

A Brief History of Gravitational Lensing in Cosmology

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Isaac Newton on gravitational lensing (1704)

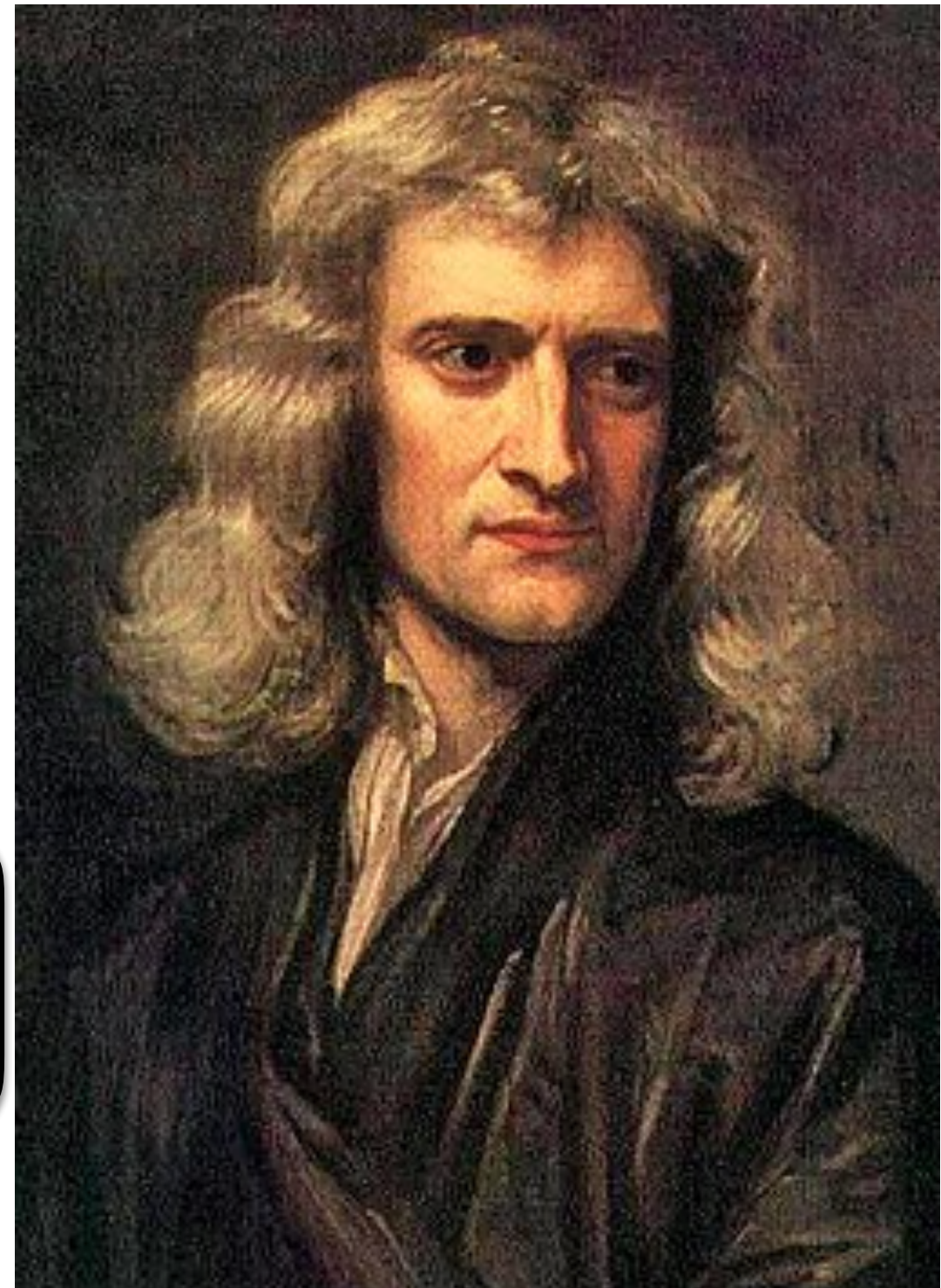
B O O K III.

When I made the foregoing Observations, I design'd to repeat most of them with more care and exactness, and to make some new ones for determining the manner how the Rays of Light are bent in their passage by Bodies, for making the Fringes of Colours with the dark lines between them. But I was then interrupted, and cannot now think of taking these things into farther Consideration. And since I have not finish'd this part of my Design, I shall conclude with proposing only some Queries, in order to a farther search to be made by others.

Query 1. Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action (*cæteris paribus*) strongest at the least distance?

Note: Ole Romer had measured speed of light (to 20% precision) in 1676

Newton in confinement
(from the plague)

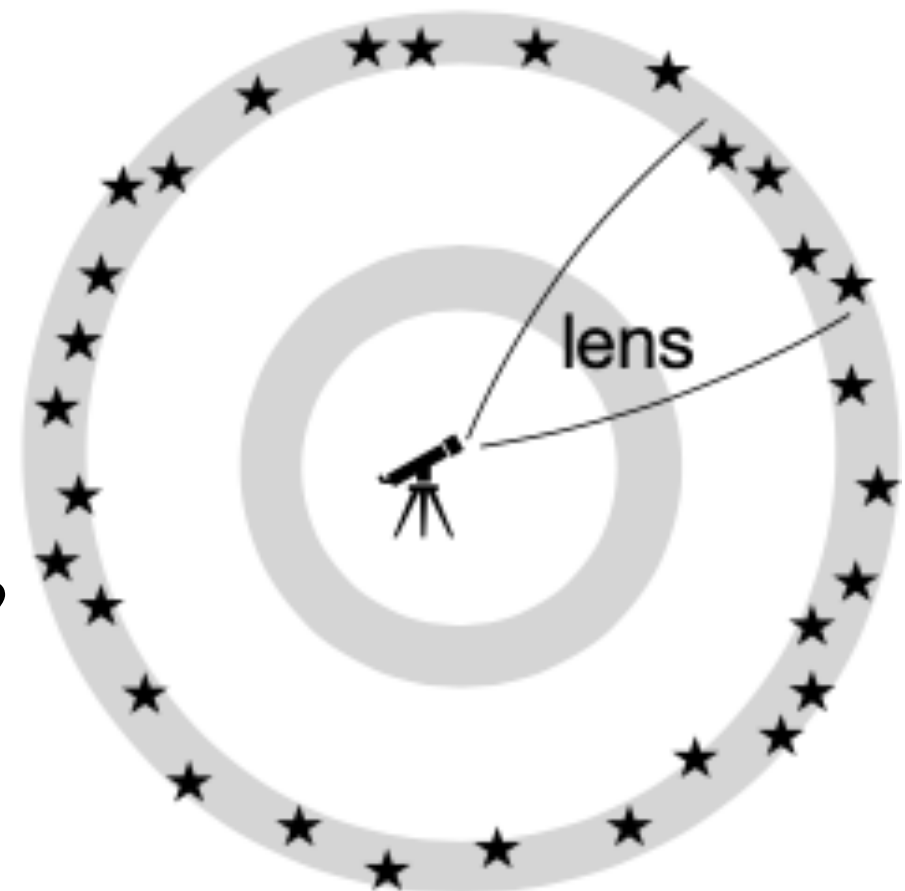
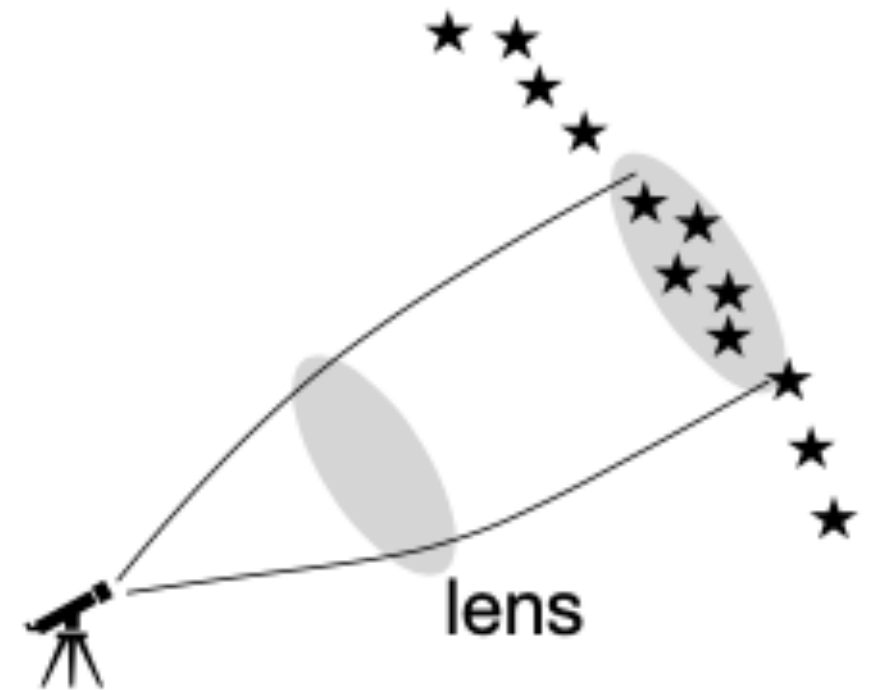


Why didn't Newton do "Newtonian Cosmology"

- *"All of the phenomena observable at the present could have been predicted by the founders of mathematical hydrodynamics in the 18th century, or even by Newton himself"* E.A. Milne and Bill McCrea (1934)
- Why weren't they?
- Newtonian theory can describe the dynamics of a uniform density expanding sphere of dust of arbitrarily large radius R .
 - it gives Friedmann's equation -- observers can't tell where the centre is -- the sphere can be arbitrarily large -- has 'horizon' and all other features of FLRW models
- But he had problems letting $R \rightarrow \infty$ (known as "Bentley's paradox")
- *"But if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space. And thus might the sun and fixt stars be formed..."*

What if Newton *had* done Newtonian cosmology?

- He'd have found Friedmann's eqⁿ, energy eqⁿ, continuity eqⁿ, for an expanding universe
 - You might ask "*what would have prompted him to do so?*". Good question: but it didn't stop Alexander Friedmann in 1922.
 - 7 years before the expansion was discovered by Hubble
- But he would probably have had difficulty with the angular diameter distance
 - for the same reason he had trouble with "Bentley's paradox"
- What'd he have said about "Hoekstra's paradox"?
 - does a spherical shell lens deflect light?



John Mitchell & Laplace -> Black holes ca. 1783



John Mitchell

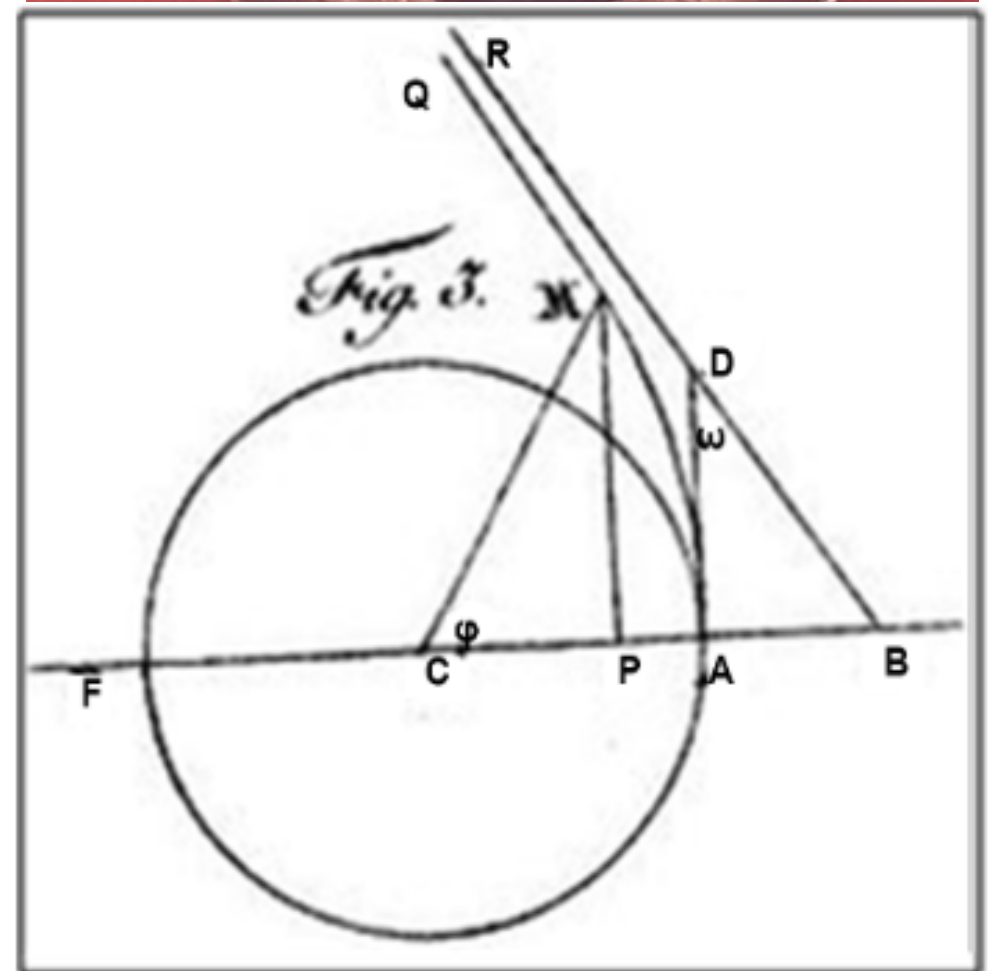
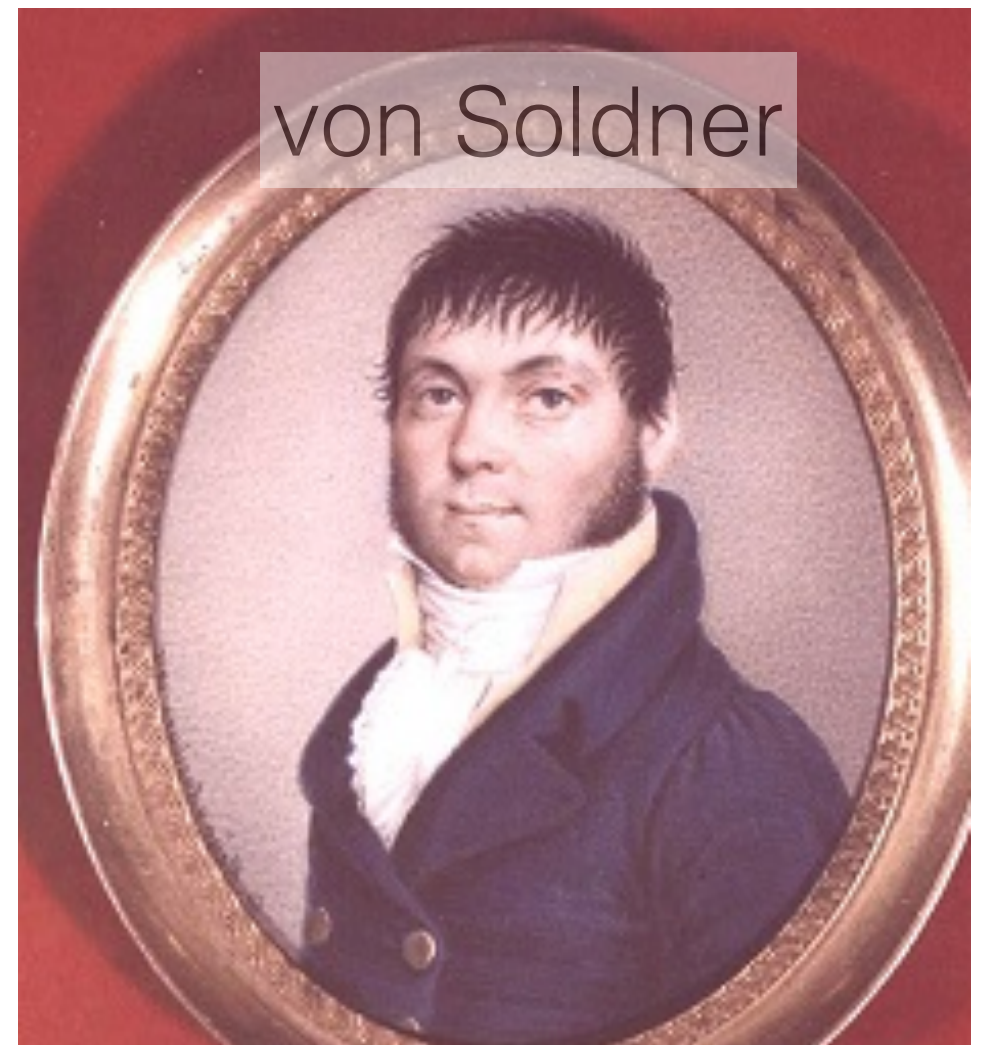
Pierre Simon de Laplace



