Quantum Coherence Arguments for Cosmological Scale

James Lindesay

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Abstract

Homogeneity and correlations in the observed CMB are indicative of some form of cosmological coherence in early times. Quantum coherence in the early universe would be expected to give space-like phase coherence to any effects sourced to those times. If dark energy de-coherence is assumed to occur when the rate of expansion of the relevant cosmological scale parameter in the Friedmann-Lemaitre equations is no longer supra-luminal, a critical energy density is immediately defined. It is shown that the general class of dynamical models so defined necessarily requires a spatially flat cosmology in order to be consistent with observed structure formation. The basic assumption is that the dark energy density which is fixed during de-coherence is to be identified with the cosmological constant. It is shown for the entire class of models that the expected amplitude of fluctuations driven by the dark energy de-coherence process is of the order needed to evolve into the fluctuations observed in cosmic microwave background radiation and galactic clustering. The densities involved during de-coherence which correspond to the measured dark energy density turn out to be of the electro-weak symmetry restoration scale. In an inflationary cosmology, this choice of the scale parameter in the FL equations directly relates the scale of dark energy de-coherence to the De Sitter scales (associated with the positive cosmological constants) at both early and late times.
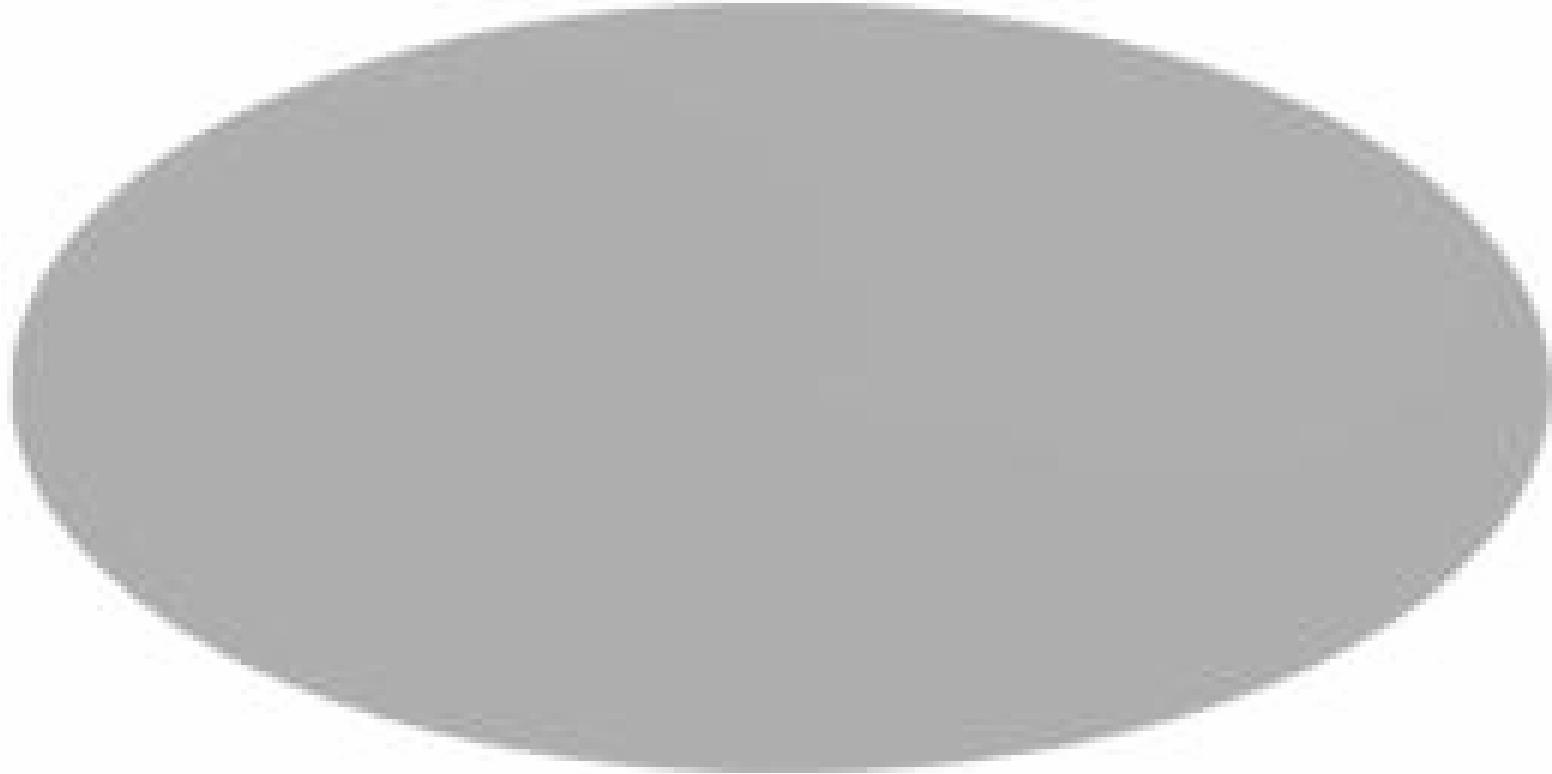
Outline of Presentation

