The Atoms of Space and Gravity

T. Padmanabhan

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T.P., arXiv:1603.08658

The Major Challenges to GR

SINGULARITIES: BLACK HOLES, UNIVERSE

COSMOLOGICAL CONSTANT

THE THERMODYNAMIC CONNECTION

These challenges involve $\hbar$!

$$A_{Planck} = \frac{G\hbar}{c^3}; \quad \Lambda\left(\frac{G\hbar}{c^3}\right) \approx 10^{-123}; \quad k_B T = \frac{\hbar}{c}\left(\frac{g}{2\pi}\right)$$

HOW DO WE PUT TOGETHER THE PRINCIPLES OF QUANTUM THEORY AND GRAVITY?

Everybody Wants To Quantize Gravity!

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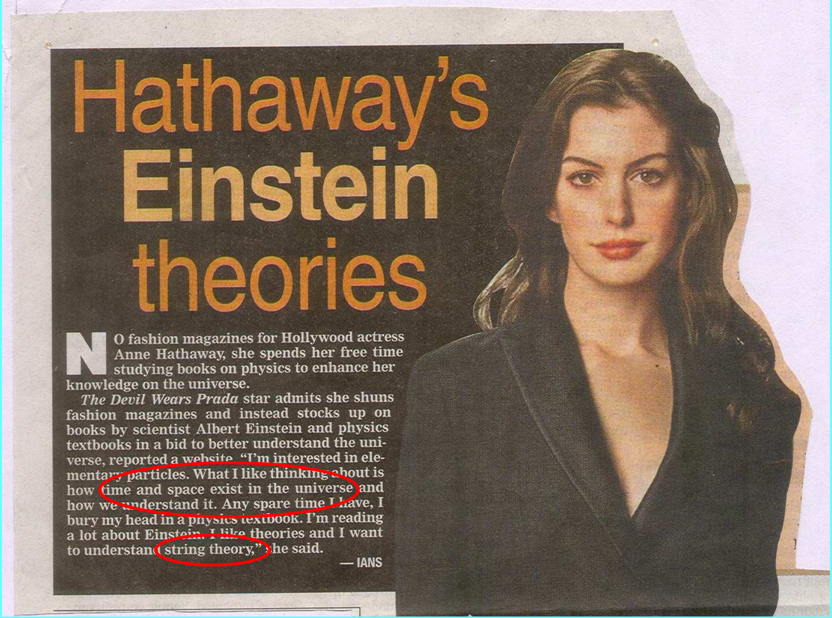

Hathaway's Einstein theories

NO fashion magazines for Hollywood actress Anne Hathaway, she spends her free time studying books on physics to enhance her knowledge on the universe.

The Devil Wears Prada star admits she shuns fashion magazines and instead stocks up on books by scientist Albert Einstein and physics textbooks in a bid to better understand the universe, reported a website. "I'm interested in elementary particles. What I like thinking about is how time and space exist in the universe and how we understand it. Any spare time I have, I bury my head in a physics textbook. I'm reading a lot about Einstein. I like theories and I want to understand string theory," she said.

— IANS

... But Nobody Has Succeeded!

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- ***The perturbative approach does not work***
- ***Virtually every interesting question about gravity is non-perturbative by nature***
- ***No guiding principle; metric is assumed to be a quantum variable***

GR: THE NEXT 100 YEARS

Needs another paradigm shift

The equations governing classical gravity has the same conceptual status as those describing elasticity/hydrodynamics.

Related Ideas:* Cai, Damour, Hu, Jacobson, Liberati, Sakharov, Thorne, Visser, Volovik,.... *and many others

I will describe the work by me + collaborators (2004-16)

Part 1: Review of older results

Part 2: Recent Progress (2014-16)

THE PARADIGM

Non-negotiable ingredient - 1

Spacetime dynamics should/can be described in a thermodynamic language; not in a geometrical language.

Evolution of spacetime

Review: TP, [arXiv:1410.6285]

Evolution arises from departure from 'holographic equipartition':

$$
\begin{aligned}
Time\ evolution\ &\propto\ Heating/Cooling \\
&\propto\ (N_{\rm sur} - N_{\rm bulk})
\end{aligned}
$$

All static geometries have

$$N_{\rm sur} = N_{\rm bulk}$$

See e.g. TP, [gr-qc/0308070]; [arXiv:0911.5004]; [arXiv:0912.3165]; [arXiv:1003.5665]; [arXiv:1312.3253]; [arXiv:1405.5535]; Chakraborty, T. P, [arXiv:1408.4679]

The gravity-thermodynamics connection transcends GR even when the entropy is not proportional to area.

Review: T. P, Kothawala, [arXiv:1302.2151]

All these results generalize to the Lanczos-Lovelock models of gravity with:

$$s d^2x = -\frac{1}{2}\frac{\sqrt{\sigma}\, d^{D-2}x}{4L_P^2} P^{ab}_{cd}\epsilon_{ab}\epsilon^{cd}$$

The thermodynamic connection transcends GR!

See e.g., Paranjape et al, [hep-th/0607240]; Kothawala, TP [arXiv:0904.0215]; Kolekar et al. [arXiv:1111.0973], [arXiv:1201.2947], Chakraborty, T. P, [arXiv:1408.4679]; [arXiv:1408.4791]

You should get more than what you put in!

You should get more than what you put in!

Leads to significant new insights about: (i) classical gravity (ii) the microscopic structure of spacetime and (iii) cosmological constant.

See e.g., T.P, Hamsa Padmanabhan, [arXiv:1404.2284]; T.P, [arXiv:1603.08658]

More *IS* Different

The key new variable which distinguishes thermodynamics from point mechanics

$$Heat\ Density = \mathcal{H} = \frac{Q}{V} = \frac{TS}{V} = \frac{1}{V}(E - F)$$

$$\frac{TS}{V} = Ts = p + \rho = T_{ab}\ell^a\ell^b$$

Normal matter has a heat density

Spacetime also has a heat density!

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One can associate a T and s with every event in spacetime just as you could with a glass of water!

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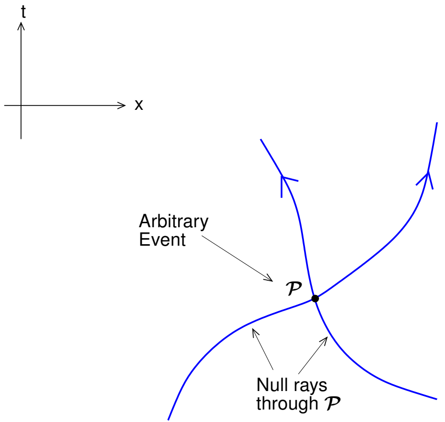
This fact transcends black hole physics and Einstein gravity.

Spacetime also has a heat density!

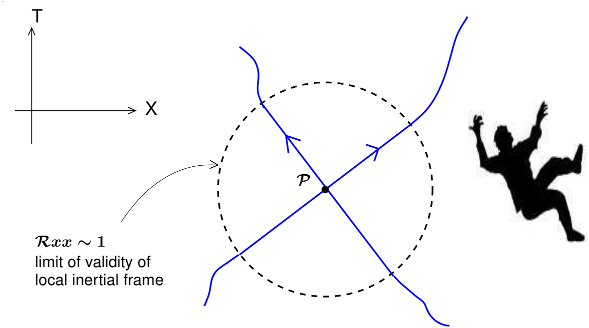
One can associate a T and s with every event in spacetime just as you could with a glass of water!

The T is independent of the theory of gravity; s depends on/determines the theory.

Spacetime in Arbitrary Coordinates



Local Inertial Observers



Validity of laws of SR $\Rightarrow$ How gravity affects matter

Matter equations of motion $\Leftrightarrow \nabla_a T^a_b = 0$

Spacetimes, Like Matter, can be Hot

***The** most beautiful result in*
the interface of quantum theory and gravity

Spacetimes, Like Matter, can be Hot

The most beautiful result in the interface of quantum theory and gravity

OBSERVERS WHO PERCEIVE A HORIZON ATTRIBUTE A TEMPERATURE TO SPACETIME

$$k_B T = \frac{\hbar}{c}\left(\frac{g}{2\pi}\right)$$

[Davies (1975), Unruh (1976)]

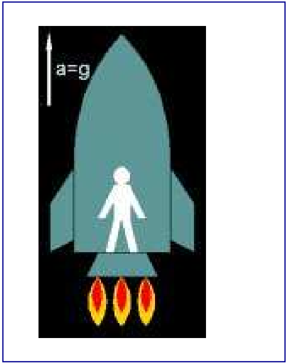
The most beautiful result in the interface of quantum theory and gravity

OBSERVERS WHO PERCEIVE A HORIZON ATTRIBUTE A TEMPERATURE TO SPACETIME

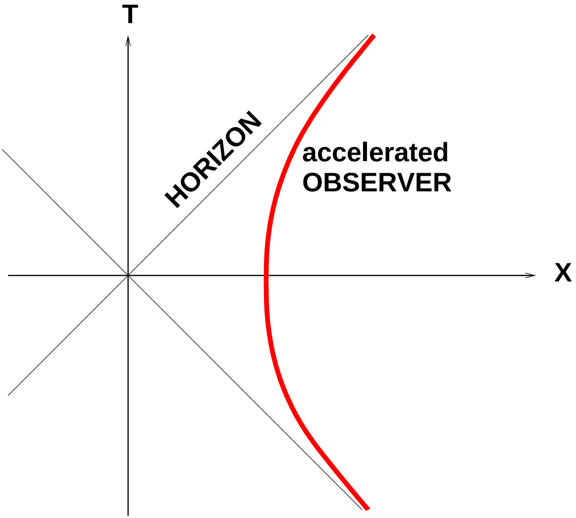
$$k_B T = \frac{\hbar}{c}\left(\frac{g}{2\pi}\right)$$

[Davies (1975), Unruh (1976)]

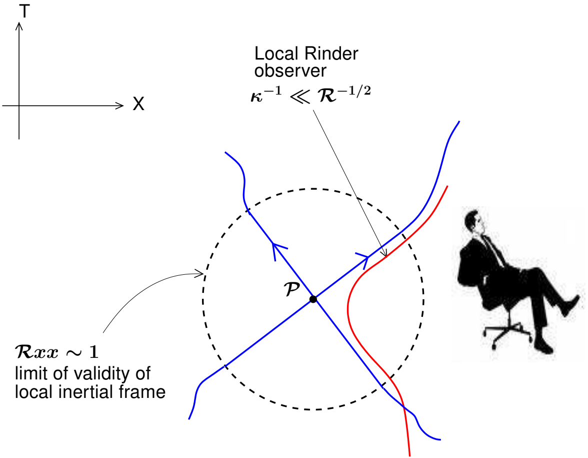
This allows you to associate a heat density $\mathcal{H} = Ts$ with every event of spacetime!

