I am happy and honored to be present at this distinguished conference.

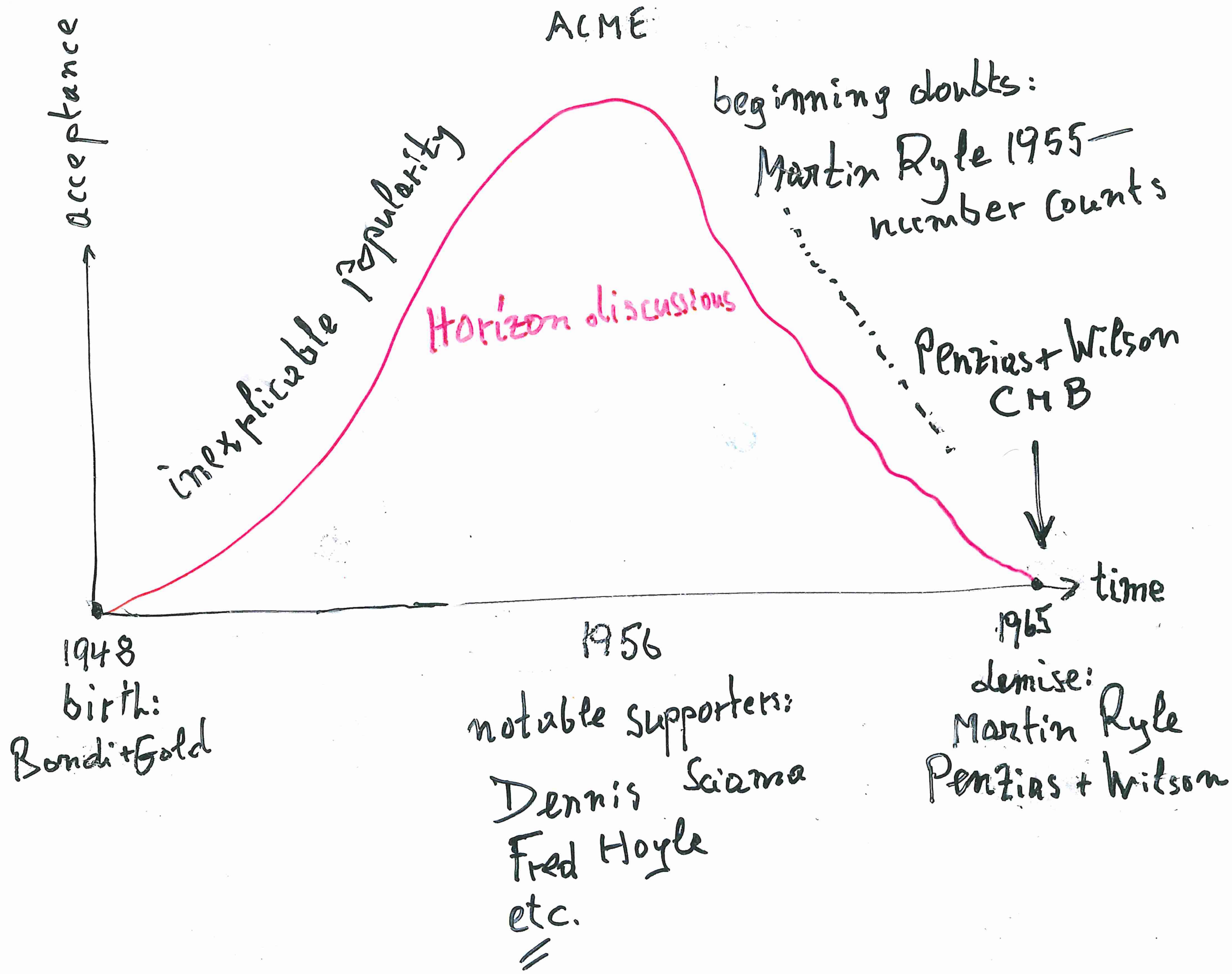
I'll start by talking about the steady state theory (SST) because that is where the modern interest in horizons came from. The SST of cosmology was invented by Hermann Bondi and Thomas Gold in 1948 and flourished for about 20 years. It asserts that the universe expands exponentially, with new matter being created continuously to keep the average density constant. This universe has no beginning and no end. The mystery of the Big Bang is replaced by the mystery of continuous creation -- at the cost of stepping outside of General Relativity.

