PERSPECTIVES ON COSMOLOGY: THE LAST THIRD OF A CENTURY

George Blumenthal

- Sandy, Joel, and I arrived at UCSC in 1972/73 as young assistant professors…
- A third of a century ago!
  - Power point was unheard of.
  - Transparencies were unheard of.
  - Personal computers were unheard of.
- The key issues in cosmology were very different then.
- I will try to compare the **State of the Universe** then to the situation today.

1972 Cosmological Parameters

- Precision cosmology wasn't a joke, it was an oxymoron!
  - Hubble constant $50<H_0<100$ km/s/Mpc
  - Observations gave $-1<\Omega<2$ assuming no cosmological constant.
  - Helium and light element abundances did work well
- There was still an age problem, but only <50%
- Few people considered nonzero Λ at all
- Dark matter was a glint in Zwicky's eye…

2005 Cosmological Parameters

- Essentially little of no debate about values
  - H_o = 72 km/s/Mpc
  - Ω_{baryon} = 0.04
  - Ω_{matter} = 0.3
  - Ω_{Λ} = 0.7
- No more age problem
- Dark matter is **COLD**
- Key questions remains:
  - What is this cold dark matter stuff?
  - Why is Λ so small?
  - What is this dark energy stuff? Why is there so much of it?

1972 Cosmic Background Radiation

- Seemed to be at 3 ^{o}K at low frequency
- Balloon and Rocket experiments found huge flux at high frequencies. Unclear whether this was to be believed
- Isotropic to 1 part in 10^3
- First evidence of a dipole was just starting to come in.

2005 Cosmic Background Radiation

- COBE showed us that the spectrum is thermal with a temperature of 2.73 ^{o}K (miniscule error bars)
- Dipole is now accurately measured
- Fluctuations down to a degree are measured at the microdegree level
- Polarization measurements provide constraints.

1972 Entropy per Baryon

- Known that $n_{photons}/n_{baryons}$ ~10^9 –10^{10}
- Normally expect that dimensionless numbers should be ~ 0, 1, or ∞
- It was already understood that an excess of baryons over antibaryons required
  - Baryon nonconservation – **no models except black holes**
  - CP violation
  - Departure from equilibrium in the Universe

2005 Entropy per Baryon

- Physics beyond the standard model provides a mechanism to get large entropy per baryon, eg
  - GUT models
  - Dines-Affleck effect
  - Etc
- Still do not have a unique result of $n_{photons}/n_{baryons} \sim 10^{10}$ -- any number might be achievable!

1972 In the Beginning …

There was a big bang, as Hoyle derisively put it.

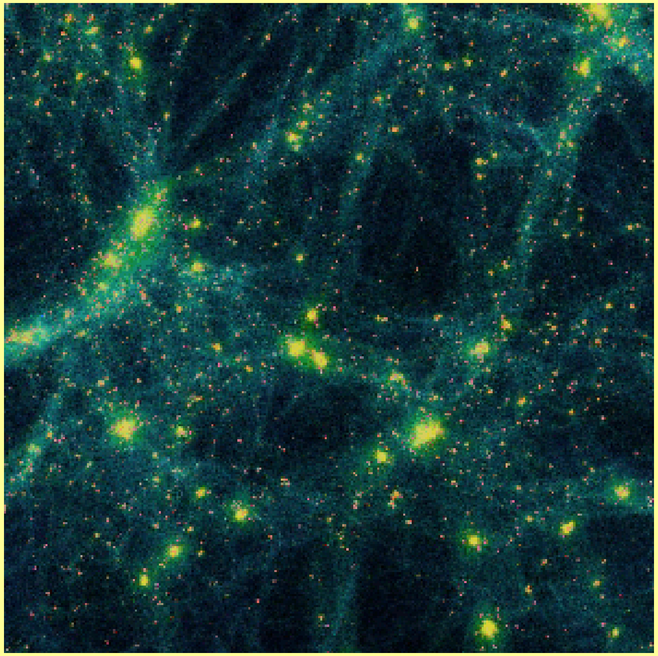
- Horizon problem
- Flatness problem

2005 In the beginning …

- Inflationary Universe
  - “Solves” the horizon and flatness problems
  - Fixes issues we never thought of (too many monopoles)
  - *Might* be a natural consequence of physics well beyond the standard model – eg scalar field
- Eternal Inflation
  - Our big bang is but one of many
  - Like the old steady-state model
    - No preferred time
    - Spontaneous creation of big bangs rather than spontaneous creation of matter
- In principle, physics (superstrings?) should help us to set the value of Λ and determine whether inflation happens.