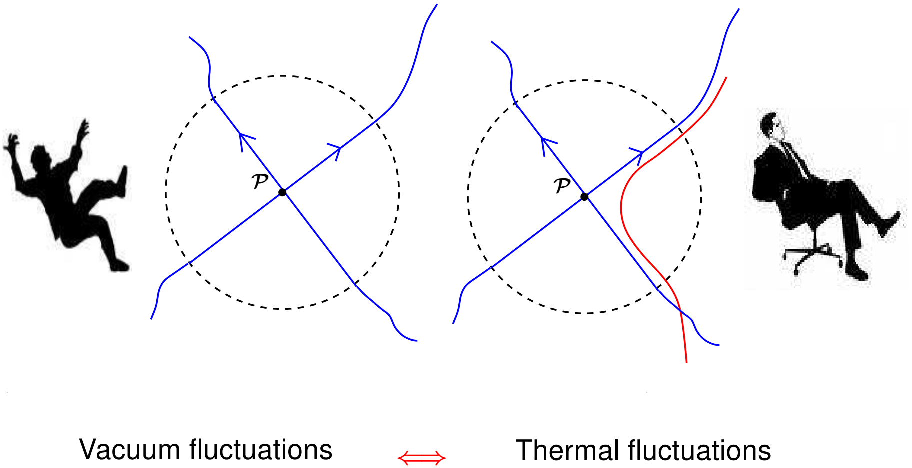


FLAT SPACETIME



Local Rindler Observers





$\mathcal{P}$
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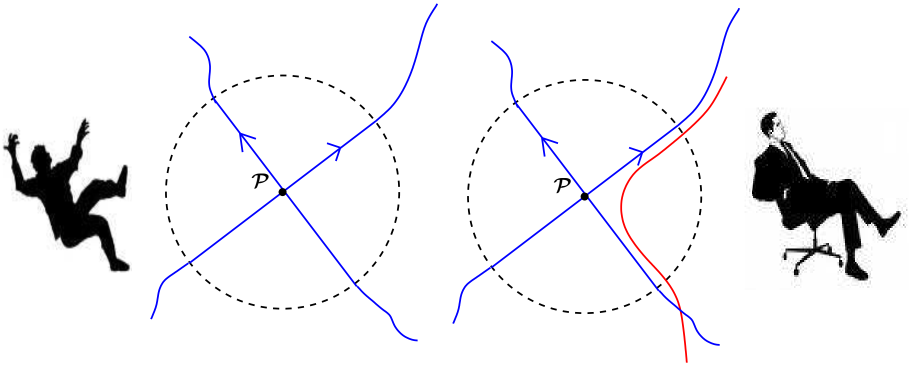
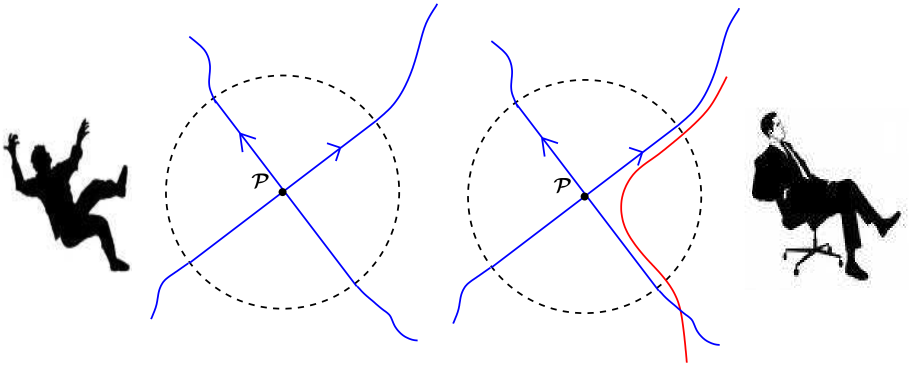
Vacuum fluctuations
$\Longleftrightarrow$
Thermal fluctuations



Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations

A VERY NON-TRIVIAL EQUIVALENCE!



Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations

A VERY NON-TRIVIAL EQUIVALENCE!

QFT in FFF introduces $\hbar$; we now have $(\hbar/c)$ in the temperature

Regions of spacetime can be inaccessible to certain class of observers in any spacetime!

Regions of spacetime can be inaccessible to certain class of observers in any spacetime!

Take non-inertial frames seriously: not "just coordinate relabeling".

Local Rindler Horizon

- **Heat transfered due to matter crossing a null surface:** [T. Jacobson, gr-qc/9504004]

$$Q_m = \int d\mathcal{V}\,(T_{ab}\ell^a\ell^b); \quad \mathcal{H}_m \equiv T_{ab}\ell^a\ell^b$$

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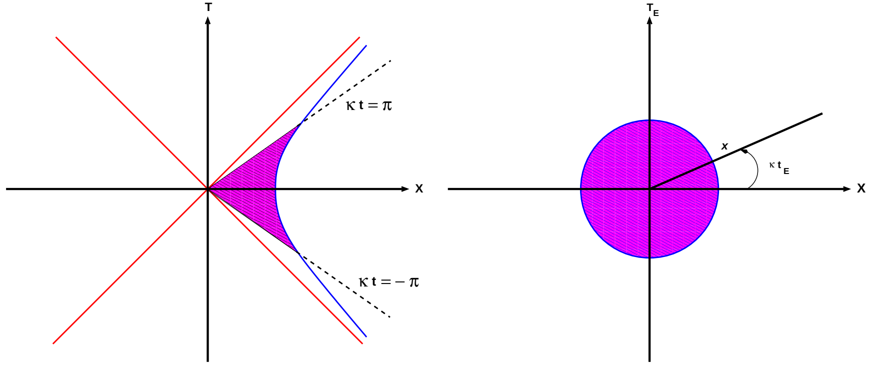
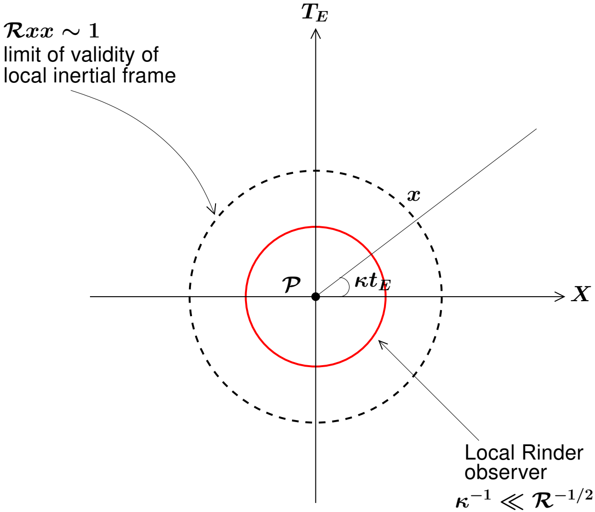
- **Note: Null horizon $\Leftrightarrow$ Euclidean origin**

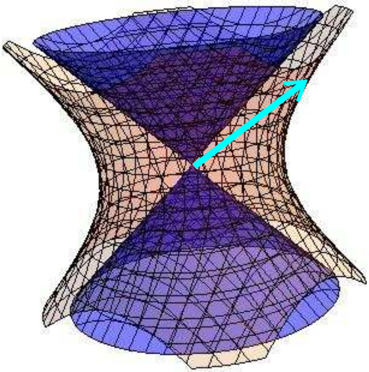
$$X^2 - T^2 = 0 \Leftrightarrow X^2 + T_E^2 = 0$$

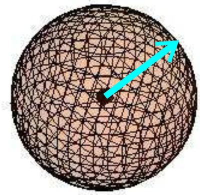


$$T = x \sinh \kappa t, \;\; X = x \cosh \kappa t \qquad T_E = x \sin \; \kappa t_E, \;\; X = x \cos \; \kappa t_E$$

$$X^2 - T^2 = 0 \Leftrightarrow X^2 + T_E^2 = 0$$


$\mathcal{R}xx \sim 1$
limit of validity of
local inertial frame
T_E
x
$\mathcal{P}$
κt_E
X
Local Rinder
observer
$\kappa^{-1} \ll \mathcal{R}^{-1/2}$





$$X^2 - T^2 = \sigma^2 \Leftrightarrow X^2 + T_E^2 = \sigma^2$$

$$X^2 - T^2 = 0 \Leftrightarrow X^2 + T_E^2 = 0$$

You could have figured out that water is made of discrete atoms without ever probing it at Angstrom scales!

Atoms of Matter

Boltzmann: If you can heat it, it must have micro-structure!

To store energy ΔE at temperature T, you need

$$\Delta n = \frac{\Delta E}{(1/2)k_B T}$$

degrees of freedom. Microphysics leaves its signature at the macro-scales

Boltzmann: If you can heat it,
it must have micro-structure!

You can heat up spacetime!

Do we have an equipartition law for the microscopic spacetime degrees of freedom?

Can you count the atoms of space?

The Quantum of Area

TP, [gr-qc/0308070]; [0912.3165]; [1003.5665]

Equipartition with a surface-bulk correspondence

$$E_{\rm bulk} = \int_{\partial\mathcal{V}} \frac{dA}{L_P^2}\left(\frac{1}{2}k_B T_{loc}\right) \equiv \frac{1}{2}k_B \int_{\partial\mathcal{V}} dn\, T_{\rm loc}$$

Associates $dn = dA/L_P^2$ microscopic degrees of freedom ('atoms') with an area dA

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Associates $dn = dA/L_P^2$ ***microscopic degrees of freedom ('atoms') with an area*** dA

Extends to all Lanczos-Lovelock models with

$$dn = (32\pi P^{ab}_{cd}\epsilon_{ab}\epsilon^{cd})\, dA/L_P^2$$

Holographic Equipartition

TP [gr-qc/0308070], [arXiv:0912.3165], [arXiv:1003.5665]

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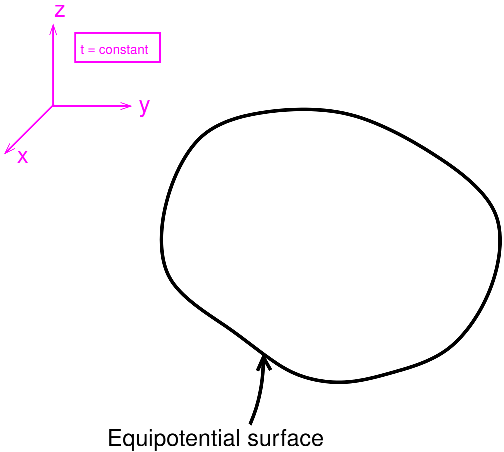

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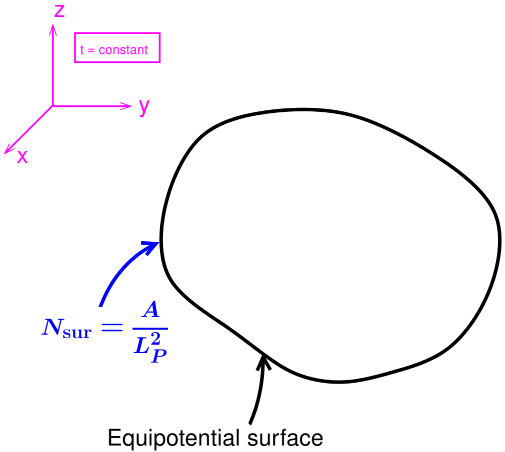

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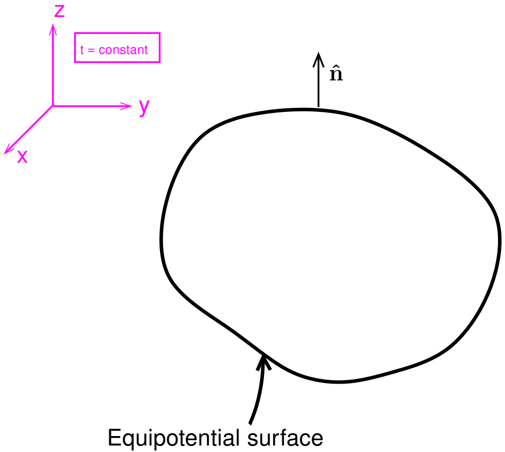

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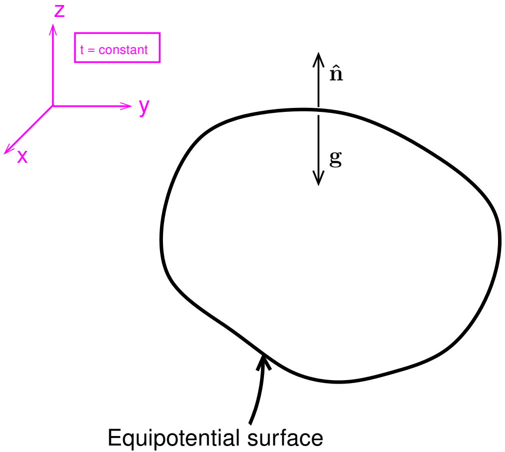