Quickly and inexplicably a majority of cosmologists adhered to the SST – and some quite emotionally. Dennis Sciama later wrote "The day when I had to give up the Steady Theory was the saddest of my life." And Fred Hoyle, in spite of all the evidence against it, never let go of the SST until he died. (A little like Lorentz hanging on to the ether.)

The SST shares its kinematics with the de Sitter Universe. So it has a horizon, which many people understood perfectly, but which troubled others. Already in the mid-1920s Eddington very aptly compared the de Sitter (event-) horizon to the winning post on an ever expanding track, which the runners (photons) try to reach in vein. But this insight was largely forgotten.

FIRST TRANSPARENCY.

THE LIFE OF SST



OBSERVATORY (RAS)

1953, No. 876

July 18 G. J. WHITROW

"A query concerning the Steady State Theory"
(An apparent paradox concerning the horizon)

1954, No. 878, p. 36

H. Bondi and T. Gold

Final paragraph:

"We do not know what hurricanes will be directed against our cosmological edifice; but we are a little aggrieved to think that it is being credited with so little structural strength that Dr Whitrow's puff could make it shudder."

Now, I happened to be Gerald Whitrow's PhD student at Imperial College, London, at the time. He showed me Bondi and Gold's embarrassing letter (surely the last paragraph smacks more of Tommy Gold than of the gentler Hermann Bondi!), and said Rindler, what shall we do? It was my lucky day. In their letter Bondi and Gold actually suggested that someone take up the study of horizons in full generality. So I finished off the problems in Milne's fast fading "Kinematic Relativity Theory" that Whitrow had suggested -- he had been a student of Milne's – and happily devoted the last chapter of my thesis to horizons, always anxiously looking over my shoulder to see if I was being scooped.

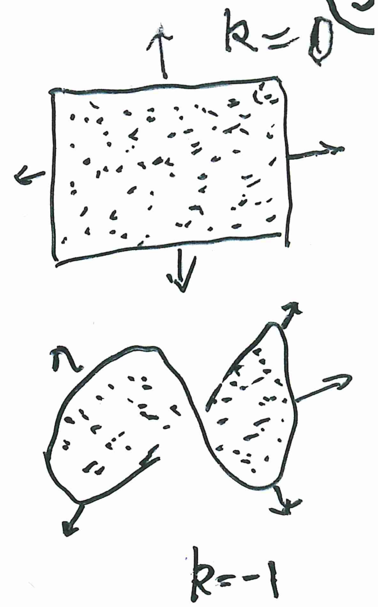
Two of the things I did not know at the time were:

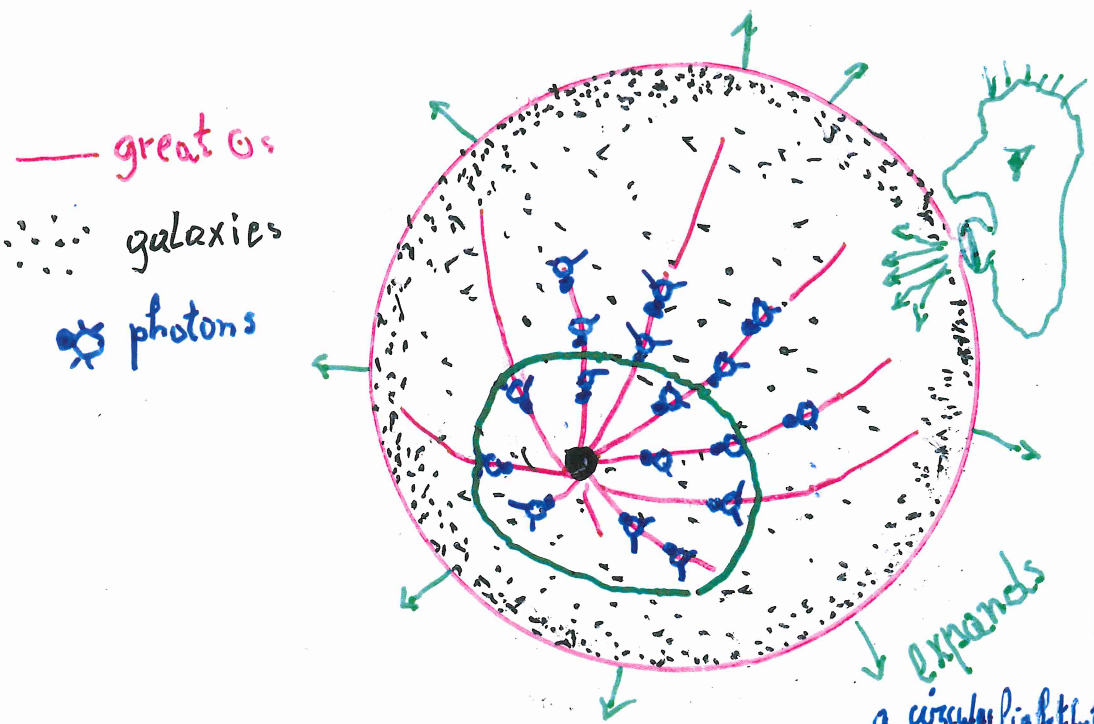
(1) The fact that the popular balloon model of the universe was actually an exact sub-universe of a Friedmann universe of positive curvature (k=1); while the corresponding subuniverses for the cases k=0 and k=-1 are pretty obvious: a plane and a saddle, respectively. So these models are the real thing and can be fully trusted!

