



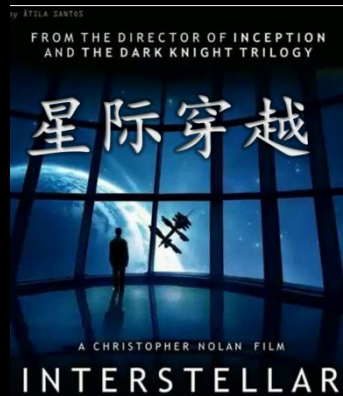
黑洞周围粒子运动

基于目标群体的课程设计演示
与同侪研讨

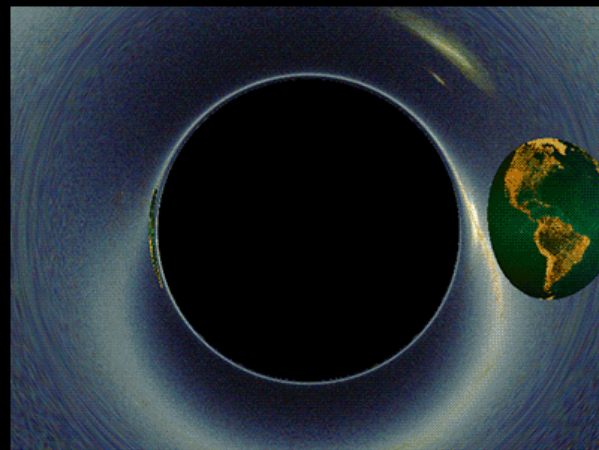
罗新炼



黑洞 一类神奇的天体



南京大学教师教学发展中心版权所有



The Dark Side of the Universe

Colossal Galactic Explosions
Where matter turns to energy p. 50

Quarks, Gluons and Strings
Physics at the boundary p. 74

The Ultimate Time Warp
A portal to the future p. 28

SCIENTIFIC AMERICAN REPORTS

SPECIAL EDITION ON ASTROPHYSICS

www.sciam.com

Display until June 12, 2007

REALITY-BENDING BLACK HOLES

Quantum Holes
Spacetime probes created on earth

Star-Making Machines
Powered by supermassive sinkholes?

Mysterious Bursts
Radiation sources now revealed

Einstein's Brainchild
What his equations foretold

COPYRIGHT 2007 SCIENTIFIC AMERICAN, INC.

THE DARK AGES of the Universe

Astronomers are trying to fill in the blank pages in our photo album of the infant universe

By Abraham Loeb

When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and I pass along my perspective for me. There are things that I would otherwise be bothered by—my own death, for example. Everyone will die sometime, but when I see the universe as a whole, it gives me a sense of longevity. I do not care so much about myself as I would otherwise, because of the big picture.

Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observations and a quantitative methodology.

Perhaps the greatest triumph of the past century has been a model of the universe that is supported by a large body of data. The value of such a model to our society is sometimes underappreciated. When I open the daily newspaper as part of my morning routine, I often see lengthy descriptions of conflicts between people about borders, possessions, or liberties. Today's news is often forgotten a few days later.

But when one opens ancient texts that have appealed to a broad audience over a longer period of time, such as the Bible, what does one often find in the opening chapter? A discussion of how the constituents of the universe—light, stars, life—were created. All though humans are often caught up with mundane problems, they are curious about the big picture. As citizens of the universe we cannot help but wonder how the first sources of light formed, how life came into existence and whether we are alone as intelligent beings in this vast space. Astronomers in the 21st century are uniquely positioned to answer these big questions.

What makes modern cosmology an empirical science is that we are literally able to peer into the past. When you look at your image reflected off a source one meter



COPYRIGHT 2006 SCIENTIFIC AMERICAN, INC.

COPYRIGHT 2006 SCIENTIFIC AMERICAN, INC.

SCIENTIFIC AMERICAN 47

In Search of DARK MATTER



SPICY DRUGS: CURES FROM CURRY? • SILICON LASER CHIPS

SCIENTIFIC AMERICAN

Prehistoric CSI:
Asteroids Did Not Kill These Dinosaurs

FEBRUARY 2007
WWW.SCIAM.COM

THE COSMIC GRIP OF DARK ENERGY

This mysterious force has a stranglehold on the shape of galaxies

Can Plants Cause Global Warming?

Digital TV's Analog Curse and What It Means for You

COPYRIGHT 2007 SCIENTIFIC AMERICAN, INC.

• one of hottest topic for public and scientist

Why does basic research exist?
Human curiosity

Albert Einstein once said, "I have no special gift, but I am passionately curious."

黑洞 (Black Hole)

罗新炼 (Xinlian Luo)
南京大学天文系
(Department of Astronomy, Nanjing University)

2007年7月10日

07年7月19日晚，南京1912“科技咖啡馆”

神奇的黑洞
Amazing Black Holes

BLACK HOLES

罗新炼

南京大学天文与空间科学学院
School of Astronomy (Space Science)

2012.4.26 晚

南京中医药大学
Nanjing University of Chinese Medicine

12年4月26日晚南京中医药大学科普讲座

相对论天体物理
漫谈

罗新炼

2011近代天文讲座


2011年11月27日

11、12年，天文系大四《近代天文讲座》课程中的内容



*Why does basic research exist?
Human curiosity*

Albert Einstein once said, "I have no special gift, but I am passionately curious."



NANJING UNIVERSITY

初等数理天文

Elementary Mathematical Astronomy

(2015.9-2016.1)

讲课人: 罗新炼
邮箱: xlluo@nju.edu.cn
电话: 89685982

南京大学天文与空间科学学院
School of Astronomy of Space Science

相对论与几何



Welcome to the
Euclid Mission Consortium

蹦极 (bungee jumping)

天文漫谈 (10-13)




BH Interstellar travel or Time travel

NANJING UNIVERSITY

大学天文学

College Astronomy

天体物理部分 (astrophysics section)
(2015.9-2016.1)

讲课人: 罗新炼

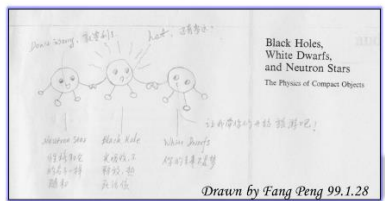
南京大学天文与空间科学学院
School of Astronomy of Space Science

• more参考《An Introduction to Modern Astrophysics》第16、17章内容

第四章 致密星

§ 4.1 白矮星 § 4.2 超新星爆发

§ 4.3 中子星 § 4.4 黑洞



Black Holes, White Dwarfs, and Neutron Stars
The Physics of Compact Objects

Drawn by Fang Peng 99.1.28

具体参见书或电子教材的第二十一和第二十二章

NANJING UNIVERSITY

GR and Cosmology


— 浅述

BEYOND WHO?

罗新炼
2013年2月 - 2013年6月

南京大学天文与空间科学学院
School of Astronomy of Space Science

第3章 广义相对论



- 能动张量
- Einstein张量
- Einstein场方程
- 弱场极限
- 球对称解

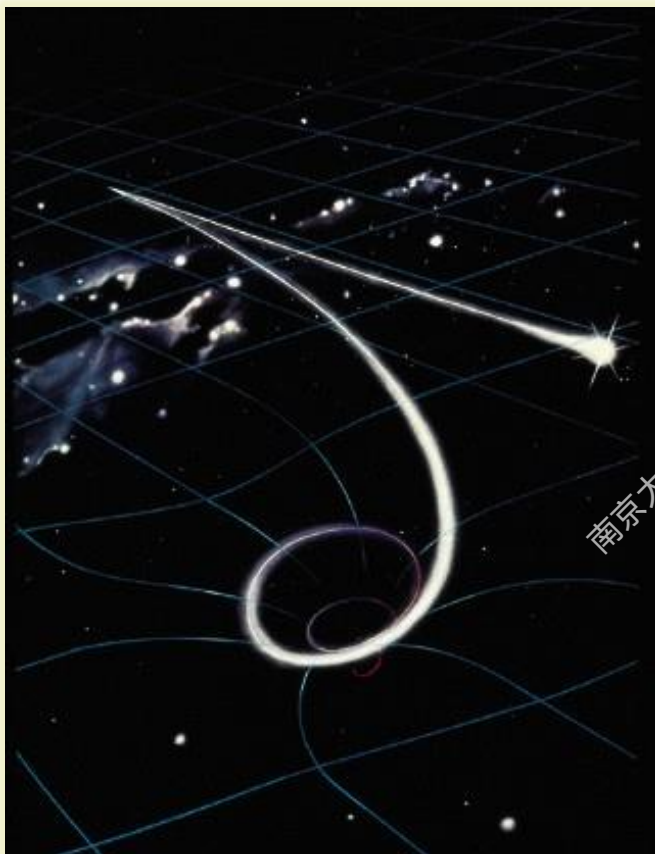
第4章 致密天体与黑洞



- 黑洞初步
- 无旋转黑洞
- 旋转黑洞
- 黑洞量子效应
- 广义相对论检验
- 致密星



内容



黑洞—时空中的无限深渊

For **Freshmen**

For **Sophomores**

Confusion

For **Juniors/Seniors**

Discussion

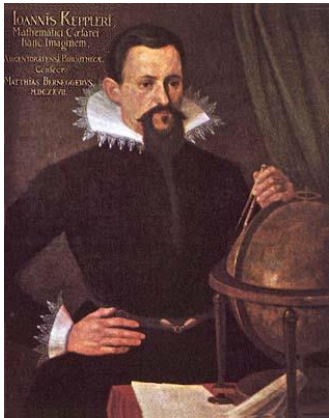
南京大学教师教学发展中心版权所有



For Freshmen

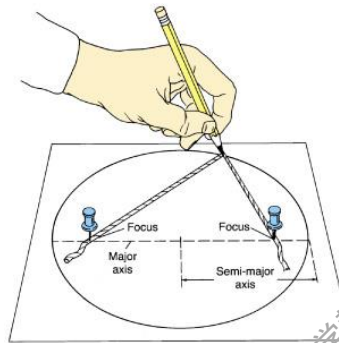


• 对行星运动的理解

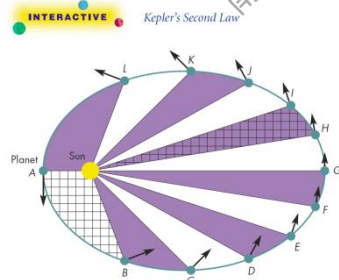


Johannes Kepler
(1571–1630)

1. 椭圆定律

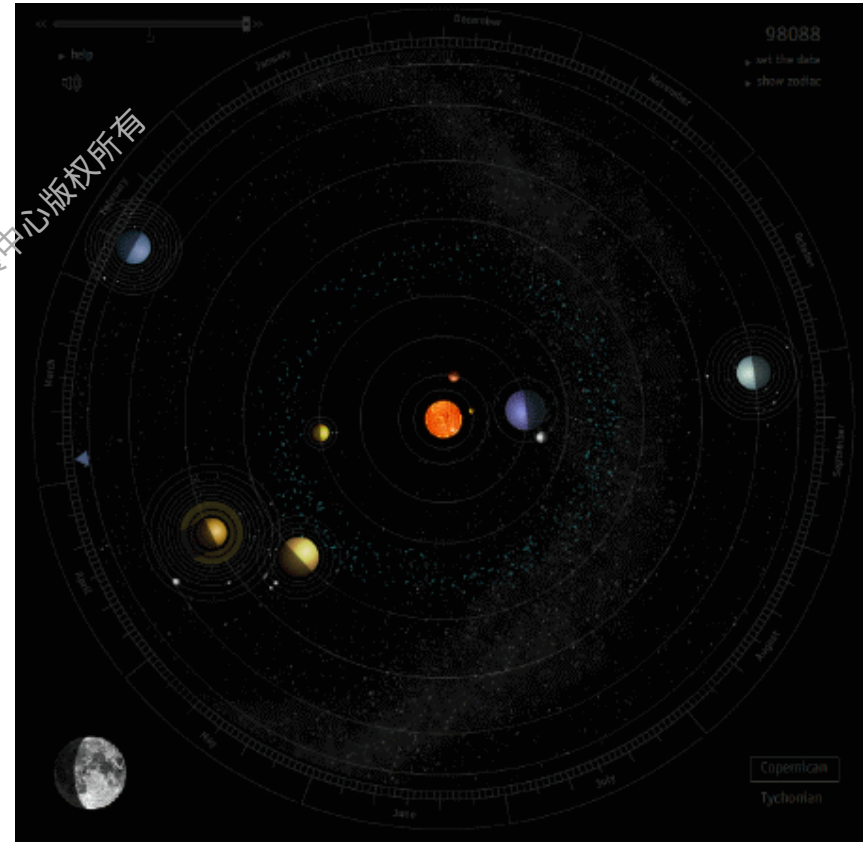
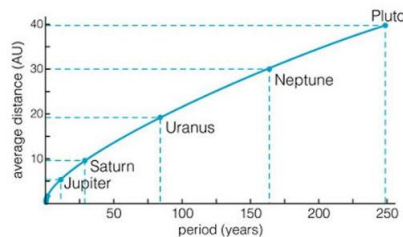


2. 面积定律



3. 调和定律

$$P^2 = a^3$$



Kepler motion applet



For Freshmen

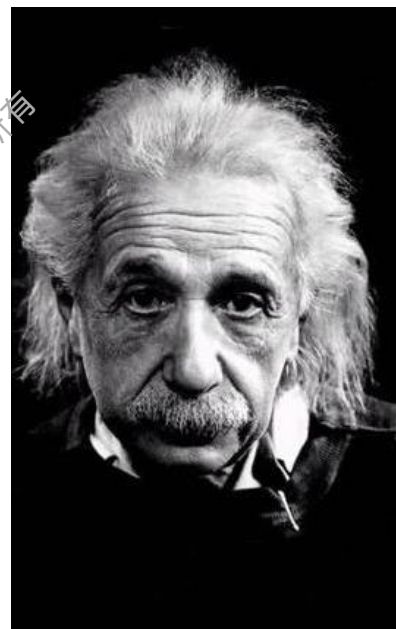


- 人类历史上最伟大的两位物理学家



Isaac Newton
(1642–1727)

(经典力学、光学、微积分)



Albert Einstein
(1879–1955)

(相对论、量子力学)



For Freshmen



- **严谨**（逻辑的严密性，结论的确定性。《几何原本》延续使用两千多年。）

公理化体系

... 几何公设仅是一些定义。
— 庞加莱

源于少数原理，...却结出累累硕果，
这就是几何的骄傲。

— 牛顿

Feynman 名言



“物理学家具有这样的习惯，对于任一类现象，研究它们的最简单例子，把这称为‘物理’，而把更复杂的情况，看作其它领域的事。”

R. P. Feynman

摘自陆埏院士的ppt

南京大学教师教学发展中心版权所有

简约之美



爱因斯坦：

如果欧几里得未
激发你少年时代
的科学热情，那
你肯定不是天才
科学家。

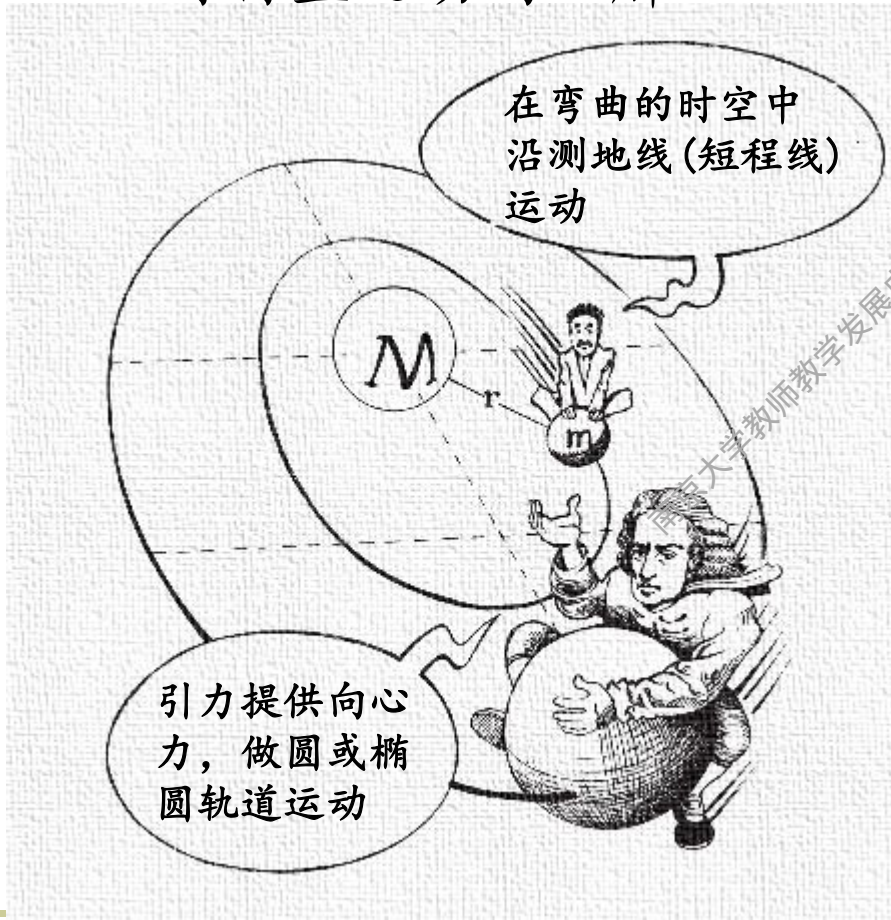
摘自李俊教授课件



For Freshmen



- 对行星运动的理解





For Freshmen

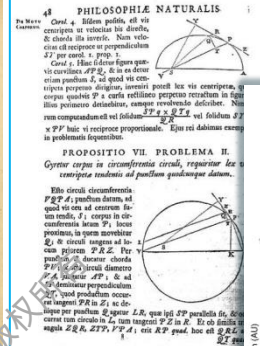
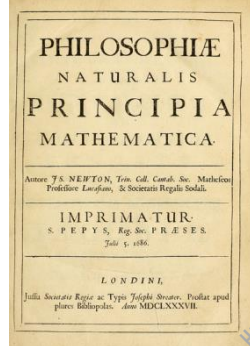


对行星运动的理解

在弯曲的时空中
沿测地线(短程线)
运动

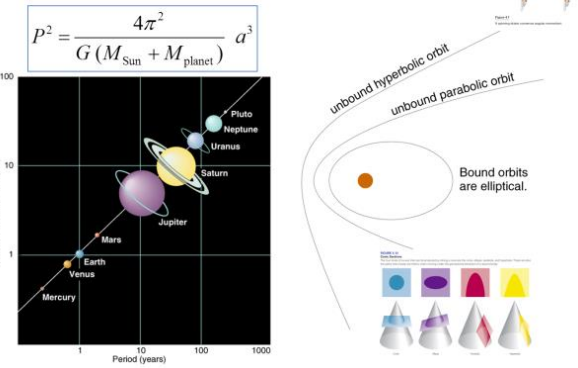


引力提供向心力, 做圆或椭圆轨道运动



巨大成功

How to explain Kepler's laws?



牛顿运动定律

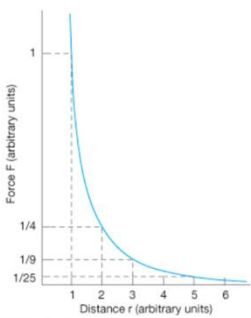
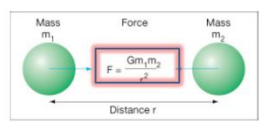
牛顿**第一定律**(惯性定律): 在不受外力的情况下, 一切物体总保持匀速直线运动或静止状态, 直到有外力迫使它改变这种状态为止。

牛顿**第二定律**(加速度定律): 物体受到力的作用, 物体将做加速运动, 其加速度跟作用力成正比, 跟物体的质量成反比。
 $a = F/m$, or $F = ma$

牛顿**第三定律**(作用与反作用定律): 两个物体之间的作用力和反作用力, 在同一直线上, 大小相等, 方向相反, 分别作用在两个物体上。

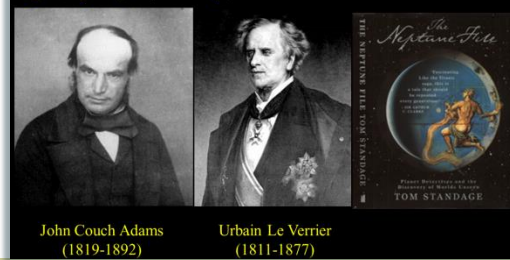
牛顿万有引力定律

- 万有引力是存在于任何物体之间的一种吸引力。
- 万有引力定律表明, 两个质点之间万有引力的大小, 与它们质量的乘积成正比, 与它们距离的平方成反比。

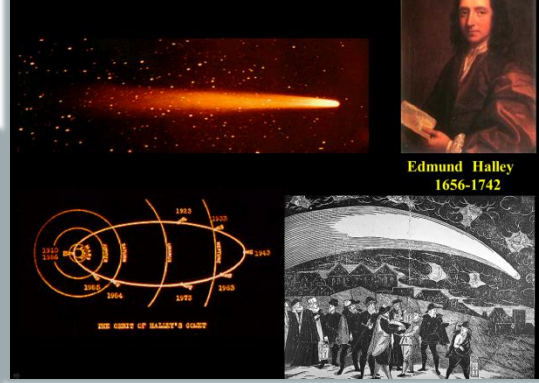


$G = \text{the gravitational constant} = 6.67 \times 10^{-11} \text{ m}^3 / (\text{kg s}^2)$

发现海王星 (1846年)



成功预言 1758年 Halley 彗星的回归



Nearer the gods no mortal may approach
凡夫俗子第一次接近了诸神



For Freshmen



对行星运动的理解

这两个质量是否一样？

how strongly it attracts and is attracted by other objects

在弯曲的时空中沿测地线(短程线)运动



引力提供向心力，做圆或椭圆轨道运动

局限

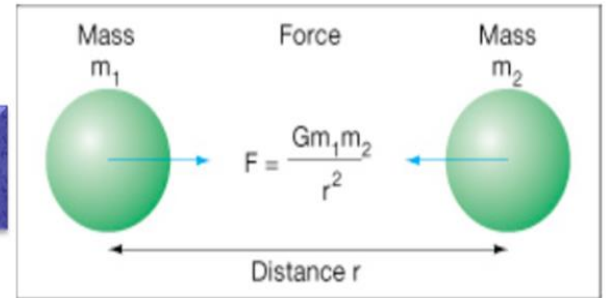
惯性质量

$$F = m a$$

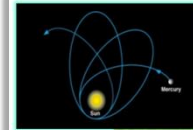
how strongly an object resists a change in its motion.



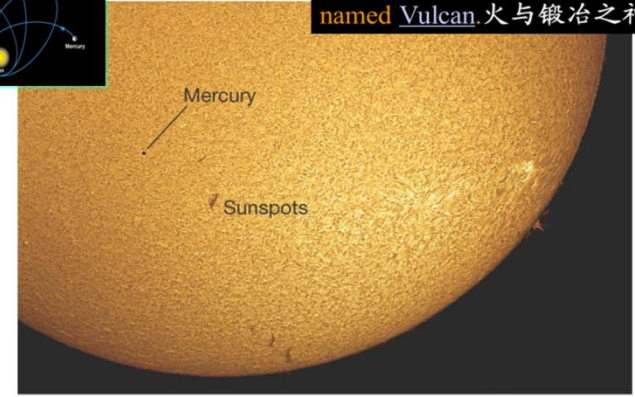
引力质量



- 不少深刻的问题未回答，如引力的本质，如何产生、如何作用到被真空隔离的物体上，瞬时地和超距地作用，...



the hypothetical planet was even named Vulcan 火与锻冶之神



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley

Le Verrier thought an asteroid belt between Mercury and the Sun caused Mercury's unusual motion.

43" (arc seconds) per century

- Nearer the gods no man... 凡夫俗子第一次接近了



For Freshmen



• 对行星运动的理解

在弯曲的时空中沿测地线(短程线)运动

引力提供向心力, 做圆或椭圆轨道运动



• 相对论

• Special relativity (1905)

– Space + time → spacetime
is constant

威力巨大的质能公式



The first A-Bomb (1945) The first H-bomb: Mike (1952)

• The island of Elugelab in the *Eniwetok Atoll*, was completely vaporized.

物理学大厦



基石



力拔山兮气盖世



孪生子佯谬(Twin paradox)



显然此理论有问题!