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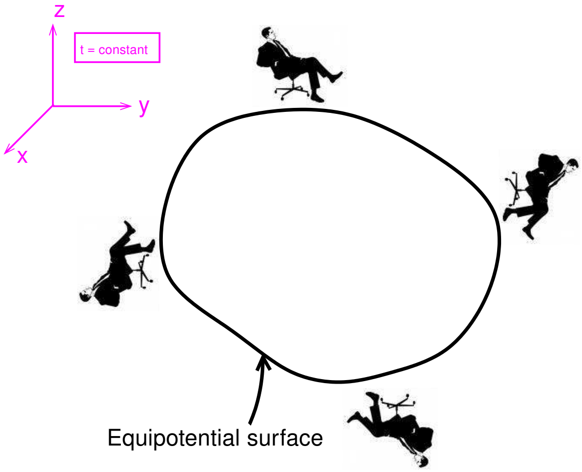

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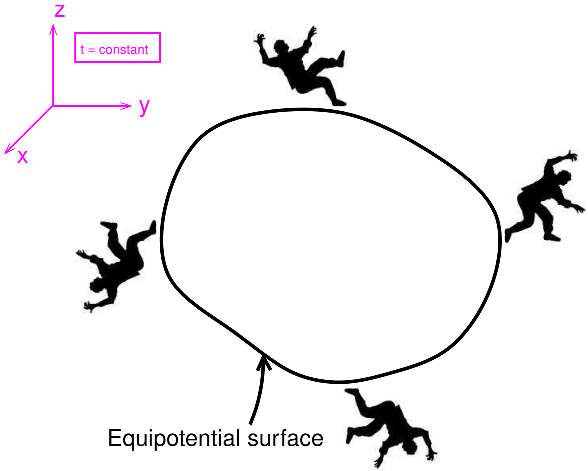

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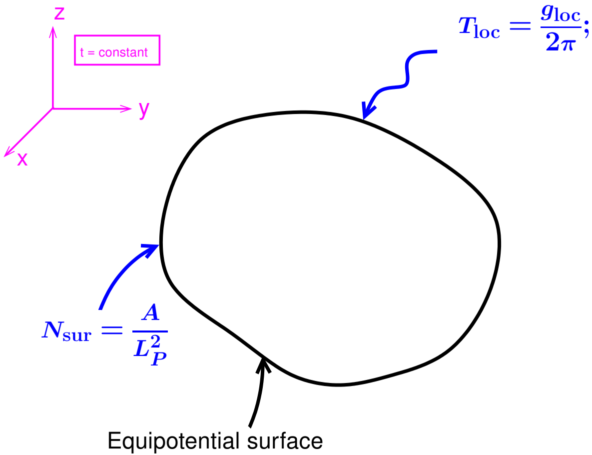

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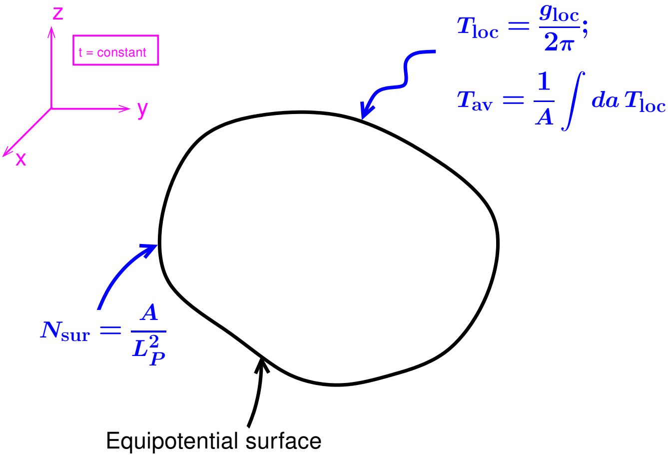

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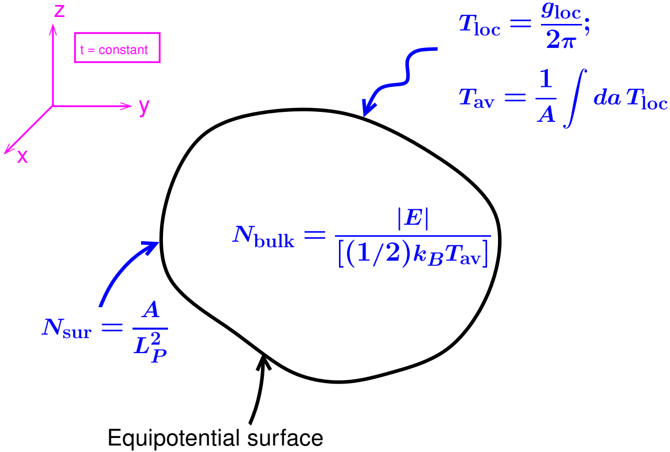

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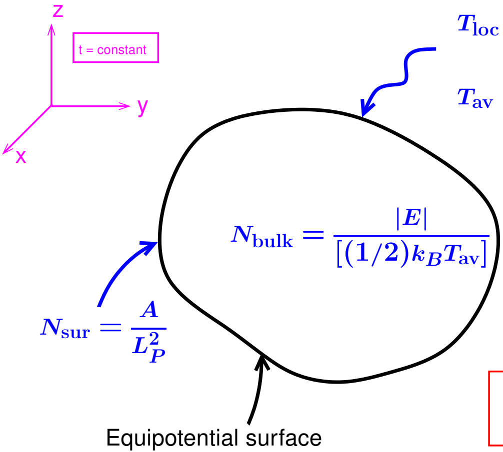

$$T_{\rm loc} = \frac{g_{\rm loc}}{2\pi};$$

$$T_{\rm av} = \frac{1}{A}\int da\, T_{\rm loc}$$

$$N_{\rm bulk} = \frac{|E|}{[(1/2)k_B T_{\rm av}]}$$

$$N_{\rm sur} = \frac{A}{L_P^2}$$

$$N_{\rm sur} = N_{\rm bulk}\,!$$

$$N_{\mathrm{sur}} = \frac{A}{L_P^2} = N_{\mathrm{bulk}} = \frac{E}{[(1/2)k_B T_{\mathrm{av}}]}$$

NEWTONIAN EXAMPLE

Gauss Law Holography

$$E = \frac{1}{2L_P^2} \int da \, k_B T_{\mathrm{loc}}$$

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$$\int \rho \, dV = \frac{1}{2L_P^2} \int da \, \left(\frac{\hbar}{c}\right) \left(\frac{g}{2\pi}\right)$$

$$E = \frac{1}{2L_P^2} \int da \; k_B T_{\rm loc}$$

$$\int \rho \, dV = \frac{1}{2L_P^2} \int da \, \frac{\hbar}{c} \left(\frac{-\mathbf{g} \cdot \hat{\mathbf{n}}}{2\pi} \right)$$

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$$\nabla \cdot \mathbf{g} = -\frac{4\pi c L_P^2}{\hbar} \rho = -4\pi G \left(\frac{\rho}{c^2} \right)$$

Geometry $\Leftrightarrow$ Thermodynamics

K. Parattu, B.R. Majhi, T.P. [arXiv:1303.1535]

$$q^{ab} \equiv \sqrt{-g}g^{ab}$$

Geometry ⇔ Thermodynamics

K. Parattu, B.R. Majhi, T.P. [arXiv:1303.1535]

$$q^{ab} \equiv \sqrt{-g}g^{ab}$$

$$p^a_{bc} \equiv -\Gamma^a_{bc} + \frac{1}{2}(\Gamma^d_{bd}\delta^a_c + \Gamma^d_{cd}\delta^a_b)$$

These variables have a thermodynamic interpretation

$$(q\delta p, p\delta q) \Leftrightarrow (s\delta T, T\delta s)$$

Geometry = Thermodynamics

K. Parattu, B.R. Majhi, T.P. (2013) [arXiv:1303.1535]

On any null surface: $(\delta p^a_{bc}, \delta q^{bc}) \Leftrightarrow (\delta T, \delta s)$

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$$\frac{1}{16\pi L_P^2}\int_{\mathcal{H}} d^2x_\perp\, \ell_c\left(p^c_{ab}\delta q^{ab}\right) = \int_{\mathcal{H}} d^2x_\perp\, T\,\delta s$$

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What makes Spacetime Evolve ?

TP, Gen.Rel.Grav (2014) [arXiv:1312.3253]

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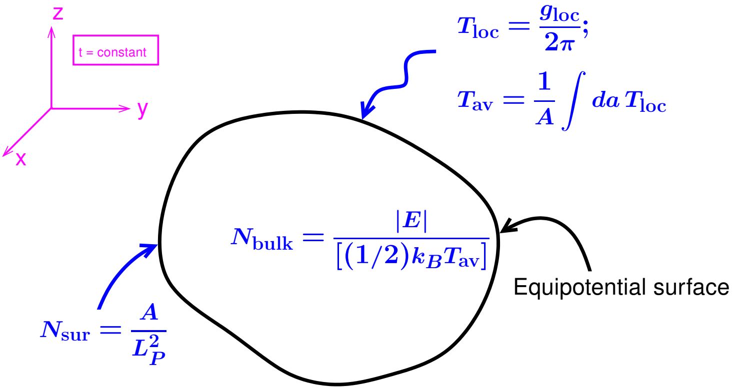

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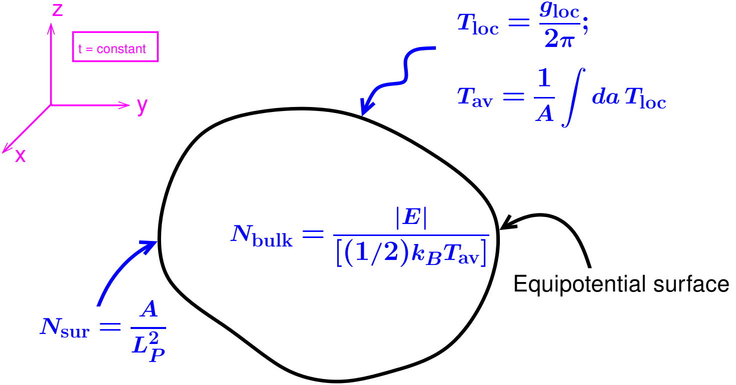

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time evolution of spacetime

= heating of spacetime

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time evolution of spacetime

= heating of spacetime

deviation from

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Evolution of spacetime is described in thermodynamic language; not in geometric language!

COSMIC EXPANSION: A QUEST FOR HOLOGRAPHIC EQUIPARTITION

T.P., [1207.0505]

$$\frac{dR_H}{dt} = (1 - \frac{\epsilon N_{\rm bulk}}{N_{\rm sur}}) \qquad \epsilon = \pm 1$$

$$N_{\rm sur} = 4\pi \frac{R_H^2}{L_P^2}; \quad N_{\rm bulk} = -\epsilon \frac{E}{(1/2)k_B T}; \quad T = \frac{H}{2\pi}$$

Remarkably enough, this leads to the standard FRW dynamics!

Provides insights into classical GR!

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For matter, $\nabla_a T^a_b = 0$ ***but***

$$\boldsymbol{\nabla_a P^a[v] \equiv -\nabla_a (T^a_b v^b) \neq 0.}$$

Why?

Provides insights into classical GR!

For matter, $\nabla_a T^a_b = 0$ ***but***

$$\nabla_a P^a[v] \equiv -\nabla_a (T^a_b v^b) \neq 0.$$

Why?

