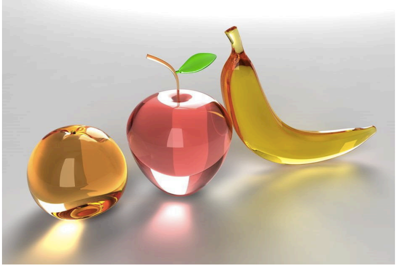
Flavours of Spacetime



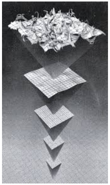
Dionysios Anninos, King's College London

Cumberland Lodge Retreat, February 19th, 2022

Limits of Spacetime

Isolated regions: featureless & smooth

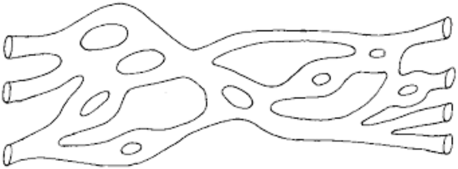
In extreme environments, general relativity breaks down



e.g. big bang/early universe, horizons/singularities, (perhaps) even the deep IR

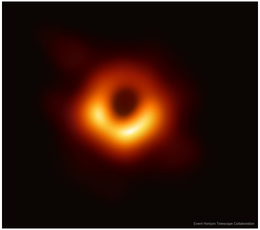
Here, our theory of spacetime requires a completion

There is a sense in which spacetime comes in many flavours. They are related to spatial or temporal asymptotia, the presence of horizons, various topologies...

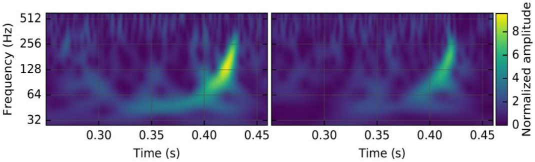


Our goal will be to discuss some of the flavours nature seems to enjoy

Black Hole Horizons



Observed in nature, recent exciting observations include LIGO and EHT



LIGO (2016)

There are possibly hundreds of milllions of black holes in a galaxy like our own.

Black Hole Thermodynamics

- Exhibit interesting features reminiscent of thermodynamics
  ...-Bardeen,Carter,Hawking-Penrose-Christodoulou-...

$$\boxed{\delta M = T\delta S + \Omega \delta J} \qquad S = \frac{c^3 A_{horizon}}{4G\hbar} = \frac{A_{horizon}}{4\ell_{Pl}} = \text{entropy} \ .$$

- Black hole horizons have a Hawking temperature $\boxed{T = \frac{1}{4\pi}\frac{\sqrt{M^4 - J^2}}{M^3 + M\sqrt{M^4 - J^2}}}$

- Exhibit interesting features reminiscent of hydrodynamics
  ...-Thone,Price,Macdonald-Damour-...

This is a measure of macroscopically indistinguishable arrangements.

For example:

$$S_{\text{photon}} \approx 10^{20}\, V\, \mathrm{m}^{-3}$$

for a box of volume V full of photons at temperature $T \approx T_{\text{Sun}}$.

A glass of water at room temperature has $S_{\text{water}} \approx 100 \times 10^{23}$.

- With enough angular momentum at the horizon $T \to 0$. This may (almost) happen for some astrophysical black holes.

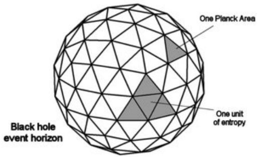
- Near horizon geometry has emergent 'conformal' $SL(2,\mathbb{R})$ symmetries. It is known as a (two-dimensional) anti-de Sitter space:

$$\boxed{ds^2 = -dt^2 \sinh^2 \rho + d\rho^2}$$

This is a Lorentzian version of the Poincaré disk!

Some questions

- Quantum information content of a black hole?

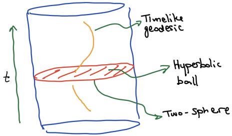


One supermassive black hole can have up to $S \sim 10^{100}$. This is more than the entropy carried by all the photons in the visible universe.

- New puzzles regarding quantum mechanics and spacetime

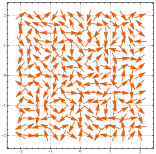
- AdS/CFT: It has been extremely useful to put the black hole in a 'test tube' universe with a large gravitational well. Ask questions via observables at the tube wall, where the effects dynamical geometry can be neglected.

  ...-Maldacena-...



- A new set of tools have recently been added: random disorder averaging.

  ...-Sachdev,Ye-...-Kitaev-...



Cosmological Event Horizons

G299 Type Ia supernova, NASA

De Sitter's Static Universe

- Observations of supernovae, as well as from the CMB, suggest that we are in a cosmological era dominated by positive vacuum energy $\rho_\Lambda \approx 6 \times 10^{-27}\,\mathrm{kg\,m^{-3}}$.

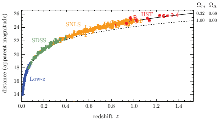


Figure 1.7: *Type IA supernovae and the discovery dark energy. If we assume a flat universe, then the supernovae clearly appear fainter (or more distant) than predicted in a matter-only universe ($\Omega_m = 1.0$). (SDSS = Sloan Digital Sky Survey; SNLS = SuperNova Legacy Survey; HST = Hubble Space Telescope.)*

- Eventually, our observable geometry will evolve into de Sitter's static universe:

$$\frac{ds^2}{\ell^2} = -\cos^2 r\, dt^2 + dr^2 + \sin^2 r\, d\Omega^2$$

- There is a cosmological event horizon of size $\ell \sim 20$ billion light years.