(2) The concept of "conformal time" and the corresponding conformal diagram, which make all properties of event and particle horizons practically self-evident.

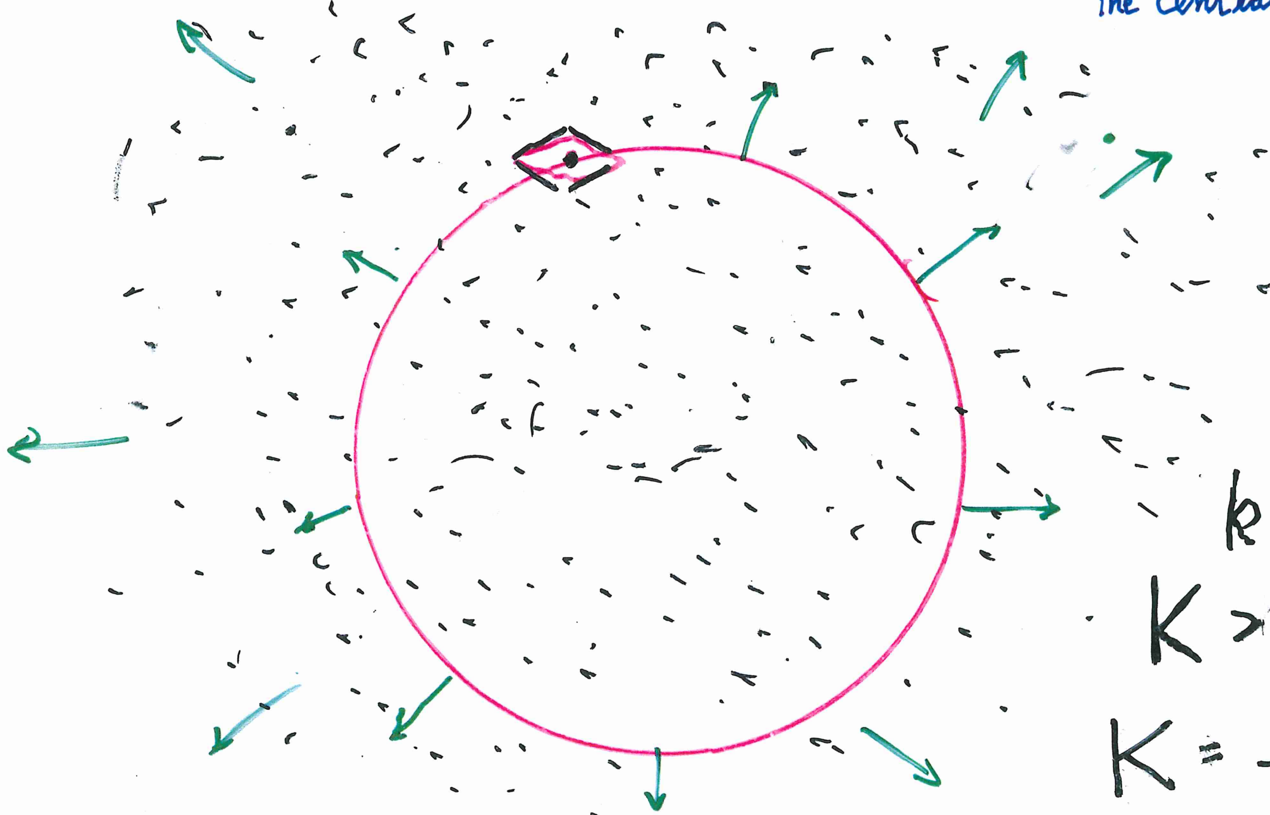
I shall discuss these next.