Because you did not add the momentum density of spacetime!

$$\nabla_a (P^a[v] + \mathcal{G}^a[v]) = 0$$

Momentum of Gravity

T.P. [arXiv:1506.03814]

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Variational principle has a physical meaning:

$$Q_{\rm tot} = -\int d\mathcal{V}\,\ell_a\,\left[P^a(\xi) + M^a(\xi)\right]$$

Fluid Mechanics Of Spacetime

S. Chakraborty, K. Parattu, and T.P. [arXiv:1505.05297]; S. Chakraborty, T.P. [arXiv:1508.04060]

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Three projections $P^a \ell_a, \; P^a k_a, \; P^a q_a^b$ on a null surface give

- Navier-Stokes equation [T.P., arXiv:1012.0119]
- $TdS = dE + PdV$ [T.P., gr-qc/0204019; D. Kothawala, T.P., arXiv:0904.0215]
- Evolution equation for the null surface

Thermodynamic variational principle

T.P., A. Paranjape [gr-qc/0701003]; T.P. [arXiv:0705.2533]

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Works for a wide class gravitational theories; entropy decides the theory.

Thermodynamic variational principle

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$$\mathcal{H}_m = T^a_b \ell_a \ell^b$$

$$\mathcal{H}_g = -\left(\frac{1}{16\pi L_P^2}\right)\left(4P^{ab}_{cd}\nabla_a \ell^c \nabla_b \ell^d\right)$$

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$$P^{ab}_{cd} \propto \delta^{aba_2b_2\ldots a_mb_m}_{cdc_2d_2\ldots c_md_m} R^{c_2d_2}_{a_2b_2} \ldots R^{c_md_m}_{a_mb_m}$$

- ***The P^{ab}_{cd} is the entropy tensor of the spacetime which determines the theory***

[Iyer and Wald (1994)]

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- *The demand* $\delta Q/\delta\ell_a = 0$ *for all null* ℓ_a *leads to:*

$$E^a_b \equiv P^{ai}_{jk} R^{jk}_{bi} - \frac{1}{2}\delta^a_b \mathcal{R} = (8\pi L_P^2) T^a_b + \Lambda \delta^a_b,$$

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- *On-shell value of* $Q_{\rm tot}$

$$Q_{\rm tot}^{\rm on-shell} = \int d^2x (T_{\rm loc}\, s)\Big|_{\lambda_1}^{\lambda_2}$$

Algebraic Aside

- ***Interestingly enough:***

$$2P^{ab}_{cd}\nabla_a n^c \nabla_b n^d = \mathcal{R}_{ab} n^a n^b + \left\{ \begin{array}{c} \textit{ignorable} \\ \textit{total divergence} \end{array} \right.$$

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- ***Alternative, dimensionless, form in GR:***

$$\mathcal{K}_g \equiv -\frac{1}{8\pi}(L_P^2 R_{ab} n^a n^b)$$

Newton's Law of Gravitation

T.P. [hep-th/0205278]

Three constants: $\hbar, c, L_P^2$

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Gravity, like matter, is intrinsically quantum and cannot exist in the limit of $\hbar \to 0$!

WHY?

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Can we understand these results from a deeper level? Can we get something new?

Degrees of Freedom

$$
\begin{aligned}
\Omega_{\text{tot}} &= \prod_{\phi_A} \prod_{x} \rho_g(\mathcal{G}_N, \phi_A)\, \rho_m(T_{ab}, \phi_A) \\
&\equiv \prod_{n_a} \exp \sum_{x} \left(\ln \rho_g + \ln \rho_m\right)
\end{aligned}
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$$\ln \rho_m \equiv L_P^4 \mathcal{H}_m = L_P^4 T_{ab} \ell^a \ell^b$$

$$\ln \rho_g \equiv L_P^4 \mathcal{H}_g \approx -\frac{L_P^2}{8\pi} R_{ab} \ell^a \ell^b$$

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$$R^a_b \ell_a \ell^b = (8\pi L_P^2) T^a_b \ell_a \ell^b$$

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\end{aligned}
$$

$$
G^a_b = (8\pi L_P^2) T^a_b + ({\rm const}) \delta^a_b
$$

Two Key Principles

- ***Variational principle must remain invariant under*** $T^a_b \to T^a_b + (const)\delta^a_b$.
- ***Quantum spacetime has a zero-point length.***

Guiding Principle For Dynamics

Guiding Principle For Dynamics

Matter equations of motion remain invariant when a constant is added to the Lagrangian

Gravity must respect this symmetry

The variational principle for the dynamics of spacetime must be invariant under

$$T^a_b \rightarrow T^a_b + (constant)\,\delta^a_b$$

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The variational principle cannot have metric as the dynamical variable!

Heat density of matter

- *Minimal possibility: The matter should enter ρ_m through*

$$\mathcal{H}_m \equiv T_{ab}\ell^a\ell^b$$

- *This has a natural interpretation of heat density contributed by matter on null surfaces*

Local Rindler Horizon

- ***Heat density (energy per unit area per unit affine time) of the null surface, contributed by matter crossing a local Rindler horizon:***

$$\mathcal{H}_m \equiv \frac{dQ_m}{\sqrt{\gamma}d^2x d\lambda} = T_{ab}\ell^a\ell^b$$

- ***This fixes the matter sector and leads to:***

$$\Omega_{\text{tot}} = \prod_{\ell} \exp \int d\mathcal{V} \left(\mathcal{H}_g + T_{ab}\ell^a\ell^b\right)$$

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Cosmological constant arises as an integration constant

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Cosmological constant arises as an integration constant

Its value is determined by a new conserved quantity for the universe!

The Challenge

How can we get $\mathcal{H}_g$ from a microscopic theory without knowing the full QG?

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We need to recognize discreteness and yet use continuum mathematics!

Atoms Of A Fluid

- ***Continuum fluid mechanics:*** $\rho(x^i), \mathrm{U}(x^i), \ldots.$ ***ignores discreteness and velocity dispersion.***

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  - ***Many atoms with different*** $\boldsymbol{p_i}$ ***can exist at same*** $\boldsymbol{x^i}$

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The distribution function for 'atoms of space' provides the microscopic origin for the variational principle

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Points in a renormalized spacetime has zero volume but finite area!

The $\mathcal{H}_g$ is proportional to the number of "atoms of space at" x^i with "momentum" n_i.

We expect $\mathcal{H}_g$ to be proportional to the volume or the area measure "associated with" the event x^i in the spacetime

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Use equi-geodesic surfaces to make this idea precise

Geodesic Interval

D. Kothawala, T.P. [arXiv:1405.4967]; [arXiv:1408.3963]

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$$\sigma(x, x') = \int_x^{x'} \sqrt{g_{ab} n^a n^b} d\lambda$$

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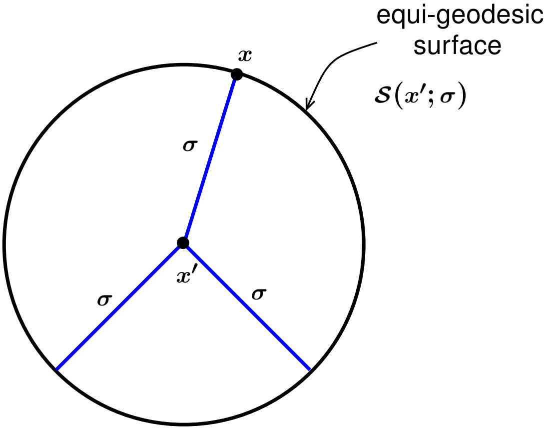
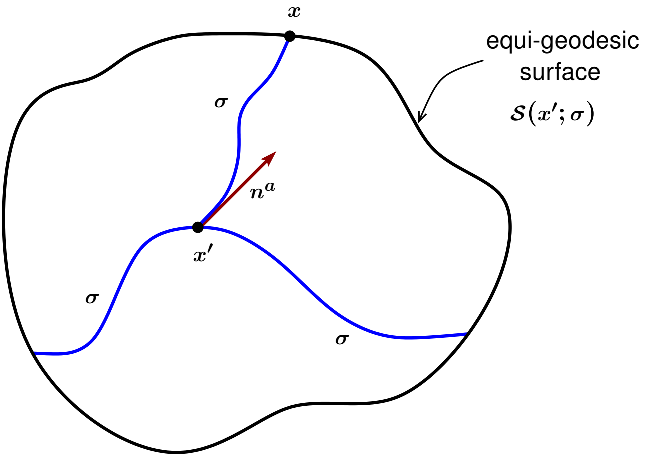
$$\frac{1}{2}\nabla_a\nabla_b\sigma^2 = g_{ab} - \frac{\lambda^2}{3}\mathcal{E}_{ab} + \frac{\lambda^2}{12}n^i\nabla_i\mathcal{E}_{ab} + \mathcal{O}(\lambda^4)$$

$$n_j = \nabla_j\sigma, \qquad \mathcal{E}_{ab} \equiv R_{akbj}n^k n^j$$



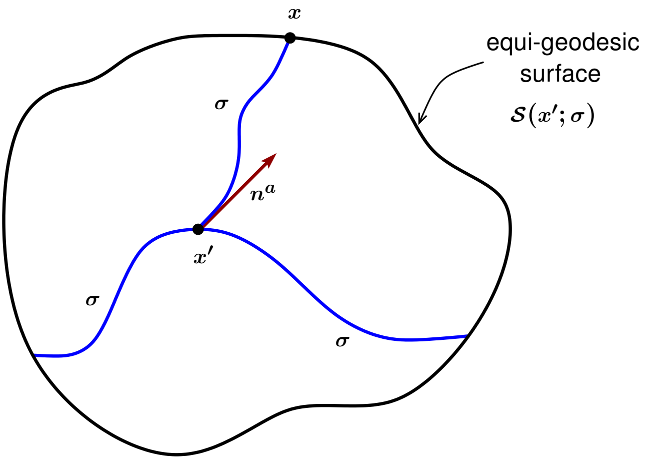
$$ds^2 = d\sigma^2 + \sigma^2 d\Omega^2_{(S3)}$$

$$\sqrt{g} \propto \sigma^3 \qquad \sqrt{h} \propto \sigma^3$$



$$ds^2 = d\sigma^2 + h_{\alpha\beta}dx^\alpha dx^\beta$$

The $\sqrt{g} = \sqrt{h}$ will pick up curvature corrections



$$ds^2 = d\sigma^2 + h_{\alpha\beta}dx^\alpha dx^\beta$$

$$\sqrt{h}(x,x') = \sqrt{g}(x,x') = \sigma^3\left(1 - \frac{\sigma^2}{6}\mathcal{E}\right)\sqrt{h_\Omega}; \quad \mathcal{E} \equiv R_{ab}n^a n^b$$

Zero-Point Length

T.P. Ann.Phy. (1985), 165, 38; PRL (1997), 78, 1854

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Quantum spacetime has a zero-point length:

D. Kothawala, T.P. [arXiv:1405.4967]; [arXiv:1408.3963]

$$\sigma^2(x,x') \;\to\; S(\sigma^2) = \sigma^2(x,x') + L_0^2$$
$$g_{ab}(x) \;\to\; q_{ab}(x,x';L_0^2)$$

In conventional units, $L_0^2 = (3/4\pi)L_P^2$.