1802: Solar light deflection = $0.84''$



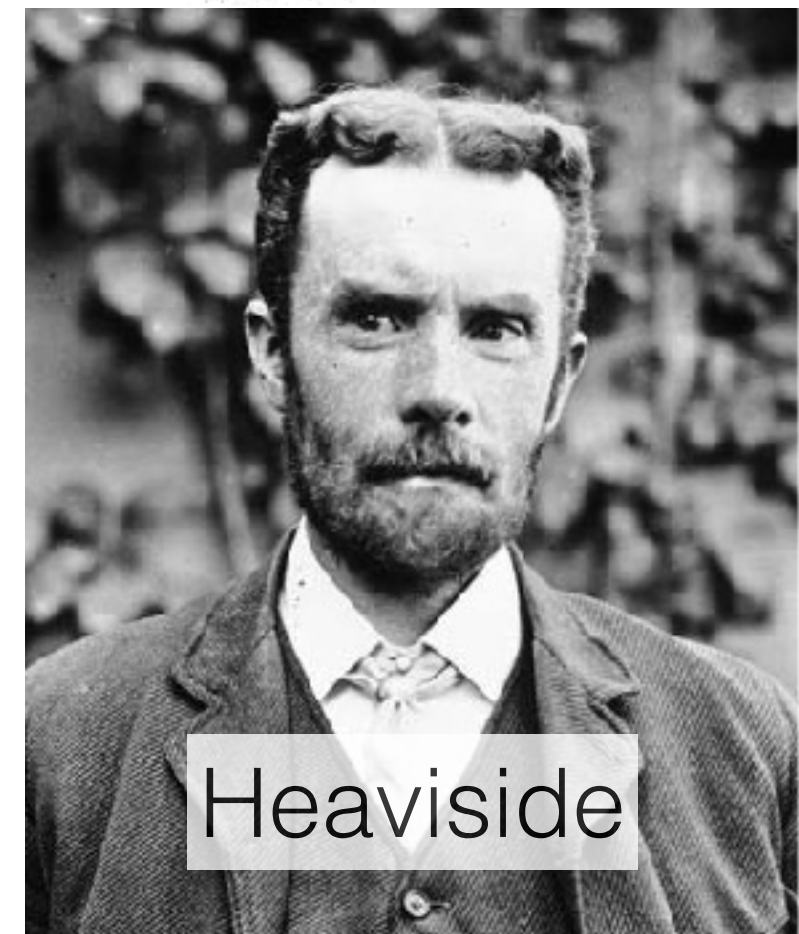
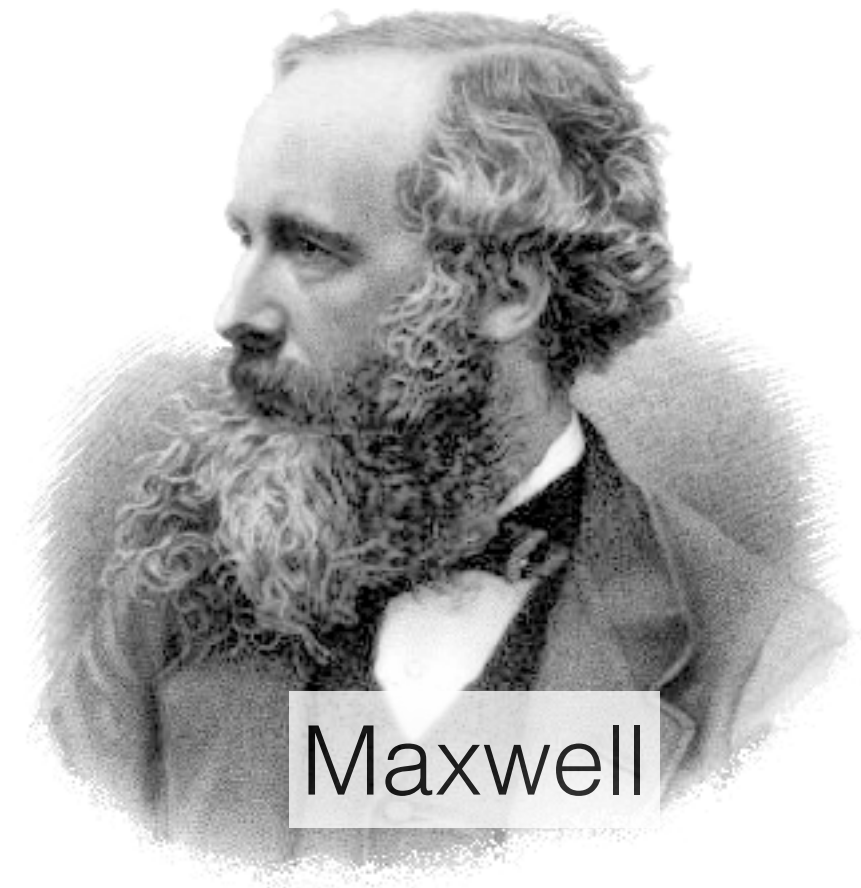
H. Cavendish



missing the famous factor 2 from GR

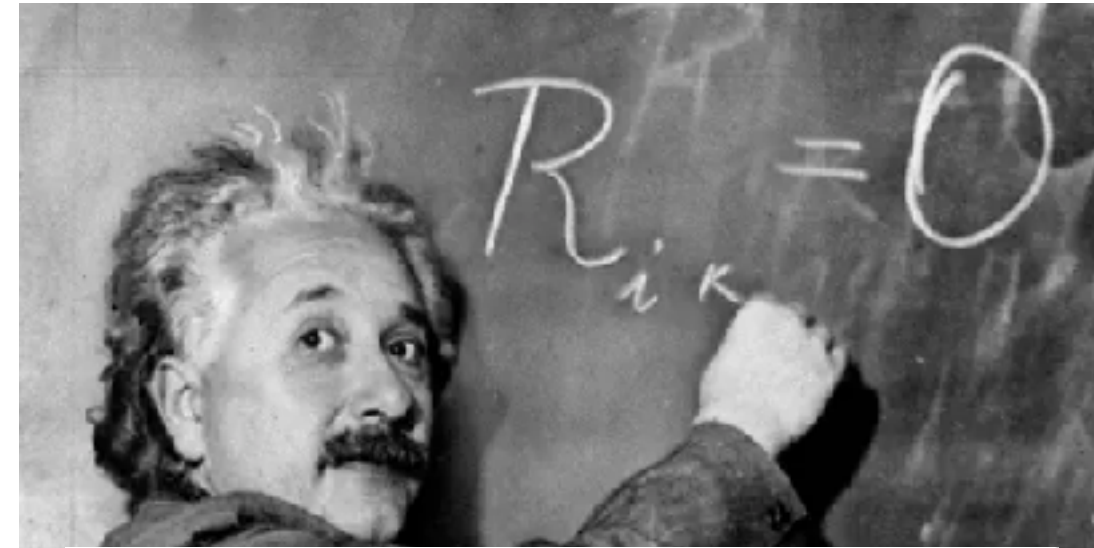
Why didn't Maxwell do gravity?

- Maxwell unified electricity and magnetism
 - a causal, relativistic, gauge, field theory...
- why didn't he follow up with gravity?
- he did get the stress tensor for gravity:
 - $T_{ij} = (g_i g_j - \frac{1}{2} \delta_{ij} |\mathbf{g}|^2) / 4\pi G$
 - just like Maxwell EM stress tensor
 - but = 32,000 tons per square inch here!
 - *"I do not think space is strong enough to withstand such a stress"*
- a sadly missed opportunity:
 - $\square A^\mu = j^\mu / \mu_0 \Rightarrow \square \bar{h}_{\mu\nu} = -T_{\mu\nu} / 16\pi G$
 - $dp^\mu / d\tau = q F^{\mu\nu} U_\nu \Rightarrow dp_\mu / d\lambda = -\frac{1}{2} h_{\alpha\beta, \mu} p^\alpha p^\beta$



Early 20th century: Einstein and GR

- 1911 - rocket thought experiments
 - predicts 0.84" solar bending angle
 - Lenard later accuses AE of plagiarism
- 1912 - Brazilian eclipse experiment
 - failed (to prove him wrong!)
- 1915 - GR paper published (with factor 2)
 - controversy over Hilbert paper
- 1919 - Eddington eclipse trip - success!



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less
Agog Over Results of Eclipse
Observations.

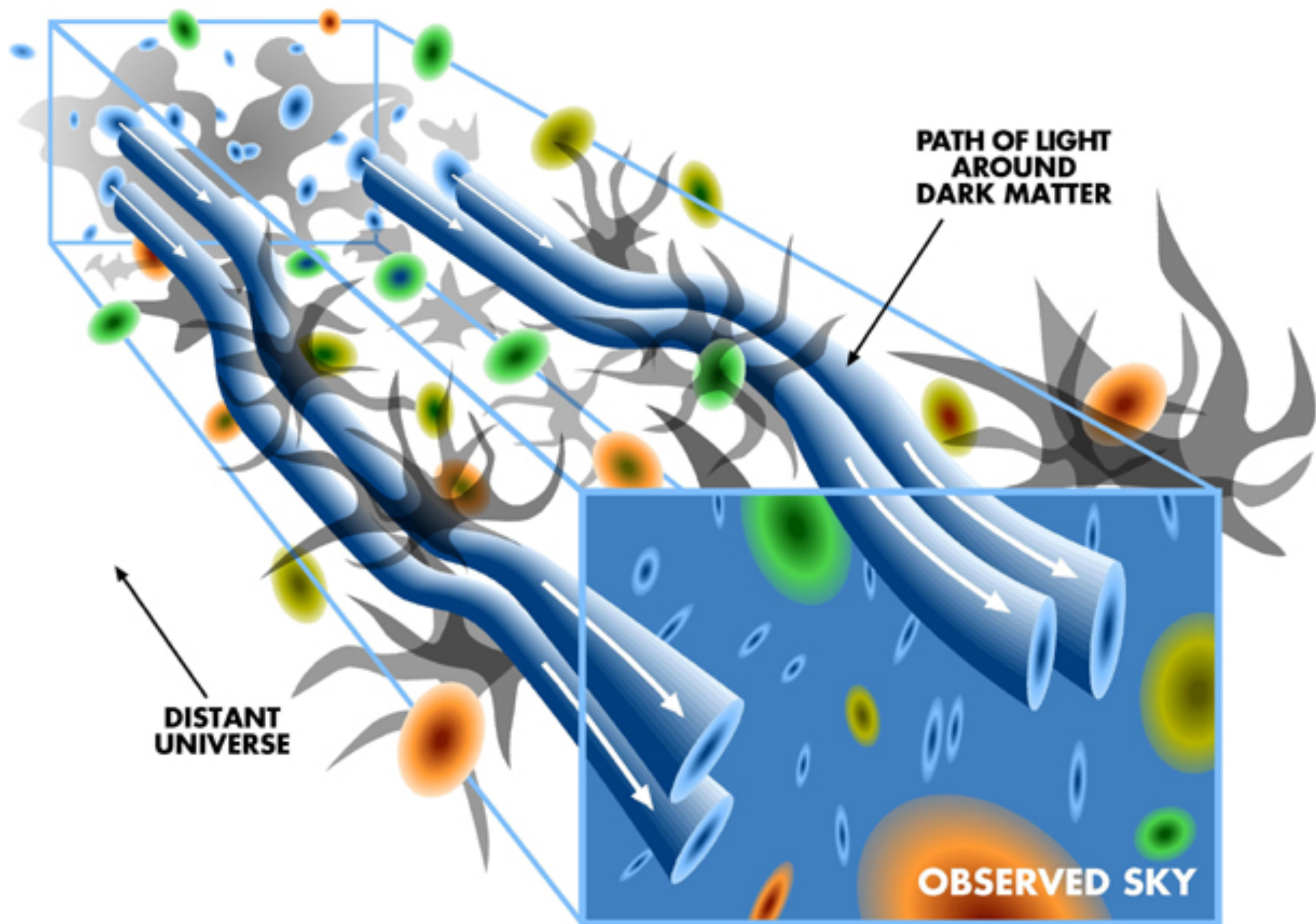
EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed
or Were Calculated to be,
but Nobody Need Worry.