I.   Cosmic Microwave Background Radiation

II.   Macroscopic Quantum Systems

III.   Friedmann-LeMaitre Dynamics

IV.   Zero-Point Motions

V.   Dark Energy Partitions and Fluctuations

VI.   Thermalization Scenarios

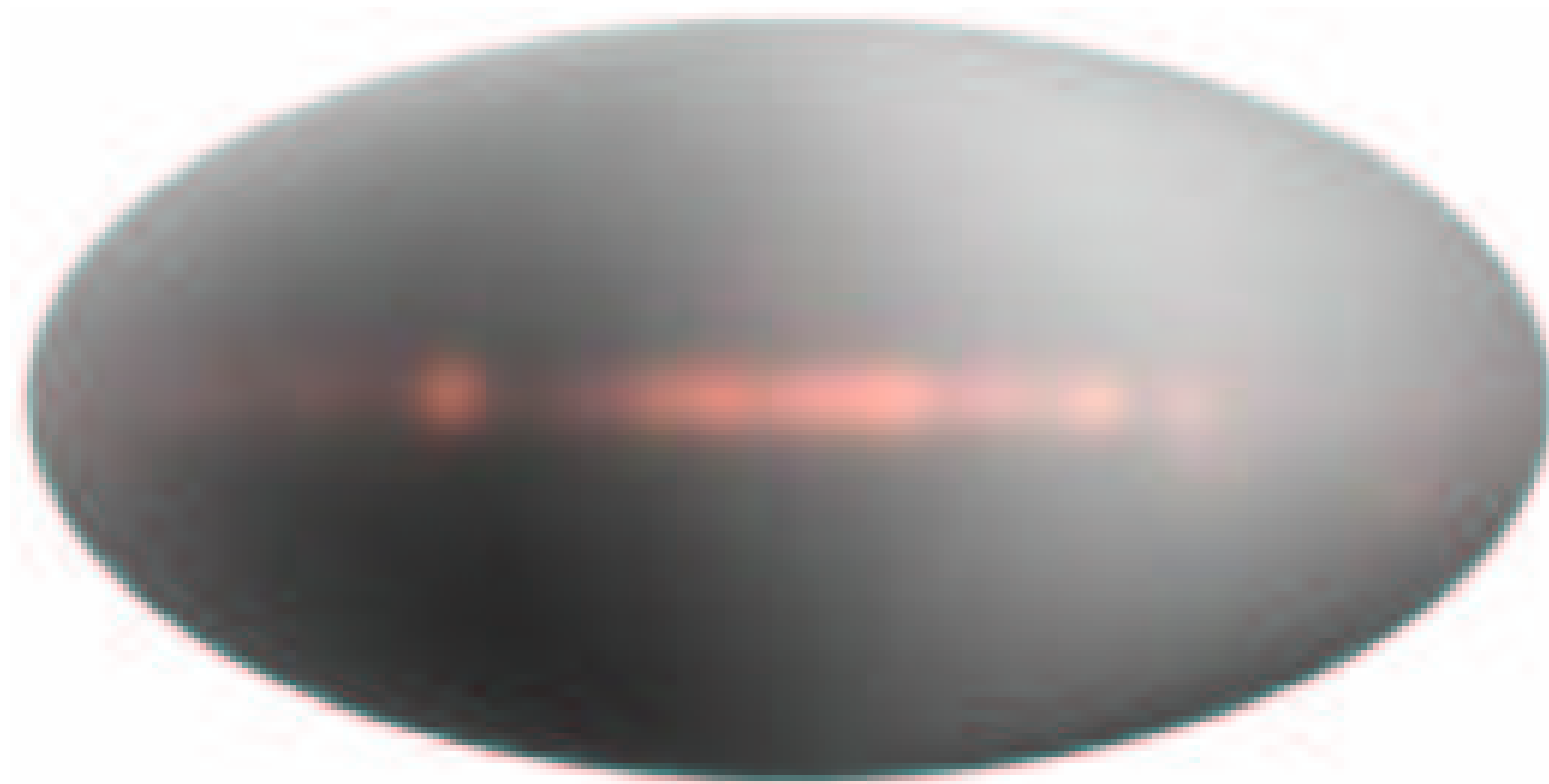VII.   Discussion and Conclusions

COBE CMB Probe
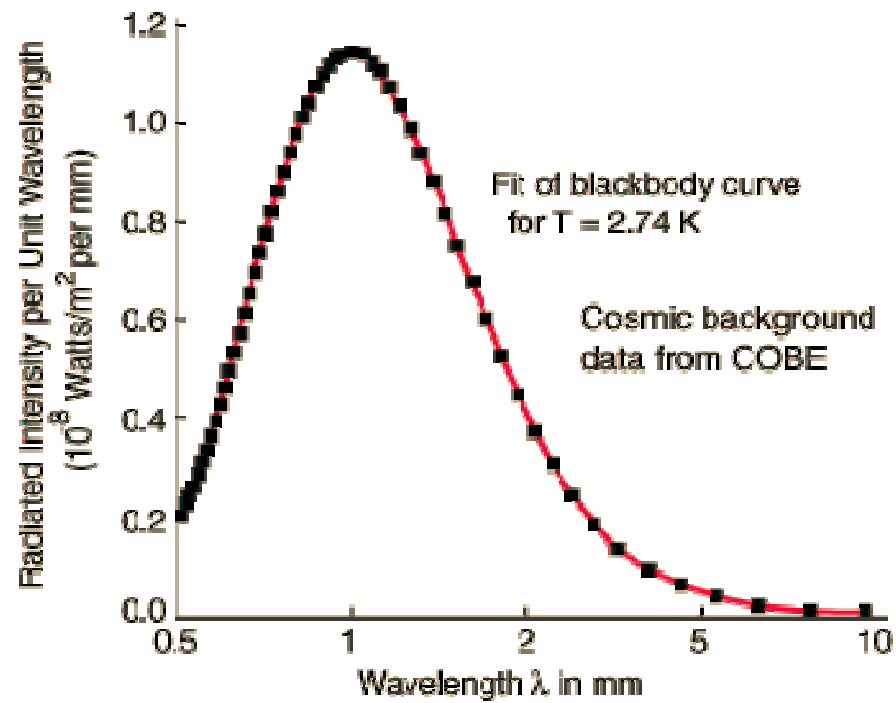
2.725 K Cosmic Microwave Background
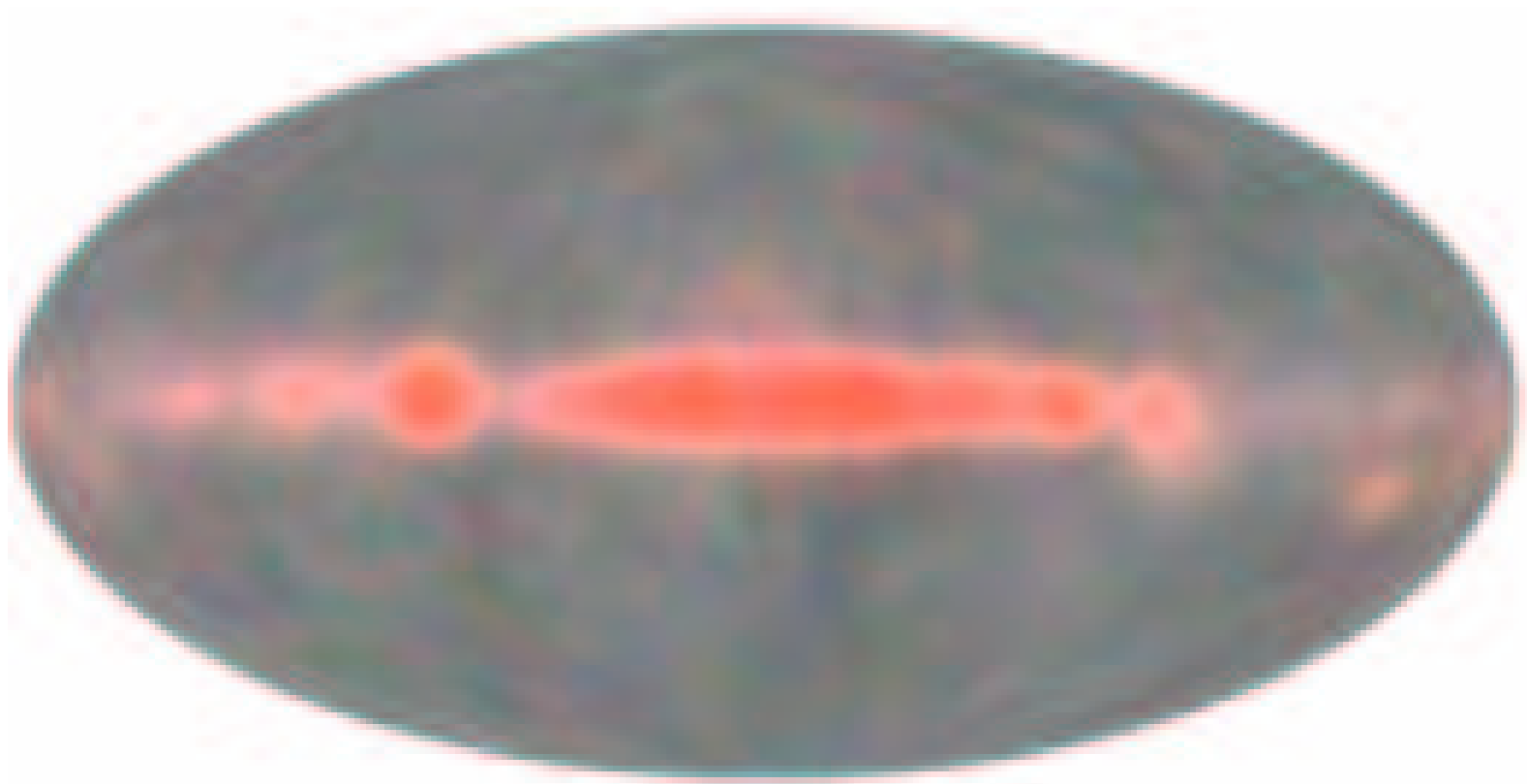
4π true view of sky without enhanced contrast

369 km/sec Dipole pattern

(Contrast times 400)