k=1 Balloon Model- Universe





Event horizon: mischievous blower! Ensures that a circular light front Never reaches the central particle



$k=1$

$K>0$

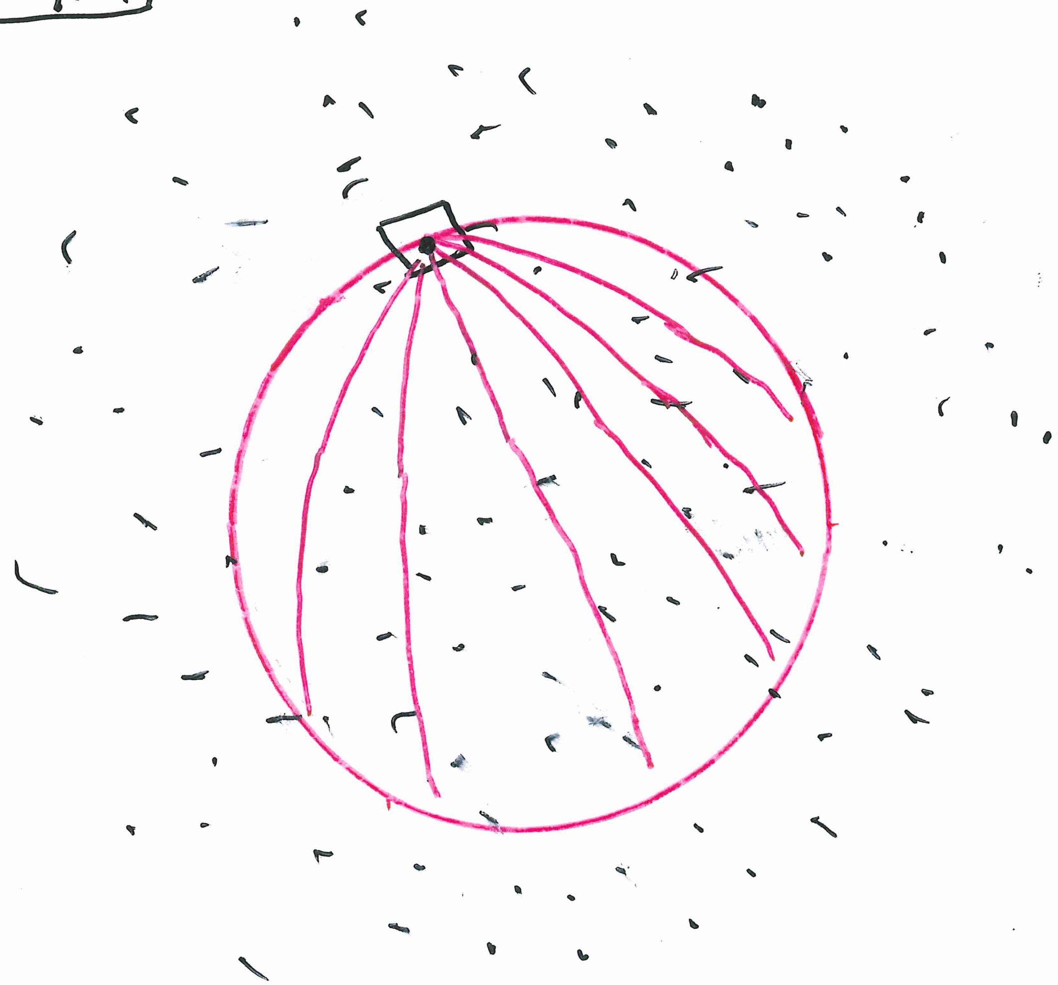
$K=\frac{1}{R^2}$

→ SUB-UNIVERSE

→ SYMMETRY SURFACE

SUB-UNIVERSE, CONTINUED

$\boxed{\text{CASE } k=1}$



AT ONE COSMIC INSTANT
DRAW ALL THE GEODESICS IN THE PLANAR DIR^{n}
THE RESULTING SUBSPACE OF THE SPATIAL LATTICE

IS A SYMMETRY SURFACE — SAME INSIDE AND OUTSIDE (ISOMETRIC HALVES) — LIKE EQUATOR ON EARTH

GEODESICS ONCE IN IT STAY IN IT (BY SYMMETRY)