For Freshmen



• 对行星运动的理解

在弯曲的时空中沿测地线(短程线)运动

引力提供向心力, 做圆或椭圆轨道运动



• 相对论

• General Relativity (1916)

建立在等效原理和广义协变要求基础上的引力理论和宏观物质的运动理论。

GR

南京大学教师教学发展中心版权保护

1. 等效原理

引力质量与惯性质量等效



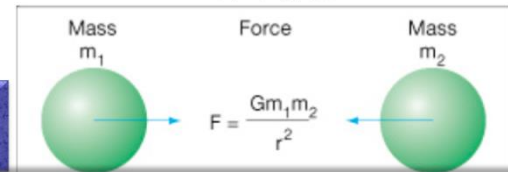
惯性质量

$$F = m a$$

how strongly an object resists a change in its motion.

引力质量

how strongly it attracts and is attracted by other objects



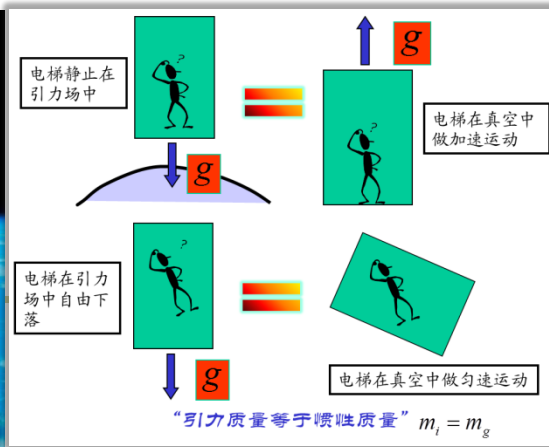
2. 广义相对性原理或协变原理

物理定律的形式在一切参考系下都是不变的。

- 实验结果可重复。
- 可运用地球实验室获取的基本物理规律来研究遥远的天体; 从太空获取信息。

Stars and galaxies are far beyond our reach, how do we get the information and do some researches of them?

- The closest neighbor of our sun, α Centauri in Proxima is 4.3 light-years away
- Andromeda Galaxy lies about 2.5 million light-years away





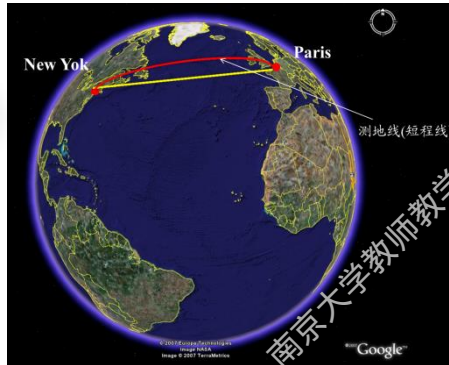
For Freshmen



对行星运动的理解

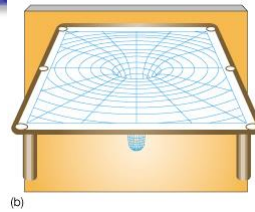
在弯曲的时空中沿测地线(短程线)运动

引力提供向心力, 做圆或椭圆轨道运动



时空弯曲

- 物质 \leftrightarrow 引力源 \leftrightarrow 时空弯曲
- 引力场强弱 \leftrightarrow 时空弯曲程度

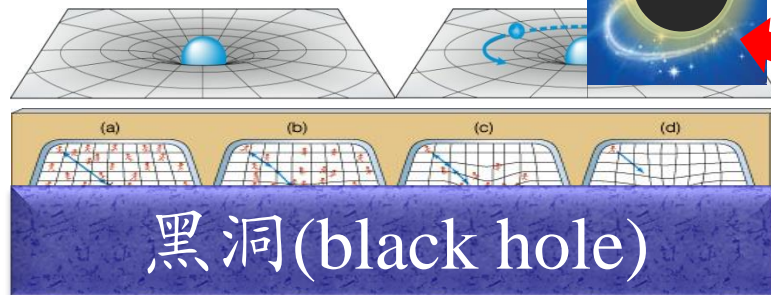


时空弯曲取代引力场

核心思想

实验粒子和光子在弯曲时空中沿测地线(短程线)运动.

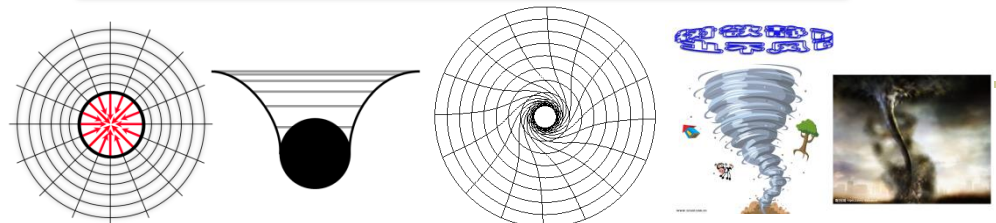
引力提供加速粒子偏离惯性



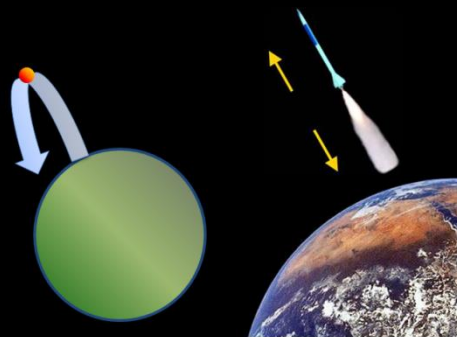
黑洞(black hole)



软表和时间的达利



什么是黑洞?



动能 \geq 势能, 火箭才可以逃逸

地球	11 km / s
月球	2.4 km / s
木星	10 km / s
太阳	620 km / s
中子星	1.5×10^5 km / s

$V_{\text{esc}} \geq$ 光速

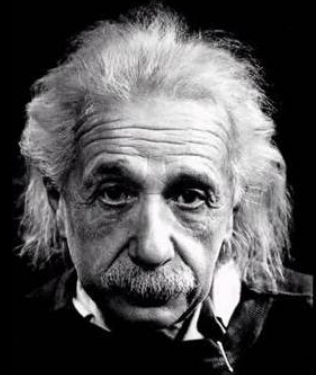
黑暗的天体

皮尔.西蒙.拉普拉斯(1796)



黑洞是时空中任何物质(包含光子)都无法逃离的一个区域

思考: 这两个观念有何不同?





For Freshmen



黑洞的大小用史瓦西半径 $R_s = 2GM/c^2$ 表示

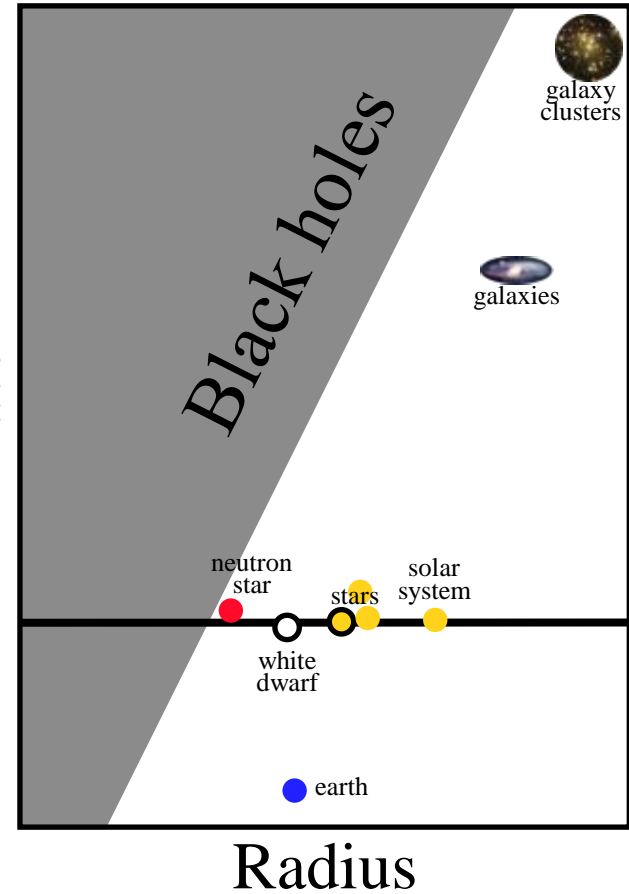
物体	质量	R	R_s	相对论
原子	10^{-26} kg			
人类	70 kg			
地球	6.0×10^{24} kg			
太阳	2.0×10^{30} kg			
白矮星	$\sim M_\odot$			
中子星	$\sim M_\odot$			
黑洞				
星系	$10^{11} M_\odot$			
宇宙(如封闭)	$10^{23} M_\odot$			

• 黑洞是一类特殊的天体，完全由引力占主导。



- 黑洞一定是极高密度的天体
- 并不一定是极高密度的天体，
- 由 R_s/R 来判断研究的天体的

Gravity complete wins! Nothing can prevent collapse.





For Freshmen



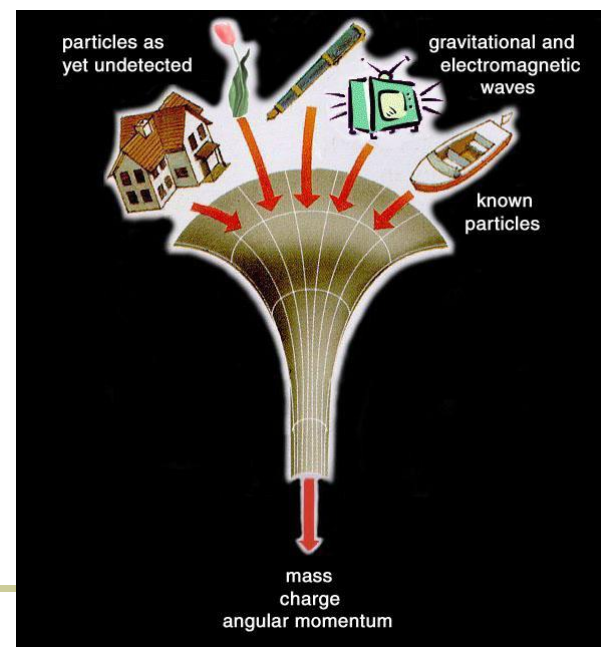
黑洞比基本粒子还要简单

按照黑洞的无毛定理

因引力波辐射，黑洞几乎不保持形成它的物质所具有的任何复杂性质，它保持的物理参数只有质量、角动量和电荷。



消繁归简



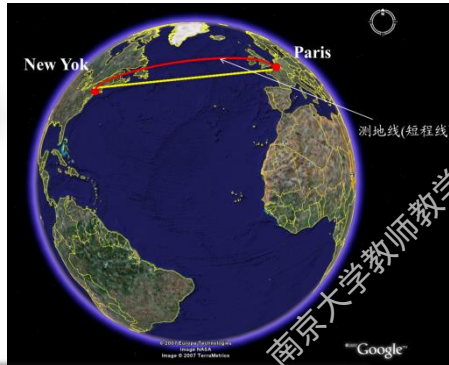


For Freshmen



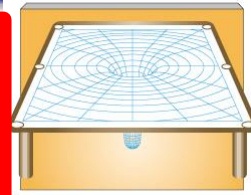
对行星运动的理解

在弯曲的时空中沿测地线(短程线)运动



时空弯曲

- 物质 \Leftrightarrow 引力源 \Leftrightarrow 时空弯曲
- 引力场强弱 \Leftrightarrow 时空弯曲程度



时空弯曲取代引力场

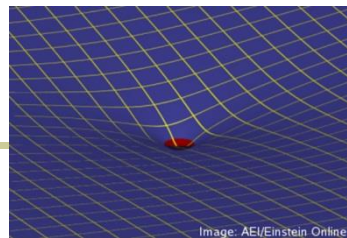
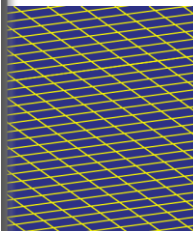
核心思想

实验粒子和光子在弯曲时空中沿测地线(短程线)运动。

引力提供加速度使得试验粒子偏离惯性运动。



What curves spacetime?



由物质的分布求解(几何)场方程

Einstein场方程

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

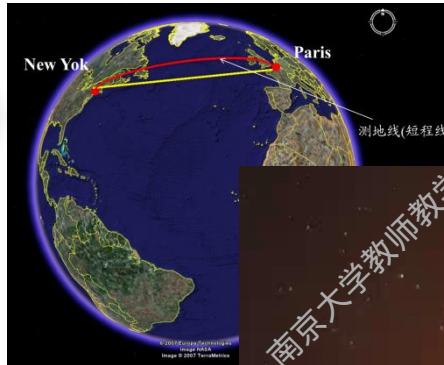


For Freshmen



- 对行星运动的理解

在弯曲的时空中沿测地线(短程线)运动



时空弯曲

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

时空弯曲取代引力场



$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

$$\frac{d^2 x^\lambda}{ds^2} + \Gamma_{\mu\nu}^\lambda \frac{dx^\mu}{ds} \frac{dx^\nu}{ds} = 0$$



For Freshmen



Einstein场方程

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Space-time is dynamic

广义相对论是一个非常成功的理论

- 具备包容性(把牛顿理论和狭义相对论作为极限包容其中)。

1.在弱场近似下场方程可回到牛顿的引力Poisson方程。

(牛顿引力理论不仅是一种能计算物体运动的数学工具,而且它具有物理的真实,当然是在弱场近似下。)

2.方程显然满足广义协变原理。

3.能-动张量满足守恒条件。 $T_{;\mu}^{\mu\nu} = 0$

测地线方程

$$\frac{d^2 x^\lambda}{ds^2} + \Gamma_{\mu\nu}^\lambda \frac{dx^\mu}{ds} \frac{dx^\nu}{ds} = 0$$



For Freshmen



Einstein场方程

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

测地线方程

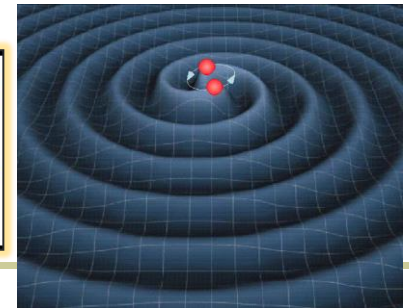
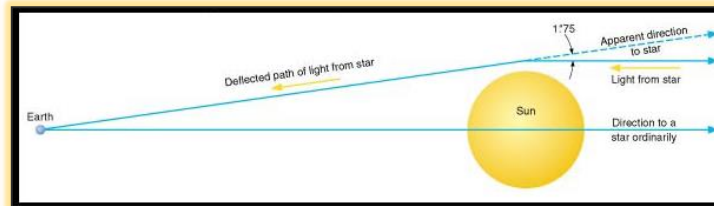
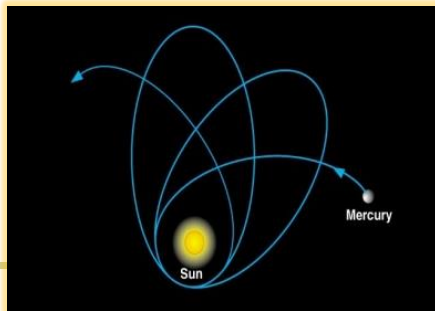
$$\frac{d^2 x^\lambda}{ds^2} + \Gamma_{\mu\nu}^\lambda \frac{dx^\mu}{ds} \frac{dx^\nu}{ds} = 0$$

- Space-time is dynamic

广义相对论是一个非常成功的理论

If you do not believe general relativity, What You should do?

- 具备包容性(把牛顿理论和狭义相对论作为极限包容其中)。
- 能够预言牛顿引力论不能解释的新引力效应。



- 所给的预言能够被实验证实。

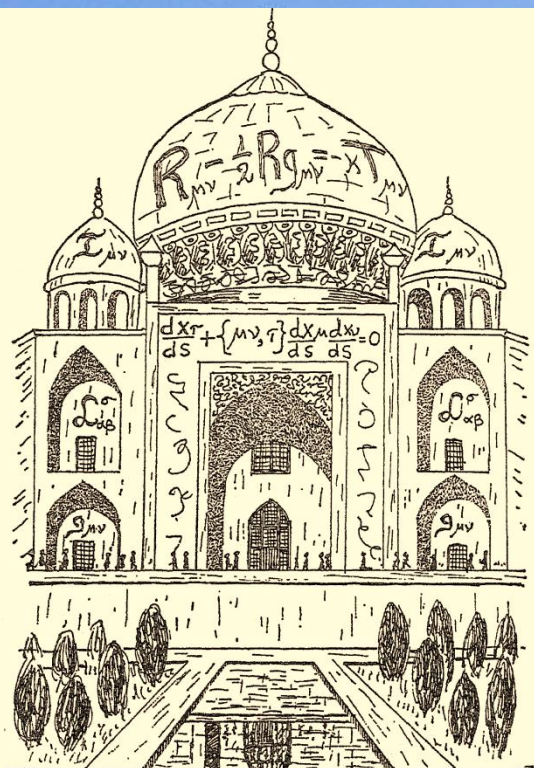


Fig. 29. The Temple of Gravity (the letterings on the temple are the basic equations of Einstein's relativistic theory of gravity).

Einstein场方程

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

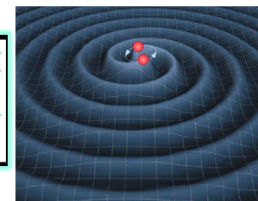
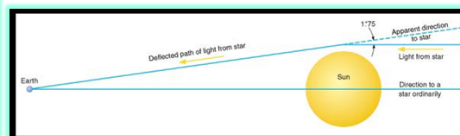
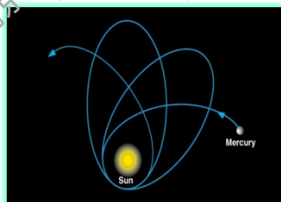
测地线方程

$$\frac{d^2 x^\lambda}{ds^2} + \Gamma_{\mu\nu}^\lambda \frac{dx^\mu}{ds} \frac{dx^\nu}{ds} = 0$$

- Space-time is dynamic

广义相对论是一个非常成功的理论

- 具备包容性(把牛顿经典理论和狭义相对论作为极限或特例包容其中)。
- 能够预言牛顿引力论不能解释的新引力效应。



- 所给的预言能够被实验证实。

If you do not believe general relativity, What You should do?



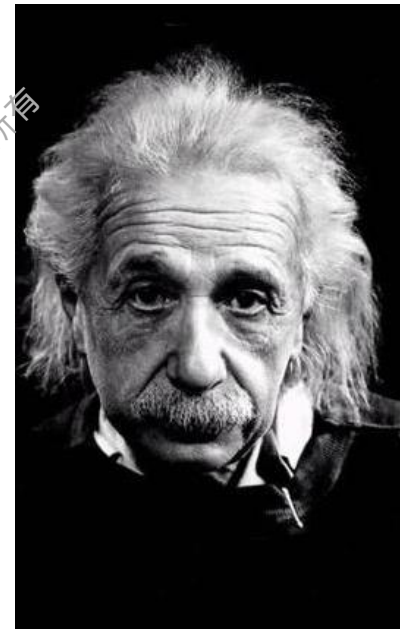
For Freshmen



- 人类历史上最伟大的两位物理学家



Isaac Newton
(1642–1727)



Albert Einstein
(1879–1955)

$$mG \frac{M}{r} \ll mc^2 \quad \Rightarrow \quad r \gg \frac{GM}{c^2} .$$

牛顿引力理论仅适用于低速度 ($\ll c$), 弱场 (试验粒子的自引力势能的大小远远小于其静止质能)。



For Freshmen



弯曲时空

欧氏几何 → 黎曼几何

1. 欧氏几何是研究平直空间的几何学----可建立统一的直线坐标系----矢量具有确定的大小和方向(可在任意位置定义)。
2. 黎曼几何是研究弯曲空间的几何学----不可 ----不可。
3. 在弯曲空间中研究物理规律也必须建立坐标系----只能在某一点建立坐标系研究在某一点的临域内的标量、矢量和张量。
4. 描述物理规律必须用数学规律来量化----建立方程(标量、矢量或张量组成, 仅这些量在坐标变化下才有意义)



闵氏时空到弯曲时空

闵氏时空线元

$$ds^2 = c^2 dt^2 - dx^2 - dy^2 - dz^2$$

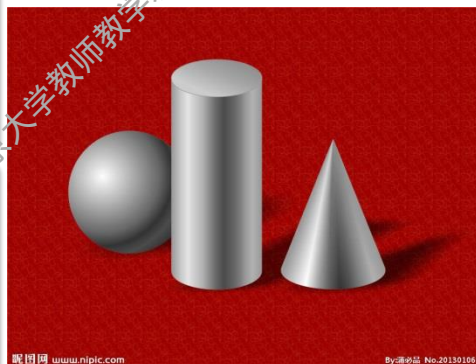
$$ds^2 = c^2 dt^2 - dr^2 - r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2$$



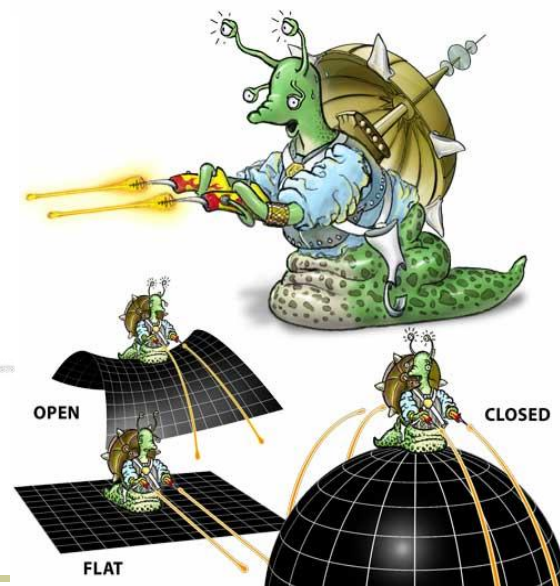
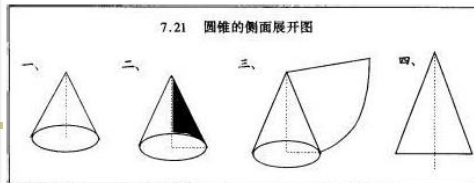
弯曲时空线元

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

取值为0、1、2、3



是否具有相同的几何?



From WMAP Homepage

具有最大对称性的空间



For Freshmen



南京大学 2015-2016 学年第一学期期末考试试卷 A 卷

课程名称: 初等数理天文 考试限时: 120 分钟

(考试类型: 开卷)

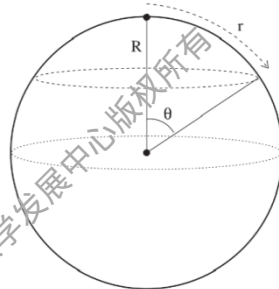
4. 线元是开启整个几何学的关键。假想的二维静态宇宙学模型(空间上满足均匀和各向同性), 其几何可分别用以下几种线元表示

$$dl^2 = dr^2 + r^2 d\phi^2, \text{ (欧几里得几何, 平面)}$$

$$dl^2 = R^2 [d\theta^2 + \sin^2 \theta d\phi^2], \text{ (R 为半径的球面)}$$

$$dl^2 = R^2 [d\theta^2 + \sinh^2 \theta d\phi^2], \text{ (Hyperbolic geometry, 双曲面)}$$

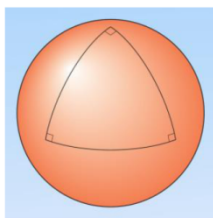
其中 $\sinh \theta = (e^\theta - e^{-\theta})/2$ 为双曲正弦函数。



1) 类似欧氏几何的直线, 用弯曲空间中的测地线(两点间最短的连线)同样可定义三角形。请证明, 二维球面上三角形的内角和为:

$$\text{内角和} = \pi + A / R^2,$$

其中 A 为三角形所包围的面积。若在双曲面上, 结论怎样?

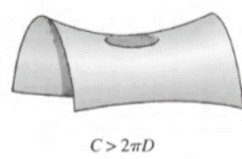


2) 假设生活在一个静态的二维球面的宇宙中, 星系的分布是均匀的, 其面密度为 n 。

请证明: 在距我们半径为 r 的范围以内星系的总数, N 为

$$N = 2\pi n R^2 \left[1 - \cos \frac{r}{R} \right].$$

请证明: 在 $r \ll R$ 时, 回到平直宇宙的结果 $n\pi r^2$ 。请探讨, 相比于平直宇宙你看到了更多或更少的星系。



3) 类似上一题, 若生活在二维双曲(或马鞍)面的宇宙中结果怎样?