Area Of A Point

T.P. [arXiv:1508.06286]

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$$\sqrt{q} = \sigma\left(\sigma^2 + L_0^2\right)\left[1 - \frac{1}{6}\mathcal{E}\left(\sigma^2 + L_0^2\right)\right]\sqrt{h_\Omega}$$

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Points have no volume but finite area:

$$\sqrt{h} = L_0^3\left[1 - \frac{1}{6}\mathcal{E}L_0^2\right]\sqrt{h_\Omega}$$

- ***The number of atoms of space at x^i scales as area measure of the equigeodesic surface when $x' \to x$***

$$\rho_g(x^i, \ell_a) \propto \lim_{\sigma \to 0} \sqrt{h(x, \sigma)} \approx 1 - \frac{1}{8\pi} L_P^2 R_{ab} \ell^a \ell^b$$

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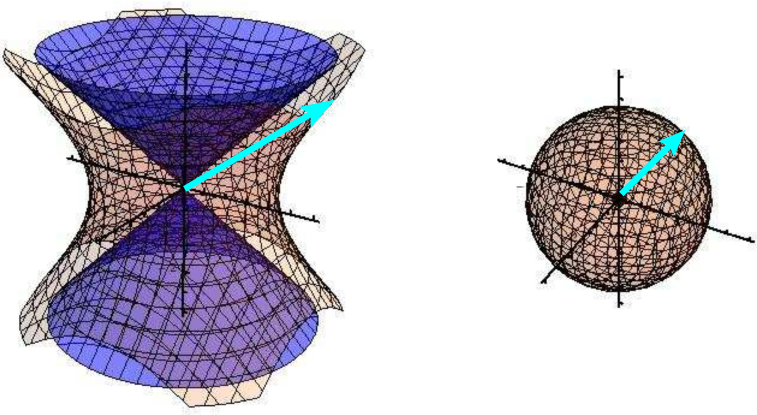

Null horizon ⇔ Euclidean origin

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- ***The variational principle leads to***

$$G_{ab} = \kappa T_{ab} + \Lambda g_{ab}$$

- ***Spacetime becomes two-dimensional close to Planck scales!***

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See e.g., Carlip et al., [arXiv:1103.5993]; [arXiv:1009.1136]; G. Calcagni et al, [arXiv:1208.0354]; [arXiv:1311.3340]; J. Ambjorn, et al. [arXiv:hep-th/0505113]; L. Modesto, [arXiv:0812.2214]; V. Husain et al., [arXiv:1305.2814] .... etc.

Quantum of Information

T.P. [arXiv:1508.06286]

- ***Spacetime becomes two-dimensional close to Planck scales!***

- ***Basic quantum of information to count spacetime degrees of freedom is***

$$I_{QG} = \frac{4\pi L_P^2}{L_P^2} = 4\pi$$

Possible new insight

May be we should not describe the cosmos as a specific solution to gravitational field equations.

Three phases, three energy-density scales, with no relation to each other!

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$$\rho_\Lambda = [(2.26 \pm 0.05) \times 10^{-3} \mathsf{eV}]^4$$

Hope: High energy physics will (eventually!) fix $\rho_{inf}^{1/4} \approx 10^{15}\mathrm{GeV}$ ***and***

$$\rho_{eq}^{1/4} \propto \left[\frac{n_{DM}}{n_\gamma} m_{DM} + \frac{n_B}{n_\gamma} m_B\right] \approx 0.86\ \mathrm{eV}$$

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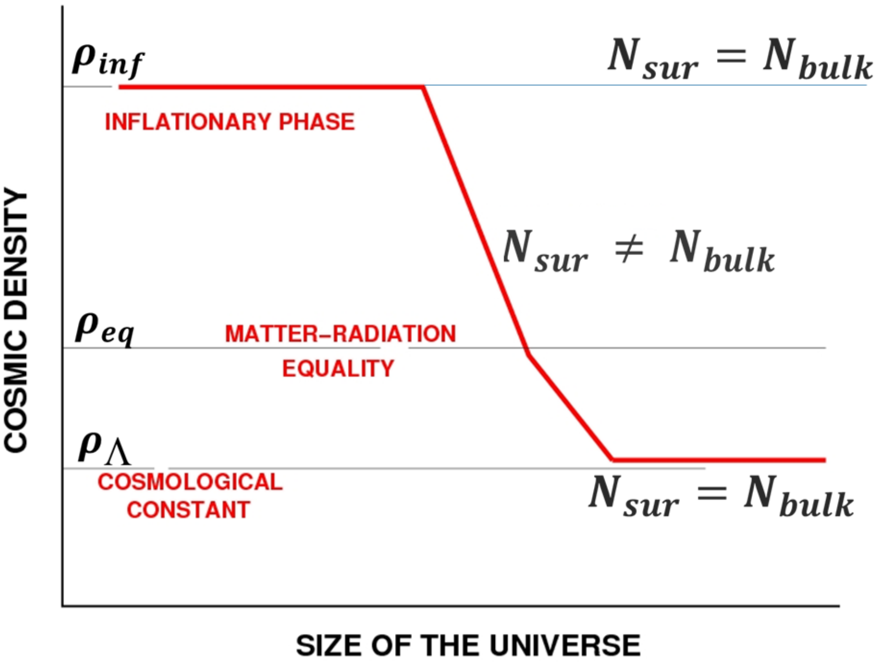
But we have no clue why

$$\rho_\Lambda L_P^4 \approx 1.4 \times 10^{-123} \approx 1.1 \times e^{-283}.$$

The FRW universe is described by the two equations (with $T = H/2\pi$)

$$\frac{dV_H}{dt} = L_P^2 (N_{sur} - N_{bulk})$$

$$\mathcal{U}_H \equiv \rho V_H = TS$$



COSMIC DENSITY
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$N_{sur} = N_{bulk}$
INFLATIONARY PHASE
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MATTER–RADIATION
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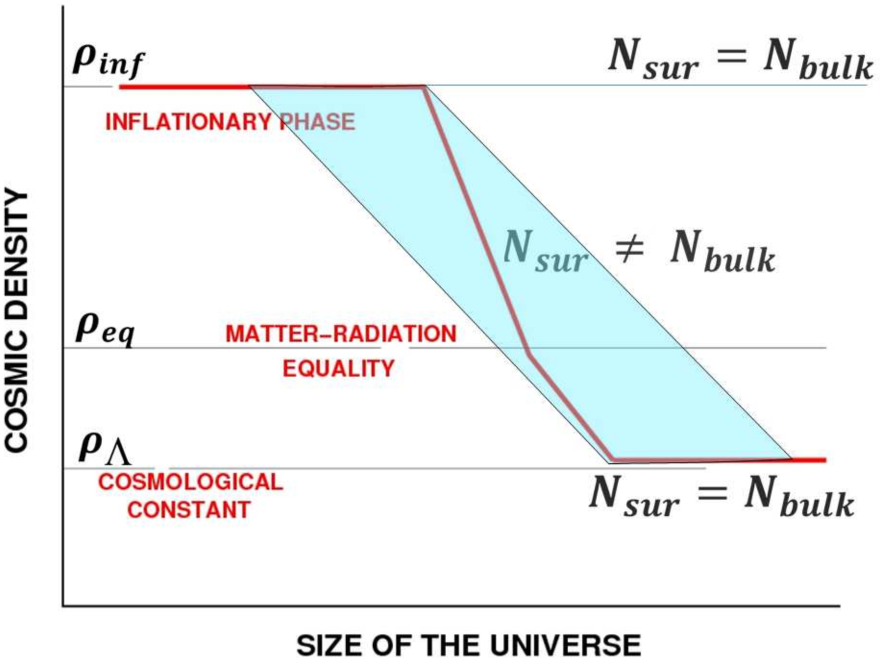

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Accessibility of Cosmic Information

$$x(a_2, a_1) = \int_{t_1}^{t_2} \frac{dt}{a(t)} = \int_{a_1}^{a_2} \frac{da}{a^2 H(a)}$$

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Boundary of accessible cosmic information for eternal observer

$$x(\infty, a) \equiv x_\infty(a) = \int_a^\infty \frac{d\bar{a}}{\bar{a}^2 H(\bar{a})}$$

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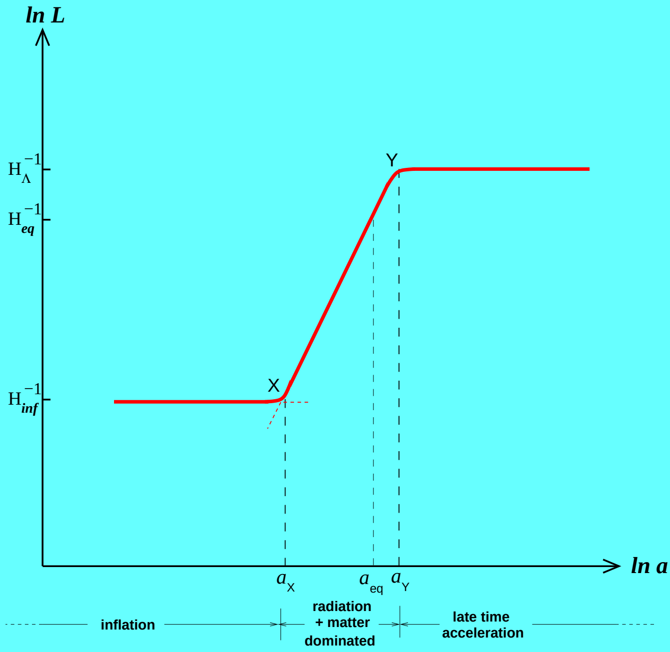
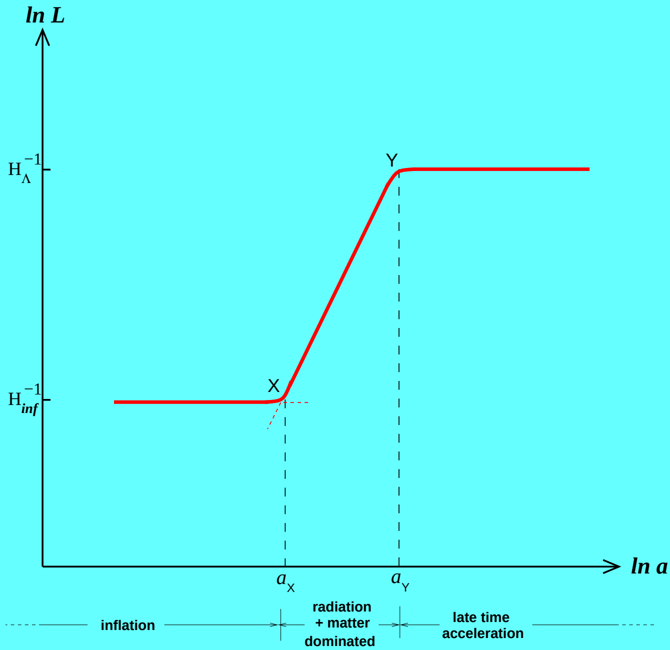
Boundary of accessible cosmic information for eternal observer

$$x(\infty, a) \equiv x_\infty(a) = \int_a^\infty \frac{d\bar{a}}{\bar{a}^2 H(\bar{a})}$$

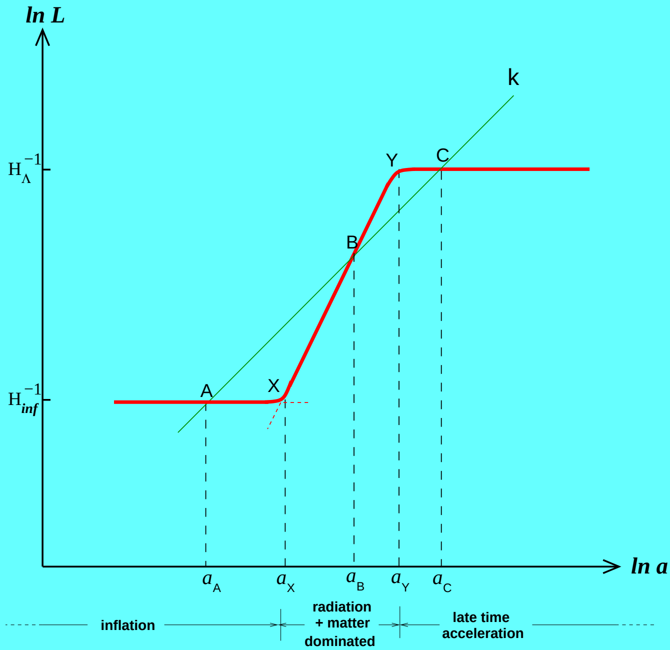
This is infinite if $\Lambda = 0$; finite if $\Lambda \neq 0$



