A One Parameter Family of Expanding Wave Solutions of the Einstein Equations that induces an Anomalous Acceleration into the Standard Model of Cosmology

Blake Temple, UC-Davis

Collaborator: *J. Smoller*

(PNAS: August 2009)

Expanding wave solutions of the Einstein equations that induce an anomalous acceleration into the Standard Model of Cosmology

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Edited by S.-T. Yau, Harvard University, Cambridge, MA, and approved June 30, 2009 (received for review January 2, 2009)

We derive a system of three coupled equations that implicitly defines a continuous one-parameter family of expanding wave solutions of the Einstein equations, such that the Friedmann universe associated with the pure radiation phase of the Standard Model of Cosmology is embedded as a single point in this family. By approximating solutions near the center to leading order in the Hubble length, the family reduces to an explicit one-parameter family of expanding spacetimes, given in closed form, that represents a perturbation of the Standard Model. By introducing a comoving coordinate system, we calculate the correction to the Hubble constant as well as the exact leading order quadratic correction to the redshift vs. luminosity relation for an observer at the center. The correction to redshift vs. luminosity entails an adjustable free parameter that introduces an anomalous acceleration. We conclude (by continuity) that corrections to the redshift vs. luminosity relation observed after the radiation phase of the Big Bang can be accounted for, at the leading order quadratic level, by adjustment of this free parameter. The next order correction is then a prediction. Since nonlinearities alone could actuate dissipation and decay in the conservation laws associated with the highly nonlinear radiation phase and since noninteracting expanding waves represent possible time-asymptotic wave patterns that could result, we propose to further investigate the possibility that these corrections to the Standard Model might be the source of the anomalous acceleration of the galaxies, an explanation not requiring the cosmological constant or dark energy.

Expansion waves and shock waves are fundamental to conservation laws because, even when dissipative terms are neglected, nonlinearities alone can cause noninteracting wave patterns to emerge from interactive solutions via the mechanism of shockwave dissipation. In this article, we construct a one-parameter family of noninteracting expanding wave solutions of the Einstein equations in which the Standard Model of Cosmology (during the pure radiation epoch) is embedded as a single point.

Our initial insight was the discovery of a set of coordinates in which the critical ($k = 0$) Fiedmann–Robertson–Walker spacetime with pure radiation sources ($p = \rho c^2/3$), referred to here simply as FRW, goes over to a standard Schwarzchild metric form (barred coordinates) in such a way that the metric components depend only on the single self-similar variable $\bar{r}/\bar{t}$ (cf. ref. 1). From this we set out to find the general equations for such self-similar solutions. In this paper we show that the partial differential equations (PDEs) for a spherically symmetric spacetime in Standard Schwarzchild coordinates (SSC) reduce, under the assumption $p = \rho c^2/3$, to a new system of three ordinary differential equations* in the same self-similar variable $\bar{r}/\bar{t}$. After removing one scaling parameter and imposing regularity at the center, we prove that there exists implicitly within the three-parameter family, a continuous one parameter family of self-similar solutions of the Einstein equations that extends the FRW metric.

Because different solutions in the family expand at different rates, our expanding wave equations introduce a acceleration parameter a, and suitable adjustment of parameter a will speed up or slow down the expansion rate. By normalization, $a = 1$ corresponds to the neutral FRW spacetime, $a < 1$ slows it down, and $a > 1$ speeds it up. Using special properties of the spacetime metrics near $a = 1$, we find an exact expression for the leading order (quadratic) correction to the redshift vs. luminosity relation of the standard model that can occur during the radiation phase of the expansion. By the continuity of the subsequent evolution with respect to the acceleration parameter, it follows that the leading order correction implied by an arbitrary anomalous acceleration observed at any time after the radiation phase of the Big Bang can be accounted for by suitable adjustment of the acceleration parameter.

Our proposal for further investigation, then, is to obtain the correction to redshift vs. luminosity induced by the expanding waves at present time by evolving forward, up through the $p = 0$ stage of the Standard Model, the correction induced by the expanding wave perturbations at the end of the radiation phase. Matching the leading order correction to the data will fix the choice of acceleration parameter, and the higher order corrections at that choice of acceleration parameter are then a verifiable prediction of the theory. The point to be made here is that decay to a noninteracting expansion wave would most likely occur during the radiation phase of the expansion because this is when the sound speed and modulus of genuine nonlinearity (GN) [in the sense of Lax (3)] are maximal (4). That is, by standard theory of hyperbolic conservation laws, GN is a measure of the magnitude of nonlinear compression that drives decay via shockwave dissipation, even when dissipative terms are neglected in the equations (cf. refs. 3, 5, and 6). That is why we focus on expanding wave solutions during the radiation phase. After this phase, the pressure drops to $p \approx 0$, and the resulting equations (for dust) have a zero modulus of GN. Thus significant decay should not occur after the uncoupling of radiation from matter. However, even though a self-similar expanding wave created when $p = \rho c^2/3$ should evolve into a noninteracting expansion wave during the $p \approx 0$ phase, there is no reason to believe that the solution would remain self-similar after the radiation phase. Moreover, we see no reason at this stage to assume that these noninteracting expansion waves should describe all of spacetime. As a consequence, the global analysis of solutions, while interesting, is of secondary interest to the purpose of this article, which is to explore the possibility that we might lie near the center of such an expansion

MATHEMATICS

Author contributions: B.T. and J.S. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]We have departed from our usual convention of listing authors alphabetically in order to recognize B.T.'s extraordinary contribution to this particular article.

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*As far as we are aware the only other known way the PDEs for metrics in SSC with perfect fluid sources reduce to ordinary differential equations (ODEs), is the time independent case when they reduce to the Oppenheimer–Volkoff equations (2).

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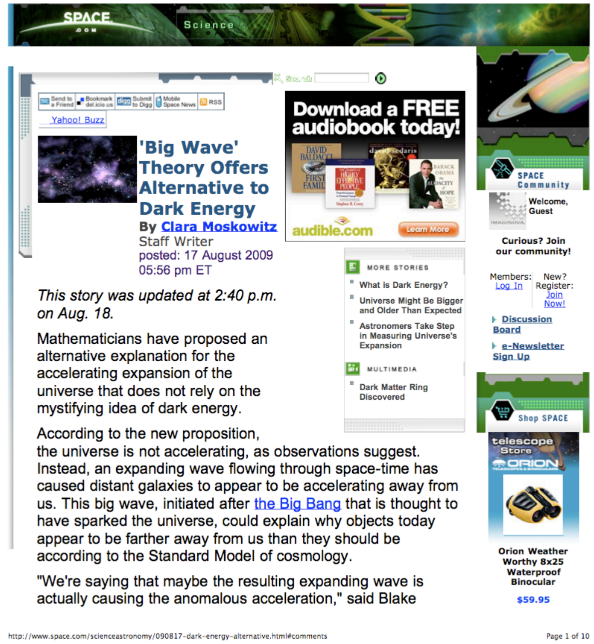
SPACE.com -- 'Big Wave' Theory Offers Alternative to Dark Energy



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'Big Wave' Theory Offers Alternative to Dark Energy

By Clara Moskowitz
Staff Writer
posted: 17 August 2009
05:56 pm ET

This story was updated at 2:40 p.m. on Aug. 18.

Mathematicians have proposed an alternative explanation for the accelerating expansion of the universe that does not rely on the mystifying idea of dark energy.

According to the new proposition, the universe is not accelerating, as observations suggest. Instead, an expanding wave flowing through space-time has caused distant galaxies to appear to be accelerating away from us. This big wave, initiated after the Big Bang that is thought to have sparked the universe, could explain why objects today appear to be farther away from us than they should be according to the Standard Model of cosmology.

"We're saying that maybe the resulting expanding wave is actually causing the anomalous acceleration," said Blake

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Dark Energy's Demise? New Theory Doesn't Use the Force

Ker Than
for National Geographic News

August 18, 2009

Dark energy, a mysterious force proposed more than a decade ago to explain why the universe is flying apart at an increasingly faster clip, is no longer necessary.

That's the conclusion of a controversial new theory that shows how the accelerated expansion of the universe could be just an illusion.

In a new study, two mathematicians present their solutions to Einstein's field equations of general relativity, which describe the relationship between gravity and matter.

The work suggests that our home galaxy sits inside a vast region of space in which there's an unusually low density of matter due to a post-big bang wave that swept through the universe.

From our viewpoint, other galaxies outside this region appear to have moved farther away than expected, when really they're right where they should be.

"If correct, these solutions can account for the anomalous accelerated expansion of galaxies without dark energy," said study team member Blake Temple of the University of California, Davis.

Other experts call the attempt to excise dark energy from models of the universe "commendable." But the same scientists note that the new theory could violate a cornerstone of modern cosmology, which would make dark energy's demise very hard for astronomers to accept.

Dark Energy Alternative

Until 1998 astronomers had thought that gravity should be slowing down the cosmic expansion triggered by the big bang.

That year two independent teams announced data showing that the universe's expansion is speeding up.

Both teams saw that light from distant supernovae appears much fainter than expected—suggesting that the explosions are farther away than they should be if the universe is being driven by the pull of gravity alone.

To explain this observation, astronomers started to entertain the idea of dark energy, a universal repulsive force that is pushing apart the very fabric of space-time.

Still, more than ten years later, no one is sure what dark energy is—or if it really exists.

To find a dark-energy alternative, other scientists have proposed versions of the newly supported theory that our galaxy sits inside an expansion wave, a ripple of space with low density.

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'Big Wave' Theory Offers Alternative to Dark Energy (SPACE.com)

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Mystery solved: Dark energy isn't there

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Mathematicians have come up with an answer Monday for the mystery of "dark energy" tearing the universe apart at an accelerating rate. It ain't there.

Discovered in 1998 with the finding that exploding stars in distant galaxies are spreading away from us at an increasing speed, dark energy has puzzled cosmologists

YAHOO! NEWS
UK & IRELAND

US pair shed light on Dark Energy

Today, 05:36 am
PRESS ASSOCIATION

Two mathematicians have boldly tampered with Albert Einstein's equations to show that "Dark Energy", the mysterious anti-gravity force that theoretically makes up three-quarters of the universe, might not exist after all.

Dark Energy is thought to be the reason why galaxies appear to be accelerating away from each other at increasing speed.

It acts as a kind of anti-gravity force which repels instead of attracts.

Einstein first came up with the idea as a modification to his theory of general relativity. The "cosmological constant", as he called it, was invoked to prevent the universe collapsing under the pull of gravity.

But Einstein was not happy with the concept, and abandoned it after astronomers discovered that the universe might be expanding rather than standing still.

Later it was confirmed that the universe was not only expanding, but accelerating outwards. To account for this acceleration, physicists resurrected the cosmological constant in the new guise of "Dark Energy".

The theory suggests that Dark Energy makes up nearly 75% of the interchangeable mass and energy in the universe.

Two US mathematicians, Professor Blake Temple from the University of California at Davis, and Dr Joel Smoller, from the University of Michigan in Ann Arbor, have now tweaked Einstein's equations in a way that makes Dark Energy unnecessary.

They suggest that expanding waves of space-time could emerge from the initial disturbance caused by the Big Bang that created the universe 14 billion years ago.

Professor Ofer Lahav, head of astrophysics at University College London, who is part of a team investigating Dark Energy, said: "This is a thought-provoking paper, challenging the concept of Dark Energy, one of the biggest mysteries in the history of science. In a nutshell, astronomers found in many different ways that 'Dark Energy' is required in order to explain the data. In this interpretation, 75% of the universe at present is made of Dark Energy."

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'Big Wave' Theory Offers Alternative to Dark Energy

SPACE

This story was updated at 2:40 p.m. on Aug. 18.

Mathematicians have proposed an alternative explanation for the accelerating expansion of the universe that does not rely on the mystifying idea of dark energy.

According to the new proposition, the universe is not accelerating, as observations suggest. Instead, an expanding wave flowing through space-time has caused distant galaxies to appear to be accelerating away from us. This big wave, initiated after the Big Bang that is thought to have sparked the universe, could explain why objects today appear to be farther away from us than they should be according to the Standard Model of cosmology.

"We're saying that maybe the resulting expanding wave is actually causing the anomalous acceleration," said Blake Temple of the University of California, Davis. "We're saying that dark energy may not really be the correct explanation."

The researchers derived a set of equations describing expanding waves that fit Einstein's theory of general relativity, and which could also account for the apparent acceleration. Temple outlines the new idea with Joel Smoller of the University of Michigan in the Aug. 17 issue of the journal Proceedings of the National Academy of Sciences.

While more research will be needed to see if the idea holds up, "the research could change the way astronomers view the composition of our universe," according to a summary from the journal.

To convince other cosmologists, the new model will have to pass muster with further inquiry.

"There are many observational tests of the standard cosmological model that the proposed model must pass, aside from the late phase of accelerated expansion," said Avi Loeb, director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. "These include big bang nucleosynthesis, the quantitative details of the microwave background anisotropies, the Lyman-alpha forest, and galaxy surveys. The authors do not discuss how their model compares to these tests, and whether the number of free parameters they require in order to fit these observational constraints is smaller than in the standard model. Until they do so, it is not clear why this alternative model should be regarded as advantageous."

Johns Hopkins University astrophysicist Mario Livio agreed that to be seriously considered, the model must be able to predict properties of the universe that astronomers can measure.

He said the real test "is in whether they are able to reproduce all the observed cosmological parameters (as determined, e.g. by a combination of the Hubble Constant and the parameters determined by the CMB

Telegraph.co.uk

Dark energy may not actually exist, scientists claim

Dark energy - the mysterious substance thought to make up three-quarters of the universe - may not actually exist, claims new research.

By Richard Alleyne (http://www.telegraph.co.uk/journalists/richard-alleyne/) , Science Correspondent
Published: 7:00AM BST 18 Aug 2009

The concept of dark energy was created by cosmologists to fit Albert Einstein's General Theory of Relativity into reality after modern space telescopes discovered that the Universe was not behaving as it should.

According to Einstein's work, the speed at which the Universe is expanding following the Big Bang should be slower than it actually is and this unexplained anomaly threatened to turn the whole theory upside down. In order to reconcile this problem the concept of dark energy was invented.

But now Blake Temple and Joel Smoller, mathematicians at the University of California and the University of Michigan, believe they have come up with a whole new set of calculations that allow for all the sums to add up without the need for this controversial substance.

The research could change the way astronomers view the composition of our Universe.

The Standard Model of Cosmology, which describes the evolution of the Universe, begins with the Big Bang. Astronomers have recently observed that the galaxies are accelerating as they move away from each other, and cosmologists have sought to explain this unexpected acceleration by introducing the concept of dark energy, which permeates space, propels matter, and accounts for nearly 75 percent of the mass-energy in our Universe.

The new research, published in the Proceedings of the National Academy of Science, is likely to be equally controversial as the work it purports to challenge especially as it relies on our galaxy being at the centre of the Universe - a concept that has been generally disregarded in modern science.

Dr Malcom Fairbairn, particle cosmologist at King's College London, said: "Ever since the concept of dark energy was first mentioned people have been trying to explain it or explain it away. It is a mystery and an inconvenience.

"This is one attempt at it. Whether it is right only time will tell."

