GR and QG: The Next 100 Years

T. Padmanabhan

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T.P., arXiv:1603.08658

T.P., arXiv:1611.03505

20th Century Physics

Top Two Discoveries

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Matter is discrete and has microscopic degrees of freedom.

The Universe has dynamics and is expanding.

21st Century Physics

Top Two Discoveries

Spacetime is discrete and has microscopic degrees of freedom.

The Universe has its own dynamics (and is not to be treated as a special solution in GR).

The Major Challenges to GR

SINGULARITIES: e.g., BLACK HOLES

COSMOLOGICAL CONSTANT

THE THERMODYNAMIC CONNECTION

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Classical GR is incomplete; we need QG!

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

GR: THE NEXT 100 YEARS

Needs another paradigm shift

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

Why did/will the usual approaches to QG fail?

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If you quantize the equations of elasticity you will only get phonons — not the physics of the atoms!

THE PARADIGM

Key ingredient - 1

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

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.

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!

Physics is all about numbers and making falsifiable predictions!

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Provides 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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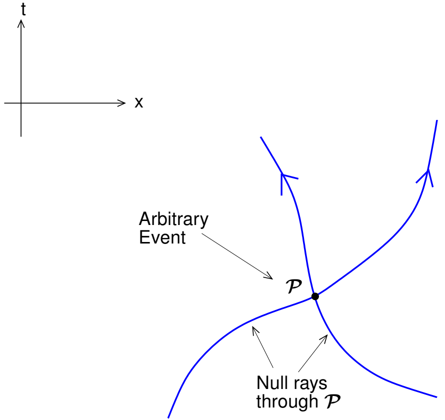
This fact transcends black hole physics and Einstein gravity.

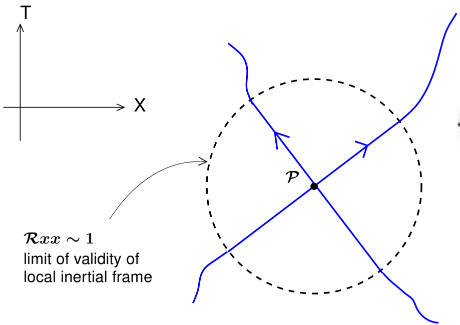
Spacetime also has a heat density!

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.

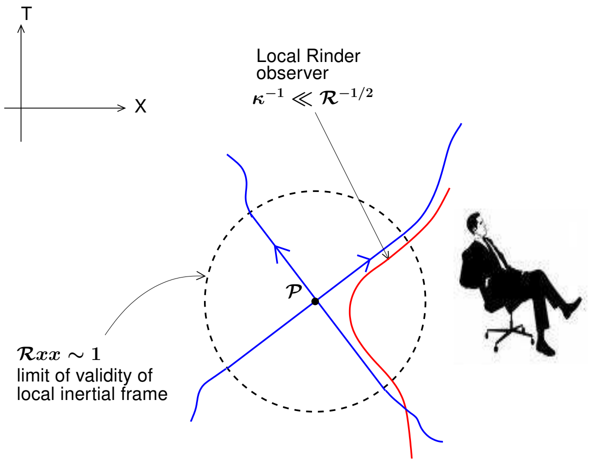
Spacetime in Arbitrary Coordinates

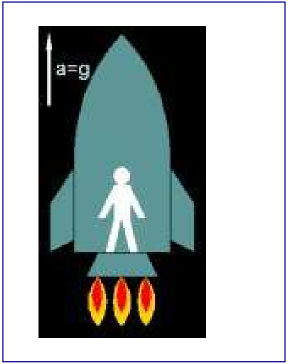




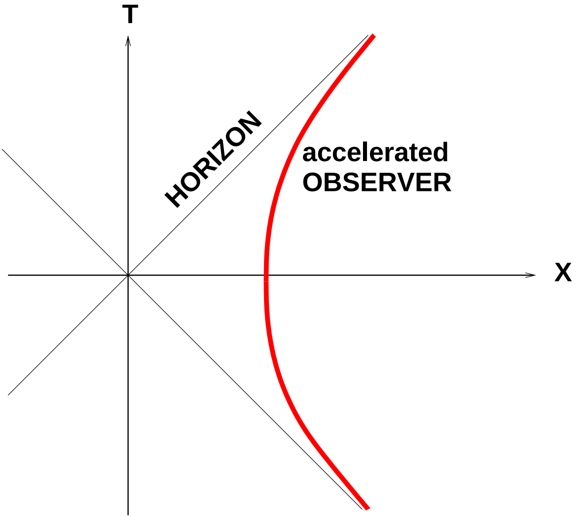
Validity of laws of SR $\Rightarrow$ How gravity affects matter

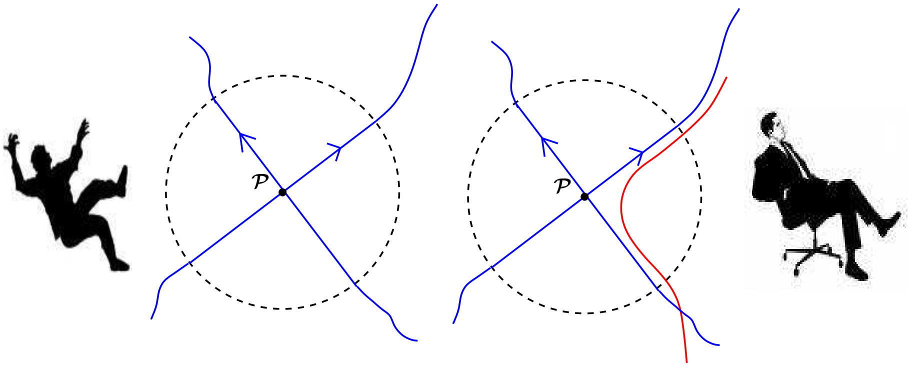
Local Rindler Observers



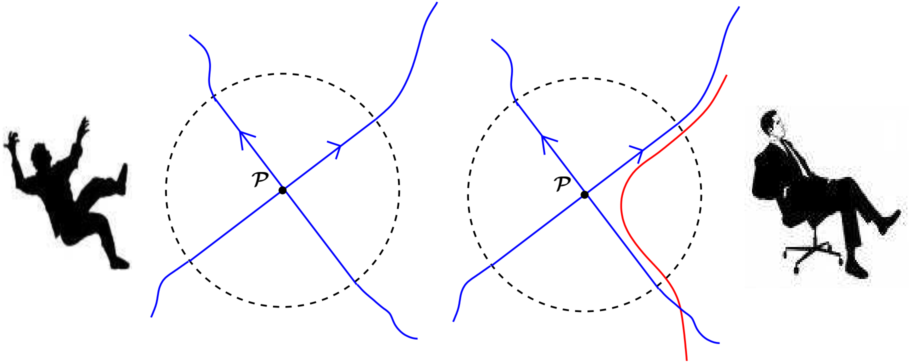


FLAT SPACETIME





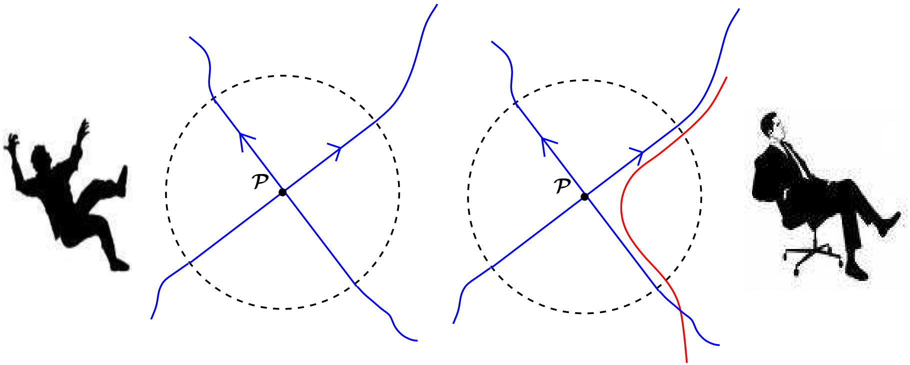
Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations



Vacuum fluctuations $\Longleftrightarrow$ Thermal fluctuations

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

A VERY NON-TRIVIAL EQUIVALENCE!



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A VERY NON-TRIVIAL EQUIVALENCE!

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

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

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[Davies (1975), Unruh (1976)]

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

[Davies (1975), Unruh (1976)]

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

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

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Inaccessibility of Information $\Leftrightarrow$ ***Entropy***

Information Content of spacetime plays a central role in the new paradigm!

The Importance Of Being Hot

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

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?

Equipartition with a surface-bulk correspondence

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

An area dA is endowed with $dn = dA/L_P^2$ microscopic degrees of freedom ('atoms')

Holographic Equipartition

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

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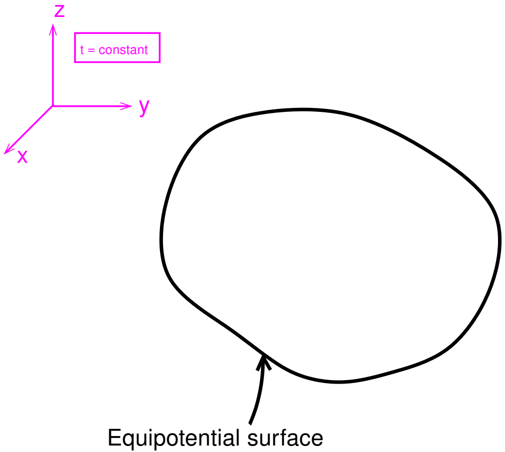

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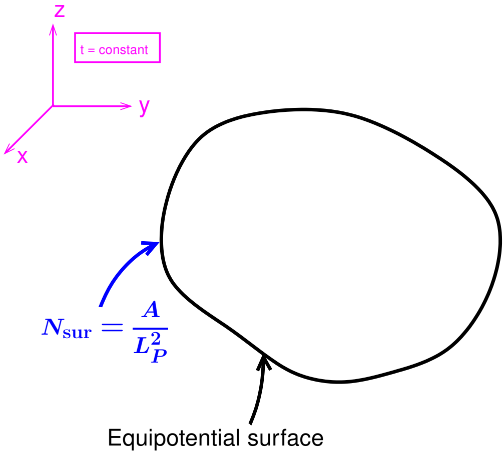

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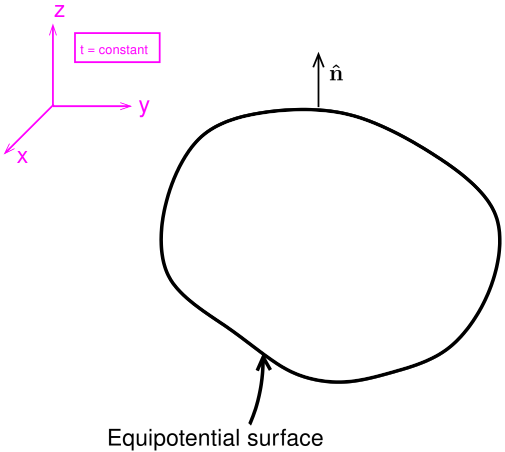

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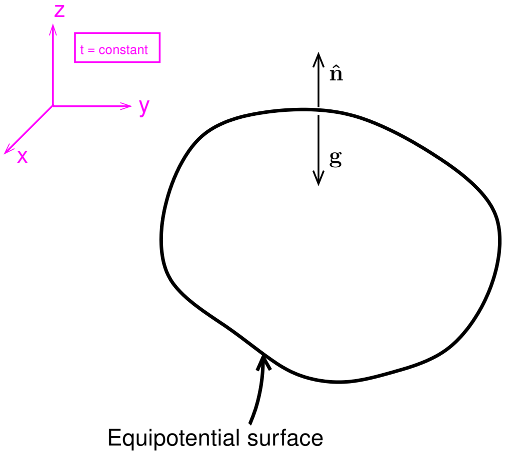