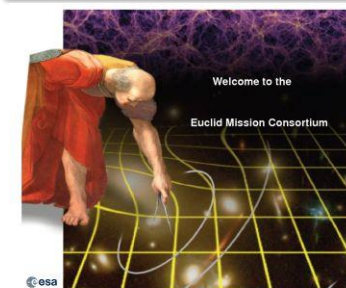
视觉效应

Flat space obeys the familiar rules of Euclidean geometry. The angular size of identical spheres is inversely proportional to distance—the usual vanishing-point perspective taught in art class.

Spherical space has the geometric properties of a globe. With increasing distance, the spheres at first seem smaller. They reach a minimum apparent size and subsequently look larger. Similarly, lines of longitude emanating from a pole separate, reach a maximum separation at the equator and then refocus into the opposite pole. This framework consists of dodecahedra.

Hyperbolic space has the geometry of a saddle. Angular size shrinks much more rapidly with distance than in Euclidean space. Because angles are more acute, five cube-like objects fit around each edge, rather than only four.

参见《Scientific American》2002, The Once and Future Cosmos



学生的潜力是无穷的



For Freshmen



1854年，黎曼在题为《关于作为几何学基础的假设》的就职讲演中正式提出黎曼几何，除年迈的高斯外没有一个听众能听得懂他在说些什么。在黎曼去世后两年即1868年，他的讲演才出版。



Carl Friedrich Gauss (1777–1855) was one of the founders of non-Euclidean geometry, sometimes described as the ‘prince of geometers’.



Bernhard Riemann (1826–1866), a proteg'e of Gauss, was a great mathematician in his own right and the founder of Riemannian geometry.

与最伟大的数学家同行

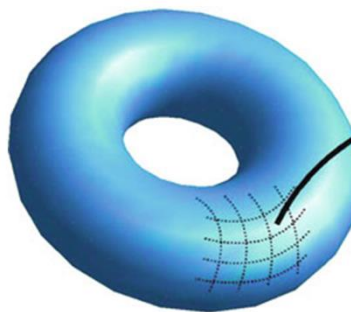
超星发现

梁灿彬 北京师范大学

TA的讲座

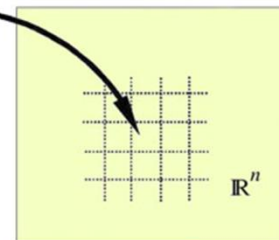
	李群李代数与纤维丛 分类: 经济管理 播放次数: 56805	★★★★☆ 4.76分 (48人评价) 主讲人单位: 北京师范大学 更新时间: 2012-11-07
	微分几何在相对论的应用 分类: 基础科学 播放次数: 118645	★★★★☆ 4.65分 (279人评价) 主讲人单位: 北京师范大学 更新时间: 2011-10-21
	高等广义相对论 分类: 基础科学 播放次数: 35628	★★★★☆ 4.54分 (28人评价) 主讲人单位: 北京师范大学 更新时间: 2014-07-31

大师简介
梁灿彬，男，1938年生于厦门。1952-1955年在广东省广雅中学读高中。1955年考入北师大物理系。1959年毕业并留系任教，1981-83年在英国芝加哥大学任访问学者，回国后长期担任基础课、专业课教学及科研工作。1986年起任教授，后任博导，1999年退休后应邀先后(3同时)在北师大、清华、中国科学院数学学院讲多次。



Differentiable Manifolds

Φ



\mathbb{R}^n

- 可以走外微分(微分几何)那套来引入广义相对论



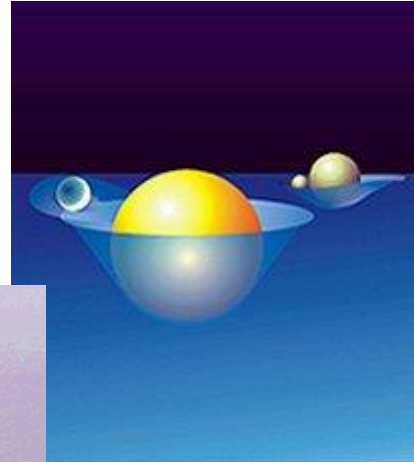


For Freshmen



求解相当不易

张量运算



THE EINSTEIN FIELD EQUATION

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

“**matter** tells spacetime how to curve, and **curved space** tells matter how to move”
J.A. Wheeler





For Freshmen



Albert Einstein
(1879-1955)



Karl Schwarzschild
(1873-1916)

1915年11月, Einstein 提出他的广义相对论。

1916年, Schwarzschild 求解了 Einstein 引力场方程, 给出静态球对称引力场的外部解。并与 Laplace 类似, 在广义相对论基础上确定了黑洞的半径, 称为

“Schwarzschild” 半径。

$$R \leq R_s = \frac{2GM}{c^2}$$



For Freshmen



- Einstein:
 - *We're NOT in a special place.*
 - The universe looks the same from everywhere and in all directions (*Cosmological Principle*).

“宇宙在大尺度范围内是均匀的和各向同性的”



- Einstein was **not an astronomer**, so he sought astronomical advice before attempting to apply general relativity on the cosmic scale.
- Actually, little was known about the large-scale structure of the Universe at the time, so Einstein was led to formulate a static model, neither expanding nor contracting, that is now known to disagree with observational evidence.
- 还需简化，工作假设
- 是否抓住了本质？

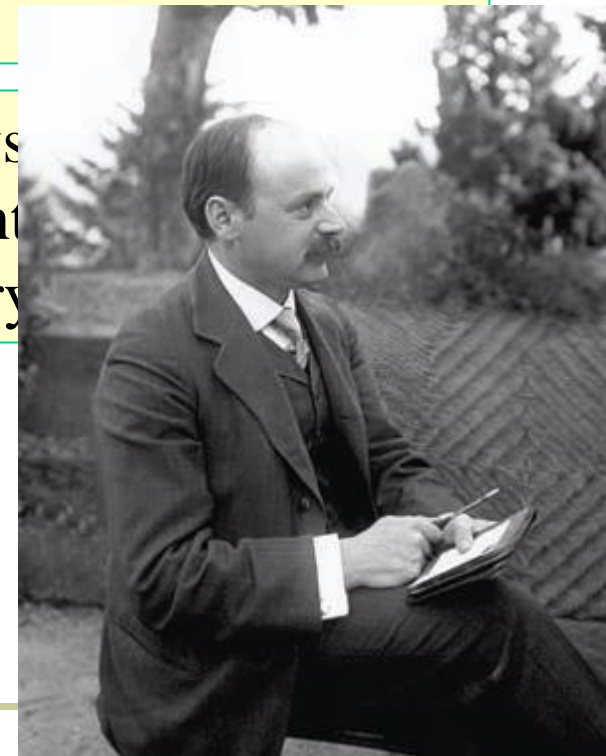


For Freshmen



- 球对称引力场外解（**Schwarzschild metric**）
- one of vacuum solutions, the first and arguably the most important non-trivial solution of the Einstein field equations.
- takes its name from the German astrophysicist Karl Schwarzschild who published the relevant paper shortly after Einstein completed his theory.

Schwarzschild had been a university professor and Director of the Potsdam Observatory outside Berlin but joined the German army at the outbreak of the First World War and was serving on the Eastern front when he made his discovery.



(1873–1916)



For Freshmen



黑洞的结构

以不转的Schwarzschild 度规为例

$$ds^2 = (1 - \frac{2GM}{rc^2})c^2 dt^2 - \frac{dr^2}{(1 - \frac{2GM}{rc^2})} - r^2(d\theta^2 - \sin^2 \theta d\phi^2)$$



Roger Penrose
(b1931)

数学上存在两类奇点

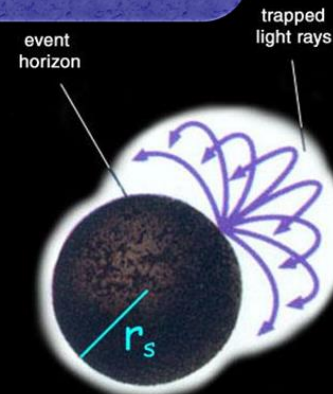
- 坐标奇点 $R_s = 2GM/c^2$
- 内禀奇点 $r=0$

Schwarzschild半径对应黑洞的无限红移面 ($g_{00}=0$)，也对应于黑洞的视界面。表示黑洞的半径（不是真实的分界半径）。

所有的物理规律在裸奇点 (Naked Singularity) 处失效。

宇宙监督原理(Cosmic censorship hypothesis)

A singularity that is not inside a black hole (not surrounded by an event horizon), and therefore can be seen by someone outside it.





For Freshmen

Stretching of time

问?

山顶上的钟和地面的钟，哪个走得快？

洞中方一日，世上已千年；"深挖洞、广积粮、不称霸"

- Clock in gravitational field go slower
- Clocks in space go faster than on ground
- GPS satellites: extremely accurate clocks
- Easily measure gravitational time dilation



■ APPLYING PHYSICS 26.1

Faster Clocks in a "Mile-High City"

Atomic clocks are extremely accurate; in fact, an error of 1 s in 3 million years is typical. This error can be described as about one part in 10^{14} . On the other hand, the atomic clock in Boulder, Colorado, is often 15 ns faster than the atomic clock in Washington, D.C., after only one day. This error is about one part in 6×10^{12} , which is about 17 times larger than the typical error. If atomic clocks are so accurate, why does a clock in Boulder not remain synchronous with one in Washington, D.C.?

EXPLANATION According to the general theory of relativity, the passage of time depends on gravity: clocks run more slowly in strong gravitational fields. Washington, D.C., is at an elevation very close to sea level, whereas Boulder is about a mile higher in altitude, so the gravitational field at Boulder is weaker than at Washington, D.C. As a result, an atomic clock runs more rapidly in Boulder than in Washington, D.C. (This effect has been verified by experiment.) ■

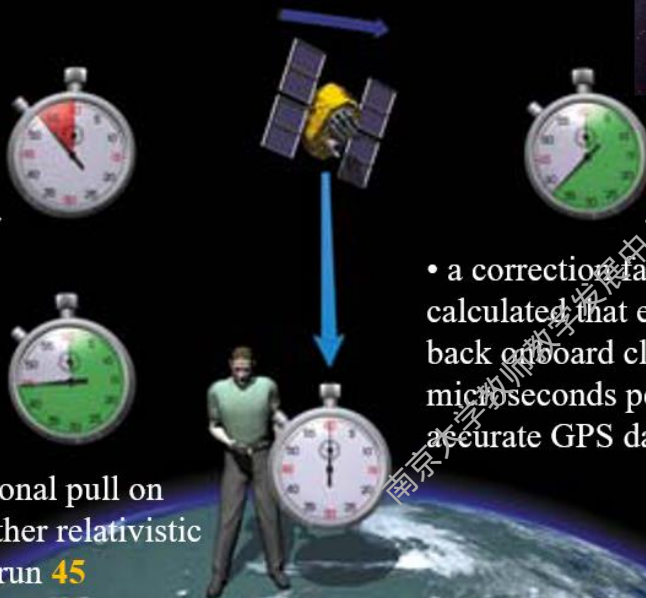


For Freshmen



GPS (Global Positioning System)

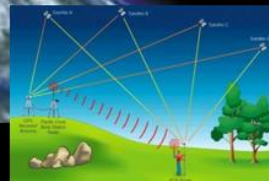
- velocity of GPS satellites, onboard clocks run about **seven microseconds slower per day** than ground clocks. (动钟延缓)



- a correction factor must be calculated that effectively turns back onboard clocks by 38 microseconds per day to yield accurate GPS data

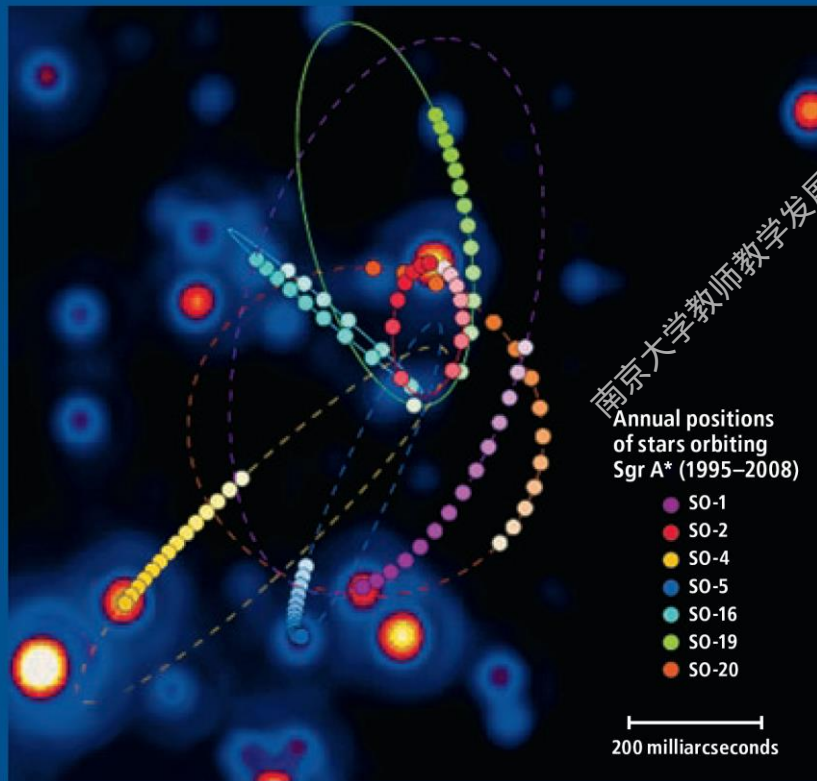
- The weaker gravitational pull on the satellites adds another relativistic effect, making clocks run **45 microseconds faster per day**. (引力效应)

需要考虑相对论修正。



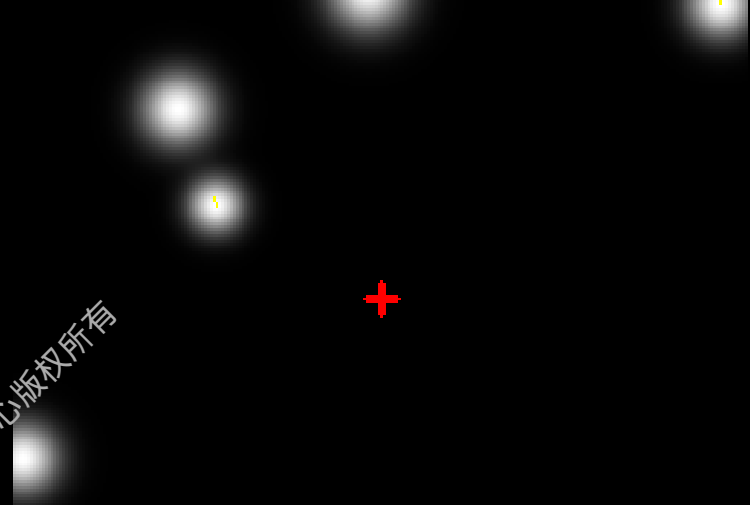
CLOSING IN ON THE GIANT

Until recently, observations of the motions of stars near the Milky Way's center have been the closest that astronomers have come to observing the event horizon of the black hole Sgr A*. The stars' orbits (*dashed lines*) reveal that they are in the thrall of a very compact object with a mass of 4.5 million suns. Colored dots mark the stars' positions each year from 1995 to 2008. The background is a 2008 infrared image of the stars (and others). The star S0-16 comes closest to Sgr A*—within seven light-hours—but even that distance remains 600 times larger than the event horizon's radius.



1992

10 light days



南京大学教师教学发展中心版权所有



目前认为约四百万太阳质量大小。



For Freshmen



黑洞附近的引力效应

黑洞周围的时空弯曲程度最大

广义相对论的检验



引力红移

水星近日点进动

光线弯曲

雷达回波延迟

引力波

黑洞热力学

黑洞的蒸发

黑洞与高能现象

均可作为供参考的课程论文：对大二

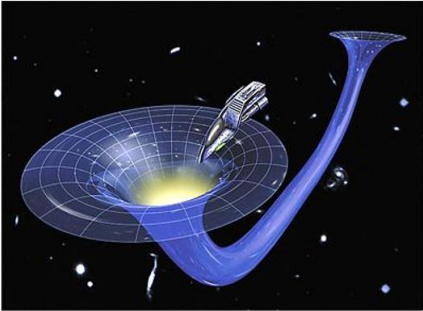




For Freshmen



蹦极 (bungee jumping)

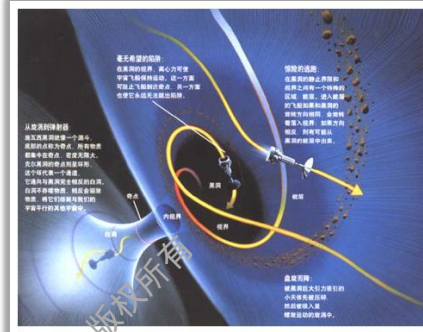


BH

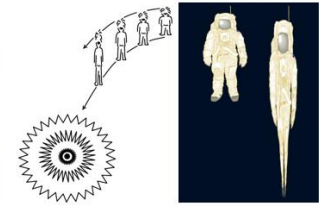
Interstellar travel or Time travel



The.Universe.S02E02.Cosmic.Holes

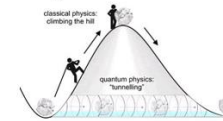


• Before Enter BH Undergoes the tidal force, Pain!!!



• Enter event horizon of BH, (No-hair theorem)

Pass through **Wormhole** (tunneling effect of quantum mechanics)



科学狂想

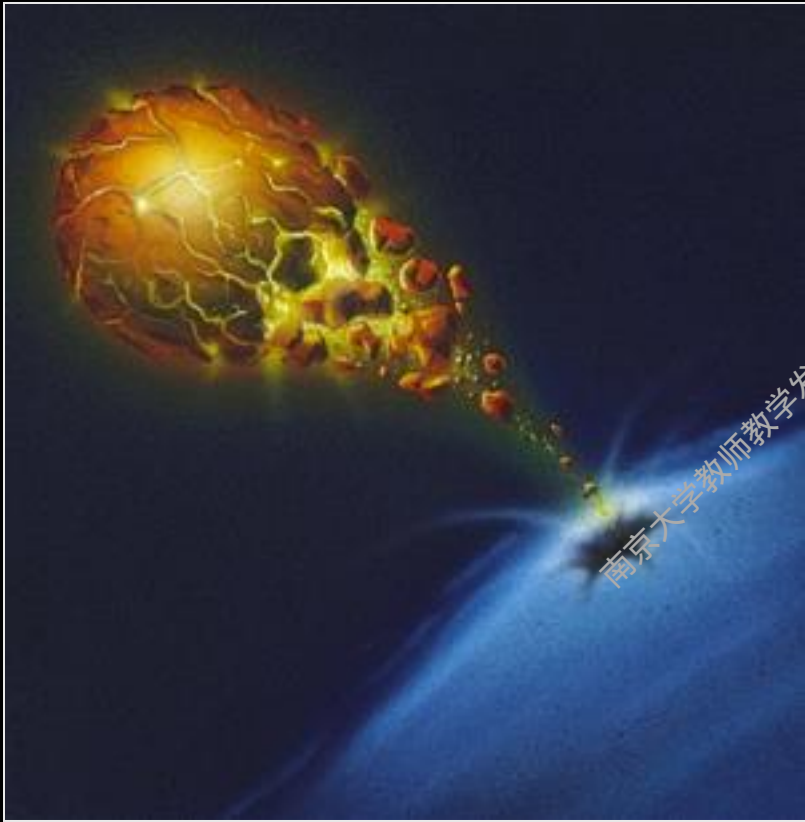
难道我们宇宙就处在一大堆宇宙巨泡中的一个里吗?

找到通往另一个世界的通道可以有朝一日拯救人类

一个门户连接着这两个宇宙

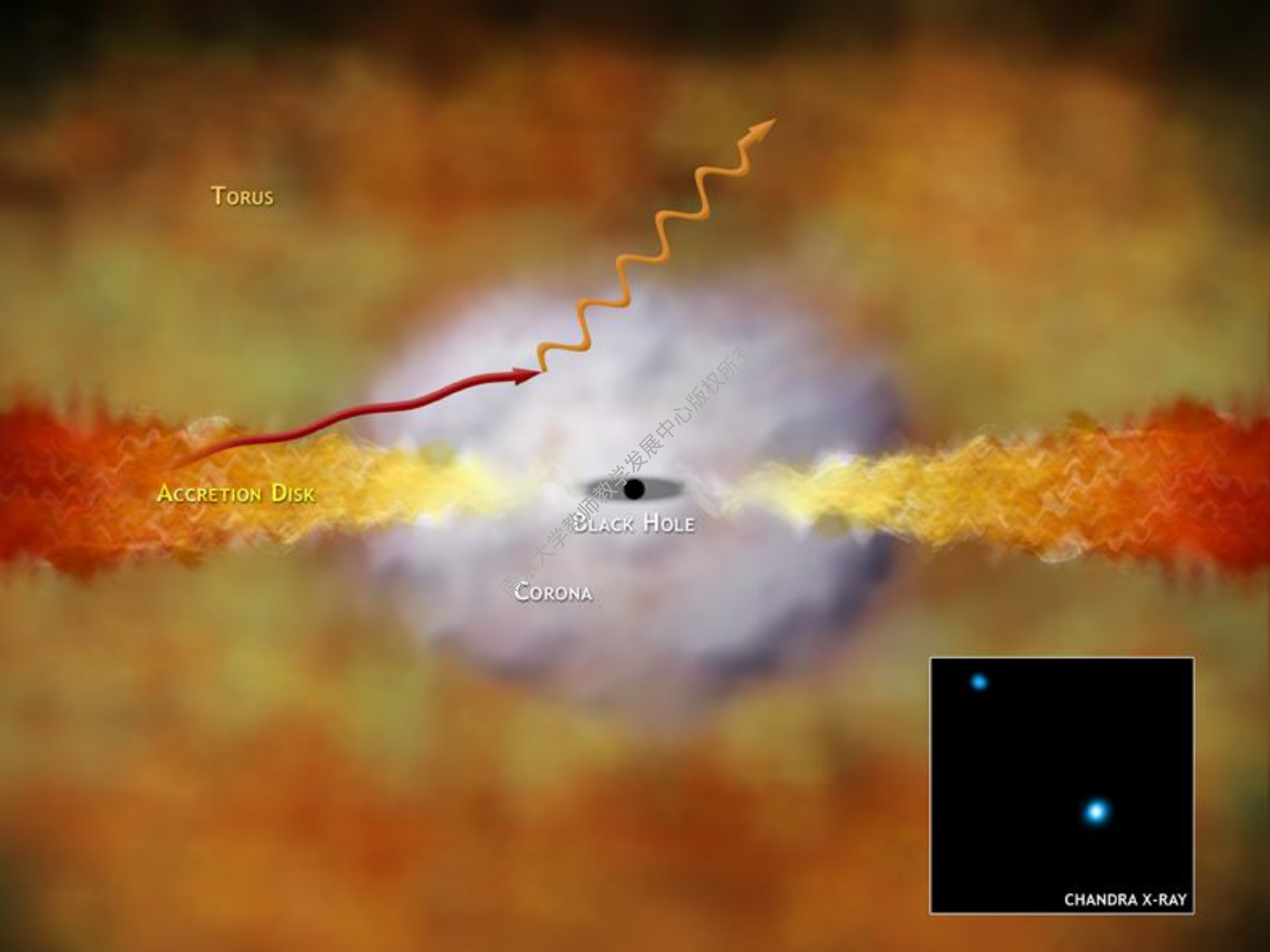
The.Universe.S03E02.Parallel.Universe

Seeing Holes



- Can't see black hole itself, but can see matter falling into a hole.
Gravitational forces stretch and rip matter: heats up.
- Very hot objects emit in X-rays (interior of Sun)
- Cygnus X-1.