Seed Magazineabout

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Erasing Dark Energy

Wide Angle / by Veronique Greenwood / September 24, 2009

Why do we need dark energy to explain the observable universe? Two mathematicians propose an alternate solution that, while beautiful, may raise even **more questions than it answers.**

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Illustration by Mike Pick

Against all reason, the universe is accelerating its expansion.

http://chinese.eurekalert.ort/en/pub.release/2009-08/potn-081409.php

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A universe without Dark Energy

Mathematicians have derived a set of equations that describes our ever-expanding universe using a technique that does not rely on the mysterious, hypothetical concept known as Dark Energy. The research could change the way astronomers view the composition of our universe. The Standard Model of Cosmology, which describes the evolution of the universe, begins with the Big Bang. Astronomers have observed that the galaxies are accelerating as they move away from each other, and cosmologists have rectified this anomalous acceleration by introducing the concept of Dark Energy, which permeates space, propels matter, and accounts for nearly 75 percent of the mass-energy in our universe. This explanation, however, requires introducing the speculative "cosmological constant" to Einstein's equations of general relativity. Blake Temple and Joel Smoller derived a family of expanding wave solutions of Einstein's equation, and their solutions could account for the observed anomalous acceleration of the galaxies without Dark Energy or the cosmological constant. The authors suggest that these expanding waves could emerge in time from the initial disturbance of the Big Bang and propel matter in a manner similar to Dark Energy.

Article #09-01627: "Expanding wave solutions of the Einstein equations that induce an anomalous acceleration into the standard model of cosmology," by Blake Temple and Joel Smoller

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A Big Wave after the Big Bang?

August 18th, 2009 @ 2:06 pm by andy

Mathematicians Blake Temple from UC Davis and Joel Smoller from the University of Michigan have published a new theory to explain why the universe appears to be expanding at an accelerating pace, without invoking "dark energy."

About a decade ago, astronomers realized that the universe is not only expanding — the expansion appears to be speeding up. To explain this, they came up with the concept of dark energy: a force that pushes the galaxies apart. No one knows what dark energy actually is; one idea is that is a sort of energy that bubbles out of the fabric of space as it expands. Physicists' calculations, though, show that it should make up about 70 percent of the universe. (Roughly another 30 percent is made of dark matter, which is nearly as mysterious: matter and energy that we can feel and touch make up a trivial portion of the universe).

Temple and Smoller though, have a different explanation for why the galaxies are further apart than they ought to be. A "big wave," started after the Big Bang at the beginning of the universe, is spreading out through space, pushing the galaxies apart.

"We're saying that maybe the resulting expanding wave is actually causing the anomalous acceleration," Temple told Space.com.

Several other cosmologists quoted by Space.com were sceptical, noting that the new theory needs to explain all the aspects of the known universe, and make predictions that can be checked by astronomers and physicists.

The paper is published in the Aug. 17 issue of the *Proceedings of the National Academy of Sciences*.

For an overview of physics, cosmology and dark energy, read this.

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Dark Energy May Not Exist At All

Quote:

Experts in advanced mathematics have recently proposed a new model to explain our Universe that is so different from what we have held as true thus far, that it has left many gasping for air. According to the new theory, it may be that our Universe is not expanding at all. Rather, galaxies appear to be pushing away from each other on account of a Big Bang-triggered phenomenon aptly named the Big Wave, which is essentially an expanding wave flowing through space-time. The team believes that these waves could help explain why some of the most distant galaxies out there appear to be more distant than they should be, according to the Standard Model of Cosmology (SM).

"We're saying that maybe these expanding waves are actually causing the anomalous acceleration. We're saying dark energy is not really the correct explanation," University of California in Davis (UCD) expert Blake Temple explains. The new set of equations revolves around Einstein's general theory of relativity, but also seems to offer a decent explanation for the observed cosmic expansion. Temple worked on the new calculations with University of Michigan colleague Joel Smoller, and the team published its results in the August 17th issue of the journal Proceedings of the National Academy of Sciences (PNAS).

"The research could change the way astronomers view the composition of our universe," the authors write in the summary of their journal entry, admitting, however, that more verifications are in order before a final conclusion is drawn. They also say that the new equations may prove to be a very potent alternative to dark energy theories simply because the latter were developed hastily, when astronomers discovered that the Universe was expanding at an ever-increasing speed, and had no explanation for this.

Dark energy "just seems like an unnatural correction to the equations – it's like a fudge factor. The equations don't make quite as much physical sense when you put it in. You just put it in to fit the data," Temple says, quoted by Space. "At this stage we think [the new equations are] a very plausible theory. We're saying there isn't any acceleration. The galaxies are displaced from where they're supposed to be because we're in the aftermath

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ABSTRACT: In 1927, the American astronomer Edwin Hubble showed the Universe is expanding: distant galaxies are receding from each other. This confirmed the so-called *Standard Model of Cosmology*, that the universe, on the largest scale, is evolving according to a Friedman-Robertson-Walker spacetime. The starting assumption in this model is the *Cosmological Principle*—that on the largest scale, we are not in a special place in the universe—that the universe is homogeneous and isotropic about every point like the FRW spacetime. In 1998, more accurate measurements of the recessional velocity of distant galaxies based on new Type 1a supernova data, made the astounding discovery that the Universe was actually *accelerating* relative to the standard model. So the Standard Model is incorrect. The explanation for the *Anomalous Acceleration of the Galaxies* is one of the great open problems of physics.

The only way to account for the Anomalous Acceleration *and* preserve the FRW framework and the Cosmological Principle is to modify the Einstein equations by adding a *Fudge Factor* called the *Cosmological Constant.* *Dark Energy*, the physical interpretation of the Cosmological Constant, is then an unknown source of anti-gravitation that, for the model to be correct, must account for some 70 percent of the energy density of the universe. This is stated as a fact on the NASA webpage. In this talk I introduce a new family of expanding wave perturbations of the Standard Model, and explore the possibility that these might account for the Anomalous Acceleration of the galaxies without the Cosmological Constant or Dark Energy. [Joint work with Joel Smoller]

We prove that all of the
self-similar spacetimes
in the family
are distinct from the non-critical
$k \neq 0$ Friedmann spacetimes
thereby *characterizing* the
critical $k = 0$ Friedmann universe as
the unique spacetime
lying at the intersection
of these two one-parameter families.

START

- In the standard model of cosmology, the expanding universe of galaxies evolves from a critically expanding Friedmann Universe $(k = 0,\ p = \frac{c^2}{3}\,\rho)$
- This is the special case of a

Non-interacting
General Relativistic

"Expansion Wave"

- We show that the standard Friedmann Universe $(k = 0,\ p = \frac{c^2}{3}\,\rho)$ can be extended to a 3-parameter family of exact non-interacting expansion waves in GR
- Removing a scaling law and imposing regularity at the center this reduces to a 1-parameter family of distict spacetimes that include the standard model, and introduce a correction to the Hubble constant

- Since non-interacting self-similar expansion waves represent possible time-asymptotic solutions in the theory of conservation laws:
- Q: Could corrections account for the anomalous acceleration of the galaxies w/o cosmological constant/dark energy?
- Q: A new set of solutions to test against the observations?

INTRODUCTION
TO
COSMOLOGY

Edwin Hubble (1889-1953)

- Hubble's Law (1929):

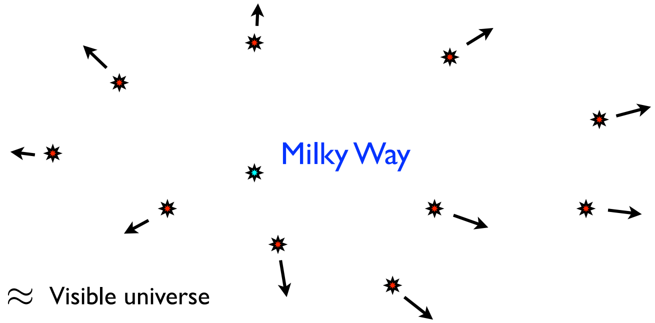
``The galaxies are receding from us at a velocity proportional to distance"

↓

Universe is Expanding

- Based on Redshift vs Luminosity

Cosmic Length Scales



- 10 billion lightyears ≈ Visible universe
  - 1 billion lightyears ≈ Uniform density
- 50 million lightyears ≈ Separation between clusters of galaxies
  - 10 million lightyears ≈ Diameter of a cluster
- 1 million lightyears ≈ Separation between galaxies in a cluster
  - 100 thousand lightyears ≈ Distance across Milky Way
- 28 thousand lightyears ≈ Distance to galactic center
  - 4 lightyears ≈ Distance to the nearest star

Standard Model of Cosmology

- 1922 *Alexander Friedmann*:

  Derived FRW solutions of the Einstein equations:
  3-space of constant curvature expanding in time:

$$ds^2 = -dt^2 + R(t)^2 \left\{ \frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right\}$$

- The Big Bang theory based on the FRW metric was worked out by *George Lemaître* in the late 1920's leading to Hubble's comfirmation of redshift vs luminoscity consistent with an FRW spacetime

$$\text{Hubble's Constant} \equiv H \equiv \frac{\dot{R}}{R}$$

- In 1935: Howard Robertson and Arthur Walker derived FRW from the

Copernican Principle:
"Earth is not in a special place in the Universe"

- R-W proved: FRW uniquely determined by condition

Homogeneous and Isotropic about every point

↓

Any point can be taken as $r = 0$

↓

Each t=const surface is a 3-space of constant scalar curvature

Standard Model of Cosmology

Observations of the
micro-wave background
IMPLY

$$k = 0$$

"Critical expansion to within about 2-percent"

The FRW metric when k=0:

- $$ds^2 = -dt^2 + R(t)^2 \left\{ dr^2 + r^2 d\Omega^2 \right\}$$

The universe is infinite flat space $\mathbb{R}^3$ at each fixed time:

- "Galaxies move along $r = const.$, and $\bar{r} = R(t)r$ measures distance at each fixed time"

The FRW metric when k=0:

- $$ds^2 = -dt^2 + R(t)^2 \left\{ dr^2 + r^2 d\Omega^2 \right\}$$

The universe is infinite flat space $\mathbb{R}^3$ at each fixed time:

- "E.g., in Standard Model, during radiation phase, after inflation..."

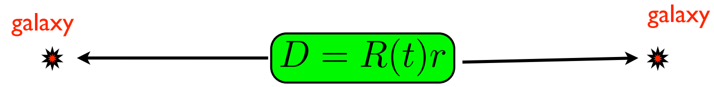
$$R(t) = \sqrt{t}$$

Standard Model of Cosmology

- FRW metric, *k=0:*

$$ds^2 = -dt^2 + R(t)^2 \left\{dr^2 + r^2 d\Omega^2\right\}$$

- $D = Rr$ Measures distance between galaxies at each fixed t



- Conclude: $$\dot{D} = \dot{R}r = \frac{\dot{R}}{R} Rr = HD$$

$$\dot{D} = HD$$ ← Hubble's Law

$$\text{Hubble's Constant} \equiv H \equiv \frac{\dot{R}}{R}$$

- Standard Model of Cosmology

$$ds^2 = -dt^2 + R(t)^2 \left\{ dr^2 + r^2 d\Omega^2 \right\}$$

- Hubble's Law:

$$\dot{D} = HD$$

- Conclude--

``The universe is expanding like a balloon"

$$R = 0$$

The Hubble "Constant" at present time

$$H = \frac{\dot{R}}{R} \approx h_0 \frac{100\ km}{s\ mpc}$$

- A galaxy at 1 mpc $\approx$ 3.26 million lightyears

  recedes at $h_0 \dfrac{100\ km}{sec}$ $\quad .5 \leq h_0 \leq .8$

$$\frac{1}{H_0} \approx 10^{10}\ years \approx age\ of\ universe$$

- $\frac{c}{H_0} \approx$ Hubble Length $\approx 10^{10}$ lightyears

  $\approx$ farthest we can see across the universe

Recent supernova data have tested the dependence of the Hubble constant on time, and the results don't fit standard model...

↓

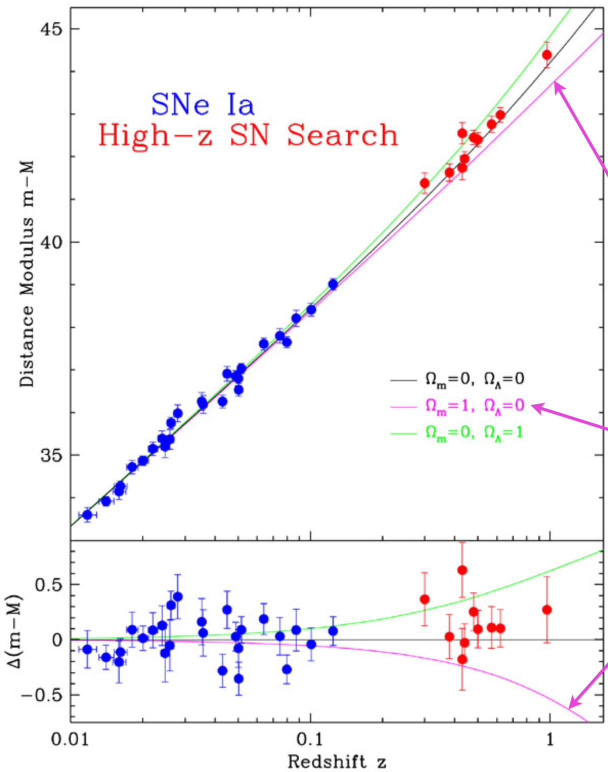
"Anomalous Acceleration of Galaxies"

↓

Introduction of
"Cosmological Const" and "Dark Energy"

Dark energy is non-classical
Negative pressure → Anti-gravity effect

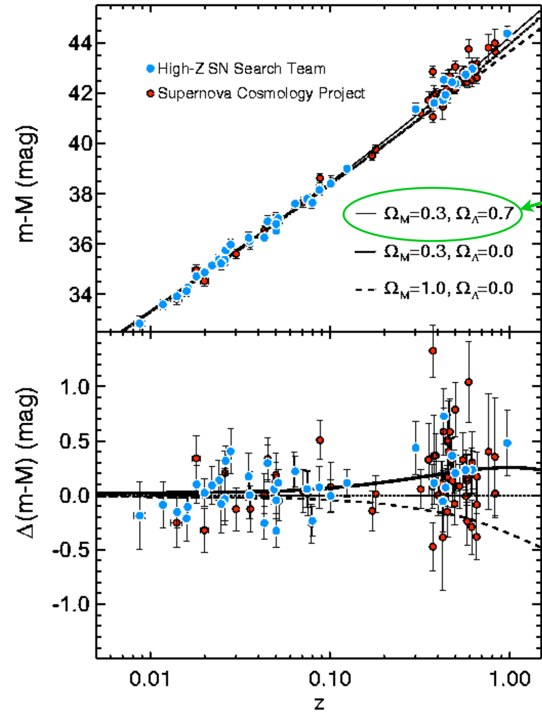
Supernova Data



Standard Model
k=0 FRW

"Not a Good Fit"

Thanks to Philip Hughs
UM-Astronomy



✷ Best Fit: ———

70% Dark Energy

30% Classical Energy

Thanks to Philip Hughs
UM-Astronomy

The FRW Mathematical Model:

- Einstein Equations (1915): $G_{ij} = \kappa T_{ij}$

G_{ij}=Einstein Curvature Tensor

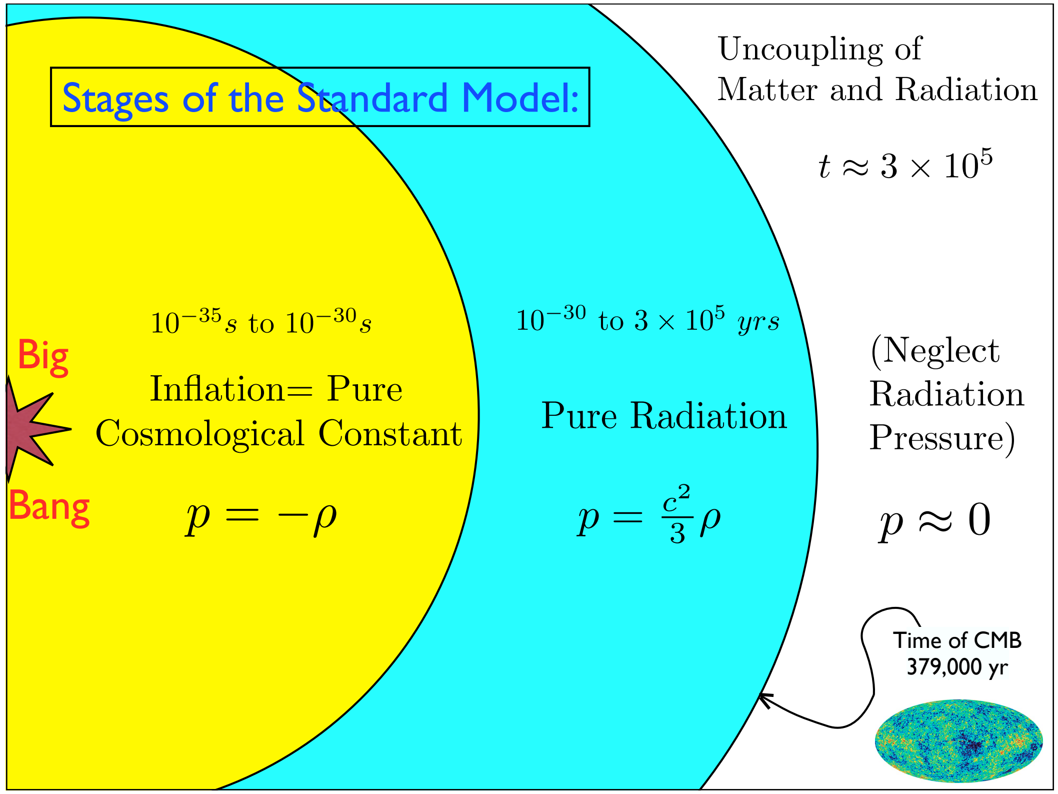
$T_{ij} = (\rho + p)u_i u_j + p g_{ij}$=Stress Energy Tensor (perfect fluid)

- Einstein Equations for k=0 Friedmann metric:

$$H^2 = \frac{\kappa}{3}\rho$$

$$\dot{\rho} = -3(\rho + p)H$$

Solutions determined by equation of state: $p = p(\rho)$

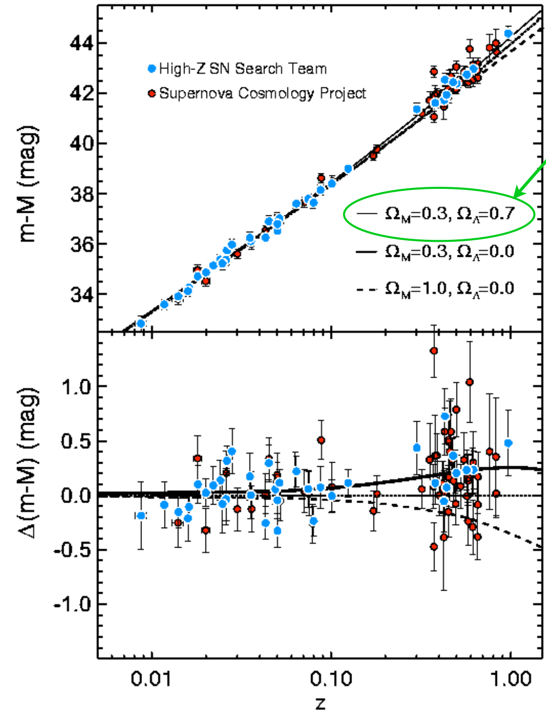

Stages of the Standard Model:
Big
Bang
$10^{-35}s$ to $10^{-30}s$
Inflation= Pure
Cosmological Constant
$p = -\rho$
10^{-30} to 3×10^5 yrs
Pure Radiation
$p = \frac{c^2}{3}\rho$
Uncoupling of
Matter and Radiation
$t \approx 3 \times 10^5$
(Neglect
Radiation
Pressure)
$p \approx 0$
Time of CMB
379,000 yr

Standard Model for Dark Energy

- Assume Einstein equations with a cosmological constant:

$$G_{ij} = 8\pi T_{ij} + \Lambda g_{ij}$$

- Assume $k = 0$ FRW: $ds^2 = -dt^2 + R(t)^2 \left\{ dr^2 + r^2 d\Omega^2 \right\}$
- Leads to: $H^2 = \frac{\kappa}{3}\rho + \frac{\kappa}{3}\Lambda$
- Divide by $H^2 = \frac{\kappa}{3}\rho_{crit}$ $\quad 1 = \Omega_M + \Omega_\Lambda$
- Best data fit leads to $\Omega_\Lambda \approx .73$ and $\Omega_M \approx .27$
- Implies: The universe is 73 percent dark energy



Best Fit:
70% Dark Energy
30% Classical Energy

- m - M = "Distance Modulus"

  M=absolute Magnitude

  m=apparent magnitude

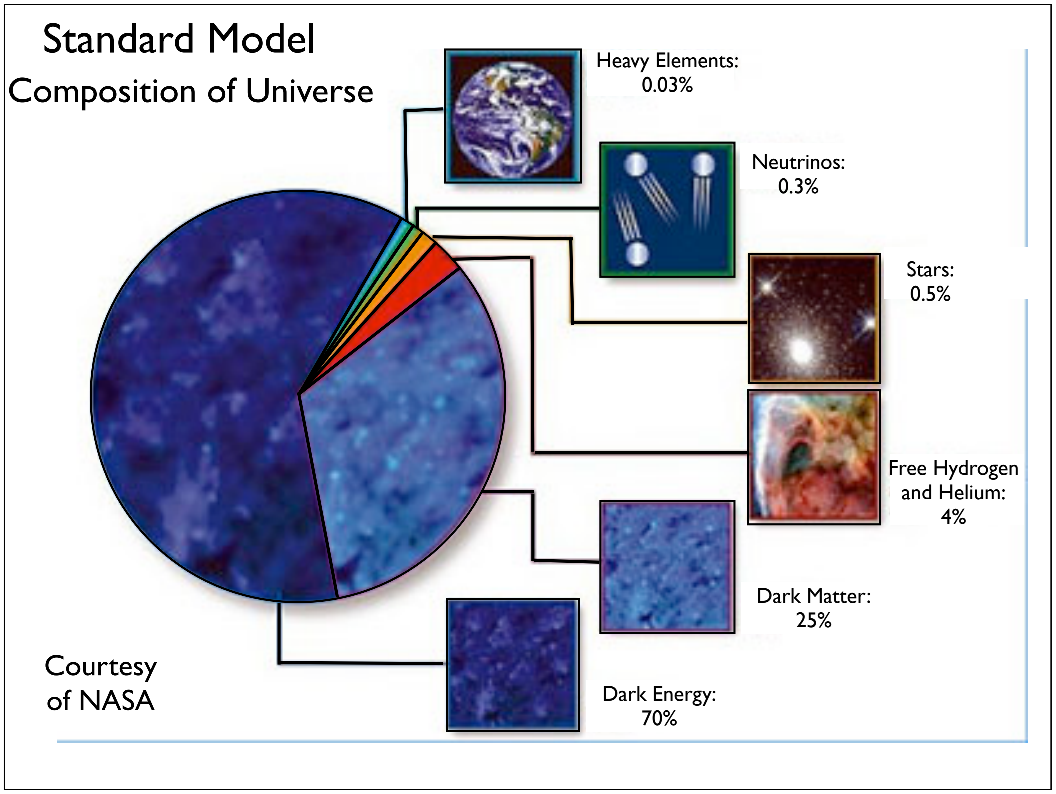
- d=distance in parsecs:

  m - M = 5 log(d) - 5

- z=redshift factor

  $1+z = \frac{\lambda_{emit}}{\lambda_{obs}}$

- $\Omega_m + \Omega_\Lambda = 1$ for a flat $(k = 0)$ universe.



Standard Model
Composition of Universe
Heavy Elements: 0.03%
Neutrinos: 0.3%
Stars: 0.5%
Free Hydrogen and Helium: 4%
Dark Matter: 25%
Dark Energy: 70%
Courtesy of NASA

The Question we Explore:

"Could the anomalous acceleration of the galaxies be due to the fact that we are looking outward into an expansion wave different from the k=0 FRW spacetime, and NOT due to a cosmological constant?"

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- The Einstein equations have been confirmed without the cosmological constant in every setting except cosmology...

The Question we Explore:

"Could the anomalous acceleration of the galaxies be due to the fact that we are looking out into an expansion wave different from the k=0 FRW spacetime, and NOT due to a cosmological constant?"

- The Einstein equations have been confirmed without the cosmological constant in every setting except cosmology...

Note: A general expansion wave has a center of expansion...

The Einstein equations that describe the expansion of the Universe during the radiation phase of the expansion form a highly nonlinear system of coupled wave equations in the form of conservation laws.

Such wave equations support the propagation of waves,
and self-similar expansion waves are important because even when dissipative terms are neglected in conservation laws, the nonlinearities alone provide a mechanism whereby non-interacting self-similar wave patterns can emerge from general interactive solutions, via the process of wave interaction and shock wave dissipation

Mathematical Theory of Conservation Laws

Mathematical Theory of Conservation Laws

✷ Our Conjecture: ✷

Decay to a "non-interacting expansion wave" would most likely have occurred during the radiation phase when the Modulus of Genuine Nonlinearity is maximal...

Mathematical Theory of Conservation Laws

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Solutions decay to non-interacting wave patterns by the mechanism of shock-wave dissipation...

Mathematical Theory of Conservation Laws

✸ Our Conjecture: ✸

Decay to a "non-interacting expansion wave" would most likely have occurred during the radiation phase when the Modulus of Genuine Nonlinearity is maximal...

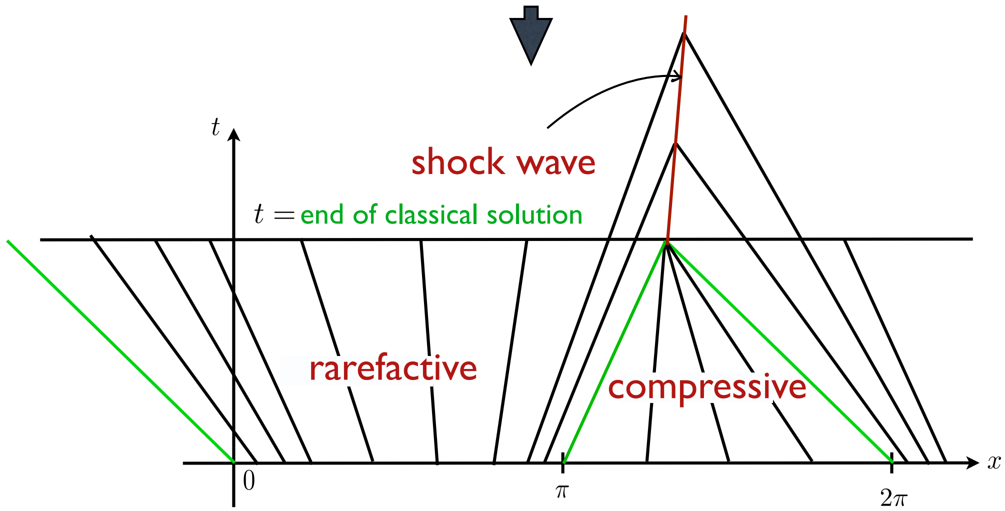
Solutions decay to non-interacting wave patterns by the mechanism of shock-wave dissipation...

DECAY OCCURS EVEN WHEN
DISSIPATIVE TERMS ARE NEGLECTED
(A Subtle Point!)

- Basic warmup problem: scalar Burgers Equation:

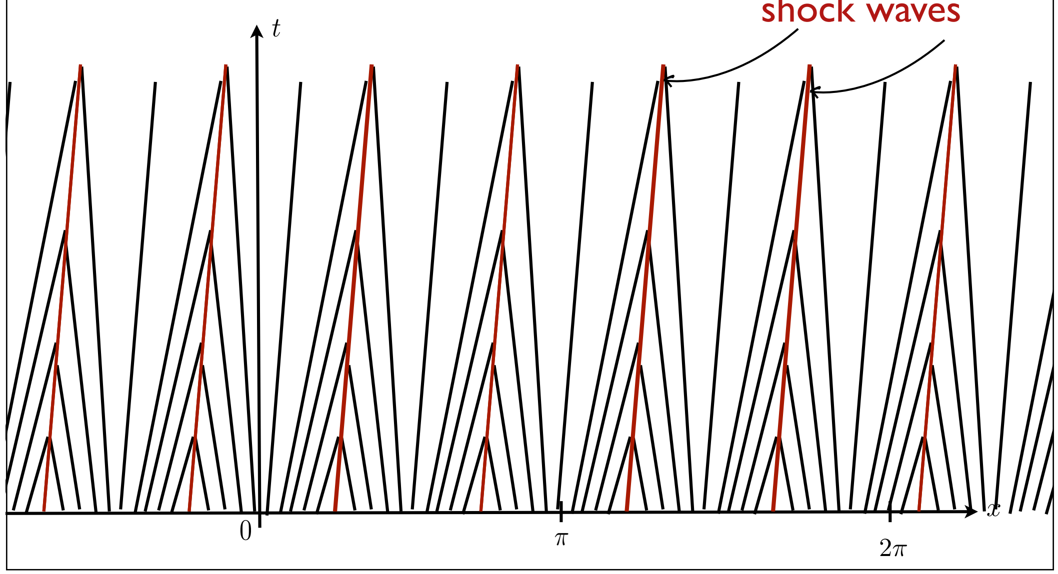
$$u_t + uu_x = 0$$

Decay to non-interacting simple waves by "shock wave dissipation"



Nonlinearites Produce Dissipation
(even when dissipative terms are neglected)

- Decay by Shock-Wave Dissipation...