Temperature variation of plus/minus 0.00335 K

CMB Contrast times 2000

Variation due to Milky Way Galaxy

Remnant of the BIG BANG

Contrast = 30,000 times
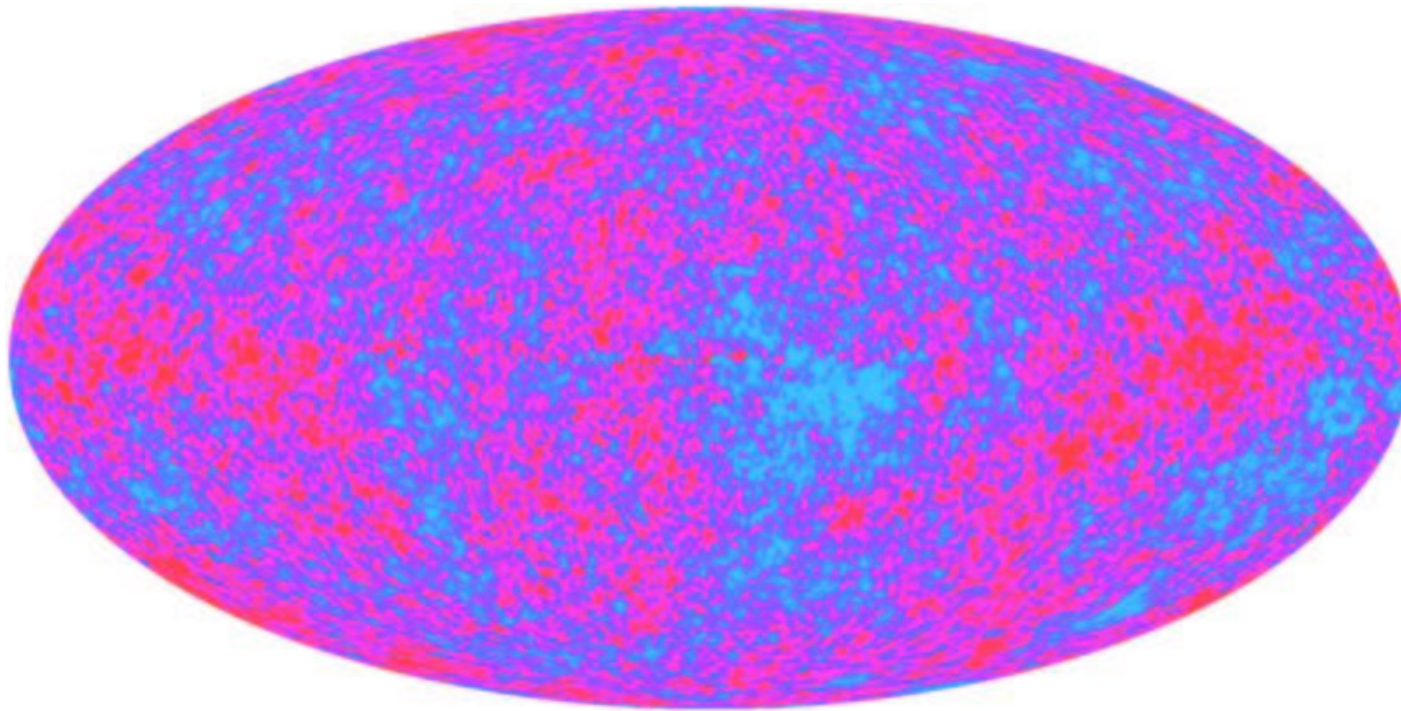
Fluctuations
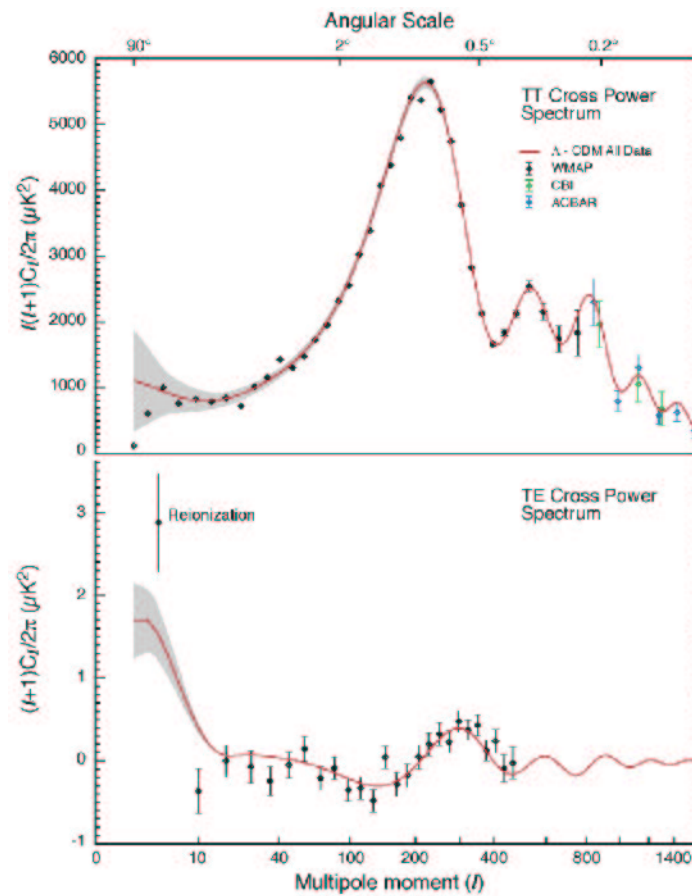
Observed Power Spectrum

The Horizon Problem

A. Why is the Cosmic Microwave Background so uniform?

B. How can there be space-like correlations in the fluctuations and phase?

OUR APPROACH: At sometime in the past, the whole cosmology had global quantum coherence.

We will extrapolate our present understanding of physics backwards until we have trouble with basic concepts.

Quantum Basics

Space-Like Correlations: Vacuum expectation values of the symmetric sum of a field operator at different points is non-vanishing for space-like related events

$$< vac \mid \phi(x)\phi(y) + \phi(y)\phi(x) \mid vac >= \frac{1}{4\pi^2 s^2}$$

$$s^2 = \mid \vec{x} - \vec{y} \mid^2 - \left(x^0 - y^0\right)^2$$

Since the vacuum expectation value of the field is expected to vanish, this requires spacelike correlations

$$< vac \mid \phi(x)\phi(y) + \phi(y)\phi(x) \mid vac > \neq$$

$$2 < vac \mid \phi(x) \mid vac >< vac \mid \phi(y) \mid vac >$$

However, the commutator of the field does vanish for space-like separations, preventing measurement at y from changing the probability distribution at x.

Quantum Measurement

The Triangle Inequality: A fundamental limit is placed on quantum measurements due to non-commutivity of operations
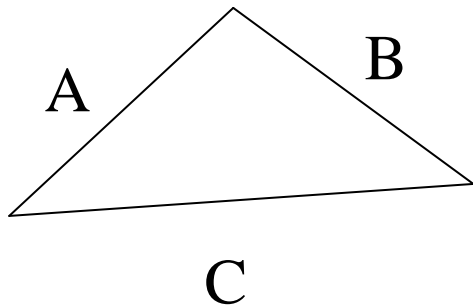
$$C = A + B, \qquad |C| \leq |A| + |B|$$

$$|A||B| \geq |[A,B]|/2$$

Let $A = X - \langle X \rangle, \quad B = P - \langle P \rangle$

$$\Rightarrow \quad \Delta X\, \Delta P \;\geq\; \frac{\hbar}{2}$$

About Zero-Point Motions

- Zero-point motion of sources correspond to vacuum energy of the associated quanta.

- Physical effects associated with the zero point motions do not depend on the coupling constant of the involved interactions, but do depend on the nature of the interaction.

- In physical systems, zero-point motions correspond to saturation of the triangle inequality.

