Statistical mechanical perspectives on cosmological puzzles

Th. Smiths

ICTS, Bangalore – 18 November 2019

Statistical mechanics:

a method, a language

connecting hierarchies of scales and levels of description… using **fluctuation theory**

With preferred subjects such as:

- **Deriving/Correcting thermodynamics**
- **Phase transitions, critical phenomena**
- **Emergent behavior from micro-laws**

With preferred applications:

- **Condensed matter, symmetry breaking, hydrodynamics + corrections,…**
- **Information theory, biophysics,…**

Statistical mechanics:

Connecting hierarchies of scales and moving between levels of physical description…

…as a branch of probability theory

is also applicable to the biggest system in the universe, where strong coupling and nonlinearities rule….

Statistical mechanics:

Connecting hierarchies of scales
and levels of description…
…as a branch of probability theory

is also applicable to the biggest system in the universe, where strong coupling and nonlinearities rule…. *i.e.*, to

The Universe itself !

Many opportunities in cosmology nowadays...
(COBE, WMAP, PLANCK – missions, data-driven precision science)
(cf similar developments in biophysics, quantum optics,...)

Fluctuations become measured and detailed structure and background information.

Statistical cosmology ! **(and not only via data-science)**
Stochastic cosmology !

Statistical mechanics in Astrophysics&Cosmology:

- **Statistical methods – description of structure** –

e.g. correlations in galaxy catalogues from the theory of liquids.
Statistical Physics for cosmic structures, Gabrielli, Labini, Joyce and Pietronero Springer, 2005

- **Fluctuation theory**

e.g. **Brownian Motion, Dynamical Friction, and Stellar Dynamics effects of fluctuating gravitational fields S. Chandrasekhar**
Chandrasekhar derived the Fokker-Planck equation for stars and showed that long-range gravitational encounters provide a drag force, dynamical friction, which is important in the evolution of star clusters and the formation of galaxies.

- **Kinetic theory, thermal history, plasma physics**

e.g. Particle velocity distribution functions in space plasmas often show non Maxwellian suprathermal tails decreasing as a power law of the velocity.

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S. Chandrasekhar, Rev. Mod. P July 1949:

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e.g. Particle velocity distribution functions in space plasmas often show non Maxwellian suprathermal tails decreasing as a power law of the velocity.

Let’s start
This is how we start
This is how we start

Not with a whimper but a bang

When asked in 1958 if he would write these lines again, Eliot responded with a ’no‘.

The bangs of this talk:

Dark energy puzzle
(how to explain observed acceleration in cosmic expansion)

Space Roar
(how to explain observed deviation from Planck law in CMB)

Information paradox
(within black hole physics, since Hawking radiation)

Horizon problem
(traditionally one of the major motivations for inflation theory)

Flatness problem
(traditionally yet another major motivation for inflation theory)

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Information paradox *(10 min)*
(within black hole physics, since Hawking radiation)

Horizon problem *(6 min)*
(traditionally one of the major motivations for inflation theory)

Flatness problem *(4 min)*
(traditionally yet another major motivation for inflation theory)

Christian Maes, No information or horizon paradoxes for Th. Smiths. European Journal of Physics Plus **130**, 196 (2015).

Marco Baiesi, Carlo Burigana, Livia Conti, Gianmaria Falasco, Christian Maes, Lamberto Rondoni and Tiziana Trombetti, On a possible nonequilibrium imprint in the cosmic background at low frequencies. arXiv:1908.08876v1 [astro-ph.CO].

Thibaut Demaerel, Christian Maes and Ward Struyve, Cosmic acceleration from quantum Friedmann equations. arXiv:1901.09767

What would (or, could perhaps)

THe Statistical Mechanician In THe Street,

Th. Smiths, (cf magnetism and the Ising model)

say about more recent cosmological/HEP **paradoxes :**

1. Dark energy puzzle

(how to explain observed acceleration in cosmic expansion)

2. Space Roar

(low frequency deviations from Planck's law in CMB)

3. Information paradox

(within black hole physics, since Hawking radiation)

4. Horizon problem

(traditionally one of the major motivations for inflation theory)

5. Flatness problem

(traditionally yet another major motivation for inflation theory)

1. Dark energy puzzle:

Universe is **expanding**! And, so we saw recently, in an **accelerating** way.
(1998 Supernova Cosmology Project , High-Z Supernova Search Team)

objects further away appear dimmer, so use the observed brightness of type 1a supernovae to measure the distance to them. Compare that distance to supernovae's cosmological redshift (=how much universe has expanded since the supernova occurred): objects in the universe are moving away from one another at an accelerated rate.

➔ Cosmological constant is needed (again)
➔ Nature of cosmological constant = dark energy

1. Dark energy puzzle:

Universe is **expanding**! And, so we saw recently, in an **accelerating** way. (= the velocity at which a distant galaxy is receding from the observer is continuously increasing with time.)

The traditional way and starting point for theoretical discussion is to suppose a completely and isotropic universe and to use the FLRW-metric where the only parameters are

(1) the scaling factor and
(2) the density/pressure as functions of time (only).

Within the classical Friedmann-Lemaitre-Robertson-Walker model of the universe: assume a homogeneous and isotropic universe with metric

$$ds^2 = dt^2 - a(t)^2\, d\Omega_k^2$$

If matter is a perfect fluid with mass density ρ and pressure p, then the scale factor enters the Hubble parameter

$$H = \dot{a}/a$$

to satisfy

$$H^2 = 2\kappa^2 \rho - k\,\frac{c^2}{a^2 R^2} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}}{a} = -\kappa^2 \left(\rho + 3\frac{p}{c^2}\right) + \frac{\Lambda\, c^2}{3}$$

$$\frac{\ddot{a}}{a} = -\kappa^2 \left(\rho + 3\frac{p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

Conclusion: so it seems.....
we need to introduce *again* cosmological constant Λ > 0 to enable acceleration

Cosmological constant = negative pressure, contribution in the stress-energy tensor, called **DARK ENERGY**, unknown form of energy which is hypothesized to permeate all of space.