<http://www.owl.net.rice.edu/~spac250/steve/ident.html>



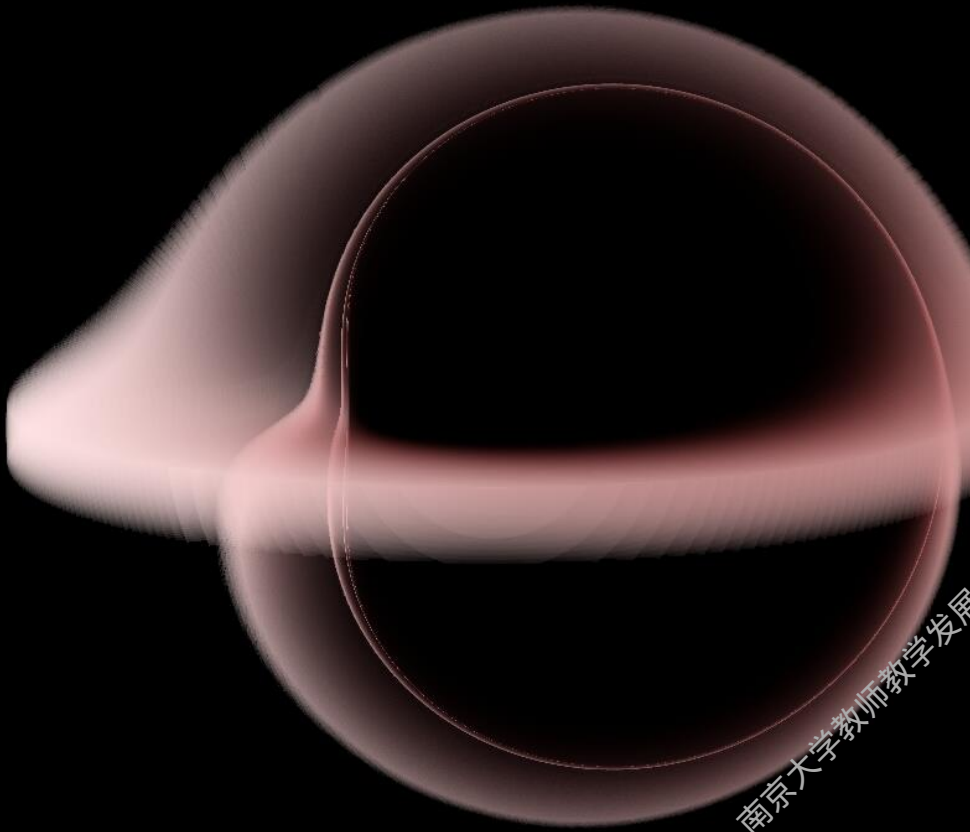
TORUS

ACCRETION DISK

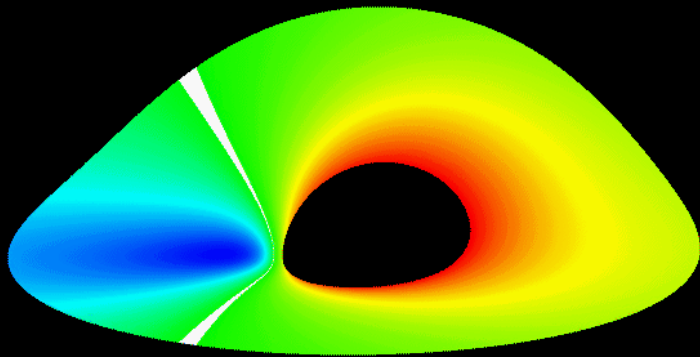
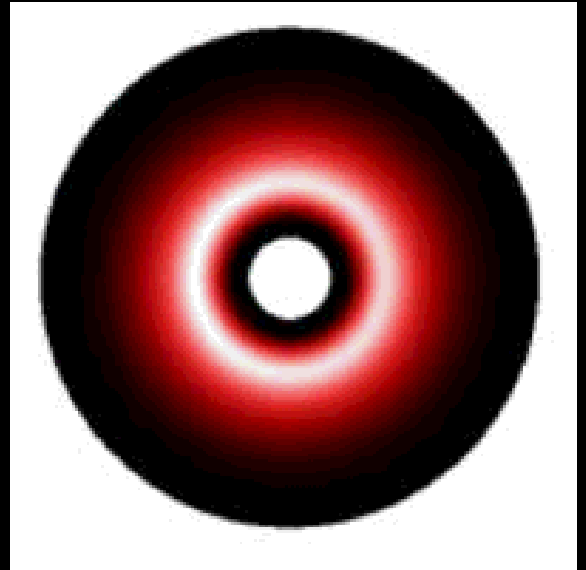
BLACK HOLE

CORONA

CHANDRA X-RAY



南京大学教师教学发展中心版权所有



问题一：黑洞就是电影里那个样子吗？



民宿网 | 树枝粉碎机 | 村妇炒股赚12万 | 帕劳旅游攻略 | 平板 | 安卓

只能说，星际穿越里的黑洞形态综合了各种考虑，给出了很合理的假设。展现给观众的是比较震撼的形象化的黑洞，但并非真正黑洞的展现形态。不过明亮耀眼的吸积盘倒是很符合现实。



For Freshmen

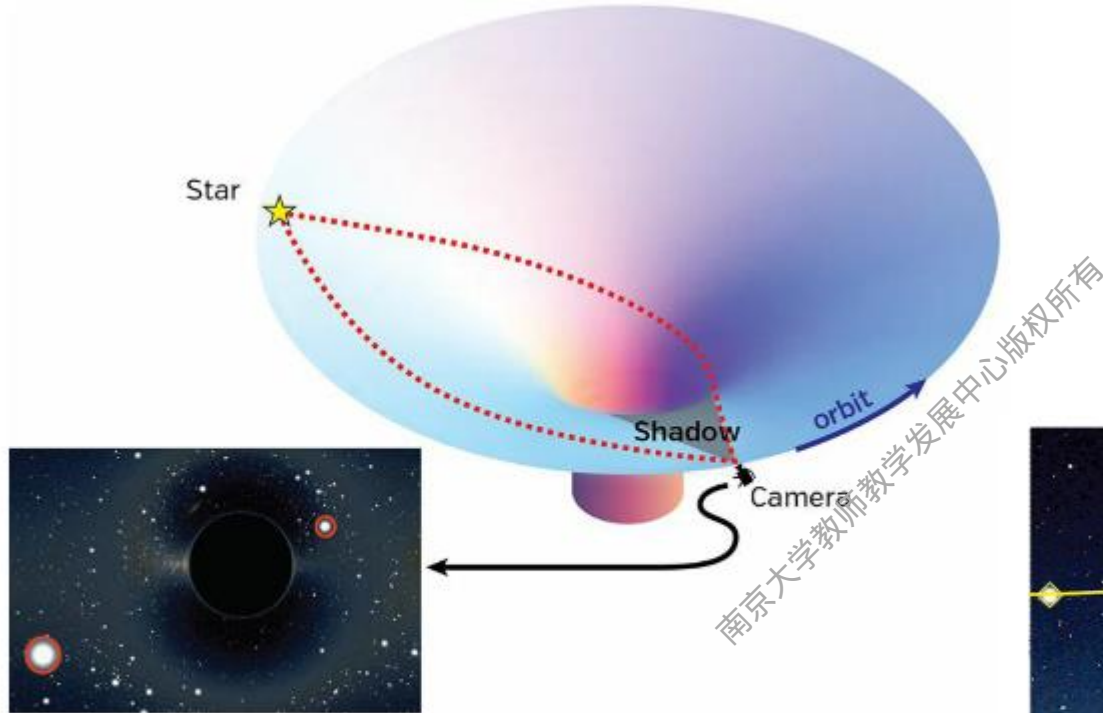


Fig. 8.3. Top: The warped space around a nonspinning black hole as seen from the bulk, and two light rays that travel through the warped space from a star to the camera. Bottom: The gravitationally lensed pattern of stars that is seen by the camera. [From a simulation by Alain Riazuelo; for a film clip of his simulation, see www2.iap.fr/users/riazuelo/interstellar/]

与黑洞附近实验粒子（含光子）的运动行为有关

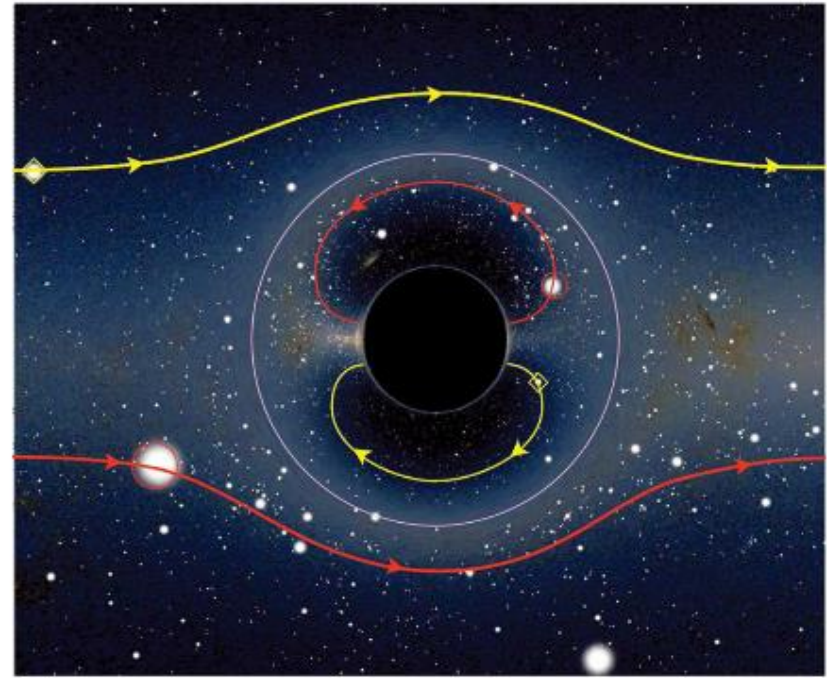
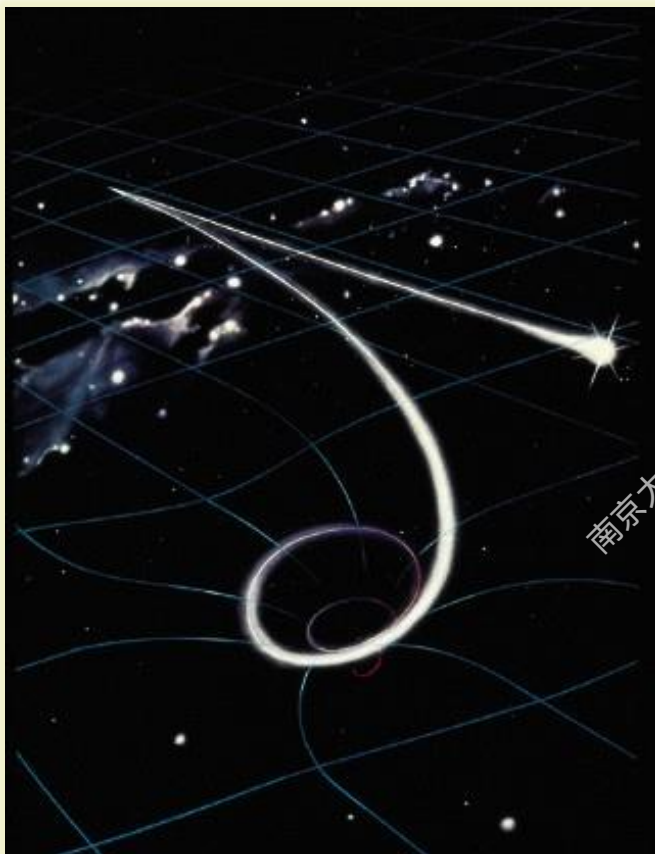


Fig. 8.4. The changing star pattern seen by the camera as it moves rightward in its orbit in Figure 8.3. [from the simulation by Alain Riazuelo; see www2.iap.fr/users/riazuelo/interstellar/]



内容



黑洞—时空中的无限深渊

For **Freshmen**

For **Sophomores**

For **Juniors/Seniors**

Discussion

南京大学教师教学发展中心版权所有

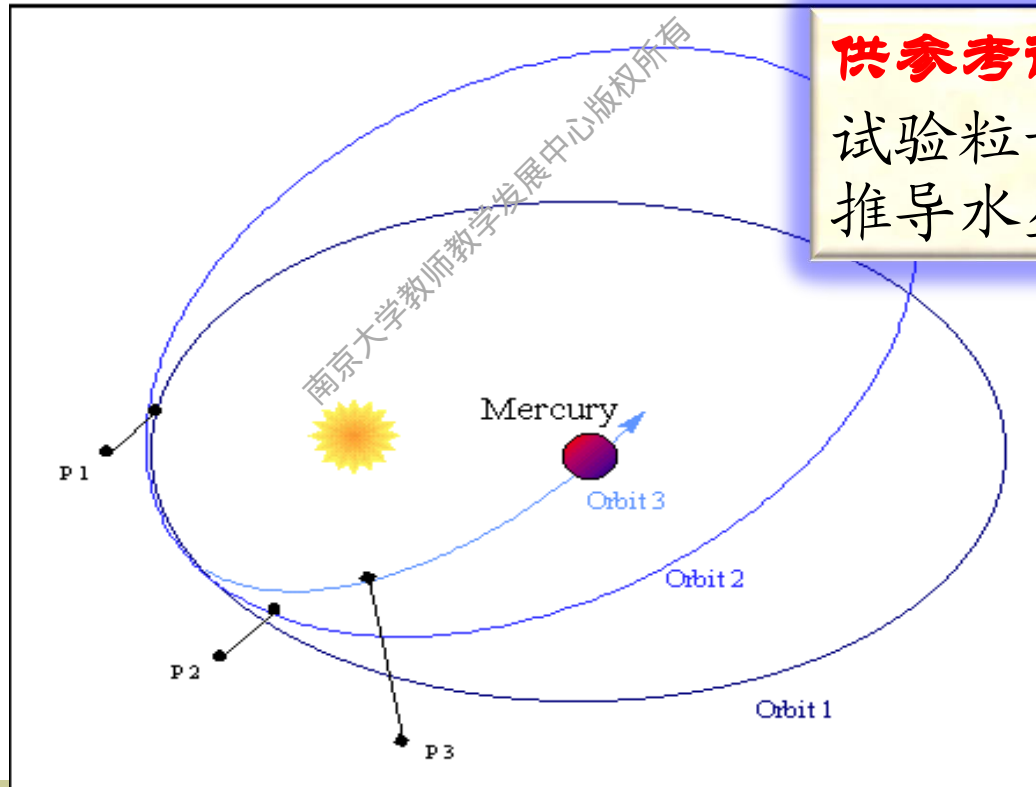


For Sophomores



示例

- 水星近日点进动
(Advance of the Perihelion of Mercury)



供参考课程论文:利用
试验粒子运动方程来
推导水星近日点进动。

General relativity predicts an additional 43 seconds of arc and was one of the first triumphs of Einstein's theory.

Orbital motion in Schwarzschild spacetime

- The shape of an orbit in the $\theta = \pi/2$ plane of Schwarzschild spacetime is described by expressing r as a function of ϕ .

$$\frac{E}{mc^2} = \left(1 - \frac{2GM}{c^2 r}\right) \frac{dt}{d\tau}$$

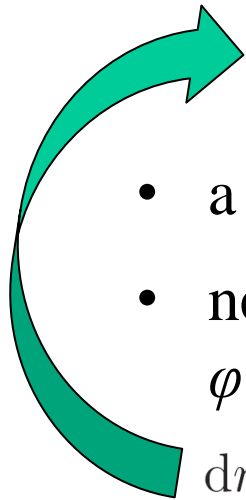
$$\frac{J}{m} = r^2 \sin^2 \theta \frac{d\phi}{d\tau}$$

$$\left(\frac{dr}{d\tau}\right)^2 + \frac{J^2}{m^2 r^2} \left(1 - \frac{2GM}{c^2 r}\right) - \frac{2GM}{r} = c^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1 \right]$$

- a differential equation relating r to τ .
- need to convert that into a tractable relation between r and ϕ , and then investigate its solution

$$\frac{dr}{d\tau} = \frac{d\phi}{d\tau} \frac{dr}{d\phi}$$

$$\frac{dr}{d\tau} = \frac{J}{r^2 m} \frac{dr}{d\phi}$$



南京师范大学教师教学发展中心版权所有



第一章绪论

第一部分力学

第二章运动学

第三章质点动力学

第四章引力

4.1引力定律

4.2引力势能

4.3引力质量引力红移引力塌缩

4.4开普勒问题和散射

4.5引力场

第五章质点系动力学

第六章刚体动力学

第七章振动

第八章波

第九章相对论力学

正在学习理论力学，在质量心系相互绕转双星 (M_1, M_2) 的拉格朗日为：

$$L = \frac{1}{2}m(\dot{r}^2 + r^2\dot{\phi}^2) - V(r)$$

$V(r)$ 为引力势

$$V(r) = \frac{-GM_1M_2}{r}$$

m 为约化质量。

1) 证明面积定律

$$\frac{dA}{dt} = \text{constant.}$$

2) 证明轨道定理：

$$\frac{1}{r} = \frac{mGM_1M_2}{l^2} [1 + \varepsilon \cos(\phi - \phi_0)],$$

偏心率

$$\varepsilon = \left(1 + \frac{2El^2}{m(GM_1M_2)^2}\right)^{1/2} \quad E = \frac{1}{2}m(\dot{r}^2 + r^2\dot{\phi}^2) + V(r)$$

3) 证明调和定理：

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)}$$

a 为轨道半长径。

$$\left(\frac{dr}{d\phi}\right)^2 + r^2 \left(1 - \frac{2GM}{c^2 r}\right) - m^2 r^3 \frac{2GM}{J^2} = \left(\frac{r^2 mc}{J}\right)^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1\right].$$

- apply a standard ‘trick’ of orbital analysis by introducing the reciprocal variable $u = 1/r$, and rewrite this equation as

$$\frac{d}{d\phi} \left(\frac{du}{d\phi}\right)^2 + u^2 = \left(\frac{mc}{J}\right)^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1\right] + \frac{2GMum^2}{J^2} + \frac{2GMu^3}{c^2}.$$

Orbital shape equation

$$\frac{d^2u}{d\phi^2} + u = \frac{GMm^2}{J^2} + \frac{3GMu^2}{c^2}.$$

- Newtonian mechanics

$$\frac{d^2u}{d\phi^2} + u = \frac{GMm^2}{J^2}$$

- the radial motion equation

$$\left(\frac{dr}{d\tau}\right)^2 + \frac{J^2}{m^2 r^2} \left(1 - \frac{2GM}{c^2 r}\right) - \frac{2GM}{r} = c^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1\right]$$

rewrite

- ‘effective potential’ and the symbol V_{eff} .

$$\frac{c^2}{2} \left[\left(\frac{E}{mc^2}\right)^2 - 1\right] = \frac{1}{2} \left(\frac{dr}{d\tau}\right)^2 + \frac{J^2}{2m^2 r^2} \left(1 - \frac{2GM}{c^2 r}\right) - \frac{GM}{r}.$$

- The quantity on the left is not an energy, but for a particle of given mass it is determined by the orbital energy.
- The expression on the right consists of a ‘kinetic’ term (proportional to $(dr/d\tau)^2$) added to a sum of terms that depend only on r for given values of J and m .

- the radial motion equation

$$\frac{c^2}{2} \left[\left(\frac{E}{mc^2} \right)^2 - 1 \right] = \frac{1}{2} \left(\frac{dr}{d\tau} \right)^2 + V_{\text{eff}},$$

$$V_{\text{eff}} = \frac{J^2}{2m^2r^2} \left(1 - \frac{2GM}{c^2r} \right) - \frac{GM}{r}.$$

a very similar equation arises in Newtonian orbital analysis

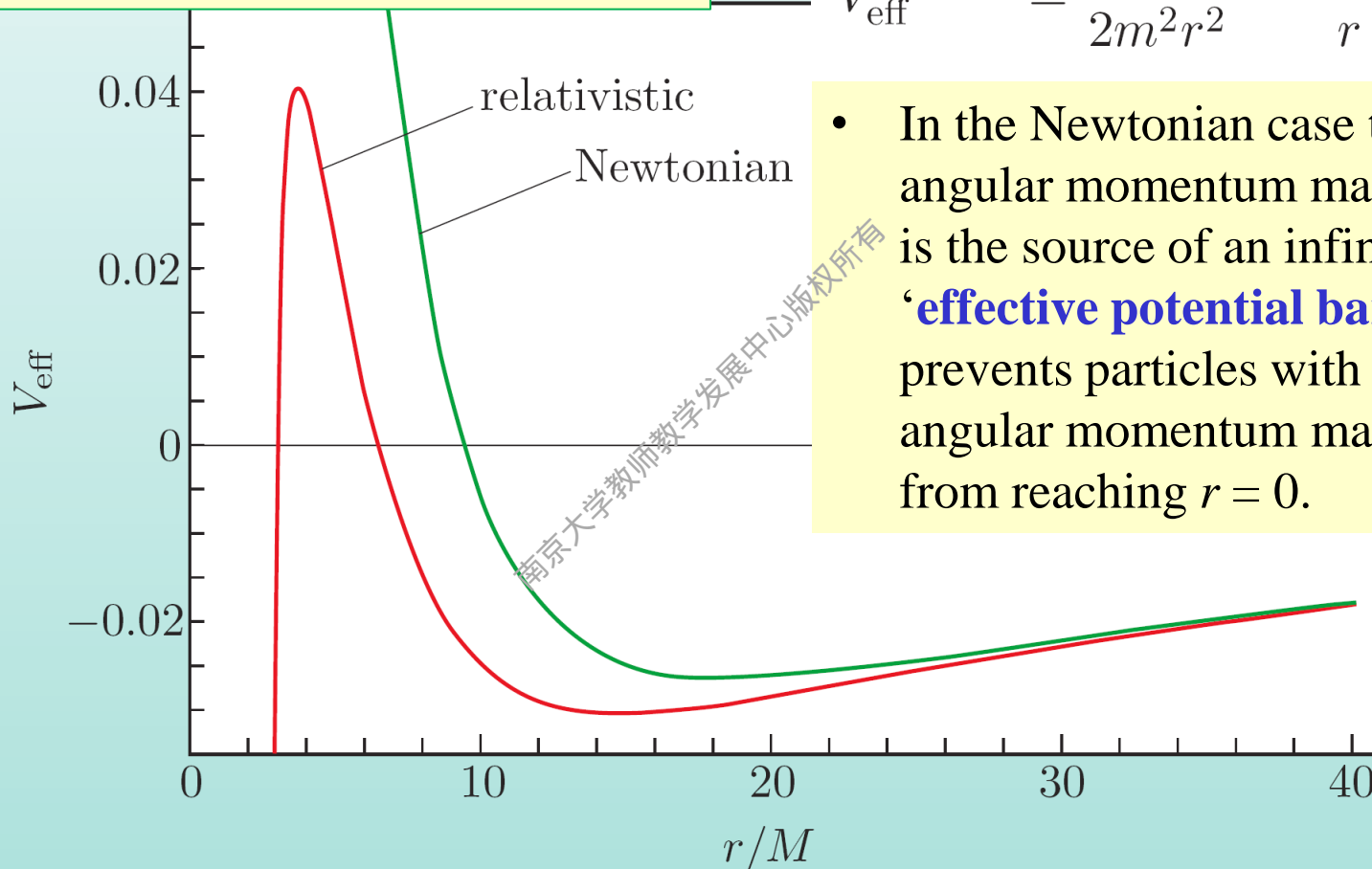
$$\frac{E^{\text{Newton}}}{m} = \frac{1}{2} \left(\frac{dr}{dt} \right)^2 + V_{\text{eff}}^{\text{Newton}},$$

$$V_{\text{eff}}^{\text{Newton}} = \frac{J^2}{2m^2r^2} - \frac{GM}{r}.$$

- Schwarzschild case the behaviour at small values of r is quite different. Indeed, for sufficiently small values of J there is no barrier at all.