Coherence Length Scales

Zero-point motions

$$\Delta P \, \Delta X = \frac{\hbar}{2}$$

Macroscopic quantum systems

$$k_B T_{crit} \approx thermal\ energies \approx \sqrt{(\Delta P)^2 + m^2} - m \approx \frac{\hbar c}{\xi_{thermal}}$$

$$\Rightarrow \xi_{thermal} \; \lambda_m \approx 8 (\Delta X)^2$$

General zero-point motions

$$\frac{(\Delta P)^2}{2m} = \varepsilon \equiv \frac{\hbar c}{R_\varepsilon} \Rightarrow R_\varepsilon \, \lambda_m = 8 (\Delta X)^2$$

Macroscopic coherence length

Microscopic coherence length

Degenerate Fermi gas

$$n = \frac{g_m}{6\pi^2} (2m\varepsilon_{thermal})^{3/2} \Rightarrow R_\varepsilon \, \lambda_m = \frac{1}{2} \left(\frac{6\pi^2}{g_m} \right)^{2/3} (\Delta X)^2$$

Macroscopic Quantum Systems

- For ^{4}He, atomic spacing, and low particle mass give comparable zero-point energies to the weak inter-atomic forces

- The Casimir effect gives measured effects due to vacuum energy and geometry

- The Casimir effect is equivalent to energies produced by zero-point motions of the sources at absolute zero

- For gravitating masses within their Compton wavelength, we expect significant zero-point motions

$$\Delta p \, \Delta R > \hbar \rightarrow KE \sim \frac{(\Delta p)^2}{2m} \sim \frac{\hbar^2}{2m\overline{V}^{2/3}}$$

$$E_{vacuum} = \sum_{modes} \frac{1}{2}\hbar\omega_k$$

$$\frac{\Delta E_{vacuum}^{plates}}{Area} = -\frac{\pi^2}{720}\frac{\hbar c}{a^3}$$

$$\Delta E_{vacuum}^{sphere} = +0.92353\frac{\hbar c}{a}$$

$$E_o \sim \sqrt{\left(\frac{\hbar c}{\lambda_m}\right)^2 + \left(mc^2\right)^2} \sim \sqrt{2}mc^2$$

$$V \sim -\frac{G_N m^2}{\lambda_m} \sim \frac{m^2}{M_P^2}mc^2 << E_o$$

An Example: Cold Dark Bosonic Matter

For non-relativistic particulate bosonic dark matter, the relationship between number density and critical density for a free bose gas is given by

$$\frac{N_{DM}}{V} = \frac{\zeta(3/2)\Gamma(3/2)}{(2\pi)^2 \hbar^3}\left(2m_{DM}k_B T_{crit}\right)^{3/2} \quad , \quad \rho_{DM} \cong \frac{N_{DM}}{V} m_{DM} c^2$$

$$k_B T_{crit} = \frac{1}{2}\frac{\rho_{DM}^{2/3}}{\left(m_{DM}c^2\right)^{5/3}}\frac{(2\pi)^2\left(\hbar c\right)^3}{\zeta(3/2)\Gamma(3/2)} \cong 1.69\times 10^{-31}\, GeV \;\; \frac{z^2}{g_{m_{DM}}^{2/3}}\left(\frac{GeV}{m_{DM}c^2}\right)^{5/3}$$

The temperature of the photon gas is expected to scale with the redshift when appropriate pair creation threshold effects are properly incorporated. Setting critical temperature the same as the photon temperature

$$z_{crit} = \left(\frac{g(T_{\gamma o})}{g(T_{crit})}\right)^{1/3}\frac{2\,g_{m_{DM}}}{\left(\hbar c\right)^2}\left(\frac{\left(k_B T_{\gamma o}\right)^{3/2}}{\rho_{DM}}\frac{\zeta(3/2)\Gamma(3/2)}{(2\pi)^2}\right)^{2/3}\left(m_{DM}c^2\right)^{5/3}$$

$$\cong 1.38\times 10^{18}\left(\frac{g(T_{\gamma o})}{g(T_{crit})}\right)^{1/3} g_{m_{DM}}^{2/3}\left(\frac{m_{DM}c^2}{GeV}\right)^{5/3}$$

where g(z) counts the number of low mass degrees of freedom available at redshift z. Transition is non-relativistic if $T_{crit} < m_{DM}$

$$\Rightarrow m_{DM} > \frac{15\ eV}{g_{m_{DM}}}$$

Particulate Dark Matter/Photon Ratio

Adiabatic expansion is expected to preserve the ratio of particulate dark matter number to photon number. Relating photon energy density to number density gives

$$\frac{N_{DM}}{N_\gamma} = \frac{\zeta(4)\,\Gamma(4)}{\zeta(3)\,\Gamma(3)} \left(\frac{\Omega_{DMo}}{\Omega_{\gamma o}} \right) \frac{k_B T_{\gamma o}}{m_{DM} c^2}$$

$$\cong 3.70 \times 10^{-9} \left(\frac{GeV}{m_{DM} c^2} \right)$$

This should give a phenomenological handle on the thermalization process for the dark matter.

De-Coherence Due to Microscopic Scale

- One expects a quantum phase change occurs when the energy density of the expanding cosmology reaches a critical density within a region of coherence λ_m.
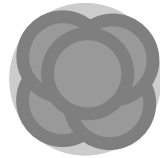
$$R < R_\varepsilon$$
$$\rho_M > \rho_m$$
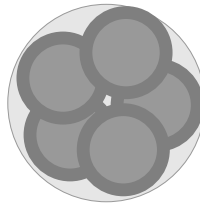
$$R = R_\varepsilon$$
$$\rho_M \cong \rho_m$$
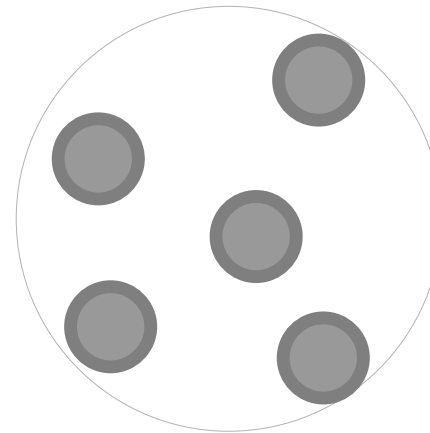
$$R > R_\varepsilon$$
$$\rho_M < \rho_m$$

Einstein's Equation

- Experiments by Overhauser, et.al. have demonstrated gravitation of coherent systems
- We will assume that Einstein's equation describes the evolution of the cosmology during the epoch of interest (post-decoherence)

$$G_{\mu\nu} \equiv \Re_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \Re = \frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Purely
Geometric

Conserved energy-
momentum tensor

A big blunder

Cosmological Constant

$\Omega_m = 0.00, 0.16, 0.32, 0.48, 0.64, 0.80, 1.00$
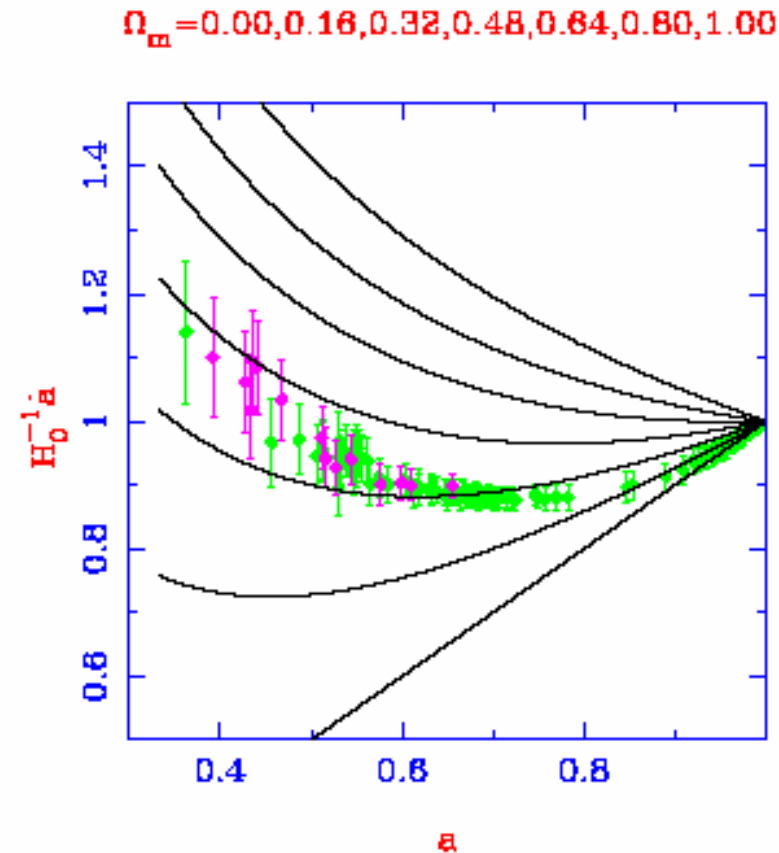
Observed deceleration followed by acceleration in late times is best fit by a cosmological constant.