I.e., start program to interpret Λ > 0 as positive energy of quantum vacuum to be computed by string theory, multiverses, anthropic principle,…. and still be wrong by factor 10^{50}.

But how would Th. Smiths react to that?

Which statistical mechanician, somewhat versed in statistical dynamical problems in disordered media, would believe that the traditional Friedmann equations, within the completely homogeneous/isotropic set-up of FLWR,
would be adequate to start a fundamental discussion on the origin of the (recent) accelerated expansion of the universe?

Who would not seek alternatives to the programme of identifying the accelerated expansion with (highly unstable) vacuum energy calculations?

cf. failure of mean field theory near critical points
cf. failure of chemical kinetics
cf. failure of dynamical mean field equations

Th. Smiths is pragmatic, taking models, simplifying….

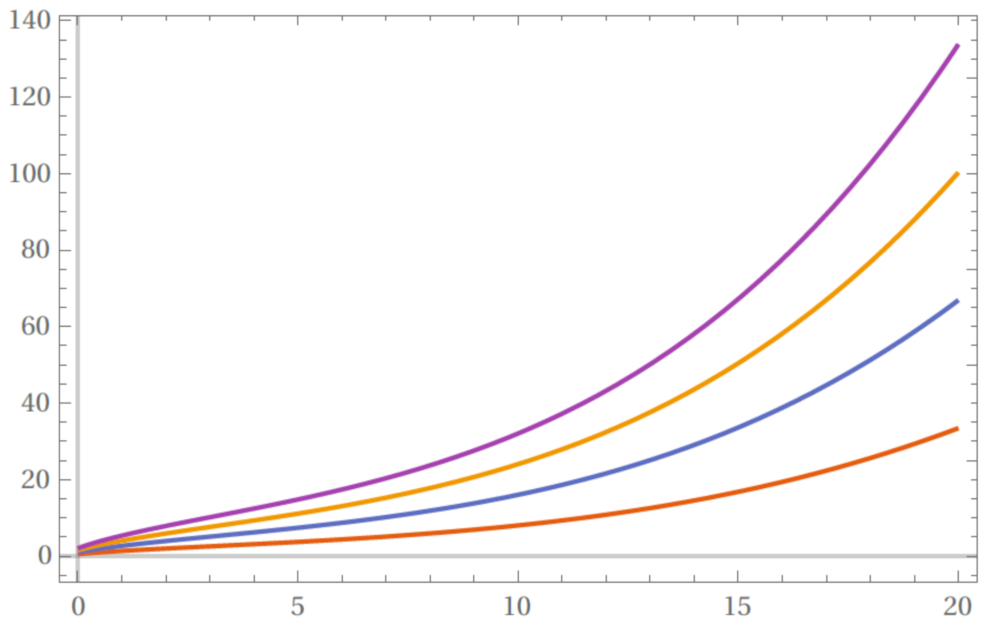
Remember the strength and the role of fluctuations, to correct mean field.
Inhomogeneities on meso-scale can change transport properties:
RWRE with changing environment

Indeed, such programmes are running (back-reaction). TRY
the minimal opportunistic idea: add noise to the Friedman equations.

$$\begin{cases} \dot{a} = \kappa\sqrt{\rho}\, a \\ \dot{\rho} = -3\kappa\sqrt{\rho}\,(\rho + p) \end{cases}$$

CHANGE

$$\rho + p \to \rho + \sqrt{2C(a(t))}\,\xi(t)$$



The numerical solution $\langle a(t) \rangle$ of (13) for $\kappa = 1$, $C(a) = \frac{2}{300}$ and $a(t = 0) = 0.5$, $\rho(t = 0) = 5$.

Fig. 1. On short time-scales the behaviour agrees with that of a standard dusty FLRW-universe ($a(t) \propto t^{2/3}$). The deceleration comes to a standstill on a longer time-scale (due to the fluctuations) and $\langle a(t) \rangle$ becomes linear. Finally it is overtaken by an abrupt acceleration in the case where $C(a)$ is increasing with a. We observe that depite the simplicity of the arguments accelerated expansion appears to be immediate when adding fluctuations.

Motivation of noise: backreaction – disorder – inhomo fluctuations, or quantum effects… ?

Brown-Kuchař description of dust

the Wheeler–DeWitt equation[1]

$$\mathrm{i}\hbar\,\partial_T\,\psi(a,T) = \frac{\hbar^2\kappa^2}{2Vc^2}\left(\frac{1}{\sqrt{a}}\partial_a\right)^2\psi(a,T)$$

with conserved current

$$J = (J_a, J_T) = (\frac{\kappa^2}{Vc^2}\frac{1}{\sqrt{a}}\partial_a S|\psi|^2, -\sqrt{a}|\psi|^2)$$

the Wheeler–DeWitt equation[1]

$$\mathrm{i}\hbar\,\partial_T\,\psi(a,T) = \frac{\hbar^2\kappa^2}{2Vc^2}\left(\frac{1}{\sqrt{a}}\partial_a\right)^2\psi(a,T)$$

$$J = (J_a, J_T) = \left(\frac{\kappa^2}{Vc^2}\frac{1}{\sqrt{a}}\partial_a S|\psi|^2, -\sqrt{a}|\psi|^2\right)$$

With polar decomposition $\psi = |\psi|\mathrm{e}^{\mathrm{i}S/\hbar}$

So let us determine the trajectory of the scale factor via the streamlines:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{J_a}{\sqrt{a}|\psi|^2} \equiv \frac{\kappa^2}{Vc^2}\frac{1}{a}\partial_a S, \qquad \frac{\mathrm{d}T}{\mathrm{d}t} \equiv \frac{J_T}{\sqrt{a}|\psi|^2} = -1$$