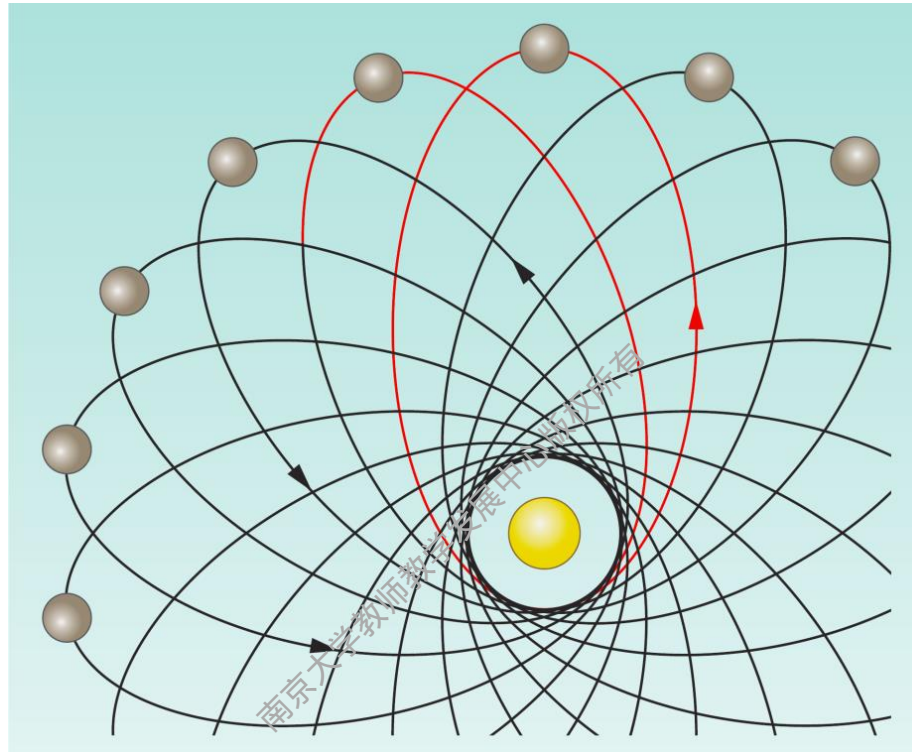
$$V_{\text{eff}} = \frac{J^2}{2m^2r^2} \left(1 - \frac{2GM}{c^2r} \right) - \frac{GM}{r}$$

$$V_{\text{eff}}^{\text{Newton}} = \frac{J^2}{2m^2r^2} - \frac{GM}{r}$$



- In the Newtonian case the angular momentum magnitude J is the source of an infinite ‘**effective potential barrier**’ that prevents particles with non-zero angular momentum magnitude from reaching $r = 0$.

Effective potentials for orbital motion with fixed angular momentum magnitude J in Newtonian gravity and GR



- The difference between the Newtonian and Schwarzschild effective potentials comes from the extra term $-GMJ^2/m^2c^2r^3$ in the Schwarzschild case.
- One of its effects is to cause the orbits of particles to rotate in the $\theta = \pi/2$ plane. This effect is negligible at large values of r but significant for small values, preventing elliptical orbits from closing and causing them to follow the kind of rosette pattern

Orbital shape equation

$$\frac{d^2u}{d\phi^2} + u = \frac{GMm^2}{J^2} + \frac{3GMu^2}{c^2}$$

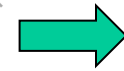
- Newtonian mechanics

$$\frac{d^2u}{d\phi^2} + u = \frac{GMm^2}{J^2}$$

牛顿力学情况有恒定策动力的，谐振子方程

$$\text{In[1]:= DSolve}[u''[\phi] + u[\phi] == \frac{GMm^2}{J^2}, u[\phi], \phi]$$

$$\text{Out[1]:= } \left\{ \left\{ u[\phi] \rightarrow \frac{Gm^2M}{J^2} + C[1] \text{Cos}[\phi] + C[2] \text{Sin}[\phi] \right\} \right\}$$



$$\frac{1}{r} = \frac{mGM_1M_2}{l^2} [1 + \epsilon \cos(\phi - \phi_0)]$$

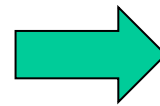
无解析解

圆轨道 细微偏离

Perturbation Calculation 方法

$$u(\phi) = u_c + u_c w(\phi)$$

$$\frac{d^2w}{d\phi^2} + w = 6GMu_c w + 3GMu_c w^2$$



$$\frac{d^2w}{d\phi^2} + (1 - 6GMu_c)w \approx 0$$

$$w(\phi) = A \cos(\omega\phi + \phi_0) \quad \text{where } \omega \equiv \left(1 - \frac{6GM}{r_c}\right)^{1/2}$$

$$u(\phi) = u_c + u_c w(\phi)$$

轨道进动发生在 $\omega(\phi)$ 取极小处

$$\omega\phi + \phi_0 = \pi + 2\pi n$$

连续两次极小位置的差为进动

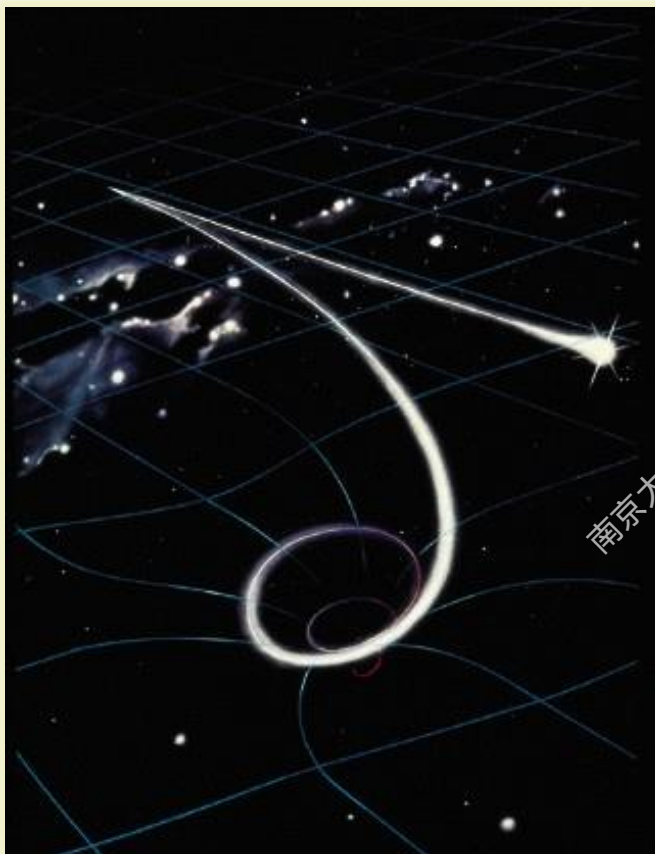
$$\omega\Delta\phi = \left(1 - \frac{6GM}{rc}\right)^{1/2} \Delta\phi = 2\pi$$

$$\Delta\phi = \left(1 - \frac{6GM}{rc}\right)^{-1/2} 2\pi \approx 2\pi \left(1 + \frac{3GM}{rc}\right) = 2\pi + \frac{6\pi GM}{rc}$$

带入太阳质量，水星轨道参数可得。



内容



黑洞—时空中的无限深渊

For **Freshmen**

For **Sophomores**

For **Juniors/Seniors**

Discussion

南京大学教师教学发展中心版权所有



For Juniors/Seniors



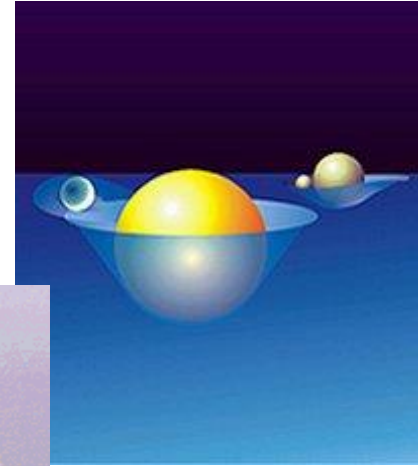
求解相当不易

张量运算

THE EINSTEIN FIELD EQUATION

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

南京大学教师教学发展中心版权所有



“**matter** tells spacetime how to curve, and **curved space** tells matter how to move”

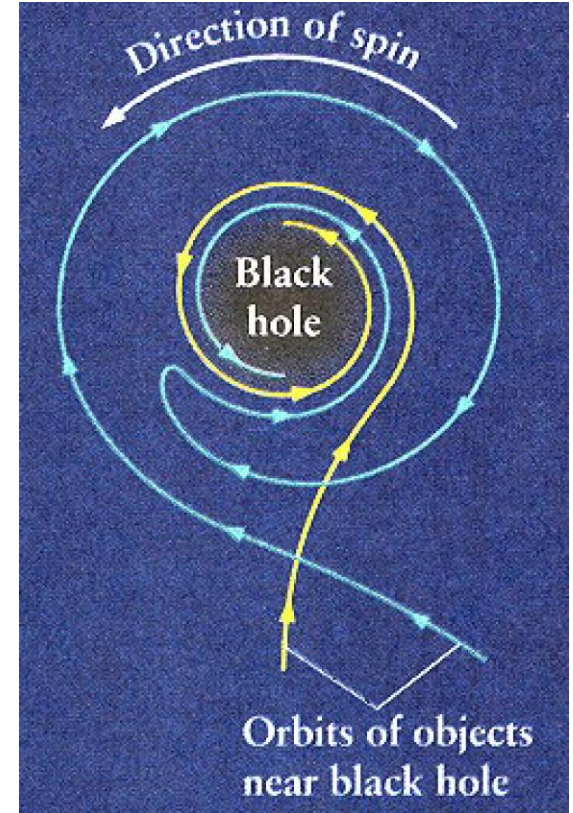
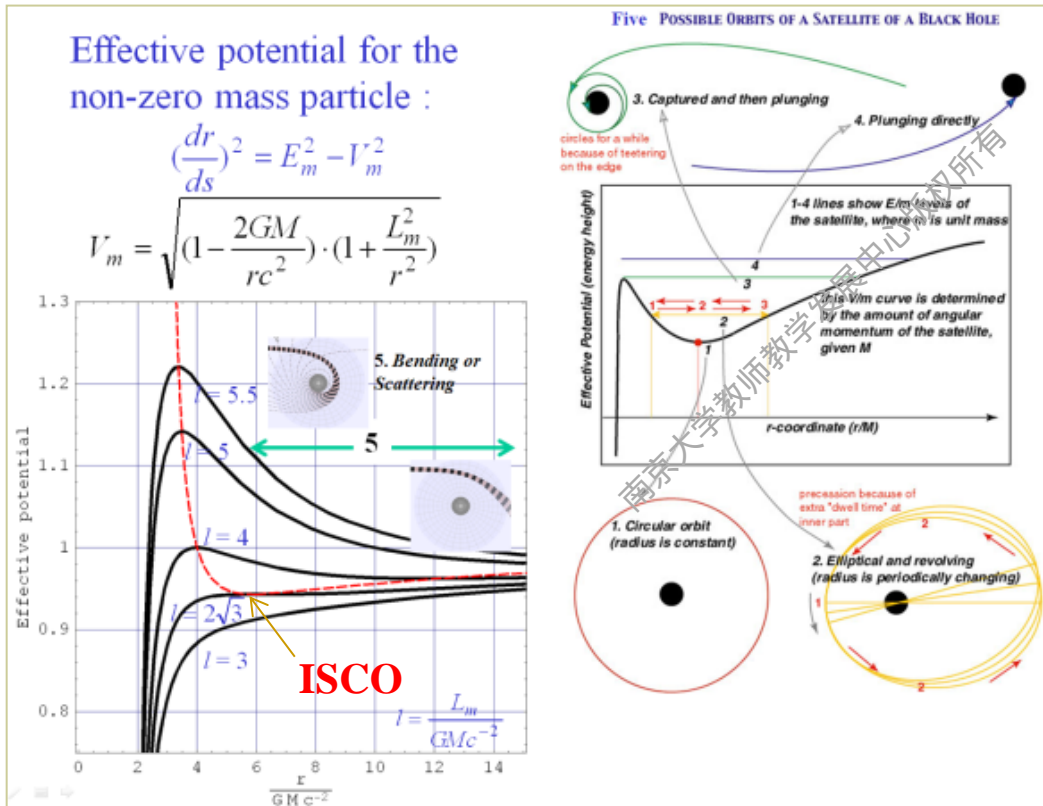
J.A. Wheeler



For Juniors/Seniors



黑洞周围实验粒子的运行



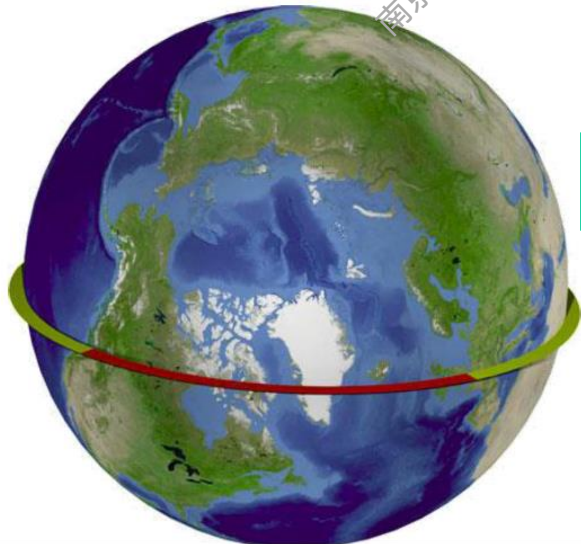
丰富得多。查 http://demonstrations.wolfram.com/Orbits_around_Schwarzschild_Black_Holes

The geodesic equations

- 平坦空间中，**直线**是连接**两点**之间的**最短**路径。
- 球体表面，大圆中短的那段圆弧。
- 更一般情况: **geodesics in Riemannian space**

• **Most direct route** between two points

• **Shortest distance** between two points



参见第二章

- Intuitively, a geodesic is a line that is ‘as **straight** as possible’ on a curved surface.

The geodesic equations

$$\frac{d^2 x^\mu}{d\lambda^2} + \sum_{\nu, \rho} \Gamma_{\nu\rho}^\mu \frac{dx^\nu}{d\lambda} \frac{dx^\rho}{d\lambda} = 0,$$

- λ is an **affine parameter** that varies along the geodesic. (the proper time τ for a massive particle moving along a time-like geodesic; for a null geodesic since $d\tau = ds/c = 0$)
- $\Gamma_{\nu\rho}^\mu$ are the connection coefficients

$$\Gamma_{\mu\nu}^\sigma = \frac{1}{2} \sum_{\rho} g^{\sigma\rho} \left\{ \frac{\partial g_{\rho\nu}}{\partial x^\mu} + \frac{\partial g_{\mu\rho}}{\partial x^\nu} - \frac{\partial g_{\mu\nu}}{\partial x^\rho} \right\}$$

$$\frac{d^2 x^\mu}{d\lambda^2} + \sum_{\nu, \rho} \Gamma_{\nu\rho}^\mu \frac{dx^\nu}{d\lambda} \frac{dx^\rho}{d\lambda} = 0,$$

the **non-zero** connection coefficients

$$\begin{aligned}\Gamma^0_{01} &= \frac{GM}{r^2 c^2 \left(1 - \frac{2GM}{c^2 r}\right)} (= \Gamma^0_{10}), & \Gamma^1_{33} &= -r \left(1 - \frac{2GM}{c^2 r}\right) \sin^2 \theta, \\ \Gamma^1_{00} &= \frac{GM \left(1 - \frac{2GM}{c^2 r}\right)}{r^2 c^2}, & \Gamma^2_{12} &= \frac{1}{r} (= \Gamma^2_{21}), \\ \Gamma^1_{11} &= -\frac{GM}{r^2 c^2 \left(1 - \frac{2GM}{c^2 r}\right)}, & \Gamma^2_{33} &= -\sin \theta \cos \theta, \\ \Gamma^1_{22} &= -r \left(1 - \frac{2GM}{c^2 r}\right), & \Gamma^3_{13} &= \frac{1}{r} (= \Gamma^3_{31}), \\ & & \Gamma^3_{23} &= \cot \theta (= \Gamma^3_{32}).\end{aligned}$$

$$\frac{d^2 x^\mu}{d\lambda^2} + \sum_{\nu, \rho} \Gamma_{\nu\rho}^\mu \frac{dx^\nu}{d\lambda} \frac{dx^\rho}{d\lambda} = 0,$$

the geodesic equations for four coordinate functions

$$x^0 = t(\lambda), x^1 = r(\lambda), x^2 = \theta(\lambda), x^3 = \phi(\lambda)$$

$$\frac{d^2 t}{d\lambda^2} + \frac{2GM}{c^2 r^2 \left(1 - \frac{2GM}{c^2 r}\right)} \frac{dr}{d\lambda} \frac{dt}{d\lambda} = 0,$$

$$\begin{aligned} \frac{d^2 r}{d\lambda^2} + \frac{GM}{r^2} \left(1 - \frac{2GM}{c^2 r}\right) \left(\frac{dt}{d\lambda}\right)^2 - \frac{GM}{c^2 r^2 \left(1 - \frac{2GM}{c^2 r}\right)} \left(\frac{dr}{d\lambda}\right)^2 \\ - r \left(1 - \frac{2GM}{c^2 r}\right) \left[\left(\frac{d\theta}{d\lambda}\right)^2 + \sin^2 \theta \left(\frac{d\phi}{d\lambda}\right)^2 \right] = 0, \end{aligned}$$

$$\frac{d^2 \theta}{d\lambda^2} + \frac{2}{r} \frac{dr}{d\lambda} \frac{d\theta}{d\lambda} - \sin \theta \cos \theta \left(\frac{d\phi}{d\lambda}\right)^2 = 0,$$

$$\frac{d^2 \phi}{d\lambda^2} + \frac{2}{r} \frac{dr}{d\lambda} \frac{d\phi}{d\lambda} + 2 \frac{\cos \theta}{\sin \theta} \frac{d\theta}{d\lambda} \frac{d\phi}{d\lambda} = 0.$$

the geodesic equations are the general relativistic analogues of **Newton's second law of motion.**

$$\frac{d^2 t}{d\lambda^2} + \frac{2GM}{c^2 r^2 \left(1 - \frac{2GM}{c^2 r}\right)} \frac{dr}{d\lambda} \frac{dt}{d\lambda} = 0,$$

$$\frac{d^2 r}{d\lambda^2} + \frac{GM}{r^2} \left(1 - \frac{2GM}{c^2 r}\right) \left(\frac{dt}{d\lambda}\right)^2 - \frac{GM}{c^2 r^2 \left(1 - \frac{2GM}{c^2 r}\right)} \left(\frac{dr}{d\lambda}\right)^2 - r \left(1 - \frac{2GM}{c^2 r}\right) \left[\left(\frac{d\theta}{d\lambda}\right)^2 + \sin^2 \theta \left(\frac{d\phi}{d\lambda}\right)^2 \right] = 0,$$

$$\frac{d^2 \theta}{d\lambda^2} + \frac{2}{r} \frac{dr}{d\lambda} \frac{d\theta}{d\lambda} - \sin \theta \cos \theta \left(\frac{d\phi}{d\lambda}\right)^2 = 0,$$

$$\frac{d^2 \phi}{d\lambda^2} + \frac{2}{r} \frac{dr}{d\lambda} \frac{d\phi}{d\lambda} + 2 \frac{\cos \theta}{\sin \theta} \frac{d\theta}{d\lambda} \frac{d\phi}{d\lambda} = 0.$$

复杂，一眼看不出首次积分。

Given **the initial location** of a particle in Schwarzschild spacetime and **the initial values of the four components of its tangent vector** $t^\mu = dx^\mu/d\lambda$, these **four coupled, second-order, ordinary differential equations** can be solved (numerically if not analytically) to determine the unique world-line of the particle.

- **Lagrangian approach**

Shortest distance between two points

- In an n -dimensional Riemannian space,

$$dl^2 = \sum_{i,j} g_{ij} dx^i dx^j,$$

- the length of a curve

$$L(P, Q) = \int_{u_P}^{u_Q} \left(\sum_{i,j} g_{ij} \frac{dx^i}{du} \frac{dx^j}{du} \right)^{1/2} du$$

the calculus of variations

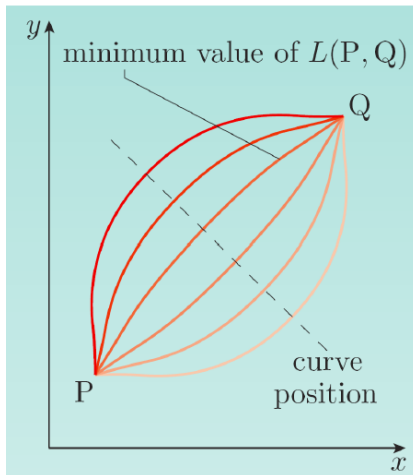
用变分来做 (δL is **zero**.)

$$\delta L = \delta \int_{u_P}^{u_Q} F du = \int_{u_P}^{u_Q} \sum_m \left(\frac{\partial F}{\partial x^m} \delta x^m + \frac{\partial F}{\partial \left(\frac{dx^m}{du} \right)} \delta \left(\frac{dx^m}{du} \right) \right) du.$$

$$\delta L = \delta \int_{u_P}^{u_Q} F du$$

$$= \int_{u_P}^{u_Q} \sum_m \left(\frac{\partial F}{\partial x^m} \delta x^m + \frac{\partial F}{\partial \left(\frac{dx^m}{du} \right)} \delta \left(\frac{dx^m}{du} \right) \right) du.$$

注意 $\frac{d}{du}(\delta x^m) = \delta \left(\frac{dx^m}{du} \right)$, 利用分部积分



We want to find a curve $(x^1(u), x^2(u))$ and Q that gives

$L(P, Q)$, i.e. the **shortest distance between the two points.**

- Such a curve would be a **straight line**, an **geodesic**.

$$\delta L = \left[\sum_m \frac{\partial F}{\partial \left(\frac{dx^m}{du} \right)} \delta x^m \right]_{u_P}^{u_Q} + \int_{u_P}^{u_Q} \sum_m \left(\frac{\partial F}{\partial x^m} - \frac{d}{du} \left(\frac{\partial F}{\partial \left(\frac{dx^m}{du} \right)} \right) \right) \delta x^m du$$

$$= 0$$

Since this is true for arbitrary variation δx^m ,

$$\frac{d}{du} \left(\frac{\partial F}{\partial \left(\frac{dx^m}{du} \right)} \right) - \frac{\partial F}{\partial x^m} = 0, \quad (m = 0, 1, 2, 3)$$

著名的 **Euler-Lagrange equations**

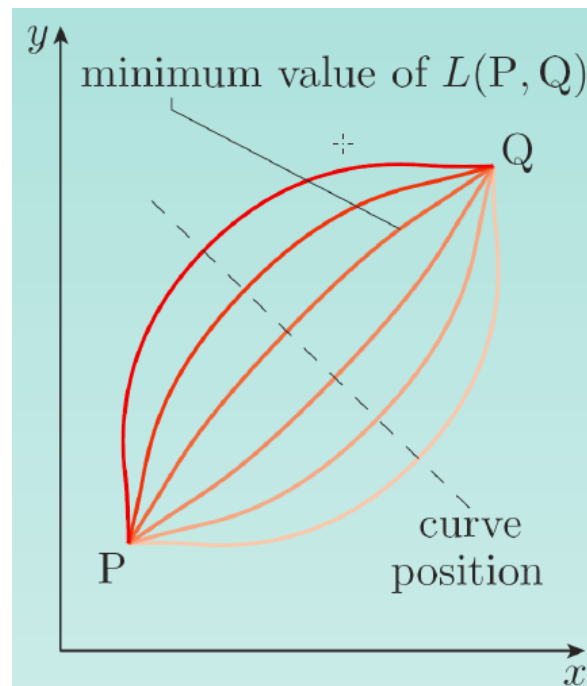
用变分来做 (δL is **zero**.)

$$F = \left(\sum_{i,j} g_{ij} \frac{dx^i}{du} \frac{dx^j}{du} \right)^{1/2},$$

$$\frac{d}{du} \left(\frac{\partial F}{\partial \left(\frac{dx^m}{du} \right)} \right) - \frac{\partial F}{\partial x^m} = 0, \quad (m = 0, 1, 2, 3)$$

- 可得测地线方程

$$\frac{d^2 x^\mu}{d\lambda^2} + \sum_{\nu,\rho} \Gamma_{\nu\rho}^\mu \frac{dx^\nu}{d\lambda} \frac{dx^\rho}{d\lambda} = 0,$$



$$F = \left(\sum_{i,j} g_{ij} \frac{dx^i}{du} \frac{dx^j}{du} \right)^{1/2}$$

- **Lagrangian approach** (写法稍微不一样)

the equations governing the geodesics in a spacetime can be derived from the energy integral given by the Lagrangian

$$2\mathcal{L} = -g_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda}$$

For Schwarzschild the Lagrangian is (here in units $c = G = 1$)

$$\mathcal{L} = \frac{1}{2} \left[\left(1 - \frac{2M}{r} \right) \dot{t}^2 - \frac{\dot{r}^2}{1 - 2M/r} - r^2 \dot{\theta}^2 - r^2 \sin^2 \theta \dot{\phi}^2 \right]$$

a dot denotes differentiation with respect to λ .

$$\mathcal{L} = \frac{1}{2} \left[\left(1 - \frac{2M}{r} \right) \dot{t}^2 - \frac{\dot{r}^2}{1 - 2M/r} - r^2 \dot{\theta}^2 - r^2 \sin^2 \theta \dot{\phi}^2 \right]$$

The corresponding canonical momenta are

$$p_t = \frac{\partial \mathcal{L}}{\partial \dot{t}} = \left(1 - \frac{2M}{r} \right) \dot{t}$$

$$p_r = -\frac{\partial \mathcal{L}}{\partial \dot{r}} = \left(1 - \frac{2M}{r} \right)^{-1} \dot{r}$$

$$p_\theta = -\frac{\partial \mathcal{L}}{\partial \dot{\theta}} = r^2 \dot{\theta}$$

$$p_\phi = -\frac{\partial \mathcal{L}}{\partial \dot{\phi}} = r^2 \sin^2 \theta \dot{\phi}.$$

$$\mathcal{H} = T + V, \quad T = \frac{p^2}{2m}, \quad V = V(q). \\ L = T - V.$$

Hamiltonian is

$$\mathcal{H} = p_t \dot{t} - (p_r \dot{r} + p_\theta \dot{\theta} + p_\phi \dot{\phi}) - \mathcal{L} = \mathcal{L}.$$

$$\mathcal{L} = \frac{1}{2} \left[\left(1 - \frac{2M}{r} \right) \dot{t}^2 - \frac{\dot{r}^2}{1 - 2M/r} - r^2 \dot{\theta}^2 - r^2 \sin^2 \theta \dot{\phi}^2 \right]$$

$$\mathcal{H} = T + V, \quad T = \frac{p^2}{2m}, \quad V = V(q). \\ L = T - V.$$

$$\mathcal{H} = p_t \dot{t} - (p_r \dot{r} + p_\theta \dot{\theta} + p_\phi \dot{\phi}) - \mathcal{L} = \mathcal{L}.$$

The equality of the Hamiltonian and the Lagrangian signifies that **there is no potential energy**, as is evident from the definition of the energy integral.