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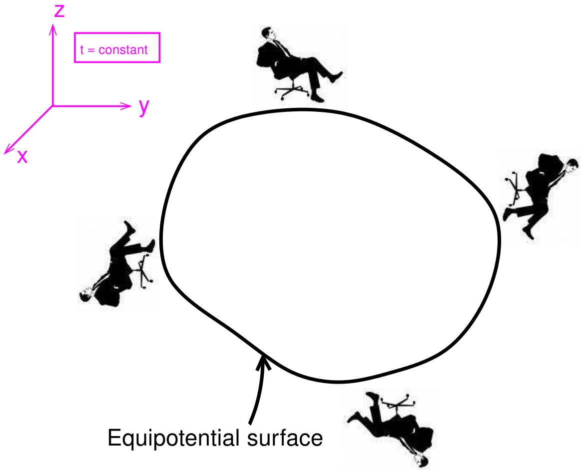

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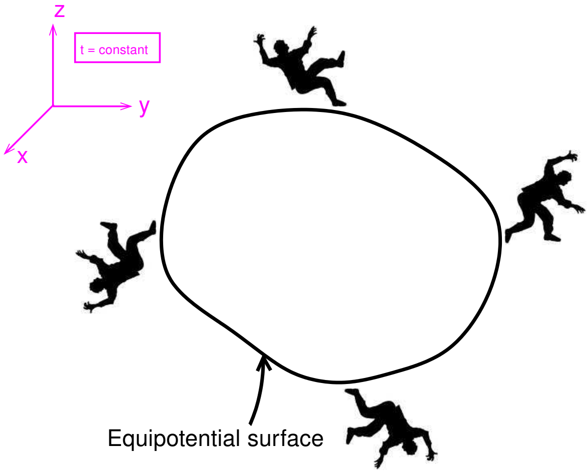

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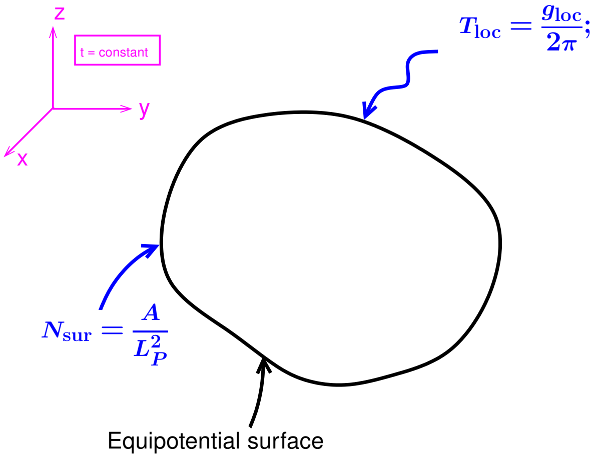

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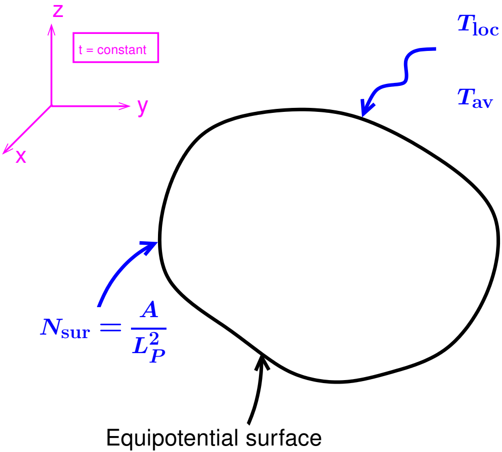

$$T_{\rm loc} = \frac{g_{\rm loc}}{2\pi};$$

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

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

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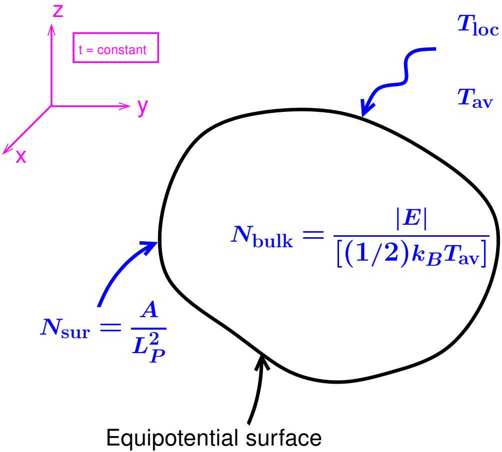

$$T_{\rm loc} = \frac{g_{\rm loc}}{2\pi};$$

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

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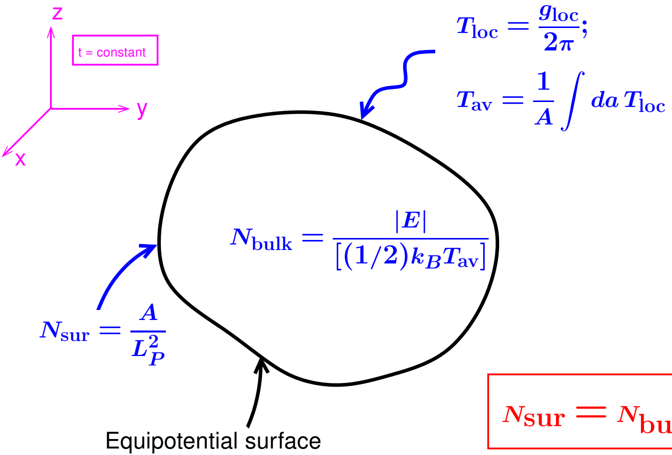

$$N_{\rm sur} = N_{\rm bulk}\,!$$

All static geometries have

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

Evolution of spacetime

Review: TP, [arXiv:1410.6285]

All static geometries have

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

Evolution arises from departure from 'holographic equipartition':

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

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]

Geometry $\Leftrightarrow$ Thermodynamics

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

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

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

These variables have a thermodynamic interpretation

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

What makes Spacetime Evolve ?

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

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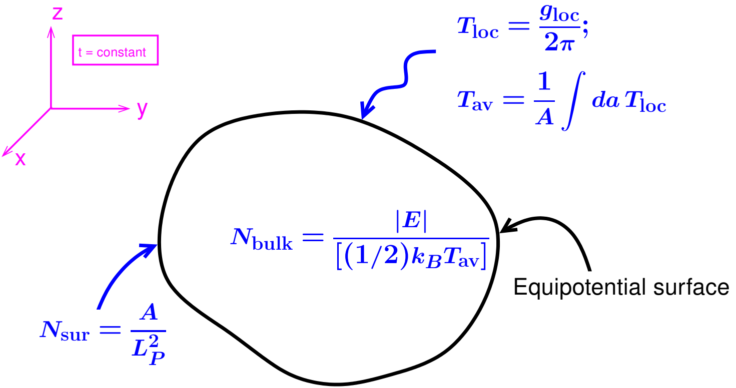

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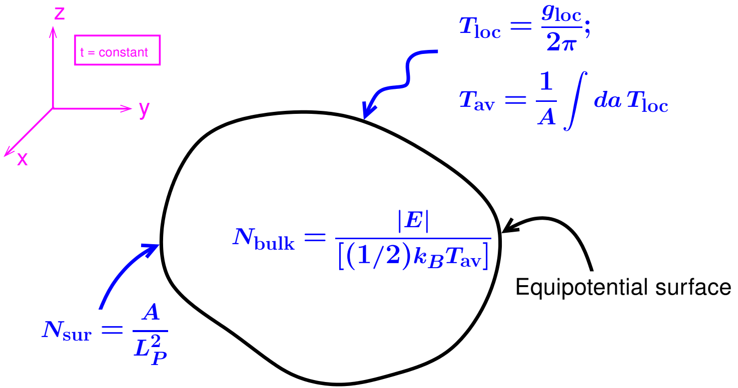

$$\int \frac{d\sigma_a}{8\pi L_P^2}\, q^{\ell m}\, \pounds_\xi\, p^a_{\ell m} = -\frac{1}{2} k_B T_{\rm av}\, \left(N_{\rm sur} - N_{\rm bulk}\right)$$

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time evolution of spacetime

= heating of spacetime

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

Newton's Law of Gravitation

T.P. [hep-th/0205278]

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

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Temperature $\Rightarrow (\hbar/\boldsymbol{c})$; ***Entropy*** $\Rightarrow \boldsymbol{L_P^2}$

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$$F = \left(\frac{c^3 L_P^2}{\hbar}\right)\left(\frac{m_1 m_2}{r^2}\right)$$

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Temperature $\Rightarrow (\hbar/c)$; ***Entropy*** $\Rightarrow L_P^2$

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

Thermodynamic variational principle

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

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Field equations arise from maximizing entropy/heat density of gravity plus matter on all null surfaces.

$$Q = \int d\mathcal{V} \ (\mathcal{H}_g + \mathcal{H}_m)$$

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

Gravity responds to heat density ($Ts = p + \rho$) — not energy density!

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Cosmological constant arises as an integration constant

Gravity responds to heat density ($Ts = p + \rho$) — not energy density!

Cosmological constant arises as an integration constant

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

Can we understand these results at a deeper level?

Can we get something new?

The Challenge

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$$Q = \int d\mathcal{V} \; (\mathcal{H}_g + \mathcal{H}_m)$$

We need to count the microscopic degrees of freedom without knowing the full QG!

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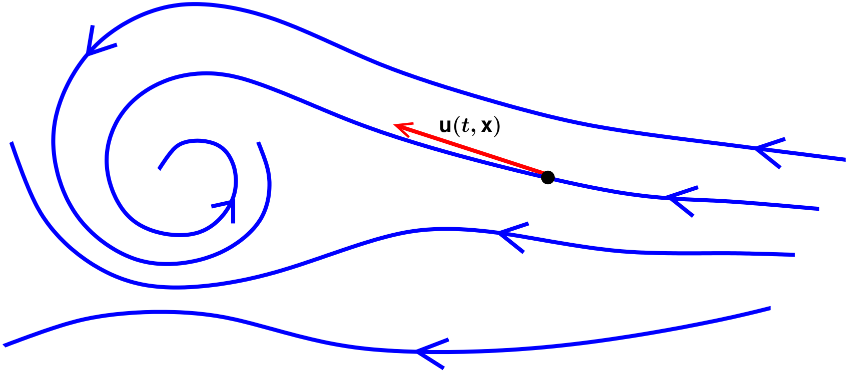
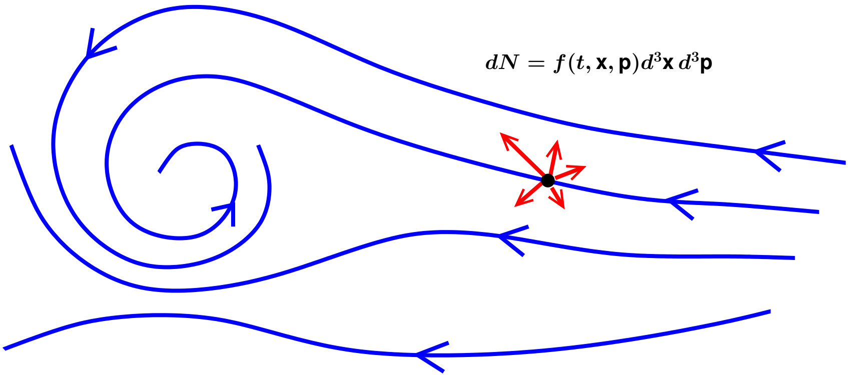
We need to recognize discreteness and yet use continuum mathematics!



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

Atoms Of A Fluid

Kinetic theory: Distribution function



Kinetic theory: Recognizes discreteness, yet uses continuum maths!

