GRAVITATIONAL LENSING

1 – DEFLECTION OF LIGHT

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AA 2019-2020

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THE COURSE

- Basics of Gravitational Lensing Theory
- Applications of Gravitational Lensing:
  - microlensing in the MW
  - lensing by galaxies and galaxy clusters
- Python

LEARNING RESOURCES

- https://github.com/maxmen/LensingLectures
- available materials:
  - lecture notes (partially)
  - lecture slides
  - python notebooks
- Suggested books:
  - Principles of Gravitational Lensing - Congdon & Keeton
  - Gravitational Lensing - Dodelson
  - Gravitational Lensing: strong, weak and micro - Schneider, Kochaneck & Wambsganss

FINAL EXAM

- three questions: the first at your choice
- all the topics discussed during the course
- you are encouraged to complement the material distributed during the course with other papers, books, etc.
- for what regards the python examples: you are strongly encouraged to study and understand the codes to fully understand the algorithms
- programming will not be part of the exam, but the knowledge of the algorithms will be required

CONTENTS OF TODAY'S LESSON

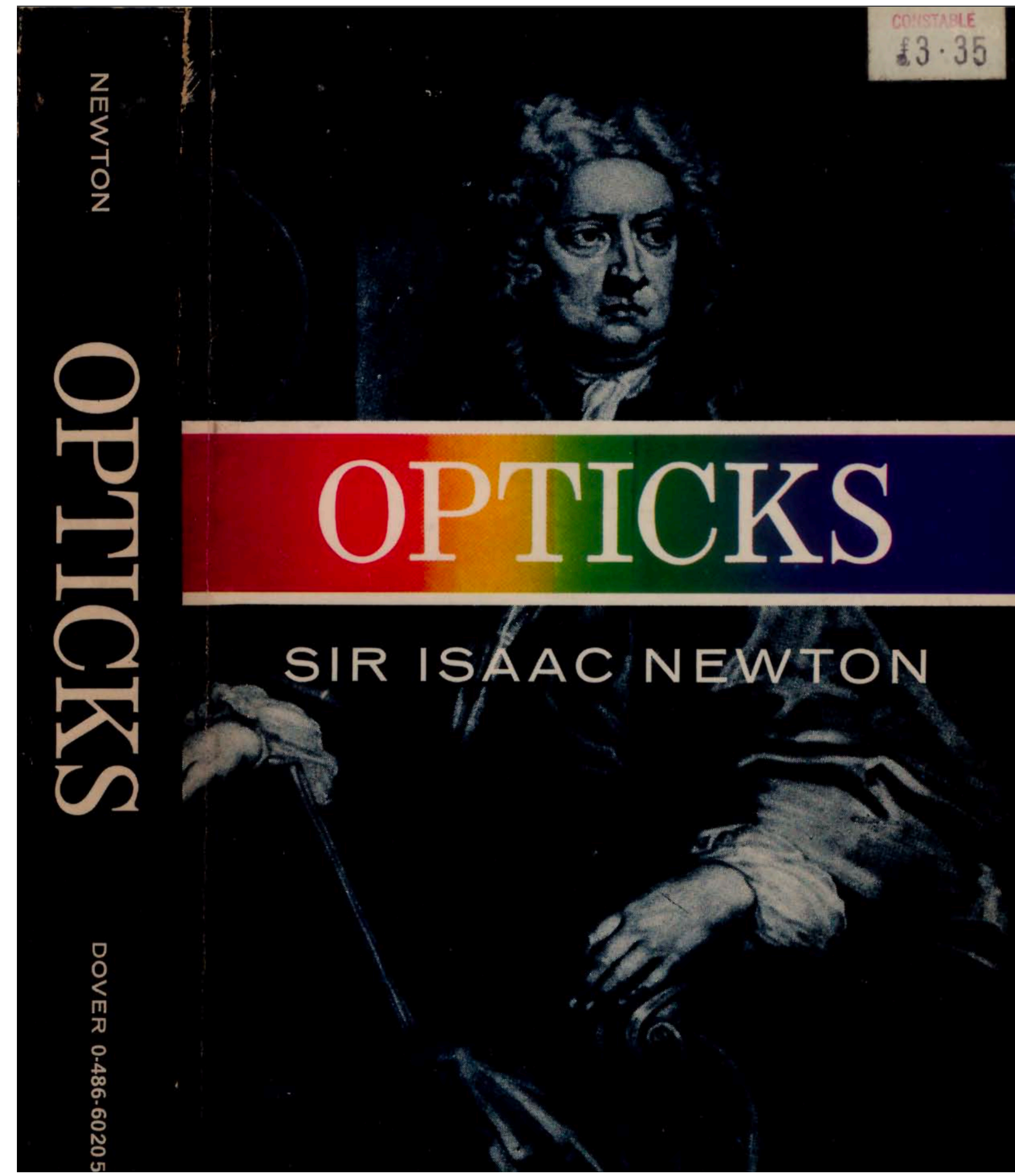
- Few historical remarks
- Deflection of light in the Newtonian limit
- Gravitational lensing in the context of general relativity
- The deflection angle

CORPUSCULAR THEORY OF LIGHT

- I. Newton, Opticks (1704-1730)
- Third volume ends with 31 queries:

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?

Qu. 29. Are not the Rays of Light very small Bodies emitted from shining Substances? For such Bodies will pass through uniform Mediums in right Lines without bending into the Shadow, which is the Nature of the Rays of Light. They will also be capable



- 1678: wave theory, Huygens

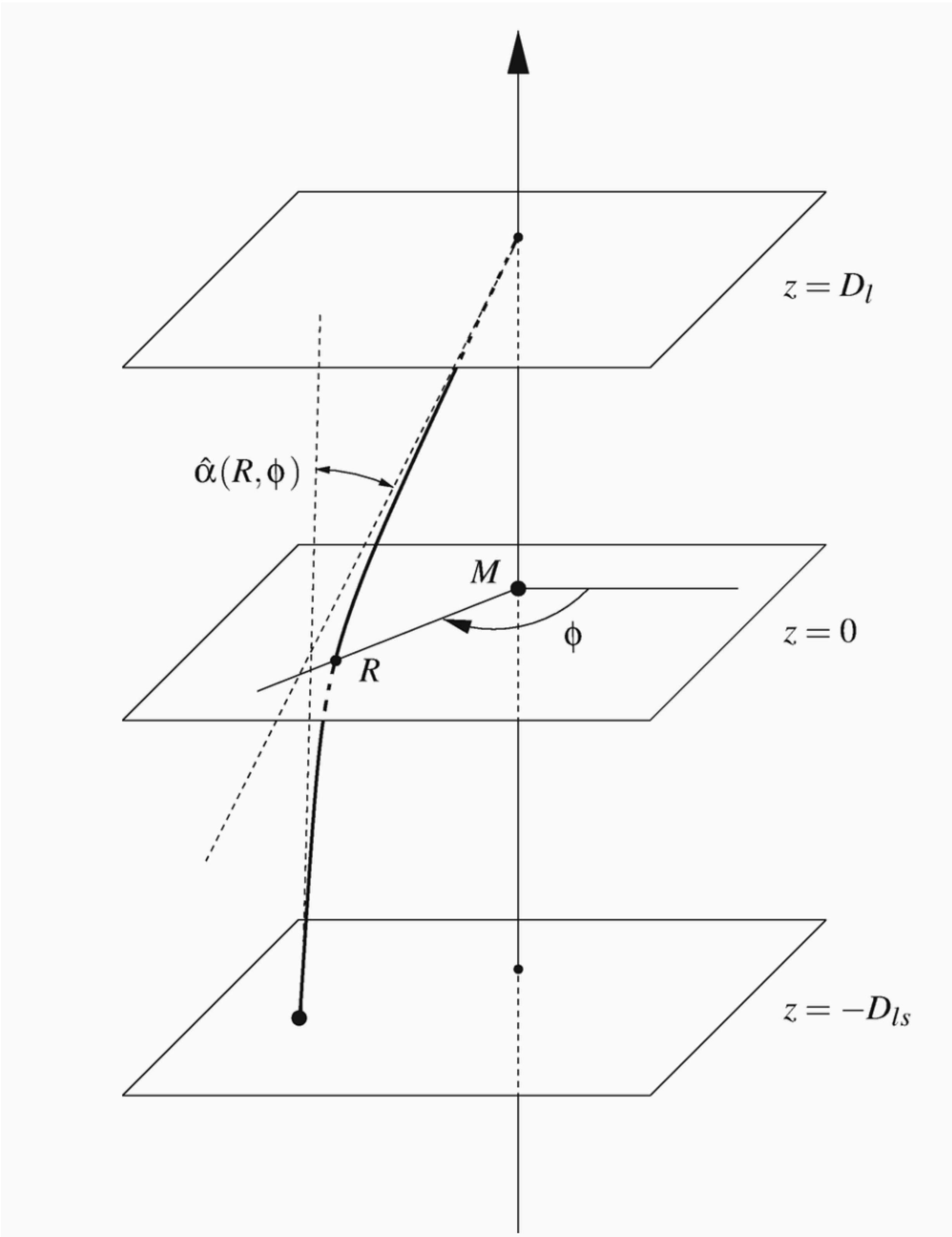
TIMELINE

- 1783: John Michell writes to Henry Cavendish. A light corpuscle might not be capable of escaping a massive star if

$$E \equiv \frac{1}{2}mv^2 - \frac{GmM}{R} \leq 0 \qquad v = c \qquad R < R_s \equiv \frac{2GM}{c^2}\ .$$

- 1784: Henry Cavendish calculates the deflection of a light corpuscle by a mass M. Unpublished until beginning of ‘900.
- 1801: Johan Soldner independently repeats the same calculation and publish it

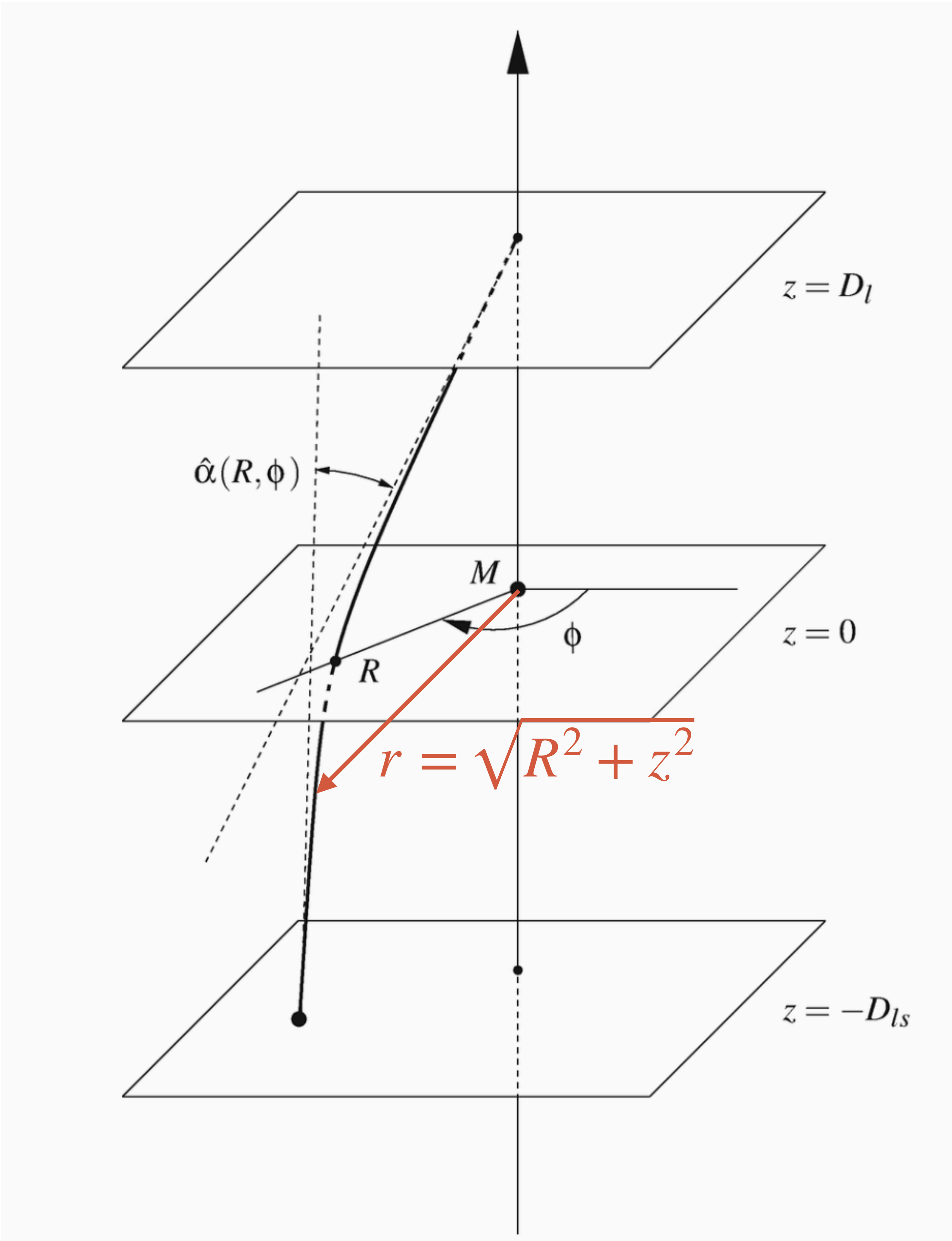
DEFLECTION OF A LIGHT CORPUSCLE



- Assumptions:
  - photons have mass and feel gravity
  - Newton's law of gravitation
  - Newton's 2nd law of motion
  - speed of light is finite

Congdon & Keeton, 2018

DEFLECTION OF A LIGHT CORPUSCLE



$$\vec{v}_0 = c\,\vec{e}_z$$

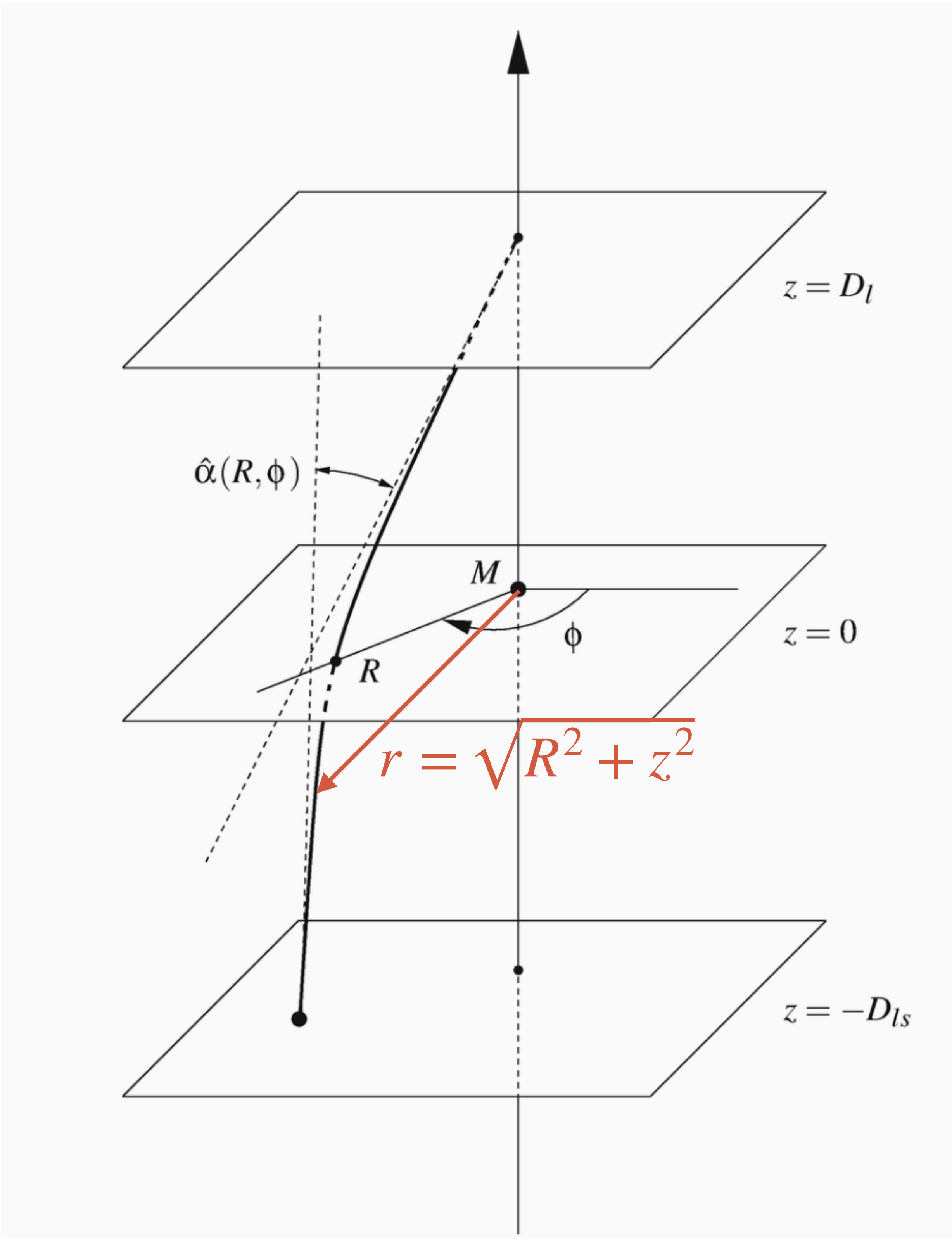
$$r = \sqrt{R^2 + z^2} \qquad dt = \frac{dz}{c}$$

$$\vec{\Delta} v = \int_{t_s}^{t_o} \vec{a}\,dt = \frac{1}{c}\int_{z_s}^{z_o} \vec{a}\,dz$$

$$\vec{a} = -\vec{\nabla}\Phi$$

$$\vec{\Delta} v = -\frac{1}{c}\int_{z_s}^{z_o} \vec{\nabla}\Phi dz$$

DEFLECTION OF A LIGHT CORPUSCLE

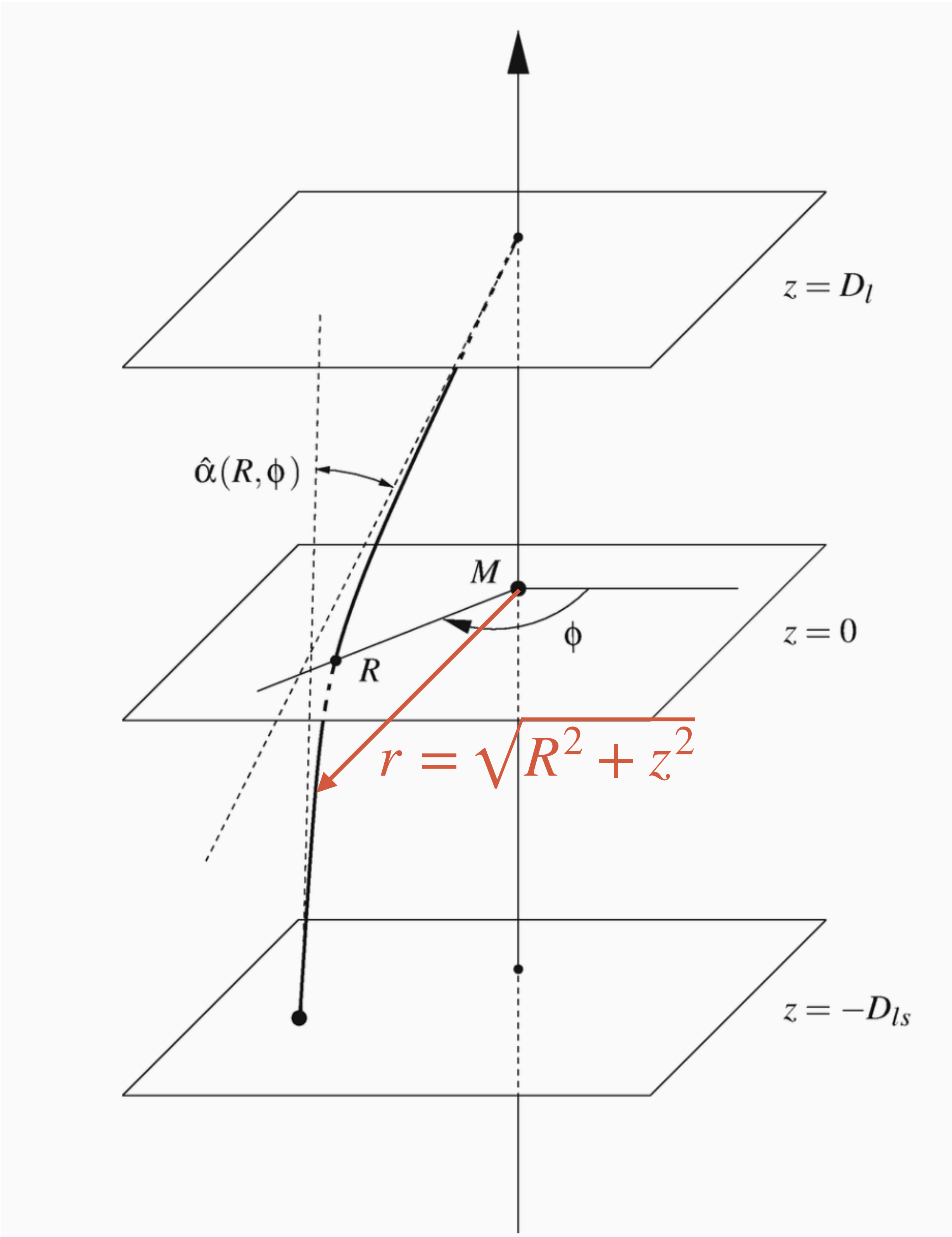


$$\overrightarrow{\Delta} v = -\frac{1}{c}\int_{z_s}^{z_o} \overrightarrow{\nabla}\Phi dz$$

$$\overrightarrow{\Delta} v = \Delta v_{||}\overrightarrow{e}_{||} + \Delta v_{\perp}\overrightarrow{e}_{R}$$

$$\overrightarrow{\nabla}\Phi = \frac{\partial \Phi}{\partial z}\overrightarrow{e}_{z} + \frac{\partial \Phi}{\partial R}\overrightarrow{e}_{R}$$

DEFLECTION OF A LIGHT CORPUSCLE



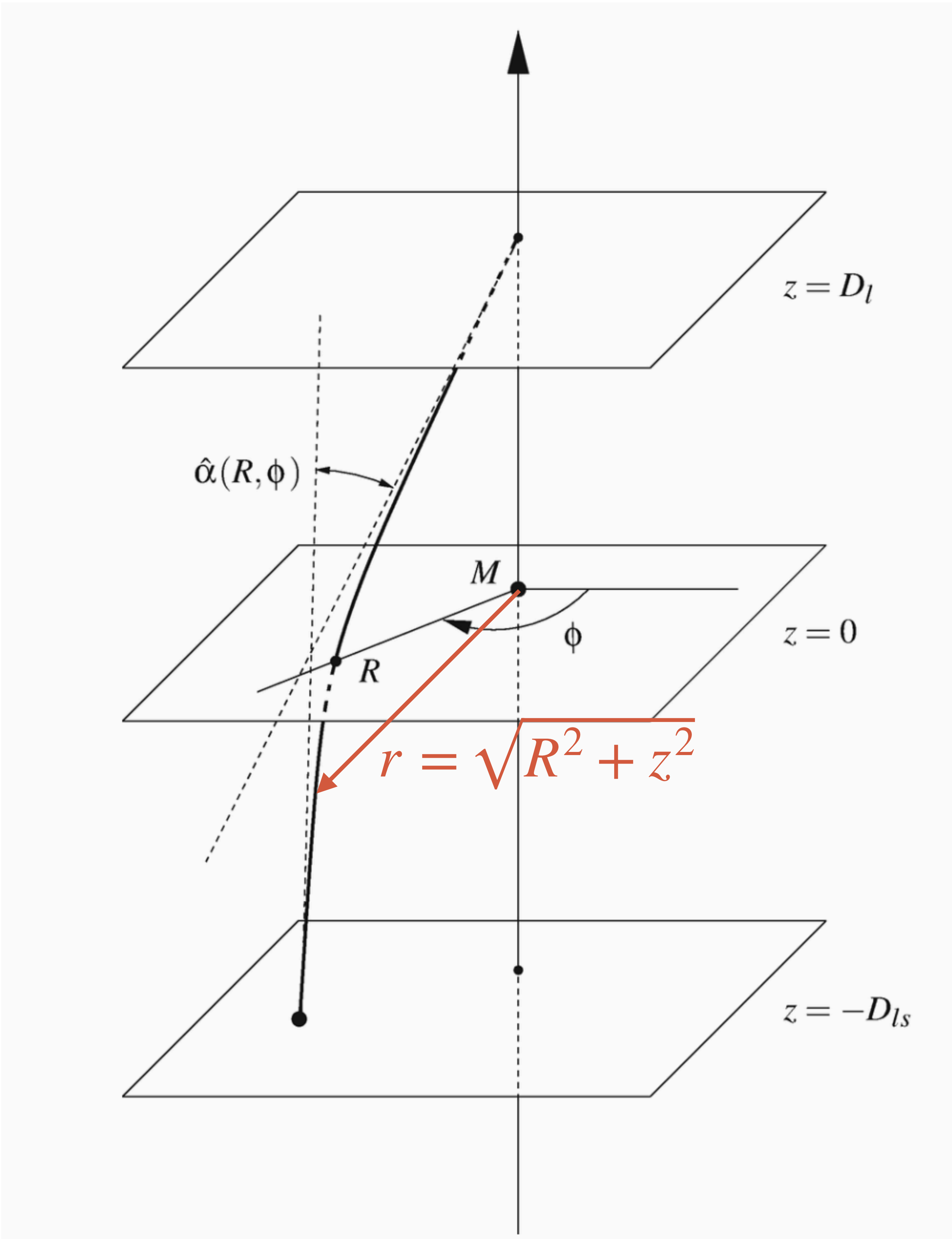
$$\vec{\Delta} v = -\frac{1}{c}\int_{z_s}^{z_o} \vec{\nabla}\Phi dz = \Delta v_{||}\vec{e}_{||} + \Delta v_{\perp}\vec{e}_R$$

$$\vec{\nabla}\Phi = \frac{\partial\Phi}{\partial z}\vec{e}_z + \frac{\partial\Phi}{\partial R}\vec{e}_R$$

$$\Delta v_{||} = -\frac{1}{c}\int_{z_s}^{z_o}\frac{\partial\Phi}{\partial z}dz$$

$$= -\frac{1}{c}[\Phi(\vec{R}, z_o) - \Phi(\vec{R}, z_s)]$$

DEFLECTION OF A LIGHT CORPUSCLE



$$\Delta v_{||} = -\frac{1}{c}\int_{z_s}^{z_o} \frac{\partial \Phi}{\partial z} dz$$

$$= -\frac{1}{c}[\Phi(\overrightarrow{R}, z_o) - \Phi(\overrightarrow{R}, z_s)]$$

Example: point mass

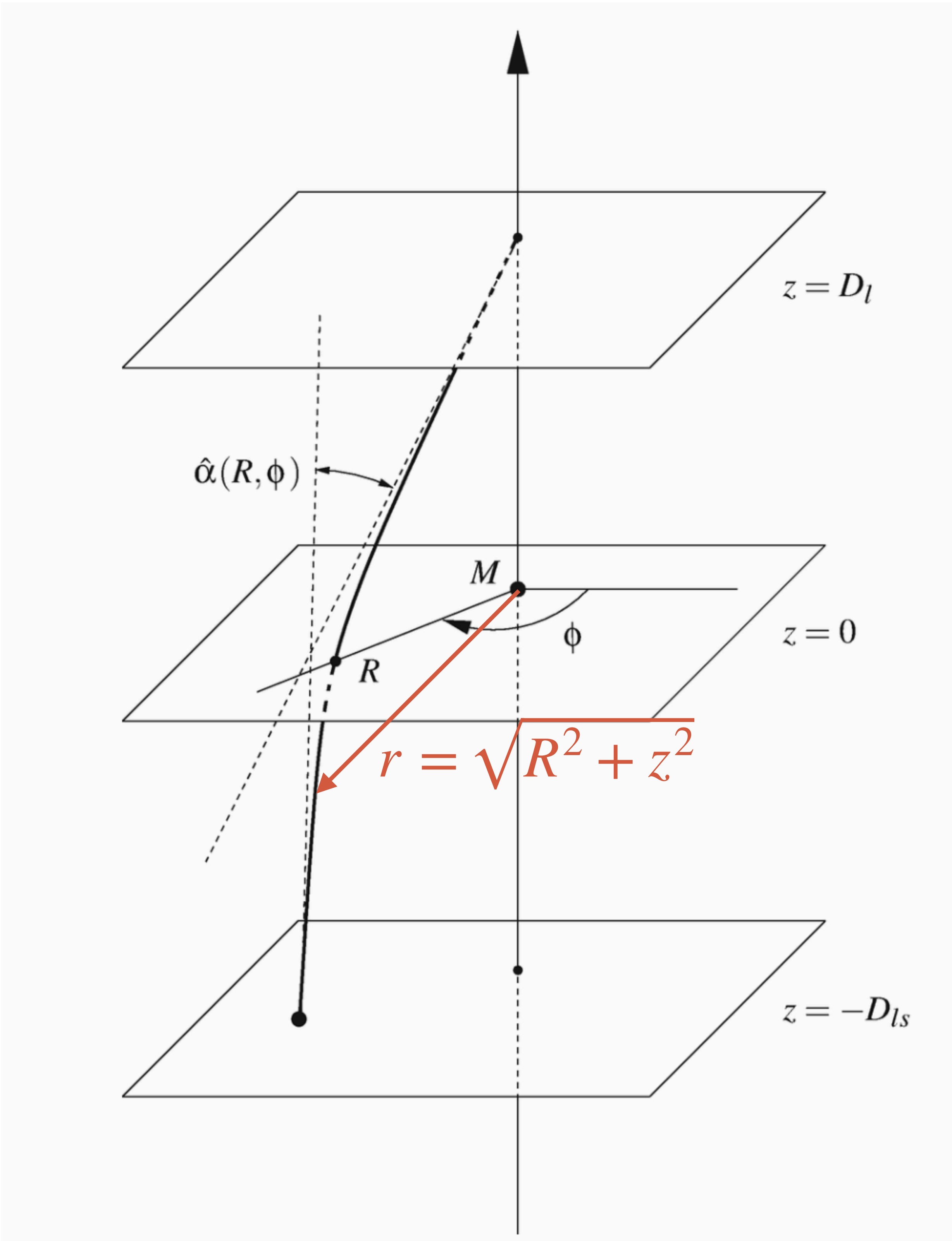
$$\Phi(r) = -\frac{GM}{r} = -\frac{GM}{\sqrt{R^2 + z^2}}$$

$$\lim_{|z|\to\infty} \Phi(r) = 0$$

If $|z_s|$ *and* $|z_o|$ *are large:*

$$\Delta v_{||} = 0$$

DEFLECTION OF A LIGHT CORPUSCLE



$$\Delta v_\perp = -\frac{1}{c}\int_{z_s}^{z_o} \frac{\partial \Phi}{\partial R} dz$$

Example: point mass

$$\Phi(r) = -\frac{GM}{r} = -\frac{GM}{\sqrt{R^2 + z^2}}$$

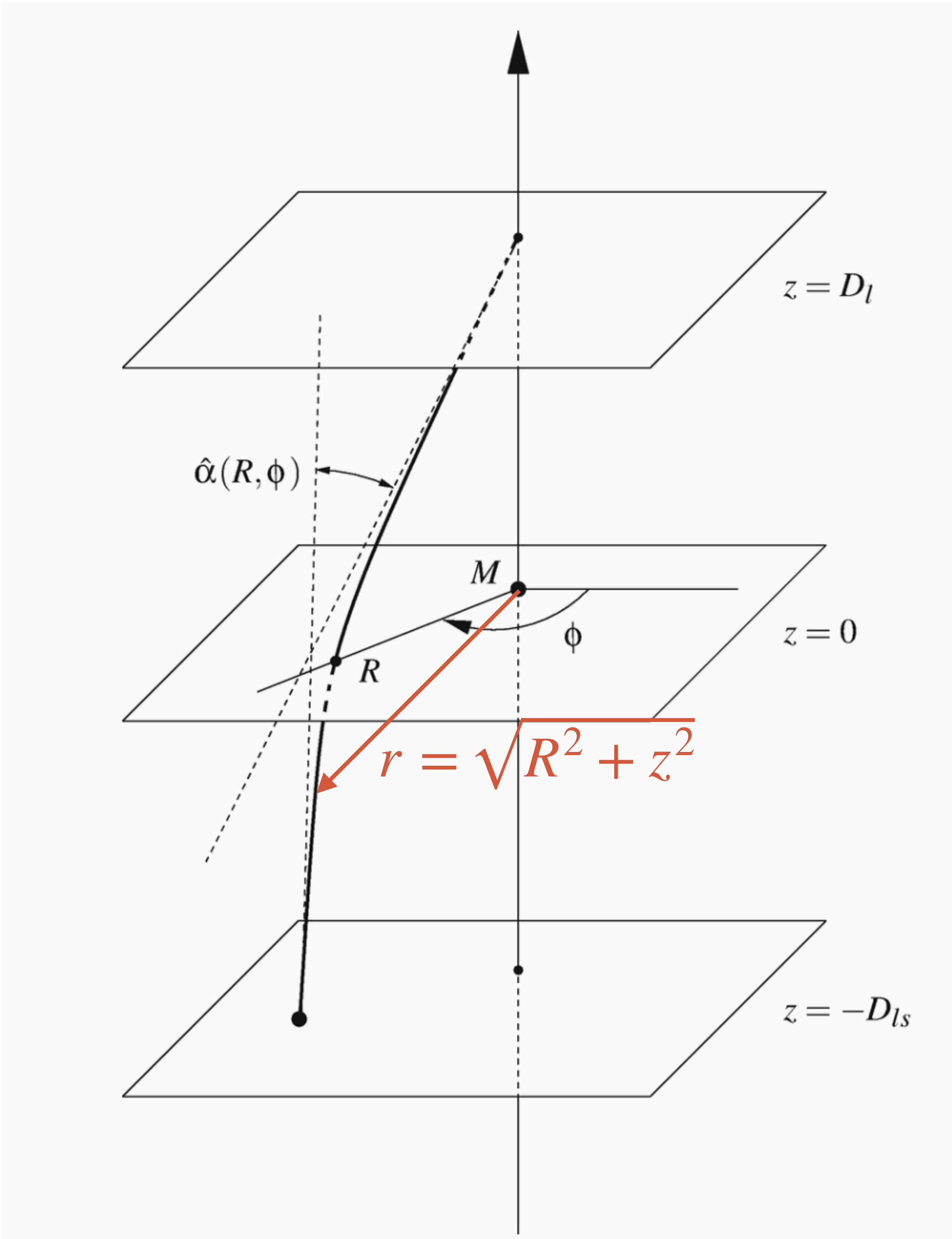
$$\Delta v_\perp = -\frac{GMR}{c}\int_{z_s}^{z_o} (R^2 + z^2)^{-3/2} dz$$

$$\tan(u) = \frac{z}{R} \qquad \frac{dz}{R} = \frac{du}{\cos^2(u)}$$

As before, if $|z_s|$ *and* $|z_o|$ *are large:*

$$\Delta v_\perp = -\frac{GM}{cR}\int_{-\pi/2}^{\pi/2} \cos(u) du = -\frac{2GM}{cR}$$

DEFLECTION OF A LIGHT CORPUSCLE



$$\Delta v_\perp = -\frac{GM}{cR}\int_{-\pi/2}^{\pi/2}\cos(u)du = -\frac{2GM}{cR}$$

Before the lens:

$$\vec{v}_0 = c\,\vec{e}_z = c\,\vec{e}_{in}$$

After the lens:

$$\vec{v} = v\,\vec{e}_{out} = c\,\vec{e}_{in} - \frac{2GM}{cR}\vec{e}_R$$

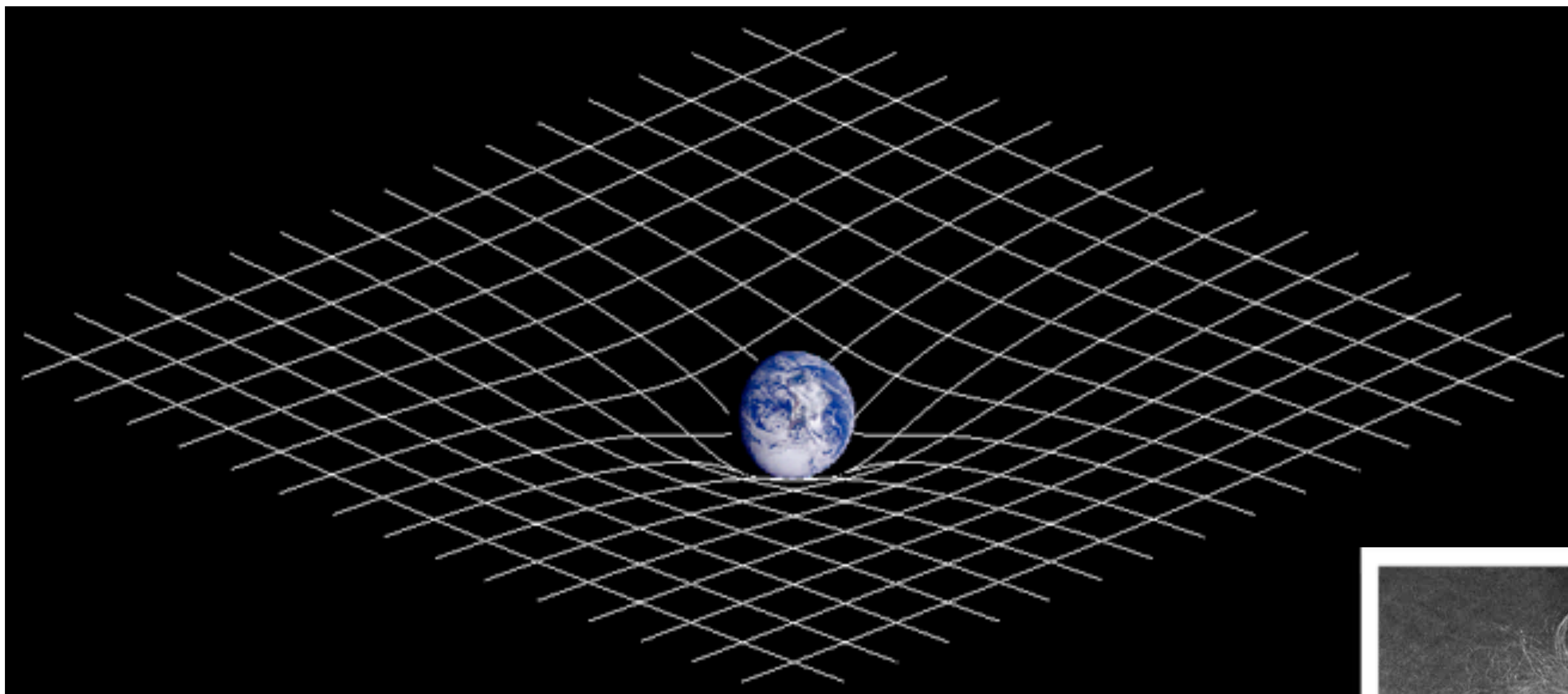
$$|v| = \sqrt{c^2 + \frac{4G^2M^2}{c^2R^2}} \simeq c$$

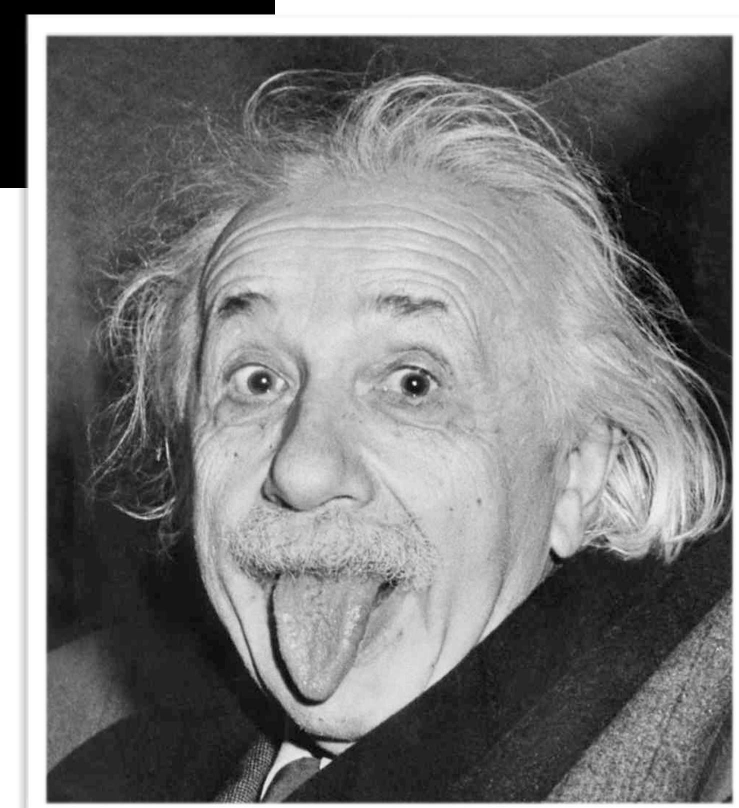
$$\vec{\hat{\alpha}}(R, \phi) = \vec{e}_{in} - \vec{e}_{out} = \frac{2GM}{c^2R}\vec{e}_R$$

TIMELINE

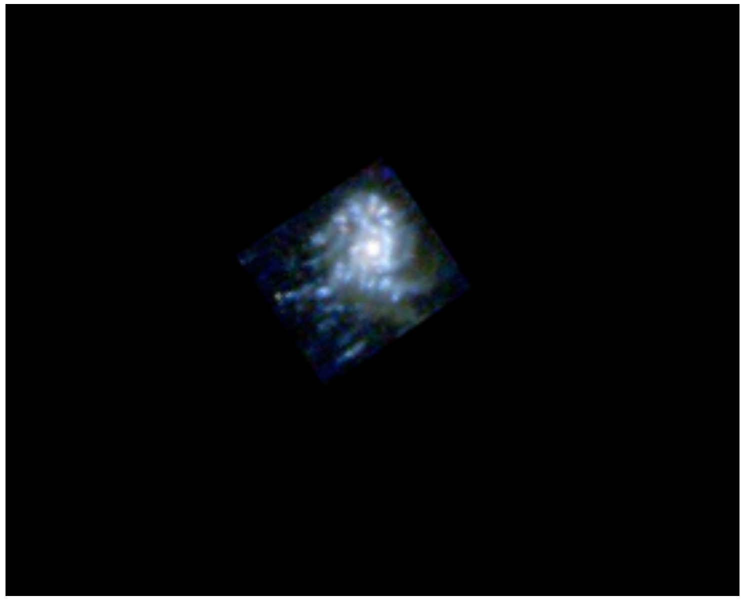
- 1801: Thomas Young demonstrates the wave nature of light using diffraction
- 1907-1911: Einstein resumes the idea of light deflection using special relativity and equivalence principle — result is identical to the one from Newtonian gravity
- 1914: Freundlich expedition to Crimea
- 1915: Einstein publishes the Theory of General Relativity…

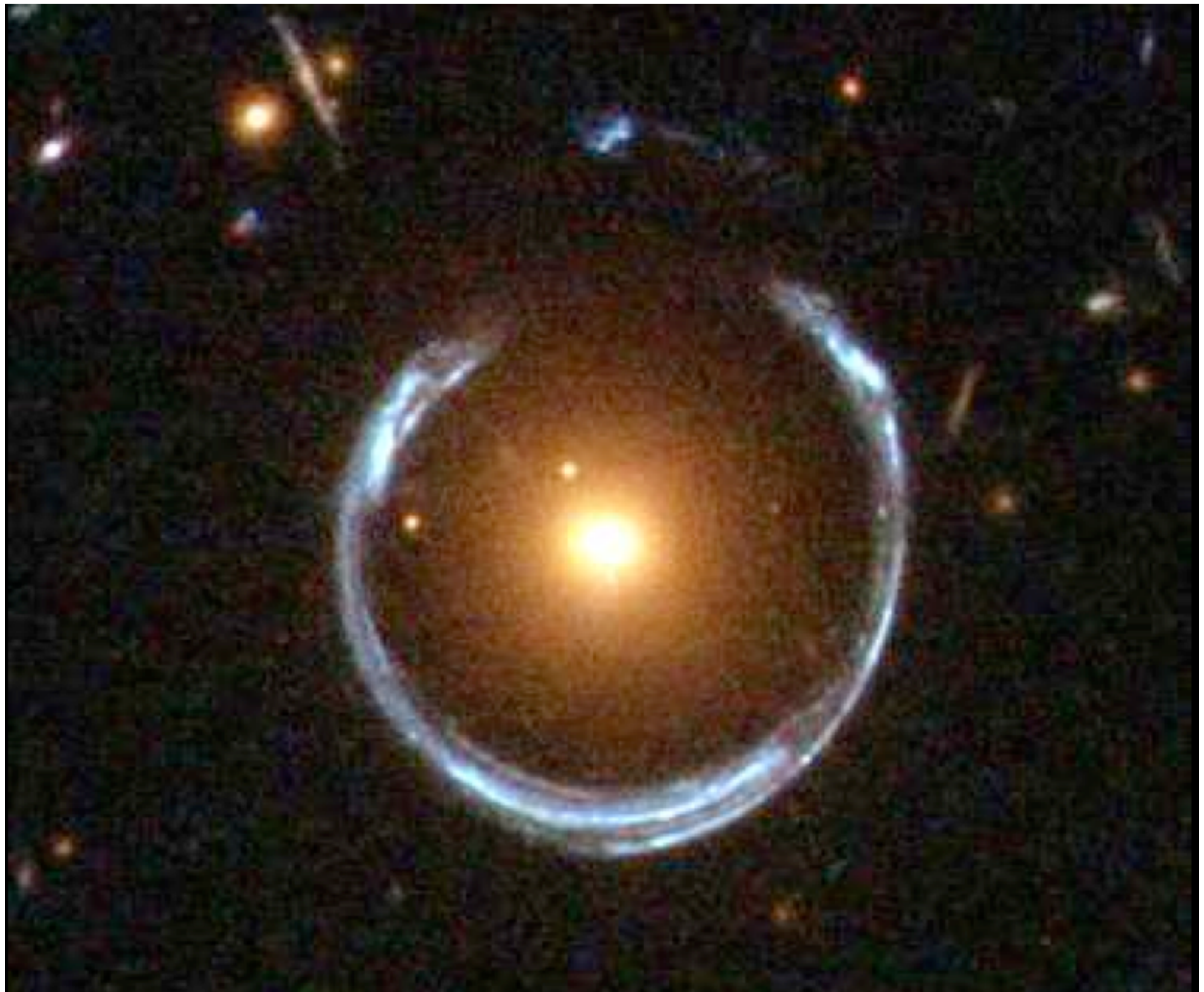
DEFLECTION OF LIGHT IN GENERAL RELATIVITY

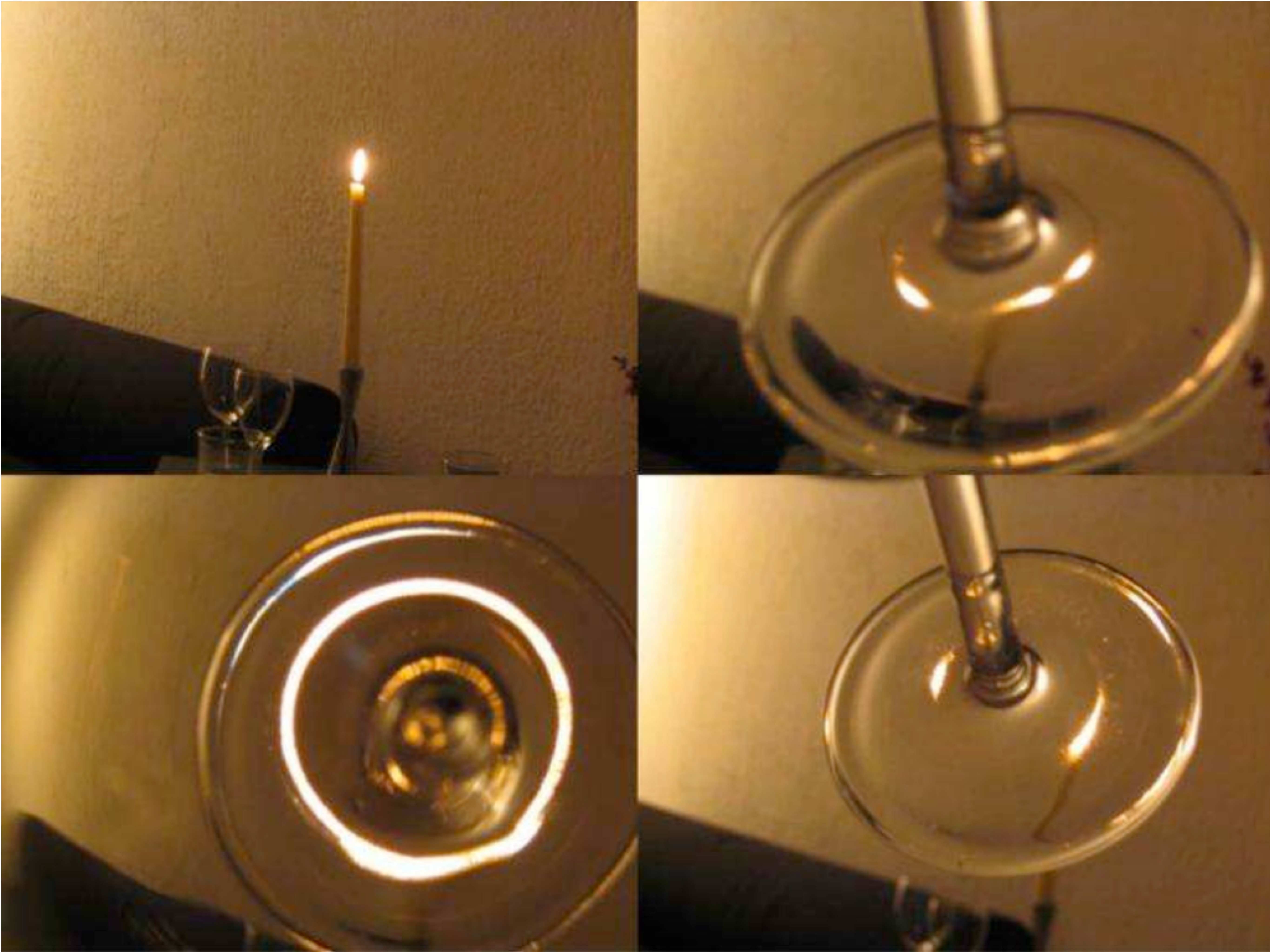




DEFLECTION OF LIGHT IN GENERAL RELATIVITY



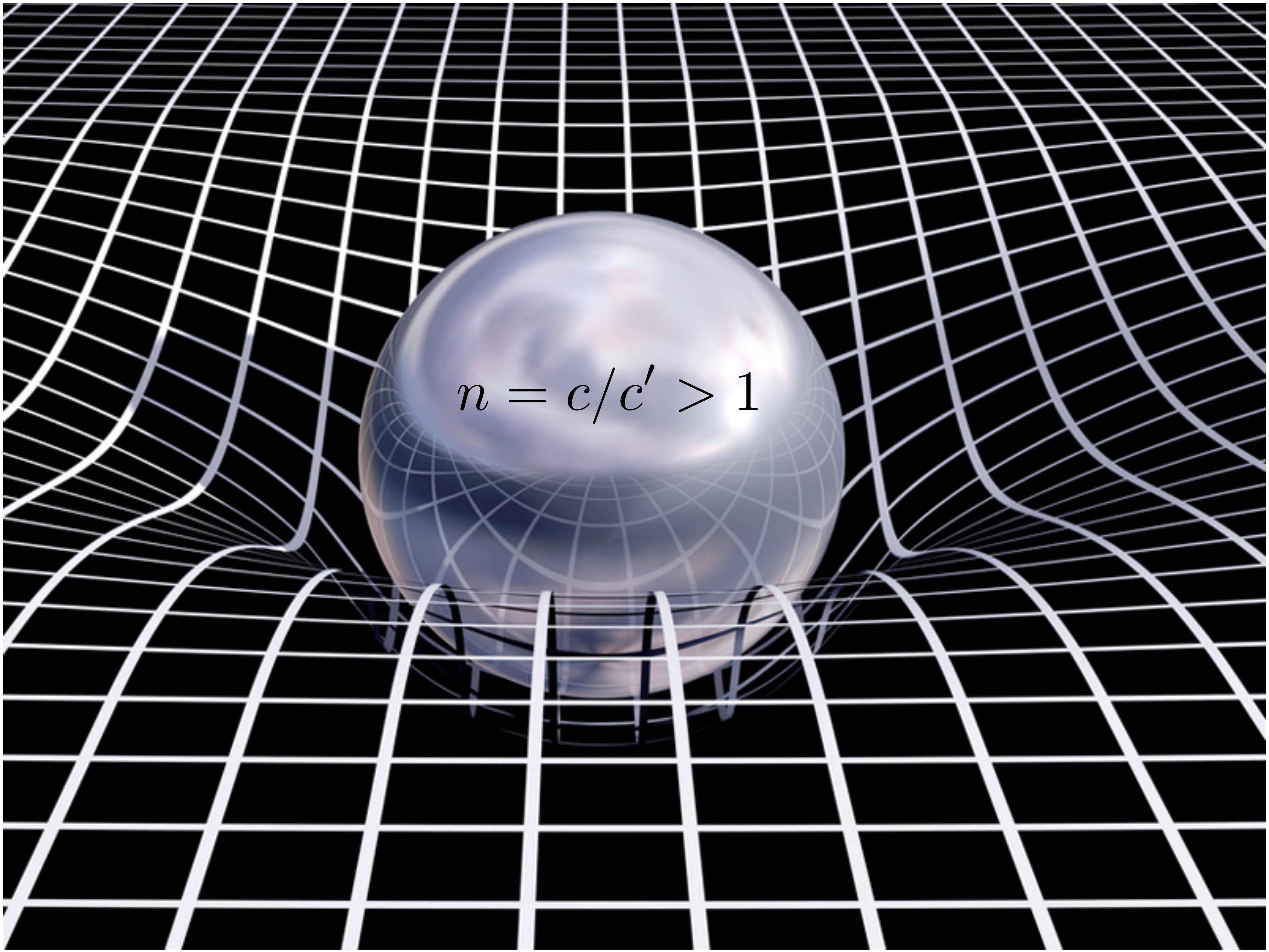




DEFLECTION OF LIGHT IN GENERAL RELATIVITY

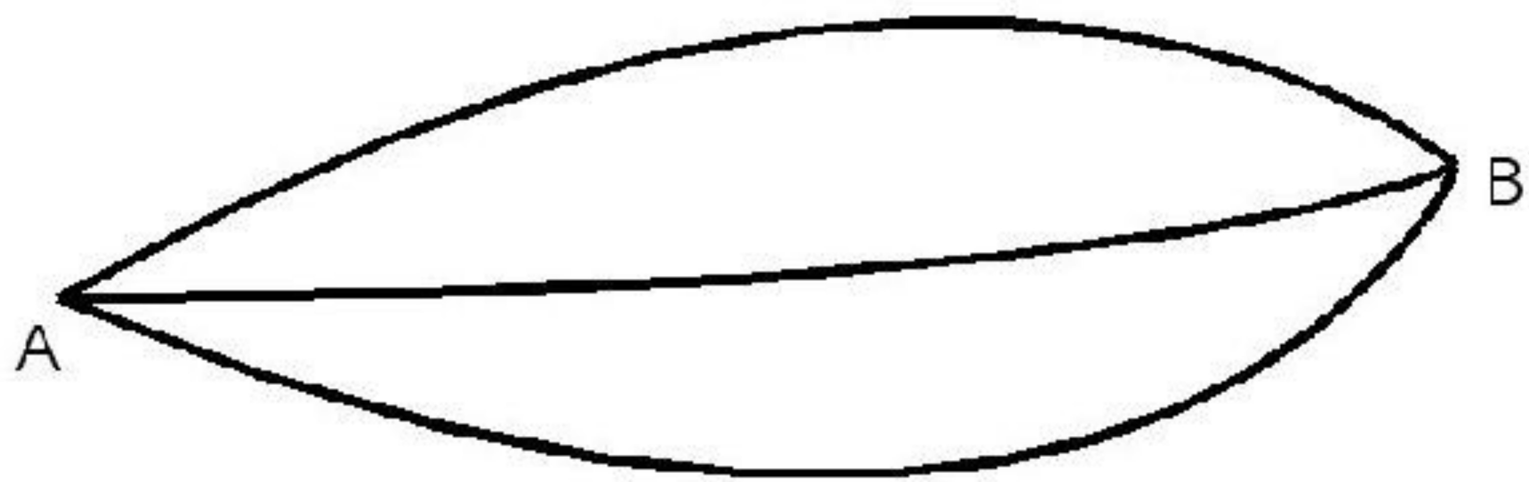
- We will now repeat the calculation of the deflection angle in the context of a locally curved space-time
- Assumptions:
  - the deflection occurs in small region of the universe and over time-scales where the expansion of the universe is not relevant
  - the weak-field limit can be safely applied: $|\Phi|/c^2 \ll 1$
  - perturbed region can be described in terms of an effective refractive index
  - Fermat principle

DEFLECTION OF LIGHT IN GENERAL RELATIVITY



DEFLECTION OF LIGHT IN GENERAL RELATIVITY

Travel time $= \int \frac{n}{c} \mathrm{d}l$



Fermat principle: $\delta \int_A^B n dl = 0$

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

How to define the effective diffraction index?

absence of lens = unperturbed space-time

described by the Minkowski metric

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\mathrm{d}s^2 = \eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = (\mathrm{d}x^0)^2 - (\mathrm{d}\vec{x})^2 = c^2\mathrm{d}t^2 - (\mathrm{d}\vec{x})^2$$

effective refractive index >1 =

perturbed space-time, described by the perturbed metric

$$\eta_{\mu\nu} \to g_{\mu\nu} = \begin{pmatrix} 1+\frac{2\Phi}{c^2} & 0 & 0 & 0 \\ 0 & -(1-\frac{2\Phi}{c^2}) & 0 & 0 \\ 0 & 0 & -(1-\frac{2\Phi}{c^2}) & \\ 0 & 0 & 0 & -(1-\frac{2\Phi}{c^2}) \end{pmatrix}$$

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 - \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

SCHWARZSCHILD METRIC (STATIC AND SPHERICALLY SYMMETRIC)

$$ds^2 = \left(1 - \frac{2GM}{Rc^2}\right) c^2 dt^2 - \left(1 - \frac{2GM}{Rc^2}\right)^{-1} dR^2 - R^2(\sin^2\theta d\phi^2 + d\theta^2)$$

$$R = \sqrt{1 + \frac{2GM}{rc^2}} r$$

$$x = r\sin\theta\cos\phi$$

$$y = r\sin\theta\sin\phi$$

$$z = r\cos\phi$$

$$dl^2 = [dr^2 + r^2(\sin^2\theta d\phi^2 + d\theta^2)]$$

$$\mathrm{d}s^2 = \left(\frac{1 - GM/2rc^2}{1 + GM/2rc^2}\right)^2 c^2\mathrm{d}t^2 - \left(1 + \frac{GM}{2rc^2}\right)^4 (\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2)$$

SCHWARZSCHILD METRIC IN THE WEAK FIELD LIMIT

$$\Phi/c^2 = -GM/rc^2 \ll 1$$

$$\begin{aligned}
\left(\frac{1-GM/2rc^2}{1+GM/2rc^2}\right)^2 &\approx \left(1-\frac{GM}{2rc^2}\right)^4 \\
&\approx \left(1-\frac{2GM}{rc^2}\right) \\
&= \left(1+\frac{2\Phi}{c^2}\right)
\end{aligned}
\qquad
\begin{aligned}
\left(1+\frac{GM}{2rc^2}\right)^4 &\approx \left(1+2\frac{GM}{rc^2}\right) \\
&= \left(1-\frac{2\Phi}{c^2}\right).
\end{aligned}$$

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 - \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

How to define the effective refractive index?

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 - \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

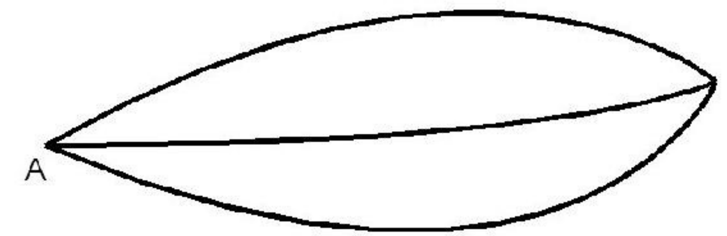
$$\left(1+\frac{2\Phi}{c^2}\right)c^2\mathrm{d}t^2 = \left(1-\frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

$$c' = \frac{|\mathrm{d}\vec{x}|}{\mathrm{d}t} = c\sqrt{\frac{1+\frac{2\Phi}{c^2}}{1-\frac{2\Phi}{c^2}}} \approx c\left(1+\frac{2\Phi}{c^2}\right)$$

$$n = \frac{c}{c'} \approx \frac{1}{1+2\Phi/c^2} \approx 1 - \frac{2\Phi}{c^2}$$

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

Let's use the Fermat principle



$$\delta \int_A^B n[\vec{x}(l)]\mathrm{d}l = 0$$

$$\mathrm{d}l = \left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| \mathrm{d}\lambda$$

$$\delta \int_{\lambda_A}^{\lambda_B} \mathrm{d}\lambda\, n[\vec{x}(\lambda)] \left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| = 0$$

generalized velocity $\dot{\vec{x}} \equiv \dfrac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}$

generalized coordinate

$$\boxed{n[\vec{x}(\lambda)] \left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| \equiv L(\dot{\vec{x}}, \vec{x}, \lambda)}$$

Langrangian!

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

Let's use the Fermat principle

$$\delta \int_{\lambda_A}^{\lambda_B} \mathrm{d}\lambda \, n[\vec{x}(\lambda)] \left| \frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda} \right| = 0$$

Euler-Langrange equation: $$\frac{\mathrm{d}}{\mathrm{d}\lambda} \frac{\partial L}{\partial \dot{\vec{x}}} - \frac{\partial L}{\partial \vec{x}} = 0$$

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

Let's use the Fermat principle

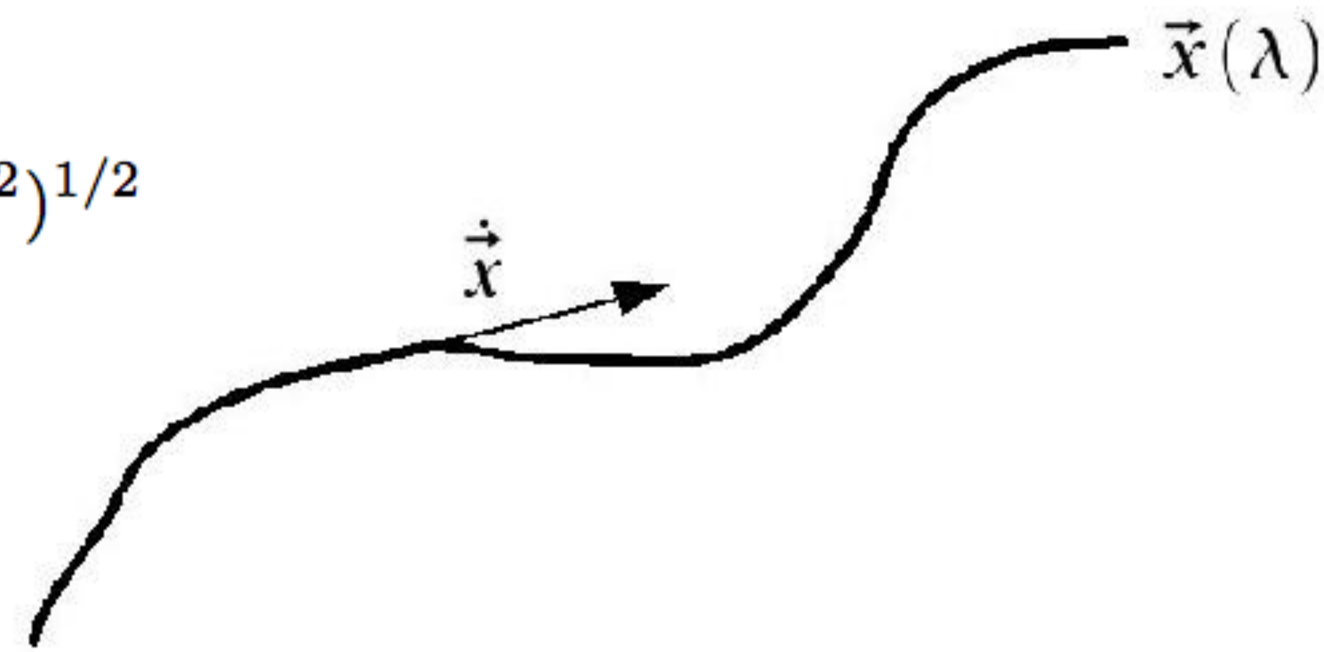
Euler-Langrange equation: $$\frac{\mathrm{d}}{\mathrm{d}\lambda}\frac{\partial L}{\partial \dot{\vec{x}}} - \frac{\partial L}{\partial \vec{x}} = 0 \qquad n[\vec{x}(\lambda)]\left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| \equiv L(\dot{\vec{x}}, \vec{x}, \lambda)$$

$$\frac{\partial L}{\partial \vec{x}} = |\dot{\vec{x}}|\frac{\partial n}{\partial \vec{x}} = (\vec{\nabla} n)|\dot{\vec{x}}|$$

$$\frac{\partial L}{\partial \dot{\vec{x}}} = n\frac{\dot{\vec{x}}}{|\dot{\vec{x}}|} \qquad \left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| = |\dot{\vec{x}}| = (\dot{\vec{x}}^2)^{1/2}$$

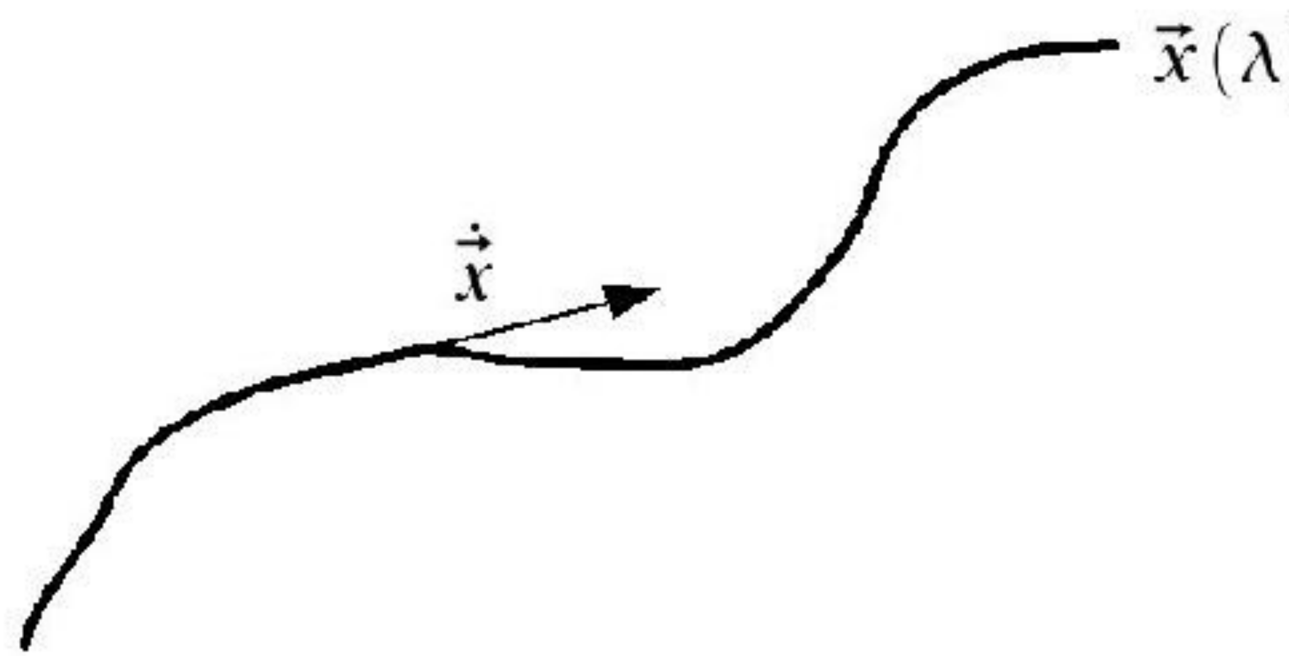
$$|\dot{\vec{x}}| = 1$$

$$\vec{e} \equiv \dot{\vec{x}}$$



DEFLECTION OF LIGHT IN GENERAL RELATIVITY

$$|\dot{\vec{x}}| = 1 \qquad \vec{e} \equiv \dot{\vec{x}}$$



$$\frac{\partial L}{\partial \vec{x}} = |\dot{\vec{x}}| \frac{\partial n}{\partial \vec{x}} = (\vec{\nabla} n)|\dot{\vec{x}}| = \vec{\nabla} n$$

$$\frac{\partial L}{\partial \dot{\vec{x}}} = n \frac{\dot{\vec{x}}}{|\dot{\vec{x}}|} = n\vec{e}$$

$$\frac{\mathrm{d}}{\mathrm{d}\lambda}(n\vec{e}) - \vec{\nabla} n = 0$$

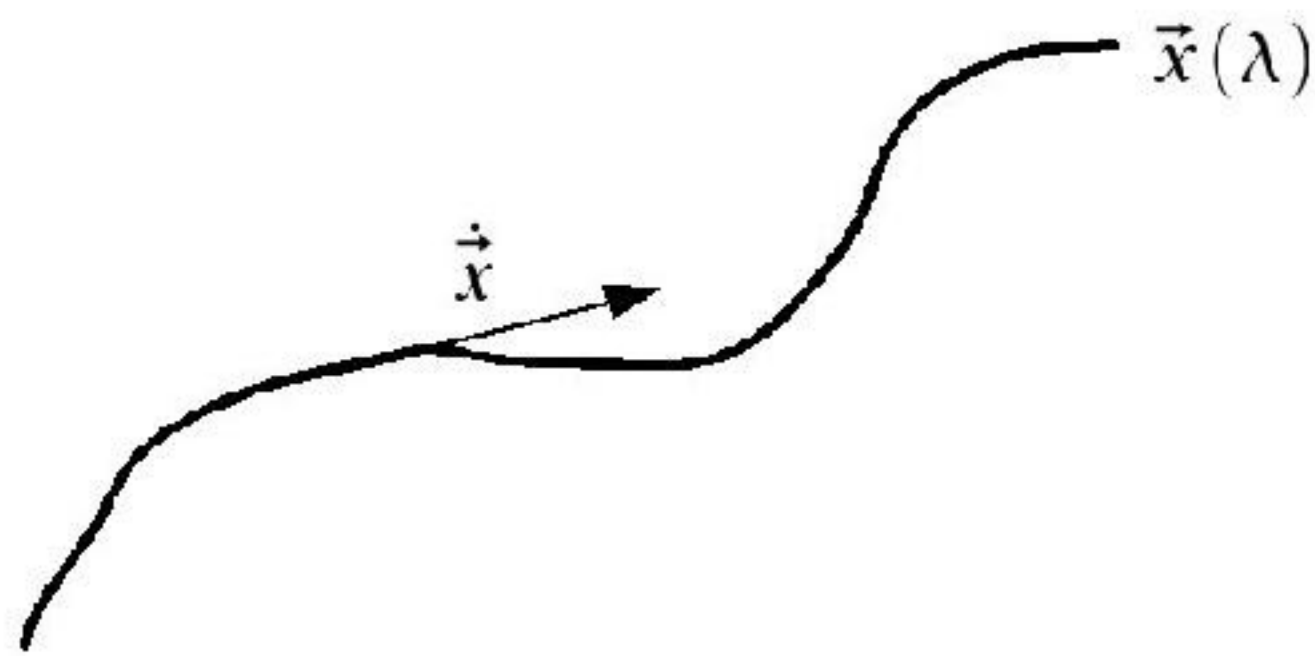
$$n\dot{\vec{e}} + \vec{e} \cdot [(\vec{\nabla} n)\dot{\vec{x}}] = \vec{\nabla} n \ ,$$

$$\Rightarrow n\dot{\vec{e}} = \vec{\nabla} n - \vec{e}(\vec{\nabla} n \cdot \vec{e})$$

$$\dot{\vec{e}} = \frac{1}{n}\vec{\nabla}_\perp n = \vec{\nabla}_\perp \ln n$$

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

$$\dot{\vec{e}} = \frac{1}{n}\vec{\nabla}_{\perp} n = \vec{\nabla}_{\perp} \ln n$$



$$n = c/c' = 1 - \frac{2\phi}{c^2} \qquad \frac{\phi}{c^2} \ll 1$$

$$\ln n \approx -2\frac{\phi}{c^2}$$

$$\dot{\vec{e}} \approx -\frac{2}{c^2}\vec{\nabla}_{\perp}\Phi$$

$$\vec{e}_{out} = \vec{e}_{in} + \int_{\lambda_A}^{\lambda_B} \dot{e}\, d\lambda$$

Deflection angle

$$\hat{\vec{\alpha}} = \vec{e}_{in} - \vec{e}_{out} = \frac{2}{c^2}\int_{\lambda_A}^{\lambda_B} \vec{\nabla}_{\perp}\Phi\, d\lambda$$

HOW BIG ARE THESE DEFLECTIONS?

The potential has the dimension of a squared velocity. We can see it as the characteristic velocity of a particle orbiting that potential. Therefore

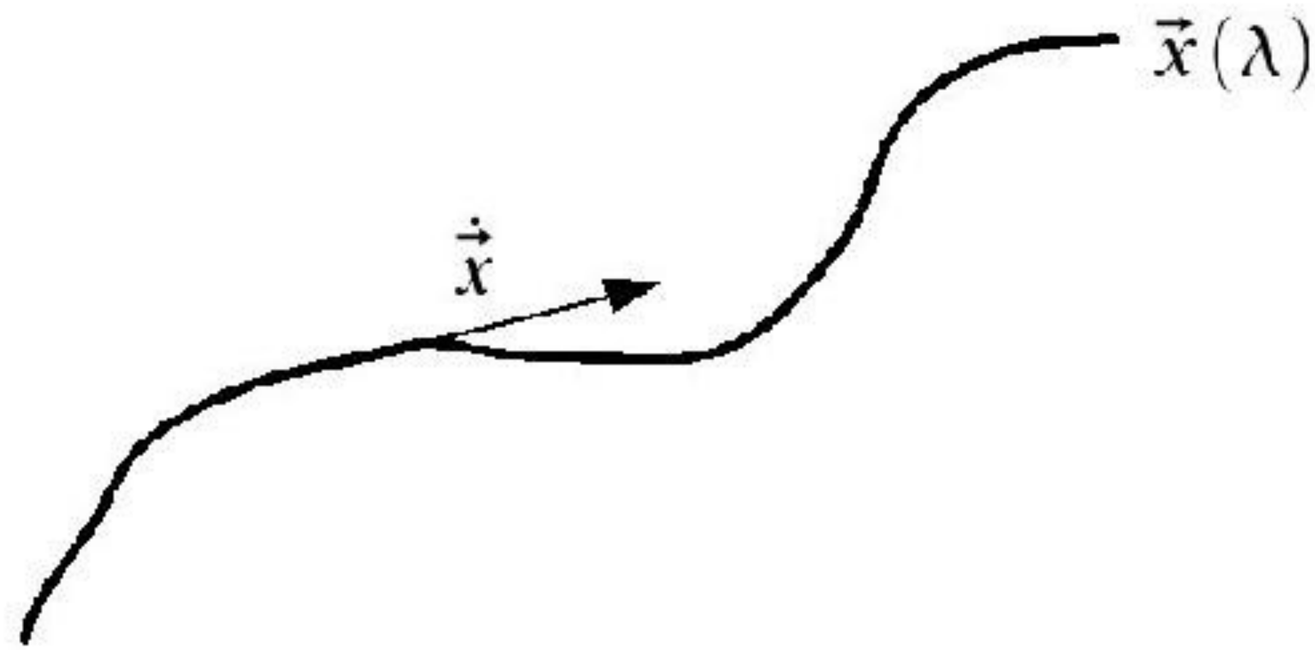
- *galaxy: ~200 km/s*
- *galaxy cluster: ~1000 km/s*

This means that deflections from astrophysical masses are very small

$$\hat{\vec{\alpha}} = \vec{e}_{in} - \vec{e}_{out} = \frac{2}{c^2} \int_{\lambda_A}^{\lambda_B} \vec{\nabla}_{\perp} \Phi d\lambda$$

DEFLECTION OF LIGHT IN GENERAL RELATIVITY

$$\hat{\vec{\alpha}} = \vec{e}_{in} - \vec{e}_{out} = \frac{2}{c^2}\int_{\lambda_A}^{\lambda_B} \vec{\nabla}_{\perp}\Phi d\lambda$$



Good news!

The integral above should be carried out over the actual light path, but it can be approximated by integrating over the straight, undeflected light path (like in Born's approximation of scattering theory).

$$\hat{\vec{\alpha}} = \vec{e}_{in} - \vec{e}_{out} = \frac{2}{c^2}\int_{-\infty}^{+\infty} \vec{\nabla}_{\perp}\Phi dz$$

A LIGHT RAY GRAZING THE SURFACE OF THE SUN

General relativity:

$$\hat{\alpha} = \frac{4GM_\odot}{c^2 R_\odot} = 1.75''$$

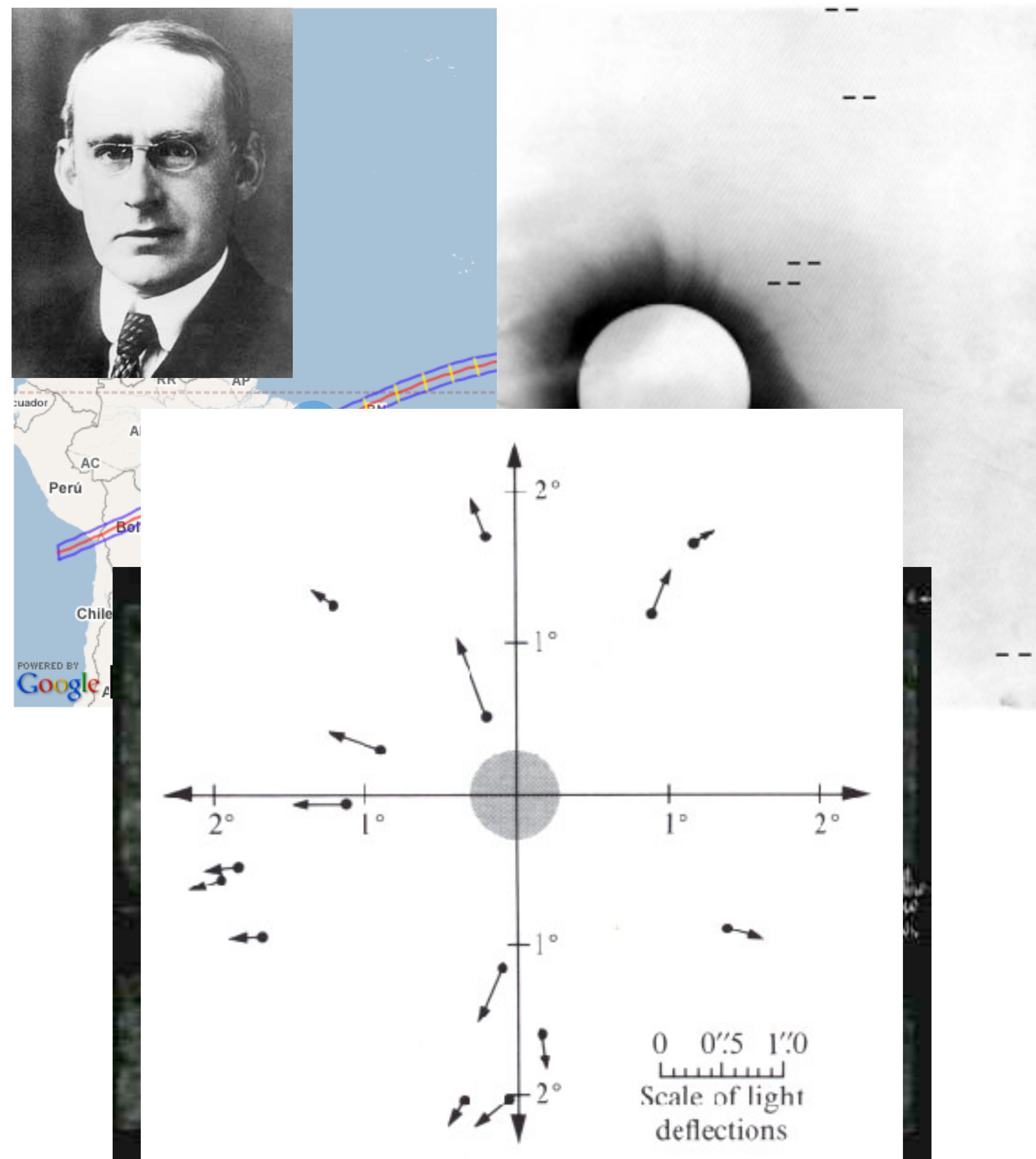
Newtonian gravity:

$$\hat{\alpha} = \frac{2GM_\odot}{c^2 R_\odot} = 0.875''$$

The reason for the factor of 2 difference is that ***both the space and time coordinates are bent*** *in the vicinity of massive objects — it is the four-dimensional space–time which is bent by the Sun.*

EDDINGTON EXPEDITIONS

- In 1919 Eddington organized two expeditions to observe a total solar eclipse (Principe Island and Sobral)
- The goal was to measure the lensing effect of the sun on background stars
- Very conveniently, the sun was well aligned with the Iades open cluster
- During the eclipse the expedition from Principe registered a shift in the apparent position of stars with respect to their night-time positions, which resulted to be consistent with the GR predictions
- The Sobral expedition measured a smaller deflection but this was interpreted as the result of a technical problem.



GRAVITY BENDS LIGHT! (7/11/1919)

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.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results ob-

"STARLIGHT BENT BY THE SUN'S ATTRACTION": THE EINSTEIN THEORY.