Particle cosmology

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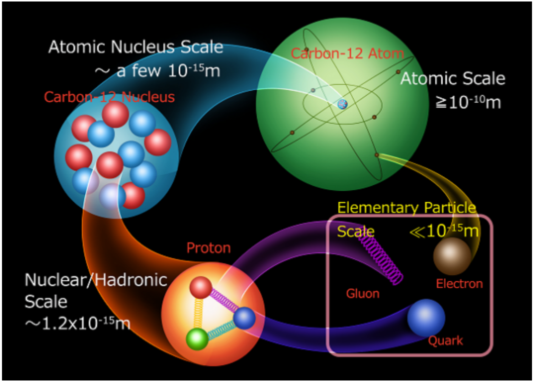
Logo of Technical University in Liberec

Founded 1953.

We are made of ...



- molecules
- atoms
- elementary particles
- something else??

Hot big bang theory

1. General Relativity(theoretical)
2. Expansion of the Universe (1930, Hubble)
3. Relative abundance of light elements (1940, Gamow)
4. Cosmic microwave background (1965, Penzias and Wilson)

Einstein equation and FLRW metric

$$G_{\mu\nu} \equiv 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

HOMOGENEITY and ISOTROPY (150-370 MPc, DISCRETE)

$$ds^2 = dt^2 - a^2(t)[\frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2\theta \; d\phi^2)]$$

$$^{(3)}R = \frac{6K}{a^2(t)}$$

$$^{(4)}R = 6\frac{\ddot{a}}{a} + 6(\frac{\dot{a}}{a})^2 + \frac{6K}{a^2}$$

Friedman equation

$$H^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{K}{a^2},\ K = -1, 0, +1,$$

$$\frac{d}{dt}(\rho a^3) + p\frac{d}{dt}(a^3) = 0,$$

$$\rho = \rho_M + \rho_R,$$

$$p = p_M + p_R$$

Densities

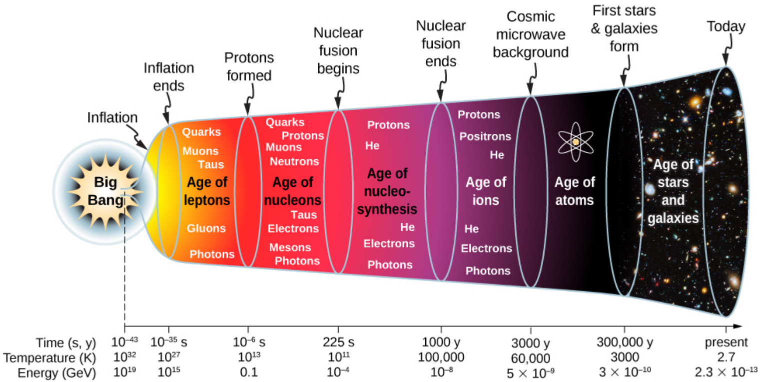
$$\Omega_M = \frac{8\pi G \rho_M}{3H_0^2},\ \Omega_R = \frac{8\pi G \rho_R}{3H_0^2}$$

$$\Omega_\Lambda = \frac{\Lambda}{3H_0^2},\ \Omega_K = -\frac{K}{a_0^2 H_0^2}$$

$$\Omega_M + \Omega_\Lambda + \Omega_K = 1$$

$$\rho_{CMB} = \frac{\pi^2}{15}(kT_{CMB})^4/(\hbar c)^3 = 4.5\ 10^{-34} g/cm^3$$

Hot Big Bang Scenario



Accelerated expansion of the Universe

The Universe is expanding in the last 5 billion years.

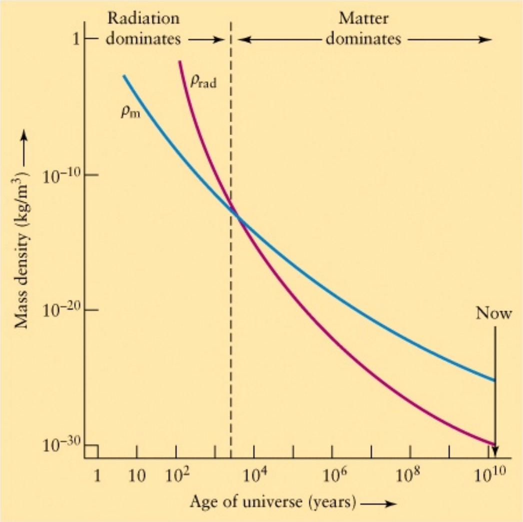
Recombination and photon decoupling

Photons will **decouple** from the plasma when their interaction rate cannot keep up with expansion of the universe and the **mean free path** becomes larger than the **horizon size**: the Universe becomes transparent;