Compare:

- Pure Radiation: $p = \frac{c^2}{3}\rho$

- Matter Dominated: $p = 0$

Compare:

- **Pure Radiation:** $p = \frac{c^2}{3}\rho$

  $\text{Sound Speed} = \frac{c}{\sqrt{3}} \approx .58\,c$

  Modulus of Genuine Nonlinearity: $\nabla\lambda_i \cdot R_i >> 1$

  (Decay)

- **Matter Dominated:** $p = 0$

Compare:

- Pure Radiation: $p = \frac{c^2}{3}\rho$

  Sound Speed $= \frac{c}{\sqrt{3}} \approx .58\,c$

  Modulus of Genuine Nonlinearity: $\nabla\lambda_i \cdot R_i >> 1$

  (Decay)

- Matter Dominated: $p = 0$

  Sound Speed $\equiv 0$

  Modulus of Genuine Nonlinearity: $\nabla\lambda_i \cdot R_i \equiv 0$

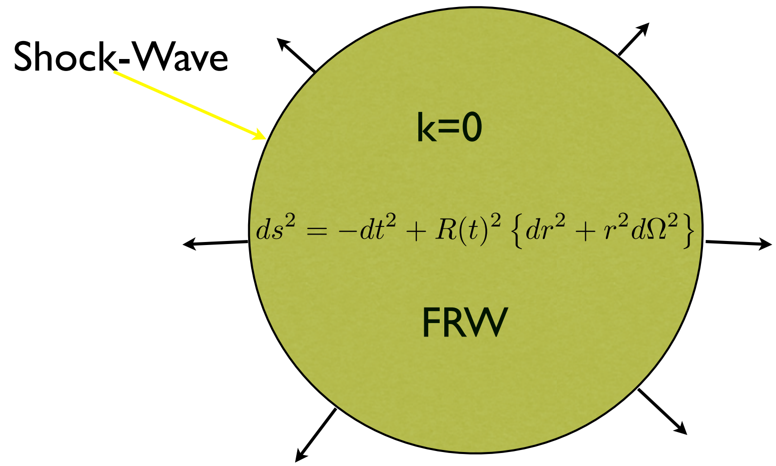
  (No Decay)

To start: we proposed to numerically simulate the secondary reflected wave reflected back in our shock wave cosmology model...

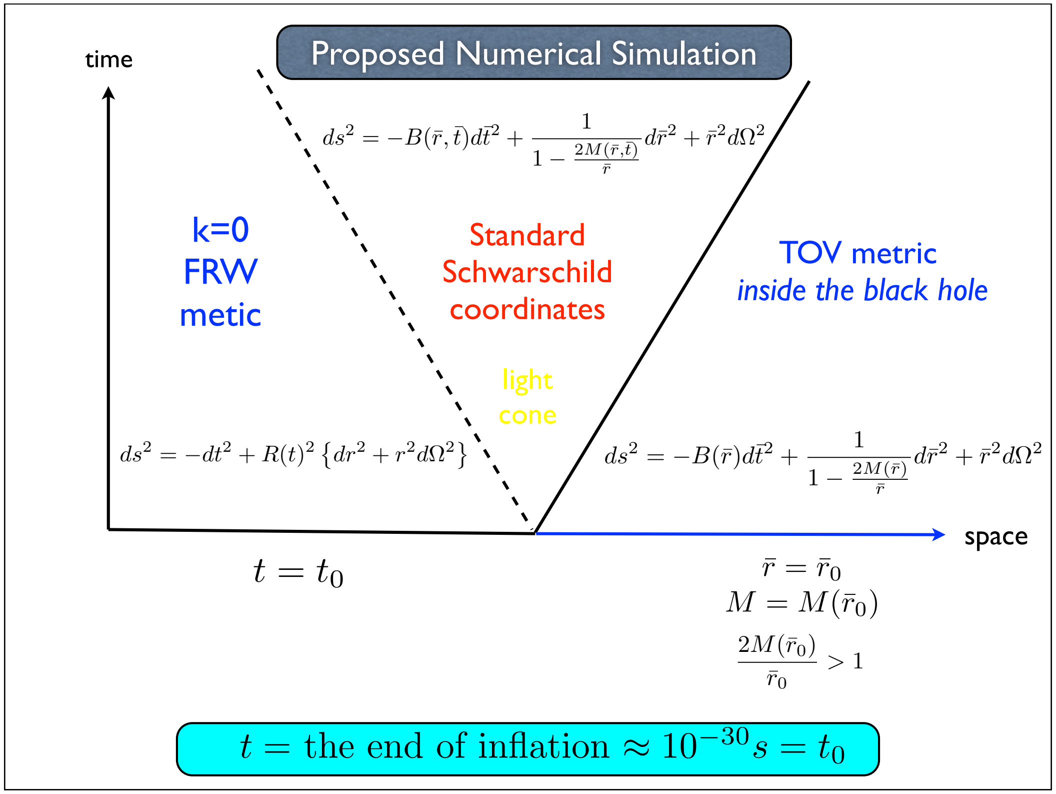
References:

- Talk: Numerical Cosmology Session, National meeting, New Orleans, January 2007 http://www.math.ucdavis.edu/~temple/
- Thesis: numerical simulation by a locally inertial Godunov method, Zeke Volger, UC-Davis, 2009

Could the Anomalous acceleration be accounted for by an expansion behind the Shock Wave?



TOV: $$ds^2 = -B(\bar{r})d\bar{t}^2 + \frac{1}{1 - \frac{2M(\bar{r})}{\bar{r}}} d\bar{r}^2 + \bar{r}^2 d\Omega^2$$



Proposed Numerical Simulation
time
$ds^2 = -B(\bar r,\bar t)d\bar t^2 + \frac{1}{1-\frac{2M(\bar r,\bar t)}{\bar r}}d\bar r^2 + \bar r^2 d\Omega^2$
k=0
FRW
metic
Standard
Schwarschild
coordinates
TOV metric
inside the black hole
light
cone
$ds^2 = -dt^2 + R(t)^2\left\{dr^2 + r^2 d\Omega^2\right\}$
$ds^2 = -B(\bar r)d\bar t^2 + \frac{1}{1-\frac{2M(\bar r)}{\bar r}}d\bar r^2 + \bar r^2 d\Omega^2$
space
$t = t_0$
$\bar r = \bar r_0$
$M = M(\bar r_0)$
$\frac{2M(\bar r_0)}{\bar r_0} > 1$
$t = \text{the end of inflation} \approx 10^{-30}s = t_0$

- The numerical method required getting an explicit form for the

$(k = 0,\ p = 1/3\ \rho)$-FRW metric

in

Standard Schwarzschild Coordinates

- The numerical method required getting an explicit form for the $(k = 0,\ p = 1/3\ \rho)$-FRW metric in Standard Schwarzschild Coordinates

- Upon doing this we found that there exists an integrating factor such that the metric satisfies an ODE in Standard Schwarzschild coordinates...the ODE's then introduce 3 extra free parameters...

  ...(the 3-initial conditions)!

Thus: we look for an expanding wave perturbation of the k=0 FRW metric during the period when:

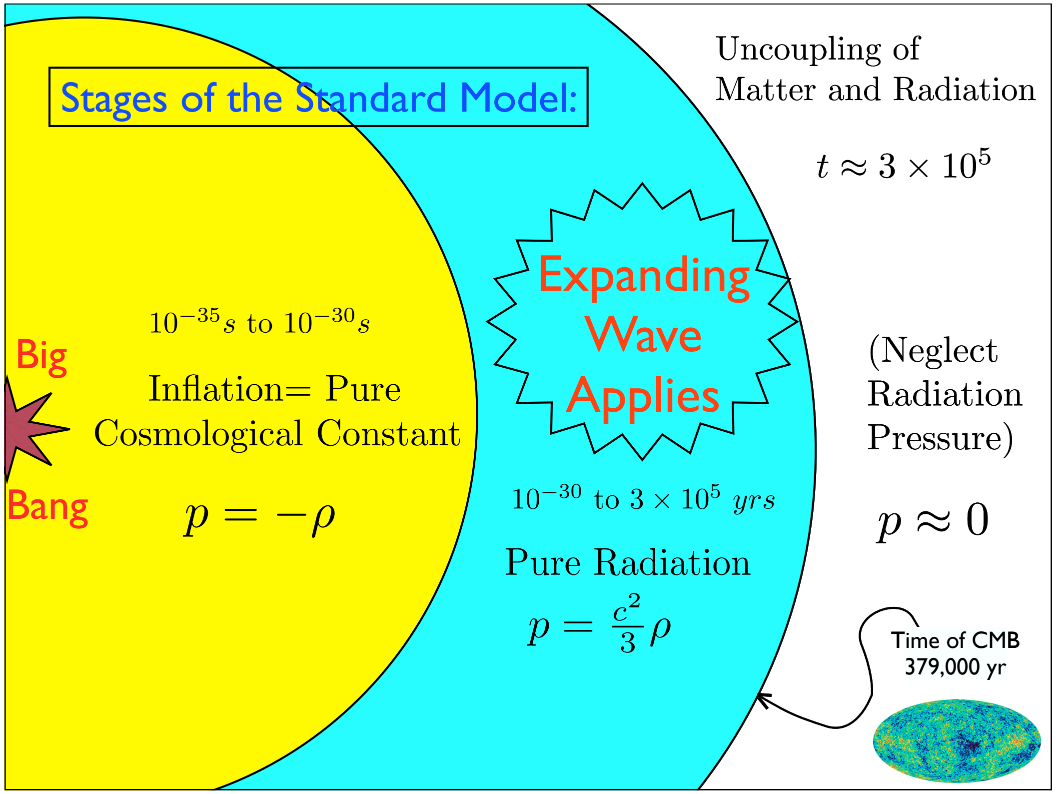
$$p = \frac{c^2}{3}\rho$$

$$ds^2 = -dt^2 + R(t)^2 \left\{ dr^2 + r^2 d\Omega^2 \right\}$$

$$\Downarrow$$

$$R(t) = \sqrt{t}$$

$$\boxed{H(t) = \frac{\dot{R}(t)}{R(t)} = \frac{1}{2t}}$$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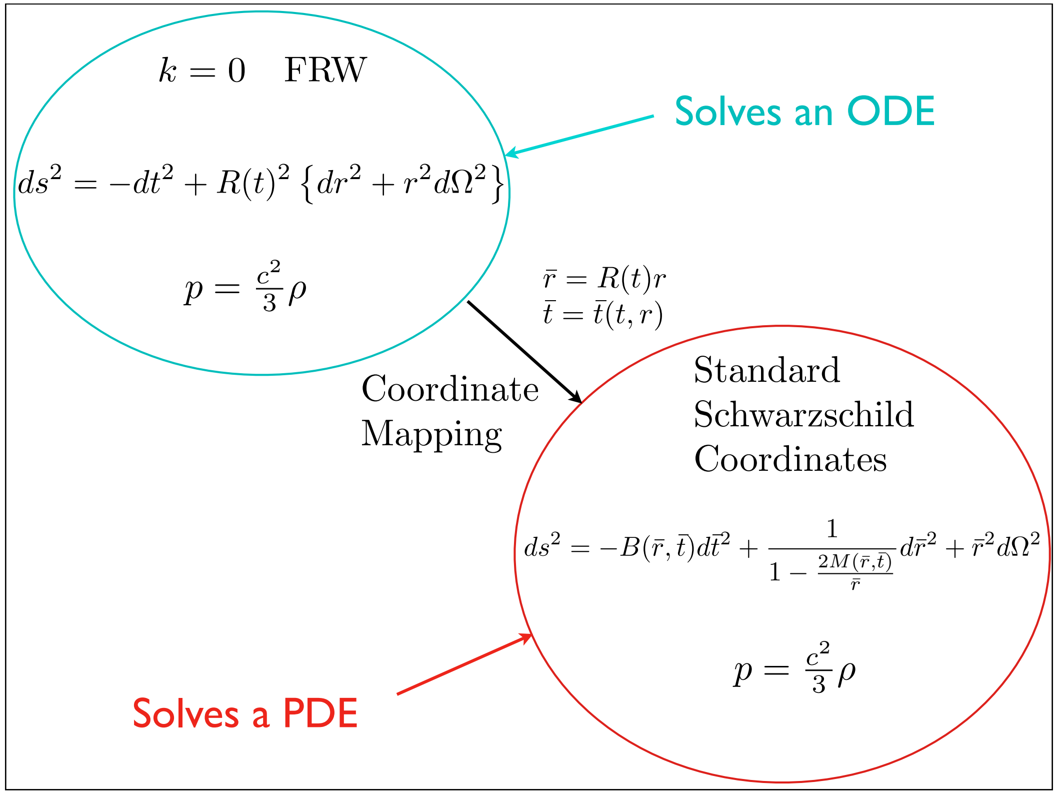
10^{-30} to 3×10^5 yrs
Pure Radiation
$p = \frac{c^2}{3}\rho$
(Neglect Radiation Pressure)
$p \approx 0$
Time of CMB
379,000 yr

A Three Parameter Family of Expanding Wave Solutions of the Einstein Equations including The Standard Model of Cosmology


$k = 0$ FRW
$ds^2 = -dt^2 + R(t)^2 \left\{ dr^2 + r^2 d\Omega^2 \right\}$
$p = \frac{c^2}{3}\rho$
Solves an ODE
$\bar{r} = R(t) r$
$\bar{t} = \bar{t}(t, r)$
Coordinate
Mapping
Standard
Schwarzschild
Coordinates
$ds^2 = -B(\bar{r}, \bar{t}) d\bar{t}^2 + \frac{1}{1 - \frac{2M(\bar{r},\bar{t})}{\bar{r}}} d\bar{r}^2 + \bar{r}^2 d\Omega^2$
$p = \frac{c^2}{3}\rho$
Solves a PDE

- Spherically symmetric spacetime metrics can "generically" be mapped over to Standard Schwarzschild Coordinates... [c.f. Wein]

- In general there exist MANY ways to do this, depending on an INTEGRATING FACTOR that solves a PDE

Theorem: Assume $p = \frac{c^2}{3}\rho$, $k = 0$. Then the FRW metric

$$ds^2 = -dt^2 + R(t)^2 dr^2 + \bar{r}^2 d\Omega^2,$$

under the mapping

$$\begin{aligned} \bar{r} &= R(t) r, \\ \bar{t} &= \left\{ 1 + \left[\frac{R(t) r}{2t} \right]^2 \right\} t, \end{aligned}$$

goes over to the SSC-metric

$$ds^2 = -\frac{d\bar{t}^2}{1 - v(\xi)^2} + \frac{d\bar{r}^2}{1 - v(\xi)^2} + \bar{r}^2 d\Omega^2,$$

where

$$\xi \equiv \frac{\bar{r}}{\bar{t}} = \frac{2v}{1 + v^2}$$

Corollary: There exists a coordinate mapping that takes the $p = \frac{1}{3}\rho$, $k = 0$ FRW metric over to SSC-coordinates such that SSC metric components

DEPEND ONLY ON THE SINGLE VARIABLE

$$\xi = \frac{\bar{r}}{\bar{t}}$$

(Like an expansion wave!)

This implies that
the standard FRW metric
after inflation
is equivalent to
a metric that satisfies an
ODE in SSC-Coordinates!

We now construct this ODE systematically...