Friedmann-Robertson-Walker-Lemaitre Cosmology

- Assume a spatially homogeneous and isotropic cosmology (The cosmological principle) $\rightarrow$ FRW metric

$$ds^2 = -c^2 dt^2 + R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\vartheta^2 + r^2 \sin^2 \vartheta\, d\varphi^2\right)$$

- Assume an ideal fluid as the form for the energy-momentum tensor in Einstein's equation $\rightarrow$ FL equations

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3}(\rho + \rho_\Lambda) - \frac{k}{R^2}$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G_N}{3}(\rho + 3P - 2\rho_\Lambda)$$

Zero-Point Motions

Uncertainty for quantum energy scale $\quad \Delta E\,\Delta t \geq \dfrac{\hbar}{2} \quad,\quad \Delta E \equiv \varepsilon \equiv \dfrac{\hbar c}{R_\varepsilon}$

Radiation dominated cosmology $\qquad \dfrac{R_\varepsilon}{R_{DC}} = \sqrt{\dfrac{t_\varepsilon}{t_{DC}}} \quad,\quad \dot{R}_{DC} \equiv c \quad,\quad t_{DC} \equiv \dfrac{R_{DC}}{2c}$

F-L Equation $\qquad \left(\dfrac{\dot{R}}{R}\right)^2 \cong \dfrac{8\pi G_N}{3c^4}\,\rho_{DC}\,\dfrac{R_{DC}^4}{R^4} = \dfrac{c^2 R_{DC}^2}{R^4} \Rightarrow \dfrac{\dot{R}}{c} = \dfrac{R_{DC}}{R}$

$$\Delta t_\varepsilon \cong t_{DC}\left(\dfrac{R_\varepsilon}{R_{DC}}\right)^2 \quad,\quad \Delta E \Delta t_\varepsilon \cong \dfrac{\hbar}{2}\dfrac{c}{\dot{R}_\varepsilon} \quad \Rightarrow \quad \dot{R}_\varepsilon \leq c$$

De-coherence Criterion

Null geodesic (Radiation dominated only) $\qquad c\,dt = R\,d\chi \quad,\quad \Delta\chi_{DC} = \int_0^{t_{DC}} \dfrac{c\,dt'}{R(t')} = 1$

$$D_{Horizon} = R_{DC}\,\Delta\chi_{DC} = R_{DC}$$

Spatial Flatness

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3c^2}(\rho + \rho_\Lambda) - \frac{kc^2}{R^2}$$

An open universe with k=-1 is excluded from undergoing the de-coherence transition due to the dark energy term. A closed universe with k=+1 never expands enough for structure to form.

$$0 = \frac{8\pi G_N}{3}\left(\rho(R_{max}) + \rho_\Lambda\right) - \left(\frac{c}{R_{max}}\right)^2 \Rightarrow R_{max}^2 \cong 2R_{DC}^2$$

For a flat cosmology, the density at de-coherence is given by

$$\rho_{DC} \equiv \frac{3c^2}{8\pi G_N}\left(\frac{c}{R_{DC}}\right)^2 - \rho_\Lambda$$

De-Coherence Extrapolation

If the cosmology remains radiation dominated in the standard way down to $t=0$, then the scale parameter satisfies

$$R(t) = \left(\frac{t}{t_{DC}} \right)^{1/2} \Rightarrow t_{DC} = \frac{R_{DC}}{2c}$$

Using the FL densities at radiation-matter (dust) equality $\rho_M(z_{eq}) = \rho_{rad}(z_{eq})$ one can extrapolate back to the de-coherence period. Ignoring threshold effects (which give small corrections near particle thresholds while they are non-relativistic), this gives

$$1 + z_{DC} = \left(\frac{\rho_{DC}}{\rho_{Mo}} \left(1 + z_{eq} \right) \right)^{1/4} \cong \left(\frac{c}{H_o R_{DC}} \right)^{1/2} \left(\frac{1 + z_{eq}}{\Omega_{Mo}} \right)^{1/4}$$

Here, Ω_{Mo} is the present normalized non-relativistic mass density. The scale parameter at the present time is then expressed in terms of this redshift using the usual definition

$$R_o = \left(1 + z_{DC} \right) R_{DC}$$

Scale Evolution

The evolution of the cosmology during the period for which the dark energy density is de-coupled from the FL energy density is modeled using the FL equations. There is a period of deceleration, followed by acceleration towards a De Sitter expansion. The rate of scale parameter expansion is sub-luminal during a finite period of this evolution, as shown in the Figures.
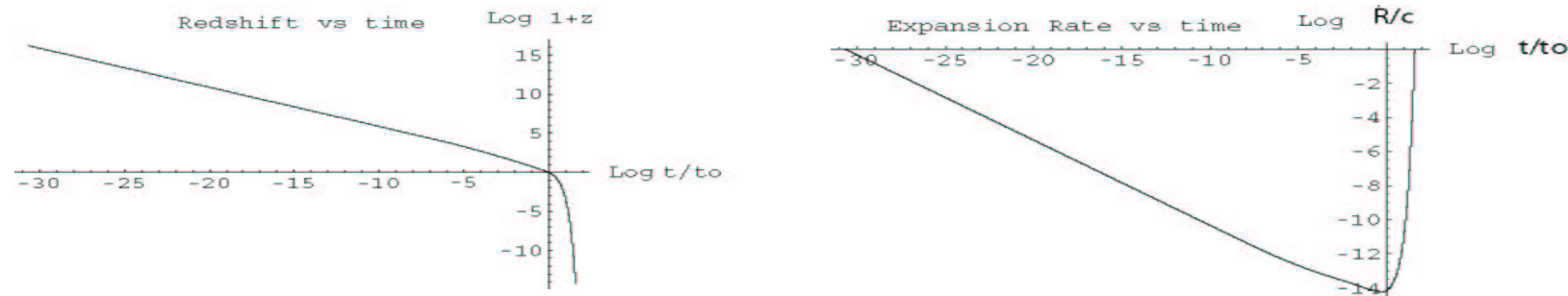
The particular value for the scale at de-coherence is determined by the microscopic makeup of the dark energy. Present time corresponds to the origin on both graphs. The value of the expansion rate is c for $R=R_{DC}$, as well as when the expansion scale reaches the De Sitter radius

$$R_\Lambda \equiv \sqrt{\frac{3}{\Lambda}} \approx 10^{28}\ cm \approx 1.6 \times 10^{10}\ ly$$

More on Zero-Point Motions

- We will assume that the cosmological vacuum energy is due to the zero point motions just at the availability of luminal equilibrations

$$\rho_\Lambda = \frac{\varepsilon}{(R_\varepsilon)^3} = \frac{\varepsilon^4}{(\hbar c)^3} \qquad \varepsilon \cong 2.37 \times 10^{-12} \, GeV$$

This means that the cosmological constant is fixed by the physical condition of luminal expansion rate (and the associated de-coherence) being met. At this stage no further assumption of microscopic scale will be made. We will construct the mass units responsible.