Optical properties of a lumpy universe

- Homogeneous universe: metric: $ds^2 = -dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$
 - $a(t)$ obeys Friedmann's equations
 - \mathbf{x} is "conformal" coordinate (galaxies have fixed \mathbf{x})
- Lumpiness: $ds^2 = -(1 + 2 \phi(\mathbf{x})) dt^2 + a^2(t)(1 - 2 \phi(\mathbf{x}))(dx^2 + dy^2 + dz^2)$
 - $\phi(\mathbf{x})$ determined by density fluctuations $\delta\rho(\mathbf{x})$ (Poisson's equation)
 - very good approximation because velocities are slow
- Light rays are null paths ($ds = 0$)
- Same as light rays in "lumpy glass" with inhomogeneous $n(\mathbf{x})$
 - effective refractive index $n(\mathbf{x}) = (1 - 2 \phi(\mathbf{x}) / c^2)$
 - $n(\mathbf{x}) = (\text{coordinate speed of light})^{-1}$
 - Snell's law: Deflection $\theta_{\text{def}} \sim \phi / c^2 \sim G\delta M / r c^2$



basics of gravitational lensing: Δt , deflection

- Gravitational time delay (Shapiro '65): $\Delta t = 2 \int d\lambda \Phi/c^2$
 - λ = distance: Φ = gravitational field from $\Delta\rho/\rho$
 - measured in "strong lensing" - multiple images of quasars
 - fundamental concept (see Blandford & Narayan '86)
- Light deflection $\theta_1 \sim \int d\lambda \nabla \Phi/c^2 \sim GM/bc^2 \sim (H\lambda/c)^2 \Delta$
 - cumulative deflection is a "random walk"
 - $\theta \sim N^{1/2} \theta_1 \sim (H\lambda/c)^{3/2} \Delta$
 - $\Delta = \Delta\rho/\rho \sim \xi^{1/2} \sim 1/\lambda$
 - θ dominated by "supercluster" scale structure (~ 30 Mpc)
 - quite large \sim few arc-minutes $\sim 10^{-3}$ radians at high z
 - but (usually) not directly observable

basics of lensing: Δt , θ_{def} + magnification & shear

- Time delay $\Delta t = 2 \int d\lambda \Phi/c$
- Light deflection - cumulative deflection $\theta \sim N^{1/2} \theta_1 \sim (H\lambda/c)^{3/2} \Delta$
 - θ dominated by large scale structure (~ 30 Mpc)
- Weak lensing: observe the *gradient* of the deflection angle
 - described by a 2x2 image distortion tensor
 - trace: κ (kappa) \rightarrow *magnification* (changes *size* of objects)
 - 2 other components: $\gamma \rightarrow$ *image shear* (changes *shapes*)
 - $\sim 1\%$ at \sim degree scales for sources at $z \sim 1$ (few % @ $z=1000$)
 - but grows with decreasing angular scale
 - potentially *very large effects* from small-scale lumpiness

application of gravitational lensing in cosmology

- Microlensing
 - constraints on e.g. primordial BH DM from MACHO etc
 - μ -lensing at cosmological distances (Gunn & Gott), GRBs etc
- Strong-lensing
 - time delays
- **Bias in cosmological distances and parameter estimation**
- **Weak-lensing - galaxy, cluster + 'cosmic'-lensing**
 - Quasar-galaxy associations
 - Image shear and magnification
 - -> DM structure and evolution -> DE

OBSERVATIONS IN A UNIVERSE HOMOGENEOUS IN THE MEAN

Ya. B. Zel'dovich

Translated from *Astronomicheskii Zhurnal*, Vol. 41, No. 1,
pp. 19-24, January-February, 1964
Original article submitted June 12, 1963

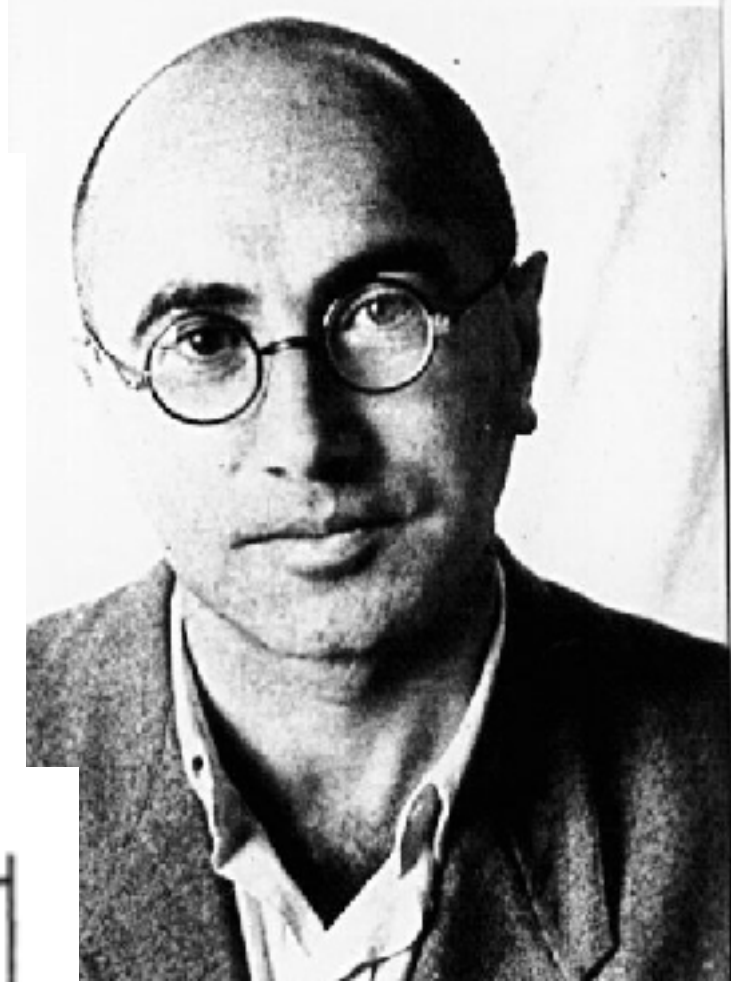


Fig. 1.



Fig. 2.

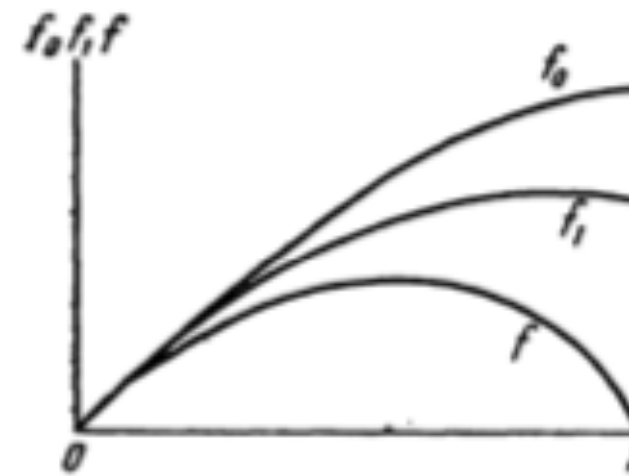
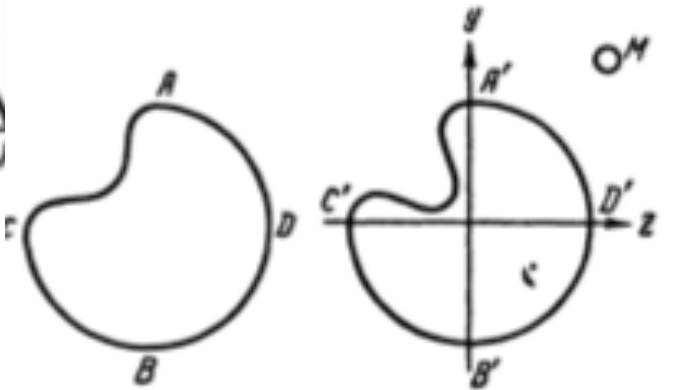


Fig. 6. $f_0 = \Delta \left(1 - \frac{\Delta}{2}\right)$;
 $f_1 = \frac{2}{5} [1 - (1 - \Delta)^{5/4}]$;
 $f = 2(1 - \Delta) (1 - \sqrt{1 - \Delta})$



The mass M deforms the observed shape of the object, so that the latter becomes contracted along the axis joining it to M and elongated in the perpendicular direction.

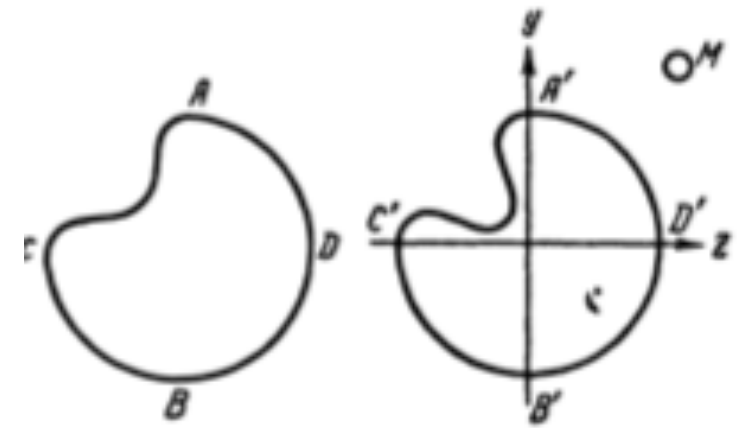
- considers light propagation in *inhomogeneous* cosmologies
- the first known "*cone diagram*"
- angular diameter $D_a(z)$ plots
 - uses $\Delta = z/(1 + z)$
- bias in D_a for galaxies seen along underdense lines of sight
- shape distortion from external mass
- FLRW curvature from local light-beam focussing - Raychaudhuri...



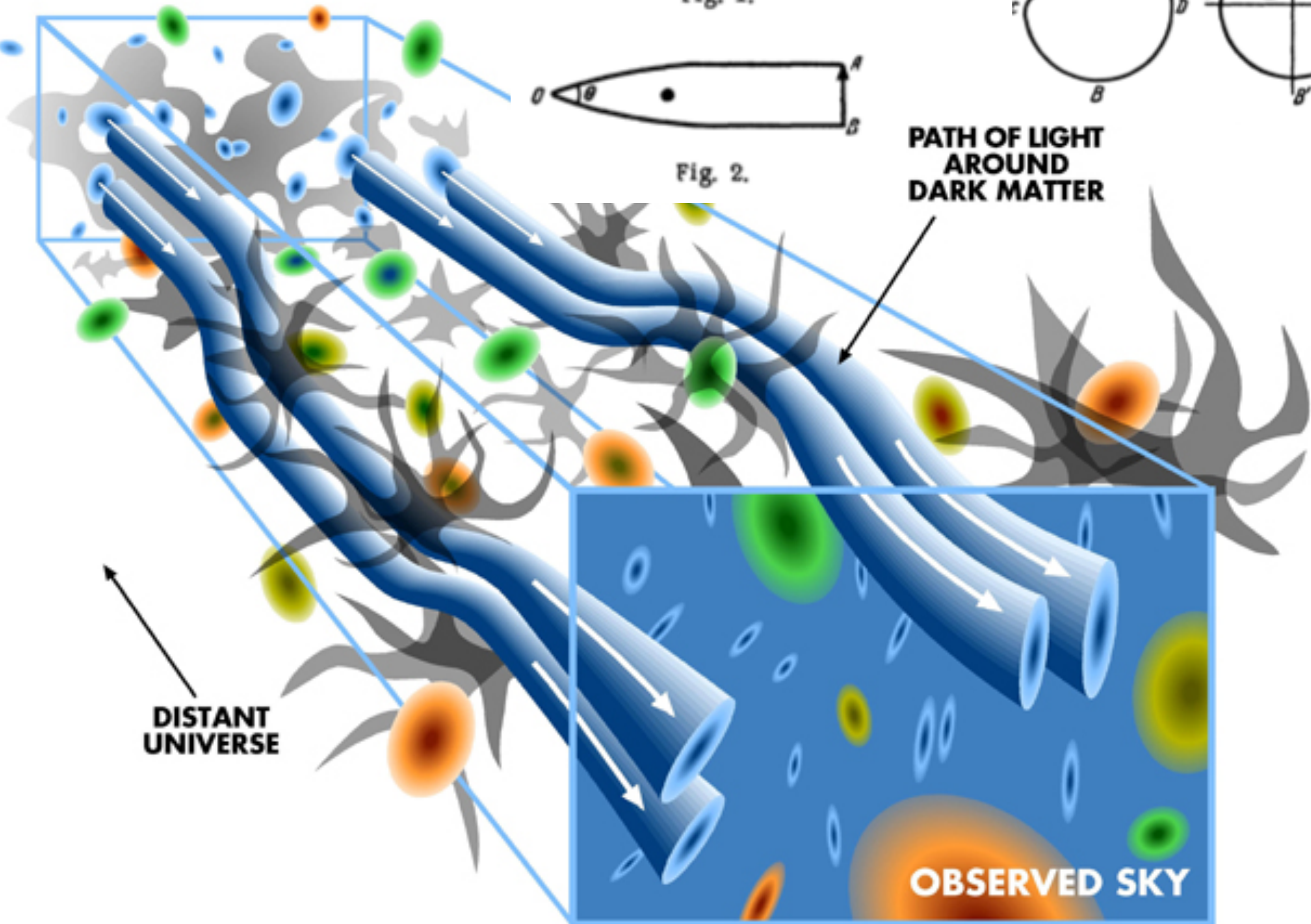
Fig. 1.



Fig. 2.



