Academy Public Lecture
Indian Academy of Sciences
January 23, 2006

Title: *A Shock Wave Cosmology*

Speaker: *Blake Temple*[1]

Abstract: In this talk I discuss a model of cosmology that refines the standard model of cosmology (based on the Friedmann universe) by the incorporation of a shock wave. The model explores the possibility that the explosion of the Big Bang that caused the outward motion of the galaxies, was an explosion of finite total mass, instead of the infinite mass explosion inherent in the standard model. In the shock wave model, (which is based on the author's recent joint work with J. Smoller, Proc. Nat. Acad. Sci., USA, Vol. 100, no. 20, pp. 11216-11218), a spacetime of constant density and constant pressure emerges instantaneously after the Big Bang, just as in the standard model. But in the shock wave model, the geometry is different far out because the the total mass is finite. As a consequence, the density and pressure start dropping faster far out than in the Friedmann universe which is close in, and this produces a gradient in the density and pressure, which then breaks into a wave. In our model, we describe the evolution of the outer pressure so that this wave is exactly resolved by a single outgoing, spherical, entropy satisfying shock wave. The shock wave emerges from the center of the explosion at the instant of the Big Bang as a zero strength wave that strengthens as it propagates outward, (something like the blast wave of a nuclear explosion), and the expanding galaxies correspond to the region inside the wave. One of the main consequences of this model is that when the shock wave is far enough out to be consistent with astronomical observations, (beyond one Hubble length–the distance light can travel since the Big Bang explosion), the whole explosion begins inside a (time reversed) Black Hole–a White Hole in which everything is exploding outward instead of collapsing inward. In the shock wave model, the universe eventually emerges from the Black Hole, and from then on expands like the famous Oppenheimer-Snyder solution–a finite ball of matter expanding into empty space. We are inside

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the explosion, but to an observer in the far field beyond the shock wave, the end stage of the explosion would look like a giant supernova. It also follows from our model that information about the shock wave propagates inward from the shock wave, into a large *shadow* region of uniform expansion at the center of the explosion–and to an observer (like us) on the inside of this *shadow* region, everything looks exactly like the Friedmann universe up until the time when the shock wave comes into view from the farthest field of observations. That is, in the shadow region, up until the time when the shock wave comes into view, everything looks the same as in the standard model. Other interesting consequences of the shock wave model include the unexpected emergence of the correct equation of state at the Big Bang, the breaking of the time symmetry by the entropy condition, and interesting mathematical consequences of the reversal of space and time inside the Black Hole. In this talk I will give an introduction to Einstein's theory of general relativity, and then discuss this shock wave cosmology within this context. The talk will begin and end with a computer visualization of our model due to Zeke Vogler. (Articles and commentaries can be found on authors website: http://www.math.ucdavis.edu/ temple/articles/)

SHOCK-WAVE COSMOLOGY

Inside

A BLACK HOLE

Blake Temple

(Joint Work with Joel Smoller)

http://www.math.ucdavis.edu/~temple

- A Blast Wave/Shock Wave Marks the leading edge of a classical explosion

≈ "Discontinuity" in pressure between explosion and material beyond explosion

- Any Explosion with a finite Energy/Mass Behind it Must generate such a Blast Wave

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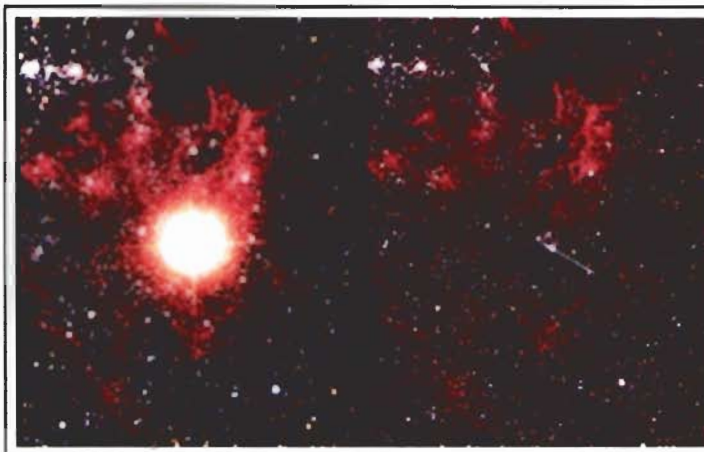


"After" and "Before" pictures of Supernova 1987A

The above two photographs are of the same part of the sky. The photo on the left was taken in 1987 during the supernova explosion of SN 1987A, while the right hand photo was taken beforehand. Supernovae are one of the most energetic explosions in nature, making them like a 10^{28} megaton bomb (*i.e.*, a few octillion nuclear warheads).

Types of Supernovae

Related Topics

Supernovae are divided into two basic physical types:

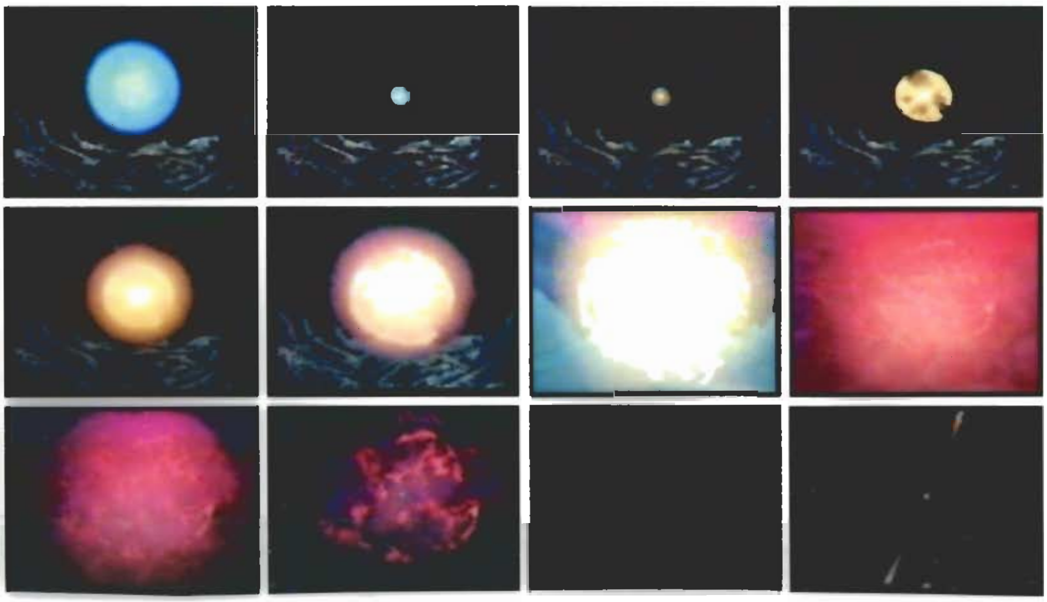
The above two photographs are of the same part of the sky. The photo on the left was taken in 1987 during the supernova explosion of SN 1987A, while the right hand photo was taken beforehand. Supernovae are one of the most energetic explosions in nature, making them like a 1028 megaton bomb (i.e., a few octillion nuclear warheads).

SN 1987A

(NASA)

Supernova Images

This is the set of images used to create the supernova inline animation.



One of the most energetic explosive events known is a supernova. These occur at the end of a star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy. If the star is particularly massive, then its core will collapse and in so doing will release a huge amount of energy. This will cause a blast wave that ejects the star's envelope into interstellar space. The result of the collapse may be, in some cases, a rapidly rotating neutron star that can be observed many years later as a radio pulsar.

-5-

Federation of American Scientists

Special Weapons Primer

Weapons of Mass Destruction

Nuclear Weapon Blast Effects

As pictures of Hiroshima, Nagasaki, and of the test structures erected at the Nevada Test Site in the 1950's amply demonstrate, the blast and shock waves produced by nuclear explosions are the principal means for destroying soft targets. Ground shock from a low-altitude, surface, or underground burst may be the only way to destroy hardened underground structures such as command facilities or missile silos.

Blast and shock effects are the primary damage-producing mechanisms for soft targets such as cities and are often the only effective mechanism for destroying underground structures such as missile silos. Nuclear weapons with yields below about one megaton are particularly identifiable as blast/shock weapons. Nuclear blast and shock phenomena differ from those produced by conventional chemical explosives because of their long duration and large overpressures. There is considerable overlap between the pressure regime of nuclear-produced blast and shock and that of air drag produced in strong hurricanes.

As a result of the very high temperatures and pressures at the point of detonation, the hot gaseous residues move outward radially from the center of the explosion with very high velocities. Most of this material is contained within a relatively thin, dense shell known as the hydrodynamic front. Acting much like a piston that pushes against and compresses the surrounding medium, the front transfers energy to the atmosphere by impulse and generates a steep-fronted, spherically expanding blast or shock wave. At first, this shock wave lags behind the surface of the developing fireball. However, within a fraction of a second after detonation, the rate of expansion of the fireball decreases to such an extent that the shock catches up with and then begins to move ahead of the fireball. For

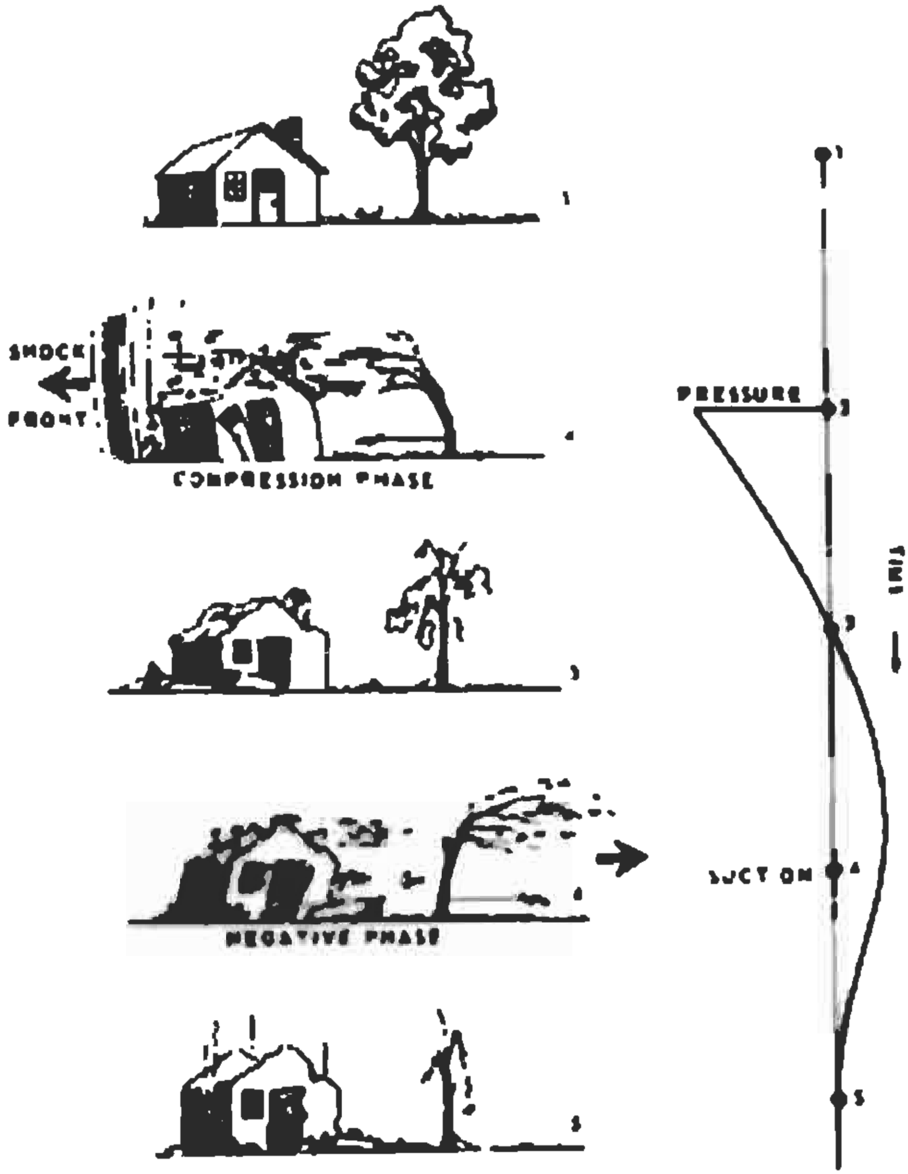


Figure 3-III. Variations of Blast Effects Associated with Positive and Negative Phase Pressures with Time

SHOCK-WAVE COSMOLOGY

Inside

A BLACK HOLE

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http://www.math.ucdavis.edu/~temple

SECOND TITLE

What Would Happen If The Big Bang Were An Explosion of Finite Total Mass?