$$(1 + z_{dec}) \approx 1100$$

$$T_{cmb} = 2.725 \pm 0.002 \ K$$

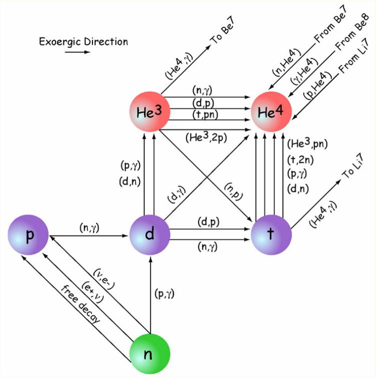
Matter-radiation equality



Primordial nucleosynthesis and light element abundance

1920 Eddington

One baryon per 10^9 photons

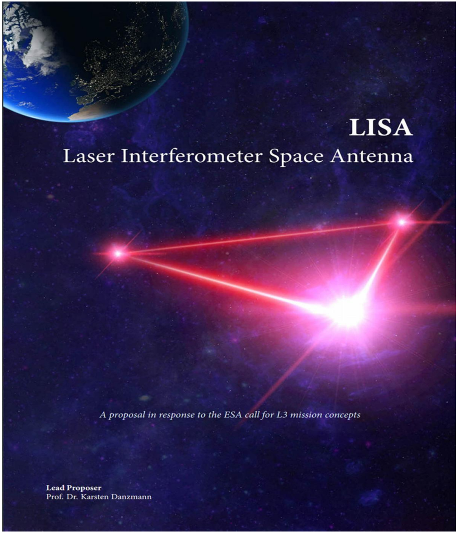


Neutrino decoupling

Before the nucleosynthesis of the lightest elements in the early Universe, weak interactions were too slow to keep neutrinos in thermal equilibrium with the plasma:

$$T_\nu = 1.945K$$

LISA



LISA
Laser Interferometer Space Antenna
A proposal in response to the ESA call for L3 mission concepts
Lead Proposer
Prof. Dr. Karsten Danzmann

First second of the evolution

- Quark-gluon plasma, 10^{-5} s
- Baryogenesis, 10^{-10} s
- Grand Unification, 10^{-36} s
- Inflation, $10^{-43} - 10^{-32}$ s

Dark matter

- Standard model neutrinos (excluded, because not abundant enough)
- Sterile neutrinos
- Axions
- Supersymmetric candidates: neutralinos, sneutralinos, gravitinos, axions
- Light scalar dark matter
- Dark matter from little Higgs model
- Kaluza-Klein states
- Superheavy dark matter
- Other candidates

Dark energy

Modeled by modified theories of gravity: for example $f(R)$-theories

$$S = \frac{1}{2\kappa^2}\int f(R)\sqrt{-g}\, d^4x + S_m$$

$$F(R)R_{\mu\nu} - \frac{1}{2}f(R)g_{\mu\nu} - \nabla_\mu\nabla_\nu F + g_{\mu\nu}\Box F = \kappa^2 T_{\mu\nu}$$

$$3\Box F + FR - 2f = \kappa^2$$

Hypothetical scalaron!

Dark energy after GW170817

$$|\frac{c_g}{c} - 1| \leq 5.10^{-16}$$

Large class of scalar-tensor theories and dark energy models are highly disfavored.

Why quantum gravity?

- That GR cannot be true at the most fundamental level is clear from singularity theorems.
- The universal coupling of gravity to all forms of energy would make it plausible that gravity has to be implemented in a quantum framework too.
- Quantum theory and GR contain a drastically different concept of time. They are incompatible.

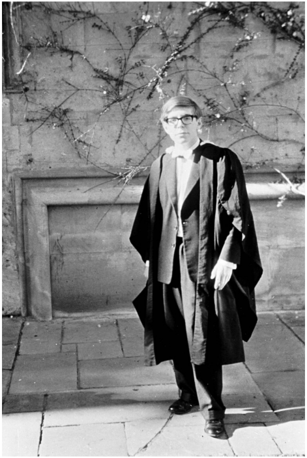
Quantum Universe

1. Higher level structure (quantum)
2. Lower level structure (classical)

- Not distinguish between on-shell and off-shell.
- Generalized Hasse diagrams.

Causal metric hypothesis

The properties of the physical Universe are manifestations of causal structure.