Standard Schwarzschild Coordinates

Standard Schwarzschild Coordinates

Metric Ansatz:

$$ds^2 = -B(t,r)dt^2 + \frac{1}{A(t,r)}dr^2 + r^2 d\Omega^2$$

Standard Schwarzschild Coordinates

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Einstein Equations:

$$G = 8\pi T$$

Standard Schwarzschild Coordinates

Metric Ansatz: $$ds^2 = -B(t,r)dt^2 + \frac{1}{A(t,r)}dr^2 + r^2 d\Omega^2$$

Einstein Equations: $$G = 8\pi T$$

$$\left\{-r\frac{A_r}{A} + \frac{1-A}{A}\right\} = \frac{\kappa B}{A} r^2 T^{00} \quad (1)$$

$$\frac{A_t}{A} = \frac{\kappa B}{A} r T^{01} \quad (2)$$

$$\left\{r\frac{B_r}{B} - \frac{1-A}{A}\right\} = \frac{\kappa}{A^2} r^2 T^{11} \quad (3)$$

$$-\left\{\left(\frac{1}{A}\right)_{tt} - B_{rr} + \Phi\right\} = 2\frac{\kappa B}{A} r^2 T^{22}, \quad (4)$$

where

$$\Phi = \frac{B_t A_t}{2A^2 B} - \frac{1}{2A}\left(\frac{A_t}{A}\right)^2 - \frac{B_r}{r} - \frac{BA_r}{rA} + \frac{B}{2}\left(\frac{B_r}{B}\right)^2 - \frac{B}{2}\frac{B_r}{B}\frac{A_r}{A}.$$

Q: When do the SSC PDE's reduce to ODE's?

Four PDE's

$$\left\{-r\frac{A_r}{A}+\frac{1-A}{A}\right\} = \frac{\kappa B}{A}r^2T^{00} \quad (1)$$

$$\frac{A_t}{A} = \frac{\kappa B}{A}rT^{01} \quad (2)$$

$$\left\{r\frac{B_r}{B}-\frac{1-A}{A}\right\} = \frac{\kappa}{A^2}r^2T^{11} \quad (3)$$

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Ans#1: A=A(r), B=B(r) time-independent

A=A(r), B=B(r) time-independent

Oppenheimer-Volkoff equations for a
Static Fluid Sphere

(The setting for the stability limits in stars)

---Buchdahl Stability Limit
---Chandresekhar Stability Limit

The Oppenheimer-Volkoff equations:

$$A'(r) = \frac{1-A}{r} - \kappa r$$

$$A(r) = 1 - \frac{2\mathcal{G}M(r)}{r}$$

$$\frac{B'(r)}{B} = -2\frac{p'(r)}{p+\rho}$$

$$p'(r) = -\frac{\mathcal{G}M\rho}{r^2}\left\{1+\frac{p}{\rho}\right\}\left\{1+\frac{4\pi r^3 p}{M}\right\}\left\{1-\frac{2\mathcal{G}M}{r}\right\}^{-1}$$

...the fundamental equation of Newtonian astrophysics, with general-relativistic corrections supplied by the last three factors, [Weinberg, page 301].

We show there is another way the SSC-Equations reduce to ODE's:

I.e., when

(1) $T_{ij} = (\rho + p)u^i u^j + pg^{ij}$ is linear in ρ

(2) A, B, v and $r^2\rho$ depend on $\xi = r/t$

This includes the case $p = \frac{c^2}{3}\rho$

The SSC-equations reduce to ODE's when:

(1) $T_{ij} = (\rho + p)u^i u^j + pg^{ij}$ is linear in ρ

(2) A, B, v and $r^2\rho$ depend on $\xi = r/t$

Claim: one choice of initial conditions gives the standard model!

We now see how this works:

Standard Schwarzschild Coordinates

Four PDE's

$$\left\{-r\frac{A_r}{A}+\frac{1-A}{A}\right\} = \frac{\kappa B}{A}r^2T^{00} \quad (1)$$

$$\frac{A_t}{A} = \frac{\kappa B}{A}rT^{01} \quad (2)$$

$$\left\{r\frac{B_r}{B}-\frac{1-A}{A}\right\} = \frac{\kappa}{A^2}r^2T^{11} \quad (3)$$

$$-\left\{\left(\frac{1}{A}\right)_{tt}-B_{rr}+\Phi\right\} = 2\frac{\kappa B}{A}r^2T^{22}, \quad (4)$$

where

$$\Phi = \frac{B_tA_t}{2A^2B}-\frac{1}{2A}\left(\frac{A_t}{A}\right)^2-\frac{B_r}{r}-\frac{BA_r}{rA} +\frac{B}{2}\left(\frac{B_r}{B}\right)^2-\frac{B}{2}\frac{B_r}{B}\frac{A_r}{A}.$$

(1)+(2)+(3)+(4) ⟺ (1)+(3)+div T=0

(weakly)

Theorem: (Te-Gr) The equations close in a "locally inertial" formulation of (1), (2) & Div T=0:

$$\{T_M^{00}\}_{,0} + \left\{\sqrt{AB}T_M^{01}\right\}_{,1} = -\frac{2}{r}\sqrt{AB}T_M^{01}, \quad (1)$$

$$\{T_M^{01}\}_{,0} + \left\{\sqrt{AB}T_M^{11}\right\}_{,1} = -\frac{1}{2}\sqrt{AB}\left\{\frac{4}{r}T_M^{11} + \frac{(1-A)}{Ar}(T_M^{00} - T_M^{11}) + \frac{2\kappa r}{A}(T_M^{00}T_M^{11} - (T_M^{01})^2) - 4rT^{22}\right\}, \quad (2)$$

$$rA_r = (1-A) - \kappa r^2 T_M^{00}, \quad (3)$$

$$rB_r = \frac{B(1-A)}{A} + \frac{B}{A}\kappa r^2 T_M^{11}. \quad (4)$$

$$T^{00} = \frac{1}{B}T_M^{00}$$

$$T^{01} = \sqrt{\frac{A}{B}}T_M^{01}$$

$$T^{11} = AT_M^{11}$$

$$p = \sigma\rho$$

$$v = \frac{1}{\sqrt{AB}}\frac{u^1}{u^0}$$

$$T_M^{00} = \frac{c^4 + \sigma^2 v^2}{c^2 - v^2}\rho$$

$$T_M^{01} = \frac{c^2 + \sigma^2}{c^2 - v^2}cv\rho$$

$$T_M^{11} = \frac{v^2 + \sigma^2}{c^2 - v^2}\rho c^2$$

For the expanding wave we take a "locally inertial" formulation of:

$$(1),\ (2),\ (3)\ \&\ Div\, T^{j1} = 0$$

$$
\begin{aligned}
rA_r &= (1-A) - \kappa r^2 T_M^{00} && (1)\\
rA_t &= \sqrt{AB}\,\kappa r^2 T_M^{01} && (2)\\
rB_r &= \frac{B}{A}\left\{(1-A) + \kappa r^2 T_M^{11}\right\} && (3)\\
\left\{T_M^{01}\right\}_{,0} + \left\{\sqrt{AB}T_M^{11}\right\}_{,1} &= -\frac{1}{2}\sqrt{AB}\left\{\frac{4}{r}T_M^{11} + \frac{(1-A)}{Ar}(T_M^{00} - T_M^{11})\right. && (4)\\
&\quad \left. + \frac{2\kappa r}{A}(T_M^{00}T_M^{11} - (T_M^{01})^2) - 4rT^{22}\right\}
\end{aligned}
$$

$$p = \sigma^2 \rho \quad \Rightarrow$$

$$
\begin{aligned}
T_M^{00} &= \frac{c^4 + \sigma^2 v^2}{c^2 - v^2}\rho\\
T_M^{01} &= \frac{c^2 + \sigma^2}{c^2 - v^2} cv\rho \qquad T^{22} = r^{-2}p\\
T_M^{11} &= \frac{v^2 + \sigma^2}{c^2 - v^2}\rho c^2
\end{aligned}
$$

- Consider (1), (2) & (3):

$$
\begin{aligned}
rA_r &= (1-A) - \kappa r^2 T_M^{00} && (1)\\
rA_t &= \sqrt{AB}\,\kappa r^2 T_M^{01} && (2)\\
rB_r &= \frac{B}{A}\left\{(1-A) + \kappa r^2 T_M^{11}\right\} && (3)
\end{aligned}
$$

"The sources are linear in $r^2\rho$"

- Set: $S^{ij} \equiv \kappa r^2 T_M^{ij}$

So: $S^{ij} \equiv \kappa w V^{ij}$

Where: $\kappa w \equiv \dfrac{\kappa}{3}\rho r^2 (1-v^2)^{-1}$, $\qquad V^{ij} \equiv V^{ij}(v)$

- Substituting S^{ij}; (1), (2) & (3) become:

$$rA_r = (1-A) - S^{00} \quad (1)$$

$$rA_t = \sqrt{AB}\, S^{01} \quad (2)$$

$$rB_r = \frac{B}{A}\left\{(1-A) + S^{11}\right\} \quad (3)$$

- Now assume A, B, S^{ij} depend only on $\xi = \frac{r}{t}$

$$A = A(\xi), \qquad B = B(\xi), \qquad S^{ij} = S^{ij}(\xi)$$

- Then (1), (2) & (3) all reduce to ODE's in ξ!

- (1), (2) & (3) reduce to ODE's in ξ!!

$$\xi A_\xi = (1-A) - \kappa S^{00} \quad (1)$$

$$\xi^2 A_\xi = \sqrt{AB}\,\kappa S^{01} \quad (2)$$

$$\xi B_\xi = \frac{B}{A}\left\{(1-A) + \kappa S^{11}\right\} \quad (3)$$

$$S^{00} = \kappa r^2 \rho \frac{c^4 + \sigma^2 v^2}{c^2 - v^2} = \kappa \left\{ \frac{r^2 \rho}{3(1-v^2)} \right\} (3 + v^2)$$

$$S^{01} = \kappa r^2 \rho \frac{c^2 + \sigma^2}{c^2 - v^2} cv = \kappa \left\{ \frac{r^2 \rho}{3(1-v^2)} \right\} 4v$$

$$S^{11} = \kappa r^2 \rho \frac{\sigma^2 + v^2}{c^2} = \kappa \underbrace{\left\{ \frac{r^2 \rho}{3(1-v^2)} \right\}}_{w} \underbrace{(1 + 3v^2)}_{V^{ij}}$$

$c = 1$, $\sigma^2 = 1/3$

$(1),\ (2)\ \&\ (3)$ reduce to ODE's in ξ ...

$$\xi A_\xi = (1-A) - \kappa S^{00} \qquad (1)$$

$$\xi^2 A_\xi = \sqrt{AB}\,\kappa S^{01} \qquad (2)$$

$$\xi B_\xi = \frac{B}{A}\left\{(1-A) + \kappa S^{11}\right\} \qquad (3)$$

- Equations (1) & (2) require the compatibility condition

$$(1-A) - \kappa S^{00} = \frac{\sqrt{AB}}{\xi}\kappa S^{01}$$

$\Longleftrightarrow$

$$\kappa w = \frac{(1-A)G}{(3+v^2)G - 4v}$$

$$G = \frac{\xi}{\sqrt{AB}}$$

- Conclude: The compatibility condition

$$\kappa w = \frac{(1-A)G}{(3+v^2)G-4v} \qquad (*)$$

removes one equation and one variable $r^2\rho$

(Linearity in ρ, correct for $p = \frac{c^2}{3}\rho$, is crucial.)

- Said differently: once we get equations for

$$(A, G, v)(\xi)$$

we can use $(*)$ to solve for $r^2\rho$

- A similar reduction applies to Equation (4):

$$\left\{T^{01}_{M}\right\}_{,0} + \left\{\sqrt{AB}T^{11}_{M}\right\}_{,1} = -\frac{1}{2}\sqrt{AB}\left\{\frac{4}{r}T^{11}_{M} + \frac{(1-A)}{Ar}(T^{00}_{M} - T^{11}_{M}) + \frac{2\kappa r}{A}(T^{00}_{M}T^{11}_{M} - (T^{01}_{M})^2) - 4rT^{22}\right\} \tag{4}$$

- A similar reduction applies to Equation (4):

$$\left\{T_M^{01}\right\}_{,0} + \left\{\sqrt{AB}T_M^{11}\right\}_{,1} = -\frac{1}{2}\sqrt{AB}\left\{\frac{4}{r}T_M^{11} + \frac{(1-A)}{Ar}(T_M^{00} - T_M^{11}) + \frac{2\kappa r}{A}(T_M^{00}T_M^{11} - (T_M^{01})^2) - 4rT^{22}\right\} \quad (4)$$

- Multiplying through by r^3 and using (*) to eliminate w and w_ξ in favor of v we obtain

(After considerable computation!)

- A similar reduction applies to Equation (4):

$$\left\{T_M^{01}\right\}_{,0} + \left\{\sqrt{AB}\,T_M^{11}\right\}_{,1} = -\frac{1}{2}\sqrt{AB}\left\{\frac{4}{r}T_M^{11} + \frac{(1-A)}{Ar}(T_M^{00} - T_M^{11}) + \frac{2\kappa r}{A}(T_M^{00}T_M^{11} - (T_M^{01})^2) - 4rT^{22}\right\} \quad (4)$$

- Multiplying through by r^3 and using (*) to eliminate w and w_ξ in favor of v we obtain

(4) ⟺

$$\xi v_\xi = -\left(\frac{1-v^2}{2\,\{\cdot\}_D}\right)\left\{(3+v^2)G - 4v + \frac{4\left(\frac{1-A}{A}\right)\{\cdot\}_N}{(3+v^2)G - 4v}\right\}$$

$$\{\cdot\}_N = \left\{-2v^2 + 2(3-v^2)vG - (3-v^4)G^2\right\}$$

$$\{\cdot\}_D = \left\{(3v^2-1) - 4vG + (3-v^2)G^2\right\}$$

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$$G = \frac{\xi}{\sqrt{AB}}$$

$$\{\cdot\}_N = \left\{-2v^2 + 2(3-v^2)vG - (3-v^4)G^2\right\}$$

$$\{\cdot\}_D = \left\{(3v^2-1) - 4vG + (3-v^2)G^2\right\}$$

Conclude: $(1) = (2),\ (3),\ \&\ Div\, T^{j1} = 0$

are Equivalent to:

$$\xi A_\xi = -\left[\frac{4(1-A)v}{(3+v^2)G-4v}\right] \quad (1)$$

(ODE)
$$\xi G_\xi = -G\left\{\left(\frac{1-A}{A}\right)\frac{2(1+v^2)G-4v}{(3+v^2)G-4v}-1\right\} \quad (2)$$

$$\xi v_\xi = -\left(\frac{1-v^2}{2\{\cdot\}_D}\right)\left\{(3+v^2)G-4v+\frac{4\left(\frac{1-A}{A}\right)\{\cdot\}_N}{(3+v^2)G-4v}\right\} \quad (3)$$

$$\{\cdot\}_N = \left\{-2v^2+2(3-v^2)vG-(3-v^4)G^2\right\}$$
$$\{\cdot\}_D = \left\{(3v^2-1)-4vG+(3-v^2)G^2\right\}$$

$$G = \frac{\xi}{\sqrt{AB}} \quad ; \quad \xi = \frac{r}{t}$$

$$\xi A_\xi = -\left[\frac{4(1-A)v}{(3+v^2)G-4v}\right] \quad (1)$$

$$\xi G_\xi = -G\left\{\left(\frac{1-A}{A}\right)\frac{2(1+v^2)G-4v}{(3+v^2)G-4v}-1\right\} \quad (2)$$

$$\xi v_\xi = -\left(\frac{1-v^2}{2\left\{\cdot\right\}_D}\right)\left\{(3+v^2)G-4v+\frac{4\left(\frac{1-A}{A}\right)\left\{\cdot\right\}_N}{(3+v^2)G-4v}\right\} \quad (3)$$

A system of 3 ODE's analagous to the Oppenheimer-Volkoff Equations except they describe GR-Expansion Waves!