Several atoms with different p_i can exist at same x^i

Atoms Of A Fluid

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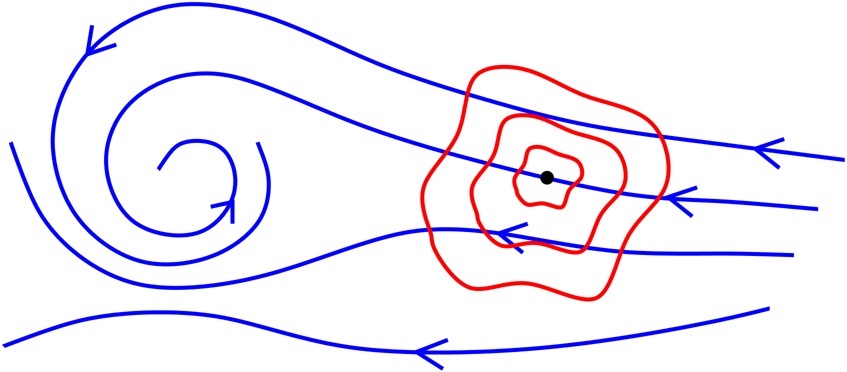

$f(x^i, p_i) =$ number of atoms "at" x^i, "with" momentum p_i; to be determined by a limiting process.

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

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You can determine it in a spacetime with zero-point length using equi-geodesic surfaces

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

$$\lim_{x' \to x} \frac{1}{2} \nabla_a \nabla_b \sigma^2 = g_{ab}$$

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:

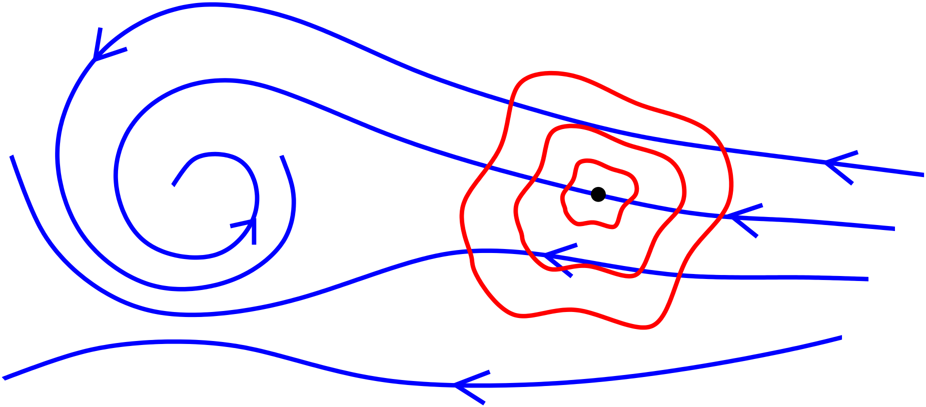
D. Kothawala, T.P. [arXiv:1405.4967]; [arXiv:1408.3963]

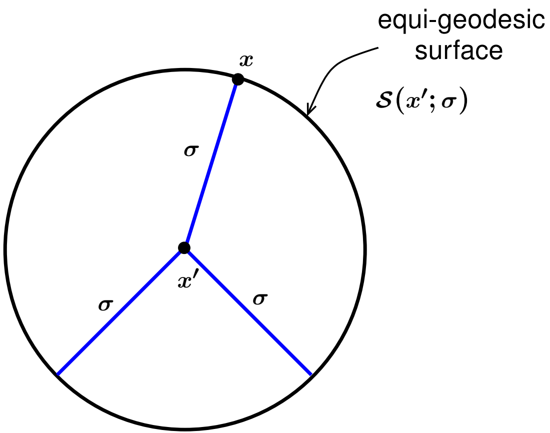
$$\begin{aligned} \sigma^2(x,x') &\rightarrow S(\sigma^2) = \sigma^2(x,x') + L_0^2 \\ g_{ab}(x) &\rightarrow q_{ab}(x,x';L_0^2) \end{aligned}$$

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

Atoms Of A Fluid

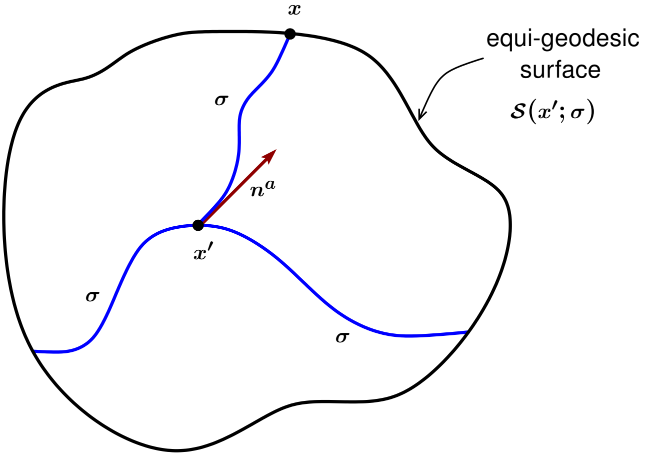
Kinetic theory: Distribution function





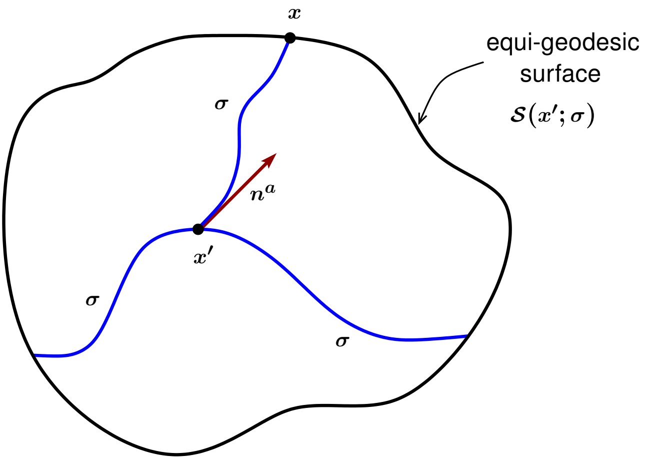
$$ds^2 = d\sigma^2 + \sigma^2 d\Omega^2_{(S3)}$$

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



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

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



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

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

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:

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

Atoms of Space

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

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

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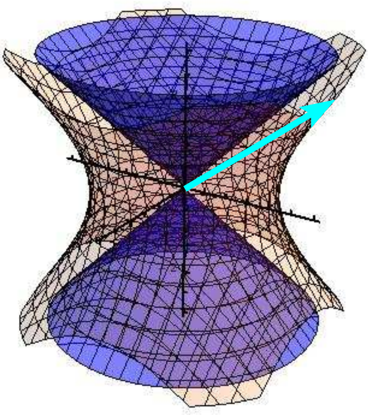
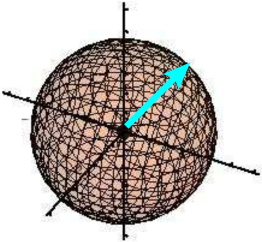
- ***Euclidean origin maps to local Rindler horizon. The $\sigma^2 \to 0$ limit picks the null vectors!***





Null horizon ⇔ Euclidean origin

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- ***Euclidean origin maps to local Rindler horizon. The $\sigma^2 \to 0$ limit picks the null vectors!***
- ***The variational principle leads to***

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

Quantum of Information

T.P, Chakraborty, Kothawala, [arXiv:1507.05669], T.P. [arXiv:1508.06286]

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

Quantum of Information

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

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]

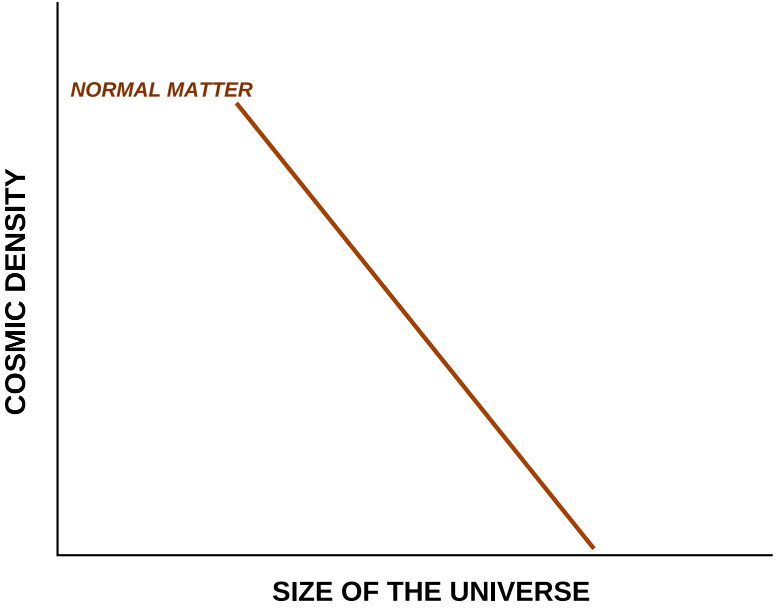
- ***Spacetime becomes two-dimensional close to Planck scales!***

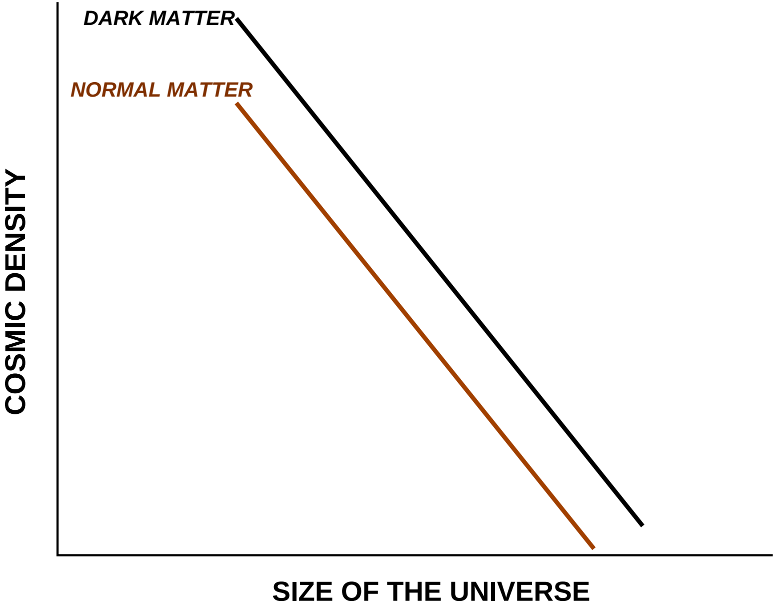
- ***Basic quantum of information to count spacetime degrees of freedom is***

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

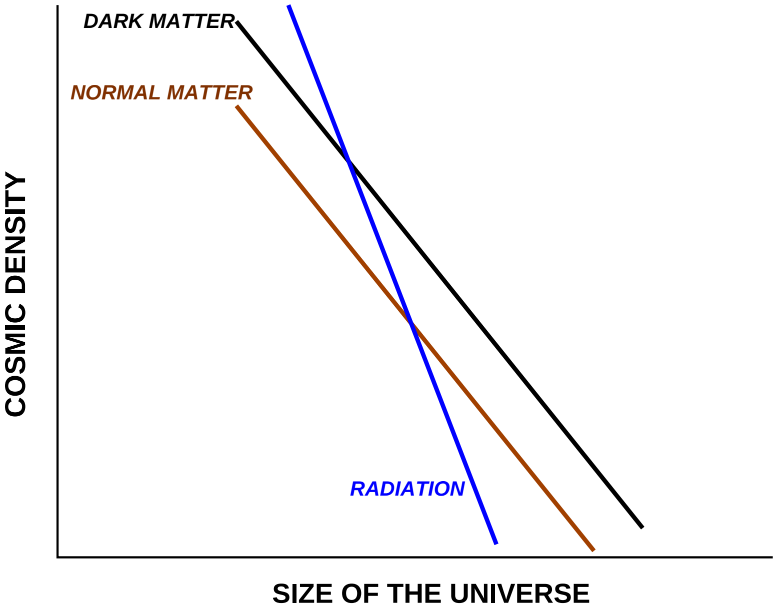
You should get more than what you put in!