- This fact indicates that both are constant

$$\mathcal{H} = \mathcal{L} = \text{const} \begin{array}{l} = 1 \text{ for time-like geodesics} \\ = 0 \text{ for null geodesics} \end{array}$$

(space-like geodesics are not covered)

- integrals of motion follow from the equations

$$\frac{dp_t}{d\tau} = \frac{\partial \mathcal{L}}{\partial t} = 0 \\ \frac{dp_\phi}{d\tau} = \frac{\partial \mathcal{L}}{\partial \phi} = 0.$$

$$\mathcal{L} = \frac{1}{2} \left[\left(1 - \frac{2M}{r}\right) \dot{t}^2 - \frac{\dot{r}^2}{1 - 2M/r} - r^2 \dot{\theta}^2 - r^2 \sin^2 \theta \dot{\phi}^2 \right]$$

Thus

$$p_t = \left(1 - \frac{2M}{r}\right) \frac{dt}{d\tau} = E = \text{const}$$

$$p_\phi = r^2 \sin^2 \theta \frac{d\phi}{d\tau} = L = \text{const}.$$

from the equation of motion

$$p_\theta = -\frac{\partial \mathcal{L}}{\partial \dot{\theta}} = r^2 \dot{\theta}$$

$$\frac{dp_\theta}{d\tau} = \frac{d}{d\tau}(r^2 \dot{\theta}) = -\frac{\partial \mathcal{L}}{\partial \theta} = (r^2 \sin \theta \cos \theta) \left(\frac{d\phi}{d\tau}\right)^2$$

when we assign $\theta = \pi/2$, it follows that $d\theta/d\lambda = 0$, $d^2\theta/d\lambda^2 = 0$, θ will remain constant at the assigned value.

- **the geodesic is described in invariant plane**

$$p_\phi = r^2 \frac{d\phi}{d\tau} = L = \text{const}.$$

恢复量纲

- the motion in Schwarzschild spacetime
- Choosing the parameter λ to be an affine parameter ensures that as the tangent vector is transported along the geodesic, it **not only remains self-parallel but also has a constant magnitude** (more properly called a norm in this context).

$$n^2 = \sum_{\mu, \nu} g_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda} = \text{constant},$$

- will be **zero** in the case of a null geodesic.
- For massive particle, choose the proper time τ (as measured by a clock falling with the particle) as the parameter λ , then

$$\sum_{\mu, \nu} g_{\mu\nu} U^\mu U^\nu = c^2. \quad n^2 = c^2$$

$$c^2 = c^2 \left(1 - \frac{2GM}{c^2 r}\right) \left(\frac{dt}{d\tau}\right)^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} \left(\frac{dr}{d\tau}\right)^2 - r^2 \left(\frac{d\theta}{d\tau}\right)^2 - r^2 \sin^2 \theta \left(\frac{d\phi}{d\tau}\right)^2.$$

four other constants of the motion

$$\frac{d^2 t}{d\lambda^2} + \frac{2GM}{c^2 r^2 \left(1 - \frac{2GM}{c^2 r}\right)} \frac{dr}{d\lambda} \frac{dt}{d\lambda} = 0,$$

$$\frac{d^2 r}{d\lambda^2} + \frac{GM}{r^2} \left(1 - \frac{2GM}{c^2 r}\right) \left(\frac{dt}{d\lambda}\right)^2 - \frac{GM}{c^2 r^2 \left(1 - \frac{2GM}{c^2 r}\right)} \left(\frac{dr}{d\lambda}\right)^2 - r \left(1 - \frac{2GM}{c^2 r}\right) \left[\left(\frac{d\theta}{d\lambda}\right)^2 + \sin^2 \theta \left(\frac{d\phi}{d\lambda}\right)^2 \right] = 0,$$

$$\frac{d^2 \theta}{d\lambda^2} + \frac{2}{r} \frac{dr}{d\lambda} \frac{d\theta}{d\lambda} - \sin \theta \cos \theta \left(\frac{d\phi}{d\lambda}\right)^2 = 0,$$

$$\frac{d^2 \phi}{d\lambda^2} + \frac{2}{r} \frac{dr}{d\lambda} \frac{d\phi}{d\lambda} + 2 \frac{\cos \theta}{\sin \theta} \frac{d\theta}{d\lambda} \frac{d\phi}{d\lambda} = 0.$$

$$p_t = \frac{\partial \mathcal{L}}{\partial \dot{t}} = \left(1 - \frac{2M}{r}\right) \dot{t}$$

$$p_r = -\frac{\partial \mathcal{L}}{\partial \dot{r}} = \left(1 - \frac{2M}{r}\right)^{-1} \dot{r}$$

$$p_\theta = -\frac{\partial \mathcal{L}}{\partial \dot{\theta}} = r^2 \dot{\theta}$$

$$p_\phi = -\frac{\partial \mathcal{L}}{\partial \dot{\phi}} = r^2 \sin^2 \theta \dot{\phi}.$$

- deducing these **four conserved quantities**

There are **deep connections** between **symmetries** and **conservation laws** throughout physics, so it is not surprising that the many symmetries of the Schwarzschild solution should give rise to conserved quantities in this case.

- the **static** nature of the Schwarzschild solution indicates a symmetry associated with **invariance under translation in time**. associated with the **conservation of energy**

$$\frac{E}{mc^2} = \left(1 - \frac{2GM}{c^2 r}\right) \frac{dt}{d\tau}. \quad \text{the energy per unit mass energy}$$

- the solution's **invariance under rotations** about the origin indicates spherical symmetry, and is associated with the **conservation of angular momentum**. $\theta = \pi/2$ without any real loss of generality
- $\theta = \pi/2$ single condition

$$\frac{J}{m} = r^2 \sin^2 \theta \frac{d\phi}{d\tau}. \quad \text{the angular momentum per unit mass}$$

$$\frac{E}{mc^2} = \left(1 - \frac{2GM}{c^2 r}\right) \frac{dt}{d\tau}$$

$$\frac{J}{m} = r^2 \sin^2 \theta \frac{d\phi}{d\tau}$$

$$\bullet \theta = \pi/2$$

$$c^2 = c^2 \left(1 - \frac{2GM}{c^2 r}\right) \left(\frac{dt}{d\tau}\right)^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} \left(\frac{dr}{d\tau}\right)^2 - r^2 \left(\frac{d\theta}{d\tau}\right)^2 - r^2 \sin^2 \theta \left(\frac{d\phi}{d\tau}\right)^2$$



$$c^2 = \frac{E^2}{m^2 c^2} \left(1 - \frac{2GM}{c^2 r}\right)^{-1} - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} \left(\frac{dr}{d\tau}\right)^2 - \frac{J^2}{m^2 r^2}$$

$$\left(\frac{dr}{d\tau}\right)^2 + \frac{J^2}{m^2 r^2} \left(1 - \frac{2GM}{c^2 r}\right) - \frac{2GM}{r} = c^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1 \right]$$

$$\left(\frac{dr}{d\tau}\right)^2 + \frac{J^2}{m^2 r^2} \left(1 - \frac{2GM}{c^2 r}\right) - \frac{2GM}{r} = c^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1 \right]$$

- already incorporates the general relativistic analogues of **energy conservation** and **angular momentum conservation**,
- describes the changes in the radial position coordinate with proper time for **a freely falling particle of non-zero mass** moving in the equatorial plane $\theta = \pi/2$.

- Show that in Schwarzschild spacetime, the motion of a test particle in radial free fall (i.e. directly towards $r = 0$) satisfies the relation

$$\frac{d^2 r}{d\tau^2} = -\frac{GM}{r^2}.$$

$$\left(\frac{dr}{d\tau}\right)^2 + \frac{J^2}{m^2 r^2} \left(1 - \frac{2GM}{c^2 r}\right) - \frac{2GM}{r} = c^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1 \right]$$

In the case of purely radial motion ϕ is constant, so $d\phi/d\tau = 0$, $J = 0$.

$$\frac{d}{d\tau} \left(\frac{dr}{d\tau}\right)^2 = c^2 \left[\left(\frac{E}{mc^2}\right)^2 - 1 \right] + \frac{2GM}{r}$$

$$2 \left(\frac{dr}{d\tau}\right) \frac{d^2 r}{d\tau^2} = -\frac{2GM}{r^2} \frac{dr}{d\tau}$$

$$\frac{d^2 r}{d\tau^2} = -\frac{GM}{r^2}$$

Newtonian result

$$\frac{d^2 r}{d\tau^2} = -\frac{GM}{r^2}.$$

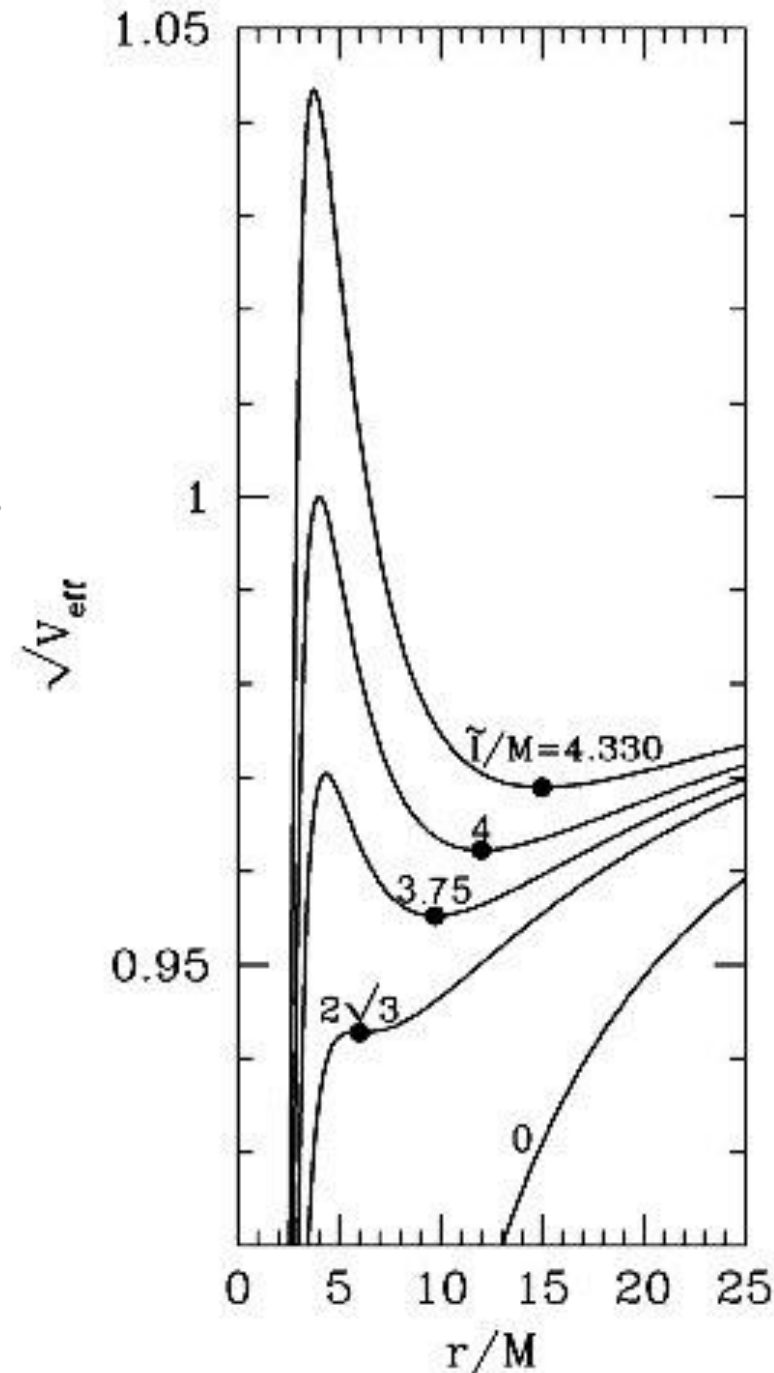
Newtonian result

Several differences between the GR result and its Newtonian counterpart.

- talking about free fall under gravity is fine in GR, but talking of the ‘pull’ of gravity or gravitational ‘attraction’ would be quite wrong since there is no gravitational ‘force’ in general relativity
- The Newtonian result directly relates the second derivative of the **radial distance** with respect to **time** to the inverse square of the **radial distance**, but in the **GR** result the second derivative is with respect to **proper time** τ , and r is the **coordinate distance**, not the ‘physical’ proper distance.
- In the Newtonian limit, when $dr/d\tau \ll c$ and the particle is sufficiently far from the spherical mass for the field to be weak, these differences vanish, and the **GR** result does reduce to the Newtonian result.
- close to the Schwarzschild radius, the differences are real and significant

Circular Orbits

- In **Newtonian gravity**, stable circular orbits are available around a point mass at all radii
- This is no longer true in **General Relativity**
- In the **Schwarzschild metric**, stable orbits allowed only down to $r = 6GM/c^2$ (innermost stable circular orbit, **ISCO**)



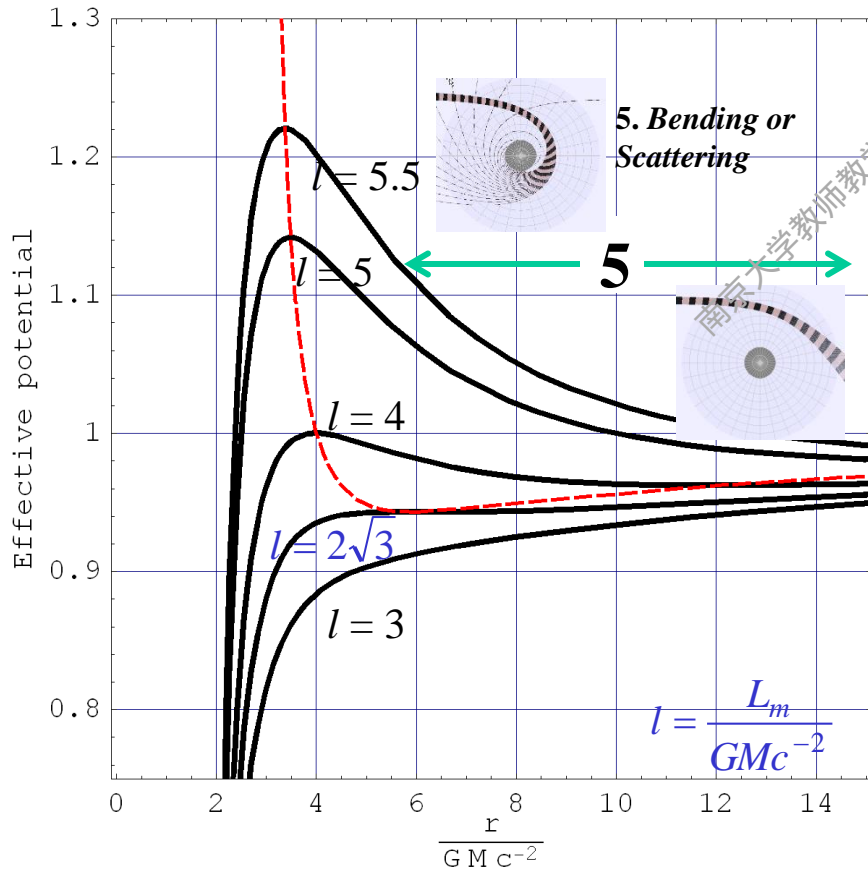
$$\frac{c^2}{2} \left[\left(\frac{E}{mc^2} \right)^2 - 1 \right] = \frac{1}{2} \left(\frac{dr}{d\tau} \right)^2 + V_{\text{eff}},$$

$$V_{\text{eff}} = \frac{J^2}{2m^2 r^2} \left(1 - \frac{2GM}{c^2 r} \right) - \frac{GM}{r}.$$

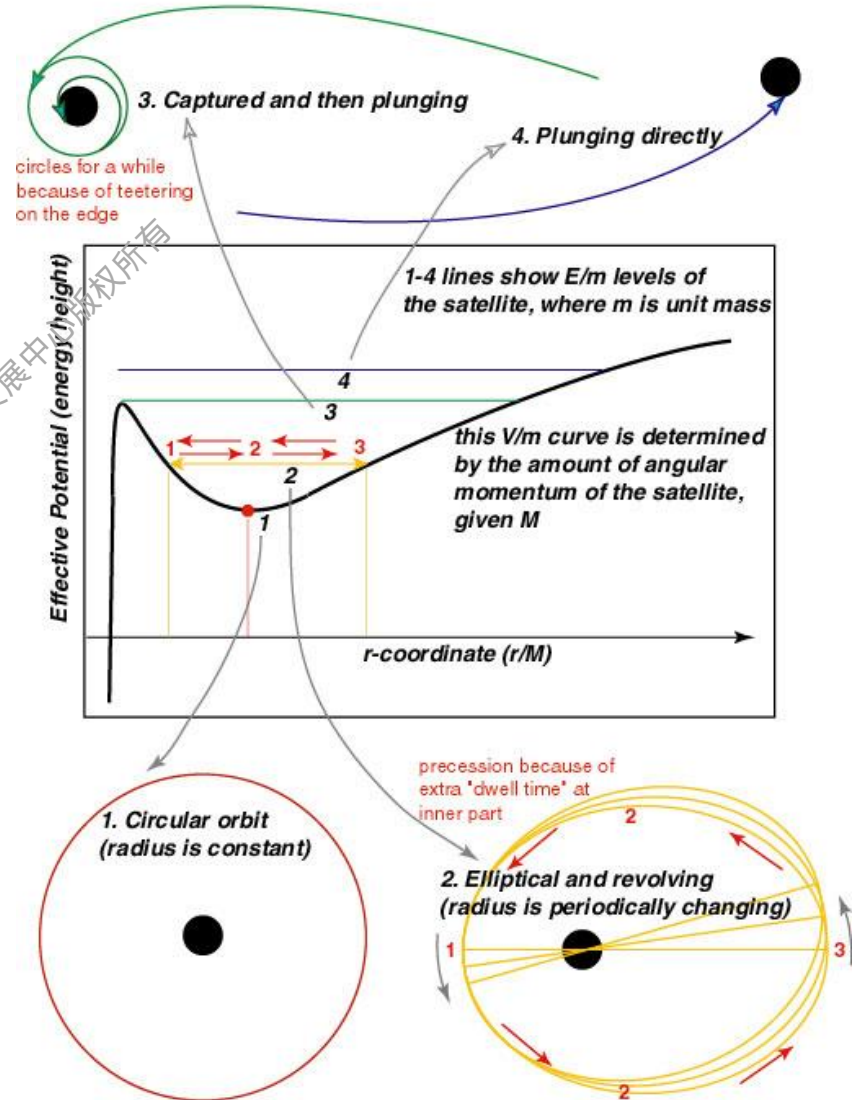
Effective potential for the non-zero mass particle :

$$\left(\frac{dr}{d\tau} \right)^2 = E_m^2 - V_m^2$$

$$V_m = \sqrt{\left(1 - \frac{2GM}{rc^2} \right) \cdot \left(1 + \frac{L_m^2}{r^2} \right)}$$



Five POSSIBLE ORBITS OF A SATELLITE OF A BLACK HOLE



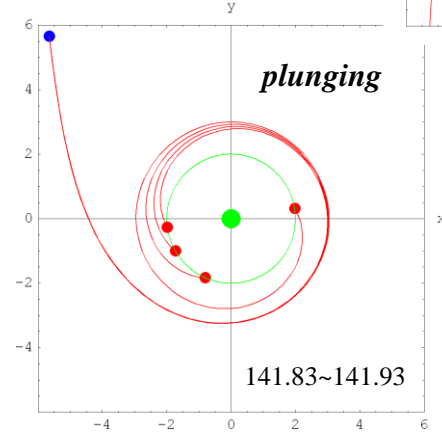
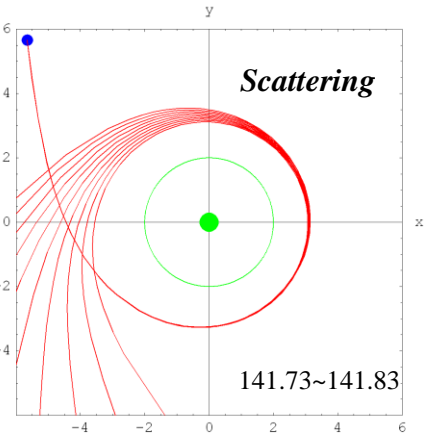
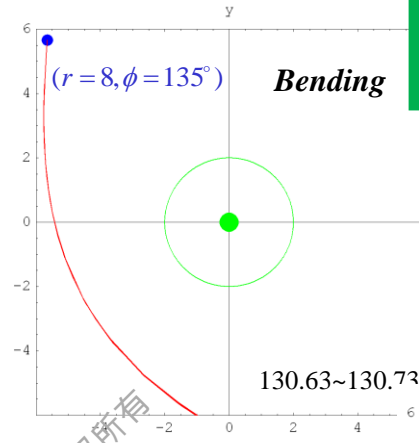
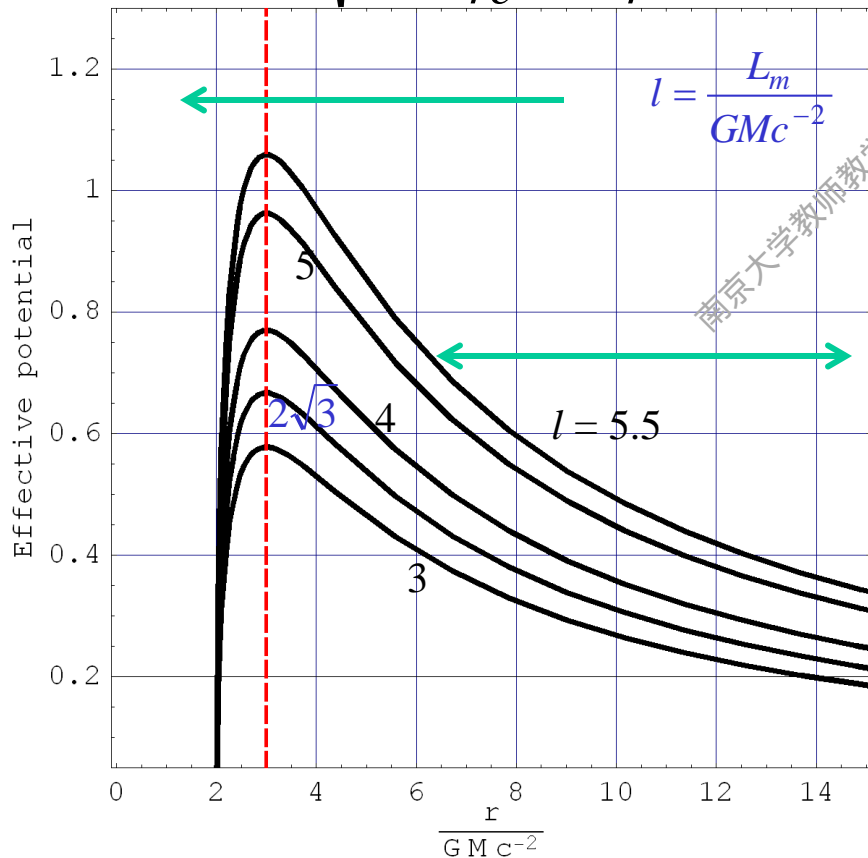
$$\frac{c^2}{2} \left[\left(\frac{E}{mc^2} \right)^2 - 1 \right] = \frac{1}{2} \left(\frac{dr}{d\tau} \right)^2 + V_{\text{eff}},$$

$$V_{\text{eff}} = \frac{J^2}{2m^2 r^2} \left(1 - \frac{2GM}{c^2 r} \right) - \frac{GM}{r}.$$

Effective potential for the null particle :

$$\left(\frac{dr}{d\lambda} \right)^2 = E_m^2 - V_m^2$$

$$V_m = \sqrt{\left(1 - \frac{2GM}{rc^2} \right) \cdot \frac{L_m^2}{r^2}}$$



南京大学教师教学发展中心版权所有



For Juniors/Seniors



schorbits.nb

THE SHAPE OF ORBITS IN THE SCHWARZSCHILD GEOMETRY

This is a *Mathematica* program to compute and display the shapes of orbits in a Schwarzschild geometry. The Schwarzschild radial coordinate is measured in units of M , so that $M=1$ in the following formulae. Throughout the variable $u=1/r$ is used. Here is a list of what you must set to run the program:

- (1) The angular momentum: ℓ .
- (2) The energy parameter: $\mathcal{E} = (e^2 - 1)/2$.
- (3) The starting radius for an orbit which is not bound: r_{st} .
- (4) The number of orbits to be computed if the orbit is bound: $norbit$.