Forming Structure in the Universe

- 1972: Forget it. Too many problems …
  - Initial fluctuations not understood
  - CBR constraints
  - No natural size for galaxies
- 2005: Hardly in doubt …



Initial Fluctuations

- Gravity only **amplifies** density inhomogeneities
- 1972 There was no sensible model.
  - Seeds (eg globular clusters) require preseeds
  - Turbulence requires constant energy input
  - Phenomenologically, we knew that $(\delta\rho/\rho)_{horizon} \sim 10^{-4}$ independent of scale
- 2005 Inflation provides roughly scale free fluctuations
  - <u>Quantum fluctuations</u> lead to large scale structure
  - Adiabatic fluctuations arise naturally
  - <u>**Beware**</u>: getting the right amplitude requires fine tuning of a dimensionless interaction strength

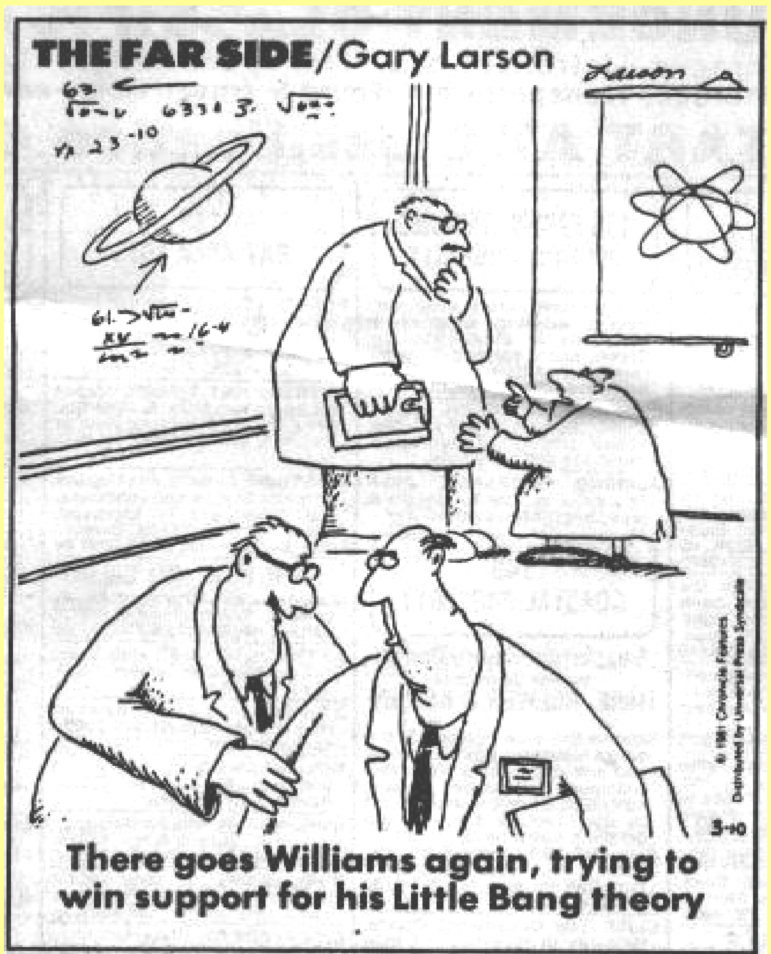
CBR Isotropy Constraints

- Linear growth of fluctuations with scale factor
- Requires $(\delta\rho/\rho)_{recombination} > 10^{-3}$
- 1972: Coupling of baryons to radiation before recombination leads to large CBR fluctuations.
- 2005: Feebly interacting dark matter solves the problem
  - Small baryonic fluctuations at recombination
  - ΛCDM models reproduce observed fluctuations remarkably well down to an angular degree

Nearly Normal Galaxies

- 1972: Couldn't form them. The natural scales were $10^5\ M_\odot$,$10^{14}\ M_\odot$, and $10^{16}\ M_\odot$
- 2005:
  - Dissipational cooling provides a rough scale for galaxies
  - ΛCDM naturally leads to core-halo structure
  - Many key features yet to understand
    - Bimodality
    - Suppressing star formation
    - AGNs and central black holes
    - Details of star formation
    - Substructure in halos
    - ….

- There has been a HUGE increase in our understanding of the Universe and structure formation since 1972.
- Another NNG meeting in 15 years would produce real **2020 hindsight**.
- Many challenges yet for theorists and observers.



There goes Williams again, trying to win support for his Little Bang theory