Thibaut Demaerel, Christian Maes and Ward Struyve,
[Cosmic acceleration from quantum Friedmann equations](). arXiv:1901.09767

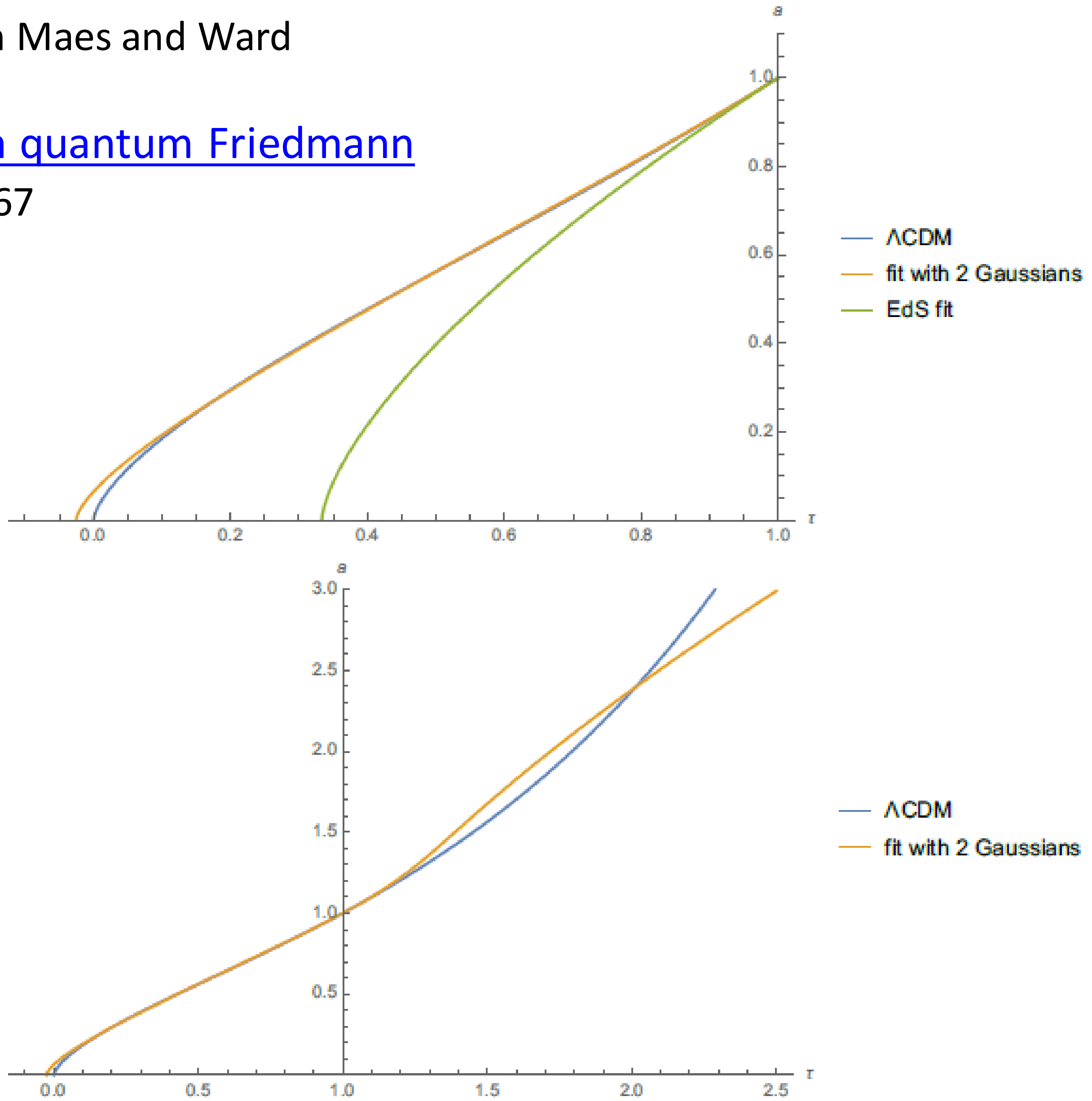


Figure 1: The evolution of the scale factor $a(\tau)$ in the case of the Gaussian superposition (18). Upper plot: the current history of the standard ΛCDM model and a fitting trajectory (which agrees very well). We also compare with an Einstein-de Sitter universe, i.e., with a dust-dominated universe, $a(\tau) \propto (\tau - \tau_B)^{2/3}$ fitting the observed expansion H_0 of today. Lower plot: a longer-time comparison of the evolution of the standard ΛCDM model with the same trajectory, showing a deviation in our future.

2. SPACE ROAR

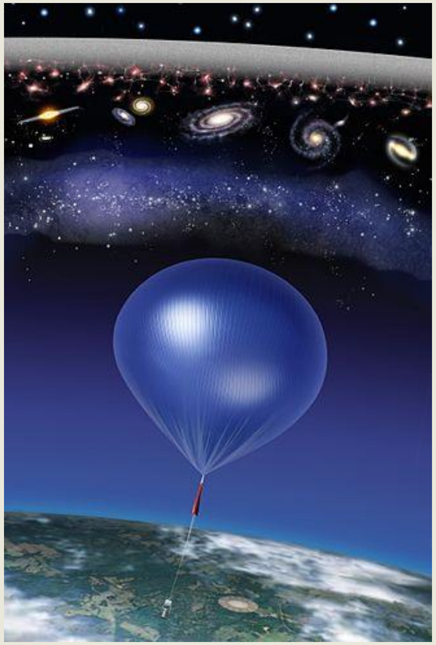
Cosmic microwave background: prime witness to the early universe.
Before neutral atoms were formed, dating from some 100 000 years after the Big Bang:
GENERAL ASSUMPTION: matter and radiation in thermodynamic equilibrium, owing to the high efficiency of Compton scattering, bremsstrahlung and radiative Compton processes, with characteristic time-scales much shorter than the cosmic expansion time-scale.

