21st Century Cosmology
(a brief overview)

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CAU Study Tour
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**What is CCAT?**

- A 25meter FIR/submillimeter telescope that will operate at wavelengths as short as $\lambda = 200 \, \mu m$, an atmospheric limit

- To be located in a high (5617m) desert environment

- Designed to take advantage of one of the fast-developing detector technologies, opening up for surveys one of the last, largely untapped frontiers of ground-based astronomical research

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**Beam size:** $\lambda [\mu m]/100$ arcsec  
  e.g. 2” @ 200 $\mu m$

**FoV:** 1 sq. deg.

**Half WF err:** 9.5 $\mu m$ rms (goal)

**Continuum Sensitivity, 5$\sigma$, 1 hr:** 1 mJy @ 350 $\mu m$

**First-light**  
short $\lambda$ camera: 50 kpix

**Several instruments in Nasmith foci**
What is CCAT?

CCAT is intended to be run in the mode of a “university radio observatory” by a consortium of mostly academic partners.

• Strong emphasis on facility as training ground for the instrumentalists, observers, telescope makers of tomorrow
• Exploit single dish flexibility to respond rapidly to new discoveries and in testing new technologies
• “Lean & mean” bureaucracy and goal to release its data with short “proprietary periods”, in order to maximize science fall-out.

**Current CCAT partners:**
Cornell University
California Institute of Technology & NASA JPL
University of Colorado
University of Cologne
University of Bonn
Canadian university consortium: Unis of British Columbia, Calgary, Dalhousie, McGill, McMaster, Toronto, Waterloo, Western Ontario
Associated Universities, Inc.
+ others (discussions on-going)
What does the universe look like?

- This is not an actual image.
- It is a computer simulation, based on our current understanding of physics, what makes up the universe, and its history since the Big Bang event 13.8 billion years ago.
- How did this structure form?
Evidence for the Hot Big Bang Model

1. Olber's paradox:
   • Why is the sky dark at night?

2. Hubble’s Law and the expansion of the universe
   • More distant galaxies receding faster

3. Cosmic Microwave Background (CMB) radiation

4. Primordial nucleosynthesis
   • Hydrogen, helium (light ones only) and in right proportions

5. Large scale distribution of galaxies today (the way galaxies cluster)

Any alternative theory of cosmology would have to explain these critical observational facts.
The History of Our Understanding

- **1664** Newton’s Theory of Gravitation
  Newton realizes the Universe must be infinite to prevent collapse and that equilibrium is unstable
- **1917** Einstein obtains new set of equations of gravitational field (TGR)
  ➞ unstable Universe, unless a “cosmological constant” term is introduced
- **1922-23** Friedmann obtains set of expanding solutions of Einstein’s equations. They are independently obtained by Lemaitre in 1927
- **1929** Hubble discovers universal expansion: \( v = H_0 \, d \)
  He determines \( H_0 \) to be \(~500 \text{ km/s/Mpc}~\) ➞ universal age \(~2 \text{ Gyr}~\)
  Einstein declares introduction of \( \Lambda \) his “greatest error ever”
- **late 1940s** Gamow, Alpher and Hermann postulate existence of cosmic radiation background with \( T \sim 5 \text{ K} \)
- **early 1960s** Quasars are shown to be at cosmological distances
- **1964** Hoyle and Tayler show that Helium abundance can be explained by primordial nucleosynthesis
- **1965** Penzias and Wilson detect Cosmic Microwave Background radiation
- **1992** COBE detects fluctuations in the CMB (teams of Smoot and Mather)
- **1998** Observations of SNeIa reveal that the universal expansion is accelerating (teams of Perlmutter, Schmidt and Reiss)
- **2003** WMAP accurately determines main cosmological parameters
- **2013** The Planck satellite provides more precision and detail (in progress)
History and Fate of the Universe

**Hot Big Bang Model**

• 13.8 billion years ago, the universe was much hotter and much denser than it is today.
• A tremendous release of energy took place: the “Big Bang” event.
• Since then, the universe has been expanding.

The attractive force of gravity of all the mass in the universe should be acting to slow the expansion... or so we would expect...
Fate of the Universe: What are the options?