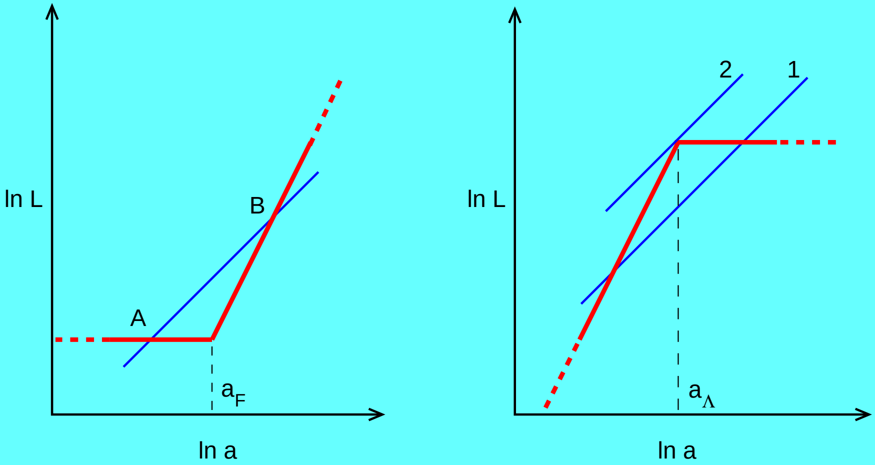
ln L
H_Λ^{-1}
H_{eq}^{-1}
H_{inf}^{-1}
Y
X
ln a
a_X
a_{eq}
a_Y
inflation
radiation + matter dominated
late time acceleration



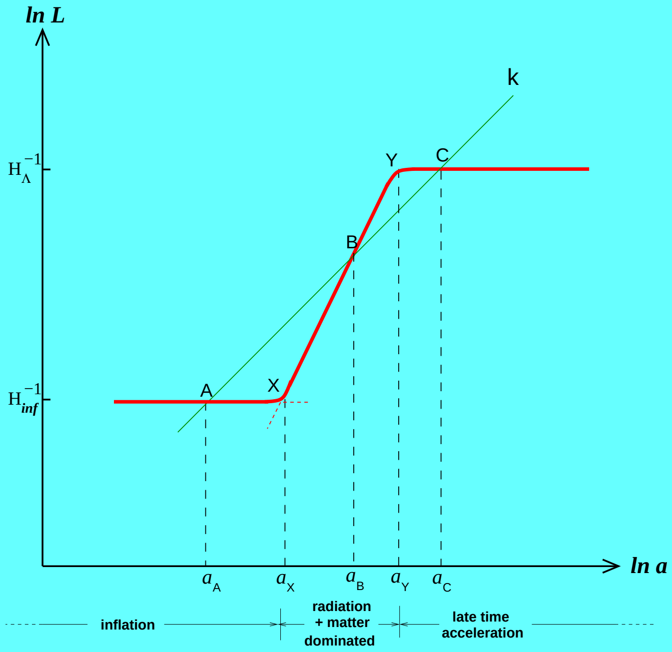
ln L
H_Λ^{-1}
H_{inf}^{-1}
Y
X
ln a
a_X
a_Y
inflation
radiation + matter dominated
late time acceleration



ln L
k
H_Λ^{-1}
H_{inf}^{-1}
Y
C
B
A
X
ln a
a_A
a_X
a_B
a_Y
a_C
inflation
radiation + matter dominated
late time acceleration



ln L
A
B
a_F
ln a
ln L
2
1
a_Λ
ln a



ln L
ln a
H_Λ^{-1}
H_{inf}^{-1}
k
A
X
B
Y
C
a_A
a_X
a_B
a_Y
a_C
inflation
radiation + matter dominated
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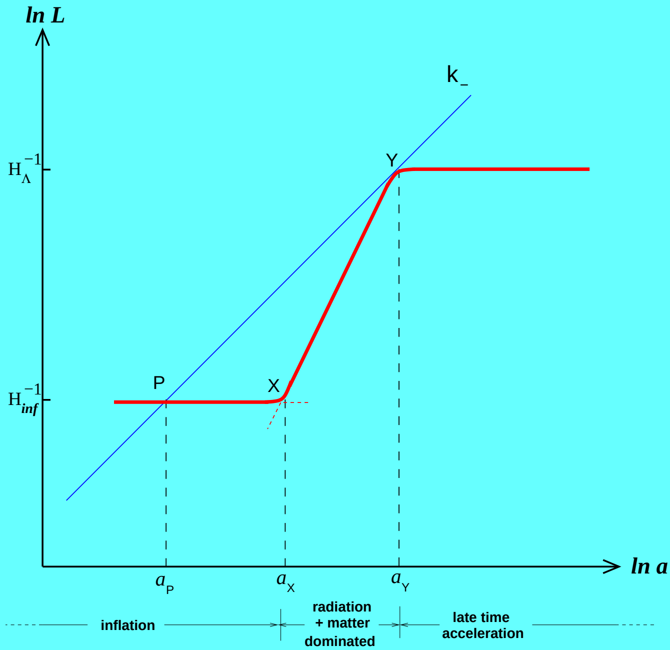
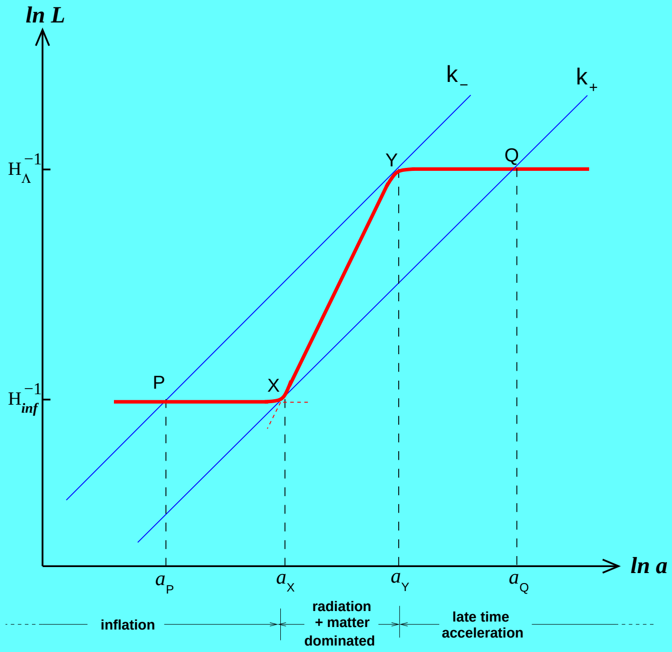
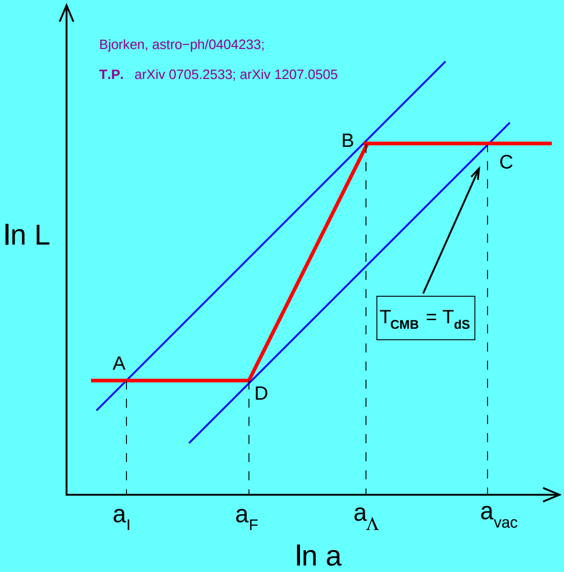


ln L
k_
Y
H_Λ^{-1}
P
X
H_{inf}^{-1}
ln a
a_P
a_X
a_Y
inflation
radiation + matter dominated
late time acceleration

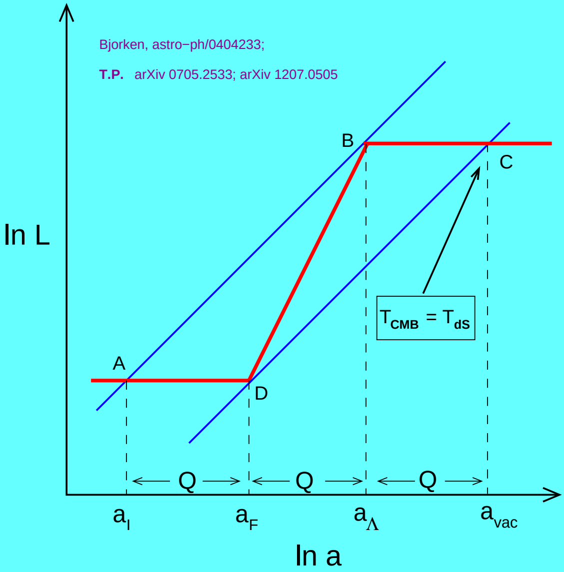


ln L
ln a
k−
k+
H_Λ^{-1}
H_{inf}^{-1}
P
X
Y
Q
a_P
a_X
a_Y
a_Q
inflation
radiation + matter dominated
late time acceleration