Causal metric hypothesis

The causal structure of relativistic spacetime determines its metric structure up to scale:
smooth, causal, metric, topological, conformal

- Rafael Sorkin: order plus number equals geometry
- Stephen Hawking: topological structure determines conformal structure
- David Malament: causal structure detemines topological structure

Axioms of irreflexive formulation

The irreflexive formulation of causal set theory is defined by the following six axioms:

1. Binary axiom
2. Measure axiom
3. Countability
4. Transitivity
5. Interval finitness
6. Irreflexivity

Basic ideas

- Experimental bounds on Lorentz invariance violation do not present a serious obstacle to the development of discrete causal theory.
- Symmetry is much less central than generally believed notion of covariance.
- Problem of recovering a classical history from its relation space looks very much like boundary value problem.

Notion of spacetime

- Spacetime is a part what happens, not merely a place where things happen.
- GR is not perfectly background independent.
- Spacetime, particles and fields as aspects of something more fundamental.
- Emergent aspects of spacetime: particle

Cosmological inflation

- Inflation: what really happened in the early Universe is that ST ran down from relatively random causal structure, to sparser but more regular structure
- Why would causal structure grow sparser?
- Why would it stabilize in "geometric" structure?

Causal set approach

- Describing fundamental spacetime structure.
- Modeling gravitation at the quantum level.
- Unifying physical laws.

One of the results: heuristic bound on the value of cosmological constant in concordance with the experiment

Related theories to causal set approach

1. Causal dynamical triangulation
2. Category theoretic approaches
3. Quantum automatons
4. Tensor networks
5. Causal nets
6. Domain theory
7. Quantum information theory
8. Loop quantum gravity
9. Twistor theory
10. Shape dynamics

Continuum based theories

1. Divergence issues
2. Lack of natural scale
3. Experimental discreteness
4. Discreteness arising from continuum based assumptions
5. Discreteness via the philosophy of measurement

Chain

Let $M = (M, R, i, t)$ be a multidirected set.

1. A chain γ in M is a sequence of elements and relations of the form $... \prec x_0 \prec x_1 \prec ...$ in M, where the notation $x_n \prec x_{n+1}$ refers to particular relation r in R such that $x_n = i(r)$ and $x_{n+1} = t(r)$. The chain set $Ch(M)$ of M is the set of all chains in M.
2. A chain of length n, or n-chain, between x and y in M, is a chain γ of the form $x = x_0 \prec x_1 \prec ... \prec x_{n-1} \prec x_n = y$. The element x is called the initial element of γ and the element y is called the terminal element of γ. The set of n-chains $Ch_n(M)$ in M is the subset of $Ch(M)$ consisting of all chains of length n. A complex chain is a chain of length at least two.

Antichain

1. A cycle in M is a chain $x_0 \prec x_1 \prec \ldots \prec x_{n-1} \prec x_n$ of nonzero length such that $x_0 = x_n$; its initial element coincides with its terminal element.
2. A relation r in R is called reducible, if there exists a complex chain from its initial element to its terminal element. Such a chain is called a reducing chain for r. If r is not reducible, it is called irreducible. M itself is called irreducible if all its relations are irreducible
3. An antichain σ in M is a subset of M admitting no chain of nonzero length in M between any pair of elements x and y in σ, distinct or otherwise.

Lemma

Lemma

Let $M = (M, R, i, t)$ *be a multidirected set, and let* σ *be an antichain in* M*. Suppose that* x *is an element of* M *belonging neither to* σ *itself, nor to the past or future of* σ*, nor to a cycle in* M*. Then the subset* $\sigma' = \sigma \cup \{x\}$ *of* M *is an antichain in* M*.*

Definition

Let $M = (M, R, i, t)$ be a multidirected set, interpreted as a model of information flow or causal structure, and let x and y be elements of M.

1. A family Γ of chains between x and y in M is called dependent if there exists another such family Γ', not containing Γ encoding all information or causal influence encoded by Γ.
2. In particular, a chain γ from x to y in M is called dependent if there exists a family Γ' of chains from x to y, not including γ encoding all information or causal influence encoded by γ.
3. If a chain or family of chains is not dependent, it is called independent.

Six arguments against transitivity

1. Multiple independent modes of influence between pairs of events are ubiquitous in conventional physics.
2. Independence of influences exerted by an event should not be constrained by details of its future.
3. Irreducibility and independence of relations between pairs of elements are a priori distinct conditions.
4. Configuration spaces of transitive binary relations are pathological, particularly from a physical perspective.
5. Structural notions from mathematics motivate the existence of independent modes of influence.
6. Recognition of nontransitive relations leads naturally to other improvements in discrete causal theory.