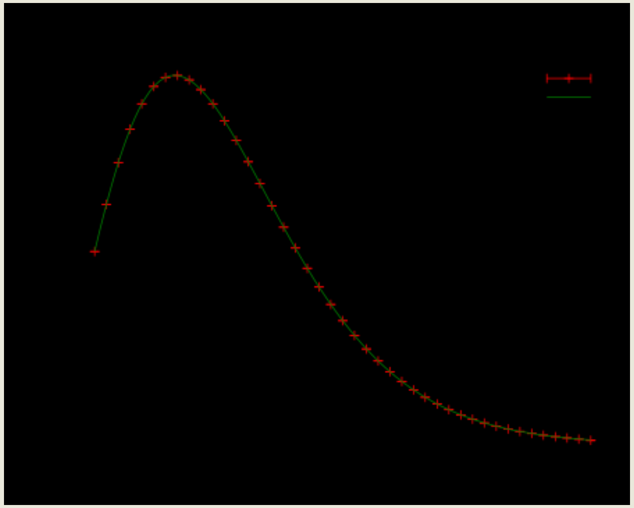
Recombination era: electrons and protons formed hydrogen atoms, and light decoupled from matter. Photons started to move almost freely through the expanding universe**. As a result, the distribution function of the CMB photons at later times is supposed to follow the blackbody spectrum at an equilibrium temperature**.
the cosmic background appears today very close to a blackbody radiation at a temperature of about 2.7K, peaking at about 160GHz, in very good agreement with the Planck spectrum from about 10GHz up to about 600GHz.

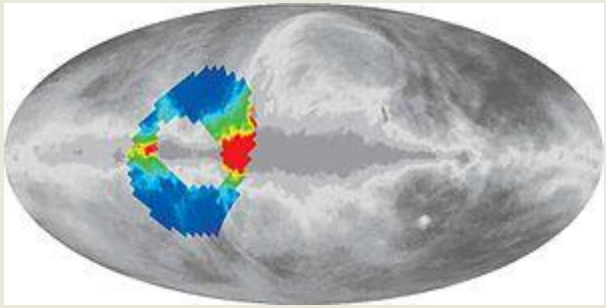
2. Space Roar:

The cosmic background radiation has been observed to deviate from the Planck law expected from a blackbody at about 2.7K at frequencies below 3GHz.

ARCADE 2 (2011): Correcting for instrumental systematic errors, and low-frequency subrtraction of (super)galacatic origin, residual emission at 3 GHz with the ARCADE 2 data, independently detected by other techniques.







There is evidence of a systematic deviation from the Planck law of a blackbody at about 2.7K at low frequencies, in the radio tail of the cosmic background.

The photon-baryon thermodynamic equilibrium between big-bang nucleosynthesis and recombination can be slightly perturbed by different physical phenomena. Not the issue here.

That aspect has been recently brought to attention by two independent types of observations: the CMB absolute temperature excess measured
by ARCADE2 and the anomalously strong absorption of the redshifted 21cm line from neutral hydrogen measured by EDGES.

Cosmic microwave background: prime witness to the early universe.

Compton scattering, bremsstrahlung and radiative Compton processes

Recombination era: electrons and protons formed hydrogen atoms, and light decoupled from matter. Photons started to move almost freely through the expanding universe.

What is the statistical mechanical model?
What physically-motivated dynamics gives a reversible evolution to Planck distribution?

Kompaneets equation (1956):

Kompaneets equation (1956): relaxation to the Planck law

1 The Kompaneets equation

Consider evolution of photon phase space density $n(\nu, t)$ in the presence of an electron gas. Assume that the electrons are thermal and hot: $T_e >> T_\gamma$. We're not going to force the photons to be strictly thermally distributed, but we will assume that they are not far from black-body, and so we define T_γ as the corresponding temperature. The Boltzman equation (BE) describes the evolution of $n(\nu, t)$:

$$\frac{\partial n(\nu,t)}{\partial t} = \int d^3p \int d\Omega \frac{d\sigma}{d\Omega} \left[f_e(\mathbf{p}_1) n(\nu_1, t) \left(1 + n(\nu, t)\right) - f_e(\mathbf{p}) n(\nu, t) \left(1 + n(\nu_1, t)\right) \right] \tag{1}$$

This equation describes energy transfer via scattering events $\mathbf{p} + \nu \leftrightarrow \mathbf{p}_1 + \nu_1$. The first term describes population of ν states by incoming photons at ν_1, while the second term describes de-population similarly (the $1 + n$ factors are due to stimulated absorption).

rescaled version of that Kompaneets equation,

$$\partial_\tau n = \frac{1}{\nu^2}\partial_\nu \left\{ \nu^4 \left[\frac{k_{\rm B}T_e}{h} \partial_\nu n + (1+n)n \right] \right\}$$

for the time-evolution of the photon occupation number $n(\tau, \nu)$

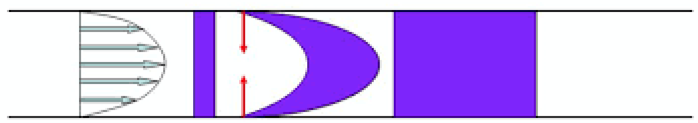
equilibrium Bose-Einstein distribution

$$n_{\rm eq}(\nu) = \frac{1}{e^{h\nu/(k_{\rm B}T_e)+C} - 1}$$

Th.Smiths investigates what would happen if the Einstein relation is broken.
What if the primordial was shown turbulent diffusion as we see today e.g. in space plasmas
Where the stationary electron velocity distribution has power-law decay (not Maxwellian).