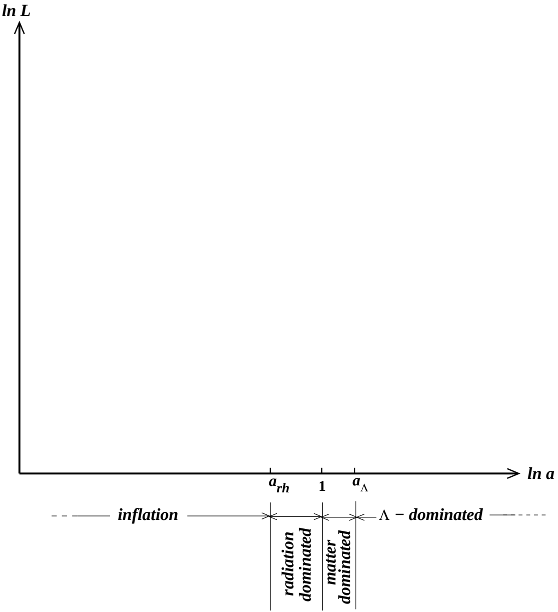
COSMIC PARALLELOGRAM



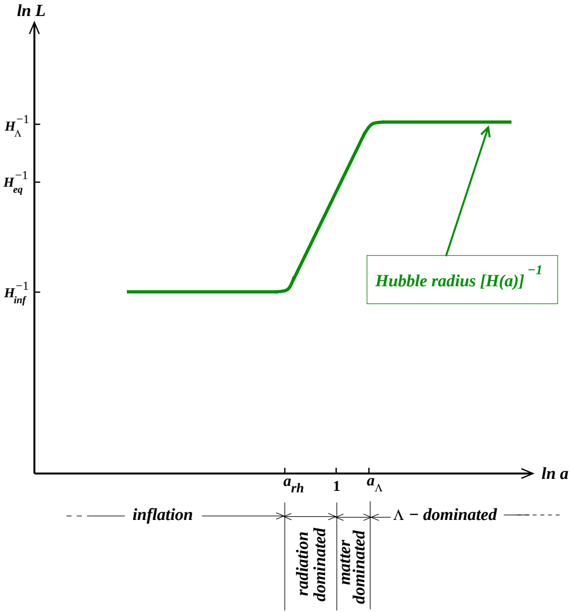
COSMIC PARALLELOGRAM

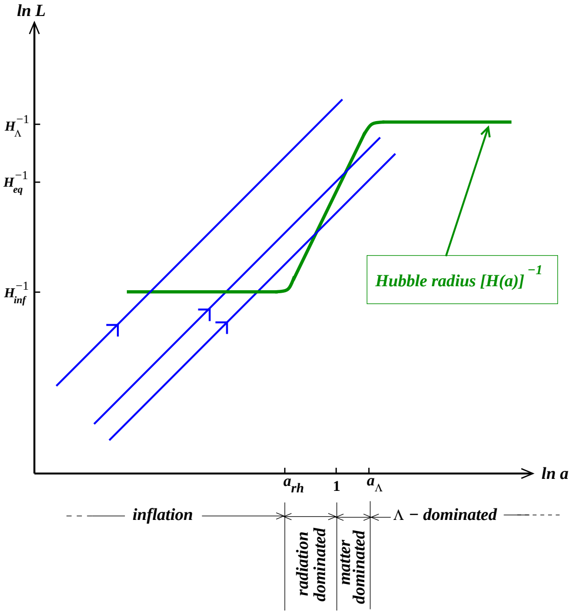


Cosmic Information: CosmIn

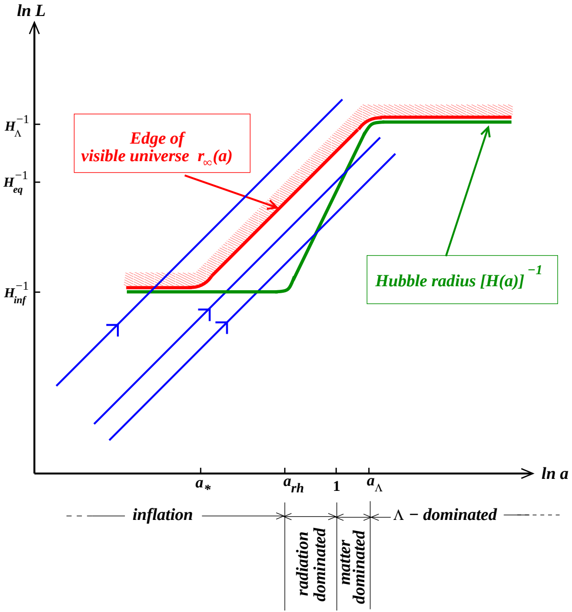


Cosmic Information: CosmIn




ln L
H_Λ^{-1}
H_{eq}^{-1}
H_{inf}^{-1}
Hubble radius $[H(a)]^{-1}$
ln a
a_{rh}
1
a_Λ
inflation
radiation dominated
matter dominated
Λ − dominated

Cosmic Information: CosmIn



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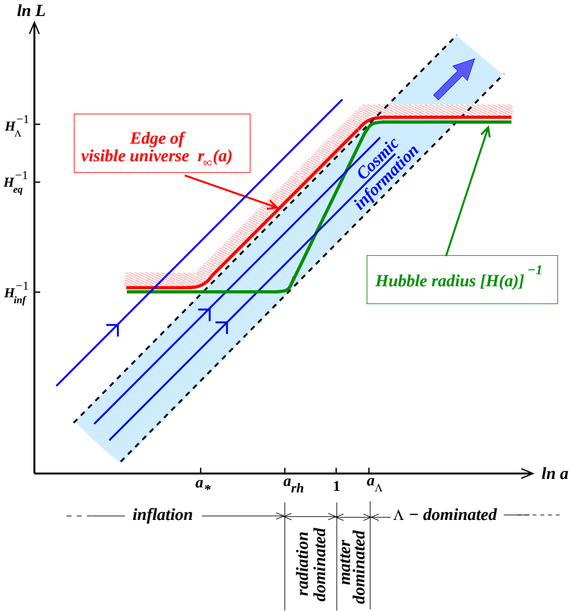

Cosmic Information: CosmIn

T.P, Hamsa Padmanabhan [arXiv:1404.2284]

A measure of cosmic information accessible to eternal observer ('CosmIn')

I_c = Number of modes (geodesics) which cross the Hubble radius during the radiation + matter dominated phase .

$$I_c = \frac{2}{3\pi} \ln \left(\frac{a_{\rm rh}}{a_*} \right)$$

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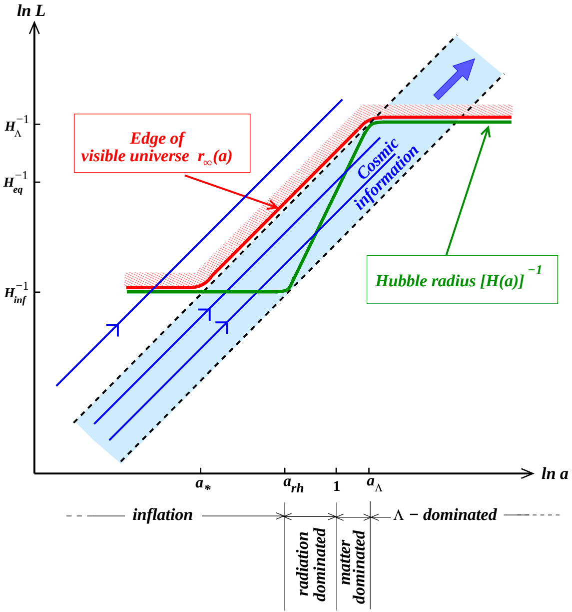

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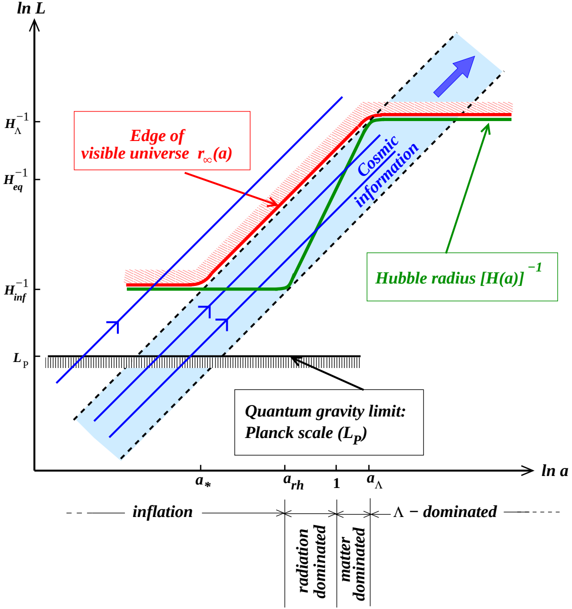

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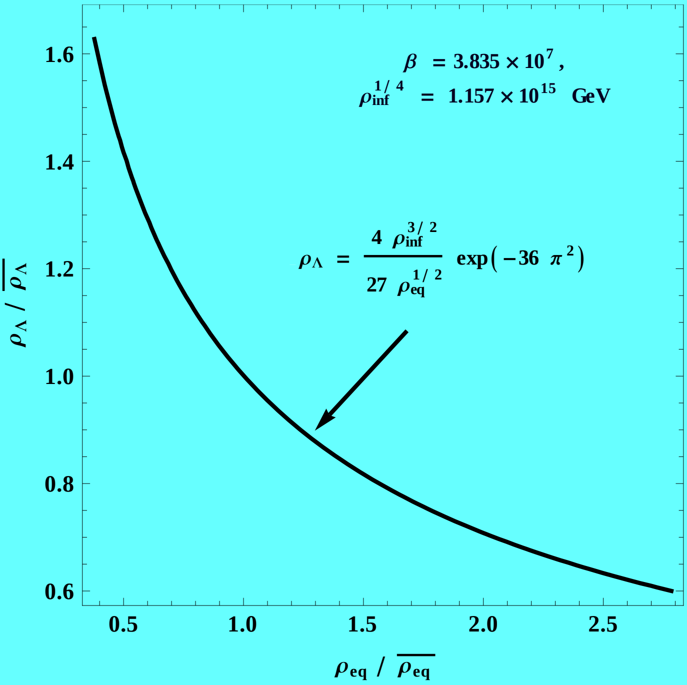
Using $I_c = I_{QG} = 4\pi$ gives the numerical value of ρ_Λ

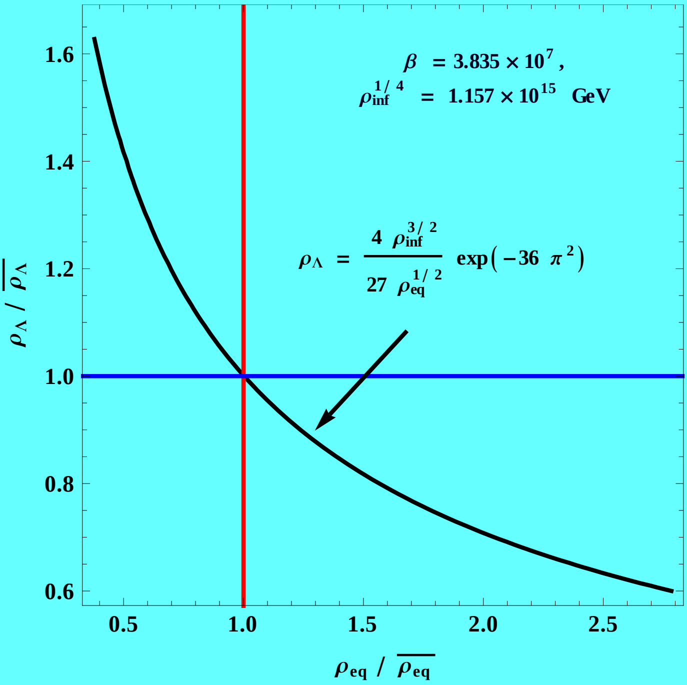
The Magical Relation!

$$\rho_\Lambda = \frac{4}{27}\frac{\rho_{inf}^{3/2}}{\rho_{eq}^{1/2}}\exp(-36\pi^2)$$

Hamsa Padmanabhan, **T.P**, *CosMIn: Solution to the Cosmological constant problem* [arXiv:1302.3226]



$\beta = 3.835 \times 10^7$,
$\rho_{inf}^{1/4} = 1.157 \times 10^{15}$ GeV
$\rho_\Lambda = \frac{4\ \rho_{inf}^{3/2}}{27\ \rho_{eq}^{1/2}} \exp(-36\ \pi^2)$
1.6
1.4
1.2
1.0
0.8
0.6
0.5
1.0
1.5
2.0
2.5
$\rho_\Lambda / \overline{\rho_\Lambda}$
$\rho_{eq} / \overline{\rho_{eq}}$



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0.6
0.5
1.0
1.5
2.0
2.5
$\rho_\Lambda / \overline{\rho_\Lambda}$
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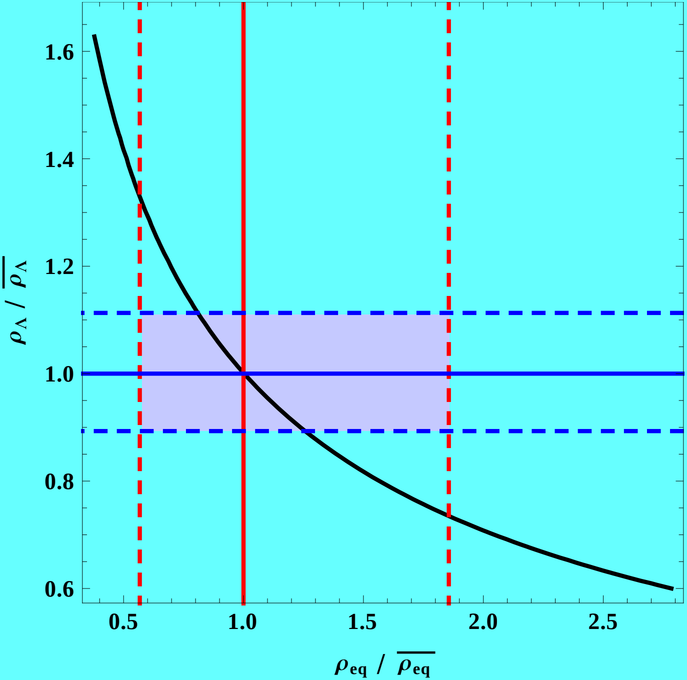
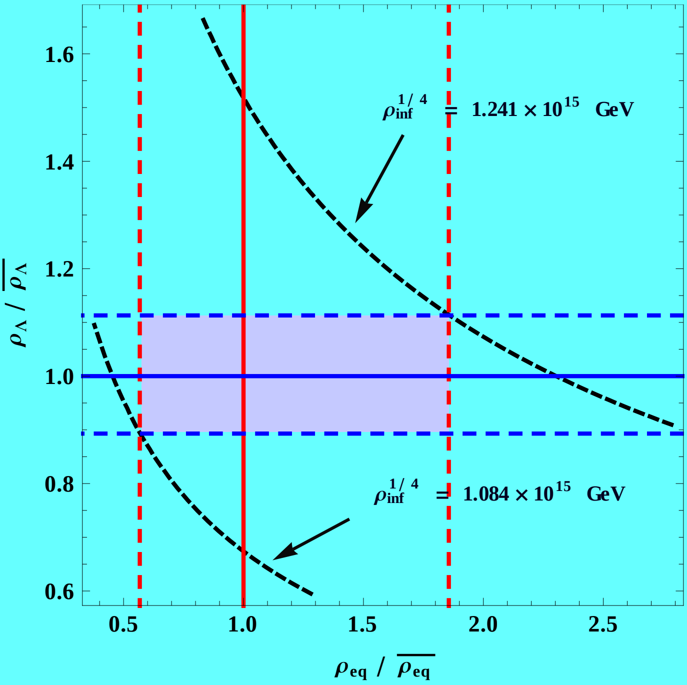