Third Title

The Big Bang

OR

Have You Ever Seen An Explosion Without A Shock-Wave Before?

- We have been working on a theory of shock-wave propagation in General Relativity

- Intriguing Question:

"Could there be a shock-wave at the leading edge of the expansion of the galaxies?"

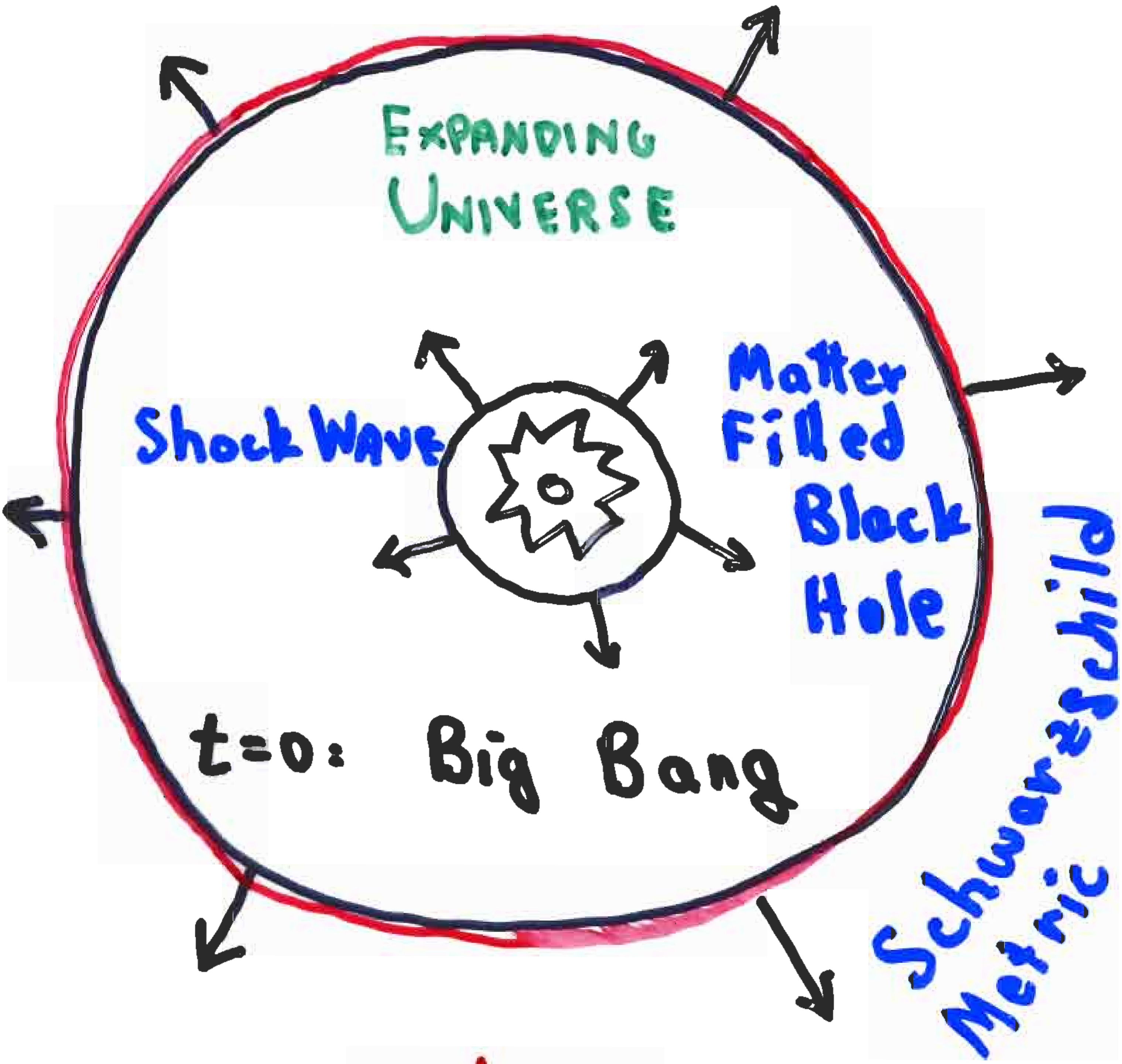
- IF there is a shock-wave, then the Big Bang was an explosion of FINITE TOTAL MASS

- IN THE STANDARD MODEL of COSMOLOGY
The Big Bang was an explosion of INFINITE Mass
INFINITE EXTENT

"There is NOTHING beyond the galaxies in the standard model"

- Topic for this talk:
  - A New exact solution of Einstein's Equations
  - $t = 0$: Shock wave emerges from origin $\bar{r} = 0$ at Big Bang
    - Inside a Black Hole -
  - $t = t_{crit}$: Shock wave emerges from event horizon of a Black Hole in a Schwarzschild metric
- Shock-wave can be arbitrarily far out

Picture



$t = t_{crit}$

Shock Emerges from White Hole

Outline

I Introduction To Cosmology

II Introduction To General Relativity

III Introduction to Shock-waves

IV Details of our Solution

Introduction to Cosmology

- Edwin Hubble (1889-1953)

Hubble's Law (1929):

"The galaxies are receding from us at a velocity proportional to distance"

⇓

Universe Is EXPANDING

- Based on redshift vs luminosity

10 billion lightyears ≈ visible universe

1 billion lightyears ≈ uniform density

50 million lightyears ≈ separation between clusters of galaxies

10 million lightyears ≈ diameter of cluster

1 million lightyears ≈ separation between galaxies in cluster

100,000 lightyears ≈ distance across Milky Way

28,000 lightyears ≈ distance to galactic center

4 lightyears ≈ distance to nearest star

Standard Model of Cosmology

$$ds^2 = -dt^2 + R(t)^2\{dr^2 + r^2 d\Omega^2\}$$

- $D = Rr$ Measures distance between galaxies at each fixed t

$$D = R(t)\, r$$

- Conclude:

$$\dot{D} = \dot{R} r = \frac{\dot{R}}{R} R r = HD$$

$$\boxed{\dot{D} = HD}$$ Hubble's Law

- H = Hubble's Constant

Standard Model of Cosmology

$$ds^2 = -dt^2 + R(t)^2 \{dr^2 + r^2 d\Omega^2\}$$

- Hubble's Law:

$$\dot{D} = HD$$

- Conclude –

The universe is expanding uniformly like a balloon

$R = 0 \iff$ Big Bang

▪ The Hubble "Constant":

$$H = \frac{\dot{R}}{R} \approx h_0 \frac{100\ \text{km}}{\text{s mpc}}$$

"A galaxy at 1 mpc ≈ 3 million light years recedes at $h_0 \frac{100\ \text{Km}}{\text{sec}}$" $.5 \leq h_0 \leq .8$

$$\frac{1}{H_0} \approx 10^{10}\ \text{years} \approx \text{age of universe}$$

$$\frac{c}{H_0} \approx \text{Hubble Length} \approx 10^{10}\ \text{light yr}$$

≈ farthest we can see across universe

- FRW metric: $ds^2 = -dt^2 + R(t)^2 \{ dr^2 + r^2 d\Omega^2 \}$

- Any point can be taken as $r = 0$

$\Downarrow$

homogeneous & isotropic about every pt

$\Downarrow$

<u>Copernican</u> <u>Principle</u>: earth is not in a special place in universe

- $$\lim_{r \to \infty} R(t) r = \infty$$

$\Downarrow$

FRW universe is <u>infinite</u> at each $t = \text{const}$ surface

Conclude: In the Standard Model —

"Even tho we can only see
≈ One HUBBLE LENGTH out,
the STANDARD MODEL presumes
that uniformity extends to
INFINITY in all directions —"

- **Our Question:** "what if the expansion of the galaxies is only a finite expansion of bounded extent?"

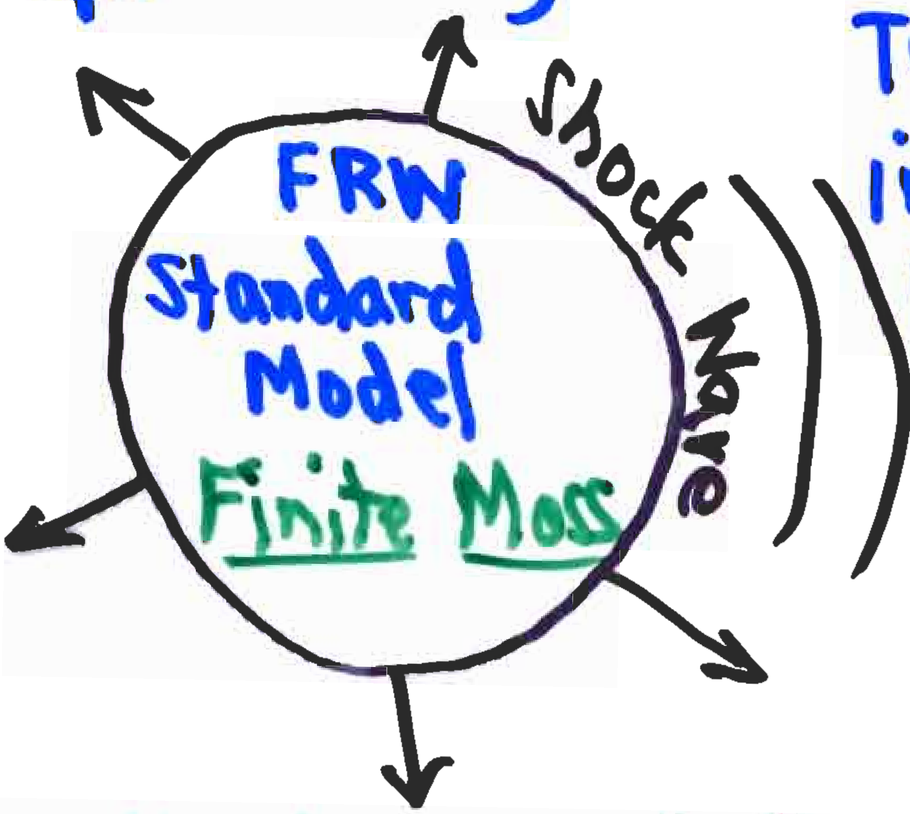
$$\Downarrow$$

$\exists$ a wave at the leading edge of the expansion of galaxies

$$\Downarrow$$

- **Math Question:** Can you incorporate a shock wave at the leading edge of galaxies in FRW metric in a rigorous mathematical model?