Cosmological Energy Density

Energy per particle $\qquad mass = M \quad , \quad \tilde{\varepsilon} \equiv \dfrac{\varepsilon}{N} \cong \dfrac{(\Delta P)^2}{2M} = \dfrac{\hbar^2}{8M(\Delta X)^2}$

Require that momentum coherence scale is same as energy coherence scale

$\Delta X = R_\varepsilon$

Masses undergoing zero-point motions

$\tilde{\varepsilon} = \dfrac{\varepsilon}{N} \cong \dfrac{\varepsilon^2}{8Mc^2} \Rightarrow Mc^2 \cong \dfrac{1}{8}N\varepsilon$

Expected energy density

$\rho \cong \dfrac{NMc^2}{R_\varepsilon^3} = \dfrac{1}{8}N^2\dfrac{\varepsilon^4}{(\hbar c)^3} = \dfrac{1}{8}N^2\rho_\Lambda$

$If \ \rho = \rho_{DC} = \dfrac{3}{8\pi}\dfrac{\left(M_P c^2 \varepsilon\right)^2}{(\hbar c)^3}\left(\cong 9.97 \times 10^{13} GeV^4\right) \Rightarrow N \cong \sqrt{\dfrac{3}{\pi}}\dfrac{M_P c^2}{\varepsilon}$

$M \cong \dfrac{1}{8}\sqrt{\dfrac{3}{\pi}}M_P$ Planck Mass scale units are undergoing the zero-point motions. ε is still arbitrary!

If space-time were Schwarzschild, the density is about that associated with a black hole

$\dfrac{R_S}{R_{DC}} \sim 1$

Dark and Cosmological Energy

Friedmann-Lemaitre Equation
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3}(\rho + \rho_\Lambda)$$

Dark energy de-coherence condition
$$\left(\frac{c}{R_\varepsilon}\right)^2 = \frac{8\pi G_N}{3}(\rho_\varepsilon + \rho_\Lambda)$$

$$= \frac{8\pi G_N}{3}\left(N_\varepsilon + \frac{1}{2}\right)\frac{\hbar\omega_\varepsilon}{R_\varepsilon^3} \equiv \frac{8\pi G_N}{3}(2N_\varepsilon + 1)\varepsilon^4$$

Number of collective mode quanta (gravons) in the de-coherent mode

"Vacuum energy"

De-coherent energy density for quantized energy mode ε
$$\rho_\varepsilon \equiv \frac{3}{8\pi}\left(M_P c^2 \varepsilon\right)^2 = 2N_\varepsilon \varepsilon^4 \cong \frac{1}{8}N^2 \varepsilon^4$$

N_ε is the number of "gravons", N is the number of coherent Planck mass units.

Why Does Dark Energy Freeze Out?

• The coherent collective modes of Planck mass units have been referred to as *gravons*.

• The zero point motions of these coherent Planck mass sized units have been shown to correspond to the vacuum energy of the gravons.

• After de-coherence, the coherence scale changes from R_ε to microscopic scale λ_m or $\Delta x \ll R_\varepsilon$ (ie a phase transition occurs).

$$2N_\varepsilon \varepsilon^4 \quad \Rightarrow \quad \rho_{DC} \equiv \rho_\varepsilon \quad \longleftarrow \quad \text{Friedmann-LeMaitre energy density}$$

$$\varepsilon^4 \quad \Rightarrow \quad \rho_\Lambda \quad \longleftarrow \quad \text{Dark energy density}$$

The vacuum energy of the gravons (or zero point motions of the coherent Planck scale mass units) de-cohere from the FL energy density, microscopically freezing this out as dark energy.
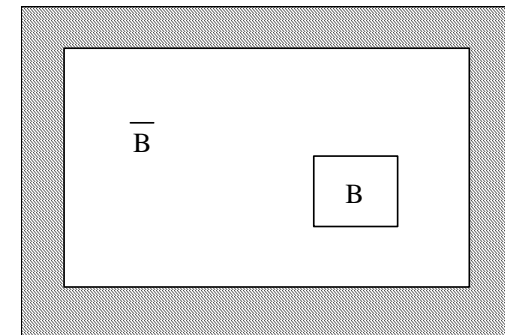
Statistical Dark Energy Partitions

Vacuum energy density physically manifests in the Casimir effect. Lifshitz and his collaborators demonstrated that the Casimir force can be thought of as the superposition of the van der Waals attractions between individual molecules that make up the attracting media resulting from the zero-point motions of the sources. Since these motions are inherently a quantum effect for systems which manifest vacuum energy, one expects space-like correlations consistent with a quantum phenomenon.

A weakly interacting sea of the quantum fluctuations due to zero point motions should establish statistical variations in this ``dark energy" density during de-coherence. One should be able to use simple counting arguments to quantify these variations. If the zero-point motions of the sources have a statistical weight $\Omega(E_B)$ associated with a partition B having energy E_B while holding total energy fixed, then the probability of such a partitioning is given by

$$P(E_B) = \frac{\Omega(E_B)}{\Omega_{tot}} = \frac{\Omega_B(E_B)\Omega_{\bar{B}}(E_{tot} - E_B)}{\Omega_{tot}}$$

where $\overline{B}$ represents all external to the B partition.

Statistics of Fluctuations

Requiring that the most likely configuration of energy partitions results when (the log of) this probability is maximized, this distribution gives a uniform dark energy distribution if

$$\frac{1}{E_\Lambda} \equiv \frac{d}{dE_B} \log \Omega(E_B)$$

(zeroth law of thermodynamics) Here E_Λ is an intensive energy associated with the statistical bath and boundary conditions. If one next examines a "small" partition B for which the reservoir has energy E_{tot}-E_B, one can examine the (log of the) lowest order fluctuations from the reservoir to show

$$\Omega_{\bar{B}}(E_{tot} - E_B) \cong \Omega_{\bar{B}}(E_{tot})\, e^{-E/E_\Lambda}$$ thus defining a probability distribution

$$P(E) = \frac{e^{-E/E_\Lambda}}{\sum_{E'} e^{-E'/E_\Lambda}}$$

For such an ensemble, the fluctuations satisfy the usual relation

$$\left\langle (\delta E)^2 \right\rangle = E_\Lambda^2 \frac{d}{dE_\Lambda} \left\langle E \right\rangle$$

Equation of State

A typical equation of state will connect the extensive variable *<E>* to a dimensionless extensive variable that counts the available degrees of freedom N_{DoF}. A general equation of state satisfies

$$E = N_{DoF} \frac{E_\Lambda^a}{e^{a-1}}$$

$$\Rightarrow \frac{\left\langle (\delta E)^2 \right\rangle}{\left\langle E \right\rangle^2} = a \frac{E_\Lambda}{E} \sim \frac{1}{N_{DoF}}$$

e is an internal energy scale

In terms of the densities, one can directly write

$$\frac{\left\langle (\delta E)^2 \right\rangle}{\left\langle E \right\rangle^2} = \frac{\left\langle (\delta\rho)^2 \right\rangle}{\left\langle \rho \right\rangle^2} \sim \frac{\rho_\Lambda}{\rho}$$

This means that the amplitude of relative fluctuations $\delta\rho/\rho$ is expected to be of the order

$$\Delta \equiv \left(\frac{\rho_\Lambda}{\rho} \right)^{1/2}$$

Pre-coherence and De-coherence

- We define dark energy de-coherence to occur when the relevant FRW expansion rate is c. We have found this to be most consistent with a flat space.

$$\left(\frac{c}{R_\varepsilon}\right)^2 = \frac{8\pi G_N}{3}\left(\rho_{DC} + \rho_\Lambda\right) \cong \frac{8\pi G_N}{3}\rho_{DC}$$

- This allows us to calculate the temperature of a thermal system at de-coherence as (or into which) the FL energy density thermalizes.

$$\rho_{DC} = g(T_\varepsilon)\frac{\pi^2}{30}\frac{(k_B T_\varepsilon)^4}{(\hbar c)^3}$$

Fluctuations

- The quantum fluctuations which become manifest during de-coherence are driven by the vacuum energy. This gives the scale of the amplitude of density fluctuations as

$$\left.\frac{\delta\rho}{\rho}\right|_{de-coherence} \sim \left(\frac{\rho_\Lambda}{\rho_{DC}}\right)^{1/2} \sim \left(\frac{1}{N_{DoF}}\right)^{1/2}$$