Turbulent diffusion means that the variance of the random force field is source of extra diffusion,

such as in Taylor dispersion.



$$D_{eff} = D + \frac{a^2 u_{max}^2}{192 D}$$

$$D_{\rm eff} = \frac{A^2}{2\alpha}$$

→

$$B(\nu) \propto \frac{1}{\nu} \quad \text{for} \quad \nu \gg \nu_1$$

$$\partial_\tau n = \frac{1}{\nu^2}\partial_\nu \left\{ \nu^4 \left[\frac{k_{\rm B} T_e}{h}\,\partial_\nu n + (1+n)n \right] \right\} + \frac{1}{\nu^2}\partial_\nu \left\{ \nu^2 \frac{k_{\rm B} T_e}{h}\, B(\nu)\,\partial_\nu n \right\}$$

What if the primordial was shown turbulent diffusion as we see today e.g. in space plasmas

Turbulent diffusion means that the variance of the random force field is source of extra diffusion,

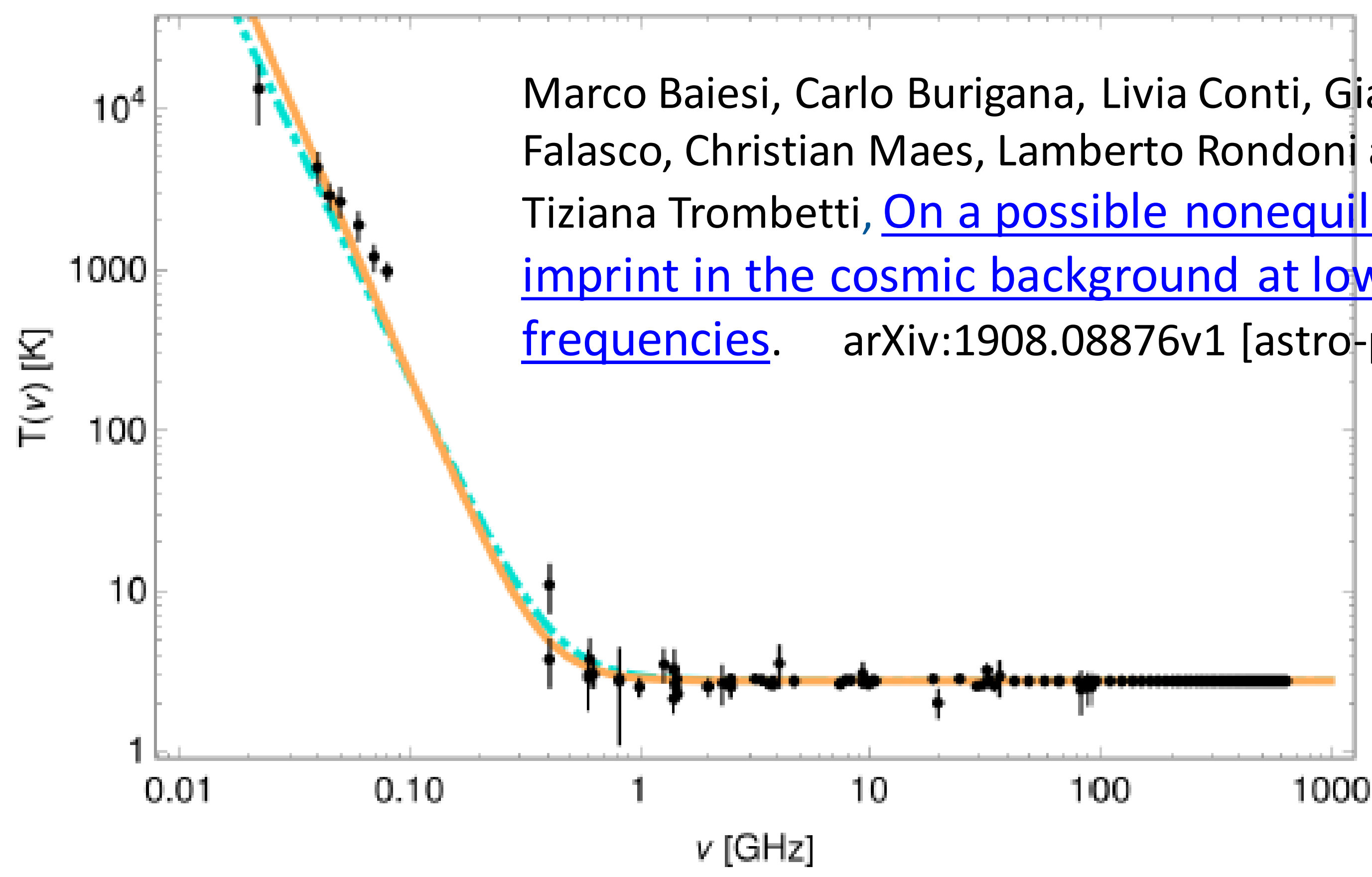
such as in **active velocity processes**

A. Dhar *et. al.* *Run-and-tumble particle in one-dimensional confining potentials: Steady-state, relaxation, and first-passage properties*, Phys. Rev. E., **99**, 032132 (2017).

$$D_{\rm eff} = \frac{A^2}{2\alpha} \rightarrow B(\nu) \propto \frac{1}{\nu} \quad \text{for} \quad \nu \gg \nu_1$$

$$\partial_\tau n = \frac{1}{\nu^2}\partial_\nu \left\{ \nu^4 \left[\frac{k_{\rm B}T_e}{h}\,\partial_\nu n + (1+n)n \right] \right\} + \frac{1}{\nu^2}\partial_\nu \left\{ \nu^2 \frac{k_{\rm B}T_e}{h}\, B(\nu)\, \partial_\nu n \right\}$$

Result of adding active velocity process: Clear enhancement of lower photon frequencies compatible with the best data available for the CMB spectrum.