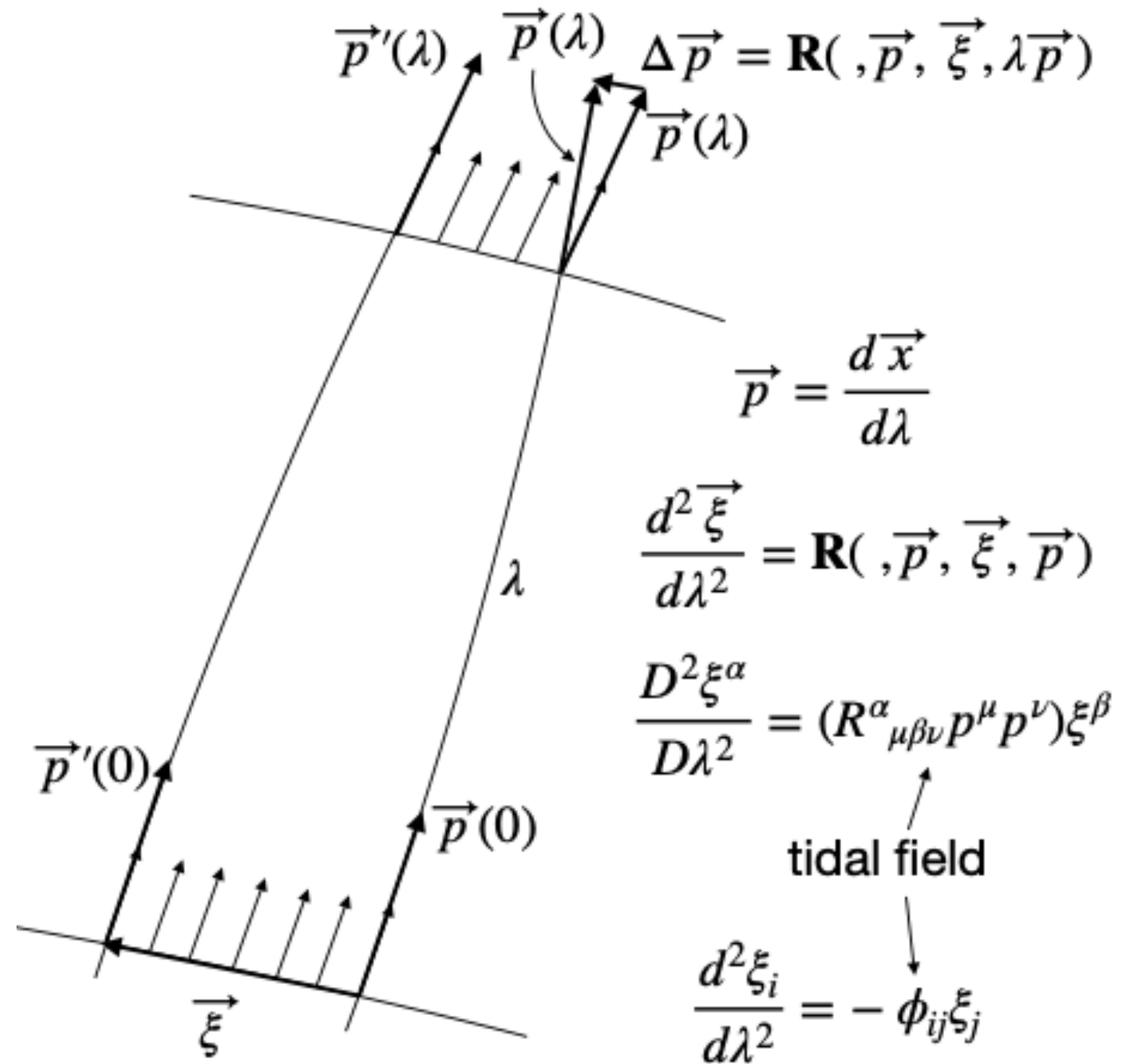
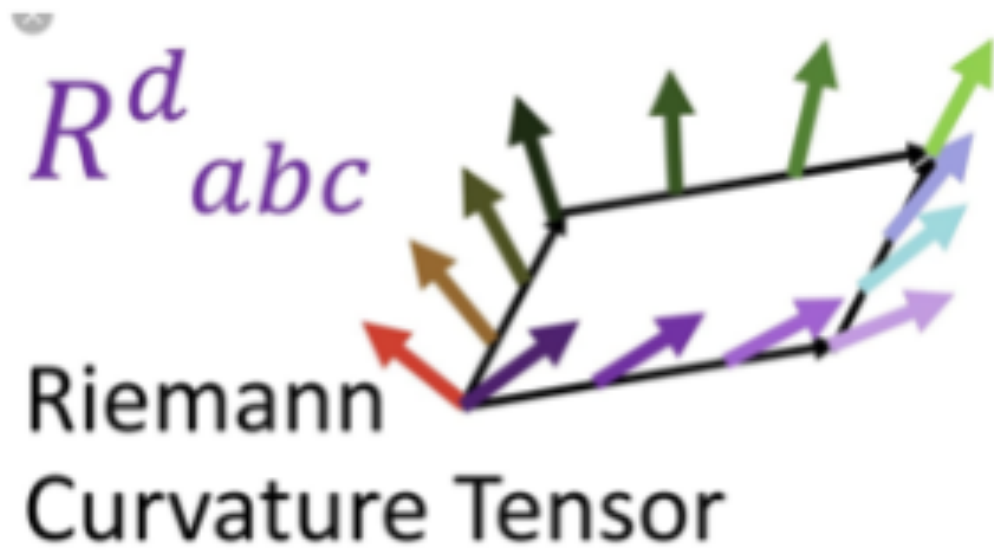
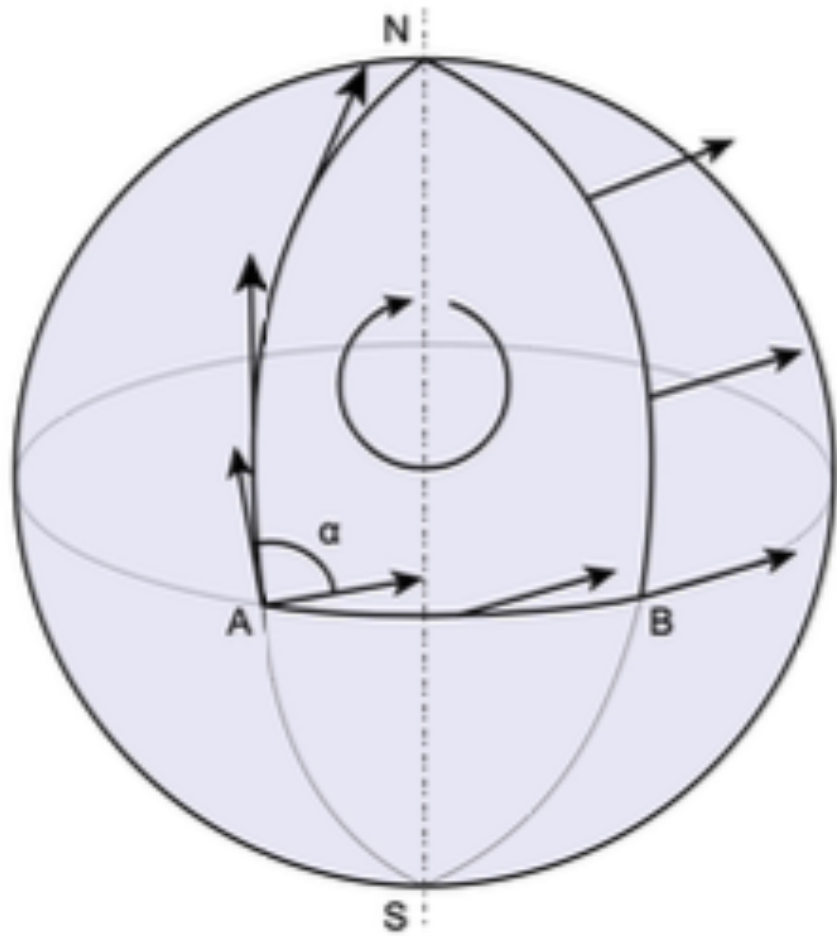
**PATH OF LIGHT
AROUND
DARK MATTER**



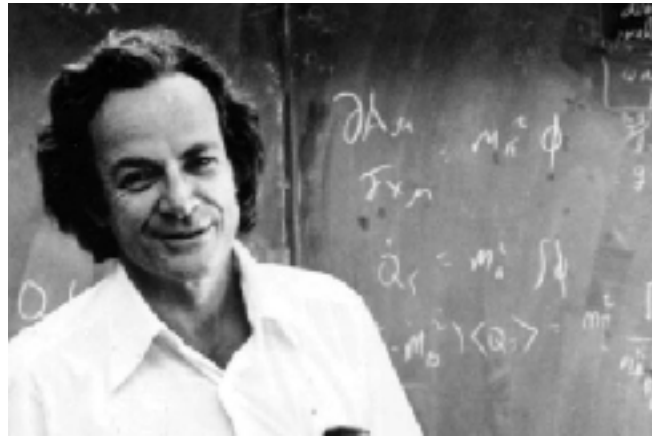
**DISTANT
UNIVERSE**

OBSERVED SKY

parallel transport \rightarrow curvature \rightarrow focussing \rightarrow Raychaudhuri



ON THE PROPAGATION OF LIGHT IN INHOMOGENEOUS COSMOLOGIES. I. MEAN EFFECTS



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Received February 23, 1967; revised May 23, 1967

ABSTRACT

The statistical effects of local inhomogeneities on the propagation of light are investigated, and deviations (including rms fluctuations) from the idealized behavior in homogeneous universes are investigated by a perturbation-theoretic approach. The effect discussed by Feynman and recently by Bertotti of the density of the intergalactic medium being systematically lower than the mean mass density is examined, and expressions for the effect valid at all redshifts are derived.

I. INTRODUCTION

In an unpublished colloquium given at the California Institute of Technology in 1964, Feynman discussed the effect on observed angular diameters of distant objects if the intergalactic medium has lower density than the mean mass density, as would be the case if a significant fraction of the total mass were contained in galaxies. It is an obvious extension of the existence of this effect that luminosities will also be affected, though this was apparently not realized at the time. This realization prompted the conviction that the effect of known kinds of deviations of the real Universe from the homogeneous isotropic models (upon which predictions had been based in the past) upon observable quantities like luminosity and angular diameter should be investigated. The author (1967) has recently made such a study for angular diameters; the present work deals primarily with mean statistical effects upon luminosity. A third paper will deal with possible extreme effects one may expect to encounter more rarely. Some of the results discussed here have been discussed independently by Bertotti (1966) and Zel'dovich (1965).

Kantowski '69

CORRECTIONS IN THE LUMINOSITY-REDSHIFT RELATIONS OF THE HOMOGENEOUS FRIEDMANN MODELS

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Received January 22, 1968; revised March 22, 1968

ABSTRACT

In this paper the bolometric luminosity-redshift relations of the Friedmann dust universes ($\Lambda = 0$) are corrected for the presence of inhomogeneities. The “locally” inhomogeneous Swiss-cheese models are used, and it is first shown that the introduction of clumps of matter into Friedmann models does not significantly affect the $R(z)$ or $R(v)$ relations (Friedmann radius versus the redshift or affine parameter) along a null ray. Then, by the use of the optical scalar equations, a linear third-order differential equation is arrived at for the mean cross-sectional area of a light beam as a function of the affine parameter. This differential equation is confirmed by rederiving its small redshift solution from an interesting geometrical point of view. The geometrical argument is then extended to show that “mild” inhomogeneities of a transparent type have no effect on the mean area of a light beam.

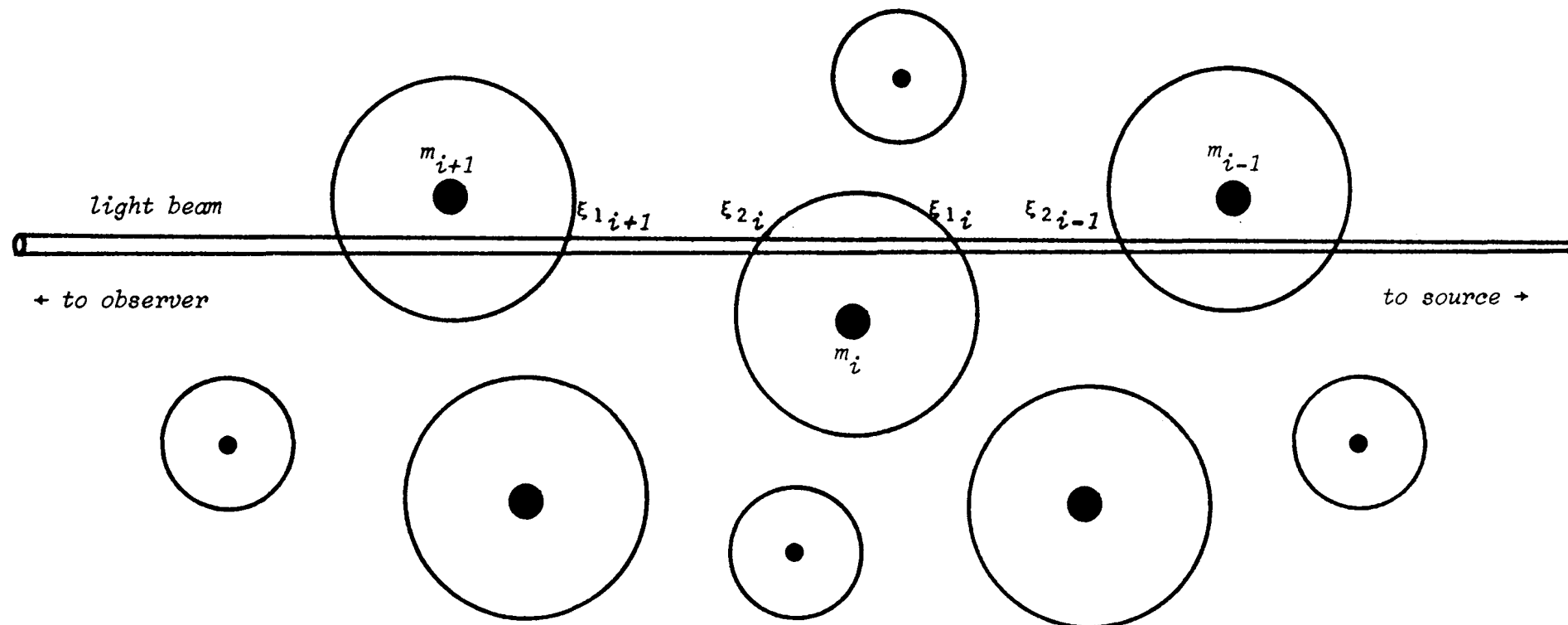


FIG. 1.—Spacelike section of a typical Swiss-cheese universe



Dyer & Roeder '72

THE DISTANCE-REDSHIFT RELATION FOR UNIVERSES WITH NO INTERGALACTIC MEDIUM

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Received 1972 April 19

ABSTRACT

The distance-redshift relation is derived for model universes in which there is negligible intergalactic matter and in which the line of sight to a distant object does not pass close to intervening galaxies. When fitted to observations, this relation yields a higher value of q_0 than does a homogeneous model.

No. 3, 1972

DISTANCE-REDSHIFT RELATION

L117

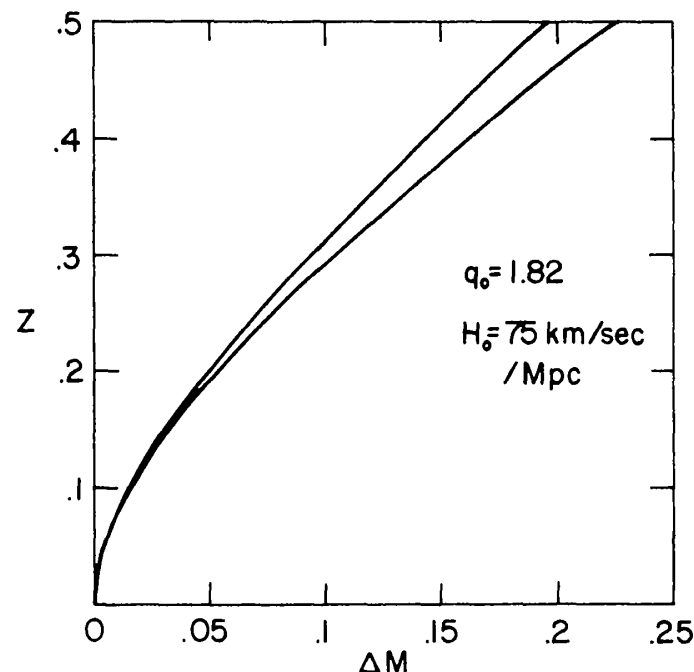
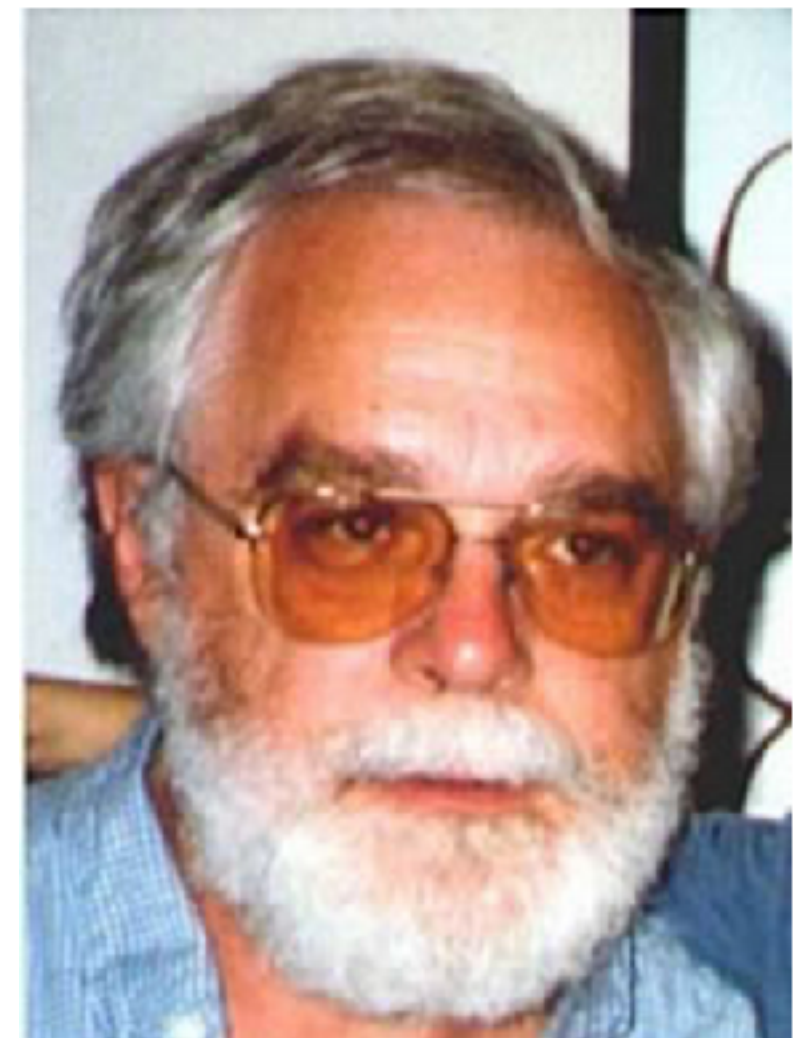


FIG. 1.—The dimming, relative to the homogeneous model, assuming that the beam passes far from any intervening galaxies (*lower curve*) and assuming that the beam passes no closer than 2 kpc to the center of galaxies similar to our own (*upper curve*).