- Recall that the red shift at de-coherence is

$$1 + z_{DC} = \left(\frac{\rho_{DC}}{\rho_{Mo}}\left(1 + z_{eq}\right)\right)^{1/4} \cong \left(\frac{c}{H_o R_{DC}}\right)^{1/2} \left(\frac{1 + z_{eq}}{\Omega_{Mo}}\right)^{1/4}$$

CMB Fluctuations

Adiabatic perturbations (those that fractionally perturb the number densities of photons and matter equally) grow according to

$$\Delta = \begin{cases} \Delta_{DC}\left(\dfrac{R(t)}{R_{DC}}\right)^2 & \text{radiation} - \text{dominated} \\[4mm] \Delta_{eq}\left(\dfrac{R(t)}{R_{eq}}\right) & \text{matter} - \text{dominated} \end{cases}$$

An estimation of the scale of fluctuations at last scattering is given by

$$\Delta_{LS} = \left(\frac{R_{LS}}{R_{eq}}\right)\left(\frac{R_{eq}}{R_{DC}}\right)^2 \Delta_{DC} = \frac{(1+z_{DC})^2}{(1+z_{eq})(1+z_{LS})}\Delta_{DC}$$

Size of Fluctuations

The energy driving fluctuations during dark energy de-coherence is expected to be given by the cosmological dark energy. This means that the amplitude of relative fluctuations δρ/ρ is expected to be of the order

$$\Delta_{DC} \equiv \left(\frac{\rho_\Lambda}{\rho_{DC}} \right)^{1/2} = \frac{R_{DC}}{R_\Lambda}$$

Using the previous equations, this amplitude at last scattering is given by

$$\Delta_{LS} = \frac{(1+z_{DC})^2}{(1+z_{eq})(1+z_{LS})} \frac{R_{DC}}{R_\Lambda} \cong \frac{1}{1+z_{LS}} \sqrt{\frac{\Omega_{\Lambda o}}{(1-\Omega_{\Lambda o})(1+z_{eq})}} \approx 2.6 \times 10^{-5}$$

where a spatially flat cosmology has been assumed. This estimate is independent of the scale parameter during de-coherence R_{DC}, and is of the order observed for the fluctuations in the CMB. Fluctuations in the CMB at last scattering of this order are consistent with the currently observed clustering of galaxies.

DE-COHERENCE DURING DUST/PLASMA DOMINATION

The previous results have demonstrated NO dependency on the energy density during the transition period if de-coherence occurs during radiation domination. For completeness, the amplitude of expected fluctuations if the phase transition occurs during the dust/plasma dominated era is next examined. The acoustic wave has coherent phase information that is transmitted to the CMB at last scattering. There must have been a significant enough passage of time from the creation of the acoustic wave to the time of last scattering such that peaks and troughs of the various modes should be present $\delta t > D_s/v_s$, where D_s is the distance scale of the longest wavelength (sound horizon), and $v_s \sim c / \sqrt{3}$ is the speed of the acoustic wave.

Generally, if the phase transition occurs while the energy density is dominated by dust/plasma, prior to last scattering then the amplitude satisfies

$$\Delta_{LS} \cong \left(\frac{1+z_{DC}}{1+z_{LS}} \right) \sqrt{\frac{\Omega_{\Lambda o}}{\left(1-\Omega_{\Lambda o}\right)\left(1+z_{DC}\right)^3 \left(1+\frac{1+z_{DC}}{1+z_{eq}}\right)}}$$

which varies from 2×10^{-5} if the phase transition occurs at radiation dust equality, to 4×10^{-5} if it occurs at last scattering.

Thermalization Scenarios

- System undergoes a thermal phase transition at de-coherence

- System undergoes an inflationary transition at de-coherence

- System undergoes a purely quantum phase transistion at de-coherence

- System initially classical

Thermal Expansion

Assume the cosmology remains a hot radiation dominated thermal system during de-coherence with the microscopic degrees of freedom due to the particle spectrum included.

$$\rho_{DC} = \frac{8\pi}{3}\left(M_P^2 \varepsilon^2\right) = g\left(T_{DC}\right)\frac{\pi^2}{30}\left(k_B T_{DC}\right)^4$$

$$\Rightarrow k_B T_{DC} \cong 1298\ GeV$$

Here $g(T_{DC})$ counts the number of degrees of freedom associated with particles of mass $mc^2 \ll k_B T_{DC}$, and M_P is the Planck mass.

This would correspond to a redshift of

$$z_{DC} \cong 1.35 \times 10^{16}$$

Dark Matter Condensation

If the de-coherence scale corresponds to the evaporation of a dark matter condensate, the mass scale of the dark matter can be determined

$$z_{DC} \cong 1.35 \times 10^{16}$$

$$z_{crit} \cong 1.38 \times 10^{18} \left(\frac{g(T_{\gamma o})}{g(T_{crit})} \right)^{1/3} g_{m_{DM}}^{2/3} \left(\frac{m_{DM} c^2}{GeV} \right)^{5/3}$$

$$\Rightarrow \quad m_{DM} c^2 \cong \frac{0.107 \, GeV}{g_{m_{DM}}^{2/5}}$$

Inflationary Transition

If the energy density at de-coherence is the inflationary dark energy density, this then defines the de-Sitter scale of inflation

$$\rho_{\Lambda_i} = \frac{\Lambda_i}{8\pi G_N} = \frac{3}{8\pi} M_P^2 \varepsilon^2 \Rightarrow \Lambda_i = \frac{3}{R_\varepsilon^2}$$

Scale associated with present cosmological constant defines inflationary scale

De Sitter entropy

$$S_\varepsilon = \frac{A_\varepsilon}{4G_N} = \pi \left(\frac{M_P c^2}{\varepsilon} \right)^2 k_B$$

De Sitter temperature at de-coherence

$$k_B T_\varepsilon = \frac{1}{2\pi R_\varepsilon} = \frac{\varepsilon}{2\pi}$$

This means that the scale of the horizon temperature during inflation is comparable to the dark energy today (ie the thermal energy from the previous expansion corresponds to the dark energy of the present expansion). We indeed expect this thermal energy to drive the initial fluctuations!

What's So Special about ε ?

Thus far, ANY value for ε will give the observed scale for the amplitude of fluctuations in the CMB. The observed scale of the dark energy might just be a random fluctuation. One might alternatively expect microscopic physics to fix the particular scale as a quantum phase transition associated with a UV momentum or mass scale for the gravitational modes.

$$\rho_{\Lambda_i} = \frac{1}{V} \sum_{P_{IR}}^{P_{UV}} \frac{1}{2} \hbar c P_j \cong \left(\frac{1}{2\pi}\right)^2 \frac{1}{4} P_{UV}^4 \equiv m_{UV}^4$$

Space filling until phase transition at de-coherence

$$m_{UV} \cong 3160 \, GeV$$

At de-coherence, actual masses m separated by their Compton wavelengths can produce this energy density. Such particles would have coherence distances satisfying

$$8(\Delta X)^2 \cong R_\varepsilon \lambda_m \quad , \quad \frac{(\Delta P)^2}{2m} \cong \varepsilon \qquad \text{Independent of coupling!}$$

Input of Microscopic Scale

- ΔX and λ_m are microscopic scales.
- Critical density of cosmology must be reached before microscopic mass scale can "de-cohere". Prior to reaching this density there is no space to de-cohere into.
- Many mass units are still within the coherence distance, leading one to suspect a macroscopic quantum system
- Expected equation of state

$$E = \frac{1}{8} N^2 \varepsilon = m_{UV}^4 \varepsilon^3 \implies \frac{\left\langle (\delta\rho)^2 \right\rangle}{\left\langle \rho \right\rangle^2} = 3 \frac{\rho_\Lambda}{\rho_{DC}}$$