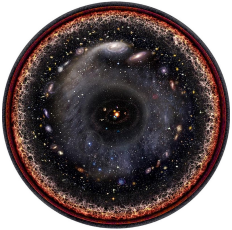
A Cosmic Question

- Conjectural entropy of cosmological horizon:

...-Gibbons-Hawking-...

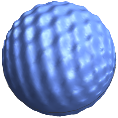
$$\boxed{S_{\mathrm{dS}} = \frac{A_{\mathrm{horizon}}}{4G} = \frac{\pi \ell^2 c^3}{\hbar G}}$$

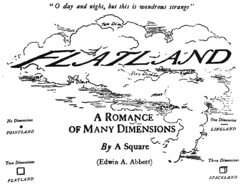
$S_{\mathrm{dS}} \sim 10^{120}$ for our universe.



Physical implications of this large number?

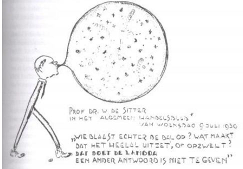
- Remarkable connection between the cosmological horizon entropy and the theory of fluctuating geometries on compact manifolds, the sphere being the simplest.





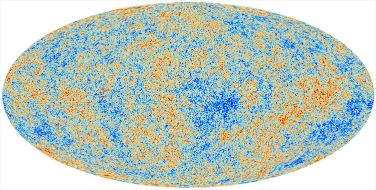
- Precise results in two and three spacetime dimensions. What about four...

Big Bang Spacetimes



The quote is translated by van der Laan as: "What, however, blows up the ball? What makes the universe expand or swell up? That is done by the Lambda. Another answer cannot be given."

- Scale invariant spectrum of density perturbations in the sky



Planck collaboration (2013)

- Inflationary Hypothesis
  ...-Guth-Linde-Albrecht,Steinhardt-...

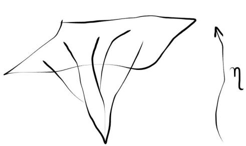
$$ds^2 = -dT^2 + e^{2T/\ell_{\text{inflation}}} d\mathbf{x}^2 \ , \qquad T \in \mathbb{R}$$

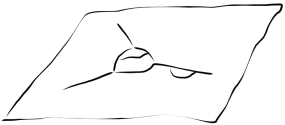
Late-time fluctuations governed by conformal $SO(4,1)$ symmetries.

$$\mathbf{x} \to \lambda \mathbf{x} \ , \quad \mathbf{x} \to M \cdot \mathbf{x} + \mathbf{a} \ , \quad \mathbf{x} \to \frac{\mathbf{x} + \mathbf{b} x^2}{1 + 2\mathbf{b} \cdot \mathbf{x} + b^2 x^2}$$

Some questions

- Active attempts to recast cosmic history onto a constant time slice.





$f(\mathbf{k}_i) = \int \frac{d\eta}{\eta^4} \prod_i G(\mathbf{k}_i, \eta)$

$f(\mathbf{k}_i) = \langle \prod_i \mathcal{O}(\mathbf{k}_i) \rangle_{CFT}$

- Continuous production of new degrees of space as time evolves – unitarity?

- Superstring theory has proven extremely difficult to employ to study the early universe...

- Perhaps other types mathematical toy models with exotic symmetries and particle spectra may help model expanding spacetimes. The quest remains an important open avenue.

Outlook

Spacetime as a large $\mathcal{N}$ limit?

Large entropies we encountered are not explained by conventional physics.
Composition of spacetime at the fundamental level?

Perhaps general relativity emerges in limiting sense from large $\mathcal{N}$ constituents

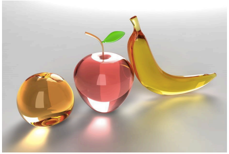
...-Sakharov-...-Bekenstein-Hawking-...-'t Hooft-...-Jacobson-...-Maldacena-...

Analogy: Navier-Stokes equations emerging from large $\mathcal{N}$ (e.g. 6×10^{23}) molecules

this would suggest geometry is not a microscopic quantum operator

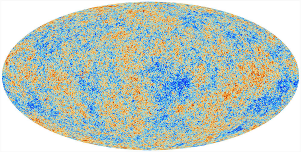
Ingredients?

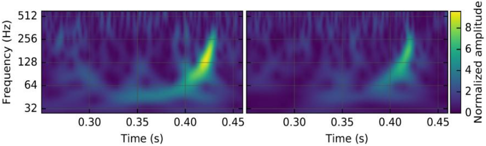
- Nature has presented us with a diverse collection of spacetime flavours.
- The observations I referred to are all remarkably recent. The flavours are surprising and intriguing.

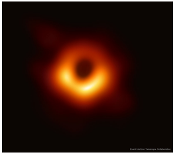


- Insights from string theory, such as the idea that spacetime may be a collective, emergent phenomenon of an underlying large N 'atomic' theory, may well apply.
- Our task is to understand the ingredients behind these remarkable flavors.

We have our work cut out for us!







LIGO (2016)

Thank you