Theorem: Assume that $A(\xi)$, $G(\xi)$ and $v(\xi)$ solve ODE and use the constraint

$$\kappa w \equiv \frac{r^2\rho}{3(1-v^2)} = \frac{(1-A)G}{(3+v^2)G-4v}$$

to define ρ

$$\rho = \frac{1}{\kappa}\frac{3(1-v^2)(1-A)G}{(3+v^2)G-4v}\frac{1}{\bar{r}^2}.$$

Then the metric

$$ds^2 = -B(\xi)d\bar{t}^2 + \frac{1}{A(\xi)}d\bar{r}^2 + \bar{r}^2 d\Omega^2$$

solves the Einstein equations with

equation of state $p = \rho c^2/3.$

- The Result: a system of three ODE's plus one constraint equivalent to the Einstein equations assuming A, B, v and $r^2\rho$ depend only on $\xi = \frac{r}{t}$:

$$\xi \begin{pmatrix} A \\ E \\ v \end{pmatrix}_\xi = F \begin{pmatrix} A \\ E \\ v \end{pmatrix} \qquad \begin{matrix} (2) \\ (3) \\ (4) \end{matrix}$$

$$\kappa w = \frac{1 - A}{3 + v^2 - 4vE} \qquad (1)=(2)$$

- The equations for a three parameter family of GR-expansion waves

$$\xi A_\xi = -\left[\frac{4(1-A)v}{(3+v^2)G-4v}\right] \quad (1)$$

$$\xi G_\xi = -G\left\{\left(\frac{1-A}{A}\right)\frac{2(1+v^2)G-4v}{(3+v^2)G-4v}-1\right\} \quad (2)$$

$$\xi v_\xi = -\left(\frac{1-v^2}{2\{\cdot\}_D}\right)\left\{(3+v^2)G-4v+\frac{4\left(\frac{1-A}{A}\right)\{\cdot\}_N}{(3+v^2)G-4v}\right\} \quad (3)$$

$$\{\cdot\}_N = \left\{-2v^2+2(3-v^2)vG-(3-v^4)G^2\right\}$$

$$\{\cdot\}_D = \left\{(3v^2-1)-4vG+(3-v^2)G^2\right\}$$

$$\kappa w = \frac{(1-A)G}{(3+v^2)G-4v} \quad \text{(Compatibility Constraint)} \quad (4)$$

THEOREM: The equations are invariant under time-scaling

$$t \to \alpha t \, .$$

Except for this, solutions describe

Distinct Spacetimes

CONCLUDE: 3-initial condts + 1-scaling law ➡

2-parameter family of GR-expansion waves

Theorem: The coordinate mapping

$$\bar{r}(t,r) = \sqrt{t}\, r$$
$$\bar{t}(t,r) = \psi_0 \left(1 + \frac{r^2}{4}\right) t$$

takes the $k=0, p=\frac{c^2}{3}\rho$ Freidmann universe

$$ds^2 = -dt^2 + R(t)^2 \left\{dr^2 + r^2 d\Omega^2\right\}$$

to 1-point in this 2-parameter family of

GR-expansion waves

Proof: Coordinate mapping IMPLIES:

$$A = 1 - v^2, \quad E = \frac{1}{\psi_0 \xi}, \quad \xi = \frac{2v}{\psi_0(1+v^2)}, \quad v_\xi = \frac{\psi_0(1+v^2)^2}{2(1-v^2)}$$

Plug in and check:

$$\xi A_\xi = -\left[\frac{4(1-A)v}{(3+v^2)G - 4v}\right] \qquad (1)$$

$$\xi G_\xi = -G\left\{\left(\frac{1-A}{A}\right)\frac{2(1+v^2)G-4v}{(3+v^2)G-4v} - 1\right\} \qquad (2)$$

$$\xi v_\xi = -\left(\frac{1-v^2}{2\{\cdot\}_D}\right)\left\{(3+v^2)G - 4v + \frac{4\left(\frac{1-A}{A}\right)\{\cdot\}_N}{(3+v^2)G-4v}\right\} \qquad (3)$$

$$\{\cdot\}_N = \left\{-2v^2 + 2(3-v^2)vG - (3-v^4)G^2\right\}$$

$$\{\cdot\}_D = \left\{(3v^2-1) - 4vG + (3-v^2)G^2\right\}$$

$$\kappa w = \frac{(1-A)G}{(3+v^2)G-4v} \qquad \text{(Compatibility Constraint)} \qquad (4)$$

"A surprisingly long calculation!"

Technicalities (for the $v_\xi -$equation):

$$0 = \left(-V^{01} + EV^{11}\right)\xi\frac{w_\xi}{w} + \left(-4 + 2EV^{01}\right)\xi v_\xi + \xi\frac{A_\xi}{A}V^{01}$$

① ② ③

$$+E\xi\frac{B_\xi}{B}V^{01}\left(V^{00} + V^{11}\right) - 2EV^{22}$$

④ ⑤

Using identities that hold for standard Model as expressed in SSC's, we can reduce this sum to:

$$① = \left(-4v + \frac{1+v^2}{2v}(1+3v^2)\right)\frac{2(1+v^2)}{(1-v^2)^2}$$

+

$$② = 2\left(-2 + 3\frac{1+v^2}{2}\right)\frac{v(1+v^2)}{(1-v^2)}$$

+

$$③ = -4\frac{2(1+v^2)}{(1-v^2)^2}v^3$$

+

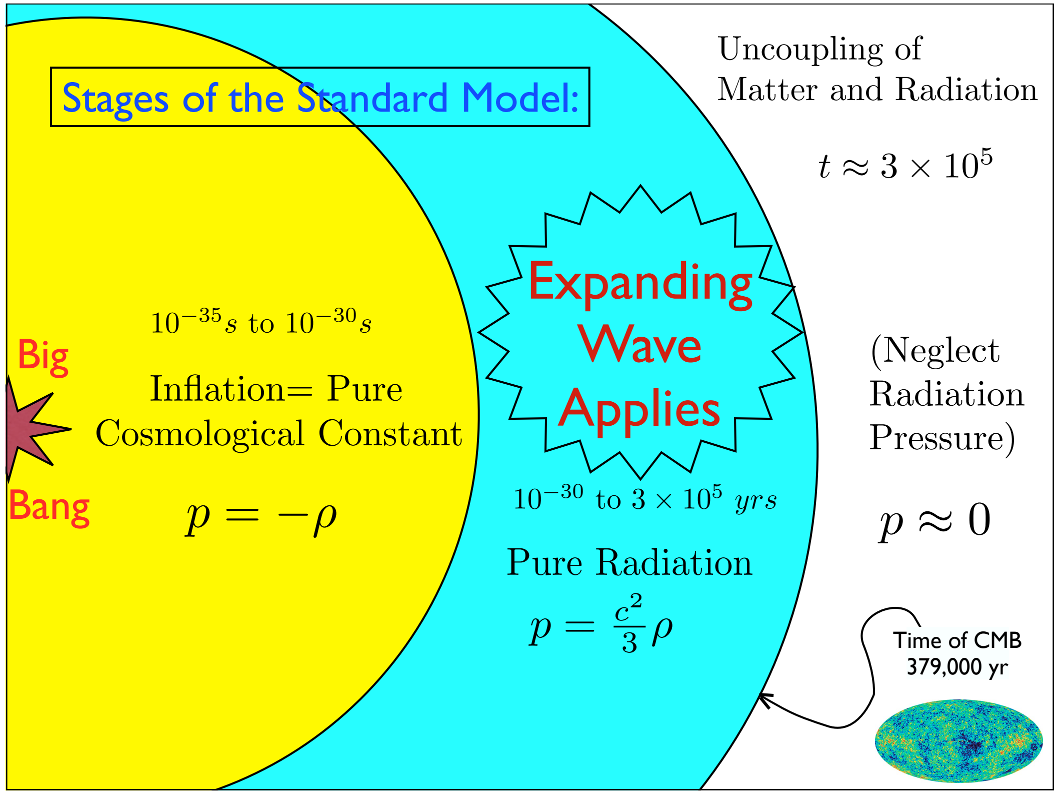
$$④ = 4\frac{(1+v^2)^3}{2v(1-v^2)^2}$$

+

$$⑤ = -2\frac{1+v^2}{2v}(1-v^2)$$

The sum is equal to zero! ■

Conclude: The standard model of cosmology after inflation represents one solution of our ODE's corresponding to one initial condition...



Stages of the Standard Model:
Uncoupling of
Matter and Radiation
$t \approx 3 \times 10^5$
Expanding
Wave
Applies
$10^{-35}s$ to $10^{-30}s$
Big
Inflation= Pure
Cosmological Constant
Bang
$p = -\rho$
(Neglect
Radiation
Pressure)
10^{-30} to 3×10^5 yrs
$p \approx 0$
Pure Radiation
$p = \frac{c^2}{3}\rho$
Time of CMB
379,000 yr

Since the standard model represents 1-point in a 2-parameter family, we look for leading order corrections to the standard model determined from the nearby GR-expansion waves

Linearizing about the center $\xi = 0$:

- One eigen-family tends to infinity as $\xi \to 0$
- Two eigen-solutions stay finite as $\xi \to 0$ and:

$$A \to 1, \; B \to 1, \; v \to 0$$

(One parameter is the scaling law...)

- Conclude: There is a smooth 1-parameter family of distinct spacetimes that extend the standard model!

Let

$$\psi_0 \equiv \text{Scaling Parameter}$$

$$a \equiv \text{Acceleration Parameter}$$

and let

$$v \equiv v_1(\xi)$$

denote the velocity profile for the FRW standard model...

The following Theorem shows:

"Nearby solutions
stay surprising close to FRW..."

Theorem: There exist positive constants (ψ_0, a) such that the following estimates hold near $\xi = 0$.

$$
\begin{aligned}
v(\xi) &= v_1(\xi) + \frac{(1-a^2)}{8}\psi_0^3\xi^3 + O(1)|a-1|\xi^4 \\
A(\xi) &= 1 - \frac{a^2\psi_0^2}{4}\xi^2 + O(1)|a-1|\xi^4 \\
G(\xi) &= \psi_0\xi + O(1)|a-1|\xi^5 \\
\sqrt{AB} &= \frac{1}{\psi_0} + O(1)|a-1|\xi^4
\end{aligned}
$$

Theorem 1: *To leading order in ξ, the 1-parameter family that extends the standard model of cosmology is given in SSC's by*

$$ds^2 = -\frac{d\bar{t}^2}{\psi_0^2\left(1 - \frac{a^2\psi_0^2\xi^2}{4}\right)} + \frac{d\bar{r}^2}{\left(1 - \frac{a^2\psi_0^2\xi^2}{4}\right)} + \bar{r}^2\Omega^2$$

$$v = \frac{\psi_0}{2}\xi$$
$$\xi = \frac{\bar{r}}{\bar{t}}$$

$(a = 1) \equiv$ Standard Model

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$\psi_0 \equiv$ scaling parameter

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$(a = 1) \equiv$ Standard Model

$$\xi = \frac{\bar{r}}{\bar{t}}$$

$a \equiv$ "new" acceleration parameter

Theorem 1: *To leading order in ξ, the 1-parameter family that extends the standard model of cosmology is given in SSC's by*

$$ds^2 = -\frac{d\bar{t}^2}{\psi_0^2\left(1 - \frac{a^2\psi_0^2\xi^2}{4}\right)} + \frac{d\bar{r}^2}{\left(1 - \frac{a^2\psi_0^2\xi^2}{4}\right)} + \bar{r}^2\Omega^2$$

$$v = \frac{\psi_0}{2}\xi$$

The velocity is independent of a!

Since the velocity field is $\approx$ independent of "a", it follows that the inverse mapping from Standard Model to SSC's provides

a co-moving coordinate system to leading order in ξ

$$\bar{r}(t,r) = \sqrt{t}\, r$$

$$\bar{t}(t,r) = \psi_0 \left(1 + \frac{r^2}{4}\right) t$$

Back in Friedmann coordinates, the metric "corrections" depend only on

$$\zeta = \frac{\bar{r}}{t}$$

$\approx$ "Distance from Center to Hubble Length"

$$0 \leq \zeta << 1$$

Back in Friedmann coordinates,
the metric "corrections" depend only on

$$\zeta = \frac{\bar{r}}{t}$$

$$\zeta \equiv \frac{\bar{r}}{ct} \approx \frac{R(t)r}{(c/H)} \approx \frac{Dist}{Hubble\ Length}$$

$\approx$ "Fractional Distance From Center to Hubble Length"

$$0 \leq \zeta << 1$$

The coord. mapping:

$$\bar{r}(t,r) = \sqrt{t}\ r$$
$$\bar{t}(t,r) = \psi_0 \left(1 + \frac{r^2}{4}\right) t$$

$$ds^2 = -F_a(\zeta)^2 dt^2 + F_a(\zeta)^2\ t dr^2 + \bar{r}^2 d\Omega^2$$

$$F_a(\zeta)^2 = 1 + (a^2 - 1)\frac{\zeta^2}{4} + O(|a-1|\zeta^4)$$

$$v = O(|1-a|\, t^{\frac{1}{2}}\, \zeta^3)$$

$\zeta = \frac{\bar{r}}{t} \approx$ "Distance from Center to Hubble Length"

$$0 \leq \zeta << 1$$

C.f. Standard Model:

$$ds^2 = -F_a(\zeta)^2 dt^2 + \underbrace{F_a(\zeta)^2\ t}_{R_a(t,\zeta)^2}\ dr^2 + \bar{r}^2 d\Omega^2$$

Define the "Hubble Constant": $H_a(t,\zeta) = \frac{1}{R}\frac{\partial}{\partial t}R$

Then:

$$\boxed{H_a(t,\zeta) = \frac{1}{2t}\left\{1 - \frac{3}{8}(a^2-1)\zeta^2 + O\left(|a^2-1|\zeta^4\right)\right\}}$$

C.f. Standard Model: $\boxed{H_1 = \frac{1}{2t}}$

Conclude: an observer at the center would measure a fractional correction to the Hubble constant on the order of...

$$\Delta_a \equiv \frac{H_a - H}{H} = \frac{3}{8}(1 - a^2)\zeta^2 + O\left(|a^2 - 1|\zeta^4\right)$$

$$\zeta \quad \equiv \quad \frac{\bar{r}}{ct} \approx \frac{\bar{r}}{(c/H)} \approx \frac{Dist}{Hubble\ Length}$$

$$\approx \text{“ Fractional Distance from Center to Furthest Visible Objects”}$$

Moreover: using co-moving coordinates, we can calculate the leading order correction to the redshift vs luminosity relation as measured by an observer at the center of the spacetime:

LET:

$$d_\ell \equiv Luminosity\ Distance = \left(\frac{L}{4\pi\ell}\right)^{1/2}$$

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LET:

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$$\ell \equiv Apparent\ Luminosity = \frac{\text{Power Recieved}}{\text{Area}}$$

$$z = \frac{\lambda_0}{\lambda_e} - 1 = Redshift\ Factor$$

THEN:

A calculation implies...