HENCE : AUTONYMOUS SUB-UNIVERSE

CONFORMAL TIME : $t \to T$

→ FRIEDMANN METRIC:

$$\underline{ds}^2 = dt^2 - R^2(t)\{d\psi^2 + \eta^2(\psi)\underbrace{(d\theta^2 + \sin^2\theta\, d\phi^2)}_{d\omega^2}\}$$

$$\eta = \begin{cases} \sin\psi & : k=1 \\ \psi & : k=0 \\ \sinh\psi & : k=-1 \end{cases}$$

t: cosmic time

R: expansion factor

→ ONE ANGULAR DIMENSION SUFFICES FOR OUR DISCUSSION: $\theta, \phi = \text{const}$

$$\underline{ds}^2 = dt^2 - R^2(t)\, d\psi^2 = R^2(t)\left[\frac{dt^2}{R^2(t)} - d\psi^2\right] \quad !$$

Key!

→ DEFINE (conformal time)

$$\boxed{T(t) = \int_{t_0}^{t} \frac{dt}{R(t)}}$$

$T = T(t)$

$t = t(T)$

write $R(t) = R(t(T)) =: R[T]$

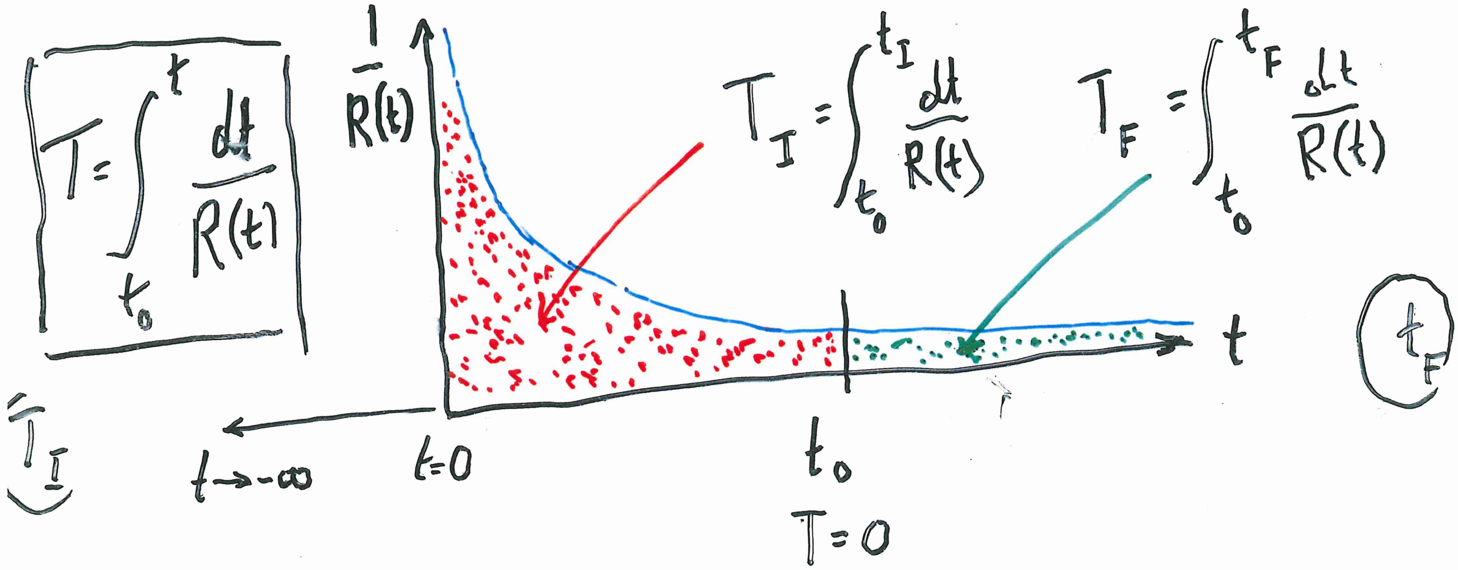
→ conformal metric :

$$\boxed{\underline{ds}^2 = R^2[T]\underbrace{(dT^2 - d\psi^2)}_{M_2}}$$

SHARE NULL GEODESICS → $\underline{ds}^2 = R^2 \underline{d\tilde{s}}^2$

T, t, and $R(t)$:

$$\boxed{T = \int_{t_0}^{t} \frac{dt}{R(t)}}$$



I: initial ($t_I = 0$ for BB; $t_I = -\infty$ for de Sitter)
F: final ($t_F = \infty$ for open U's, e.g. de S; $t_F = 0$ for closed U's)