Loss of IR Modes

Assume spatially flat FRW Cosmology, and a harmonic oscillator

$$\mathcal{L} = \frac{1}{2}\left(-g^{\mu\nu}\partial_\mu\psi\,\partial_\nu\psi - \omega^2\psi^2\right) \quad ; \quad W = \int \sqrt{-g}\;\mathcal{L}\,d^4x$$

$$\ddot{\psi} - \frac{1}{R^2}\nabla^2\psi + \omega^2\psi + 3\left(\frac{\dot{R}}{R}\right)\dot{\psi} = 0$$

Expect significant damping if frequencies are of Hubble scale

Similarly, using quantum measurability arguments, quantized energy scale E_{IR} cannot satisfy uncertainty relation prior to time

$$\dot{R}_{IR} = c\;,\; R_{IR} \equiv \frac{\hbar c}{E_{IR}}\;,\; t_{IR} = \frac{R_{IR}}{2c} \longleftarrow$$

assuming radiation dominated epoch

Early Time Thermal Behavior

Friedmann-LeMaitre+Quantum Uncertainty imply a loss of IR energy modes as the cosmology becomes denser going back in time. If there is a UV gravitating mode (needed for finite vacuum energy density in terms of interaction quanta), then the early time thermal behavior should change from the T^4 behavior far from the cutoff.

$$\sum_{IR}^{UV} \doteq \frac{V}{(2\pi\hbar)^3} \int_{P_{IR}}^{P_{UV}} 4\pi P^2 dP$$

Expect $\left(\frac{P_{UV}}{P_\Lambda}\right)^4 = \frac{8\pi}{3}\left(\frac{M_P c^2}{\varepsilon}\right)^2 = \frac{8\pi^2}{9}N^2$

As the IR cutoff approaches the UV cutoff, the thermal energy should behave as

$$U = U_{IR} + g(T)\frac{4\pi V}{(2\pi\hbar)^3}(P_{UV}c)^4 \frac{1-\dfrac{P_{IR}}{P_{UV}}}{e^{P_{UV}c/k_B T}-1}$$

where U_{IR} might have macroscopic occupation. Stephan's Law is expected to no longer hold.

Alternative Scenarios

In any such scenario, we expect independent (Gaussian) fluctuations to develop in each mode as expansion proceeds.

Scenario 1: Low temperature behavior

Macroscopic occupation in IR mode, reheating of entropy as modes become available

Scenario 2: High temperature bosonic system

$$U = U_{IR} + g(T)\frac{4\pi V}{(2\pi\hbar c)^3}(P_{UV}c)^4\left(1 - \frac{P_{IR}}{P_{UV}}\right)\frac{k_B T}{P_{UV}c}$$

$$S = S_{IR} + g(T)\frac{4\pi V}{(2\pi\hbar c)^3}(P_{UV}c)^4\left(1 - \frac{P_{IR}}{P_{UV}}\right)\frac{k_B}{P_{UV}c}\log\left(\frac{T}{T_{IR}}\right)$$

Black Hole Evaporation

Expected rate of evaporation

$$-\frac{dM_{BH}}{dt} \cong \sum_{\substack{j \\ species}} E_j \frac{dN_j}{dt}$$

Energy/quantum

Emission rate

"Thermal" phase space

$$k_B T_H = \frac{1}{8\pi M G_N} = \frac{1}{8\pi} \frac{\left(M_P c^2\right)^2}{Mc^2} \Rightarrow E_j \cong k_B T_H$$

Most emitted quanta will be s-wave, and the barrier height is proportional to the temperature. This means one expects about 1 quantum per unit Rindler time, which in Schwarzschild time results in

$$\frac{dN_j}{dt} \cong f \, g_j \frac{c}{R_S} \Theta(k_B T_H - m_j c^2)$$

Black hole will not begin emitting particles m_j until its Hawking temperature is sufficient: $k_B T_H > m_j c^2$

$$\mathcal{M}_j \equiv \frac{1}{8\pi} \frac{M_P^2}{m_j}$$

Number of Low Mass Quanta

$$M_{BH}(t_j < t < t_{j+1}) \cong \left(\boldsymbol{\mathcal{M}_j^3} - \frac{3f}{16\pi} g(m_j) M_P^4 \frac{c^2}{\hbar}(t - t_j) \right)^{1/3}$$

$$N_j(t_j < t < t_{j+1}) \cong 4\pi \frac{g_j}{g(m_j)} \left\{ \left(\frac{\boldsymbol{\mathcal{M}_j}}{M_P} \right)^2 - \left(\left(\frac{\boldsymbol{\mathcal{M}_j}}{M_P} \right)^3 - \frac{3f}{16\pi} g(m_j) \frac{M_P c^2}{\hbar}(t - t_j) \right)^{2/3} \right\}$$

If the subscript F represents the highest mass particle in the spectrum, the total such particles emitted is

$$N_F^{Total} \cong 4\pi \frac{g_F}{g(m_F)} \left(\frac{\boldsymbol{\mathcal{M}_F}}{M_P} \right)^2 = \frac{1}{16\pi^2} \frac{g_F}{g(m_F)} \left(\frac{M_P}{m_F} \right)^2$$

Similarly, the number of zero mass quanta emitted is

$$N_0^{Total} \cong$$

$$4\pi \left\{ \left(\frac{M_{BH}}{M_P} \right)^2 + \sum_{j=0}^{F-1} g_0 \left(\frac{1}{g(m_{j+1})} - \frac{1}{g(m_j)} \right) \frac{1}{64\pi^2} \left(\frac{M_P}{m_{j+1}} \right)^2 + \frac{1}{64\pi^2} \frac{g_0}{g(m_j)} \left(\frac{M_P}{m_F} \right)^2 \right\}$$

Ratio of Evaporated Particle Number

If initial thermalization into the particle spectrum proceeds primarily through black hole evaporations, ratios of gravitating only masses should be fixed at this stage. If dark matter only gravitates, the number should correspond to

$$\frac{N_{DM}}{N_{\gamma}} \cong 3.70 \times 10^{-9} \left(\frac{GeV}{m_{DM}c^2} \right)$$

If dark matter is particulate, this number should be generated through some sort of gravitational dynamics (ie due to its gravitational coupling $G_N m_{DM}^2$) during this de-coherence phase.

Quantum Early Universe

Examine symmetry breaking in early universe

$$L = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2}\left(D_\mu \Phi_a\right) g^{\mu\nu}\left(D_\nu \Phi_a\right) + \frac{1}{4} m_\Phi^2 \Phi_a^2 - \frac{1}{8} f^2 \Phi_a^4$$

Classical solution, gauge fields vanish A=0

$$|<\Phi_b>| = \frac{m_\Phi}{f} = \frac{m_B}{e}$$

Higgs   Vector Boson

$$T_0^0 = \frac{1}{8}\left(\frac{m_\Phi^2}{f}\right)^2$$

Can argue this as density scale of de-coherence ρ_{DC}

Choosing electro-weak symmetry restoration estimates of the early 90's, Ed Jones predicted a cosmological constant with $\Omega_\Lambda \sim 0.6$ BEFORE this idea was fashionable!

Discussion and Conclusion

- We have shown that de-coherence driven by dark energy gives the expected order for the amplitude of fluctuations in the CMB radiation.

- We generally expect some form of cosmological quantum coherence at a scale far from the Planck scale, implying space-like correlations and phase coherence.

- We expect microscopic luminal interactions to differentiate amongst pre-coherent cosmologies, all of which give the same amplitude of fluctuations, fixing a cosmological constant for sub-luminal scale expansion. For the observed dark energy density, the cosmological density at de-coherence turns out to be given by the electro-weak symmetry scale.

- Spatial flatness is required for observed structure formation using the relevant microscopic scale in the FL equation.

- Some form of microscopic manifestation of gravitational physics is expected on the TeV energy scale.

Acknowledgements

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