Physics is all about numbers and making falsifiable predictions!

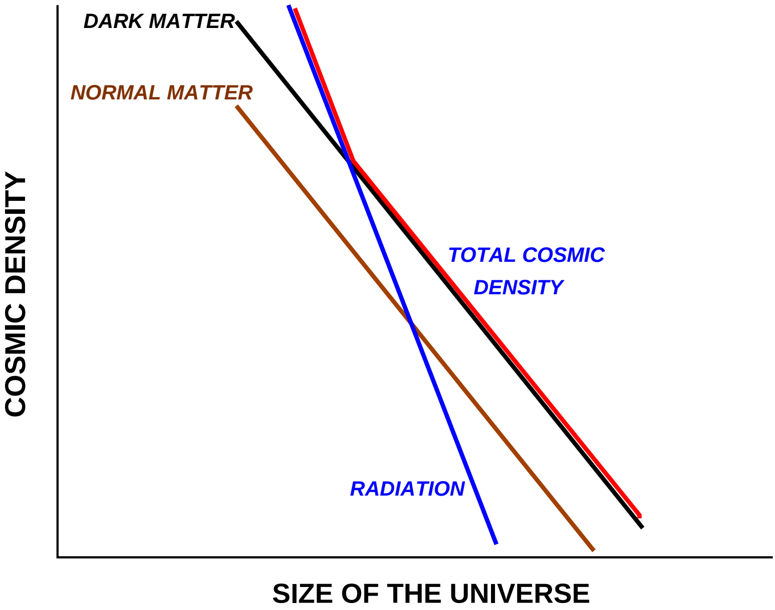

NORMAL MATTER
COSMIC DENSITY
SIZE OF THE UNIVERSE

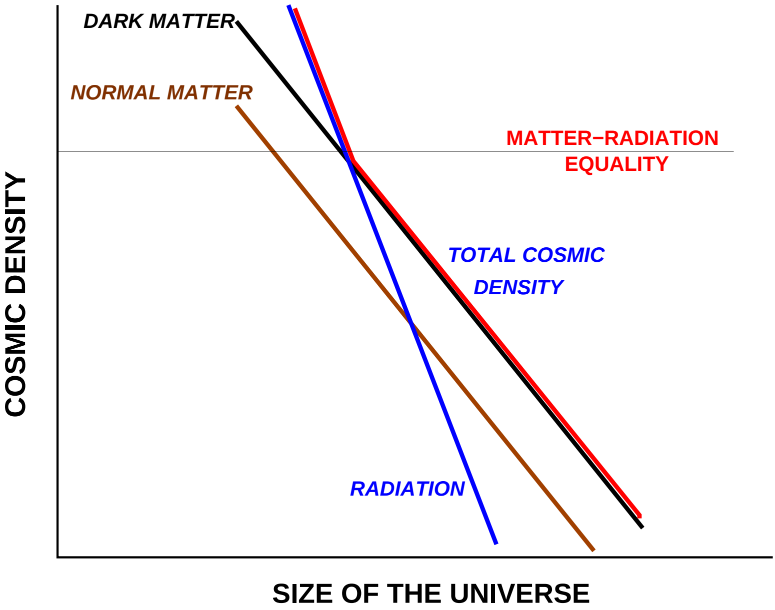

DARK MATTER
NORMAL MATTER
COSMIC DENSITY
SIZE OF THE UNIVERSE

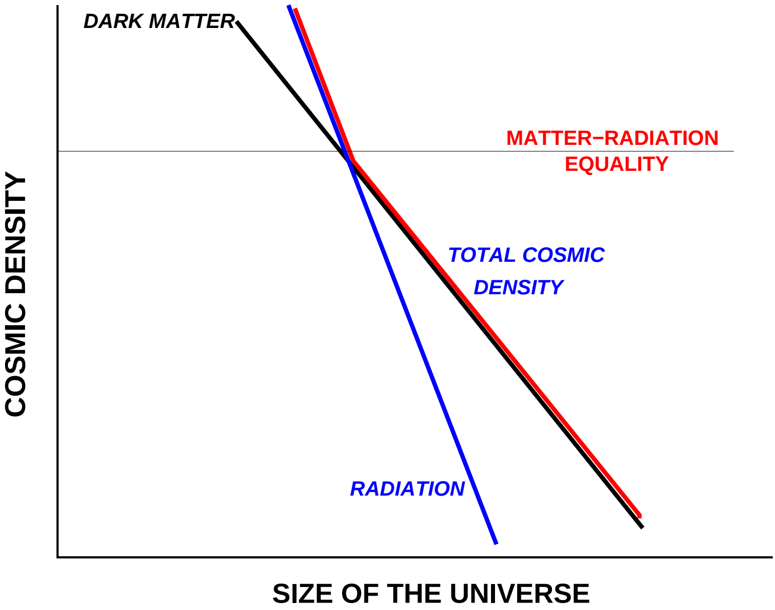
Our Strange Universe



Our Strange Universe




DARK MATTER
NORMAL MATTER
MATTER−RADIATION
EQUALITY
TOTAL COSMIC
DENSITY
RADIATION
COSMIC DENSITY
SIZE OF THE UNIVERSE


DARK MATTER
MATTER−RADIATION
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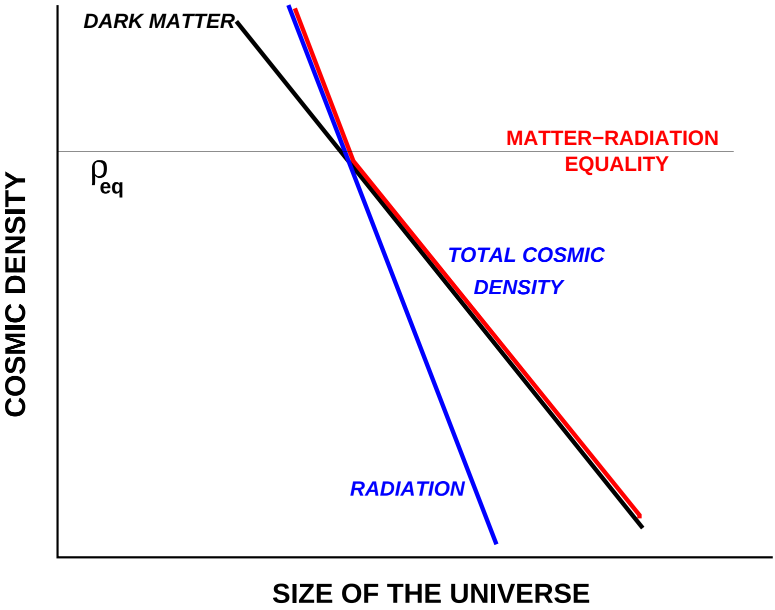
SIZE OF THE UNIVERSE


DARK MATTER
MATTER−RADIATION
EQUALITY
ρ_{eq}
TOTAL COSMIC
DENSITY
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COSMIC DENSITY
SIZE OF THE UNIVERSE

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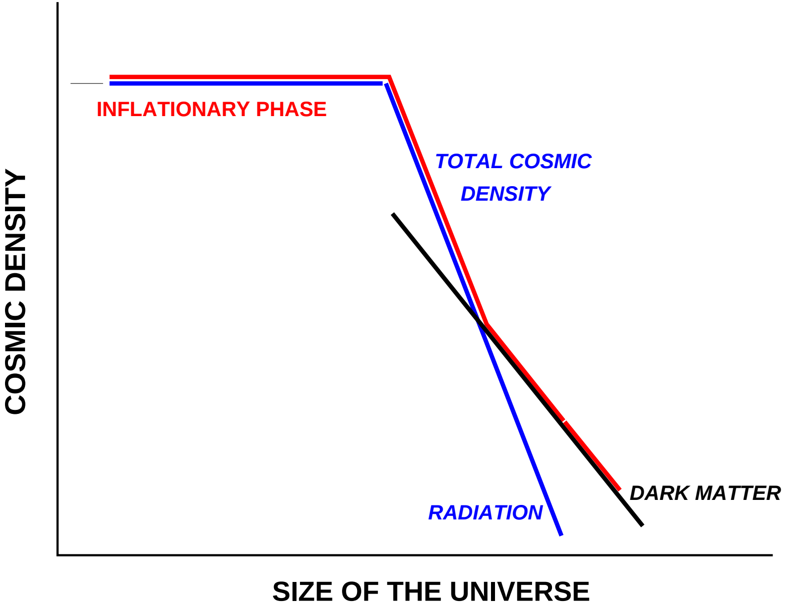

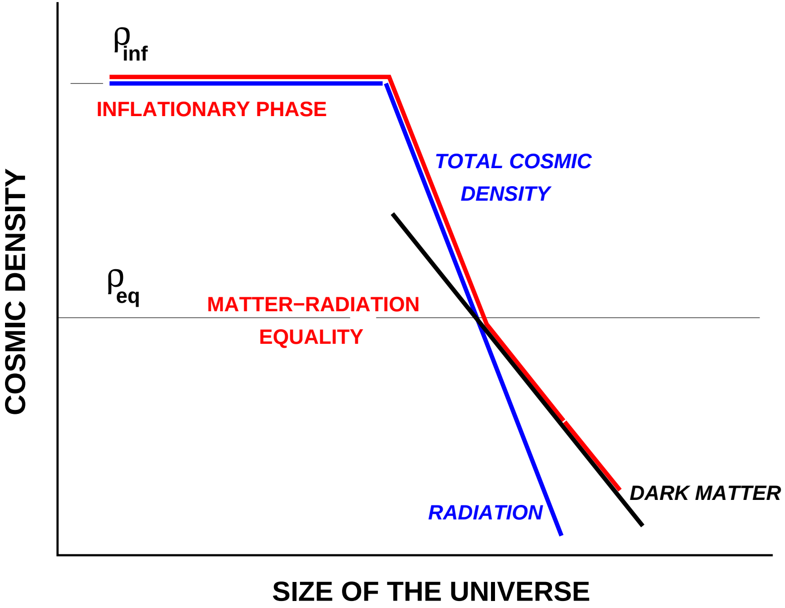

ρ_{inf}
INFLATIONARY PHASE
TOTAL COSMIC
DENSITY
COSMIC DENSITY
ρ_{eq}
MATTER−RADIATION
EQUALITY
DARK MATTER
RADIATION
SIZE OF THE UNIVERSE

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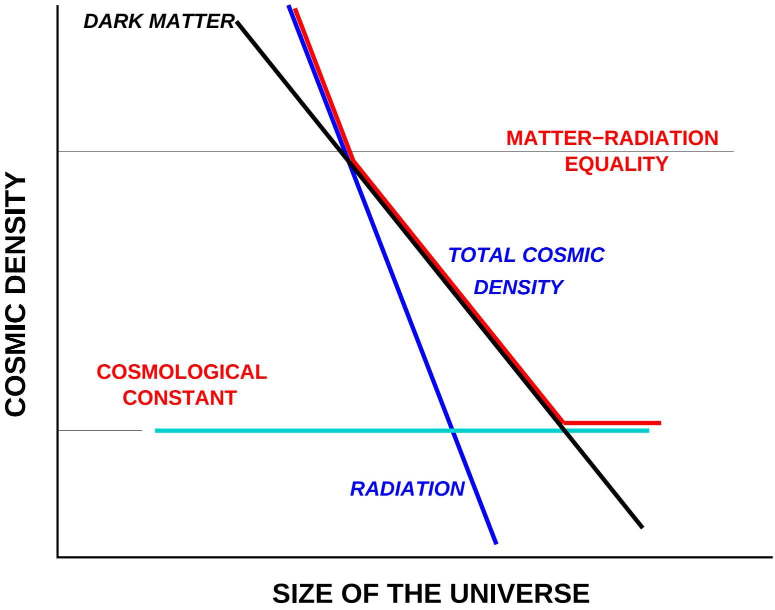