The redshift vs luminosity relation as measured by an observer at the center of the spacetime is given by:

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z + \cdots \right\}$$

$+H.O.T$

The redshift vs luminosity relation as measured by an observer at the center of the spacetime is given by:

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z \right\}$$

$$+ H.O.T$$

...Quadratic correction quoted in PNAS...

The redshift vs luminosity relation as measured by an observer at the center of the spacetime is given by:

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z + \frac{(a^2-1)(6a^2+13)}{6} z^2 \right\}$$

$$+H.O.T$$

The redshift vs luminosity relation as measured by an observer at the center of the spacetime is given by:

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z + \frac{(a^2-1)(6a^2+13)}{6} z^2 \right\}$$

$$+H.O.T$$

...Cubic correction MUCH harder...
(to appear SM/TE)

The redshift vs luminosity relation as measured by an observer at the center of the spacetime is given by:

$$d_\ell = 2t_0 z\left\{1+\frac{a^2-1}{2}z+\frac{(a^2-1)(6a^2+13)}{6}z^2\right\}$$

$$+H.O.T$$

(The calculation is nontrivial, and relies on simplifying features of the spacetime metric of the nearby expanding wave solutions...)

The relation reduces to the correct redshift vs luminosity relation for the standard model when $a = 1$ ...

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z + \frac{(a^2-1)(6a^2+13)}{6} z^2 \right\}$$

$+H.O.T$ (O crossed out)

FRW

$k = 0, \ p = 1/3\ \rho$

$a = 1$

in

Standard Model

When $a \neq 1$ this give rise to an "anomalous acceleration"...

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z + \frac{(a^2 - 1)(6a^2 + 13)}{6} z^2 \right\}$$

New Acceleration Parameter

$+H.O.T$

When $a \neq 1$ this give rise to an "anomalous acceleration"...

$$d_\ell = 2t_0 z \left\{ 1 + \frac{a^2 - 1}{2} z + \frac{(a^2 - 1)(6a^2 + 13)}{6} z^2 \right\}$$

New Acceleration Parameter

$+H.O.T$

...a rigorous observable and quantifiable correction to the redshift vs luminosity relation...

After the radiation phase:

The redshift vs luminosity relation evolves continuously with time

Therefore...

We conclude (by continuity) corrections to the redshift vs luminosity relation observed after the radiation phase of the Big Bang can be accounted for, at the leading order quadratic level, by adjustment of the free parameter “a”.

The next order correction

is a

VERIFIABLE PREDICTION

of the model!!

(Work in progress)

A different coord. mapping casts new metric in a different light:

A different coord. mapping casts new metric in a different light:

$$\bar{r}(t,r) = \frac{t^a}{2}\, r$$

$$\bar{t}(t,r) = \psi_0 \left(1 + \frac{a^2\zeta^2}{4}\right) t$$

A different coord. mapping casts new metric in a different light:

$$\bar{r}(t,r) = t^{a/2}\, r$$

$$\bar{t}(t,r) = \psi_0 \left(1 + \frac{a^2\zeta^2}{4}\right) t$$

$$ds^2 = -dt^2 + t^a dr^2 + \bar{r}^2 d\Omega^2 + a(1-a)\zeta dt d\bar{r}$$

Conclude: in special non-comoving coords:

$$ds^2 = -dt^2 + t^a dr^2 + \bar{r}^2 d\Omega^2 + a(1-a)\zeta dt d\bar{r}$$

$k = 0$ FRW

with $R(t) = t^{a/2}$

"Looks like standard model with a small correction to the expansion rate, and a small corrective mixed term"

Error: $O\left(|t + (a-1)|\zeta^3\right)$

“In Fact: In these coordinates...
metric is
exactly flat 3-space
at each fixed
t=const
...just like the standard model...”

$$ds^2 = -dt^2 + t^a \left\{dr^2 + r^2 d\Omega^2\right\} + a(1-a)\zeta dt d\bar{r}$$

A "Conservation Law" Scenario of the Big Bang w/o Cosmological Constant:

- Conservation Laws Decay to Non-interacting Time-Asymptotic Wave Patterns.
- After inflation, Universe is nearly flat, but due to errors, it decays by the nonlinearities of the radiation phase $a \neq 1$ to a nearby non-interacting expansion wave
- We happen to be near the center of expansion, so looking outward, we observe a critical FRW with a small correction

The Lesson of Conservation Laws...

"Expansion waves and shock waves are fundamental to conservation laws, because even when dissipative terms are neglected, shock-wave dissipation by itself causes non-interacting wave patterns to emerge from interactive solutions"

"I.e. The one fact most certain about the Standard Model is an early hot dense epoch in which all energy was radiation..."

"...one might reasonably conjecture that decay to a non-interacting expanding wave might have occured (locally??) during the radiation phase due to the large nonlinearities associated with the large sound speed when $p = \frac{c^2}{3}\rho$."

This part violates
Copernican Principle...
"we are not in a special place
in the universe..."

- We happen to be near the center of expansion, so looking out, we observe a critical FRW with a small correction

To make a testable prediction, we need to get the corrections at

t=379,000 yrs,

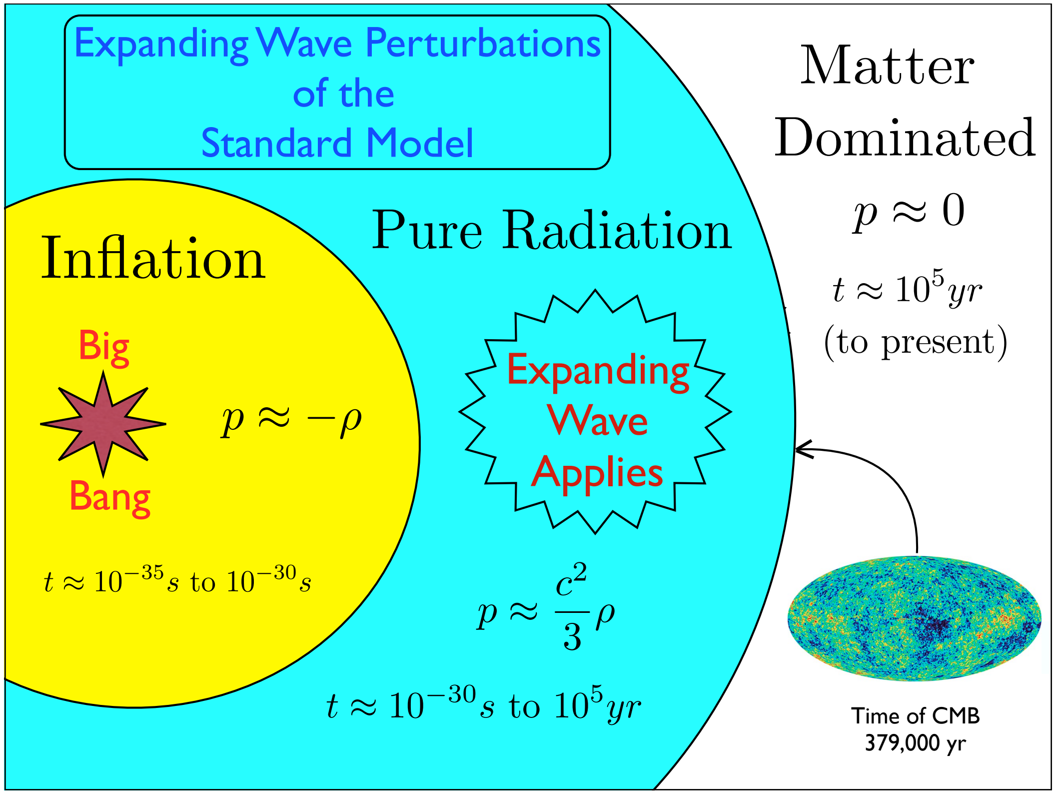
propagate errors with

p=0

to present time,

and

look for the best fit.


Expanding Wave Perturbations of the Standard Model
Matter Dominated
$p \approx 0$
$t \approx 10^5 yr$ (to present)
Inflation
Big Bang
$p \approx -\rho$
$t \approx 10^{-35}s$ to $10^{-30}s$
Pure Radiation
Expanding Wave Applies
$p \approx \frac{c^2}{3}\rho$
$t \approx 10^{-30}s$ to $10^5 yr$
Time of CMB
379,000 yr

Note: The expansion wave may not propagate as self-similar AFTER the radiation phase!

We Like:

- This correction to the Hubble Constant is not put in "Ad Hoc"...
- It is derived from first principles starting from a theory of

Expansion Waves

We Wonder:

- What scale might such expanding waves exist on...?
- Is there an inconsistency with WMAP Data...?
- Can this be accounted for in some inflationary scenario...?

Final Comment: These expanding waves near k=0 FRW represent a sort of "instability" in the Standard Model...

Thus: Even if they do not account for the anomalous acceleration...

One Has to Wonder why the Universe would choose a=1, k=0, FRW, and not one of these nearby non-interacting

Expansion Waves?

Scientists: Earth May Exist in Giant Cosmic Bubble

Wednesday, October 01, 2008

By Clara Moskowitz

SPACE

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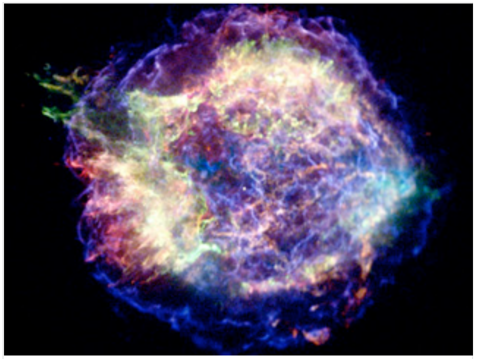

NASA/CXC/MIT/UMass

If the notion of dark energy sounds improbable, get ready for an even more outlandish suggestion.

Earth may be trapped in an abnorma bubble of space-time that is particularly devoid of matter.

Scientists say this condition could account for the apparent acceleratior of the universe's expansion, for which **dark energy** currently is the leading explanation.

Dark energy is the name given to the hypothetical force that could be drawing all the stuff in the universe outward at an **ever-increasing rate**.

Current thinking is that 74 percent of the universe could be made up of this exotic dark energy, with another


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Does DARK ENERGY Really Exist?

Maybe not. The observations that led astronomers to deduce its existence could have another explanation: that our galaxy lies at the center of a giant cosmic void

By Timothy Clifton and Pedro G. Ferreira

In science, the grandest revolutions are often triggered by the smallest discrepancies. In the 16th century, based on what struck many of his contemporaries as the esoteric minutiae of celestial motions, Copernicus suggested that Earth was not, in fact, at the center of the universe. In our own era, another revolution began to unfold 11 years ago with the discovery of the accelerating universe. A tiny deviation in the brightness of exploding stars led astronomers to conclude that they had no idea what 70 percent of the cosmos consists of. All they could tell was that space is filled with a substance unlike any other—one that pushes along the expansion of the universe rather than holding it back. This substance became known as dark energy.

It is now over a decade later, and the existence of dark energy is still so puzzling that some cosmologists are revisiting the fundamental postulates that led them to deduce its existence in the first place. One of these is the product of that earlier revolution: the Copernican principle, that Earth is not in a central or otherwise special position in the universe. If we discard this basic principle, a surprisingly different picture of what could account for the observations emerges.

Most of us are very familiar with the idea that our planet is nothing more than a tiny speck orbiting a typical star, somewhere near the edge of an otherwise unnoteworthy galaxy. In the midst of a universe populated by billions of galaxies that stretch out to our cosmic horizon, we are led to believe that there is nothing special or unique about our location. But what is the evidence for this cosmic humility? And how would we be able to tell if we *were* in a special place? Astronomers typically gloss over these questions, assuming our own typicality sufficiently obvious to warrant no further discussion. To entertain the notion that we may, in fact, have a special location in the universe is, for many, unthinkable. Nevertheless, that is exactly what some small groups of physicists around the world have recently been considering.

Ironically, assuming ourselves to be insignificant has granted cosmologists great explanatory power. It has allowed us to extrapolate from what we see in our own cosmic neighborhood to the universe at large. Huge efforts have been made in constructing state-of-the-art models of the universe based on the cosmological principle—a generalization of the Copernican principle that states that at any moment in time all points and directions in space look the same. Combined with our modern understanding of space, time and matter, the cosmological principle implies that space is expanding, that the universe is getting cooler and that it is populated by relics from its hot beginning—predictions that are all borne out by observations.

KEY CONCEPTS

- The universe appears to be expanding at an accelerating rate, implying the existence of a strange new form of energy—dark energy. The problem: no one is sure what dark energy is.
- Cosmologists may not actually need to invoke exotic forms of energy. If we live in an emptier-than-average region of space, then the cosmic expansion rate varies with position, which could be mistaken for a variation in time, or acceleration.
- A giant void strikes most cosmologists as highly unlikely but so for that matter does dark energy. Observations over the coming years will differentiate between the two possibilities.

—The Editors

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Until now, there has been no good way to choose between dark energy or the void explanation, but a new study outlines a potential test of the bubble scenario.

If we were in an unusually sparse area of the universe, then things could look farther away than they really are and there would be no need to rely on dark energy as an explanation for certain astronomical observations.

"If we lived in a very large under-density, then the space-time itself wouldn't be accelerating," said researcher Timothy Clifton of Oxford University in England. "It would just be that the observations, if interpreted in the usual way, would look like they were."

Scientists first detected the acceleration by noting that **distant supernovae** seemed to be moving away from us faster than they should be.

One type of supernova (called Type Ia) is a useful distance indicator, because the explosions always have the same intrinsic brightness.

Since light gets dimmer the farther it travels, that means that when the supernovae appear faint to us, they are far away, and when they appear bright, they are closer in.

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Scientists first detected the acceleration by noting that **distant supernovae** seemed to be moving away from us faster than they should be.

According to them...

$$
\begin{aligned}
\text{Center} &\approx 15\ MPC \\
&\approx 50\ Million\ Light\ Years \\
&\approx Distance\ between \\
&\quad\ clusters\ of\ galaxies \\
&\approx 1/200\ Distance\ Across \\
&\quad\ Visible\ Universe
\end{aligned}
$$

According to them...

$$
\begin{aligned}
\text{Extent} &\approx 800\ MPC \\
&\approx 2.5\ Billion\ Light\ Years \\
&\approx 1/5\ Distance\ Across \\
&\quad\ Visible\ Universe
\end{aligned}
$$

Our view...

"Modeling an under-density during
the p=0 stage
can only model evolution
after the wave has formed,
but cannot give an explanation for
the creation of such a wave..."

p=0 is "non-interacting"

Conclude:

We are exploring the possibility that these expanding waves might provide a quantitative explanation for the formation of such an underdensity...