Definition

Let $D = (D, \prec)$ be a directed set, viewed as a model of causal structure under the independence convention. In this context, the binary relation $\prec$ on D is called the causal relation on D.

Definition

Let $D = (D, \prec)$ be a directed set.

1. The transitive closure of D is the directed set $tr(D) \equiv (D, \prec_{tr})$ whose binary relation $\prec_{tr}$ is defined by setting $x \prec_{tr} y$ if and only if there exists a chain of nonzero length between x and y in D. The binary relation $\prec_{tr}$ is called the transitive relation on D.
2. The skeleton of D is the acyclic directed set $sk(D) \equiv (D, \prec_{tr})$ whose binary relation $\prec_{sk}$ is defined by setting $x \prec_{sk} y$ if and only if $x \prec y$ is an irreducible relation in D. The binary relation $\prec_{sk}$ is called the skeletal relation on D.

Star finite and interval finite causal set

Interval finitness does not imply star finitness! An example is an infinite bouquet.

Star finitness does not imply interval finitness. An example is the Jacob's ladder.

A typical causal set defined via global sprinkling into $\mathbb{R}^{3+1}$, is star infinite at every element .

New version of axioms

A new version of discrete classical causal theory may be defined by:

1. Binary axiom
2. Generalized measure axiom
3. Countability
4. Star finitness
5. Acyclicity

Emergent particles

- emerge from discrete causal structure without the necessity of importing auxiliary mathematical content as Hilbert spaces
- Spatially localized family of events that retains similar internal structure over time interval.
- Emergent aspect of ST, rather than as "separate entities" existing on ST, can lead to possible insights into famous problems as the magnitude of the cosmological constant and the nature of dark matter.

Poincare group

- the symmetry properties of Minkowski ST $\mathbb{R}^{3+1}$ are crucial to every area of physics that incorporates special relativity
- we need to find the emergence of P : how "near-symmetries" including Poincare symmetries may arise from causal structure at the fundamental scale

Poincare group

We will now talk about directed sets:

individual elements of the Poincare group may be viewed either actively or passively, but "active-passive" role of the Poincare group is largely an artifact of continuum theory;

Under the active viewpoint, P may be generalized by comparing it to the group of automorphisms of Minkowski spacetime $\mathbb{R}^{3+1}$ in a different category; namely, the category of partially ordered sets.

The partial order in this context is the order defined by the relativistic causal relation $\prec_{GR}$ on $\mathbb{R}^{3+1}$, which encodes potential influences between pairs of events.

We define the **causality group** G of $\mathbb{R}^{3+1}$ to be the group of bijections $f : \mathbb{R}^{3+1} \to \mathbb{R}^{3+1}$ such that both f and f^{-1} preserve the causal relation $\prec_{GR}$. We can prove the following theorem:

Theorem

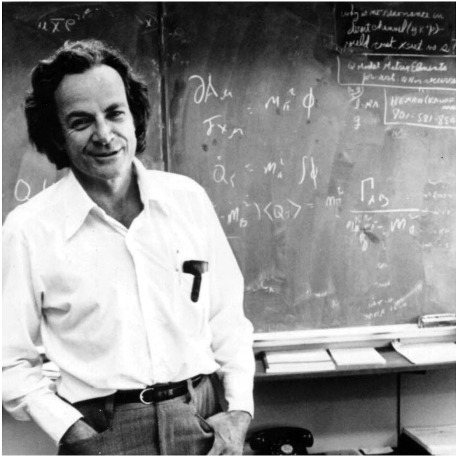
The causality group G is generated by the orthochronous Lorentz group L', together with translations and dilations.

Symmetry annalogy: the Poincare group is analogous to the group of automorphisms of a directed set;

Passive viewpoint

Under the passive viewpoint, the Poincare group P may be generalized in terms of the relativity of simultaneity. Events x and y in Minkowski spacetime $\mathbb{R}^{3+1}$ are causally unrelated if $x \nprec_{GR} y$ and $y \nprec_{GR} x$. In this case, an inertial frame of reference F for $\mathbb{R}^{3+1}$ may be chosen under which x temporally precedes y; this may be done in many different ways. Each frame F therefore induces a special refinement $\prec_{GR}$, encoding the temporal order with respect to F. In this context, Poincare covariance says that the laws of physics do not depend on a choice of refinement of the causal relation.

It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are or what your name is. If it doesn’t agree with an experiment, it is wrong.



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