These are set by editing the definition statements at various places in the program. **You have to make sure these parameters are set so the orbit is classically allowed and doesn't start at a position where the value of the effective potential that is greater than \mathcal{E} .**

■ **The potential:**

The effective potential for radial motion V_{eff} given in (9.28) is here denoted simply by V . To be slightly more general a parameter `signewt` is introduced which multiplies the non-Newtonian $1/r^3$ term in the potential. Set it equal to 1 for general relativity, 0 for a Newtonian $1/r$ potential, and an appropriate value for a Newtonian $1/r$ potential with an additional quadrupole moment term.

```
signewt = 1.
```

1.

```
:= -u +  $\ell^2$  u^2 / 2 - signewt  $\ell^2$  u^3
```

■ **Specifying the orbit:**

It takes four numbers to specify an orbit: (1) the angular momentum ℓ , (2) the energy parameter \mathcal{E} , (3) the starting radius r_{st} , and (4) the number of orbits to be calculated, $norbit$.

125%



For Juniors/Seniors



Schwarzschild.nb

Curvature and the Einstein Equation (Sch Derivation)

This is the *Mathematica* notebook *Curvature and the Einstein Equation* available from the book website. From a given metric $g_{\alpha\beta}$, it computes the components of the following: the inverse metric, $g^{\lambda\sigma}$, the Christoffel symbols or affine connection,

$$\Gamma^{\lambda}_{\mu\nu} = \frac{1}{2} g^{\lambda\sigma} (\partial_{\mu} g_{\sigma\nu} + \partial_{\nu} g_{\sigma\mu} - \partial_{\sigma} g_{\mu\nu}),$$

(∂_{α} stands for the partial derivative $\partial / \partial x^{\alpha}$), the Riemann tensor,

$$R^{\lambda}_{\mu\nu\sigma} = \partial_{\nu} \Gamma^{\lambda}_{\mu\sigma} - \partial_{\sigma} \Gamma^{\lambda}_{\mu\nu} + \Gamma^{\eta}_{\mu\sigma} \Gamma^{\lambda}_{\eta\nu} - \Gamma^{\eta}_{\mu\nu} \Gamma^{\lambda}_{\eta\sigma},$$

the Ricci tensor

$$R_{\mu\nu} = R^{\lambda}_{\mu\lambda\nu},$$

the scalar curvature,

$$R = g^{\mu\nu} R_{\mu\nu},$$

and the Einstein tensor,

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R.$$

You must input the covariant components of the metric tensor $g_{\mu\nu}$ by editing the relevant input line in this *Mathematica* notebook. You may also wish to change the names of the coordinates. Only the nonzero components of the above quantities are displayed as the output. All the components computed are in the *coordinate basis* in which the metric was specified.

- Clearing the values of symbols:**
 First clear any values that may already have been assigned to the names of the various objects to be calculated. The names of the coordinates that you will use are also cleared.

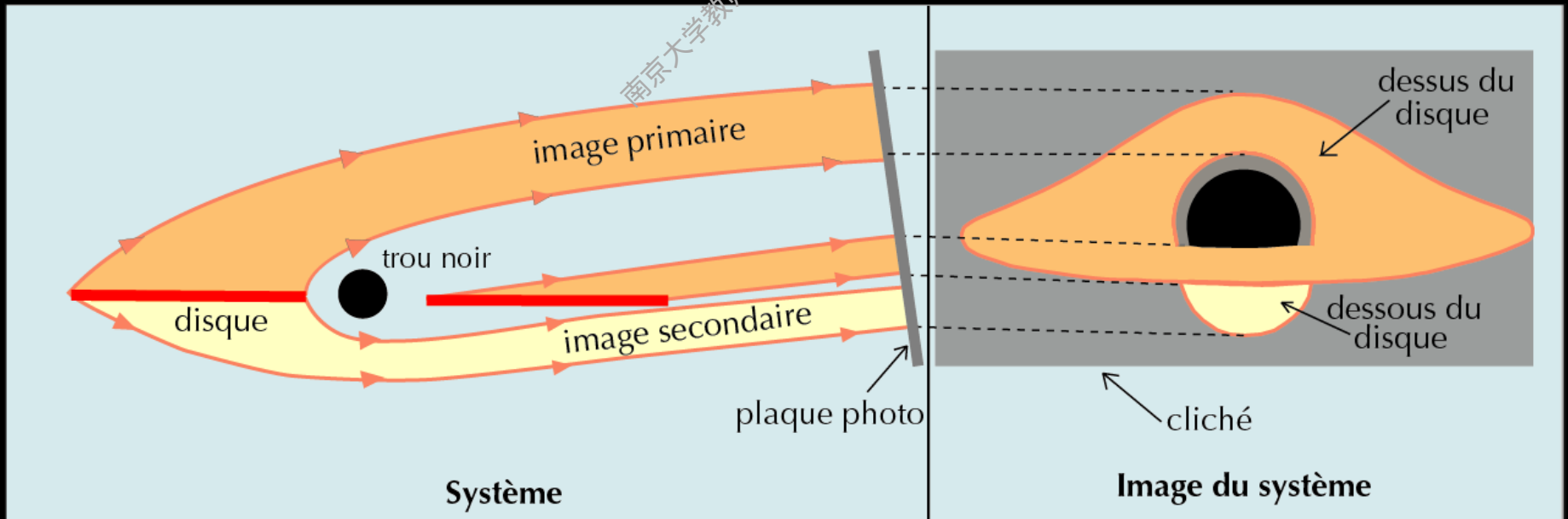
`Clear[coord, metric, inversemetric, affine, riemann, ricci, scalar, einstein, x, y, z, t]`
- Setting the dimension:**
 The dimension n of the spacetime (or space) must be set:
`n = 4`
`4`
- Defining a list of coordinates:**
 The example given here is the Schwarzschild metric. The coordinate choice of Schwarzschild is appropriate for this spherically

100%

Newtonian spacetime

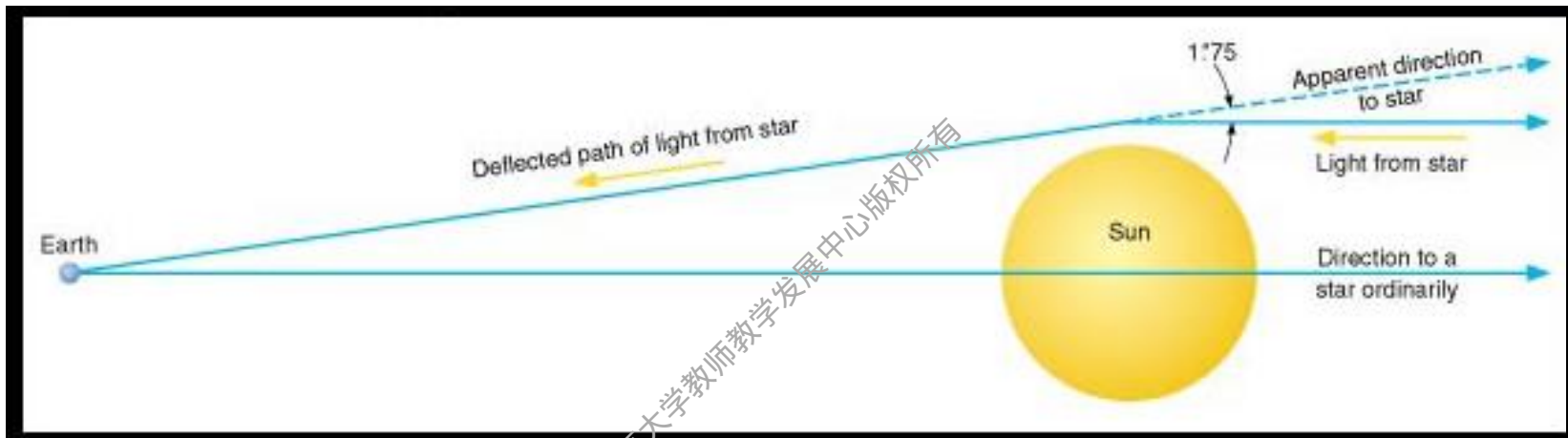


curved spacetime



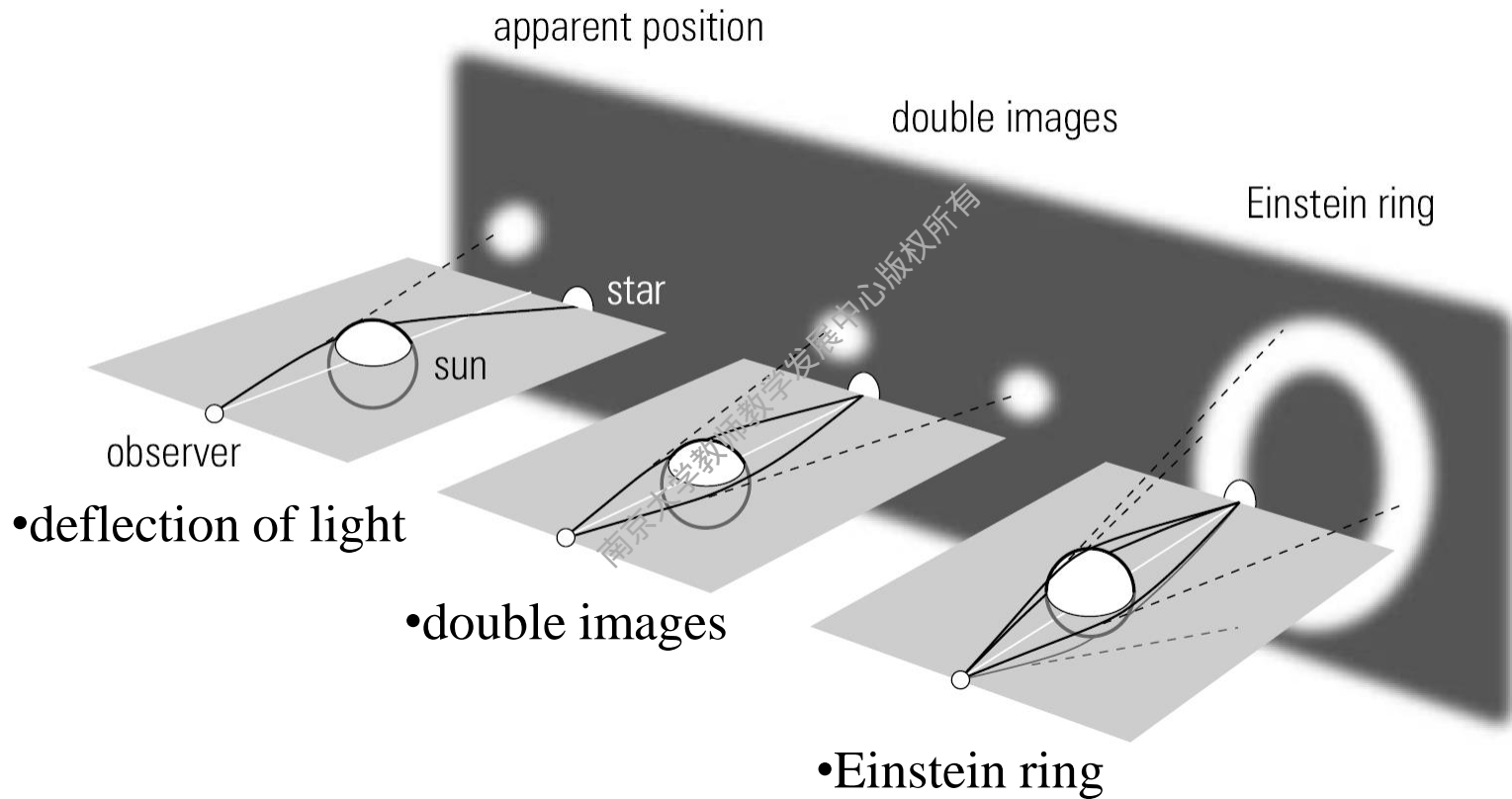
南京大学教师教学发展中心版权所有

- 光线弯曲
(Deflection of Star Light)



Einstein's calculations in his newly developed general relativity indicated that the light from a star which just grazed the sun should be deflected by **1.75** seconds of arc. It was tested during the total eclipse of 1919 and during most of those which have occurred since.

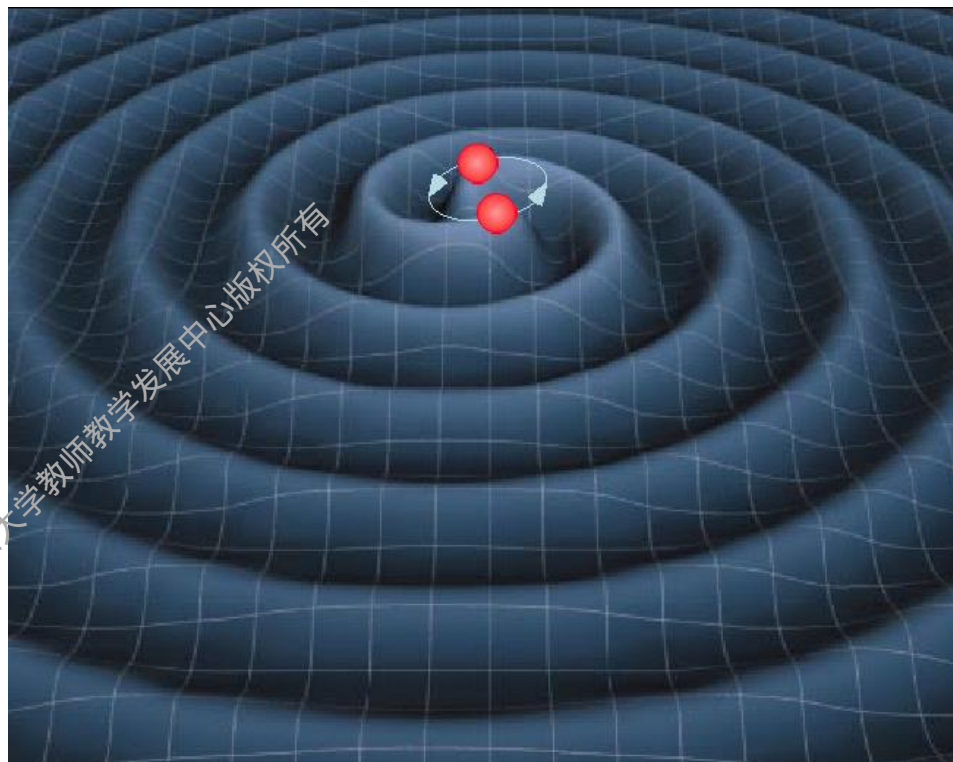
Gravitational lensing by a massive object



引力波辐射

- 相对论要求任何物质在真空中的传播速度不能超过光速，这意味着引力场的变化如果是通过引力波来实现，其速度最多为光速。

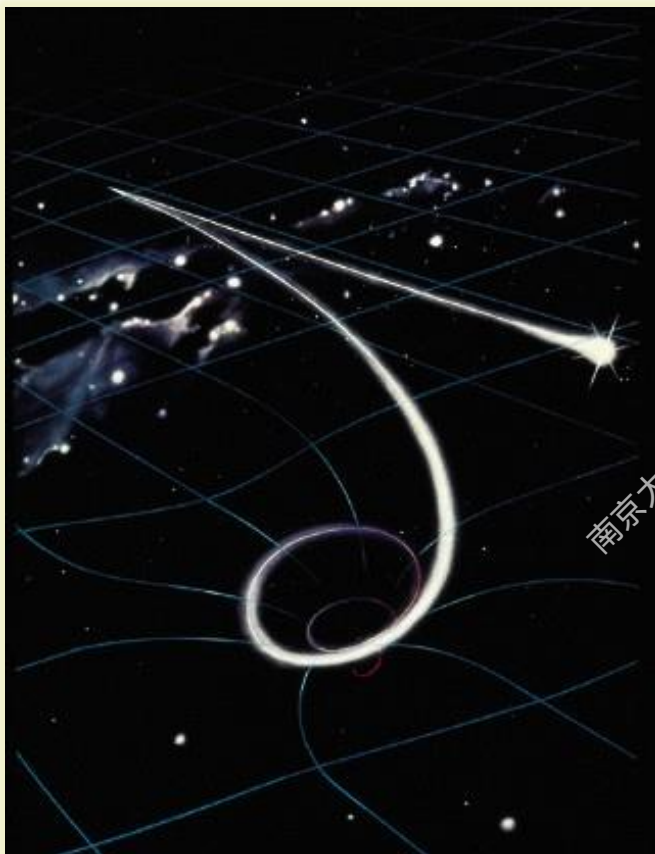
- 天体环境下具体的引力波源有：双星，恒星爆发，旋转的中子星，宇宙大爆炸后形成的原初引力波背景。



南京大学教师教学发展中心版权所有



内容



黑洞—时空中的无限深渊

For **Freshmen**

For **Sophomores**

For **Juniors/Seniors**

Discussion

南京大学教师教学发展中心版权所有



Discussion



- 授课的目的要明确
- 对象的基础要清楚
- 合适的参考教材
- 时代技术在变，允许学生高效
- 不能“求”着学生学

南京大学教师教学发展中心版权所有



Discussion



天文漫谈 (10-13)

天文探秘 (14-)

课程内容

科普的层次

- 自然界中稳定的物质结构
- 行星 (系外行星的搜寻, 潜在的威胁)
- 恒星 (太阳风暴)
- 致密天体 (表现与探寻)

- 不强调知识的系统和全面性
- 引导、激发学生对学科的兴趣, 举一反三、融汇贯通
- 开启探究式教学
- 实现师生互动, 活跃讨论氛围



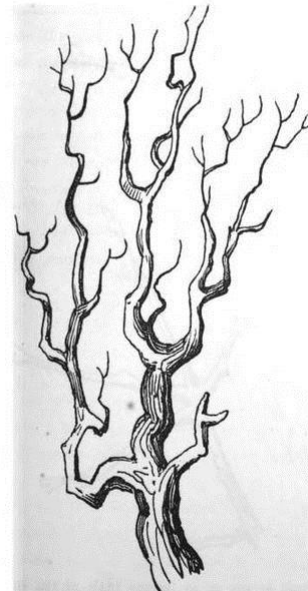
南京大学教师教育与发展中心版权所有



Discussion




课程内容 大学天文



主要的枝干

仙女座星系距我们250万光年



人们如何去研究如此遥远的天体?

天文观测


太阳——燃烧不息的原子弹



当太阳燃烧不久，我们将逐渐地看见星在夜空中闪烁。太阳是银河系中大约一亿颗恒星中的一颗，它不断地向外发出光和热。不同的恒星燃烧着不同的燃料，不能燃烧完的燃料大小，因为太阳比地球大一千五百倍，比其他恒星小的多。

太阳所发出的光和热，对我们地球来说是至关重要的。如果没有太阳，地球将有漫长的生命生存的机会，没有太阳，地球已变成了一个死气沉沉的世界，根本不可能存在生命了。

太阳



在夜色中，
我们可领略这璀璨星空的无穷之美。
可贵的知识是人类保护之中的繁星密布，
浩无边际而绚丽的星空，
其实是我们的仰望之所，
所能读到的最好的
诗画、散文、小说和戏剧。

——仰望星空

恒星演化

Death of a Star



How about forever?

致密星

参考书目



ASTRONOMY AND ASTROPHYSICS LIBRARY

ASTROPHYSICS AND SPACE SCIENCE LIBRARY 357

Max Camenzind

Compact Objects in Astrophysics

White Dwarfs, Neutron Stars and Black Holes

AAU

Springer

ASTROPHYSICS AND SPACE SCIENCE LIBRARY

NEUTRON STARS 1

Equation of State and Structure

F. HAENSEL, A.Y. POTERKHIN, D.G. YAKOVLEV

Springer

ASTROPHYSICS AND SPACE SCIENCE LIBRARY

Werner Becker

Editor

Neutron Stars and Pulsars

ASL

Springer

<http://arxiv.org/abs/nucl-th/0309041>

Neutron Stars for Undergraduates

远古之初，孰谓肇之？
上下未形，何由考之？
——程颢



The galaxies remind us that our position in the universe is no more special than that of a boat adrift at sea.

星系

Chronology to the study of the biggest puzzle of how "big" is the Universe



How to know the "end", what is the origin and the large-scale structure of the Universe, how long time it takes to form, how long will it last, what will be the fate, ...?