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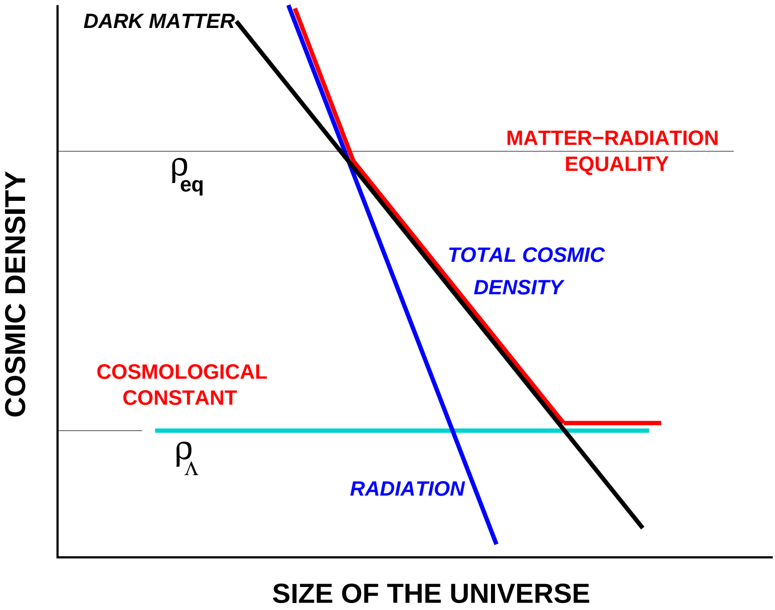

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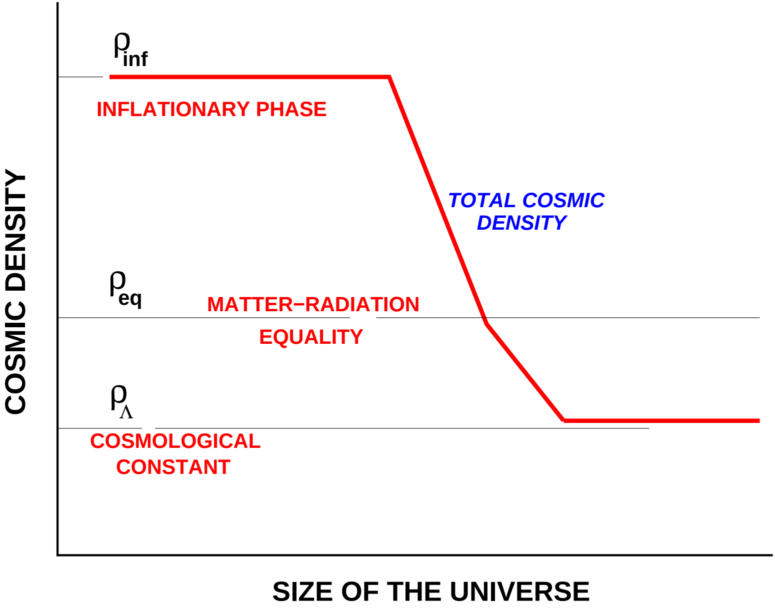

Three phases, three energy-density scales, with no relation to each other!

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$$\rho_{\rm inf} < (1.94 \times 10^{16}\ \mathsf{GeV})^4$$

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

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

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

- ***Compute the combination:***

$$I = \frac{1}{9\pi} \ln\left(\frac{4}{27}\frac{\rho_{\rm inf}^{3/2}}{\rho_\Lambda\, \rho_{\rm eq}^{1/2}}\right)$$

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$$I \approx 4\pi \left(1 \pm \mathcal{O}\left(10^{-3}\right)\right) = I_{QG}$$

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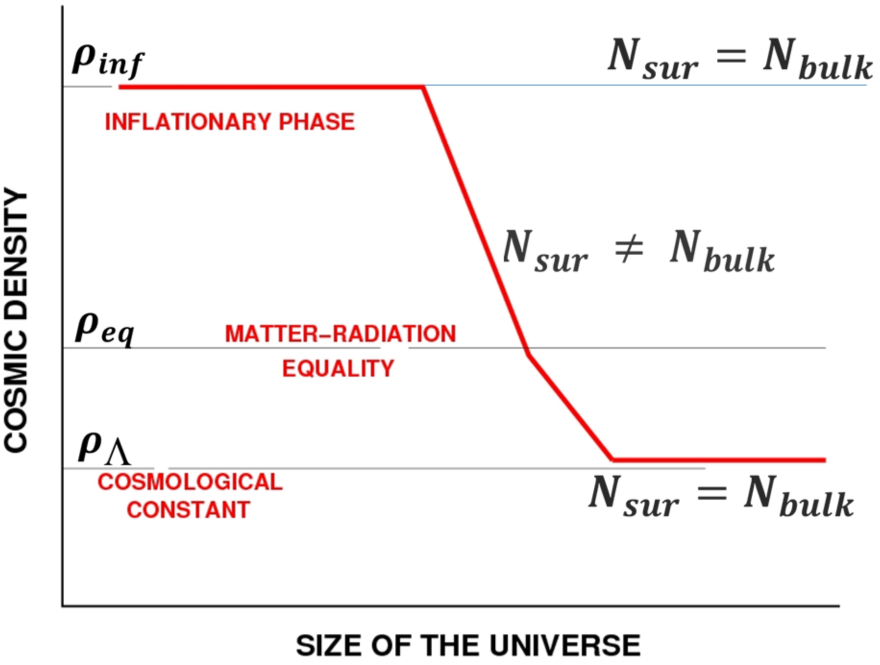
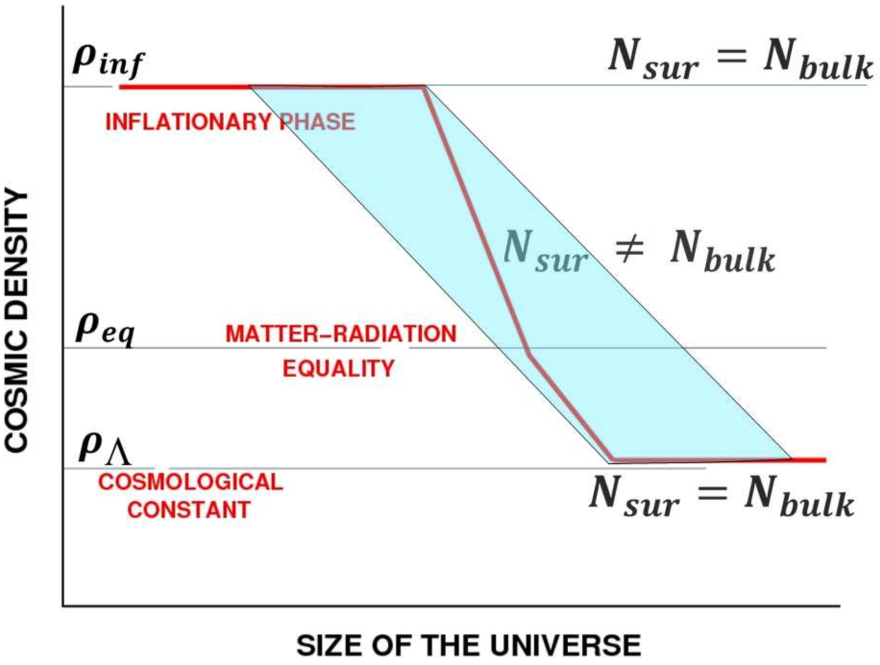
Why?



ρ_{inf}
$N_{sur} = N_{bulk}$
INFLATIONARY PHASE
$N_{sur} \neq N_{bulk}$
ρ_{eq}
MATTER–RADIATION EQUALITY
ρ_{Λ}
COSMOLOGICAL CONSTANT
$N_{sur} = N_{bulk}$
COSMIC DENSITY
SIZE OF THE UNIVERSE



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Accessibility of Cosmic Information

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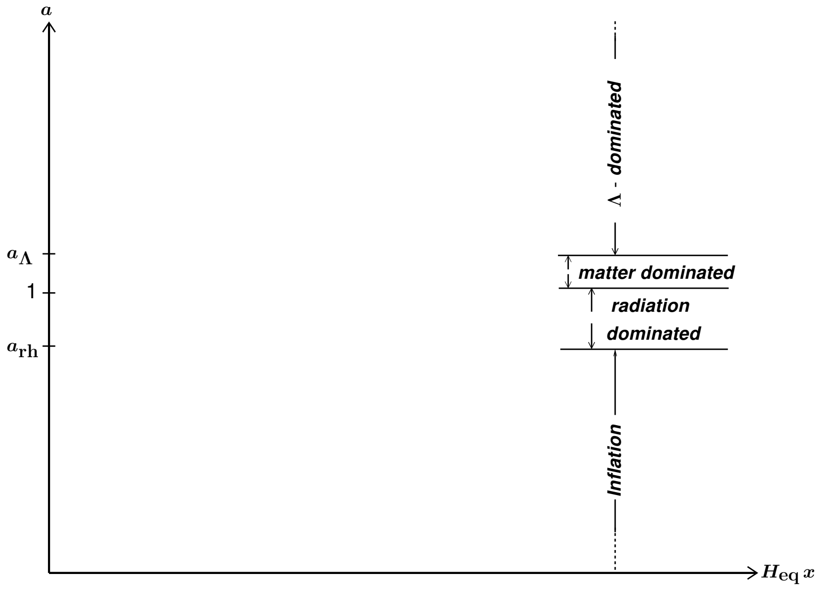
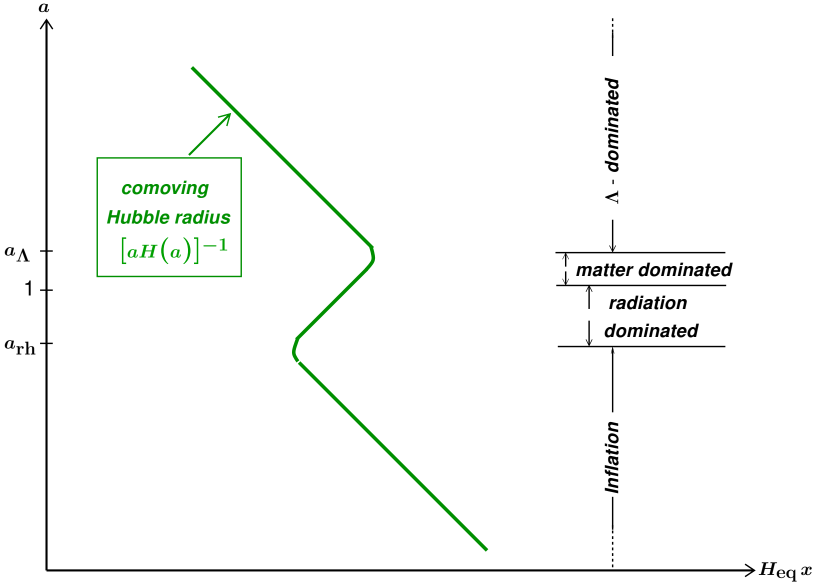
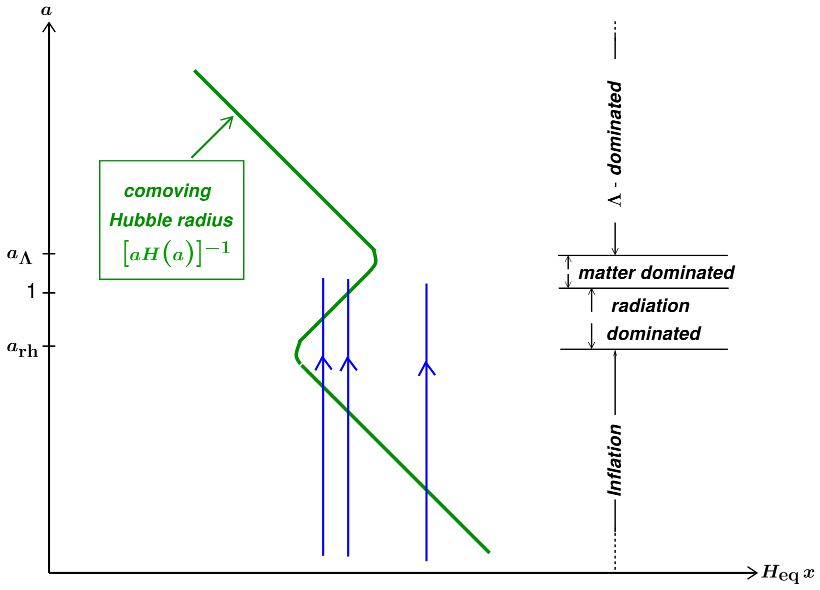
This is infinite if $\Lambda = 0$; finite if $\Lambda \neq 0$