APPARENT LUMINOSITIES IN A LOCALLY INHOMOGENEOUS UNIVERSE

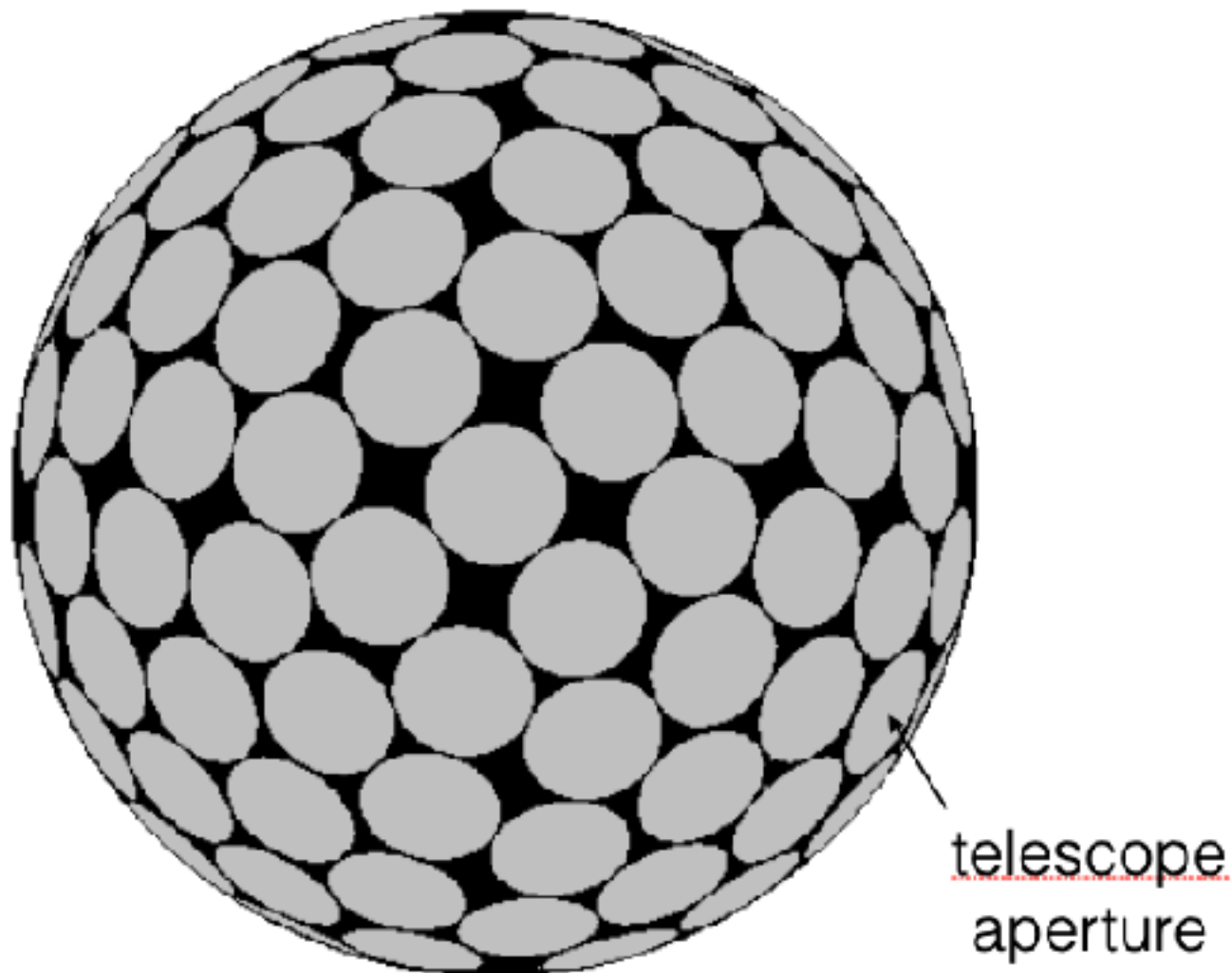
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Received 1976 April 6; revised 1976 May 20

ABSTRACT

Apparent luminosities are considered in a locally inhomogeneous universe, with gravitational deflection by individual clumps of matter taken into account. It is shown that as long as the clump radii are sufficiently small, gravitational deflection by the clumps will produce the same average effect as would be produced if the mass were spread out homogeneously. The conventional formulae for luminosity distance as a function of redshift consequently remain valid, despite the presence of any local inhomogeneities of less than galactic dimensions. For clumps of galactic size, the validity of the conventional formulae depends on the selection procedure used and the redshift of the object studied.



Lensing and caustic effects on cosmological distances.

EBD '98



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December 4, 2013

Abstract

We consider the changes which occur in cosmological distances due to the combined effects of some null geodesics passing through low-density regions while others pass through lensing-induced caustics. This combination of effects increases observed areas corresponding to a given solid angle even when averaged over large angular scales, through the additive effect of increases on all scales, but particularly on micro-angular scales; however angular sizes will not be significantly effected on large angular scales (when caustics occur, area distances and angular-diameter distances no longer coincide). We compare our results with other works on lensing, which claim there is no such effect, and explain why the effect will indeed occur in the (realistic) situation where caustics due to lensing are significant. Whether or not the effect is significant for number counts depends on the associated angular scales and on the distribution of inhomogeneities in the universe. It could also possibly affect the spectrum of CBR anisotropies on small angular scales, indeed caustics can induce a non-Gaussian signature into the CMB at small scales and lead to stronger mixing of anisotropies than occurs in weak lensing.

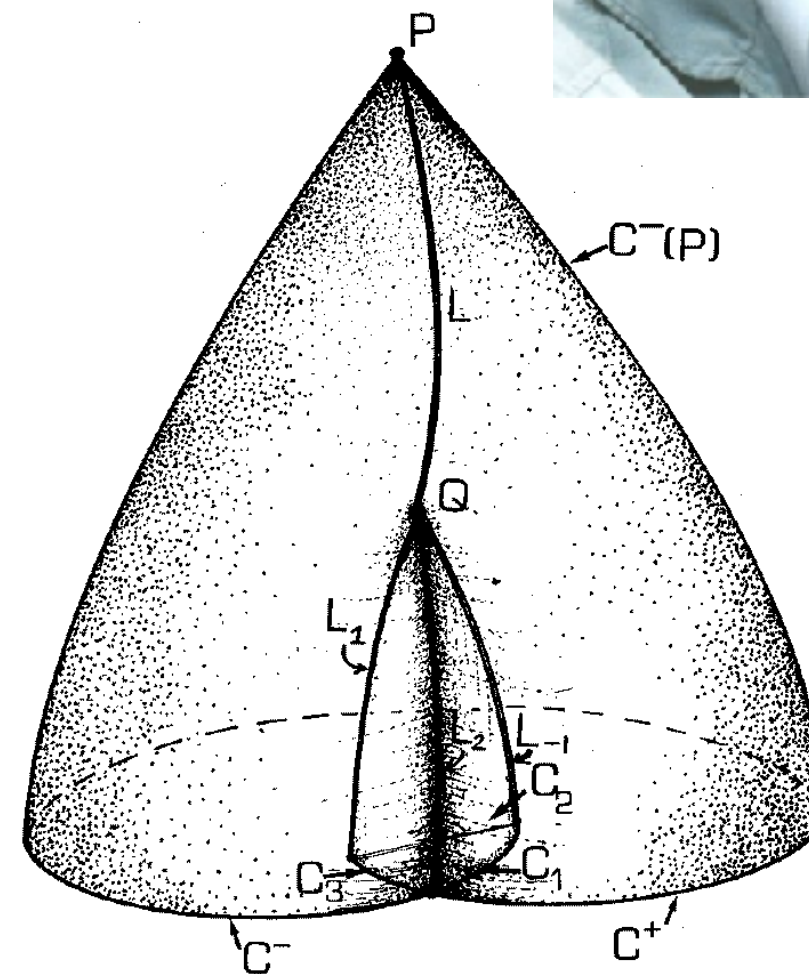


Figure 1: A lens L and resulting caustics on the past light cone $C^-(P)$ (2-dimensional section of the full light cone), showing in particular the cross-over line L_2 and cusp lines L_{-1} , L_1 meeting at the conjugate point Q . The intersection of the past light cone with a surface of constant time defines exterior segments C^- , C^+ of the light cone together with interior segments C_1 , C_2 , C_3 .

Enter Schneider, Ehlers, Seitz etc... ('80s, '90s)

- Two consistent threads:
 - Lens equation:
 - at least one image is made **brighter**
 - Optical scalar equations (Sachs 1961):
 - from Raychaudhuri
 - \rightarrow *focusing theorem* (Seitz+ 1994)
 - Things viewed through 'clumpiness' are further than they appear...
- opposite to what Zel'dovich, Kantowski, Dyer & Roeder etc concluded
- and in conflict with Weinberg too...



Seitz, Schneider & Ehlers (1994)



Finally, we have derived an equation for the size of a light beam in a clumpy universe, relative to the size of a beam which is unaffected by the matter inhomogeneities. If we require that this second-order differential equation contains only the contribution by matter clumps as source term, the independent variable is uniquely defined and agrees with the χ -function previously introduced [see SEF, eq. (4.68)] for other reasons. This relative focusing equation immediately yields the result that a light beam cannot be less focused than a reference beam which is unaffected by matter inhomogeneities, prior to the propagation through its first conjugate point. In other words, no source can appear fainter to the observer than in the case that there are no matter inhomogeneities close to the line-of-sight to this source, a result previously demonstrated for the case of one (Schneider 1984) and several (Paper I, Seitz & Schneider 1994) lens planes.

On Seitz, Schneider & Ehlers 94

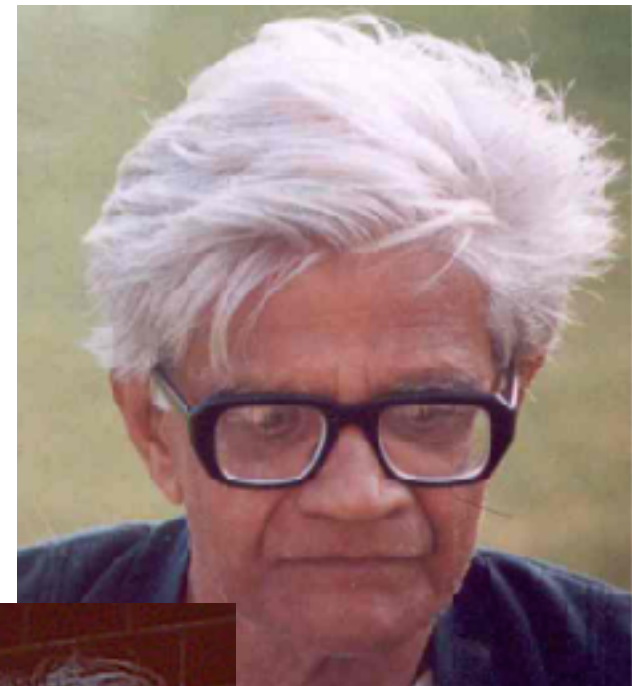
1992). Taking a somewhat different approach, Seitz, Schneider & Ehlers (1994) have used the optical scalars formalism of Sachs (1961) to show that the square root of the proper area of a narrow bundle of rays $D = \sqrt{A}$ obeys the ‘focusing equation’:

$$\ddot{D}/D = -(R + \Sigma^2). \quad (1)$$

Here \ddot{D} is the second derivative of D with respect to affine distance along the bundle; $R = R_{\alpha\beta}k^\alpha k^\beta / 2$ is the local Ricci focusing from matter in the beam, which for non-relativistic velocities is just proportional to the matter density; and Σ^2 is the squared rate of shear from the integrated effect of up-beam Weyl focusing – i.e. the tidal field of matter outside the beam. The resulting focusing theorem is that the RHS of (1) is non-positive, so that beams are always focused to smaller sizes, at least as compared to empty space-time,

More on the focusing theorem: $\ddot{D}/D = -(R + \Sigma^2)$

- Derived from Sachs '61 "optical scalars"
- from A.K. Raychaudhuri's equation
 - transport of expansion, vorticity and shear
- $R = R_{ab}k^ak^b$ local effect of matter in beam
- Σ^2 is the cumulative effect of matter *outside* the beam
 - Σ being the *rate* of image shearing
- Like cosmological acceleration equation:
 - $d^2a/dt^2 = -4\pi G(\rho + 3P/c^2)a$
 - so Σ^2 here plays the role of pressure!
- Also recalls Hawking-Ellis singularity theorem
 - both terms are positive \Rightarrow focusing
- e.g. Narlikar (Introduction to Relativity):
 - "*Thus the normal tendency of matter*
 - *is to focus light rays*"



Narlikar on the focusing theorem

The **Raychaudhuri** equation can be stated in a slightly different form as a *focussing theorem*. In this form it describes the effect of gravity on a bundle of null geodesics spanning a finite cross section. Denoting the cross section by A , we write the equation of the surface spanning the geodesics as $f = \text{constant}$. Define the normal **to** the cross-sectional surface by $k_i = \partial f / \partial x^i$. Figure 18.3 shows the geometry of the bundle.