1.6
1.4
1.2
1.0
0.8
0.6
0.5
1.0
1.5
2.0
2.5
ρΛ / ρΛ
ρeq / ρeq



$\rho_{inf}^{1/4} = 1.241 \times 10^{15}$ GeV
$\rho_{inf}^{1/4} = 1.084 \times 10^{15}$ GeV
1.6
1.4
1.2
1.0
0.8
0.6
0.5
1.0
1.5
2.0
2.5
$\rho_\Lambda / \overline{\rho_\Lambda}$
$\rho_{eq} / \overline{\rho_{eq}}$

Matter and Geometry need to emerge together for proper interpretation of $T^{ab}n_a n_b$ at the microscopic scale. How do we do this?

Key Open Question

Possibility for Matter Sector

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$$2\mu L_P^4 \, \langle \bar{T}_{ab} n^a n^b \rangle \approx 2\mu L_P^4 \, \langle \bar{T}_{ab} \rangle \langle n^a n^b \rangle = 1$$

Summary

Demand that: (i) Gravity is immune to zero-level of energy. (ii) The number of atoms of spacetime at a point to be proportional to the area measure in a spacetime with zero-point length. Then:

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- ***The cosmological constant is related to the amount of information accessible to an eternal observer.***
- ***At Planck scales spacetime is 2-dimensional with 4π units of information; this allows the determination of the value of the cosmological constant.***

References

T.P, *General Relativity from a Thermodynamic Perspective*, *Gen. Rel. Grav.*, **46**, 1673 (2014) [arXiv:1312.3253].

***Review:* T.P**, *The Atoms Of Space, Gravity and the Cosmological Constant*, *IJMPD,* **25**, 1630020 (2016) [arXiv:1603.08658].

Acknowledgements

Sunu Engineer, Krishna Parattu, Aseem Paranjape
Dawood Kothawala, Sumanta Chakraborty, Hamsa Padmanabhan
Bibhas Majhi, James Bjorken, Donald Lynden-Bell

THANK YOU FOR YOUR TIME!

- ***Compute the combination:***

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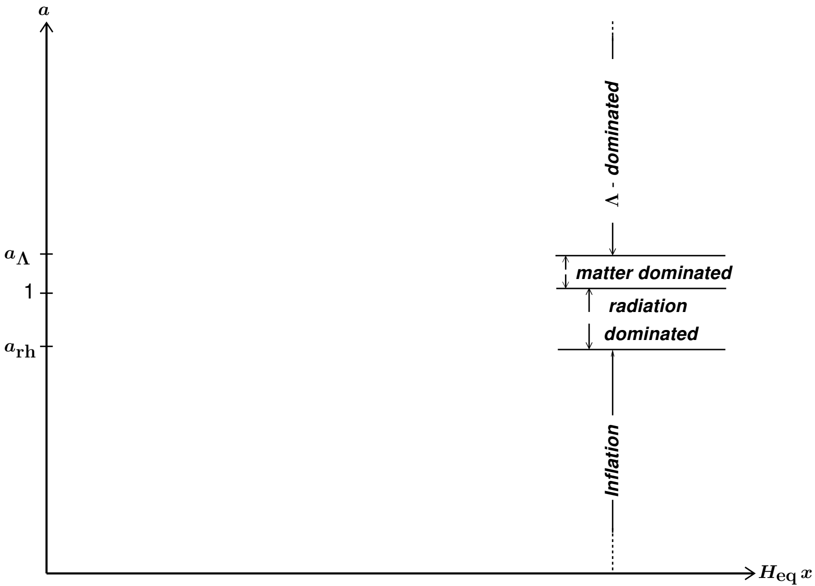
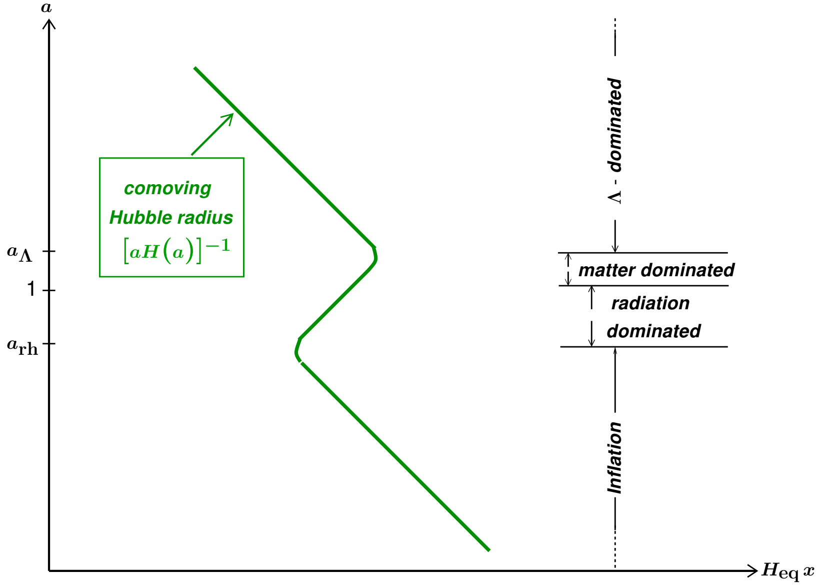
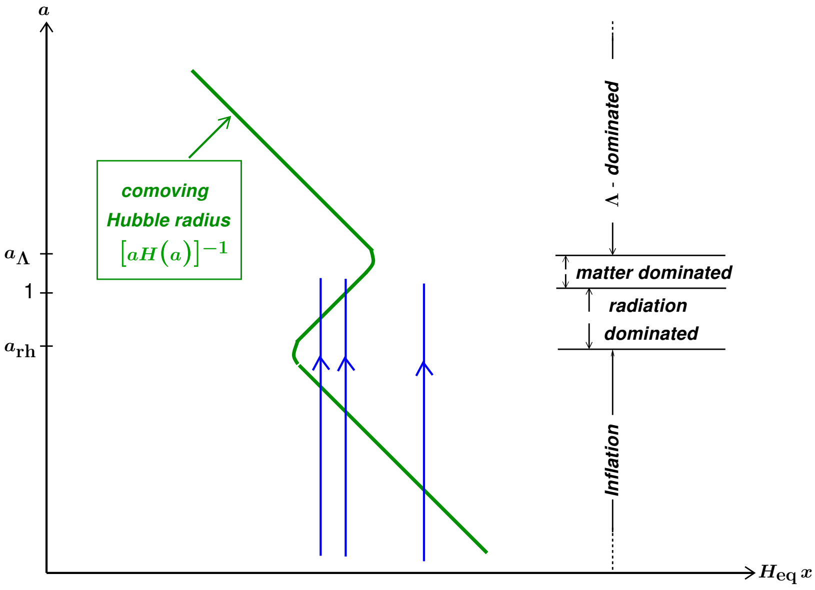
Why?

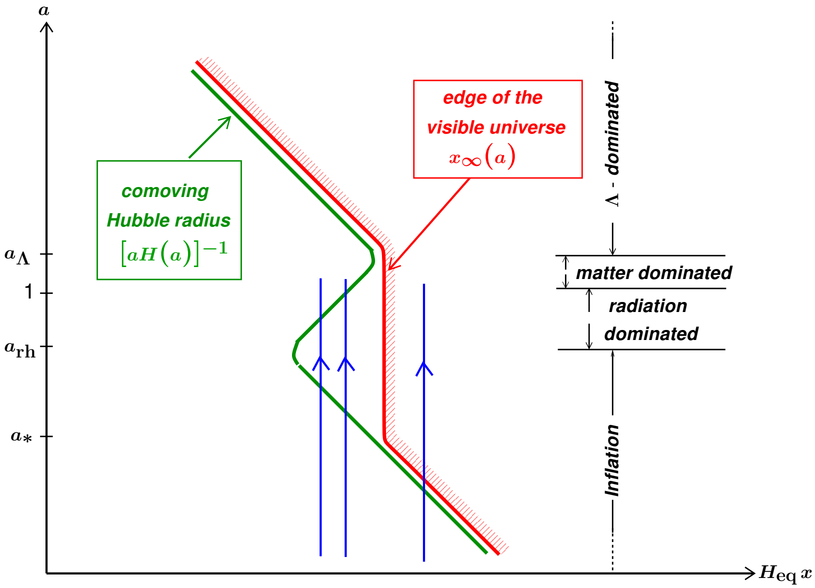

a
a_Λ
1
$a_{\rm rh}$
$H_{\rm eq}\, x$
Λ - dominated
matter dominated
radiation
dominated
Inflation



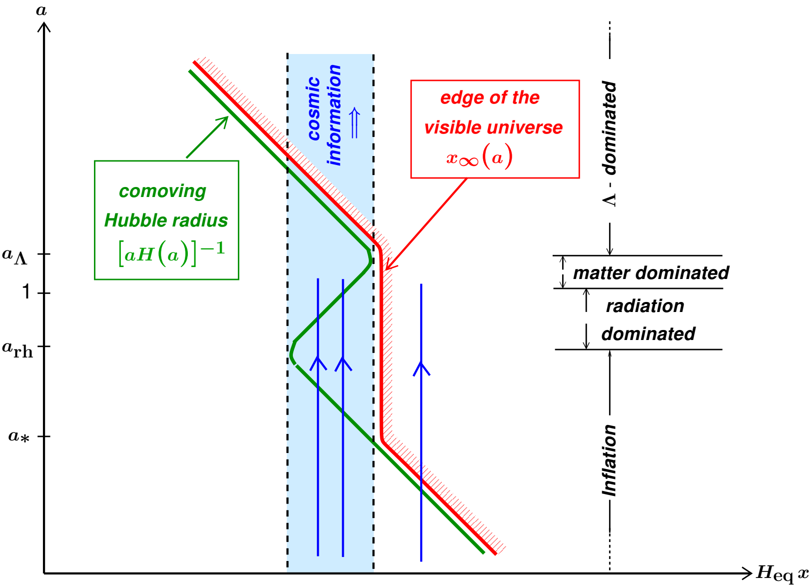
a
comoving
Hubble radius
$[aH(a)]^{-1}$
a_Λ
1
$a_{\rm rh}$
Λ - dominated
matter dominated
radiation
dominated
Inflation
$H_{\rm eq}\,x$

Cosmic Information: CosmIn




a
a_Λ
1
a_{rh}
a_*
$H_{eq}\,x$
comoving
Hubble radius
$[aH(a)]^{-1}$
edge of the
visible universe
$x_\infty(a)$
Λ - dominated
matter dominated
radiation
dominated
Inflation

Cosmic Information: CosmIn



Cosmic Information: CosmIn