Marco Baiesi, Carlo Burigana, Livia Conti, Gianmaria Falasco, Christian Maes, Lamberto Rondoni and Tiziana Trombetti, [On a possible nonequilibrium imprint in the cosmic background at low frequencies](). arXiv:1908.08876v1 [astro-ph.CO].

the low-frequency data may be evidence for important nonequilibrium features in the early universe.

3. Information **paradox:** **here it is much more difficult to find what exactly is the problem, the paradox,…**

Soft general version…

The so called information paradox consists of
multiple questions and problems
related to the construction of a quantum theory of gravity.

It turns out that our understanding today is rather bad,
and in particular that shows up in various
specific attempts that run into inconsistencies.

Focus is on black hole physics:

black hole as destroyer of information ???

Soft general version…

Physical information could
permanently disappear in a black hole, allowing many physical states to devolve into the same state.

From the no-hair theorem: Hawking radiation is completely independent of the material entering the black hole. Nevertheless, if the material entering the black hole were a pure quantum state, the transformation of that state into the mixed state of Hawking radiation would destroy information about the original quantum state.

Information paradox

More specific versions…

How could all black holes be equal (up to mass, charge,…): so called **No Hair Theorem** ?

How could different initial conditions lead to the same state, if evolving unitarily? **Origin of dissipation?**

How can Hawking radiation be **thermal?**
How could Shannon entropy of the inside of an evaporating black hole decrease when equal to the growing equilibrium entropy of Hawking radiation? **Unitarity conflict?**

Information paradox

How could all black holes be equal (up to mass, charge,…):
so called **No Hair Theorem** ?

A stationary four-dimensional solution of the Einstein-Maxwell equations (in Lorentzian signature) is uniquely characterized by its mass , angular momentum, electric charge, and magnetic charge.

But why not? Think of ideal gas, and their dynamical description
In Boltzmann-Grad limit. Think of Maxwellian.

After all: the no-hair theorem already supposes a stationary limit-situation.

No-hair theorems in black hole physics involve limiting procedures and considerations of asymptotic stationary behavior both in time and in degrees of freedom. A collapsing shell of matter only becomes Schwarzschild in an infinite time limit.

Information paradox

More specific versions…

How could different initial conditions lead to the same state, if evolving unitarily? **Origin of dissipation?**

BUT:
Is this not essentially the problem of relaxation to equilibrium?

Clearly, unitary evolutions may give rise to dissipative evolutions when restricted to some macroscopic variables, and with conservation of nonabelian structure.

$$\omega_t^N[\cdot] = \omega^N \left[(U_N)^{-t} \cdot (U_N)^t\right]$$

$$\omega_t^N \left[F(M_\alpha^N)\right] \to F((\phi_t m)_\alpha)$$

$$M_\alpha^N = \frac{1}{N}\sum_{i=1}^{N} \sigma_\alpha(i),$$ $$\phi_t(m) = \mathrm{Tr}[\nu_t \, \sigma]$$

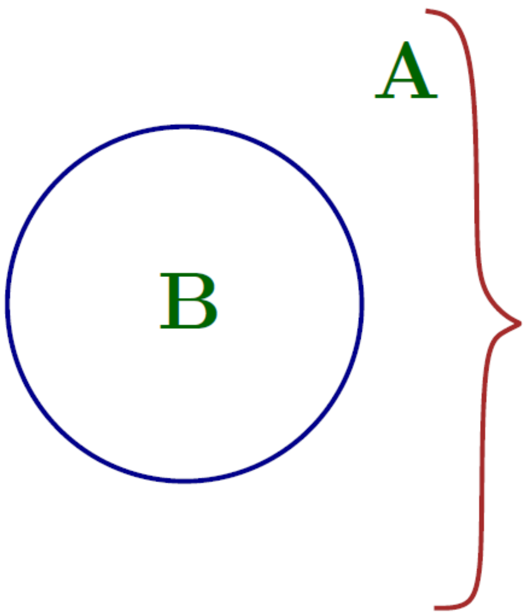
with density matrix $\nu_t = \hat{\phi}^t(\nu)$ evolving dissipatively

Most modern version …

If there is an entangled pure state, and one part of the entangled system is thrown into the black hole while keeping the other part outside,

the result is a mixed state after the partial trace is taken into the interior of the black hole.

But since everything within the interior of the black hole will hit the singularity within a finite time, the part which is traced over partially might disappear completely from the physical system



$\boldsymbol{\Psi}(\mathbf{t})$

$$\rho_{\mathbf{t}} = \mathbf{Tr_B} |\boldsymbol{\Psi}(\mathbf{t})\rangle\langle\boldsymbol{\Psi}(\mathbf{t})|$$

Density matrix of “outside”

Hawking radiation:
$\rho(t)$ is thermal (black body radiation)

↓

Contradiction: Entanglement entropy =
Shannon entropy of $\rho(t)$ is
DECREASING after some time t.

In other words, to Th. Smiths it would be like saying that the Shannon entropy of the Liouville evolved probability distribution equals the (real) thermodynamic entropy.

That is certainly false, even though there is good reason to say that the distribution is thermal indeed!

Ad information paradox:

1. Macroscopic steady state descriptions are by their nature approximations, valid in some limiting regimes.

E.g. Boltzmann equation
E.g. Entropy production
E.g. Description of magnet

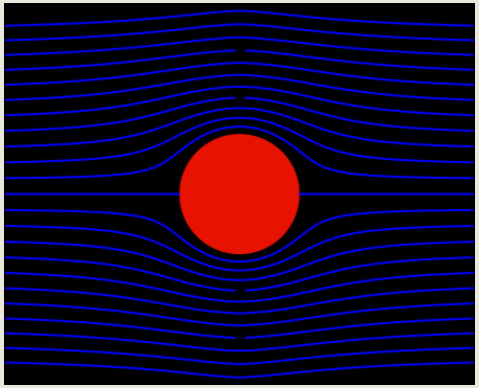
2. How serious should we take the distribution or density matrix evolved from the Liouville-von Neumann evolution equation?