Using a calculation similar **to** that which led **to** the geodesic deviation equation in Chapter 5, we get the focussing equation as

$$\frac{1}{\sqrt{A}} \frac{d^2 \sqrt{A}}{d\lambda^2} = \frac{1}{2} R_{im} k^i k^m - |\sigma|^2, \quad (18.10)$$

Equation (18.10) is similar **to** the **Raychaudhuri** equation with $|\sigma|^2$ being the square of the magnitude of shear. With Einstein's equations, we can rewrite (18.10) as

$$\frac{1}{\sqrt{A}} \frac{d^2 \sqrt{A}}{d\lambda^2} = -4\pi G \left(T_{im} - \frac{1}{2} g_{im} T \right) k^i k^m - |\sigma|^2. \quad (18.12)$$

For dust we have $T_{im} = \rho u_i u_m$ and this condition is satisfied with the left-hand side equalling $\rho(u_i k^i)^2$. (Remember that k_i is a null vector, so $g_{im} k^i k^m = 0$.) Thus the normal tendency of matter is **to** focus light rays by gravity.

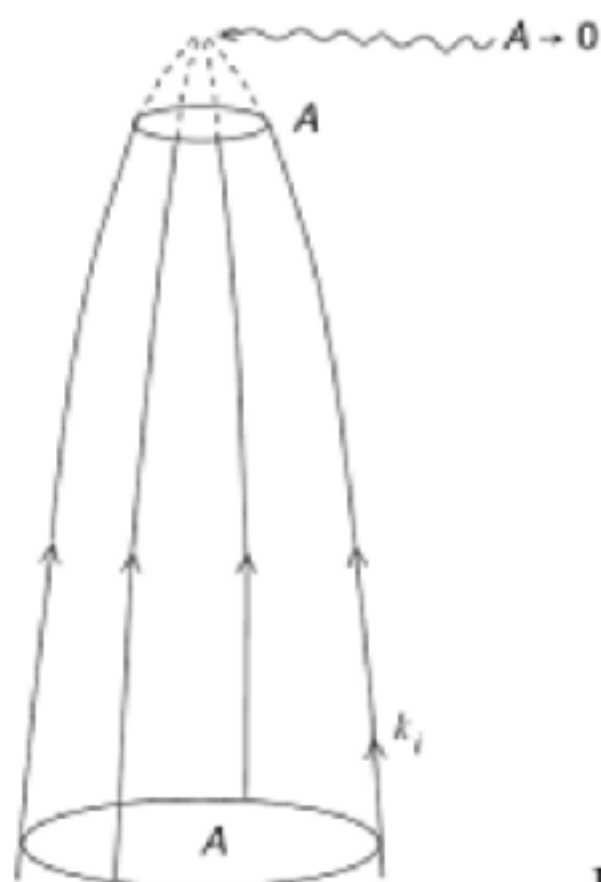


Fig. 18.3. The bundle of geodesics focusses in the future with its cross section A decreasing **to** zero. This effect was discussed in the context of spacetime singularity by A. K. **Raychaudhuri**.



Kibble & Lieu (2005)



AVERAGE MAGNIFICATION EFFECT OF CLUMPING OF MATTER

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ABSTRACT

The aim of this paper is to reexamine the question of the average magnification in a universe with some inhomogeneously distributed matter. We present an analytic proof, valid under rather general conditions, including clumps of any shape and size and strong lensing, that as long as the clumps are uncorrelated, the average “reciprocal” magnification (in one of several possible senses) is precisely the same as in a homogeneous universe with an equal mean density. From this result, we also show that a similar statement can be made about one definition of the average “direct” magnification. We discuss, in the context of observations of discrete and extended sources, the physical significance of the various different measures of magnification and the circumstances in which they are appropriate.

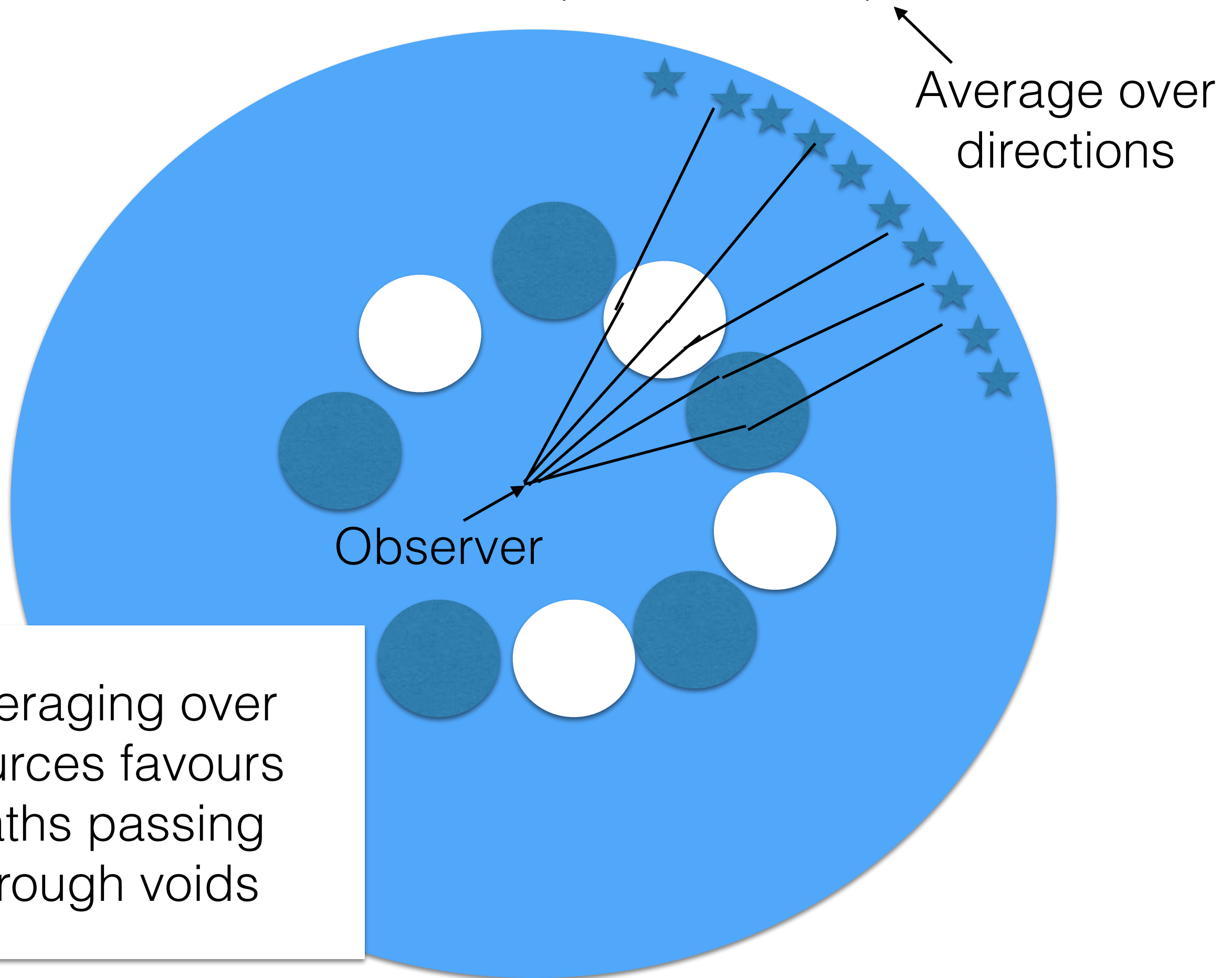
Subject headings: cosmology: miscellaneous — distance scale — galaxies: distances and redshifts — gravitational lensing

Kibble & Lieu 2005

There is another important distinction to be made. We may choose at random one of the sources at redshift z , or we may choose a random direction in the sky and look for sources there. These are not the same; the choices are differently weighted. If one part of the sky is more magnified, or at a closer angular-size distance, the corresponding area of the constant- z surface will be smaller, so fewer sources are likely to be found there. In other words, choosing a source at random will give on average a smaller magnification or larger angular-size distance.

- Weinberg: $\langle \mu \rangle = 1$ when averaged over *sources*
- Kibble & Lieu: $\langle 1/\mu \rangle = 1$ when averaged over *directions on the sky*
 - latter is more relevant for CMB observations
 - strictly only valid in weak lensing regime

Kibble + Lieu 2005: $\langle \mu \rangle = 1$ vs $\langle 1/\mu \rangle = 1$



Is there a flaw in Weinberg's argument?

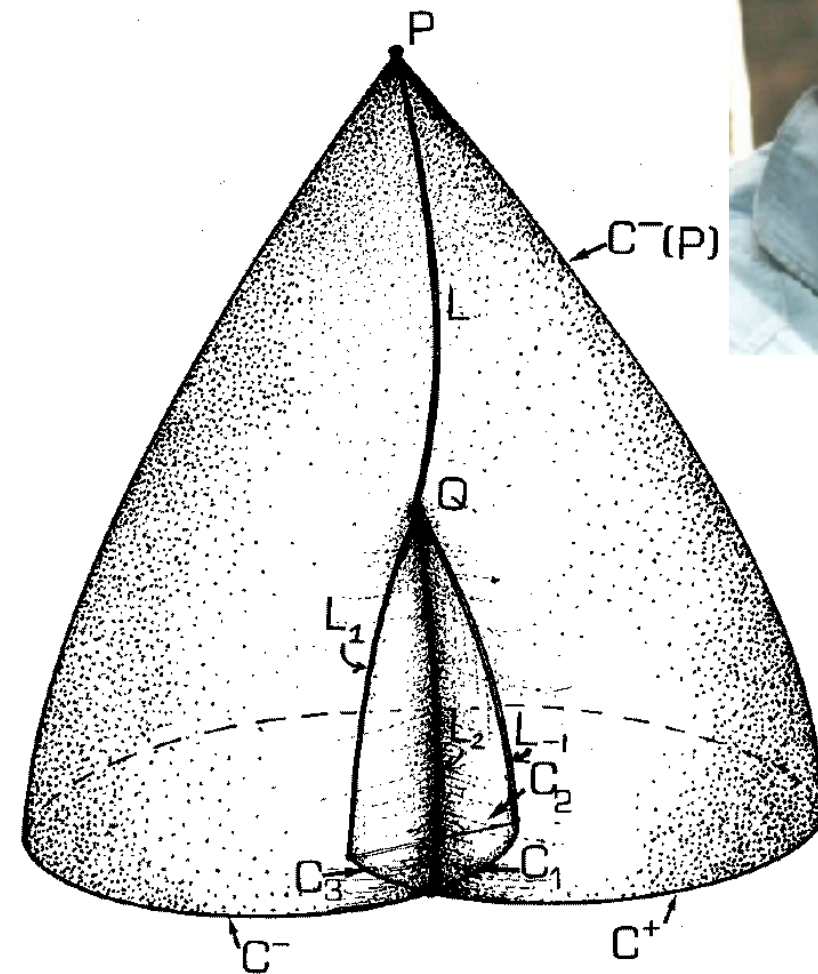
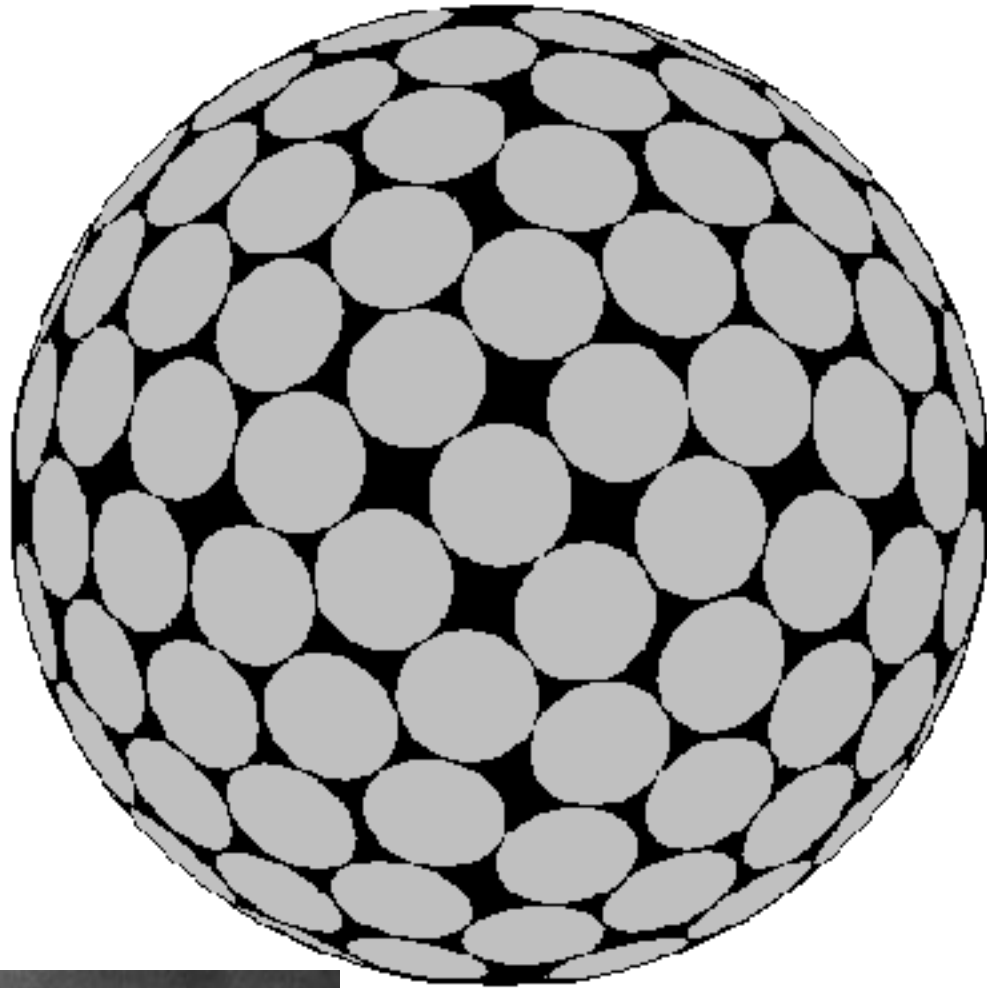
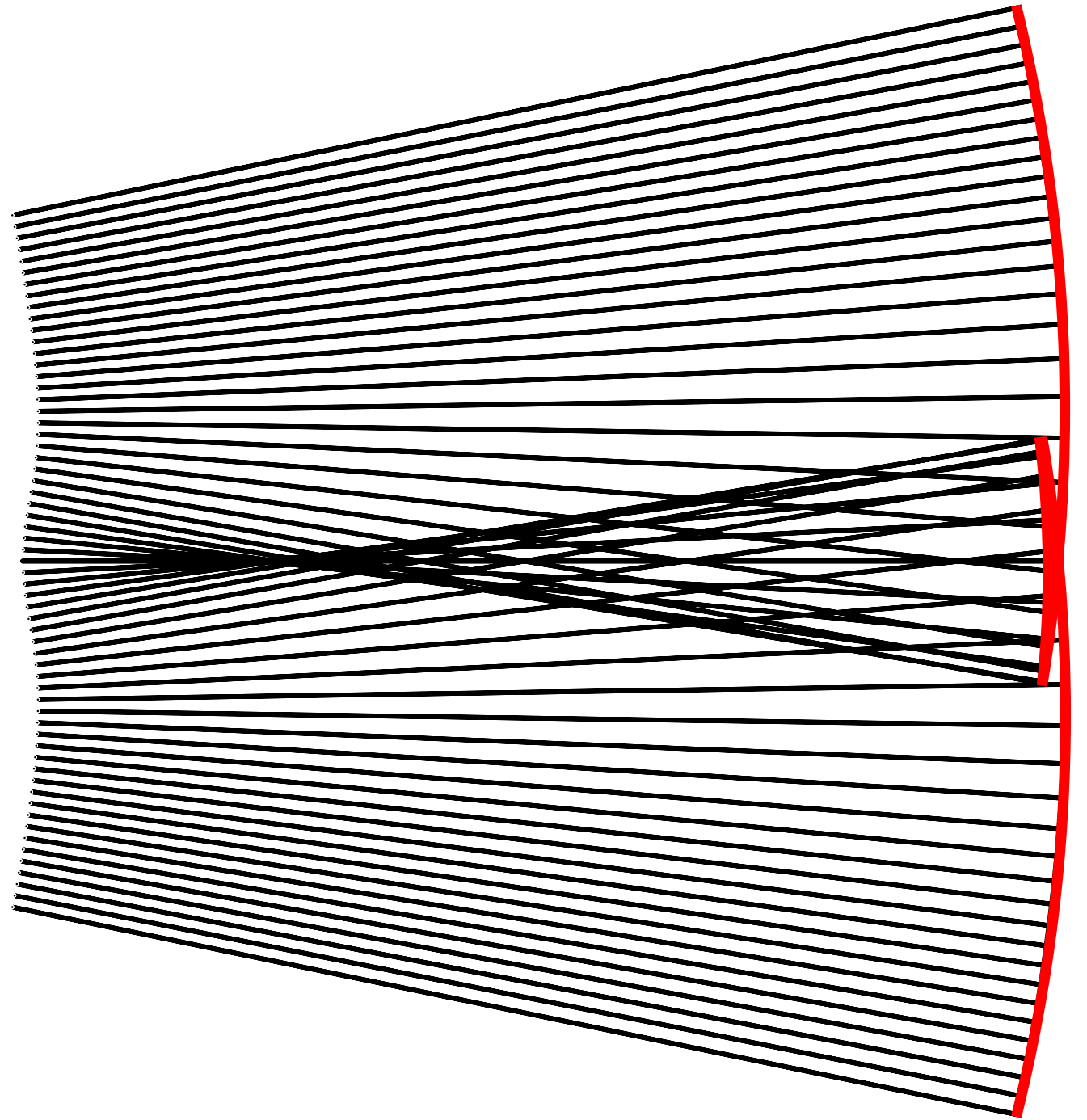


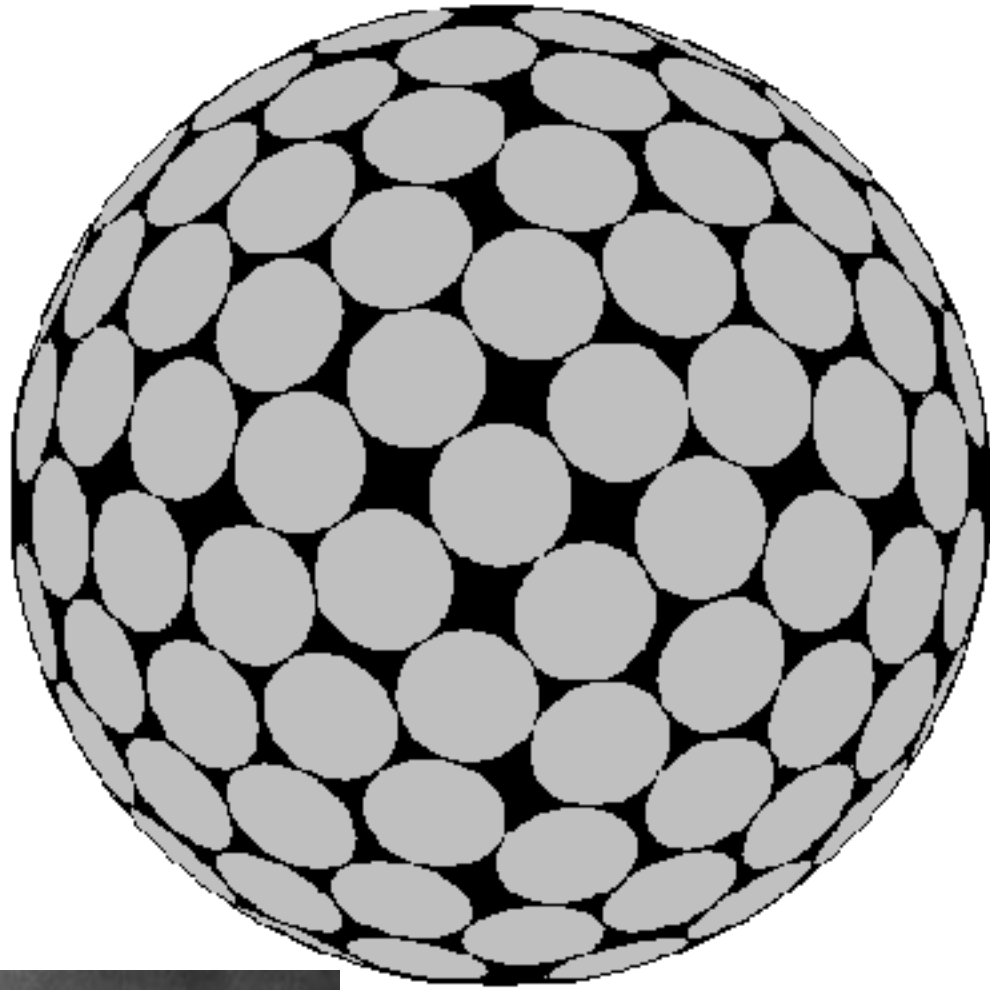
Figure 1: A lens L and resulting caustics on the past light cone $C^-(P)$ (2-dimensional section of the full light cone), showing in particular the cross-over line L_2 and cusp lines L_{-1} , L_1 meeting at the conjugate point Q . The intersection of the past light cone with a surface of constant time defines exterior segments C^- , C^+ of the light cone together with interior segments C_1 , C_2 , C_3 .

Ellis, Bassett & Dunsby '98 critique of Weinberg '76

- EDB98 make two points:
- Weinberg *assumes* that which is to be proven
 - true: W76 assumes that the surface of constant z around a source (or observer) is a sphere
- Small scale strong lensing causes the surface to be folded over on itself so total area greatly enhanced
 - possibly also true
- Thus Weinberg's claim is disproved
 - No: W76 is still valid if multiple images are unresolved



So is there a flaw in Weinberg's argument?



Early days of weak lensing

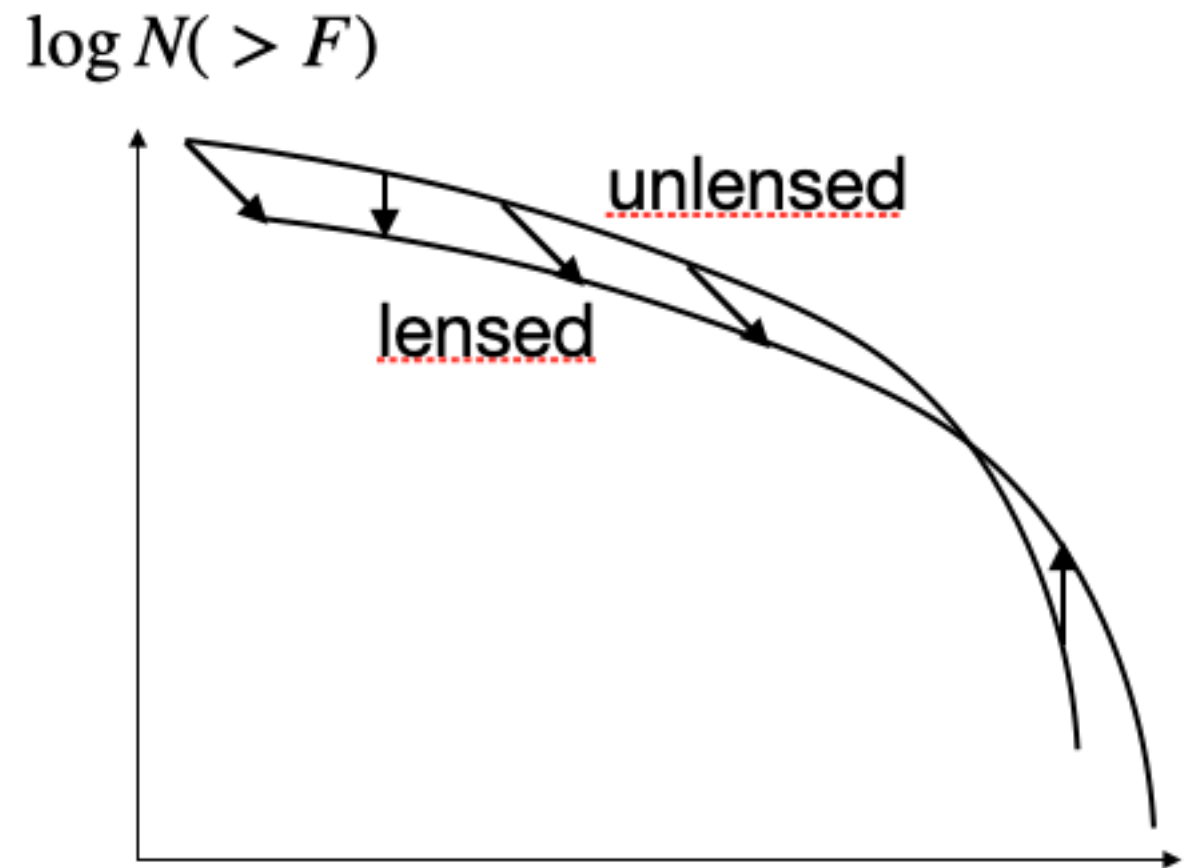
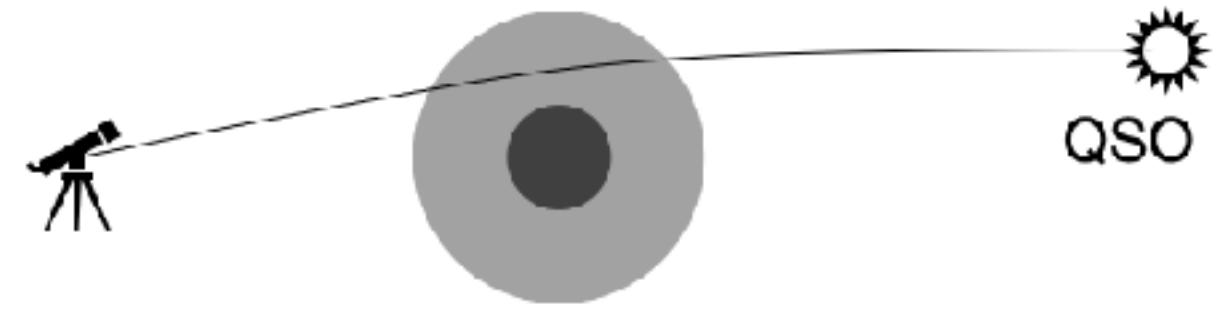
- Jacob B. Zel'dovich's pioneering 1963 paper mentioned the distortion of shapes of galaxies by the tidal shearing of bundles of rays to the source
- but this and subsequent studies focussed on the possibility of bias in mean flux density of distant galaxies
 - without particular reference to what was causing the magnification
- Rachel Webster (1985) proposed that the impact of lensing on the distribution of ellipticities be used as a cosmological probe
- around the mid-late '80s two lensing techniques emerged that were designed to probe the dark matter distribution in and around galaxy haloes
 - note that this was a very lively time for measurement of dark halos using rotation curves and using e.g. relative velocities of pairs of galaxies and using the 'cosmic virial theorem' of Davis and Peebles (1983)
- One was "quasar galaxy associations" the other was what is now known as "galaxy-galaxy lensing"
- Interestingly they gave results that were discrepant with each other

Quasar-galaxy associations

- Quasars had been discovered in the early 60s.
- Their redshifts put them at cosmological distances, and they were interpreted as being powered by accretion onto black holes
- But not all astronomers accepted this, one reason for skepticism being that there were cases where the quasars seemed to be associated with galaxies with much lower redshifts.
- Initially the evidence was questionable and controversial, and people promoting this risked being dismissed as cranks
- But as the samples of e.g. UV-excess quasars from Schmidt telescope surveys grew, the evidence became less anecdotal and statistically stronger.
- As the data improved, the interpretation changed also; rather than being considered to be physical associations - and therefore evidence that the quasar redshifts were non-cosmological - they were interpreted as being sources whose flux-densities were being amplified by the mass in the haloes of the foreground galaxies
- But strangely, the effect was stronger than predicted from kinematic studies

Quasar-galaxy associations

- The first prediction of the effect was by Claude Canizares (1981) and another quasi-contemporary study was made by John Peacock (1982)
- The effect is known as "magnification bias". One aspect of this is that sources that would otherwise be below the flux-density selection limit could be observed.
- But the other arises from the fact that the way that sources become amplified is by their solid angles becoming larger - and the same effect dilutes their number density on the sky
- The net result is an enhancement for bright sources and a diminution for faint ones



- See Narayan 1989 for a particularly clear analysis
- And Benitez et al 2001 for a more recent survey of results
- The large results persist.

Early cosmic-shear results

- The advent of CCD detectors in the 70s radically changed optical astronomy as their linearity and sensitivity were a big advantage
- Initially of very small area, they steadily increased in size and, by the mid 80's were being used - to particular effect by Tyson's group - to do imaging surveys rather than studies of individual objects.
- Valdes, Tyson and Jarvis, in their pioneering study of 1983, measured quadrupole moments M_{ij} of $\sim 45,000$ galaxies in 35 fields and computed a mean of the ellipticities $e_1 = \langle M_{xx} - M_{yy} \rangle$ and $e_2 = \langle 2M_{xy} \rangle$ in each field.
- They found a null result.
- This was perhaps not overwhelmingly surprising based on what we now know about the large-scale mass distribution, but one should put this in the context of the time when there were hints of strong inhomogeneity on large scales:
 - one, then relatively recent, discovery was the "Rubin-Ford effect"
 - this was that we have a large (~ 500 km/s) motion with respect to a shell of galaxies at $3500 \text{ km/s} < cz < 6500 \text{ km/s}$ which did *not* agree with our motion with respect to the CMB. I.e. the shell itself had a large peculiar velocity.

Early galaxy-galaxy lensing

- Top figure is from Valdes et al 1983.
- Tyson, Jarvis, Valdes & Mills (1984) used the same data to measure galaxy-galaxy lensing
- The result was a surprisingly weak signal (lower right)
 - barely compatible with kinematic estimates of extended flat rotation curves
 - and very different from what was emerging from quasar-galaxy associations

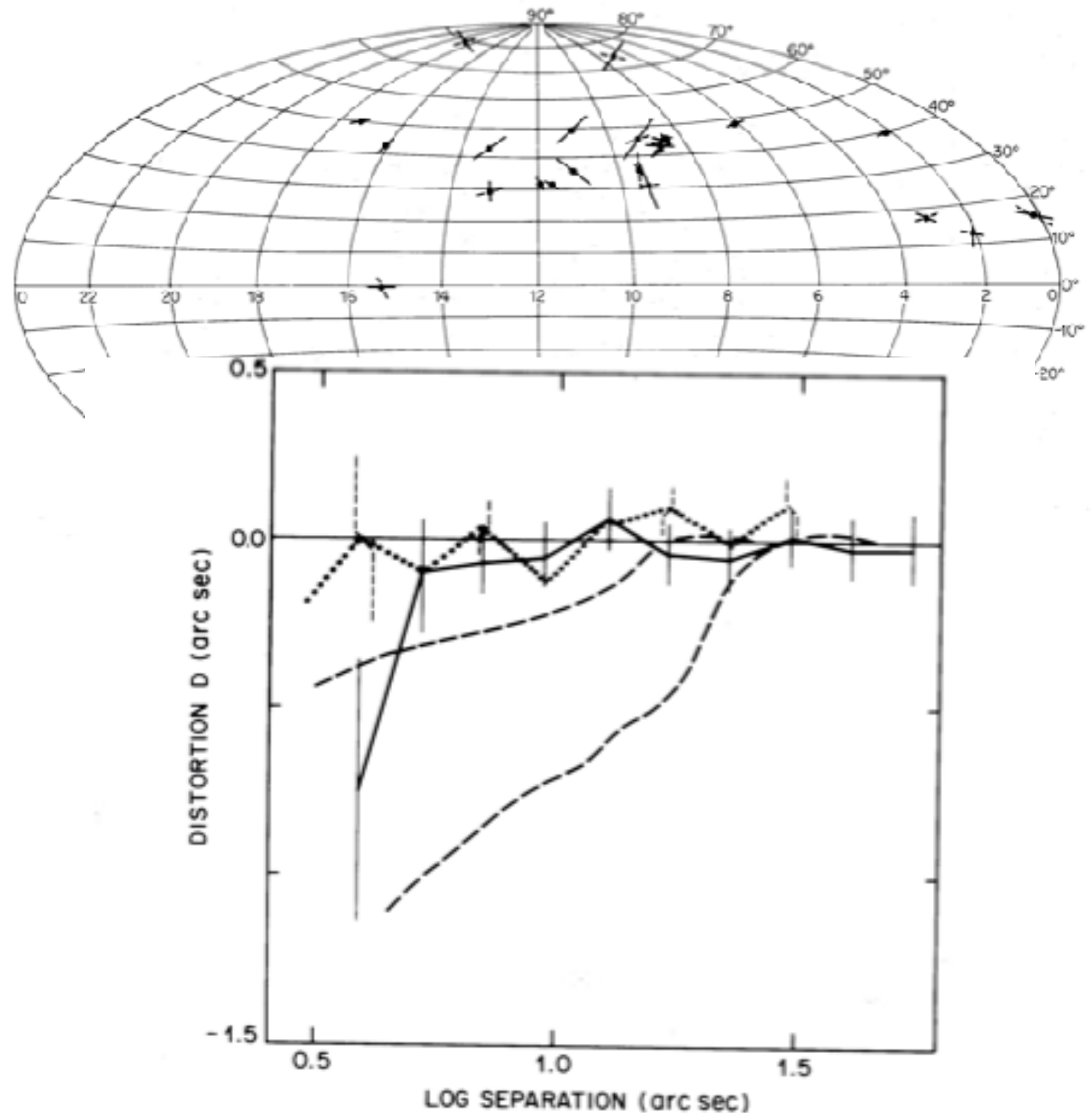
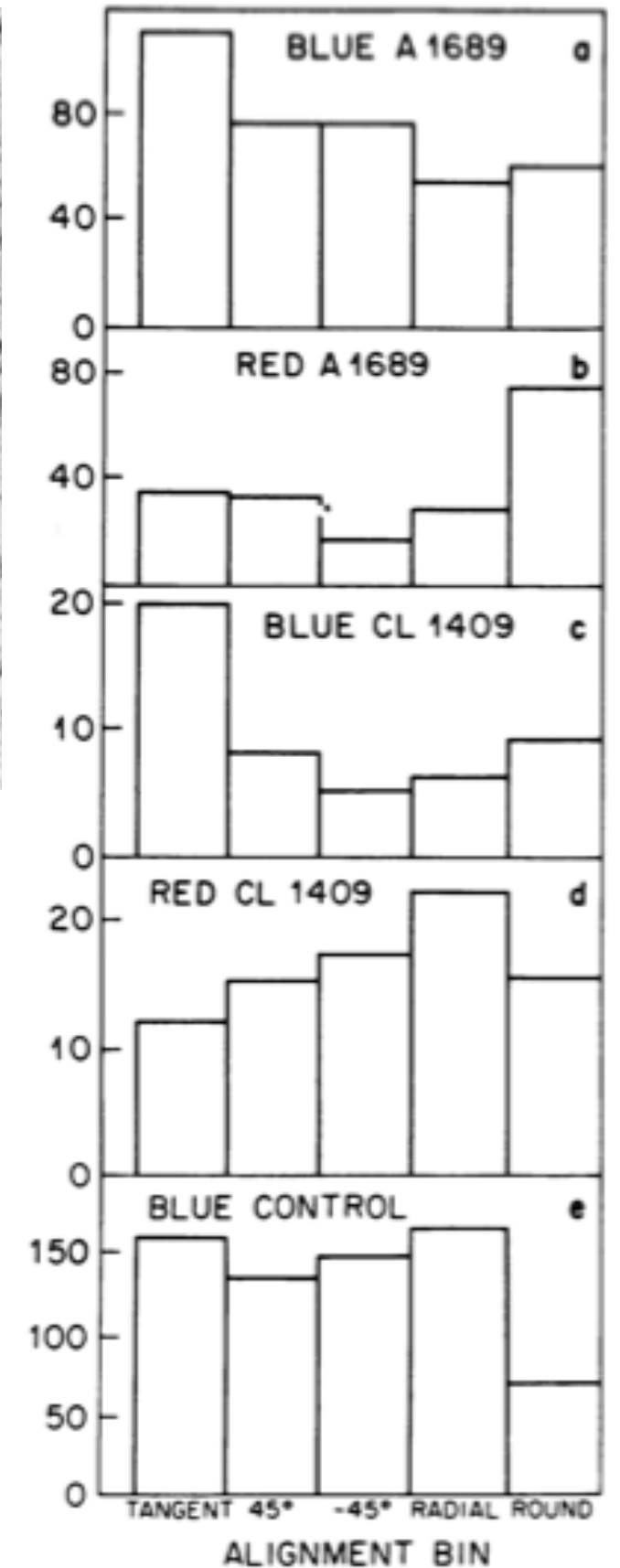
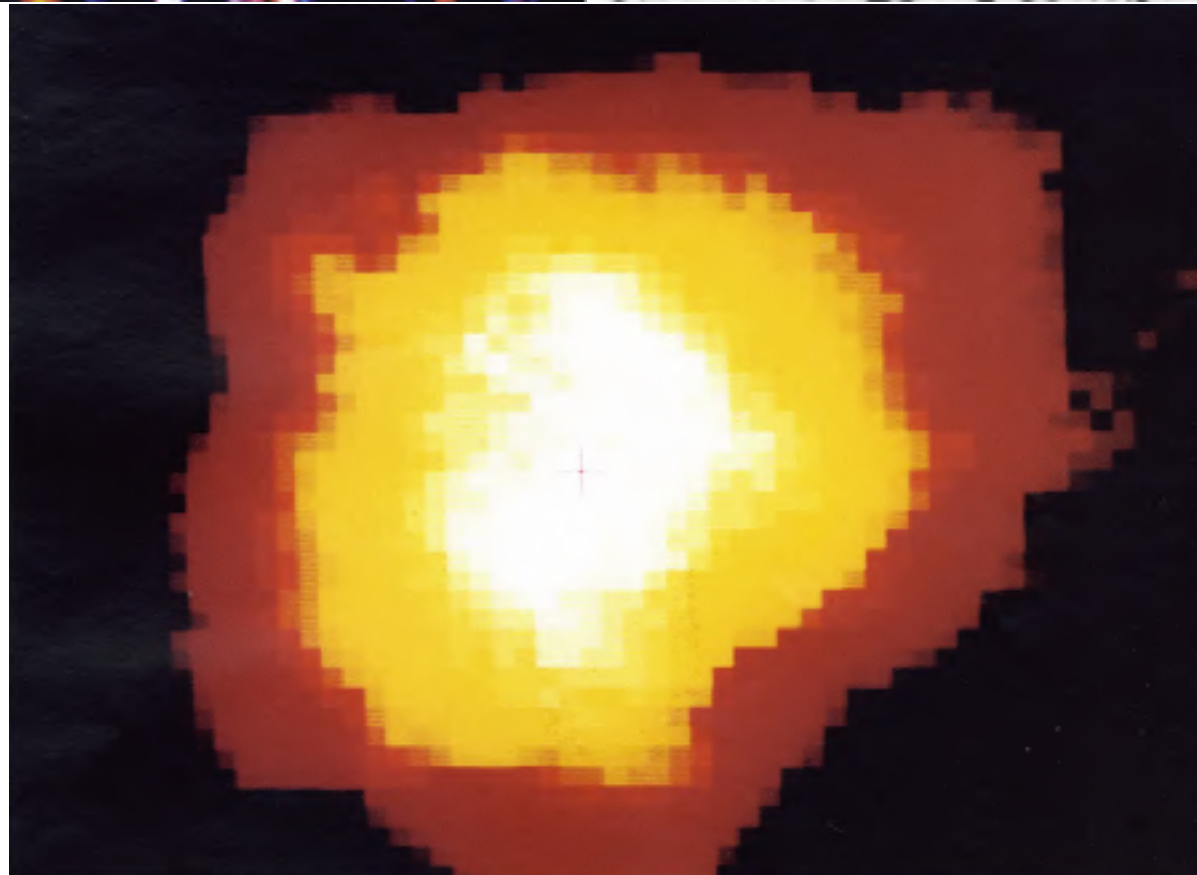
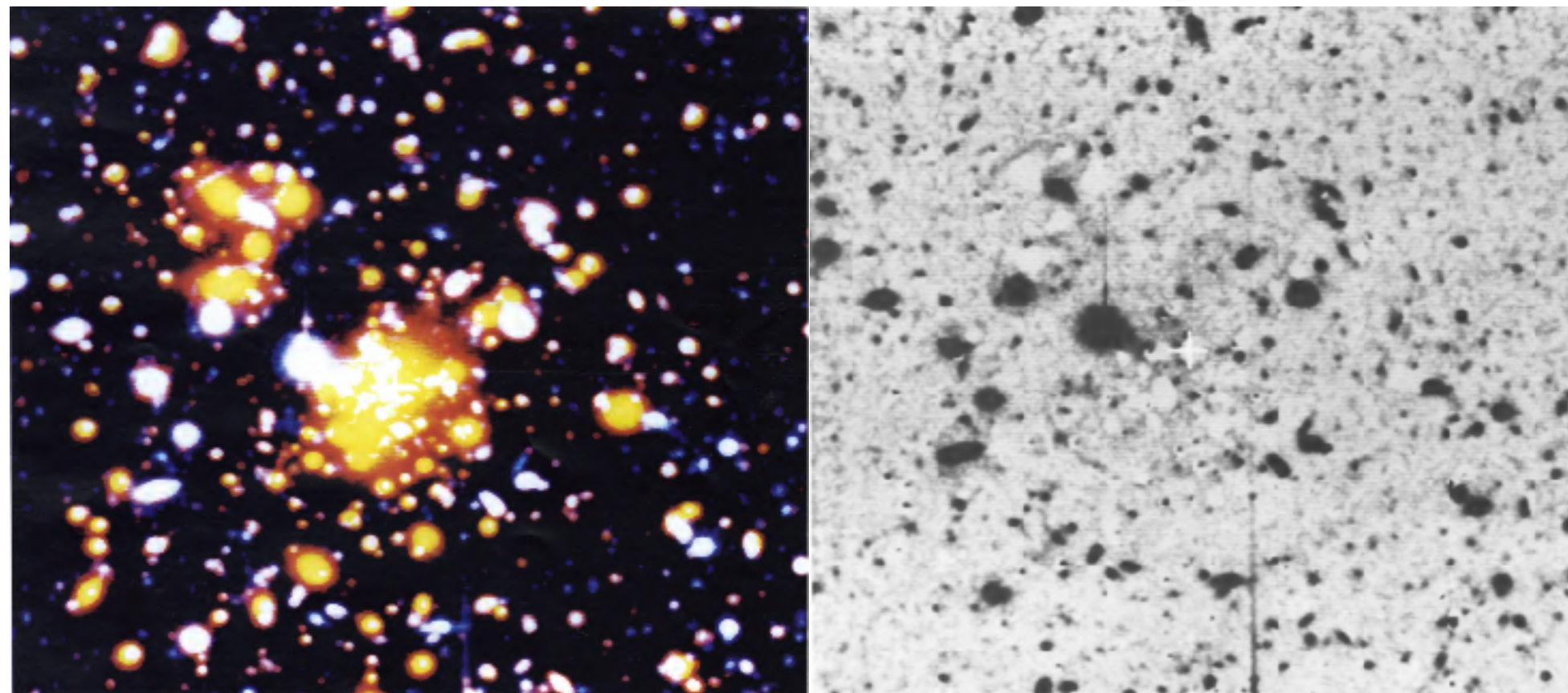


FIG. 1.—The dimensionless gravitational image distortion parameter $\mathcal{D} = \psi(M_r - M_\theta)/(M_r + M_\theta)$ in arc seconds as a function of the radial separation ψ of the foreground-background galaxy pair on the sky in arc seconds (*solid line*). Also shown (*dotted line*) is the result of a control test in which bright stars on the plate were substituted for the foreground galaxy position in the measurement of \mathcal{D} . The result is null (within 2σ) in both cases, 1σ error bars. Also shown are simulated distortions (*dashed lines*) from galaxies of mass cutoff radius $65 h^{-1} \text{ kpc}$ and equivalent circular velocities of 200 and 300 km s^{-1} .

DETECTION OF SYSTEMATIC GRAVITATIONAL LENS GALAXY IMAGE ALIGNMENTS: MAPPING DARK MATTER IN GALAXY CLUSTERS

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Received 1989 July 19; accepted 1989 October 16



The impact of Tyson, Valdes and Wenk's "mass maps"

- The measurement of the tangential alignment in A1689 (and CL1409) was a revolutionary and exciting event.
 - particularly after the earlier null results on cosmic and GG-lensing
- It was clear that what they were seeing wasn't just coming from the "giant arcs", but was driven by the bulk of the faint galaxies
- Moreover, while the fields were quite small (and the shear correspondingly large), it was evident that, with the number of background galaxies increasing as θ^2 , and the signal expected going like $|\gamma| \propto 1/\theta$, the prospects for extending this to larger scales were good
- But what exactly was the colourful DM image actually measuring? The surface density? The potential? Or something else?
- How could one calibrate the measurement (it was becoming clear that the null GG-lensing result was due to the seeing diluting the signal)
- The next few years saw intense activity in all of these areas.