The “curvature” of the universe determines the path light follows through it, and hence how long it takes a photon to reach us from a distant object (the “light travel time” or “lookback time”).

Energy of Expansion versus Gravitational Energy

What will win this tug of war?
How much matter does the universe contain?
2014 cosmic census

- Precision cosmology!
- Age: 13.8 billion years since BB (1% error!)
- First stars ignited 200 million years after BB
- Light from CMB is from 400,000 years after BB
  - 4.9% “normal” matter
  - 26.8% dark matter
  - 68.3% dark energy
- Looks like Universe will expand forever
Cosmology in 2014

The Universe expands

The expansion appears to be *accelerating*

The main dynamical component in the accelerating Universe is, now:
NOT baryonic matter
NOT dark matter
but rather

**Dark Energy**
2011 Nobel Prize for physics

- Saul Perlmutter
- Adam Reiss
- Brian Schmidt

- Two different teams, doing independent work, set out to measure the geometry of the universe by comparing redshift-distances with distances measured by other means.

- Both got the same results, looking at different objects
Distances to supernovae

Host Galaxies of Distant Supernovae

HST04Sas  HST04Yow  HST04Zwi  HST05Lan  HST05Str

NASA, ESA, and A. Riess (STScI)
Evidence for acceleration

- Type Ia supernovae as “standard candles”
- We assume all SNeIa reach the same maximum luminosity.
- Then we observe the maximum apparent brightness.
- \( \Rightarrow \) get the distance.

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Supernova Cosmology Project
Knop et al. (2003)

Distant SNeIa appear fainter than we expect
Evidence for acceleration

- Type Ia supernovae as “standard candles”
- We assume all SNeIa reach the same maximum luminosity.
- Then we observe the maximum apparent brightness.
- => They appear to be too faint!

Supernova Cosmology Project
Knop et al. (2003)

\[ \Omega_M, \Omega_A \]
\[ 0.25, 0.75 \]
\[ 0.25, 0 \]
\[ 1, 0 \]

Distant SNeIa appear fainter than we expect
History of the Universe

Size of universe

Time (billion years)

Accelerating

Constant expansion

Low density

Critical density

High density

Globular cluster formation

$1/H_0$

Present time

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21st century cosmology

- The Big Bang occurred everywhere in the universe 13.8 billion years ago.
- The expansion of the universe today is accelerating.
  - Evidence:
    - Distant supernovae appear fainter than expected
    - Details of fluctuations in CMB
- As far as we can tell the geometry of the universe is "flat" (Euclidean) because the universe is close to "critical" (matter only).
- Therefore, the universe will expand forever.

There are still fundamental but unanswered questions!

And there are real PROBLEMS!
What happened before the CMB was emitted?

The Cosmic Microwave Background photons were emitted about 300,000 years after the Big Bang at \( z \sim 1000 \)

That corresponds to

- a “lookback time” of \(~13.8\) Gyr
- a recessional velocity of \(~0.99\) c
- an “age of the Universe” of \(~400,000\) years

That is as far back as we can “see”; beyond that we have to try to understand the physics of the early universe.

But, it is possible to learn indirectly from the CMB about the universe at earlier times.
**Omega Ω**

Ω = The ratio of the average density of the universe to the critical density

Flat universe => if density implies critical density (in absence of dark energy)
The 2014 Cosmic Census Problem

\[ \Omega_{\text{total}} = \Omega_{\text{matter}} + \Omega_{\Lambda} + \Omega_{\text{radiation}} \]

\[ \Omega_{\text{matter}} = \Omega_{\text{dark matter}} + \Omega_{\text{baryons}} \]

\[ \Omega_{\Lambda} \] is the contribution due to “dark energy”

\[ \Lambda = \text{Lambda or the “cosmological constant”} \]
\[ \text{Einstein’s “blunder”} \]

\[ \Omega_{\text{radiation}} \] is the contribution due to radiation => negligible

\[ \Omega = \text{density of universe relative to “critical universe”} \]

Clues to dark matter and dark energy and the early universe are found in elementary particle physics
Outstanding Problems in Modern Cosmology

The Flatness Problem: Why is the universe so (close to) flat?