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

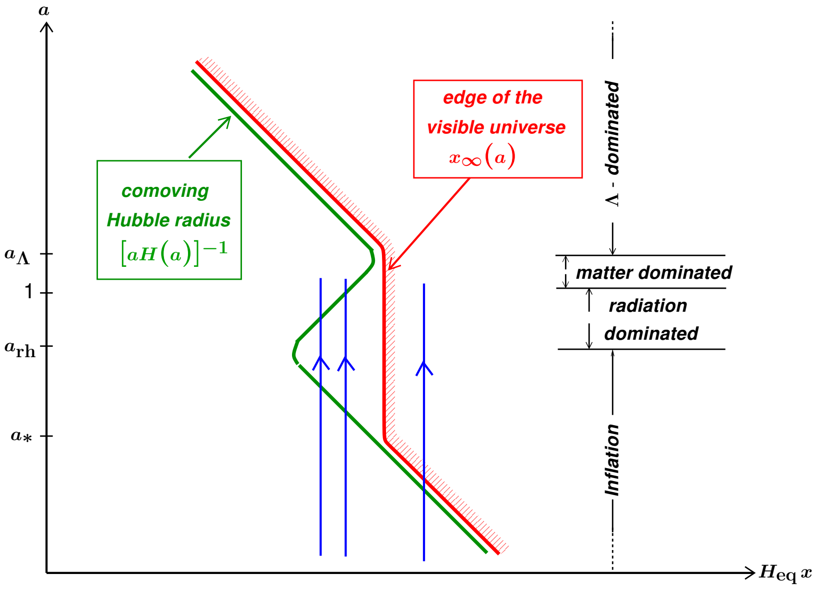
Cosmic Information: CosmIn



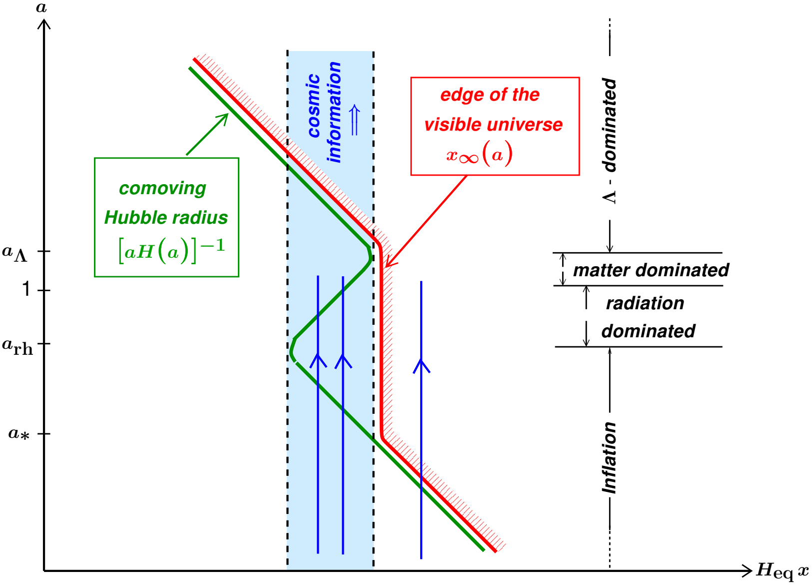


a
a_Λ
1
$a_{\rm rh}$
comoving
Hubble radius
$[aH(a)]^{-1}$
Λ - dominated
matter dominated
radiation
dominated
Inflation
$H_{\rm eq}\, x$

Cosmic Information: CosmIn



Cosmic Information: CosmIn



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*** .

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

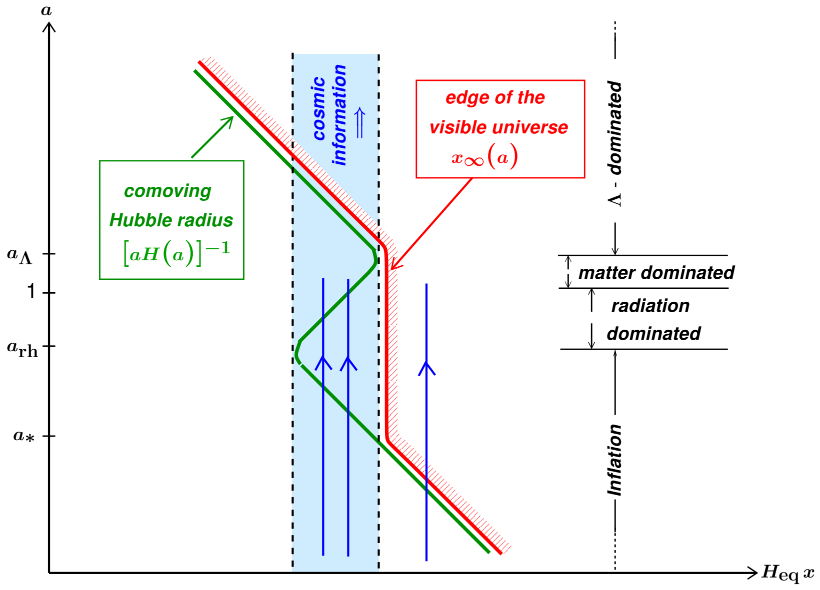
A measure of cosmic information accessible to eternal observer ('CosmIn')

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

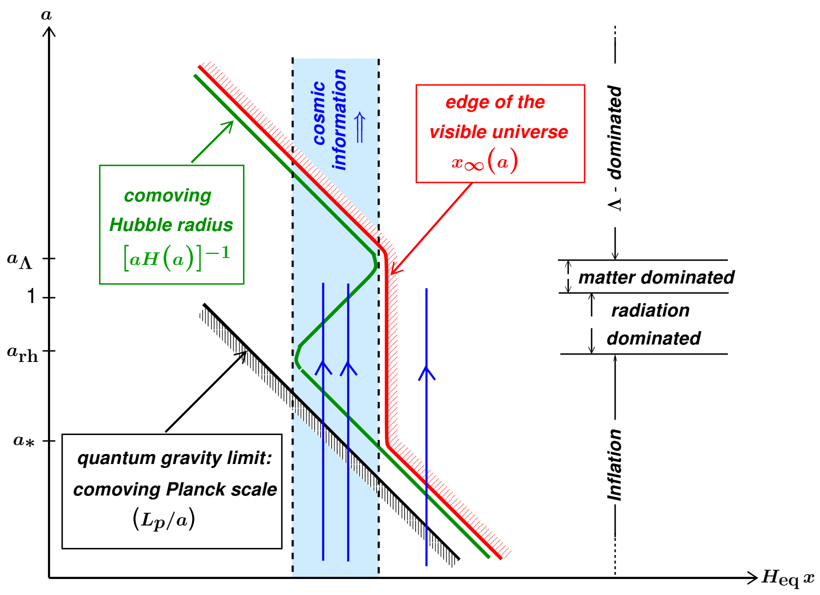
$$I_c = \frac{1}{9\pi}\,\ln\left(\frac{4}{27}\frac{\rho_{\rm inf}^{3/2}}{\rho_\Lambda\,\rho_{\rm eq}^{1/2}}\right)$$

$$\rho_\Lambda = \frac{4}{27}\,\frac{\rho_{\rm inf}^{3/2}}{\rho_{\rm eq}^{1/2}}\,\exp\left(-9\pi I_c\right)$$

Cosmic Information: CosmIn



Cosmic Information: CosmIn



$$\rho_\Lambda = \frac{4}{27} \frac{\rho_{\text{inf}}^{3/2}}{\rho_{\text{eq}}^{1/2}} \exp\left(-9\pi I_c\right)$$

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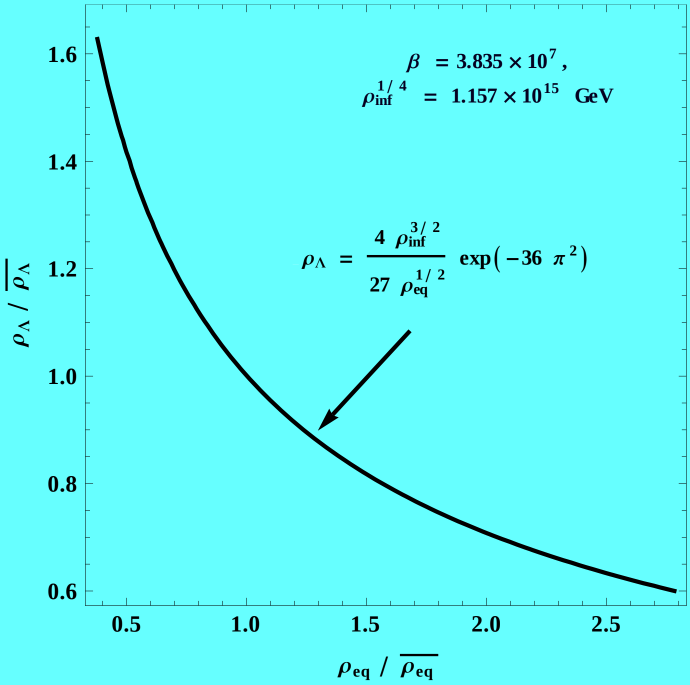
Using $I_c = I_{QG} = 4\pi$ ***gives the numerical value of*** ρ_Λ

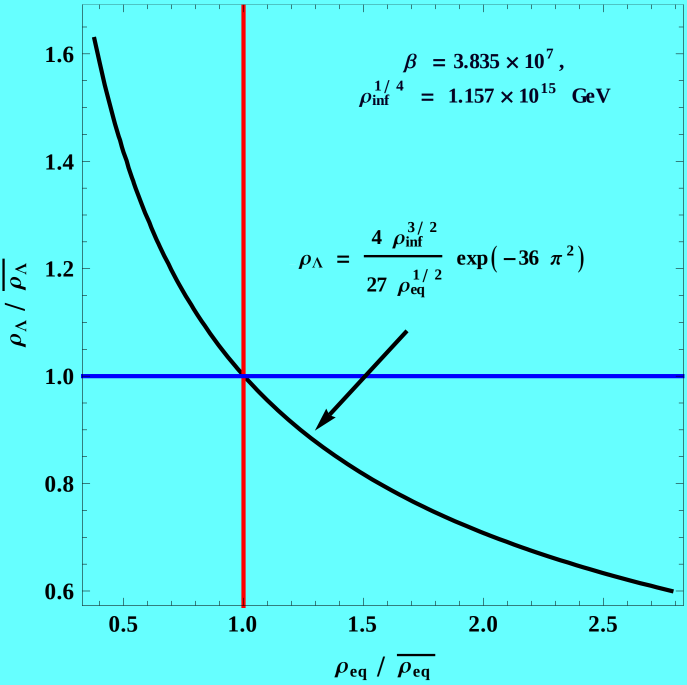
The Magical Relation!