E.g. Shannon entropy is constant over Liouville evolution; yet, the thermodynamic entropy increases and coincides with the Shannon entropy of thermal distributions.
E.g. Entanglement entropy of ground states and thermal states can be very different (area law versus volume law); yet, they can easily be considered as perturbations of each other for local observables.

Similar to ‘historical paradoxes’ of statistical mechanics:

The d'Alembert paradox (1759), meaning the rigorous conclusion from classical mechanics that **birds cannot fly**.

(More precisely, d'Alembert saw that both drag and lift are zero in potential flow which is incompressible, inviscid, irrotational and stationary.)
The resolution is of course found in the nature of viscosity and the boundary effects as explained by the Navier-Stokes equation of 1822 - 1845.



Poincaré theorem (1889) showing that **no monotonically increasing (entropy) function** could be defined in terms of the canonical variables in a theory of N-body Hamiltonian dynamics.

In this way he added to the so called irreversibility paradox, and indeed its solution shows that the Poincaré theorem is quite irrelevant.

But, we are not at all sure where/what is the information paradox: it changes in time and from place to place. It seems that the problem is just….

..how to construct quantum gravity..??

We can be fast on the last two 'problems'…

Horizon problem

(traditionally one of the major motivations for inflation theory)

Flatness problem

(traditionally yet another major motivation for inflation theory)

… as by today, people agree more and more that at least their formulation was mistaken. The real issue is the 'specialness of initial conditions.'

See also: R. Penrose, **Difficulties with inflationary cosmology**. Annals N.Y. Acad. Sci. 571 (1989) 249–264.

Sean M. Carroll, **In What Sense Is the Early Universe Fine-Tuned?** arXiv:1406.3057v1 [astro-ph.CO]

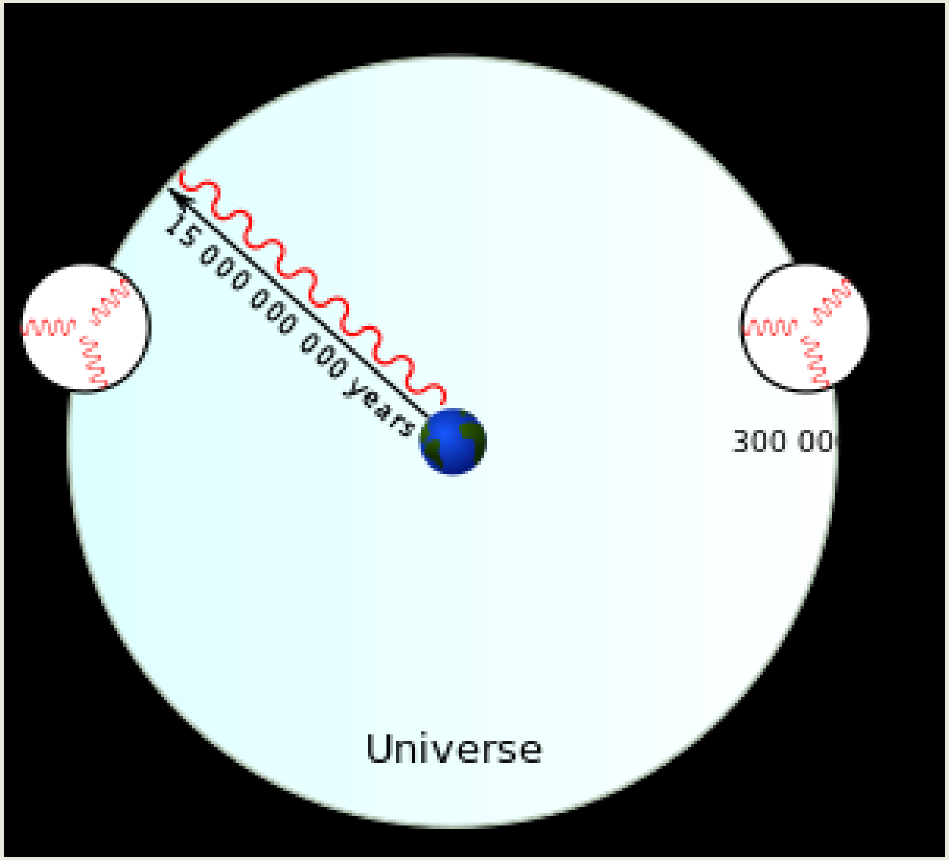
4. Horizon problem, *Wikipedia version*

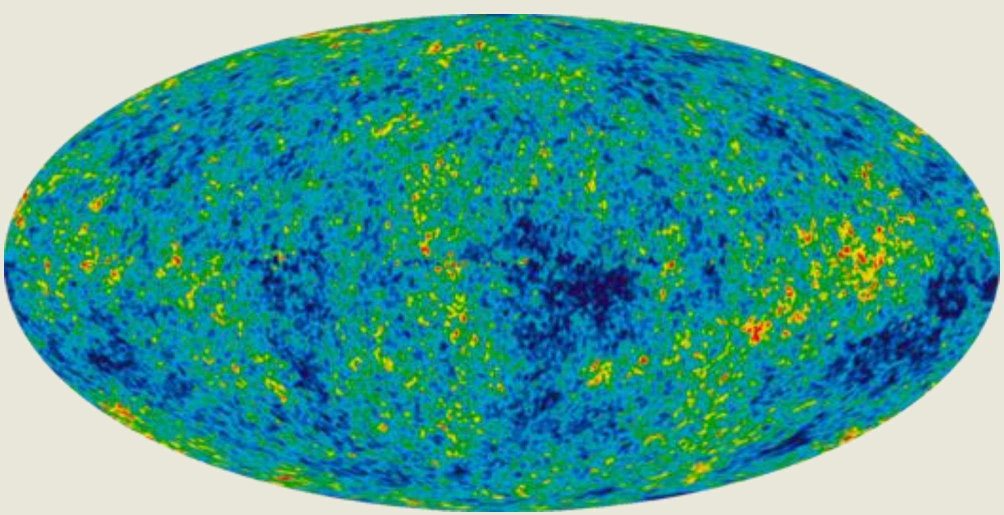
The **horizon problem** is a problem with the standard cosmological model of the Big Bang which was identified in the late 1960s, primarily by Charles Misner.

