Physics colloquia addresses the future of cosmology and celebrates the opening of the Eckhardt Research Center and the 125th anniversary of The University of Chicago.

All talks will take place in the Eckhardt Auditorium. 3:00 – 5:00 PM, with discussion and reception to follow.
First Movement: The Data!
New ways of measuring the Rate at which the Universe is Expanding

\[ H_0 = 72.7 \pm 2.0 \text{ [stat]} \pm 0.5 \text{ [sys]} \text{ km s}^{-1} \text{ Mpc} \]

**Beaton et al. (2015)**
Percent Level Determination of the Redshift-Distance Relation

\[ d_L(z) = \int_0^z \frac{dz'}{H(z')} \]

Infer expansion rate in the past!
Not just from Supernovae; also from Baryonic Acoustic Oscillations
Beginning the Historic Journey of measuring Growth of Structure
Anisotropies in the Cosmic Microwave Background
Acoustic Peaks

- Restoring force of photon/electron pressure \(\rightarrow\) system similar to guitar string
- Fundamental frequency \(\rightarrow\) Sound Horizon
- Higher harmonics \(\rightarrow\) information about contents of the universe
- Factor of ten smaller
- Out of phase with temperature anisotropies ... as predicted
- First detected by DASI
Clusters with the Sunyaev-Zel’dovich Effect
CMB Lensing Maps

Based on formalism developed by Wayne 15 years ago, using data from SPT built and operated by (John, Tom, Steve, Steve, Brad, Clarence, Lindsey, ...), analysis spearheaded by Gil

This is a mass map!!
The Onset of the Era of Cross-Correlations

Exploiting Chicagoland vision for DES, led by Josh
Highest Energy Cosmic Rays: GZK Cut-off
Dwarf Galaxies with Rapidly moving Stars

17 New Dwarf Satellite Galaxies discovered by DES last year in our cosmic backyard

Bechtol, Drlica-Wagner, et al
Splashback radius predicted by simulations
And ...
Second Movement: A Cosmological Model
Hard to understand any of these observations if only electrons and protons are responsible.
How did the Universe evolve from being very smooth to very clumpy?

UNIFORM TO ONE PART IN 10,000

VERY NONLINEAR
Gravitational Instability

Z = 28.62
How did the Universe evolve from being very smooth to very clumpy?

UNIFORM TO ONE PART IN 10,000

General Relativity predicts how much clumpier the Universe becomes due to gravity:
ONLY BY A FACTOR OF 1000, NOT ENOUGH!
How did the Universe evolve from being very smooth to very clumpy?

General Relativity predicts how much clumpier the Universe becomes due to gravity: **ONLY BY A FACTOR OF 1000, NOT ENOUGH!**

This is how the electrons, protons, and photons were distributed. There was another species – **dark matter** -- that did not interact with these and was much clumpier.

**UNIFORM TO ONE PART IN 10,000**

**VERY NONLINEAR**
Dark Matter Solves Cosmic Structure Problem

Dark matter was much clumpier than baryons were at the time of the picture of cosmic microwave background (CMB). Enough time for structure to grow!
Finding Dark Matter

Dark Matter can be probed in 3 ways ... and will be over the coming decade
The expansion rate is speeding up.
... AND IT SHOULDN’T BE

\[ S = \frac{1}{16\pi G} \int d^4 x \sqrt{-g} R + \int d^4 x \sqrt{-g} L_m \]

Minimizing this action leads to Einstein’s Equations:

**GEOMETRY**

Expansion Rate

**ENERGY**

Gravitational Potential Energy, proportional to density

\[ \frac{da}{dt} = \sqrt{\frac{8\pi G}{3}} \rho a^2 \]
Some Fixes

• Vacuum Energy
• Dark Energy
• Modified Gravity

(Almost) all require dimensionful constant much smaller than other masses in the fundamental Lagrangian \( \rightarrow \) New physics (way) beyond the Standard Model
Motivation for DES (and SPT)
CMB Spectrum also requires new physics
CMB is different than a musical instrument because ...

Fourier Transform of spatial, not temporal, signal

Time scale much longer (400,000 yrs vs. 1/260 sec)

No finite length: all wavelengths allowed!
WHY PEAKS AND TROUGHS?

- Vibrating String: Characteristic frequencies because ends are tied down

- Temperature in the Universe: Small scale modes begin oscillating earlier than large scale modes
But: multiple Fourier Modes at fixed wavelength
In this simple example, all modes have same wavelength/frequency

More generally, at each wavelength/frequency, need to average over many modes to get spectrum
The perturbation corresponding to each mode can either have non-zero initial velocity and/or non-zero initial amplitude.