• ANS: YES (Te/Sm Proceedings of the National Academy of Sciences, Sept. 2003)



TOV metric inside the Black Hole

$$\frac{2M}{r} > 1$$

• In order to account for the large region of uniform expansion that we observe in universe today, explosion must occur within a "time reversed black hole" = White Hole

• Ans: YES

• ∃ free parameter in model
  ~ total mass of explosion
  ~ distance to the shock-wave
  ~ extent & duration of the central region of uniformity

• We expect <u>every</u> sufficiently large explosion of finite mass to look qualitatively like this

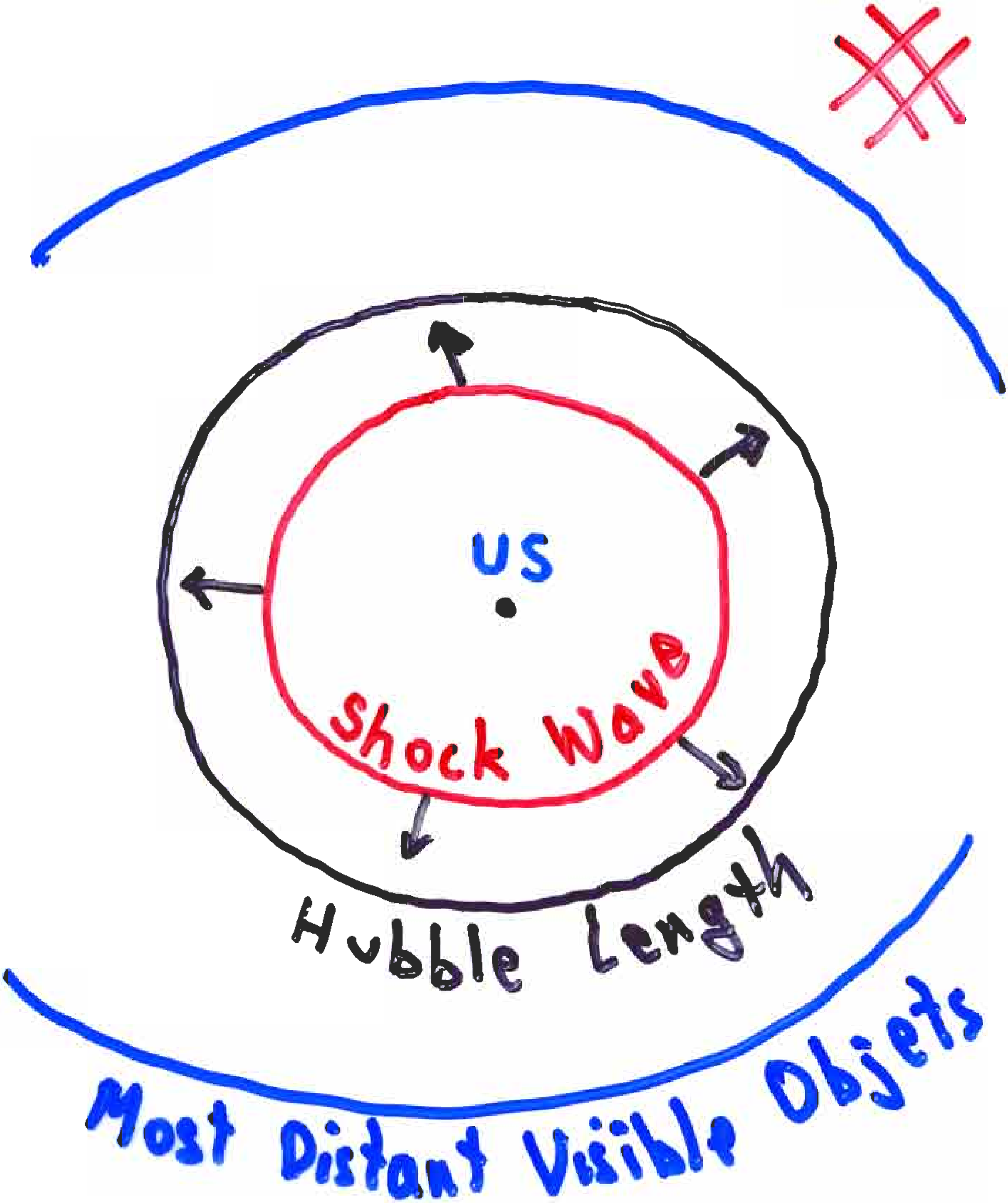
• If close enough, wave is in principle <u>observable</u>

The Main Point:

To be consistent with observations, the shock wave must lie out beyond one Hubble length, which places it inside a black hole:

$$\frac{2M}{\bar{r}} > 1$$

EG: We can see out to ≈ 1.5 Hubble Lengths...



- Schwarzschild Radius of the universe:

- $$r_s = 2GM = \frac{2G}{c^2}M$$

"radius at which M forms a Black Hole"

$r_s(\text{Earth}) \approx 3\,\text{cm}$

$r_s(\text{Sun}) \approx 2\,\text{km}$

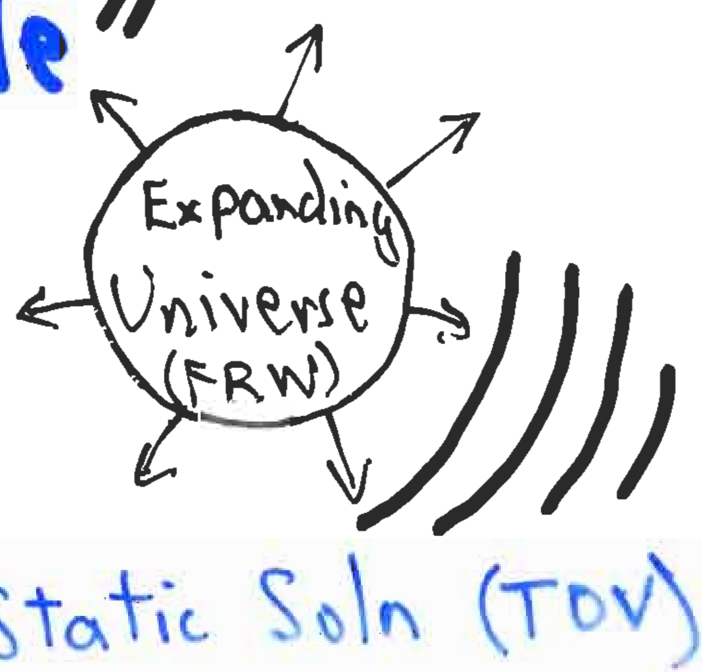
$r_s(\text{Galaxy}) \approx 10^{12} \times 2\,\text{km}$

$r_s(\text{Visible Universe}) = \frac{c}{H}$ = one H.L.

■ **Conclude:** "A Shock Wave beyond one Hubble Length must lie inside a Black Hole"

- This explains limit in our
- previous work — "A static Soln cannot be continued into a Black Hole"

$$\Rightarrow D \leq \frac{c}{H}$$



To construct a shock wave at the leading edge of the galaxies beyond one Hubble Length, we need to show

① The FRW metric continues to a spacetime metric for which

$$\frac{2M}{\bar{r}} > 1$$

$\bar{r} = Rr$

at radius $\bar{r} > \frac{c}{H}$

② The interface describes a Shock Wave

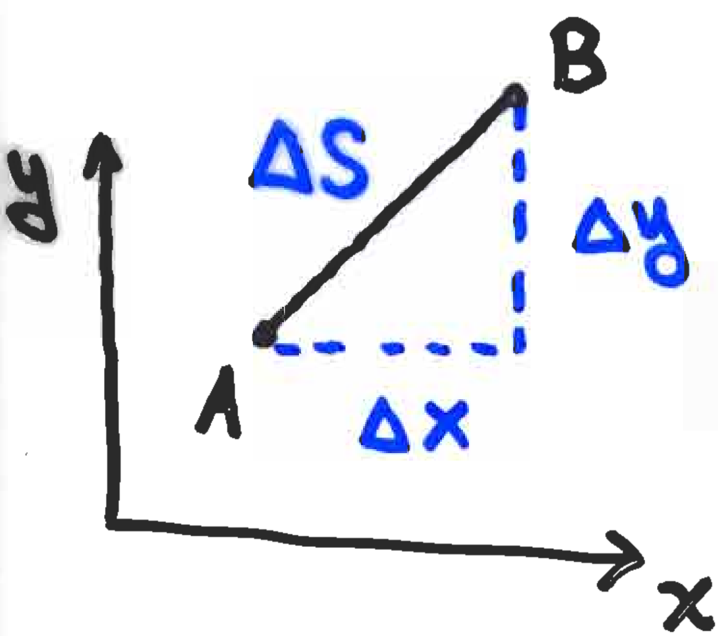
Meaning of Friedmann Metric —

- Special Relativity: "Time is a metrical quantity"

(NOT a universal coordinate)

- Euclidean Geometry:

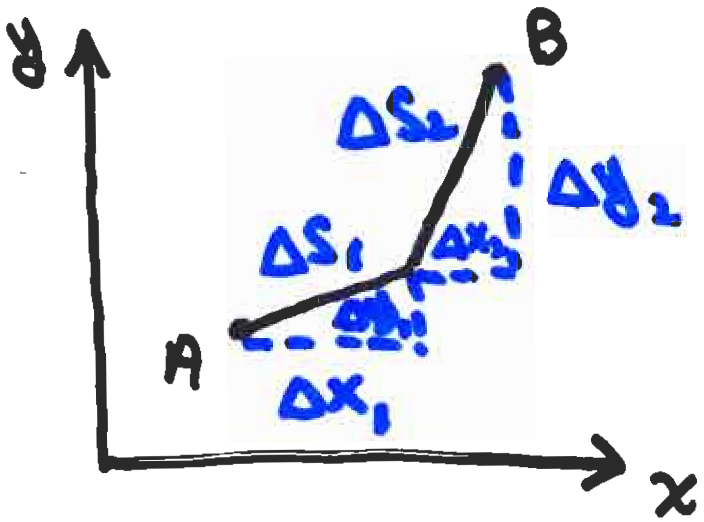
(Based on Pythagorean Theorem)



$$\Delta S = \sqrt{\Delta x^2 + \Delta y^2}$$

As a result: The distance betw two pts depends on the path

• Distance Depends on Path:



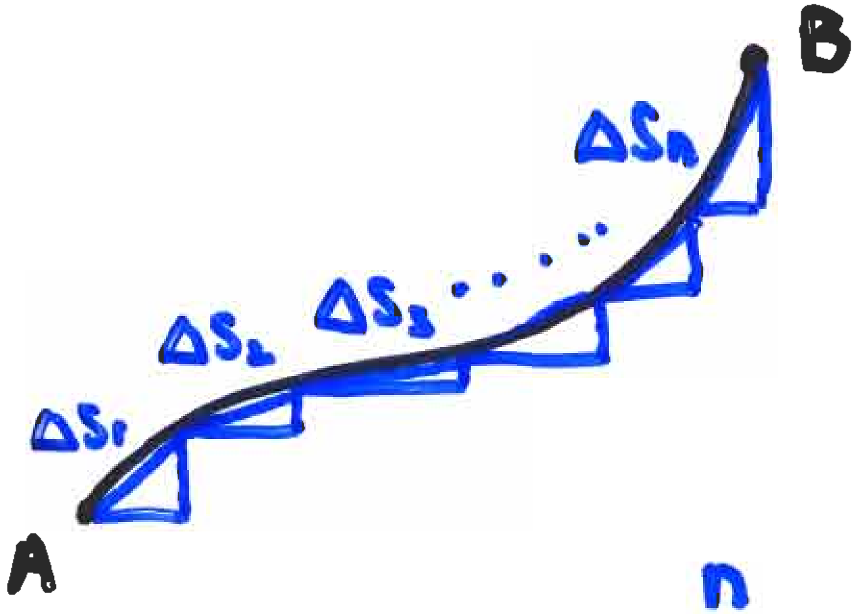
s = length of path betw A & B depends on path

$$s = \Delta s_1 + \Delta s_2 = \sqrt{\Delta x_1^2 + \Delta y_1^2} + \sqrt{\Delta x_2^2 + \Delta y_2^2}$$

$$\geq \sqrt{\Delta x^2 + \Delta y^2}$$

Conclude: Pythagorean Theorem ⇒ Distance betw. A & B depends on the path, and the straight line is the path that <u>minimizes</u> the distance.

■ In general:



$$s \cong \Delta s_1 + \Delta s_2 + \cdots + \Delta s_n = \sum_{i=1}^{n} \Delta s_i$$

$$\Delta s_i = \sqrt{\Delta x_i^2 + \Delta y_i^2}$$

In the limit $\Delta s_i \rightarrow 0$ we get the exact distance

$$s = \int ds \approx \sum \Delta s_i$$

$$ds^2 = dx^2 + dy^2$$

- We Say: $ds^2 = dx^2 + dy^2$

Is the Euclidean Metric

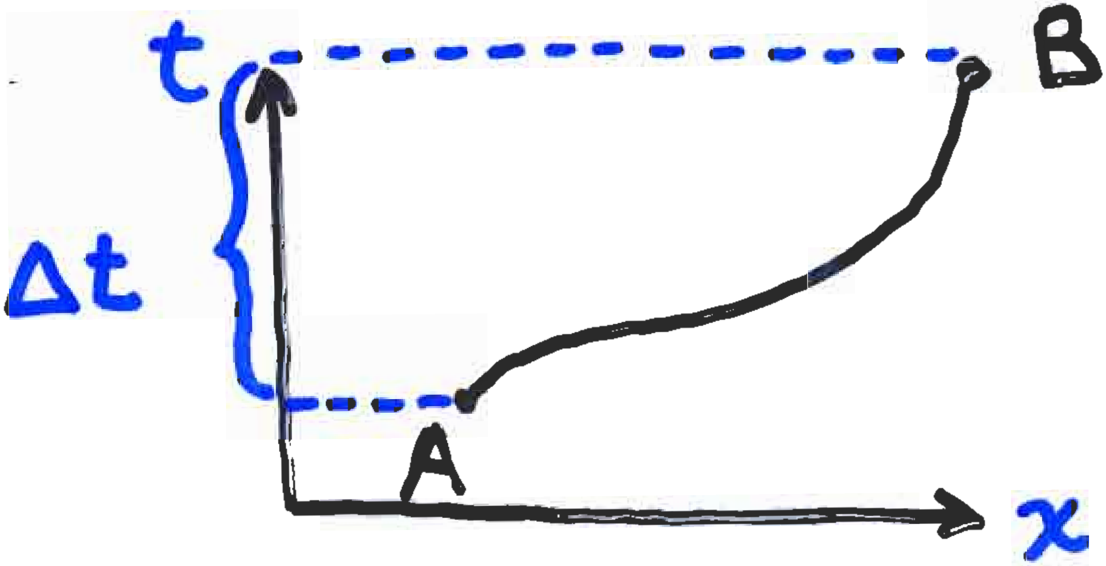
- Distance depends on the path

$$S = \int_{P} ds = \int_{P} \sqrt{dx^2 + dy^2}$$

- Conclude: "Euclidean Distance Is a metrical quantity"

- Compare this to Euclidean time change...

- Compare Euclidean distance to Euclidean time change

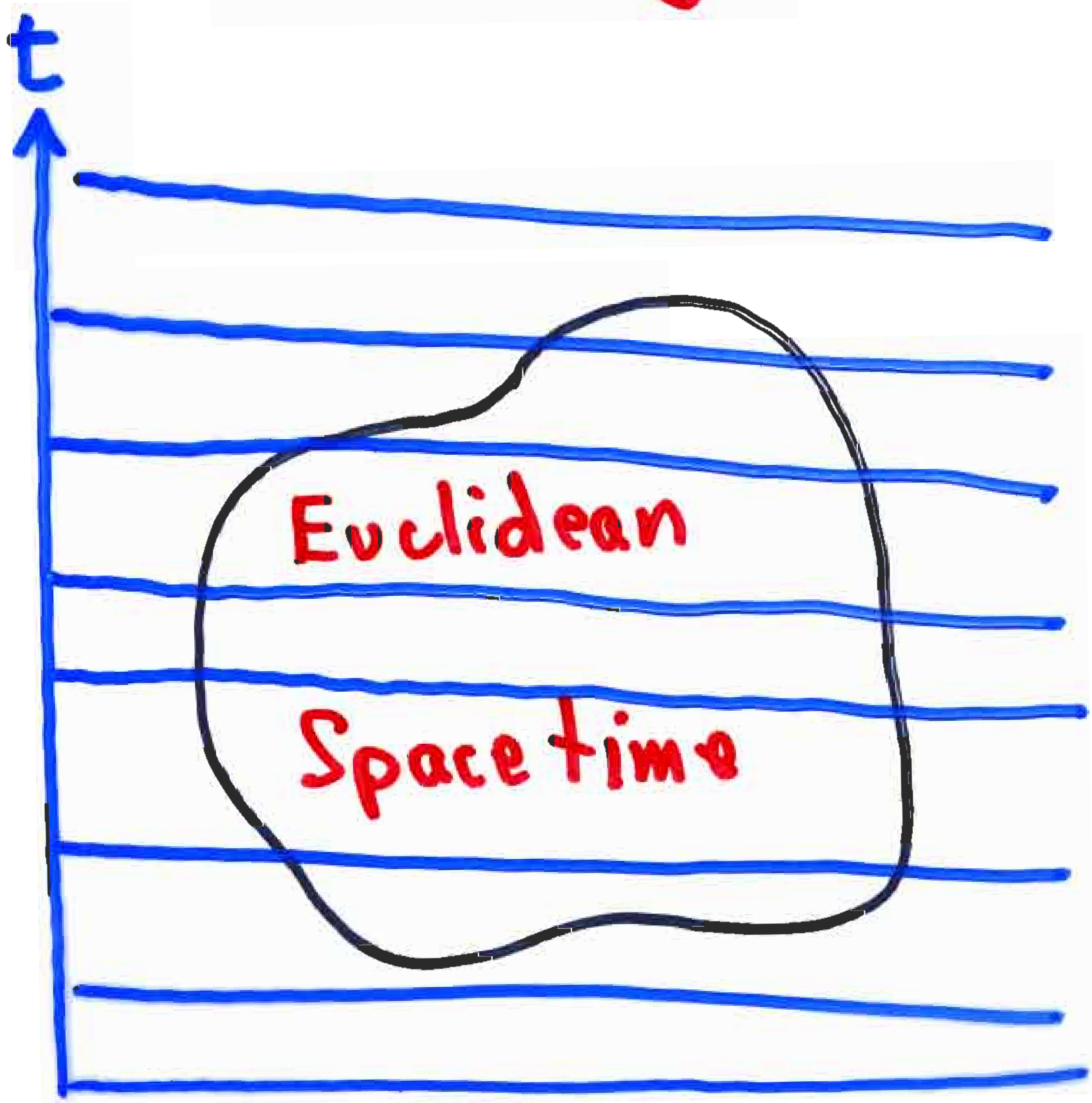


$$\Delta t = t(B) - t(A)$$

- Δt is independent of path

Conclude : Euclidean time t is a universal coordinate

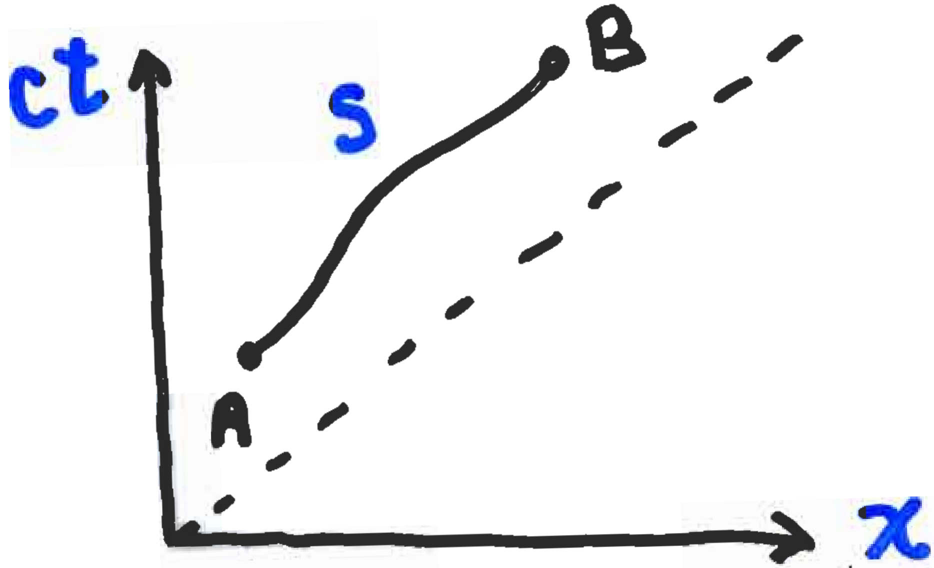
NOT a metrical quantity like length



▪ Special Relativity (Einstein 1905)

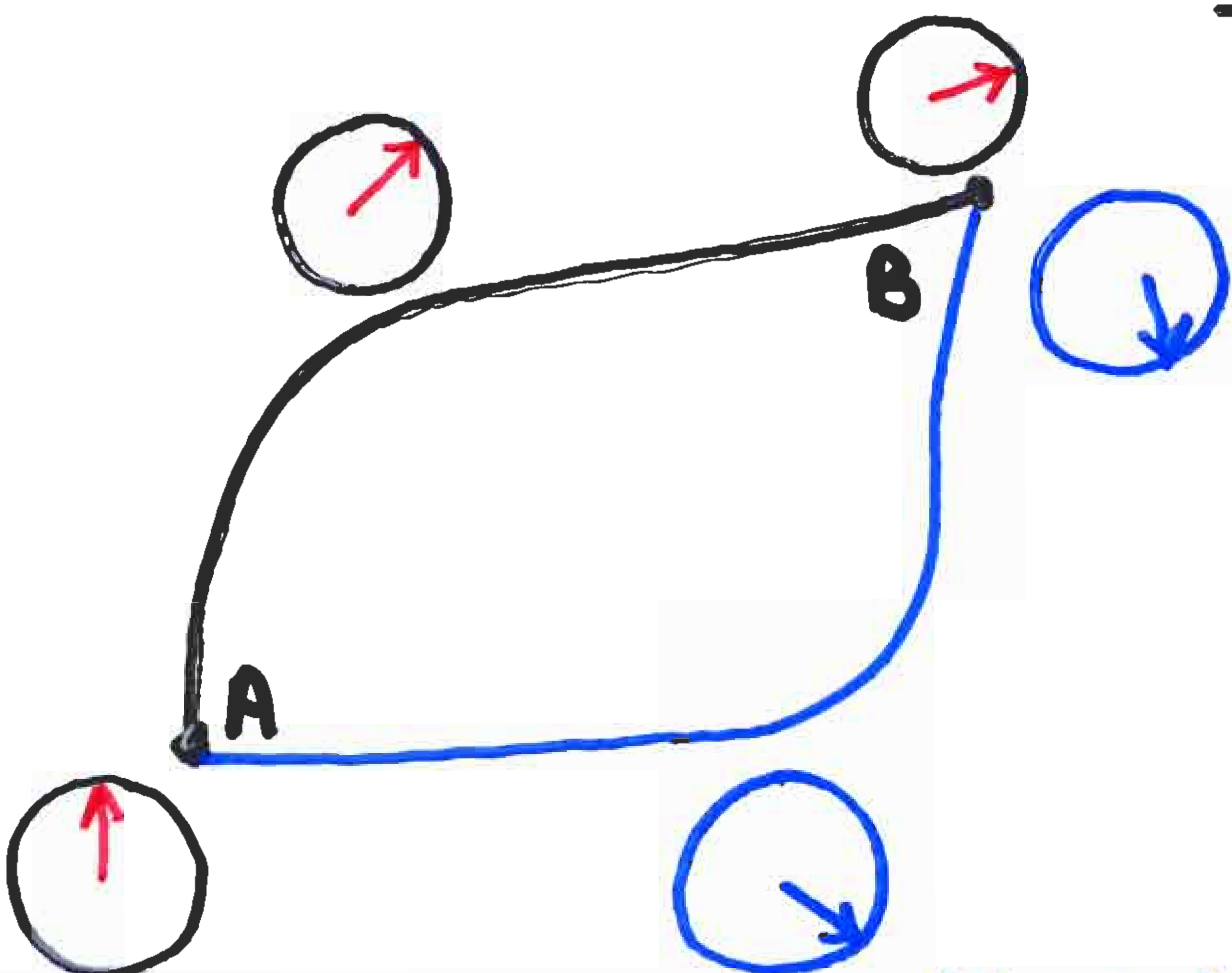
"TIME IS Metrical like SPACE"

$$ds^2 = -d(ct)^2 + dx^2$$



$$S = \int_P ds = \int_P \sqrt{-d(ct)^2 + dx^2}$$

S = Proper Time Change
Depends on Path



Summary (Special Relativity)

In an inertial coordinate system time changes are determined by a Lorentzian metric

$$ds^2 = -d(ct)^2 + dx^2 + dy^2 + dz^2$$

- Special Relativity $\Leftrightarrow$ Flat Spacetime

$\Updownarrow$

Minkowski Metric

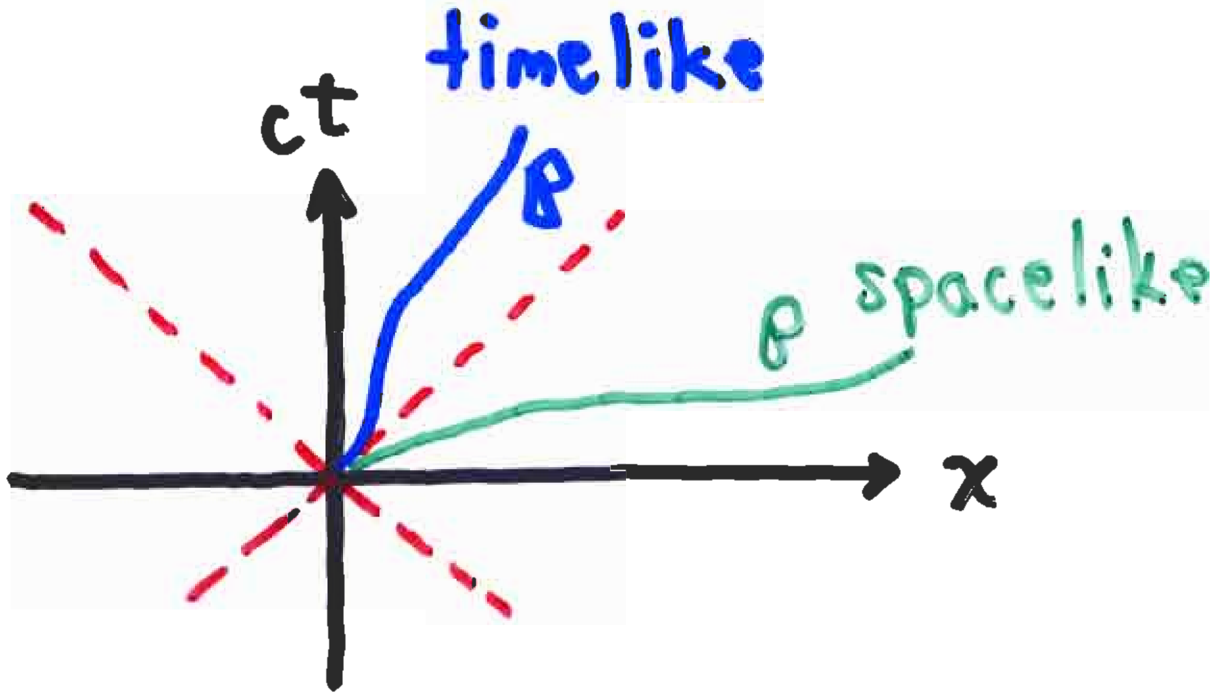
$$ds^2 = -d(ct)^2 + \underbrace{dx^2 + dy^2 + dz^2}_{r^2 d\Omega^2}$$

- Sometimes Minkowski metric is written in spherical coordinates

r = radial distance

$d\Omega^2 = d\theta^2 + \sin^2\theta \, d\phi^2$ = line element on unit sphere

■ The spacetime metric separates curves into spacelike and timelike



In either case metric gives length

$s = \int_{\mathcal{P}} ds$ = time chng along $\mathcal{P}$

$s = \int_{\mathcal{P}} ds$ = spatial length of $\mathcal{P}$

- **Conclude:** The flat spacetime metric

$$ds^2 = -d(ct)^2 + dx^2 + dy^2 + dz^2$$

Unites space and time within a single metric

- In 1915, Albert Einstein introduced general relativity

- "The gravitational field causes the inertial frames to change from point to point"

$\Rightarrow$ Curvature

Still: in a coord. system

$$\underset{\sim}{x} = (x^0, \ldots, x^3)$$

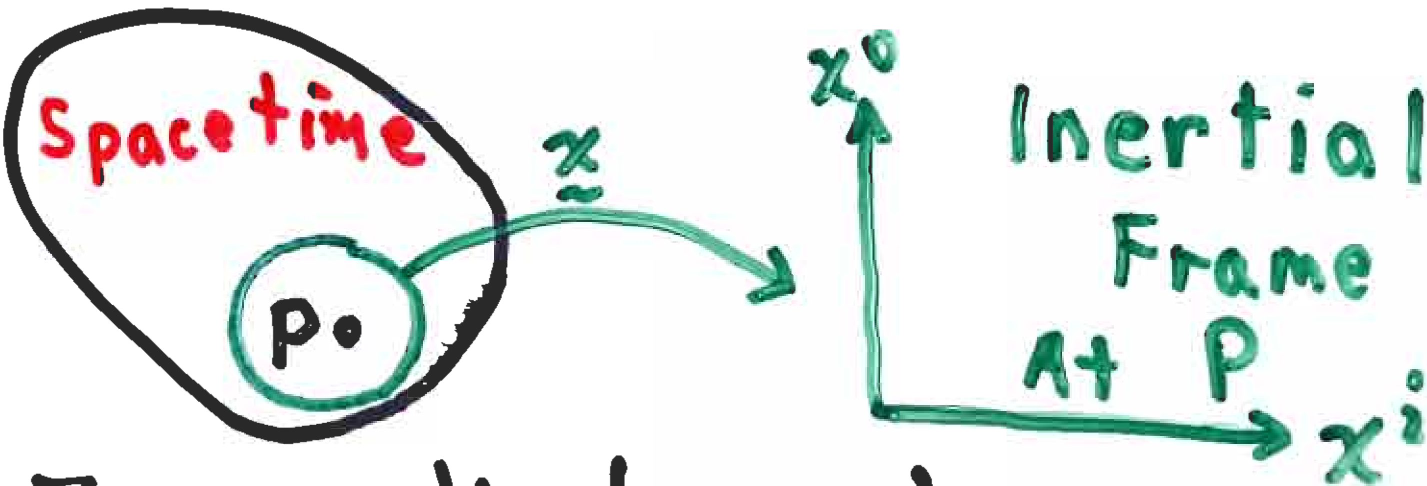
$$ds^2 = g_{ij}(\underset{\sim}{x})\, dx^i dx^j$$

$g \equiv$ Gravitational Metric Tensor

$\equiv$ Gravitational Field

■ For general g_{ij} there exist

Locally Inertial Coordinate Frames



• In coordinate system $\underset{\sim}{x}$

$$ds^2 = -d(ct)^2 + dx^2 + dy^2 + dz^2 + \underbrace{\delta_{ij}\, dx^i dx^j}_{\text{Errors}}$$

Error:

$$\delta_{ij}(P) = 0$$

$$\delta'_{ij}(P) = 0$$

$$\delta''_{ij}(P) \neq 0 \sim \text{Curvature}$$

Riemann (1854)

Riemann Curvature Tensor $R^{i}_{.jkl}$

- $R^{i}_{.jkl}$ measures the degree to which the 2nd order errors δ''_{ij} cannot be removed

- $R^{i}_{.jkl}(\underset{\sim}{x})$ measures the spacetime curvature at $\underset{\sim}{x}$

(The components of R^{i}_{jkl} transform between coordinate systems by tensor transformation laws)

- Not all metrics g_{ij} can be gravitational fields – must meet

Einstein Equations (1915)

$$G = 8\pi T$$

$$G_{ij}[g_{ij}(\underline{x})] = \frac{8\pi G}{c^4} T_{ij}[\rho, p, u]$$

↑ Einstein Curvature Tensor

$$\left(G_{ij} = R^{\sigma}_{i\sigma j} - \frac{1}{2} R^{\sigma\tau}_{\sigma\tau}\, g_{ij}\right)$$

↑ Stress Energy Tensor (Fluid Source)

"Energy-momentum densities and their fluxes are sources of spacetime curvature"

- Not all gravitational metrics g can be gravitational fields — they must meet Einstein Equations (1915)

$$G = 8\pi T$$

Einstein Curvature Tensor → G

Stress Energy Tensor → T

"Matter is a source of spacetime curvature"

- ⇒ Equations for the gravitational field g_{ij}

Einstein Equations

$$G[g_{ij}] = \frac{8\pi G}{c^4} T_{ij}[\rho, p, u]$$

↑ Curvature

Energy-Momentum densities & their fluxes

Eg: Universe on largest scale $\sim 10^9$ ltyr

ρ = density ≈ $\frac{\text{Ave Mass of Galaxies}}{\text{3-Volume}}$

u = velocity ≈ Ave Velocity of galaxies

p = Pressure $\neq 0$ early on

EXAMPLES

① Schwarzschild Metric (1916)

$$ds^2 = -\underbrace{\left(1-\frac{2M}{r}\right)}_{g_{00}}dt^2 + \underbrace{\frac{1}{1-\frac{2M}{r}}}_{g_{11}}dr^2 + r^2 d\Omega^2$$

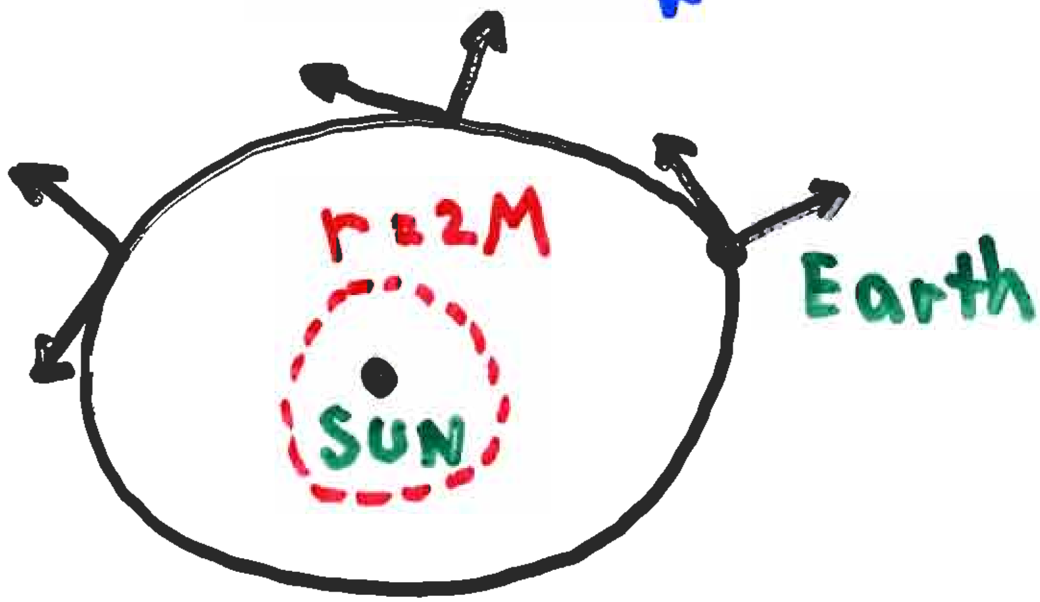
$$r^2 d\Omega^2 = \underbrace{r^2}_{g_{22}} d\theta^2 + \underbrace{r^2 \sin^2\theta}_{g_{33}} d\phi^2$$

- Gravitational metric for point mass M at $r = 0$
- $r = 2M$ = Schwarzschild radius

~ "Radius of a Black Hole of mass M"

Schwarzschild Spacetime

$$ds^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \frac{1}{1-\frac{2M}{r}}dr^2 + r^2 d\Omega^2$$



- The earth goes around the sun moving in a straight line in each locally inertial coordinate frame
- Spacetime Curvature ⇒
  Local inertial frames change from point to point
- "The earth moves in a "straight line" thru a curved space"

- **Theorem**: Free falling objects follow geodesics of the spacetime metric

Geodesic = Path of shortest distance in that geometry

EXAMPLES

② Tolmann-Oppenheimer-Volkoff Metric (1939)

$$ds^2 = -B(r)dt^2 + \frac{1}{1-\frac{2M(r)}{r}}dr^2 + r^2 d\Omega^2$$

- $\frac{2M}{r} < 1 \Rightarrow$ Gravitational metric for the interior of a star

~ Stability limits { Buchdahl, Chandrasekhar }

$\frac{2M}{r} > 1 \Rightarrow$ Dynamical metric inside a Black Hole

~ Outer metric in our shock wave

Examples

③ Friedmann-Robertson-Walker Metric (1923)

Standard Model of Cosmology

$$ds^2 = -dt^2 + R(t)^2 \left\{ \frac{1}{1-kr^2} dr^2 + r^2 d\Omega^2 \right\}$$

$R(t)$ ↗ Cosmological Scale Factor

$\{\ldots\}$: Space of Constant Curvature $K = \frac{k}{R^2}$

• WMAP (2002) ⇒ $k = 0$

"Space is flat at each t=const but spacetime is curved"

In Our PNAS Article...

- We showed that the $k=0$ FRW metric can be matched to a TOV metric

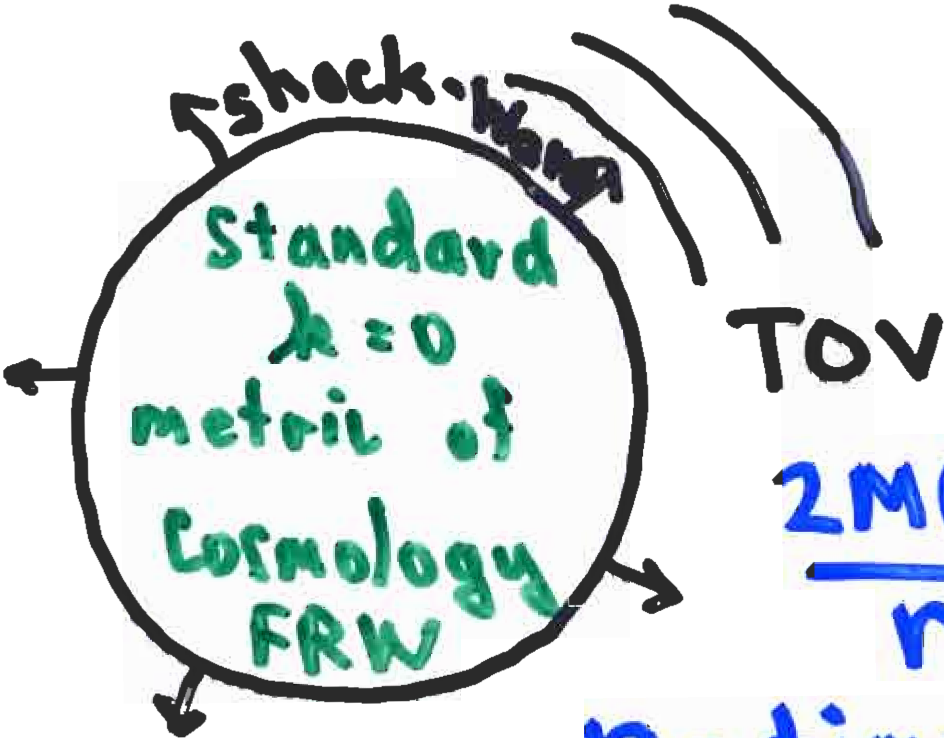
$$ds^2 = -B(r)dt^2 + \frac{1}{1-\frac{2M(r)}{r}}dr^2 + r^2 d\Omega^2$$

across a shock wave out beyond one Hubble length where $\frac{2M(r)}{r} > 1$

$\Rightarrow$ Inside a Black Hole

- r timelike $\Rightarrow$ $M(r)$ = mass at time r bounded beyond Hubble Length

Shock-Wave Model



$$\frac{2M(r)}{r} > 1$$

r = time

- The TOV metric cuts off the total mass at a finite value (simplest such metric)
- The Einstein equations give the evolution of the wave
- Several surprises!

☑ New Idea: Match FRW to "TOV inside the Black Hole"

$$ds^2 = \frac{d\bar{r}^2}{1 - \frac{2M(\bar{r})}{\bar{r}}} + B(\bar{r})\,d\bar{t}^2 + \bar{r}^2 d\Omega^2$$

$$\frac{2M}{\bar{r}} > 1 \Rightarrow \frac{\partial}{\partial \bar{r}} \text{ time like}$$

$$\frac{\partial}{\partial \bar{t}} \text{ space like}$$

⇒ Dynamical metric

Eqn's have different character

■ Shock Waves in GR

Einstein: $G_{ij}[g_{ij}] = 8\pi T_{ij}[\rho, p, u]$

- Conservation of Energy & Momentum are Automatic:

$$\Rightarrow \qquad \operatorname{div} T = 0$$

~ Relativistic Compressible Euler Equations in curved spacetime

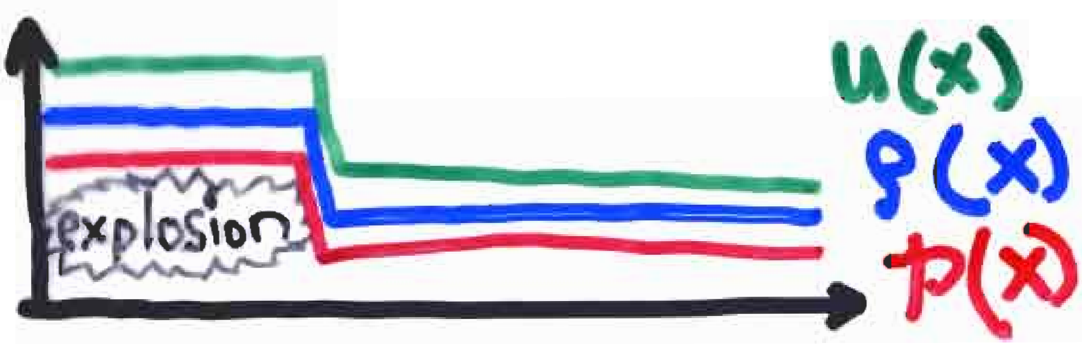
~ Setting for Theory of Shock Waves

Einstein Equations

$$G = 8\pi T$$

$$\text{“} \partial^2 g = \kappa T[\rho, p, u] \text{”}$$

- At a shock wave, ρ, p, u are discontinuous —

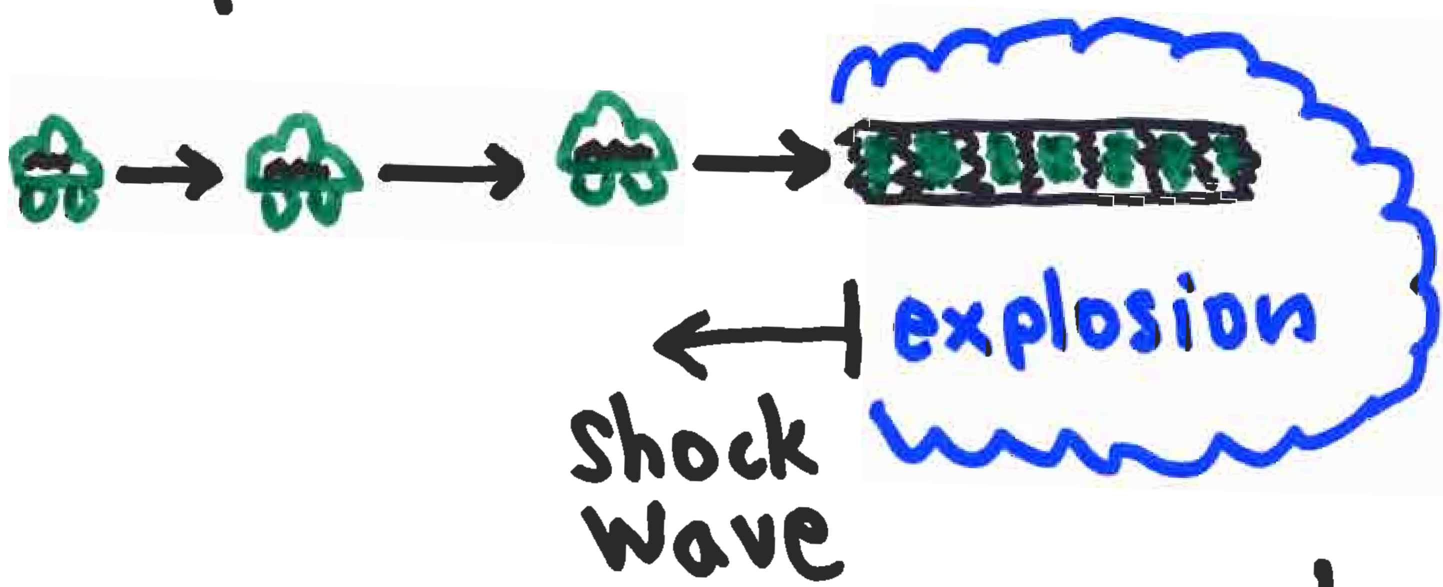


- The shock drives a jump discontinuity in the curvature of spacetime

"$\partial^2 g_{ij} \approx K\,T[\rho, p, u]$"

At shock, ρ, p, u discontinuous

Example: Traffic Picture



" Shock waves always propagate into side with lower density"

$\Updownarrow$

entropy Condition

THE CONSTRAINTS AT Shock

① g_{ij} must be continuous
(No jump in g_{ij} or M)

② ρ, p must jump down going outward across shock
(Entropy Condition)

③ A conservation Constraint must be met

* Entropy Condition breaks the time-reversal symmetry of Einstein-Euler Equations

(Theory - ISRAEL, Sm-Te)

Final Equations:

$p = \sigma \rho$

$\sigma \equiv \text{constant}$

$$S' = 2S(1+3u)\{(\sigma-u)+(1+u)S\} = F(S,u)$$

$$u' = (1+u)\{-(1-3u)(\sigma-u)+6u(1+u)S\} \equiv G(S,u)$$

(Autonomous System)

$$\text{Big Bang}\} \equiv 0 \le S \le 1 \equiv \{\text{Emerges From White Hole}$$

— Entropy Condition —

$$S < \left(\frac{1-u}{1+u}\right)\left(\frac{\sigma-u}{\sigma+u}\right) \equiv E(u)$$

Main Results:

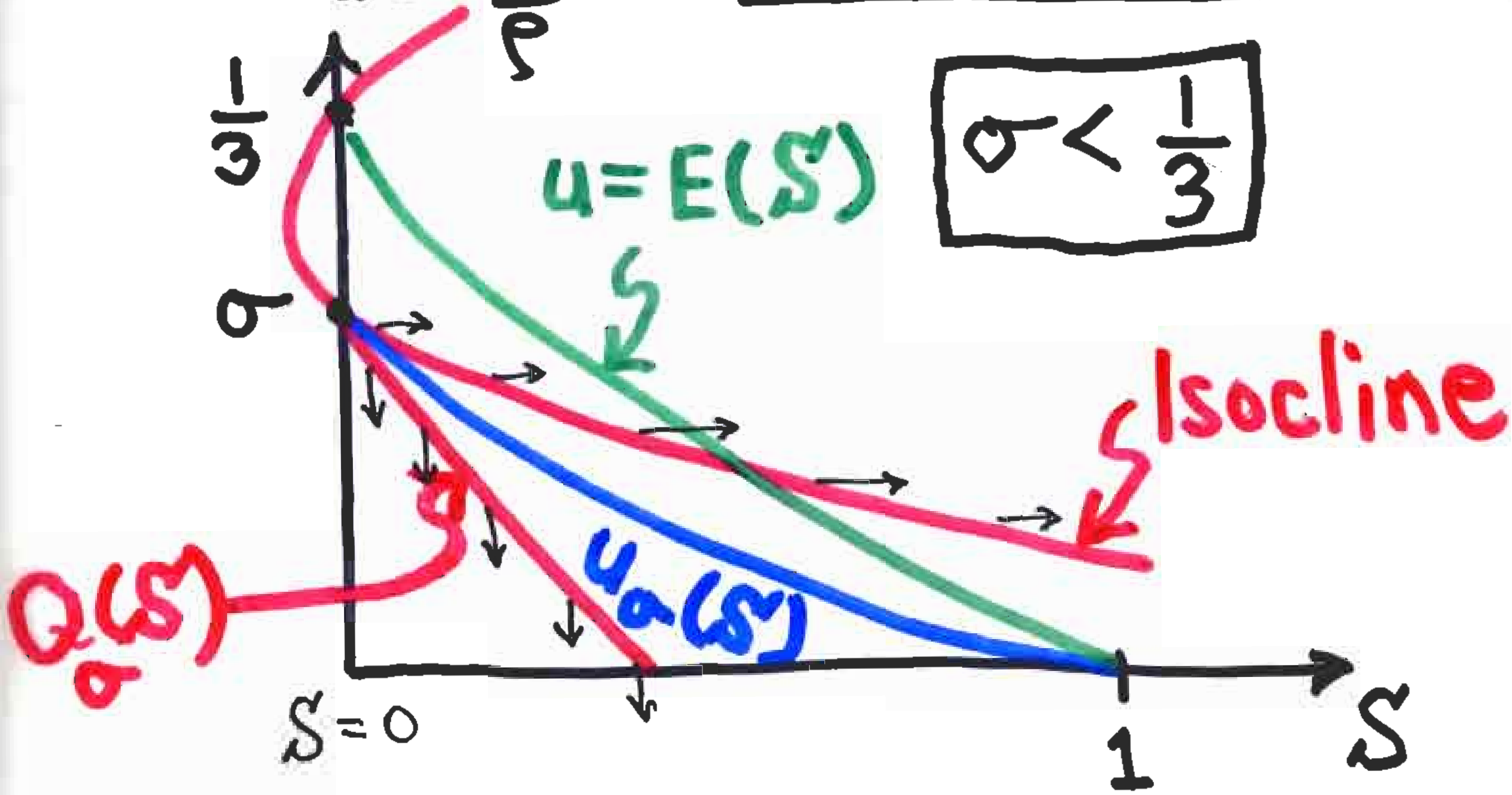
Theorem ① For every σ, $0<\sigma<1$, $\exists$ a unique Soln of (1),(2) that meets Entropy condt $\forall\ 0<\delta\leq 1$ and

$$0<u_\sigma(\delta)<\operatorname{Min}\left\{\tfrac{1}{3},\sigma\right\}$$

$$\lim_{\delta\to 0} u_\sigma(\delta)=\operatorname{Min}\left\{\tfrac{1}{3},\sigma\right\}$$

$$\lim_{\delta\to 1}\bar{\rho}=0=\lim_{\delta\to 1}\bar{p}$$

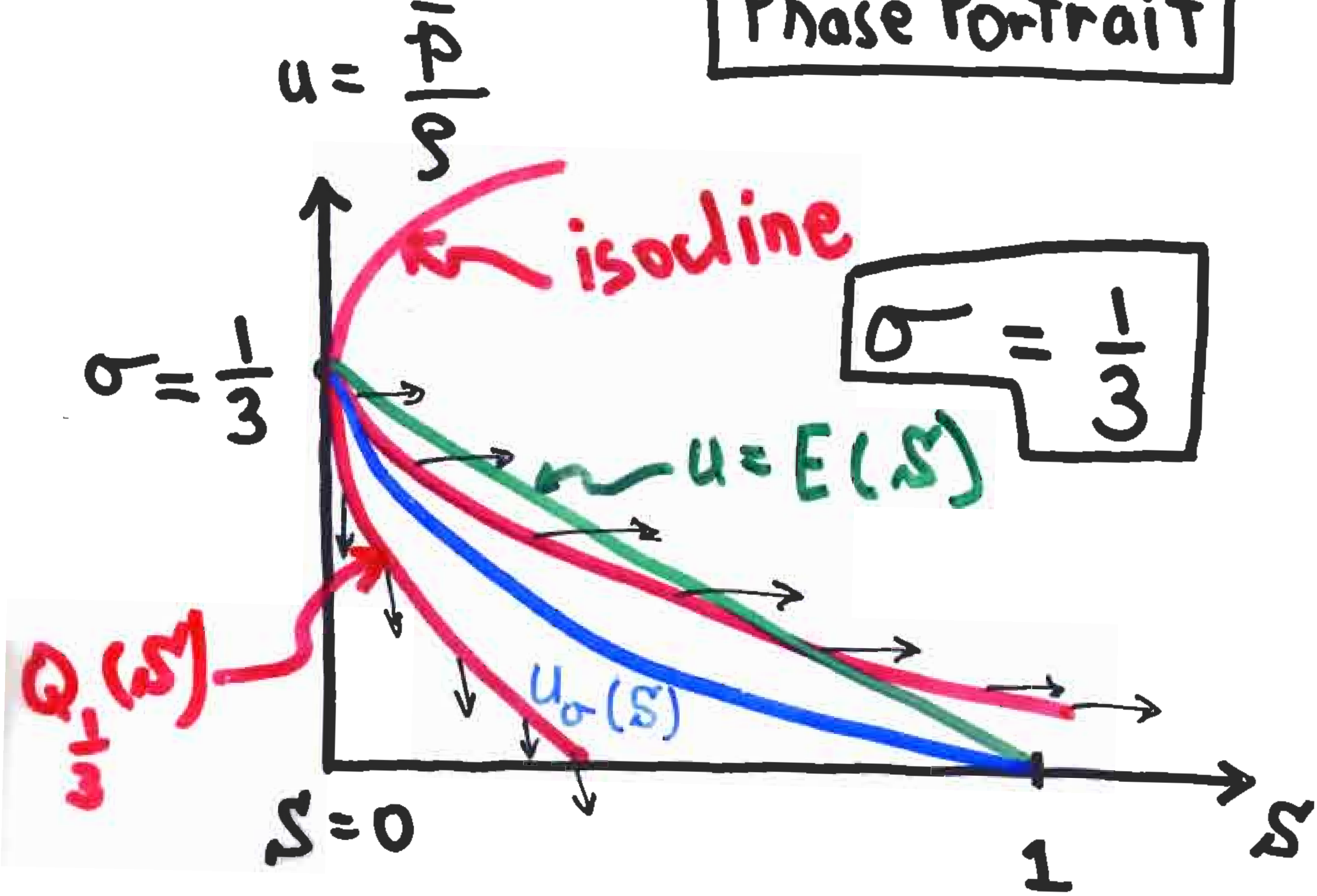
Phase Portrait



- Degenerate rest pts S=0 u = $\sigma, \frac{1}{3}$
- $\sigma = \frac{1}{3}$ special
- $S = 0 \Leftrightarrow$ Big Bang
- $S = 1$ shock wave emerges from

Black Hole as a p=0
Oppenheimer-Snyder Solution
≈ "Supernova"

Phase Portrait



- $\sigma = \frac{1}{3}$, $S = 0$ doubly degenerate rest pt.

$u_\sigma(S) \sim \sqrt{S}$ $\quad \frac{1}{3} - u_\sigma(S) \sim \frac{4}{3}\sqrt{S}$

$\Rightarrow$ Shock speed $\rightarrow 1$ as $S \rightarrow 0$

$$\text{shock speed} = \frac{1}{\sqrt{S}} \, \frac{\sigma - u_\sigma(S)}{1 + u_\sigma(S)}$$

■ **Theorem** ② For $0 < \sigma \leq \frac{1}{3}$, the shock wave is everywhere **subluminal**:

In Fact: $s_\sigma(\xi)$ = shock speed (Rel. to FRW)

$$\lim_{\xi \to 0} s_\sigma(\xi) = 0, \quad \sigma < \frac{1}{3}$$

$$\lim_{\xi \to 0} s_\sigma(\xi) = +\infty, \quad \sigma > \frac{1}{3}$$

$$\lim_{\xi \to 0} s_\sigma(\xi) = 1, \quad \sigma = \frac{1}{3}$$

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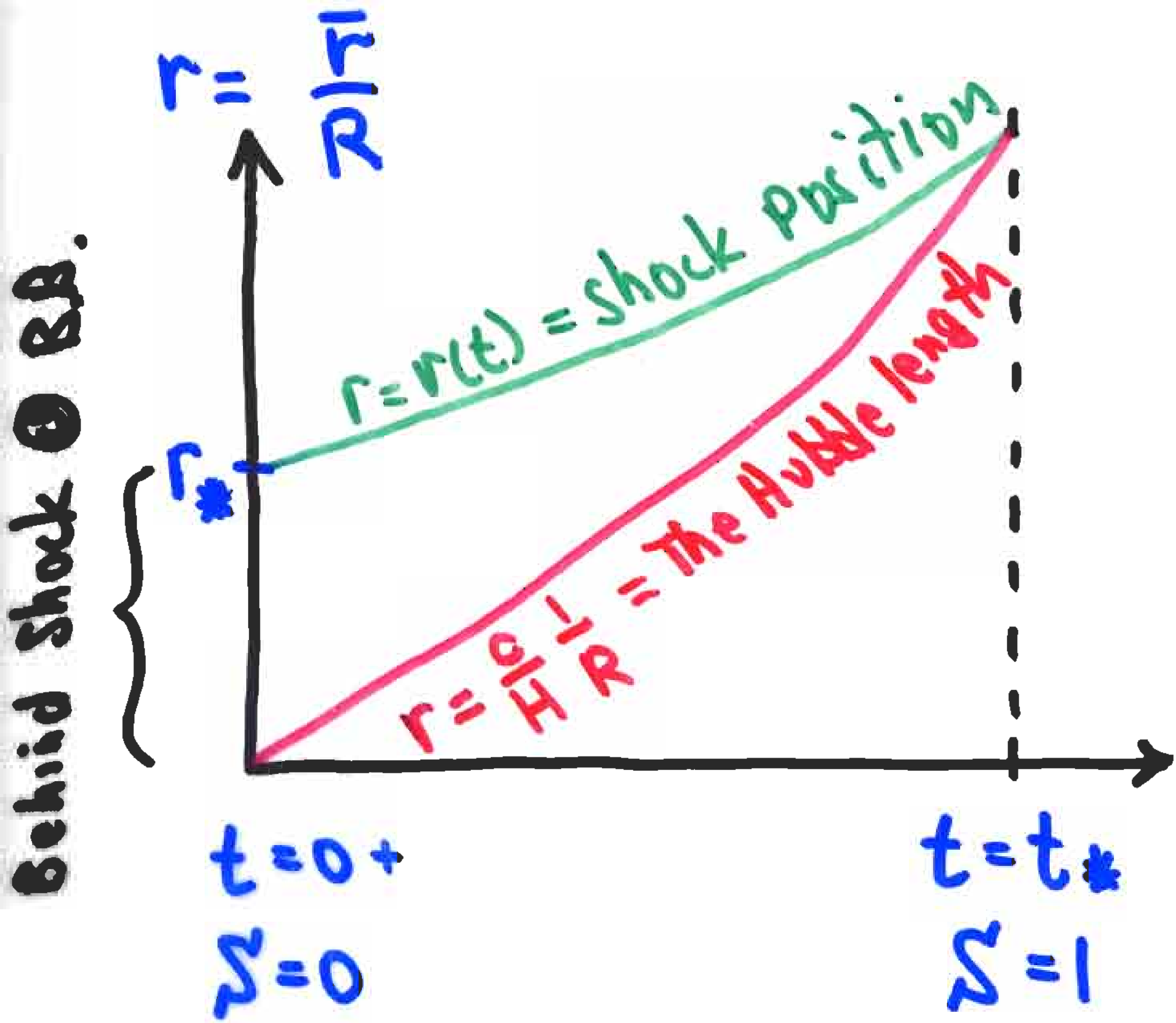
▪ <u>Conclude</u>: The analysis is picking out the equation of state $\sigma = 1/3$

$$p = \frac{1}{3}\rho$$

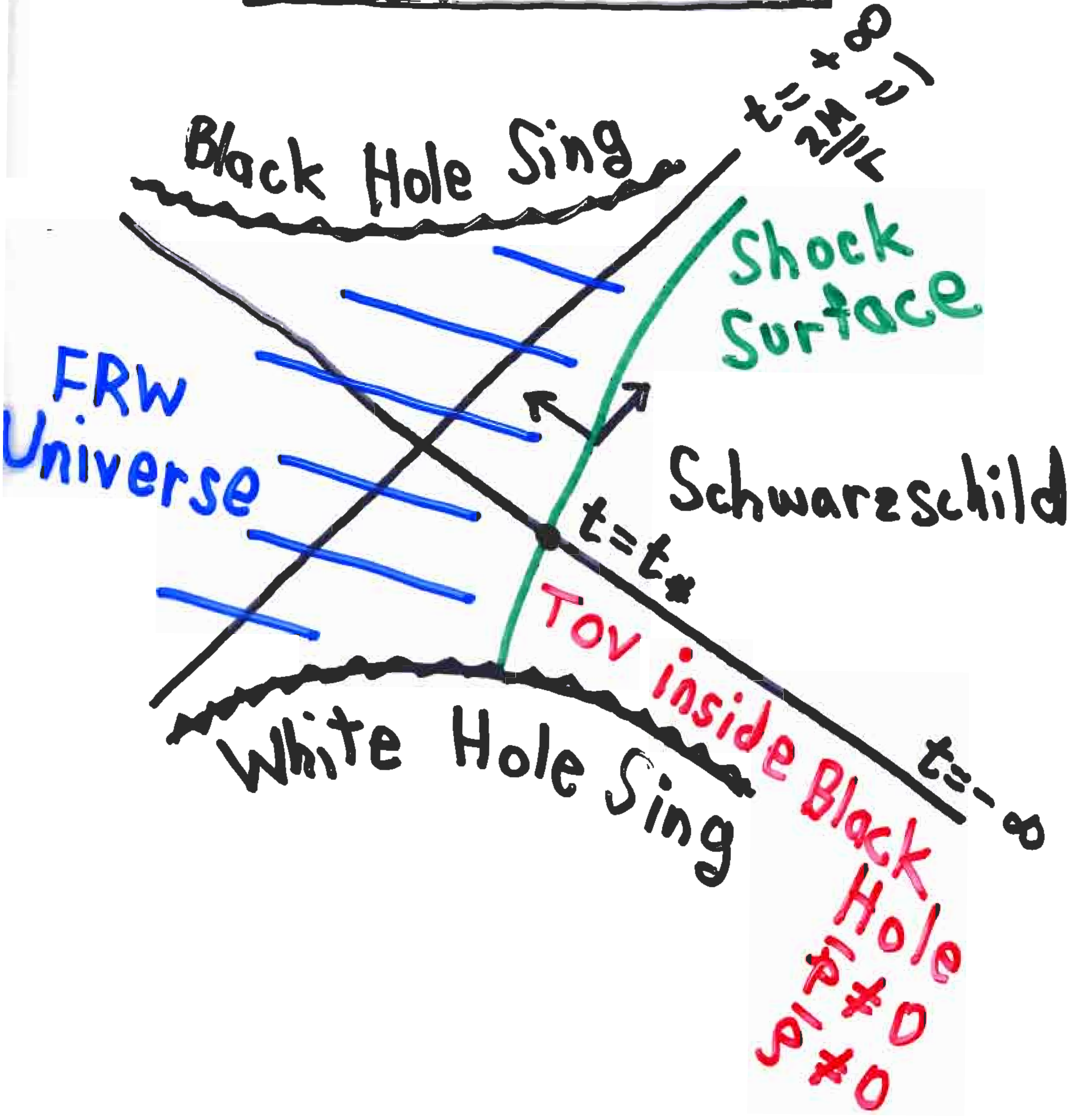
(Correct for early Big Bang Physics!)

as <u>special</u>



The Hubble length catches up to the shock at $\xi = 1 \Rightarrow$ emerges from the Black Hole

Kruskal Picture



Summary

- With the shock wave, the Big Bang is an explosion of Finite Total Mass
- The correct value $\sigma = \frac{1}{3}$ comes out of the analysis as special
- Information about the shock propagates inward from the wave

⇒ arbitrarily large region of uniform expansion at the center ~ standard model

Entropy Condt Breaks Time Symmetry*

- Chooses Explosion over Implosion (c.f. OS)
- Fixes initial condt $S=1, u=0$

⇒ unique global soln

⇒ shock continues to OS Soln out of White Hole

* Einstein + Compressible Euler Eqn's are time-reversible

⇒ Extra condition required to break time symmetry

Black Hole ↔ White Hole

k2

- Shock Solution qualitatively the same $\forall\ \sigma, r_*$ after Big Bang

$\Downarrow$

Generic Behavior for general eqn. of state $p = P(\rho)$?

- More general eq of state

$$p = P(\rho)\,,\quad \bar{p} = \bar{p}(\bar{\rho})$$

$\Rightarrow$ rarefaction waves

$\leadsto$ impossible to model in exact solution

<u>Moreover</u>: We Expect 'any' White Hole explosion of finite mass should evolve ≈ like this because

$$\frac{2M}{r} > 1 \text{ + Expansion}$$

$\Downarrow$

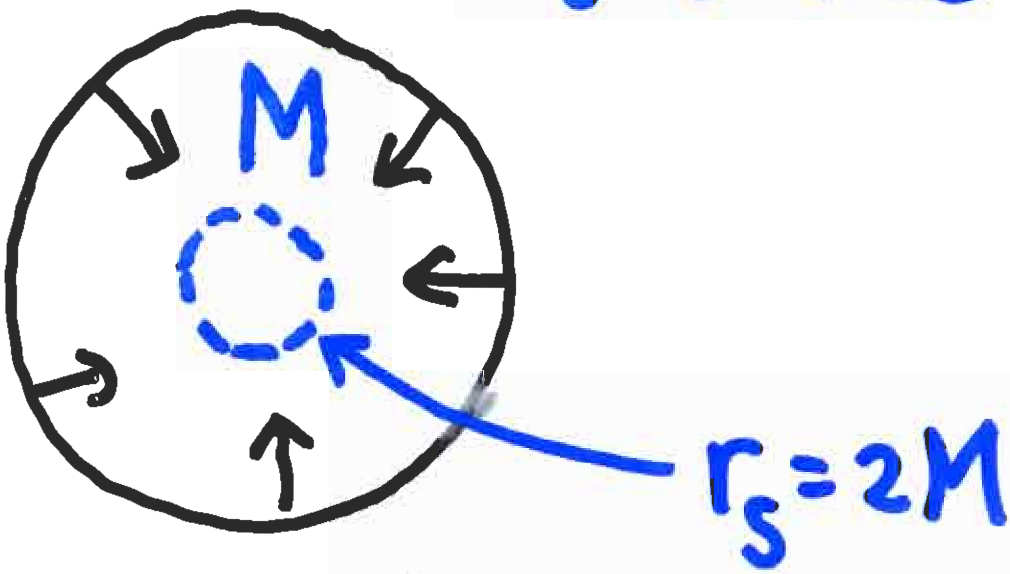
$$\frac{2M}{r} < 1 \quad \text{Eventually}$$

$\Downarrow$

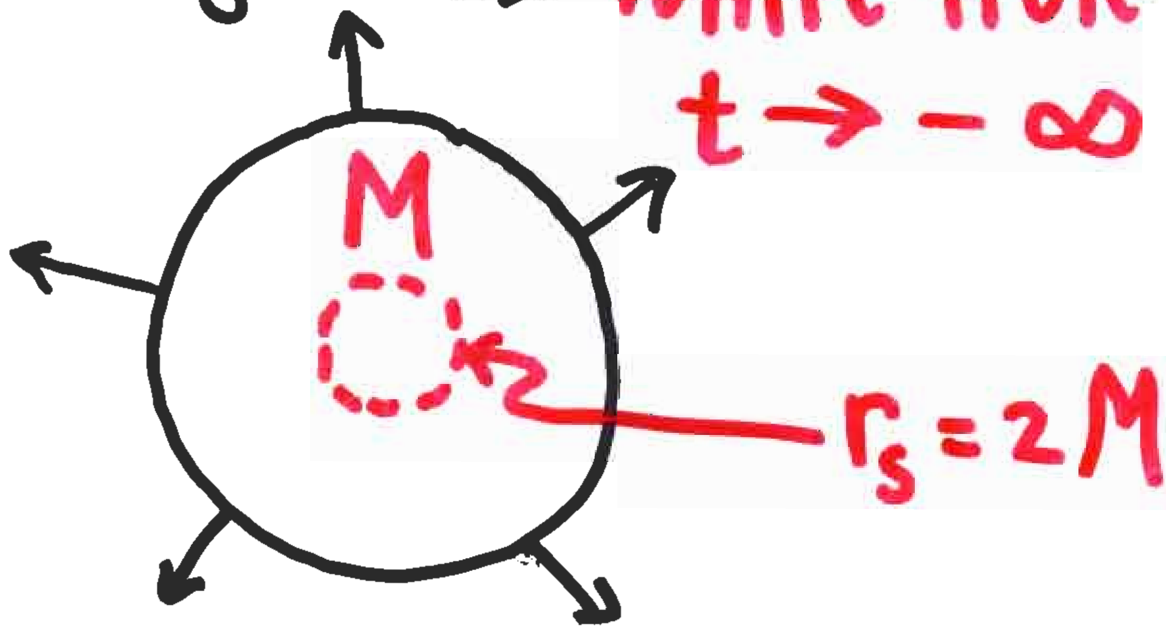
Decay to localized explosion outside Black Hole

Black Hole ↔ White Hole

- Collapse too great ⇒ Black Hole $t \to +\infty$



Expansion too great ⇒ White Hole $t \to -\infty$



Q: Could there be a Connection?

Conclusion

- We have a refinement of FRW metric in which Big Bang produces a <u>finite</u> total Mass
- In the shock wave model, the entire universe is created at the Big Bang but the total mass of the explosion is finite
- $\exists$ free parameter $\approx$ total mass of explosion

Q: Does $M < \infty$ plus uniformity out to one Hubble length $\Rightarrow$ generically like this?

Recent Work (Sm-Te)

"How a finite mass shock-wave cosmology might evolve from an inflationary spacetime"

(To appear)

Q: (Highly Speculative)
Could 'Dark Energy' be a sort of Coriolus force due to overall motion thru a spacetime beyond the galaxies?