It points out that different regions of the universe have not "contacted" each other because of the great distances between them,
but nevertheless they have the same temperature and other physical properties.

This should not be possible, given that the transfer of information (or energy, heat, etc.) can occur, at most, at the speed of light.

Horizon problem, *continued*





When we look at the CMB it comes from 46 billion comoving light years away. However when the light was emitted the universe was much younger (300,000 years old). In that time light would have only reached as far as the smaller circles. The two points indicated on the diagram would not have been able to contact each other because **their spheres of causality do not overlap.**

cf observations by **Wilkinson Microwave Anisotropy Probe (2003-2010)**

4. Horizon problem

Traditional answer: use INFLATION
to have the time to relax… (pushing back big bang)

WHY IS THAT ANSWER 2x STRANGE for Th. Smiths?

1) "Equal temperatures" is typical

2) Relaxation to equilibrium cannot be used to explain specialness…

Th. Smiths: "There is a priori nothing very strange about equal temperatures:"

In fact, equal temperatures are typical for all regions which are solely constrained to conservation of energy. If we imagine the universe with the standard cosmology according to the FLRW geometry with at an initial time short after the Big Bang an arbitrary matter distribution with a given total energy, then **we can and should expect uniform temperature all over. That is just the statement that equilibrium is typical**.

<u>But more importantly</u>:

As a matter of logic, thermalization makes the universe less special so that thermalization cannot explain specialness; "the universe would have needed to be more special before."

In other words requiring thermalization is not only not needed; it is worse than useless.

Th. Smiths is not saying there cannot be a problem with

… “almost equal temperatures” (yet….)

But to think it is solved by equilibration

is exceedingly strange.

5. Flatness Problem

Why is the universe density so nearly at the critical density or put another way, why is the universe so flat?

Currently, the universe is so incredibly well-balanced between the positively-curved closed universe and the negatively-curved open universe. Of all the possibilities from very positively-curved (very high density) to very negatively-curved (very low density), the current nearly flat condition seems a very special case. The balance would need to have been even finer nearer the time of the Big Bang because any deviation from perfect balance gets magnified over time.

Th.Smiths: whether a number is truly small or how strange it is, depends on the measure, on the distribution of what is likely, and…

Almost every Robertson-Walker cosmology is spatially flat.

The conventional formulation of the problem implicitly assumes a measure that is uniform in curvature, which seemed intuitively reasonable.

But in fact the measure in the vicinity of flat universes turns out to be inversely proportional to $|\text{curvature}|^{5/2}$ which is a dramatic difference. Rather than sufficiently flat universes being rare, they are actually generic.

The flatness problem really isn't a problem at all; it was simply a mistake to make it a problem.

In What Sense Is the Early Universe Fine-Tuned?

Sean M. Carroll   arXiv:1406.3057v1 [astro-ph.CO]

Questions of this talk:

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(traditionally one of the major motivations for inflation theory)

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(within black hole physics, since Hawking radiation)

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the ‘solutions’ from statistical mechanics:

(very fast)

1. Ad horizon problem:

a) Equilibrium is typical – equal temperatures are typical.
b) Relaxation to equilibrium presupposes a more special initial condition.

2. Ad flatness problem:

Make sure you use the good measure for estimating what it means to be strange/typical.

3. Ad information paradox: if at all…..?

a) We know since Boltzmann how unitary evolutions may become effectively dissipative in a reduced description, but do not interchange limits.
b) Do not take density matrices/distributions absolutely serious.

the ‘solutions’ from statistical mechanics:

(very fast)

3. Ad information paradox: if at all….

a) We know since Boltzmann how unitary evolutions may become effectively dissipative in a reduced description, but do not interchange limits.
b) Do not take density matrices/distributions absolutely serious.

4. Ad dark energy problem:

a) Why trust mean field to the very end: add noise!.
b) Noise maybe motivated in various ways but first attempts already work very well.

5. Ad Space Roar:

a) Why assume quasi-thermal equilibrium in primordial plasma?
b) Add nonequilibrium via stochastic acceleration and get quasi-perfect fits.

Conclusion: ideas of statistical mechanics,
in particular related to fluctuation theory
and to typicality of dynamical properties,

are important and probably crucial ingredients

in the study of physical cosmology,
even for its large scale structures.

1. Ad horizon problem:

a) Equilibrium is typical – equal temperatures are typical. Or?
b) Relaxation to equilibrium presupposes a more special initial condition.

2. Ad flatness problem:

What is the right measure for estimating what it means to be strange/typical?

3. Ad information paradox: if at all…

a) We know since Boltzmann how unitary evolutions may become effectively dissipative in a reduced description, but do not interchange limits.
b) Do not take density matrices/distributions *absolutely* serious.

4. Ad dark energy problem:

a) Why trust mean field to the very serious end: add noise!
b) Noise may be motivated in various ways and first ‘pragmatic” attempts already work very well.

5. Ad Space Roar:

a) Why assume quasi-thermal equilibrium in primordial plasma? Time-scales!
b) Add nonequilibrium via stochastic acceleration and get quasi-perfect fits.

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