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

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



β = 3.835 × 10^7 ,
ρ_inf^1/4 = 1.157 × 10^15 GeV
ρ_Λ = 4 ρ_inf^3/2 / 27 ρ_eq^1/2 exp(−36 π^2)
1.6
1.4
1.2
1.0
0.8
0.6
0.5
1.0
1.5
2.0
2.5
ρ_Λ / ρ̄_Λ
ρ_eq / ρ̄_eq



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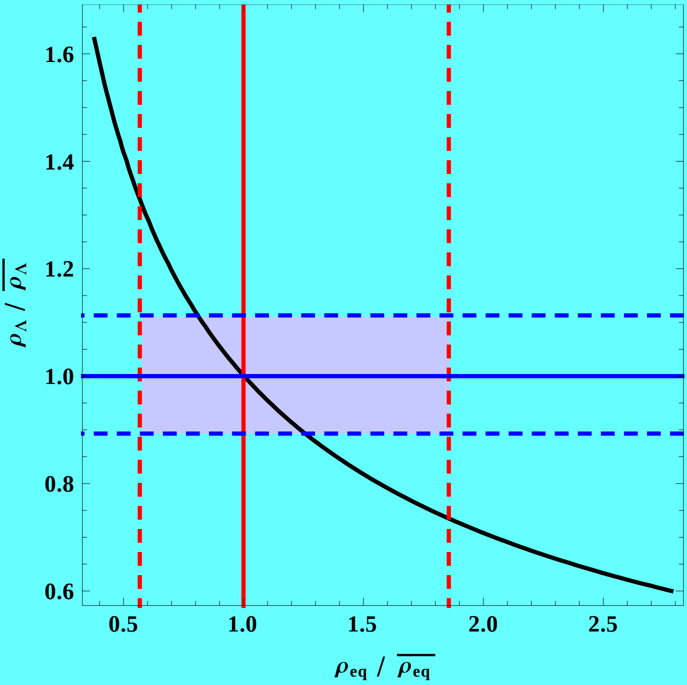
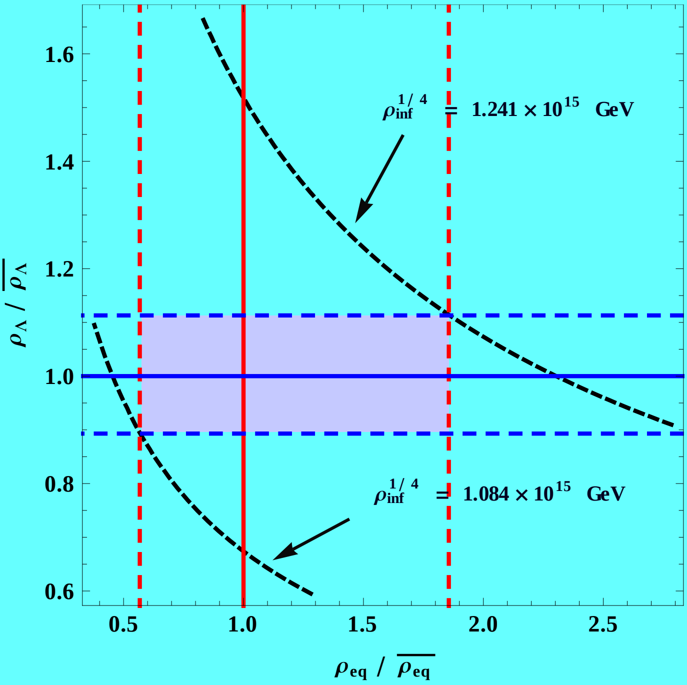
ρ_inf^(1/4) = 1.157 × 10^15 GeV
ρ_Λ = 4 ρ_inf^(3/2) / (27 ρ_eq^(1/2)) exp(−36 π^2)
1.6
1.4
1.2
1.0
0.8
0.6
0.5
1.0
1.5
2.0
2.5
ρ_Λ / ρ̄_Λ
ρ_eq / ρ̄_eq


1.6
1.4
1.2
1.0
0.8
0.6
0.5
1.0
1.5
2.0
2.5
$\rho_\Lambda / \overline{\rho_\Lambda}$
$\rho_{eq} / \overline{\rho_{eq}}$



$\rho_{inf}^{1/4}$ = 1.241 × 10^{15} GeV
$\rho_{inf}^{1/4}$ = 1.084 × 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
$\rho_\Lambda / \overline{\rho_\Lambda}$
$\rho_{eq} / \overline{\rho_{eq}}$

- ***Large scale universe defines a Lorentz frame***
- ***The universe made a spontaneous quantum to classical transition***
- ***Cosmic evolution is towards holographic equipartition***

We should not describe the cosmos as a particular solution to gravitational field equations.

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

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

$$\rho V_H = TS$$

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

$$\rho V_H = TS + \cdots$$

Summary

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- ***Gravitational dynamics arises from a thermodynamic variational principle principle. Its form can be related to the kinetic theory of atoms of space.***

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Summary

- ***Gravitational dynamics arises from a thermodynamic variational principle principle. Its form can be related to the kinetic theory of atoms of space.***
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- ***The evolution equation has a purely thermodynamic interpretation related to the information content of the spacetime.***
- ***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].

***Review:* T.P**, *Do we really understand the cosmos?*, (2016) [arXiv:1611.03505].

Acknowledgements

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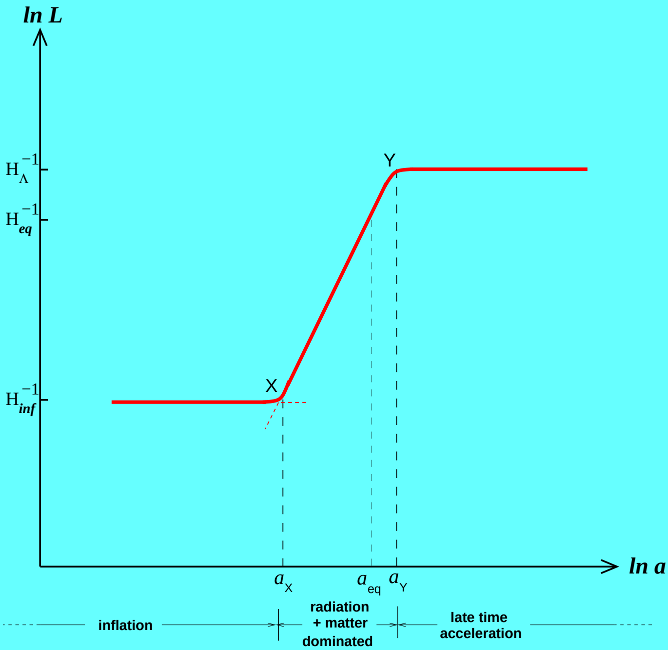
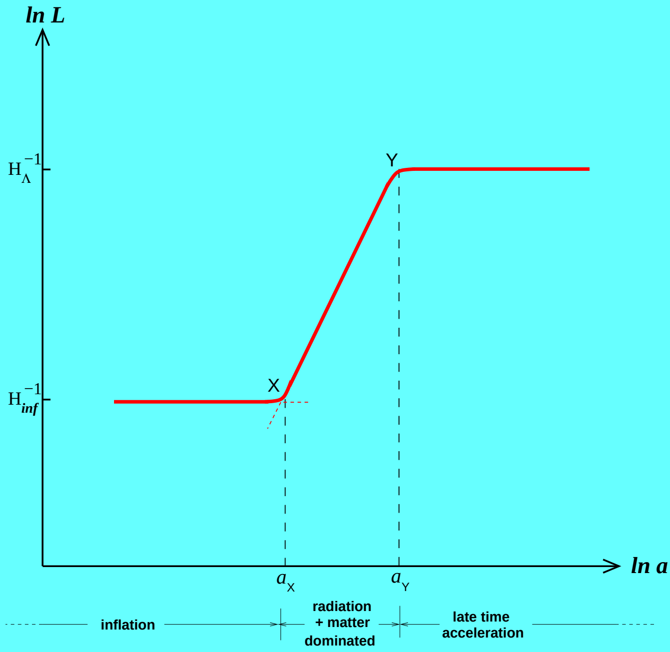
Dawood Kothawala	Sumanta Chakraborty	Hamsa Padmanabhan
Bibhas Majhi	James Bjorken	Donald Lynden-Bell

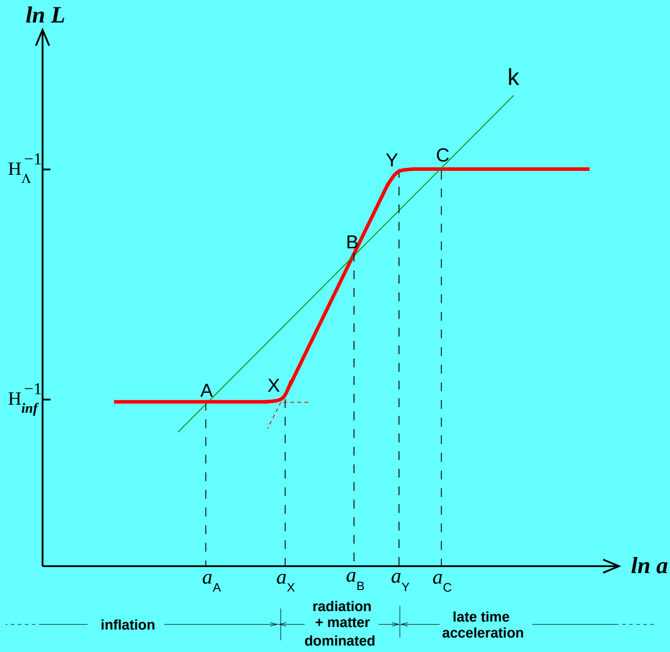
THANK YOU FOR YOUR TIME!