Define Omega ($\Omega$) = $\frac{\text{mean density of universe}}{\text{"critical" density}}$

The density of the universe changes as it expands (its volume grows)
Why is $\Omega$ not much less than or greater than 1 today?

The Horizon Problem: Why is the universe so (close to) being (perfectly) smooth?
Why do regions so far apart appear to be exactly the same temperature?

The Symmetry Problem: Where has all the “antimatter” gone?

The Dark Matter Problem: What is the dark matter?

The Dark Energy Problem: Why is the universe accelerating?
Outstanding Problems in Modern Cosmology

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                              “critical” density

The density of the universe changes as it expands (its volume grows)
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The Horizon Problem: Why is the universe so (close to) being (perfectly) smooth?
Why do regions so far apart appear to be (almost) exactly the same temperature?

While there are fluctuations, they are actually tiny (in terms of their amplitude, i.e. the amount of hotter/colder!)
Critical epochs in the history of the universe

- The Big Bang occurred about 13.8 billion years ago.

- Big Bang Nucleosynthesis: First 3 minutes

- Epoch of Recombination: 400,000 years after the Big Bang, the universe cools to 3000 degrees Kelvin and protons and electrons “recombine” to form hydrogen atoms again => Cosmic Microwave Background radiation emitted

Planck satellite map of CMB 2013
An image of the universe at age 400,000 years
The Horizon Problem

The number and size of density fluctuations on both sides of the sky are similar, yet they are separated by a distance that is greater than the speed of light times the age of the Universe, i.e., they should have no knowledge of each other by special relativity.

At some time in the early Universe, all parts of spacetime were causally connected, this must have happened after the spacetime foam era, and before the time where thermalization of matter occurred.

- The fluctuations in this map are very small, at the level of 1 part in 100,000 (out of 2.725K, the temperature differences are only at the level of 18 microKelvin (0.000018 Kelvin) => TINY
Critical epochs in the history of the universe

• The Big Bang occurred about 13.8 billion years ago.

• Beginning of cosmic history

B. Zhang, 2009, Nature 461, 1221
The Big Bang occurred about 13.8 billion years ago.

In the first tiny fractions of a second, lots of action on subatomic scales. Inflation...
Fundamental Forces...
Particles...

B. Zhang, 2009, Nature 461, 1221
“Inflation” as a solution to the horizon problem
Polarization: beyond CMB fluctuations

Inflation $\Rightarrow$ Gravity Waves $\Rightarrow$ CMB Polarization

The explosive expansion of space during inflation would have created ripples in the fabric of space. As explained below, these gravity waves should have left a signature in the polarization of the last-scattered photons (CMB).
**CMB polarization**

Polarization pattern can be decomposed into 2 components:

- **E-mode** (electric field like; no handedness)
- **B-mode** (magnetic field like; with handedness)
CMB polarization

But measurements not precise enough yet; Planck final observations done => results in progress
BICEP2 results

A team of astronomers using a ground-based experiment at the South Pole have announced they have detected the B-mode signal.
BICEP2 results

The controversy:

- A press conference announcing, in a very confident tone, the results, before the paper was refereed

March 17th Press Conference on Major Discovery at Harvard-Smithsonian Center for Astrophysics

Press Release Source: Harvard-Smithsonian Center for Astrophysics  Posted Wednesday, March 12, 2014

First Direct Evidence of Cosmic Inflation, HSCFSA

"Researchers from the BICEP2 collaboration today announced the first direct evidence for this cosmic inflation. Their data also represent the first images of gravitational waves, or ripples in space-time. These waves have been described as the "first tremors of the Big Bang." Finally, the data confirm a deep connection between quantum mechanics and general relativity."