Comparison of dark energy models: A perspective from the latest observational data

Miao Li,[1,2,*] Xiao-Dong Li,[3,2,†] and Xin Zhang[4,1,‡]

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In this paper, we compare some popular dark energy models with the assumption of a flat universe by using the latest observational data including the type Ia supernovae Constitution compilation, the baryon acoustic oscillation measurement from the Sloan Digital Sky Survey and the Two Degree Field Galaxy Redshift Survey, and the cosmic microwave background measurement given by the five-year Wilkinson Microwave Anisotropy Probe observations. Model comparison statistics such as the Bayesian and Akaike information criteria are applied to assess the worth of the models. These statistics favor models that give a good fit with fewer parameters. Based on this analysis, we find that the simplest cosmological constant model that has only one free parameter is still preferred by the current data. For other dynamical dark energy models, we find that some of them, such as the α dark energy, constant w, generalized Chaplygin gas, and holographic dark energy models, can provide good fits to the current data, and three of them, namely, the agegraphic dark energy, Dvali-Gabadadze-Porrati, and Ricci dark energy models, are clearly disfavored by the data.

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The possibility that dark energy is dynamical, for example, in a form of some light scalar field [3], has been explored by cosmologists for a long time. A basic way to explore such a dynamical dark energy model in light of observational data is to parameterize dark energy by an equation-of-state parameter w, relating the dark energy pressure p to its density ρ via $p = w\rho$. In general, this parameter w is time variable. The most commonly used forms of $w(a)$ involve the constant equation of state, $w =$ const., and the Chevalliear-Polarski-Linder form [4], $w(a) = w_0 + (1 - a)w_a$, where w_0 and w_a parameterize the present-day value of w and the first derivative. There are also many other dynamical dark energy models which stem from different aspects of new physics. For example, the "holographic dark energy" models [5, 6, 7, 8, 9, 10, 11] arise from the holographic principle of quantum gravity theory, and the Chaplygin gas models [12, 13, 14] are motivated by brane world scenarios and may be able to unify dark matter and dark energy. In addition, there is also significant interest in modifications to general relativity, in the context of explaining the acceleration of the universe. The Dvali-Gabadadze-Porrati models [15, 16, 17] arise from a class of brane-related theories in which gravity leaks out into the bulk at large distances, leading to the accelerated expansion of the universe.

In the face of so many competing dark energy candidates, it is important to find an effective way to decide which one is right, or at least, which one is most favored by the observational data. Although the accumulation of the current observational data has opened a robust window for constraining the parameter space of dark energy models, the model filtration is still a difficult mission owing to the accuracy of current data as well as the complication caused by different parameter numbers of various dark energy models. In this paper, we make an effort to assess some popular dark energy models in light of the latest observational

Dark energy, gravitation and the Copernican principle

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(15th August 2008)

To appear in *Dark Energy: Observational and Theoretical Approaches*,
Ed. P. Ruiz-Lapuente (Cambridge University Press, 2010).

cosmological model. Needless to remind that even if a cosmological model is in agreement with all observations, whatever their accuracy, it does not prove that it is the "correct" model of the Universe, in the sense that it is the correct cosmological extrapolation and solution of the local physical laws.

Dark energy confronts us with a compatibility problem since, in order to "save the phenomena" of the observations, we have to include new ingredients (constant, matter fields or interactions) beyond those of our established physical theories. However the required value for the simplest dark energy model, i.e. the cosmological constant, is more than 60 order of magnitude smaller to what is expected from theoretical grounds (§ 1.1.6). This tension between what is required by astronomy and what is expected from physics reminds us of the twenty centuries long debate between Aristotelians and Ptolemeans (Duhem, 1913), that was resolved not only by the Copernican model but more important by a better understanding of the physics since

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Comparison of dark energy models: A perspective from the latest observational data

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END

SPACE.com -- 'Big Wave' Theory Offers Alternative to Dark Energy

'Big Wave' Theory Offers Alternative to Dark Energy

By Clara Moskowitz
Staff Writer
posted: 17 August 2009
05:56 pm ET

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This story was updated at 2:40 p.m. on Aug. 18.

Mathematicians have proposed an alternative explanation for the accelerating expansion of the universe that does not rely on the mystifying idea of dark energy.

According to the new proposition, the universe is not accelerating, as observations suggest. Instead, an expanding wave flowing through space-time has caused distant galaxies to appear to be accelerating away from us. This big wave, initiated after the Big Bang that is thought to have sparked the universe, could explain why objects today appear to be farther away from us than they should be according to the Standard Model of cosmology.

"We're saying that maybe the resulting expanding wave is actually causing the anomalous acceleration," said Blake

http://www.space.com/scienceastronomy/090817-dark-energy-alternative.html

Temple of the University of California, Davis. "We're saying that dark energy may not really be the correct explanation."

The researchers derived a set of equations describing expanding waves that fit Einstein's theory of general relativity, and which could also account for the apparent acceleration. Temple outlines the new idea with Joel Smoller of the University of Michigan in the Aug. 17 issue of the journal Proceedings of the National Academy of Sciences.

While more research will be needed to see if the idea holds up, "the research could change the way astronomers view the composition of our universe," according to a summary from the journal.

To convince other cosmologists, the new model will have to pass muster with further inquiry.

"There are many observational tests of the standard cosmological model that the proposed model must pass, aside from the late phase of accelerated expansion," said Avi Loeb, director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. "These include big bang nucleosynthesis, the quantitative details of the microwave background anisotropies, the Lyman-alpha forest, and galaxy surveys. The authors do not discuss how their model compares to these tests, and whether the number of free parameters they require in order to fit these observational constraints is smaller than in the standard model. Until they do so, it is not clear why this alternative model should be regarded as advantageous."

Johns Hopkins University astrophysicist Mario Livio agreed that to be seriously considered, the model must be able to predict properties of the universe that astronomers can measure.

He said the real test "is in whether they are able to reproduce all the observed cosmological parameters (as determined, e.g. by a combination of the Hubble Constant and the parameters determined by the CMB observations). To only produce an apparent acceleration is in itself interesting, but not particularly meaningful."

Inconvenient truths

Dark energy is itself a hasty fix to an inconvenient truth discovered by astronomers in the late 1990s: that the universe is expanding, and the rate of this expansion seems to be constantly picking up speed.

To explain this startling finding, cosmologists invoked dark energy, a hypothetical form of energy that is pulling the universe apart in all directions (note that dark energy is wholly separate from the equally mysterious concept of dark matter - a hypothetical form of matter that populates the universe, interacting gravitationally with normal matter, but which cannot be seen with light). In this interpretation, the whole universe is blowing up like a balloon, and from any given point within it, all distant objects appear to be speeding away from you.

But not everyone is happy with the dark energy explanation.

"It just seems like an unnatural correction to the equations - it's like a fudge factor," Temple told SPACE.com. "The equations don't make quite as much physical sense when you put it in. You just put it in to fit the data."

Temple and Smoller think the idea of an expanding wave makes more sense.

"At this stage we think this a very plausible theory," Temple said. "We're saying there isn't any acceleration. The galaxies are displaced from where they're supposed to be because we're in the aftermath of a wave that put those galaxies in a slightly different position."

Ripples in a pond

Temple compared the wave to what happens when you throw a rock into a pond. In this case, the rock would be the Big Bang, and the concentric ripples that result are like a series of waves throughout the universe. Later on, when the first galaxies start to form, they are forming inside space-time that has already been displaced from where it would have been without the wave. So when we observe these galaxies with telescopes, they don't appear to be where we would expect if there had never been a big wave.

SPACE.com -- 'Big Wave' Theory Offers Alternative to Dark Ener

One potential issue with this idea is that it might require a big coincidence.

For the universe to appear to be accelerating at the same rate in all directions, we in the Milky Way would have to be near a local center, at the spot where an expansion wave was initiated early in the Big Bang when the universe was filled with radiation.

Temple concedes that this is a coincidence, but said it's possible that we are merely in the center of a smaller wave that affects the galaxies we can see from our vantage point - we need not be in the center of the entire universe for the idea to work.

http://www.space.com/scienceastronomy/090817-dark-energy-alternative.html#comme

The New York Times
nytimes.com

January 15, 2008

Big Brain Theory: Have Cosmologists Lost Theirs?

By DENNIS OVERBYE

Correction Appended

It could be the weirdest and most embarrassing prediction in the history of cosmology, if not science.

If true, it would mean that you yourself reading this article are more likely to be some momentary fluctuation in a field of matter and energy out in space than a person with a real past born through billions of years of evolution in an orderly star-spangled cosmos. Your memories and the world you think you see around you are illusions.

This bizarre picture is the outcome of a recent series of calculations that take some of the bedrock theories and discoveries of modern cosmology to the limit. Nobody in the field believes that this is the way things really work, however. And so in the last couple of years there has been a growing stream of debate and dueling papers, replete with references to such esoteric subjects as reincarnation, multiple universes and even the death of spacetime, as cosmologists try to square the predictions of their cherished theories with their convictions that we and the universe are real. The basic problem is that across the eons of time, the standard theories suggest, the universe can recur over

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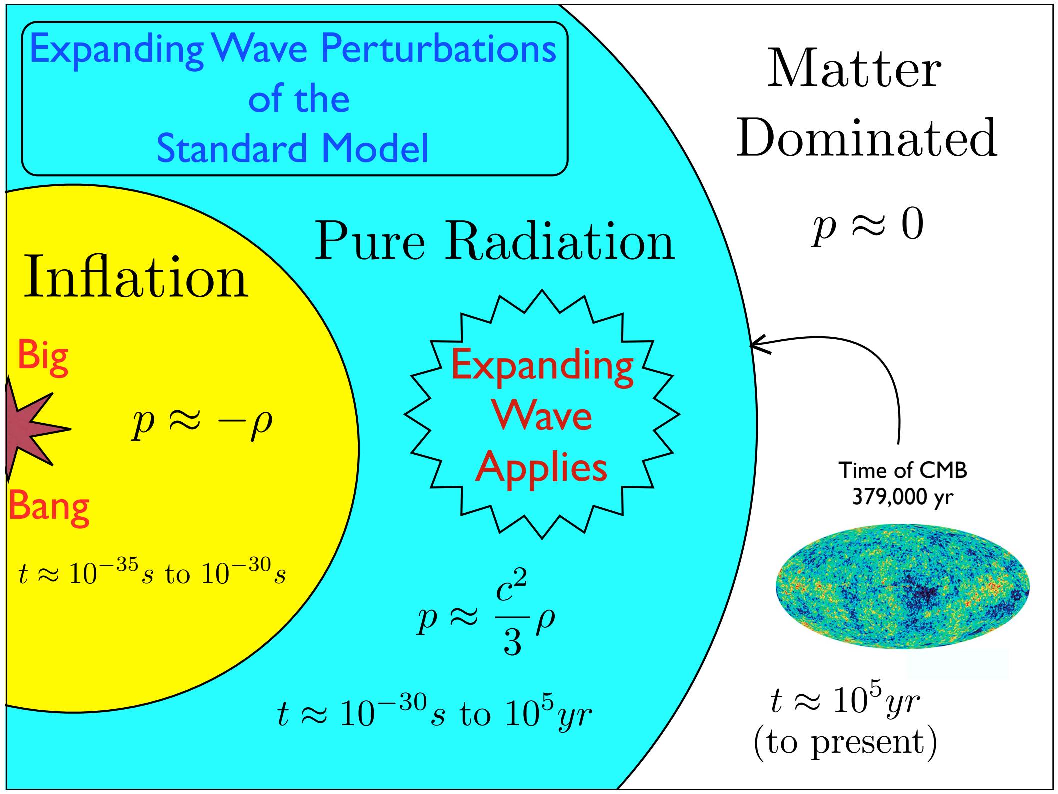
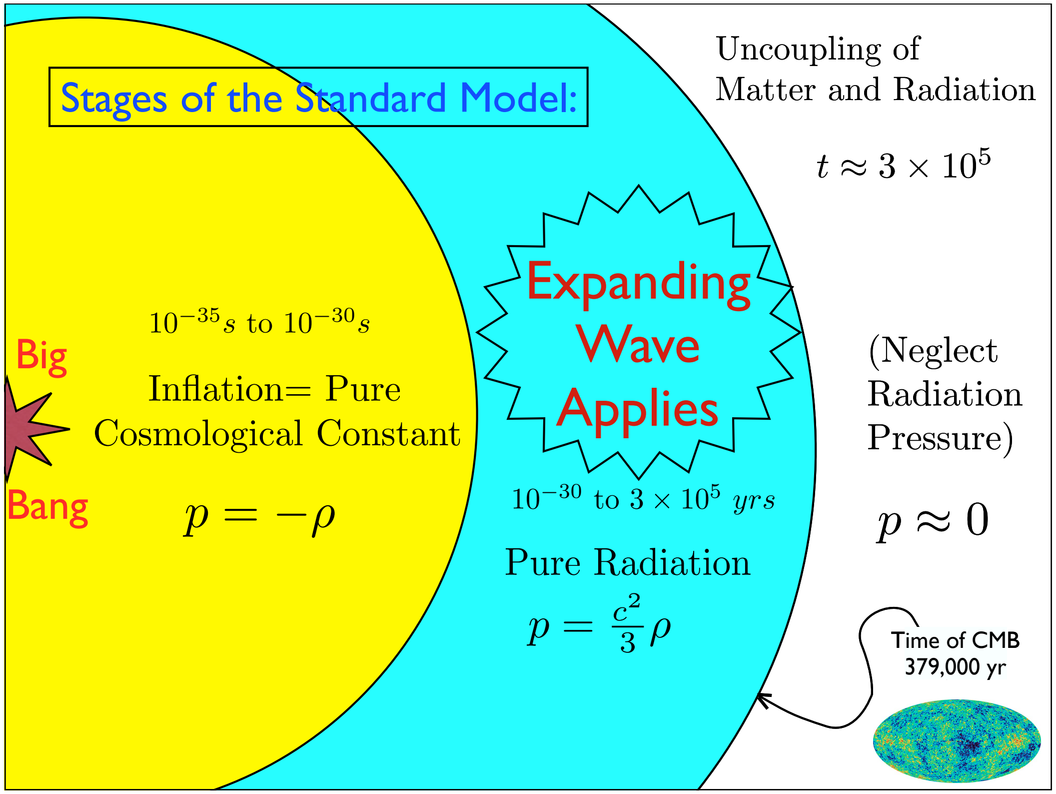
Alan Guth, a cosmologist at the Massachusetts Institute of Technology who agrees this overabundance is absurd, pointed out that some calculations result in an infinite number of free-floating brains for every normal brain, making it “infinitely unlikely for us to be normal brains.” Welcome to what physicists call the Boltzmann brain problem, named after the 19th-century Austrian physicist Ludwig Boltzmann, who suggested the mechanism by which such fluctuations could happen in a gas or in the universe.



Expanding Wave Perturbations of the Standard Model
Inflation
Big
Bang
$p \approx -\rho$
$t \approx 10^{-35}s$ to $10^{-30}s$
Pure Radiation
Expanding Wave Applies
$p \approx \frac{c^2}{3}\rho$
$t \approx 10^{-30}s$ to $10^{5}yr$
Matter Dominated
$p \approx 0$
Time of CMB
379,000 yr
$t \approx 10^{5}yr$
(to present)


Stages of the Standard Model:
Big
Bang
$10^{-35}s$ to $10^{-30}s$
Inflation= Pure Cosmological Constant
$p = -\rho$
Expanding Wave Applies
10^{-30} to 3×10^5 yrs
Pure Radiation
$p = \frac{c^2}{3}\rho$
Uncoupling of Matter and Radiation
$t \approx 3 \times 10^5$
(Neglect Radiation Pressure)
$p \approx 0$
Time of CMB
379,000 yr