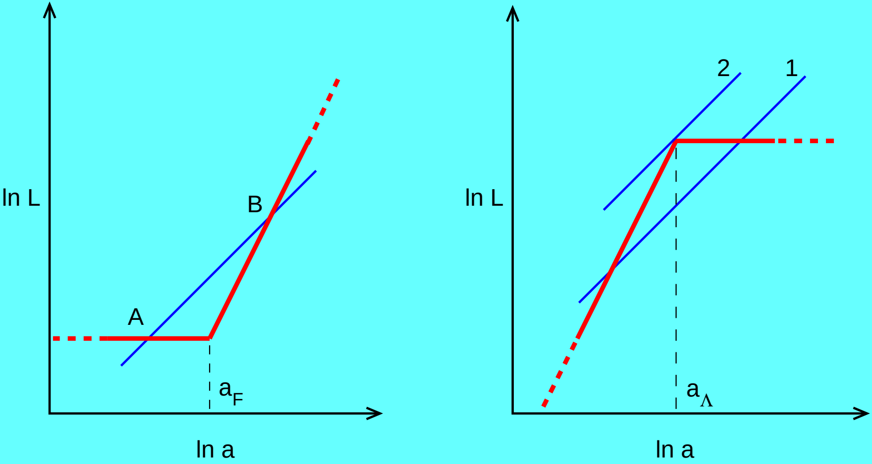
ln L
H_Λ^{-1}
H_{eq}^{-1}
H_{inf}^{-1}
X
Y
ln a
a_X
a_{eq}
a_Y
inflation
radiation
+ matter
dominated
late time
acceleration

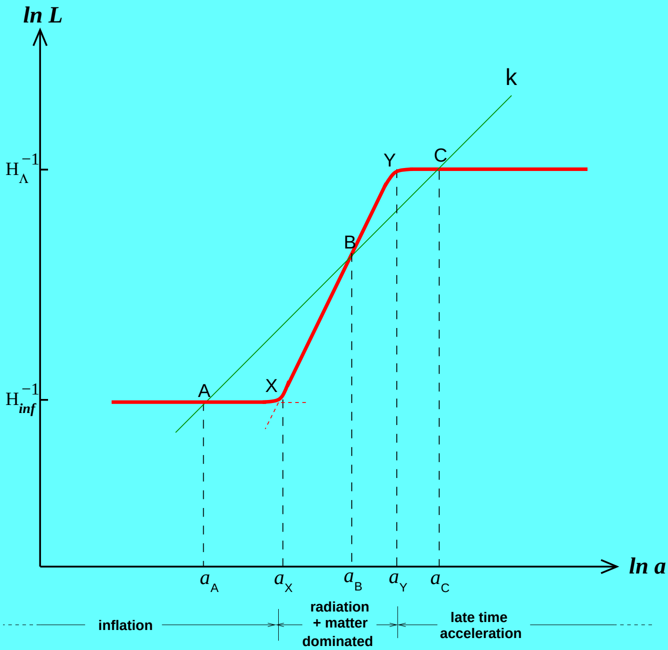


ln L
ln a
H_Λ^{-1}
H_{inf}^{-1}
X
Y
a_X
a_Y
inflation
radiation
+ matter
dominated
late time
acceleration



ln L
ln a
k
H_Λ^{-1}
H_{inf}^{-1}
A
X
B
Y
C
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
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
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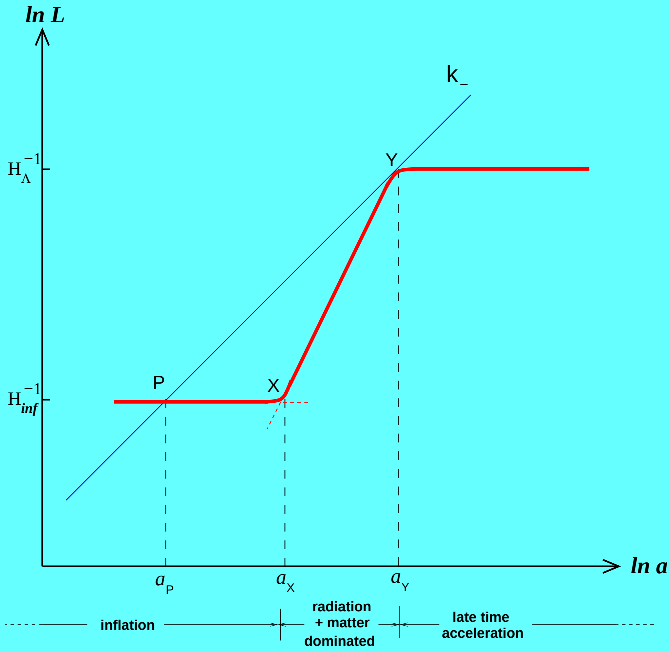
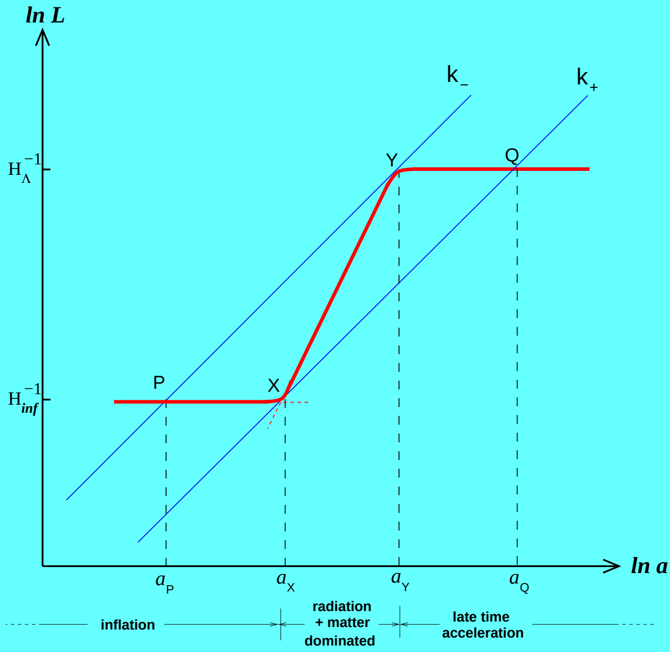


ln L
k_
Y
H_Λ^{-1}
P
X
H_{inf}^{-1}
ln a
a_P
a_X
a_Y
inflation
radiation + matter dominated
late time acceleration



ln L
k_
k+
Y
Q
H_Λ^−1
P
X
H_inf^−1
ln a
a_P
a_X
a_Y
a_Q
inflation
radiation
+ matter
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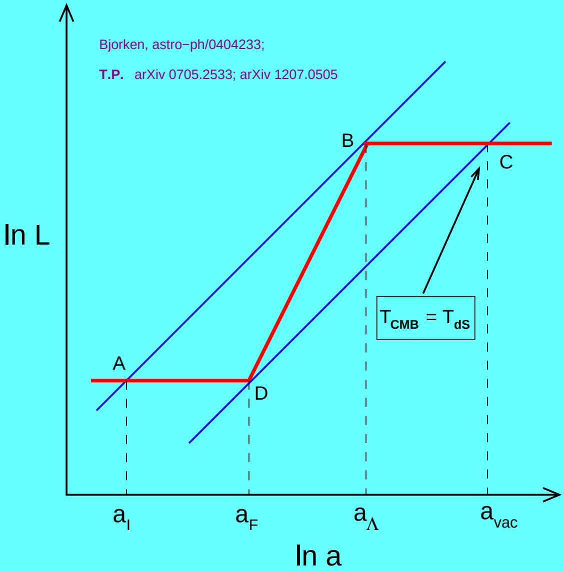
COSMIC PARALLELOGRAM



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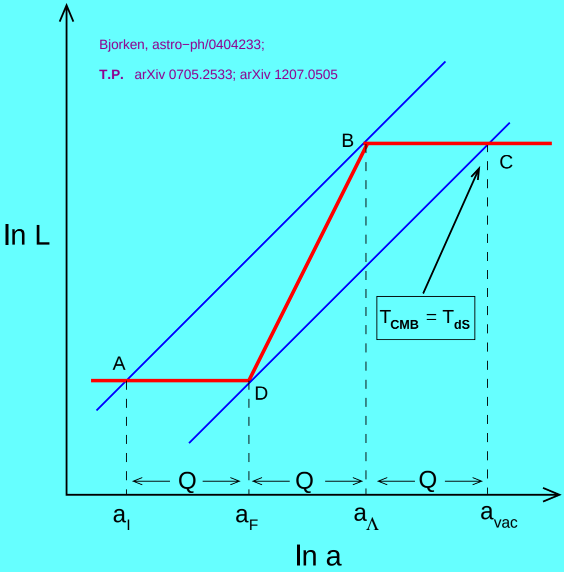

Key Open Question

Possibility for Matter Sector

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?

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$$\langle n^a n^b \rangle \approx (4\pi/\mu L_P^2) R_{ab}^{-1}$$

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

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!

NEWTONIAN EXAMPLE

Gauss Law Holography

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

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

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

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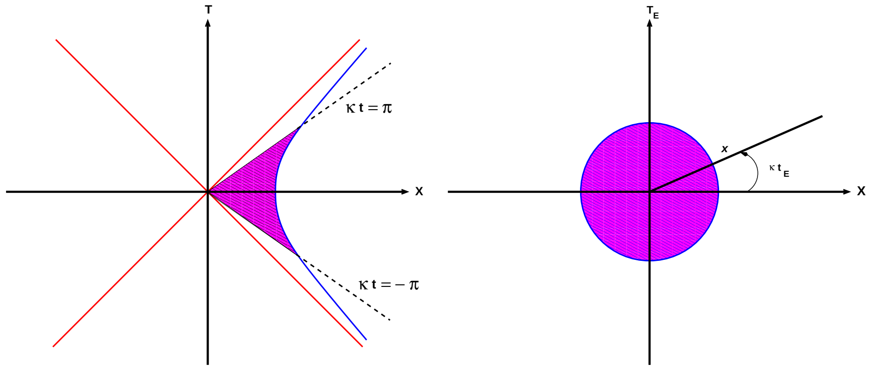
- **Note: Null horizon $\Leftrightarrow$ Euclidean origin**

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



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

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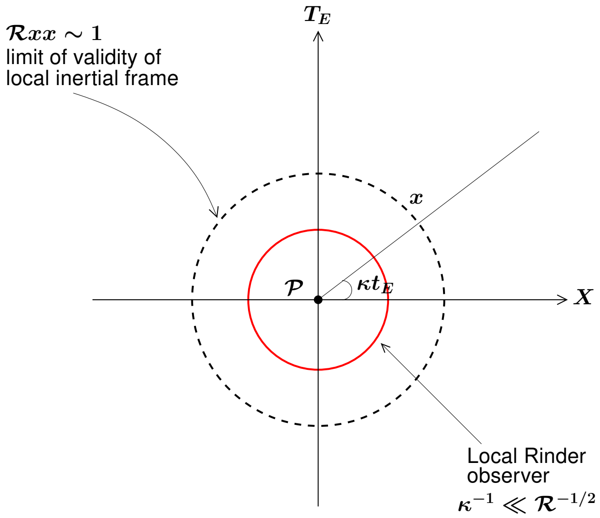
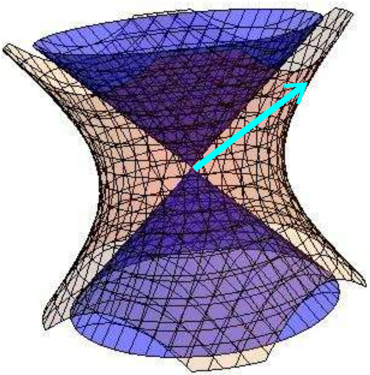
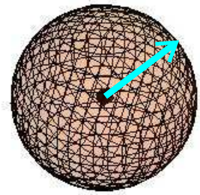


T_E
$\mathcal{R}xx \sim 1$
limit of validity of
local inertial frame
x
$\mathcal{P}$
κt_E
X
Local Rinder
observer
$\kappa^{-1} \ll \mathcal{R}^{-1/2}$

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

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Degrees of Freedom

$$\begin{aligned} \Omega_{\rm tot} &= \prod_{\phi_A} \prod_{x} \rho_g(\mathcal{G}_N, \phi_A)\, \rho_m(T_{ab}, \phi_A) \\ &\equiv \prod_{n_a} \exp \sum_{x} (\ln \rho_g + \ln \rho_m) \end{aligned}$$

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$$\begin{aligned}\ln \rho_m &\equiv L_P^4 \mathcal{H}_m = L_P^4 T_{ab} \ell^a \ell^b \\ \ln \rho_g &\equiv L_P^4 \mathcal{H}_g \approx -\frac{L_P^2}{8\pi} R_{ab} \ell^a \ell^b\end{aligned}$$

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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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$$\equiv \prod_{\ell_a} \exp \int d\mathcal{V}\, (\mathcal{H}_g(\mathcal{G}_N, \ell_a) + \mathcal{H}_m(T_{ab}, \ell_a))$$

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

Thermodynamic variational principle

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

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

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

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$$P^{ab}_{cd} \propto \delta^{aba_2b_2\ldots a_m b_m}_{cdc_2d_2\ldots c_m d_m} R^{c_2d_2}_{a_2b_2} \ldots R^{c_m d_m}_{a_m b_m}$$

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

[Iyer and Wald (1994)]

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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:*

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