The Harvard-Smithsonian Center for Astrophysics (CfA) will host a press conference at 12:00 noon EDT (16:00 UTC) on Monday, March 17th, to announce a major discovery.
BICEP2 results

The controversy:

• **The paper itself admitted possible alternatives/problems**

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First Direct Evidence of Cosmic Inflation

*Release No.: 2014-05*

*For Release: Monday, March 17, 2014 - 10:45am*

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Cambridge, MA - Almost 14 billion years ago, the universe we inhabit burst into existence in an extraordinary event that initiated the Big Bang. In the first fleeting fraction of a second, the universe expanded exponentially, stretching far beyond the view of our best telescopes. All this, of course, was just theory.

Researchers from the BICEP2 collaboration today announced the first direct evidence for this cosmic inflation. Their data also represent the first images of gravitational waves, or ripples in space-time. These waves have been described as the "first tremors of the Big Bang." Finally, the data confirm a deep connection between quantum mechanics and general relativity.
BICEP2 results

The controversy:
• The team made (some of) their data public.

BICEP2 2014 Results Release

1. BICEP2 2014 Release Papers
2. BICEP2 2014 Release Data Products
3. BICEP2 2014 Release Figures from Papers
4. Previous Publications

Videos for Technical Talk ⇒ and News Conference
⇒
BICEP2 2014 Release Frequently Asked Questions
⇒
BICEP2 2014 Release Image Gallery ⇒
BICEP2 Public Web Pages and News Releases ⇒
BICEP2 results

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BICEP2 2014 Results Release

2. BICEP2 2014 Release Data Products

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<th>Description</th>
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<td>B2_3yr_rlikelihood_20140314.txt</td>
<td>Text file containing the tabulated likelihood for the tensor-to-scalar ratio, $r$, computed using the &quot;direct likelihood calculation&quot; described in Section 9.3.1 of Barkats et al. and Section 11.1 of BICEP2 2014 I.</td>
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<td>Text file containing bandpowers and statistical uncertainties, corresponding to Figure 2 of BICEP2 2014 I.</td>
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<td>Data necessary for constructing approximate bandpower likelihoods following the method of Hamimeche &amp; Lewis (2008). See Section 9.1 of Barkats et al. Note that the likelihood for the tensor-to-scalar ratio (available above) is calculated using a different method.</td>
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BICEP2 results

The controversy:
  • The problem is that the B-mode signal is very weak and could be overwhelmed by the presence of foreground dust in the Milky Way.
  • Will be tested (and could be confirmed) by other experiments (SPTPol., Planck)

• Extraordinary claims demand extraordinary evidence...
  [Carl Sagan]
BICEP2 results

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• MZ on CMB grav waves vs. dust:
  “... sane answer is `let’s just wait.’ On the other hand... we just can’t. No scientist is that patient...”
BICEP2 results

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- **MZ on CMB grav waves vs. dust:**
  “… sane answer is `let’s just wait.’ On the other hand… we just can’t. No scientist is that patient…”

  If it were easy, it would have already been done. We can (just about) make the required measurements!
Next stop:
Cremona and its Astronomical Clock
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• In the Torrazzo’s fourth story resides the largest astronomical clock in the world (28 feet in diameter).
• The mechanism was built by Francesco and Giovan Battista Divizioli (father and son) between 1583 and 1588.
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• Bembo: Torrechiara (1463)
• Correggio: Camera di San Paolo (1518-9)
  San Giovanni Evangelista (1524)
  Duomo (1530)
• Parmigianino: Fontanellato (1524)
  “Turkish Slave” (1533)
• Copernicus: “De revolutionibus orbium coelestium” (1543)
Outermost ring: 24 hours of day in Roman numerals.
2nd ring: constellations of the Zodiac, in Latin
3rd ring (narrow band with light/dark notches): degree subdivisions within each Zodiacal sign
4th ring (very thin):
Decimal degrees
5th ring: Pictoral Zodiac and 89 most important stars; also MW
6th ring: Months of year, in Latin
7th ring (gray and red notches): day within month
8th ring (very thin): 10 day divisions within month
Ring A: Synodic lunar month => Moon phase
Ring B: Moon phase depicted
Ring B: Moon phase depicted
Ring C (central): The Earth
Pole I: Time of day
Pole II: Moon age and position in sky
Pole III: Day and month of year
Pole IV: Lunar nodes (intersection of solar and lunar orbit)