Computing Our Universe

Cosmology Summary

Eric Linder

HORRENDOUS SPACE KABLOOIE

Hobbes: *What would you call the creation of the universe?*
Calvin: *The Horrendous Space Kablooie!*

–Bill Watterson, *Calvin and Hobbes*

- Isotropy and Homogeneity
  CMB, Galaxy Counts, Redshift Surveys
- Expansion
  $T(z)$, $n(z)$, Hubble Law, Kinematics
- Age Concordance
  H_0^{-1}, Stars, Elements, $\sigma < 0$
- Nucleosynthesis
  Abundances, Ω_b
- Cosmic Microwave Background
  FIRAS, Structure Formation
- Tests of General Relativity and Principle of Equivalence
  Gravity Probe B, STEP

WILDER SHORES

Though the wheel has 30 spokes,
it is the space at the center that makes it useful,
A journey of a thousand li begins underneath one's feet...

– Lao Tse, *Dao De Qing*

- **A Touch of Spice** (exotic components)
  - Baryon Chauvinism:
    neutrinos, WIMPs, decaying particles, topological defects
  - Equation of State to be given – Entwining of Particle Physics
    quintessence, tracking fields

- **Burning Down the House** (exotic geometry)
  - Not simply connected – anisotropic
  - Small Universe – $R > 1.4\, H_0^{-1}$
  - Bianchi Model – e.g. Gödel rotation $< 10^{-6}$

- **Attack of the Higher Dimensions** (exotic physics)
  - Scalar-Tensor Gravity – scalar fields generic in high energy physics; GR is attractor solution
  - Higher Dimensions – e.g. Kaluza-Klein, M-theory
  - Phase Transitions – loss of adiabaticity

SNARKS AND BOOJUMS

He had bought a large map representing the sea
without the least vestige of land,
And the crew were much pleased when they found it to be
a map they could all understand.

– Lewis Carroll, *Hunting of the Snark*

- Cosmological Distances

$$r_c(z) = (1-\Omega)^{-1/2}\sinh\left\{(1-\Omega)^{1/2}\int_0^z dZ\, H^{-1}(Z)\right\}$$
$$r_p(z) = \int_0^z dZ\,(1+Z)^{-1}H^{-1}(Z)$$
$$dr_p(z) = (1+z)^{-1}dr_c(z) = a\,dr_c$$

- Cosmological Model
  - Cosmological Parameters
  - Baryon Density $\Omega_b = 0.0125\,h^{-2}$
  - Dark Matter
  - Astrophysical Observation + Theory, Laboratory, Simulations
- Growth of Density Perturbations
  - Primordial Origin
  - Gaussian
  - Adiabatic/Isocurvature
  - Gravitational Instability
- Structure Formation

TILT AND BIAS

Power law inflation $a \sim t^p$, $p > 1$; gravitational waves

Slow roll parameters – shape of field potential $V(\phi)$

$$\epsilon \equiv \frac{1}{16\pi G}\left(\frac{V'}{V}\right)^2$$
$$\eta \equiv \frac{1}{8\pi G}\left(\frac{V''}{V}\right)$$

- Scalar Power $\quad P_k \equiv |\delta_k^S|^2 \sim k^n$
- Tensor Power $\quad P_k^T \equiv |\delta_k^T|^2 \sim k^{n_T}$
- Indices $\quad n = 1 - 6\epsilon + 2\eta \quad ; \quad n_T = -2\epsilon \approx 1 - n$
- Tensor/Scalar power ratio $r = \frac{T}{S} \equiv \frac{C_l^T}{C_l^S} = 12.4\epsilon$ gives **tilt** $n - 1$

$$n = 1 - \frac{1}{6.2}\frac{T}{S} = \frac{p-3}{p-1}$$

- Scale Bias: $P_k \sim k$ fails because of tilt and tensors

$$b = \left(\frac{1000\,h^{-1}Mpc}{8\,h^{-1}Mpc}\right)^{(1-n)/2}\sqrt{1+\frac{T}{S}}$$
$$\approx 10^{T/(7S)}\sqrt{1+(T/S)}$$

$$T/S \approx 1 \qquad \Rightarrow \qquad n \approx 0.86, \quad b \approx 2$$

Reconstruct $V(\phi)$ from CMB, LSS

XCDM: PARAMETERS

$$h, \quad \Omega_b, \quad \Omega_X, \quad \Omega, \quad \sigma_8, \quad n$$