We implicitly assumed that every mode started with zero velocity.
If they do all start out with the same phase ...

First peak will be well-defined
As will first trough ...

And all subsequent peaks and troughs
If all modes are **not** synchronized though ... 

First “Peak” 

![Graph showing clumpiness over time](image1)

First “Trough” 

![Graph showing clumpiness over time](image2)

We will NOT get coherent series of peaks and troughs!
Is it even possible to synchronize the phases?

Distance of Light travel

Wavelength of typical Fourier mode observed in CMB

$t = 400,000\text{ yrs}$
Inflation solves the phase problem

Wavelength of typical Fourier mode observed in CMB

Distance of Light travel

$\text{Distance} \quad \text{Time}$

$t = 400,000 \text{ yrs}$
Synchronized phases

- *Quantum mechanical* fluctuations generated during inflation: New physics at very early times/high energy
- Perturbations *freeze out* when distances get larger than horizon
- *Evolution* when perturbations re-enter horizon: phases synchronized!
Inflation requires *another* epoch of acceleration.
Find the gravitational waves produced during inflation
Standard Model of Cosmology stands on 3 Pillars

Find the new physics!
Third Movement: Two Hidden Messages
Michael

Hubble

Schramm

Freedman
John
Rocky

Vladimir Lenin 1916

A WIMP!
Michael Turner (actual size)

If I have seen further, it is by sitting on the shoulders....
Wayne
Andrey
Reminiscent of this graph
Reminiscent of this graph

Why and how did Christianity grow so rapidly?
One theory: it was the people

“Heedless of danger, they took charge of the sick, attending to their every need ...” (Dionysius, 260)

Antonine Plague
Here too, it’s the people!
Hi Scott. This was my first and only MRI. For me, I concentrated on the "music" generated by the pattern of changing magnetic fields. It was really not unlike some electronic music that I used to listen to. When I finished the scan, I mentioned this to the tech who said that a French lady musician patient had come back with a recording crew and made a little video about it, from the electronic music side of things, which one could find on YouTube. I've looked but not found it.

That's a nice story about you and your sons and the Taylor expansions in your heads!

Take care,
Bruce
On Jan 12, 2011, at 11:17 AM, scott dodelson wrote:

I am glad to hear about the ups. I assume you do more productive things, but for me the calming activity during MRI's is to estimate square roots, using Taylor expansions.

It is great fun and very satisfying [e.g. I got \(\sqrt{10}\) accurate to 3 decimal places several months ago]. It is a little surprising to me that they don't teach this in schools. My sons [who may be as odd as I] were literally cheering last summer when we had 20 minutes to kill at a bus stop and we got to the 2nd order term.
Tension
Tension
Multiplicity of high-precision experiments and probes suggests there will be a number of tensions to resolve, due to systematics and/or departures from $\Lambda$CDM.
Tension

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)
Why the focus on, the excitement about, the tensions? More than finding the new physics??
Same time ... different religion
Same time ... different religion

A healthy intellectual environment thrives on young people uncovering hidden assumptions and proving everyone else wrong.
The Model rests on 3 unstable pillars

Appreciate the wisdom and accomplishments of those who built this model ... but look around you and figure out if some hidden assumption is wrong. Continue the Chicago tradition by proposing bold, testable ideas!
Fourth Movement: The Future!

Oh Friends, not these tones
Let us raise our voices in more
Pleasing and more joyful sounds
How can we extract the most information from photometric surveys? Can we constrain photometric redshifts using galaxy clustering and CMB lensing?
What was the physics that drove inflation? Can we detect mechanisms that produced isocurvature perturbations?
What is the nature of space-time? How sensitive an interferometer can we build to help us find out?
What is dark energy? Can DES distinguish core collapse supernovae from Type Ia?
What is the best way to store information in cosmological simulations?

What is the most accurate way to measure the splashback radius?
What can the cosmos teach us about neutrinos? What other experiments will best complement CMB-S4?
Do theories of massive gravity lead to super-luminal propagation?

Can we detect high-E neutrinos by observing radiation emitted by showers that propagate through ice?
Can we measure gravitational waves produced at the earliest moments of time? How amazing can we make the SPT-3G detectors?
What is driving the current epoch of acceleration? Can strong lenses in DES help us find out?
Cosmic Coda

• Unprecedented amount of high quality data inform us about the cosmos
• Standard model of cosmology explains virtually all the data and requires new physics
• Appreciate the people here ... and work hard to show they are wrong
• The future looks bright