Examples

de S: $\boxed{R = e^{Ht}}$ $\quad \int \frac{dt}{R} = -\frac{e^{-Ht}}{H}$

$$T_I = -\frac{e^{-Ht}}{H}\Bigg|_{t_0}^{-\infty} = -\infty$$

$$T_F = \uparrow \Bigg|_{t_0}^{\infty} = \frac{e^{-Ht_0}}{H}$$

BB: $R \sim t^{1/2}$ (matter dominated)
$R \sim t^{2/3}$ (radiation dom.)

$f<1$: $\int t^{-f} dt$ converges near zero $\quad \boxed{T_I \text{ always finite}}$ *

For one radial direction $\boxed{\theta, \phi = \text{const}}$

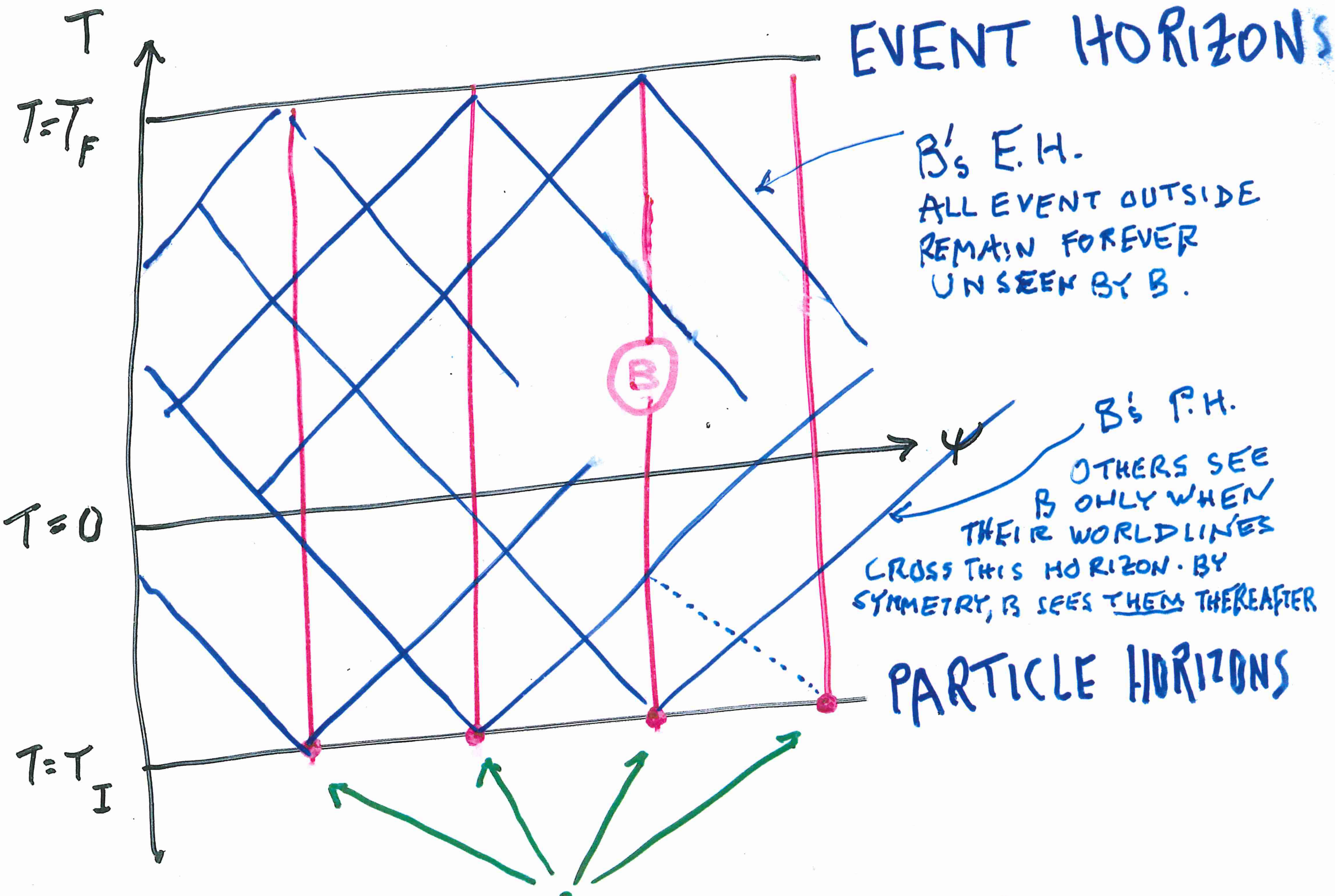
Of a specific Friedmann Universe

$$\boxed{ds^2 = R^2(T)\, d\tilde{s}^2}$$

Having finite T_I and T_F

Consider the Minkowski diagram for

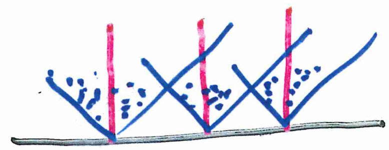
$$\boxed{d\tilde{s}^2 = dT^2 - d\psi^2} :$$



One pt: the BB (unravelled)!

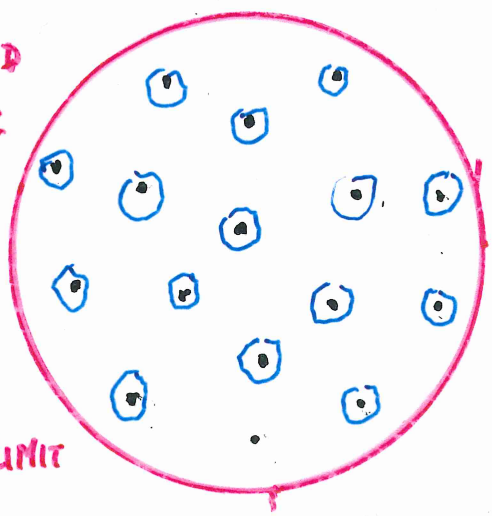
THE "PARADOXES" OF PARTICLE HORIZONS:

① AS THE DIAGRAM SHOWS:
THE PARTICLES LEAVE THE BB – WHERE THEY WERE ALL TOGETHER – WITH <u>DISJOINT</u> LIGHT CONES:



ON THE 2-D MODEL UNIVERSE, THIS LOOKS AS FOLLOWS: (AT ONE COSMIC INSTANT SHORTLY AFTER THE BB)

Q: HOW COULD EACH PART. GET OUT OF ANOTHER'S LIGHT CONE WITHOUT BREAKING THE SPEED LIMIT ?



ANSWER (?): THE BB IS A SINGULARITY, AND AT A SINGULARITY THERE ARE <u>NO</u> LAWS.

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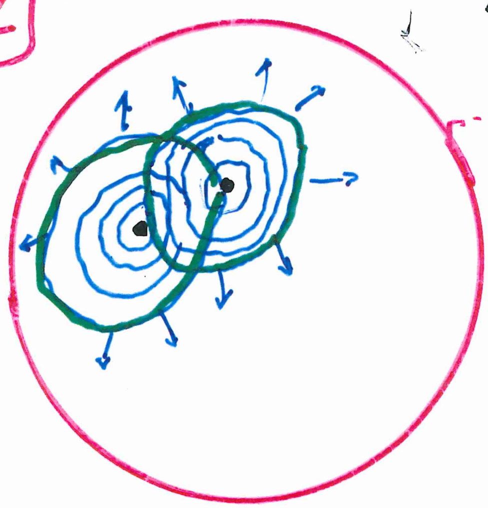
② AT A LATER TIME, 2 PARTICLES SURROUNDED BY <u>ALL</u> THE LIGHT THEY EMITTED SINCE CREATION:



ONLY WHEN THEIR RESPECTIVE CREATION LIGHT CONES REACH THE OTHR, DO THEY FIRST SEE EACH OTHER!

(SAME PROBLEM WITH IRREGULAR GEOMETRY)

Q: HOW IS THERMALISATION (HOMOGENEITY) ACHIEVED ?

Particle Worldlines
and their creation light cones
in a 5-dimensional
embedding Minkowski space: