The Steps Along The Way Whereby Einstein's General Theory Enabled The Rise of Present Day Cosmology

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General Relativity enabled cosmology

Key steps on the way

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2. Curvature and topology of space

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9. A coherent picture?

1: Consistent cosmological models

General relativistic before Newtonian

Problems with Newtonian models
(Newton? Laplace? Seeliger (1895) inconsistent: divergences)

Einstein static universe model (1917):
Local gravity everywhere $\Rightarrow$ consistent universe model
Gravity curves spacetime.

Static ($\Lambda > 0$): taken for granted by all
But unstable (Eddington)

(Generalized) Newtonian models much later

Milne and Mcrea: consistent Newtonian model (1934)

Heckmann and Schücking: spatially homogeneous?
Accn $= \{$acceleration $+$ inertia$\}$, new conditions at infinity

Positively and negatively curved 3-spaces

$$ds^2 = -dt^2 + a^2(t)\{dr^2 + f^2(r)d\Omega^2\} \tag{1}$$

in comoving coordinates: $u^a = \delta^a_0$, where $a(t)$ is the scale factor and

$$f(r) = \{\sin(r), r, \sinh(r)\} \; if \;\; k = \{+1, 0, -1\}$$

The spatial sections need not be flat. Euclid is undermined: Matter curves space (Gauss-Codazzi equations + EFE).

Then $k = +1$ necessarily implies closed spatial sections;

However $k = 0, -1$ allow closed spatial sections.

The topology need not be simply connected.
Indeed infinite possibilities if $k = -1$.

Space and spacetime

Preferred 4-velocities

In the real universe: there is always a preferred 4-velocity field $u^a(x^j)$: $u^a = dx^a/ds$, $u^a u_a = -1$ (Weyl, Ehlers). For example:

- The average motion of matter
- The Cosmic Background Radiation frame (the CBR is isotropic)
- The Ricci Eigenframe: $R_{ab}u^a = \lambda u_b$

In a Robertson-Walker geometry, they all coincide.
Generically (e.g. perturbed FLRW): the last.

Then: space and time are split into space and time by u^a, h_{ab} where

$$h_{ab} := g_{ab} + u_a u_b \Rightarrow h_a^b h_b^c = h_a^c, h_{ab}u^b = 0, h^a{}_a = 3$$

Then $X_{\|} = X_a u^a$, $X_{\perp}^b = X_a h^{ab}$, $\dot{X}^a = X_{a;b}u^b$, $D_a X_b = h_a^c h_b^d X_{d;c}$

The problem with de Sitter and Anti-de Sitter spaces: no preferred 4-velocity (spacetimes of constant curvature: Schrödinger).

3: The expanding and evolving universe

Geometry as physics: gravity governs spacetime of cosmology

Non-static models: Dynamic geometry, scale factor $a(t)$
(Friedmann, Lemaître: not Einstein!)

Raychaudhuri equation (gravitational attraction)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} \tag{2}$$

Friedmann equation (energy equation)

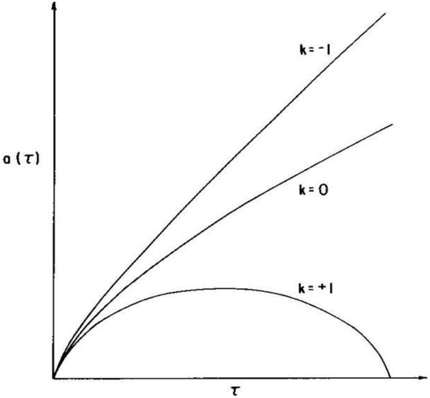
$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho}{3} + \frac{\Lambda c^2}{3} - \frac{kc^2}{a^2} \tag{3}$$

Conservation equation (consistency)

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0 \tag{4}$$

Equation of state $p = p(\rho)$: matter drives geometry

The basic dynamics (Robertson 1933)



Singular start, then competition between KE and PE.
Spatial curvature linked to recollapse: $\Omega := 8\pi G\rho/3H^2$ takes value $\Omega = 1$ for the critical case, where $H(t) := \dot{a}(t)/a(t)$.

More complex when $\Lambda \neq 0$: static and asymptotic models possible.

Energy conditions

$$\rho + \frac{3p}{c^2} \geq 0 \tag{5}$$

$$\rho + \frac{p}{c^2} \geq 0 \tag{6}$$

implies a singularity a finite time $t_0 < (1/H_0)$ ago if $\Lambda \leq 0$:

$$\{H_0 > 0,\ \Lambda \leq 0\} \Rightarrow \left[\lim_{t\to t_0} a(t) = 0,\ \lim_{t\to t_0} \rho(t) = \infty\right] \tag{7}$$

A crisis for physics: a start to time, space, and physics itself [Wheeler]

Singularity Theorems

Hawking and Penrose

Basis: General Raychaudhuri equation (Ehlers)

$$\dot{\Theta} + \frac{1}{3}\Theta^2 + 2(\sigma^2 - \omega^2) - \dot{u}^a{}_{;a} + \frac{1}{2}\kappa(\rho + 3p/c^2) - \Lambda = 0. \qquad (8)$$

But direct methods (even in Bianchi models) cannot prove no singularity.

Global methods: Penrose (1965), Hawking (1966)
Domain of dependence, Boundary of future, Null Raychaudhuri equations
$\Rightarrow$ singularities must exist (type not determined) provided energy conditions satisfied

Inflation and scalar fields: a reprieve?

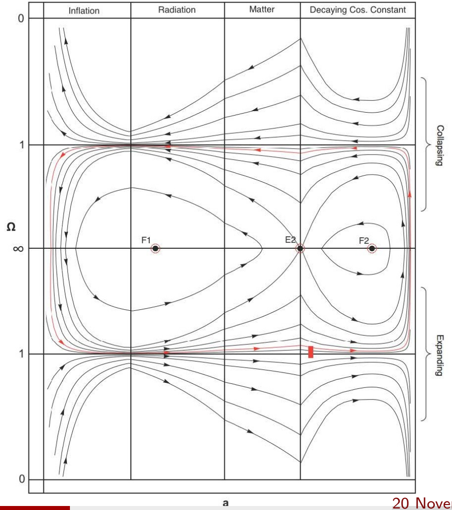
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi), \;\; p = \frac{1}{2}\dot{\phi}^2 - V(\phi) \qquad (9)$$

So $\rho + 3p = 2\dot{\phi}^2 - 2V(\phi)$ can be negative if potential dominated.

Cyclic models possible for standard GR

[arXiv:1511.03076]

If we have $k = +1$ and a decaying cosmological constant ... Ω versus $a(t)$



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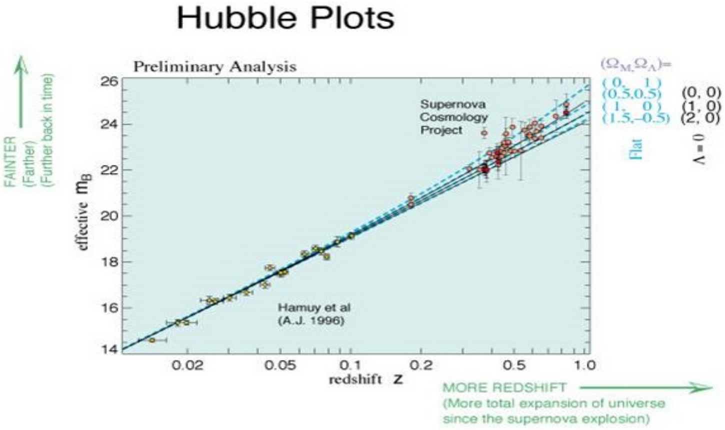
- An accelerating universe

The supernova data

SN1a as standard candles:



The universe is presently accelerating

$\Rightarrow$ Dark energy is present: $\rho + 3p/c^2 < 0$.

6: Observational and causal limits: horizons

Horizons

- Particle horizons: limit causality

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- Visual horizons:
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- Visual horizons:
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- Event horizons:
  The far future:
  Nothing about observations in cosmology.

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Refocussing of the past light cone

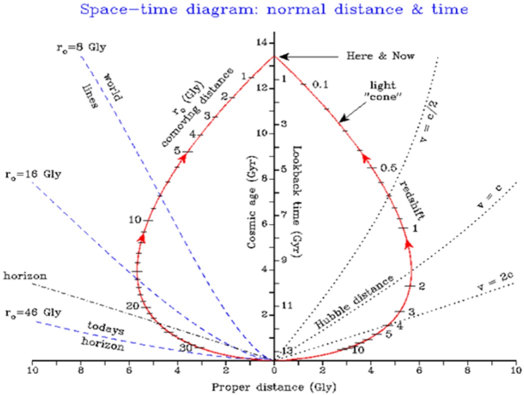

Figure: *Refocussing of Past Light Cone* [Ned Wright]

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Horizons: Penrose conformal diagram

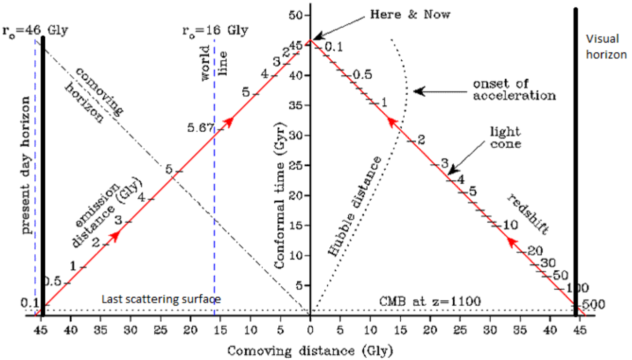

Figure: *Past Light Cone in conformal coordinates* [Ned Wright].
Particle horizon (causal limit) and visual horizon (observational limits)

7: Structure formation and inhomogeneity

Gravitational attraction forms structure: Perturbation equations

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- Interactions: CMB polarisation

The gauge problem
The issue

One can choose a constant time surface $\{t = const\}$ so as to make a density inhomogeneity

$$\delta\rho(t, x^i) := \rho(t, x^i + \delta x^i) - \rho(t, x^i) \quad (10)$$

vanish: simply choose $\{t = const\}$ surfaces to be the same as the $\{\rho = const\}$ surfaces, then

$$\rho(t, x^i + \delta x^i) = \rho(t, x^i) \Rightarrow \delta\rho = 0.$$

Indeed the value determined for $\delta\rho(t, x^i)$ is arbitrary because of the coordinate freedom $t \to t' = t'(t, x^i)$ allowed by General Relativity. This allows apparent density variations that are in fact gauge modes.

NB: this problem does not occur in Newtonian theory

Gauge invariant approaches

Bardeen; 1+3 covariant

Use Bardeen variables, or CGI variables (Hawking, Ellis and Bruni). This 3+1 gauge invariant and covariant formalism centres on the comoving fractional spatial density gradient, defined as

$$\mathcal{D}(\rho)_a := h_a^b \rho_{,b}/\rho \tag{11}$$

for an observer with 4-velocity u^a ($u_a u^a = -1$), where $h_{ab} := g_{ab} + u_a u_b$ projects orthogonal to u^a.

Sachs Theorem (Stewart and Walker): *any quantity which vanishes in the background spacetime is gauge invariant.*

1+3 CGI variables for geometrically preferred u^a (Ricci eigenvectors):
  Fluid flow: acceleration $\dot{u}^a$, shear σ_{ab}, vorticity ω^a
  Weyl tensor: $E_{ab},\ H_{ab}$ (Maxwellian equations)
  Spatial Inhomogeneity: density $\mathcal{D}(\rho)_a$, pressure $\mathcal{D}(p)_a$, expansion $\mathcal{D}(\theta)_a$.

Perturbation equations

General relativity structure formation

Take the spatial gradient of the general form of Raychaudhuri's equation and the density conservation equation.
When $w = p/\rho = const$ and $\Lambda = 0$, the linearised growth equation for modes of wave number n obtained this way is

$$\ddot{\mathcal{D}}_a + (\frac{2}{3} - w)\theta\,\dot{\mathcal{D}}_a - \left(\frac{(1-w)(1+3w)}{2}\kappa\rho\right)\mathcal{D}_a - w\frac{n^2}{a^2}\mathcal{D}_a = 0 \quad (12)$$

which directly gives the general relativistic version of the Jeans' length (competition between gravitational attraction and restoring pressure) and the density perturbation growth laws. When $w = 0$ this reduces to

$$\ddot{\mathcal{D}}_a + \frac{2}{3}\theta\,\dot{\mathcal{D}}_a - \frac{1}{2}\kappa\rho\mathcal{D}_a = 0 \quad (13)$$

which directly gives Lifshitz' 1946 results for pressure free matter.

Kinetic theory

Interaction of matter and radiation

CGI relativistic kinetic theory

Photons, $p^a = E(u^a + e^a)$, $e^a e_a = 1$, $e^a u_a = 0$. Distribution function:

$f(x^i, p^j, E) = f(x^i, E) + f(x^i, E)_a e^a + f(x^i, E)_{ab} e^a e^b + f(x^i, E)_{abc} e^a e^b e^c ...$

where $f(x^i, E)_{a_1..a_N} = f(x^i, E)_{A_N}$ are PSTF tensors, $A_N := a_1..a_N$.

Then with $p = \rho/3$ (radiation), T_{ab} is expressed entirely in terms of integrals of $f(x^i, E)$, $f_a(x^i, E)$ and $f_{ab}(x^i, E)$ as follows:

$$\rho = 4\pi \int_0^\infty E^3 F dE, \;\; q^a = \frac{4\pi}{3} \int_0^\infty E^3 F^a dE, \;\; \pi^{ab} = \frac{8\pi}{15} \int_0^\infty E^3 F^{ab} dE.$$

The matter stress tensor is

$$T_{ab} = \frac{1}{3}(4\rho u_a u_b + \rho g_{ab}) + q_{(a} u_{b)} + \pi_{ab}$$

the higher order terms do not enter the EFE.

The Boltzmann equations

Eaxct non-linear Boltzmann equations generally (except for the first few) link 5 consecutive moments $f(x^i, E)_{a_{N+2},\dots,a_{N-2}}$ to a collision term:

$$E^{-1} b_{A_\ell} = \dot{F}_{<A_\ell>} - \frac{1}{3}\theta E F'_{A_\ell} + D_{<a_\ell} F_{A_{(\ell-1)>}} + \frac{(\ell+1)}{(2\ell+3)} D^a F_a A_\ell$$
$$-\frac{(\ell+1)}{(2\ell+3)} E^{-(\ell+1)} \left[E^{(\ell+2)} F_{aA_\ell}\right]' A^a - E^\ell \left[E^{1-\ell} F_{<A_{\ell-1}}\right]' A_{a_\ell>}$$
$$-\ell \omega^b \epsilon_{bc(a_\ell} F^c_{A_{\ell-1})} - \frac{(\ell+1)(\ell+2)}{(2\ell+3)(2\ell+5)} E^{-(\ell+2)} \left[E^{\ell+3} F_{abA_\ell}\right]' \sigma^{ab}$$
$$-\frac{2\ell}{(2\ell+3)} E^{-1/2} \left[E^{3/2} F_{b<A_{\ell-1}}\right]' \sigma^b_{a_\ell>} - E^{\ell-1} \left[E^{2-\ell} F_{<A_{\ell-2}}\right]' \sigma_{a_{\ell-1} a_\ell>}.$$

(dot is $\partial/\partial t$, prime is $\partial/\partial E$, $< .. >$ is PSTF part, b_{A_ℓ} is collision term).

[Maartens, Gebbie, Ellis: arXiv astro-ph/9808163;
Challinor, Lewis, Lasenby: arXiv:astro-ph/9911177].

The data: CMB power spectrum

Inflation predictions

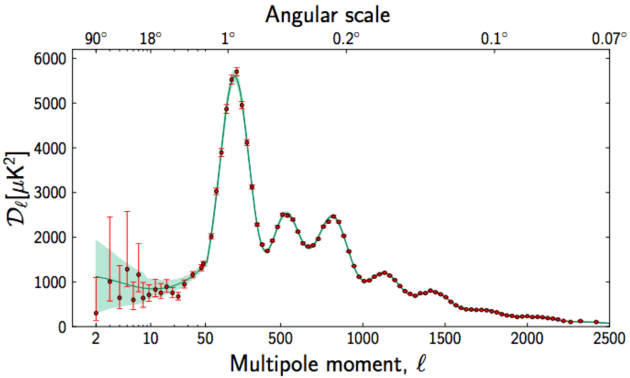

Figure: The CMB power spectrum (Planck)

The agreement of theory and observation (using observation to fix a theory parameter)

The data: Baryon Acoustic Oscillations

Inflation predictions

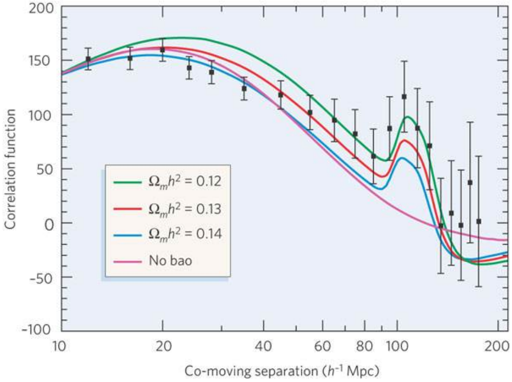

Figure: The matter power spectrum

The agreement of theory and observation (radiation and matter power spectra)

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Inhomogeneous models can explain SN1a results with no dark energy

Validity of the Copernican Principle

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- Kinetic SZ effect and CMB spectrum:
  Probably rules models out

8: Gravitational lensing

The intervening screen

Bending of light by matter (Einstein 1915, 1936)

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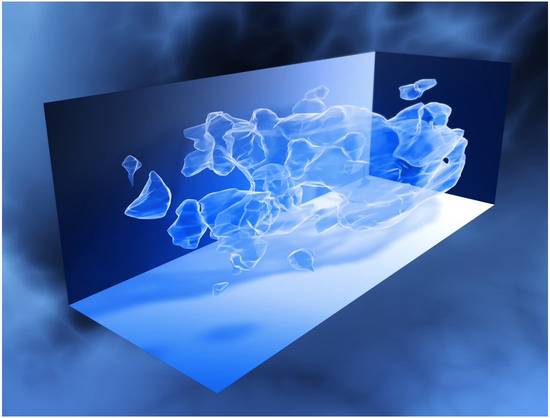
- Lenses as telescopes:
  Seeing further

A key cosmological tool

Lensing as a tool in cosmology

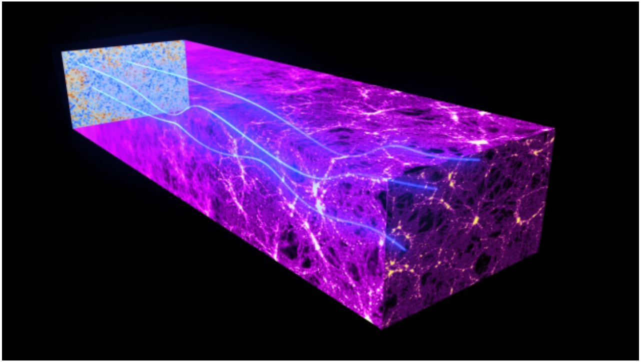
Mapping dark matter



Dark matter distribution - weak gravitational lensing (Hubble Space Telescope).

Lensing as a tool in cosmology

Affecting CMB observations



CMB photons are deflected by the gravitational lensing effect of massive cosmic structures. Data from the Planck satellite enables measuring gravitational lensing of the CMB over the whole sky.

9: A coherent picture?

Cosmic concordance

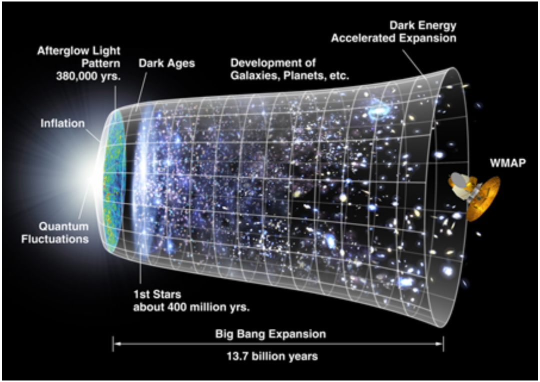


Figure: The stages of the universe (NASA)

The agreements

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  Dark matter, dark energy, the inflaton
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  The right hand side of the Field Equations
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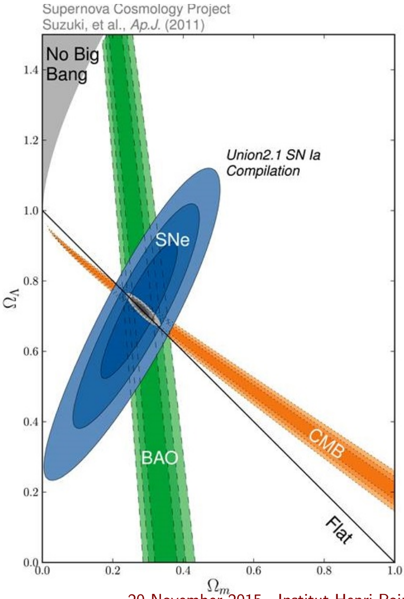
- Small universes? - circles in the sky
- The most sensitive tests: structure formation:
  CMB anisotropy: the effect of the universe on local physics

Testing the standard model

The supernova data is based on observing the background model geometry directly. The BAO data reflects how the background model has affected structure formation. The WMAP data represents how this structure affects the observed CMB temperature power spectrum.

It is the latter two, based in perturbations about the FLRW model, that together give us the best estimates of the cosmological parameters Ω_Λ, Ω_m.



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cosmology as progress in physical science

Cosmology as physics

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  Apples, the Moon, and the universe
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- Atomic physics and quantum theory (Gamow, not Tolman):
  Matter-radiation equilbrium, recombination, black body radiation

Cosmology as physics

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cosmology as progress in physical science

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  Nuclear reactors and nucleosynthesis (Alpher, Gamow, Peebles)
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- Quantum gravity and creation, quantum cosmology:
  No solid ground. We can hypothesize with no real tests.

Conclusion: General relativity and cosmology

General relativity has made present day cosmology possible

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- GPS systems

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The greatest development of the theory is not so much the background model as the perturbations about it. Handling the gauge issue is crucial.