宇宙学

感兴趣的问题
人识（并非简单科学家的层级的物理知识、天文问题？



Discussion



高年级研究生课程



根基

- 研究的基本技能
- 高效率、软件的应用
- 重复前人的工作
- 打破幻想，不纠缠
-





Discussion



- 授课的目的要明确
- 对象的基础要清楚
- 合适的参考教材
- 时代技术在变，允许学生高效
- 不能“求”着学生学

南京大学教师教学发展中心版权所有



开设课程



近年学院教师开设的课程

天文方向

普通天文学 I (1/2)	实测天体物理 (1/2)	天文漫谈 (1)	数据处理 (1)	X 射线双星 (1)
普通天文学 II (1)	实测天体物理实验 (1/2)	现代天文科研入门 (组织)	星系物理 (1/2)	轨道设计基础 (1)
普通天文学实习 (1)	天体力学基础 (1/2)	流体力学 (1/2)	近代天文讲座 (组织)	航天器轨道力学 (1/2)
球面天文 (1/2)	理论天体物理 (1/2)	数值计算方法 (1)	多波段天文学与深空探测 (组织)	宇宙学导论 (1)
射电天体物理 (?)	广义相对论 (1)	中子星物理 (1)		
空间探测中的时空系统 (?)	行星科学 (1/2)	天文参考系 (1)	星际介质物理 (1/2)	活动星系核 (1/2)
天体力学方法 (?)	磁流体力学 (1)	行星形成与动力学 (1)	太阳活动区物理 (1)	恒星结构与演化 (1)
非线性动力学引论 (1/2)	人造卫星精密定轨 (1)	天体物理辐射理论 (1)	计算天文 (1)	致密星物理 (1)
粒子天体物理 (1)	天文文献阅读 (1)			

空间方向

线性系统控制 (1/2)	控制理论基础 (1/2)	空间天气学 (1/2)		
--------------	--------------	-------------	--	--

新生研讨课及外院系课程

宇宙的命运 (1)	向往未来——人类的航天活动 (1)	大学天文学 (1)	广义相对论与宇宙学 (1)	普通天文学 (1/2)
-----------	-------------------	-----------	---------------	-------------

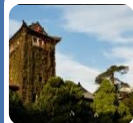
外聘教师开课

高能宇宙探索 (纪丽)	等离子体动力学 (黄光力)	等离子体天体物理学导论 (吴德金)
-------------	---------------	-------------------

光学与红外实测天文 (王洪池)



本科阶段最值得关注



平台、核心课程

计算机	C语言程序设计
数学	高数或微积分 I、II (第一层次), 线性代数 (第一层次)

课程模块	课程分类	学分构成
通识通修	通识教育	63
	通修课程	
学科专业	学科平台	53
	专业核心	
开放选修	专业选修	28
	跨专业选修	
	就业创业课程 公共选修	
毕业论文/设计		6
学分总计		150

普通物理 + 四大力学

学科平台	大学物理
	数学物理方法
	理论力学
	统计物理
	电动力学
	量子力学

国家级精品课程

专业核心

普通天文学(上、下)
普通天文学实习
原子物理
天体力学基础
球面天文
实测天体物理
实测天体物理实习
理论天体物理

长江特聘授课

杰青授课

青千授课





学习进程参考图

分专业



第1学期	第2学期	第3学期	第4学期	第5学期	第6学期	第7学期	第8学期
微积分 (10)	线性代数	数理方法	量子力学	球面天文	理论天体	毕业论文设计	
	大学物理 (8)	统计物理	电动力学	天力基础	星系物理		
计算机应用	C语言设计	理论力学	光学	实测	流体力学	X-射线双星	
计算机信息技术		普通天文 (7)	实测实验	天文热点	航天器轨道力学	广义相对论	
		普天实习	电路分析	数据处理	电路与逻辑	近代天文讲座	宇宙学导论
天文漫谈	大学物理实验		近代应用数学	数值计算方法	X-射线天文		
初等数理天文	近代天文研究入门			高能宇宙探索		暑期交换, 实习	
普天公选	天文探秘			控制理论基础		信号与系统	
宇宙命运	大学天文			电子电路	活动星系核	数字电路逻辑	
航天器				模拟电路		广义相对论与宇宙学文	
				空间天气学			



Discussion



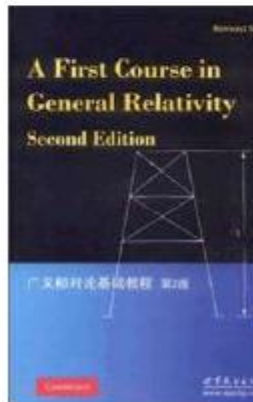
- 授课的目的要明确
- 对象的基础要清楚
- 合适的参考教材
- 时代技术在变，允许学生高效
- 不能“求”着学生学

南京大学教师教学发展中心版权所有

参考书目

1. Bernard F. Schutz, *A First Course in General Relativity*
2. James B. Hartle, *GRAVITY An Introduction to Einstein's General Relativity*
3. R. M. Wald, *General Relativity* (经典教材)
4. S. Weinberg, *Gravitation and Cosmology*

入门



5. Charles W. Misner, Kip S. Thorne, John Archibald Wheeler, *Gravitation* (大部头, Bible)

6. 梁灿斌, 微分几何入门与广义相对论, 上中下册

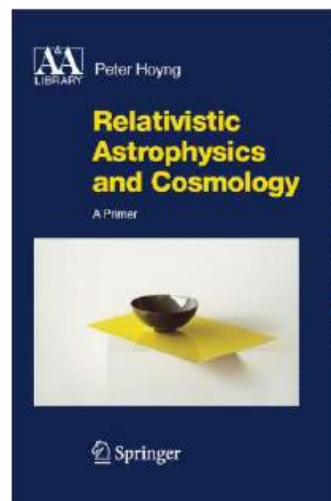
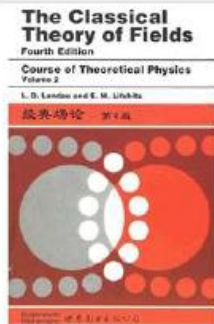
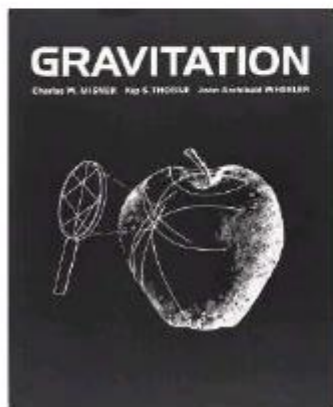
7. 俞允强, 广义相对论引论, 物理宇宙学讲义

9. 须重明, 吴雪君, 广义相对论和现代宇宙学

8. 刘辽, 赵峥, 广义相对论

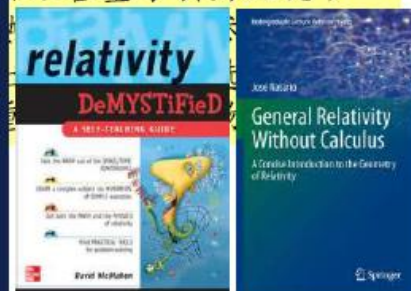
10. L. D. Landau and E. M. Lifshitz, *The Classical Theory of Fields*

11.



多太多

(不含量子引力理论)



Some recommended relativity texts

Many texts can form the basis for an excellent undergraduate course in relativity. Here are some that we recommend, along with a smattering of classic graduate-level books.

- ▶ S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, Wiley, New York (1972).
- ▶ C. W. Misner, K. S. Thorne, J. A. Wheeler, *Gravitation*, W. H. Freeman, San Francisco (1973).
- ▶ R. M. Wald, *General Relativity*, U. Chicago Press, Chicago (1984).
- ▶ B. F. Schutz, *A First Course in General Relativity*, Cambridge U. Press, New York (1985; 2nd ed. 2009).
- ▶ H. C. Ohanian, R. Ruffini, *Gravitation and Spacetime*, 2nd ed. Norton, New York (1994). The first edition was written by Ohanian alone in 1976.
- ▶ E. F. Taylor, J. A. Wheeler, *Exploring Black Holes: Introduction to General Relativity*, Addison Wesley Longman, San Francisco (2000).
- ▶ J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity*, Addison-Wesley, San Francisco (2003).
- ▶ B. F. Schutz, *Gravity from the Ground Up*, Cambridge U. Press, New York (2003).
- ▶ S. Carroll, *Spacetime and Geometry: An Introduction to General Relativity*, Addison-Wesley, San Francisco (2004).
- ▶ T.-P. Cheng, *Relativity, Gravitation and Cosmology: A Basic Introduction*, Oxford U. Press, New York (2005, 2nd ed. 2010).
- ▶ L. Ryder, *Introduction to General Relativity*, Cambridge U. Press, New York (2009).
- ▶ R. J. A. Lambourne, *Relativity, Gravitation and Cosmology*, Cambridge U. Press, New York (2010).
- ▶ R. N. Henriksen, *Practical Relativity: From First Principles to the Theory of Gravity*, Wiley, Chichester, UK (2011).
- ▶ T. A. Moore, *A General Relativity Workbook*, University Science Books, Sausalito, CA (in press). See <http://pages.pomona.edu/~tmoore/grw>.

参考书目

Teaching general relativity to undergraduates

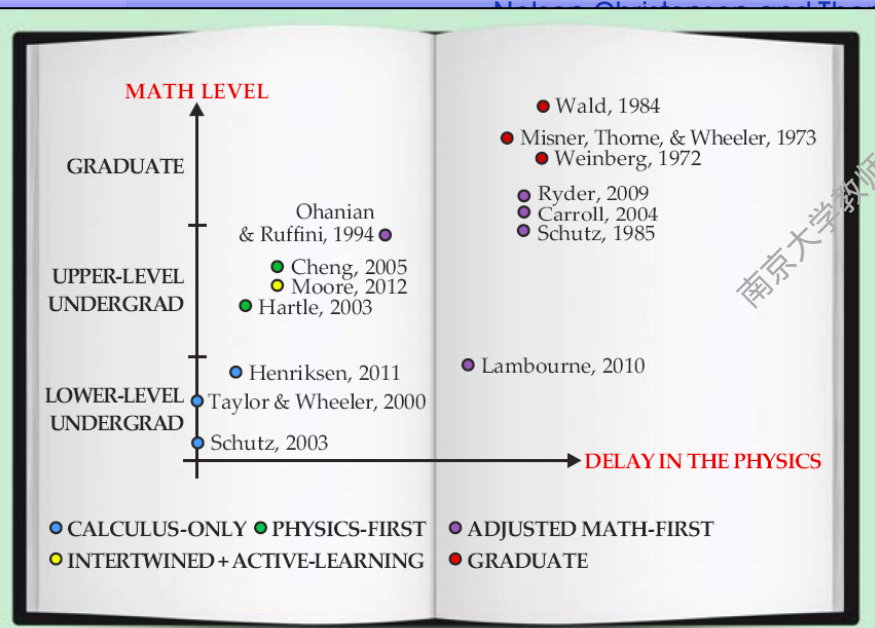


Figure 2. The main sequence. General relativity textbooks differ with regard to their level of mathematical sophistication and how long it takes for them to get to physical applications beyond special relativity. This is a limited sampling, and locations are somewhat subjective; still, they may provide for useful comparisons.

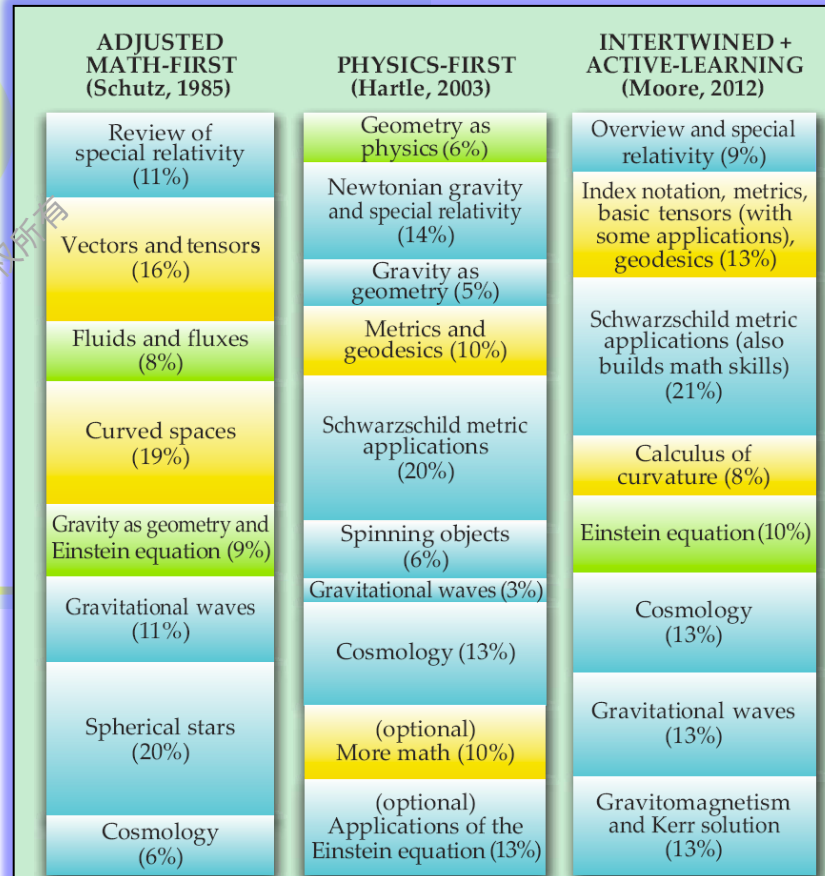


Figure 1. The relative emphasis of physics and mathematics and their positioning in exemplary texts for the adjusted math-first, physics-first, and intertwined + active-learning approaches. All three texts are designed for a one-semester, upper-level course. Blue sections are primarily physics oriented, yellow sections are primarily math oriented, and green sections blend some of each. Cited percentages are based on page counts.



Discussion



- 授课的目的要明确
- 对象的基础要清楚
- 合适的参考教材
- 时代技术在变，允许学生高效
- 不能“求”着学生学

南京大学教师教学发展中心版权所有



1969年7月21日 人类文明的一大步



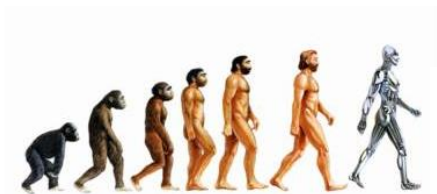
执行人类首次登月任务的阿波罗-11号任务徽章



阿波罗11号三名宇航员：阿姆斯特朗，奥尔德林以及柯林斯

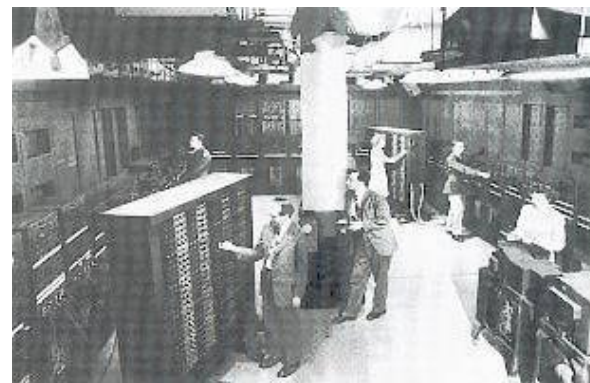


正在沿梯舷窗向下，即将登上月面的奥尔德林，照片由阿姆斯特朗使用70mm广角相机拍摄



iPhone 4 S

双核 A5 芯片。
全新 800 万像素摄像头和光学技术。
iOS 5 与 iCloud。
出色的 iPhone，如今更出色。



1946年，第一台电子管计算机 (ENIAC) 占地170平方米，重30吨，有1.8万个电子管，用十进制计算，每秒运算5000次

具体示例



Roger Blandford

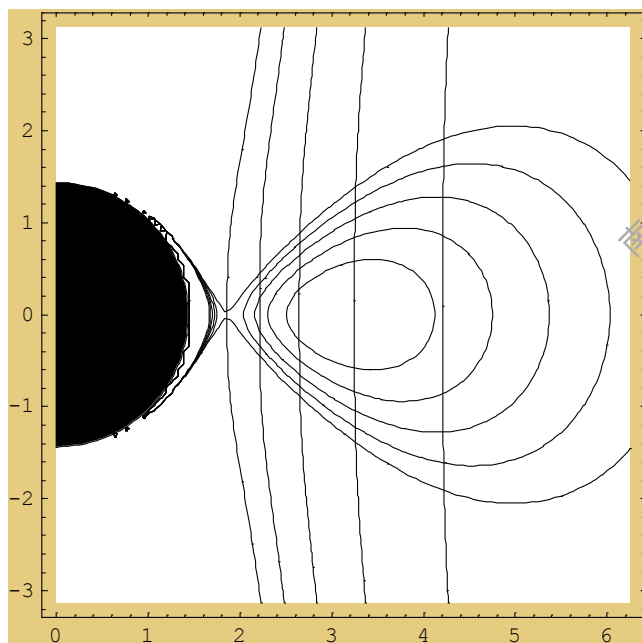
STANFORD UNIVERSITY



DEPARTMENT OF PHYSICS

Black Holes and Neutron Stars

课程完全用mathematica所写



Introduction

- 1. Spherical Holes*
- 2. Spinning Holes*
- 3. Orbits and Rays*
- 4. Thin Disks*
- 5. Thick Disks*
- 6. Tides and Oscillations*
- 7. Electromagnetic Effects*
- 8. Neutron Stars*
- 9. Gravitational Radiation*

网上似乎找不到了!



Discussion



网易公开课 传播属于全人类的知识和智慧

搜索课程、教师、公开课类别

首页 TED 国际名校公开课 中国大学视频公开课 资源 公开课策划 可汗学院 态度公开课 云课堂 中国大学MOOC

世上最后一块净土
现代环保公益 要比 现代生产公益 更重要

热门排行

01	你有拖延症吗?	179.4万
02	伟大的色情片实验	121.4万
03	如何成为一个更好的交谈者?	110.9万
04	世上最后一块净土	77.8万
05	如何与陌生人建立信任?	42.6万
06	编织我的梦	41.9万
07	幸福是什么?	41.8万
08	人类的崛起	39.9万
09	让人目瞪口呆的无人机	35.2万
10	光荣与梦想	34.8万

斯坦福大学公开课：广义相对论
学校：斯坦福大学 讲师：Leonard Susskind
集数：12 类型：物理

该课程是十二个现代物理学讲座，目标是让学生获得思考现代物理学的最小理论基础，各个讲座相对独立。主要内容是爱因斯坦的广义相对论，其中包含牛顿引力理论、高斯定理、引力加速等效原理、光线在空间中的弯曲、黎曼曲率张量、黑洞等现代物理学研究课题。

量子纠缠能否解释引力现象？
学校：DNews 讲师：Julia
集数：1 类型：物理 科普 地球科学 纪录片

量子物理的奇妙，让时空不再“纠缠”，物理学家试图解读量子力学与时空几何本质。然而过去近100年来，科学家一直认为量子力学和引力学相统一。（阿尔法小分队科普组译制，网易公开课编辑整理）

爱因斯坦的内心世界
学校：美国 讲师：PBS
集数：1 类型：社会 英语 纪录片

纪录片通俗地讲述了爱因斯坦的教学物理理论。（网易公开课编辑整理）

相对论和量子力学的世界观
学校：Sapienza University of ... 讲师：
开课时间：2014年3月10日

耶鲁大学开放课程：基础物理
学校：耶鲁大学 讲师：Ramamurti Shankar
集数：24 类型：物理

本课程为那些有较好的物理学和数学基础的同学学习物理学原理和方法提供了深入的介绍。重点放在解决问题和定量推理。本课程内容包括牛顿力学，相对论，引力，热力学，和波。

北京师范大学公开课：从爱因斯坦到霍金的宇宙
学校：北京师范大学 讲师：赵峥
集数：12 类型：物理

用通俗的语言定性介绍爱因斯坦的狭义与广义相对论，以及建立在此基础上的黑洞理论和现代宇宙学。有没有黑洞，它有什么特点？什么是弯曲的时空。膨胀的宇宙，可不可能有时空弯曲和时间机器。介绍爱因斯坦和霍金的创新经历，他们对科学的贡献。

超星发现 读书 讲座 课程 登录 注册

梁灿彬 北京师范大学

首页

TA的讲座

李群李代数与纤维丛 ★★★★★ 4.76分 (49人评价)
分类：经济管理 主讲人单位：北京师范大学
播放次数：56805 更新时间：2012-11-07

微分几何在相对论的应用 ★★★★★ 4.65分 (279人评价)
分类：基础科学 主讲人单位：北京师范大学
播放次数：116845 更新时间：2011-10-21

高等广义相对论 ★★★★★ 4.54分 (28人评价)
分类：基础科学 主讲人单位：北京师范大学
播放次数：35628 更新时间：2014-07-31



大师简介

梁灿彬，男，1938年生于澳门。1952-1955年在广东省广雅中学读高中。1955年考入北师大物理系。1959年毕业于并留系任教，1961-63年在美国芝加哥大学任访问学者，回国后长期担任基础课、专业课教学及科研工作。1966年起任教授，后任博导，1999年退休后应邀先后（同时）在北师大、清华大学、中国科学院数学所讲多次。

- 课程筛选**
- 按来源**
- 全部 TED BBC 可汗学院
 - 国际名校公开课
 - 中国大学视频公开课
 - 国立台湾大学公开课
- 按类型**
- 全部 经济 哲学
 - 心理 艺术 英语
 - 历史 生物 文学
 - 物理 伦理 环境
 - 化学 社会 管理
 - 法律 数学 演讲
 - 医学 媒体 技能
 - 其他 计算机 纪录片
 - 云课堂 冷知识 地球科学
 - 可汗学院 态度公开课
 - TED全网直播 coursera
- 按学校**
- 全部 加州大学伯克利分校
 - 牛津大学 普林斯顿大学
 - 剑桥大学 斯坦福大学
 - 哈佛大学 麻省理工学院
 - 耶鲁大学 加州大学洛杉矶分校
 - 亚琛工业大学 宾夕法尼亚大学
 - 巴黎高等商学院

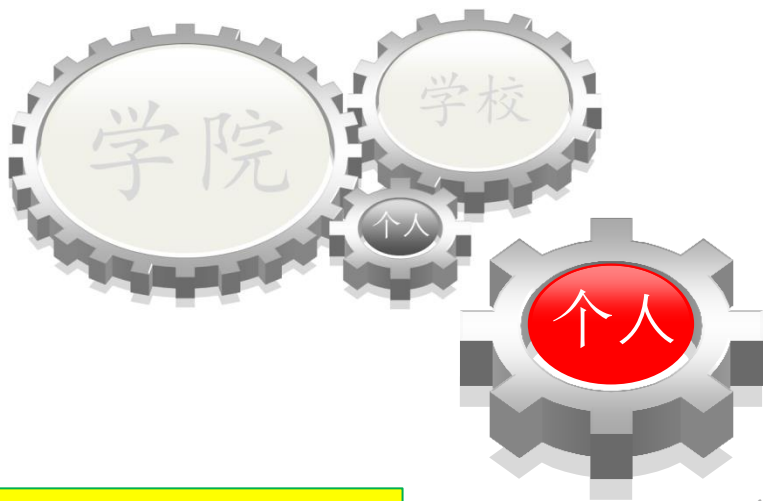


Discussion



- 授课的目的要明确
- 对象的基础要清楚
- 合适的参考教材
- 时代技术在变，允许学生高效
- 不能“求”着学生学

南京大学教师教学发展中心版权所有

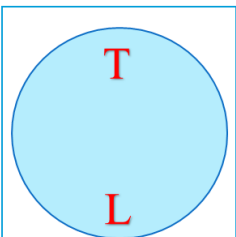


教师

教与学之间到底出了什么问题？

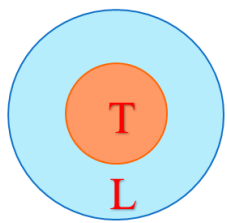
学生

西交大：郝莉 报告



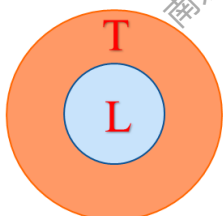
$$T=L$$

名师出高徒



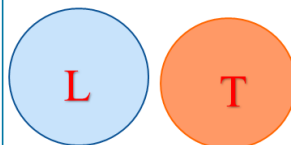
$$T \subset L$$

青出于蓝
而胜于蓝



$$L \subset T$$

言者谆谆，听者藐藐
一代不如一代



$$L \cap T = \emptyset$$

对牛弹琴

● L:学

● T:教

教了=学会了？

-台湾大学王秀槐老师《新生研讨课的带领与规划》



自己懂≠透≠能讲≠能让学生理解

学生悟道，
方是大学课程的真谛

授人以鱼，不如授之以渔，授
人以鱼只救一时之急，授人以渔
则可解一生之需。



I 教师



- 水课、冰课、森课
- 菜市场----低头族----强互动
- 读课----照本宣科、照屏宣科，PPT

浙大：陆国栋 报告



西安交通大学 马知恩
数学教授

怎样讲好一堂课

2015-06-26 马知恩 中国大学教学 中国大学教学

- 一、要有高度的敬业精神
- 二、要认真备课，精心进行教学设计
- 三、要有激情，要对学生有吸引力和感染力
- 四、练好基本功，养成良好的习惯
- 五、通过知识的传授培养学生科学的思维方法和能力
- 六、善于启发诱导，注意师生互动
- 七、注意现代信息化教学技术的应用

- 对教师的授课测评需要认真对待

教师教学发展中心
Center for Teaching and Learning



首页 中心简介 教师培训 教学咨询 教学研究 教学评估 教学资源 区域服务 联系方式 站内搜索

基于慕课的翻转课堂 教学演练与同侪研讨

主讲人：社会学院 陈昌凯博士

时间：3月31日（周四）下午2点

地点：仙林校区邵逸夫楼C50



江苏高校教师教学发展研究会成立会议

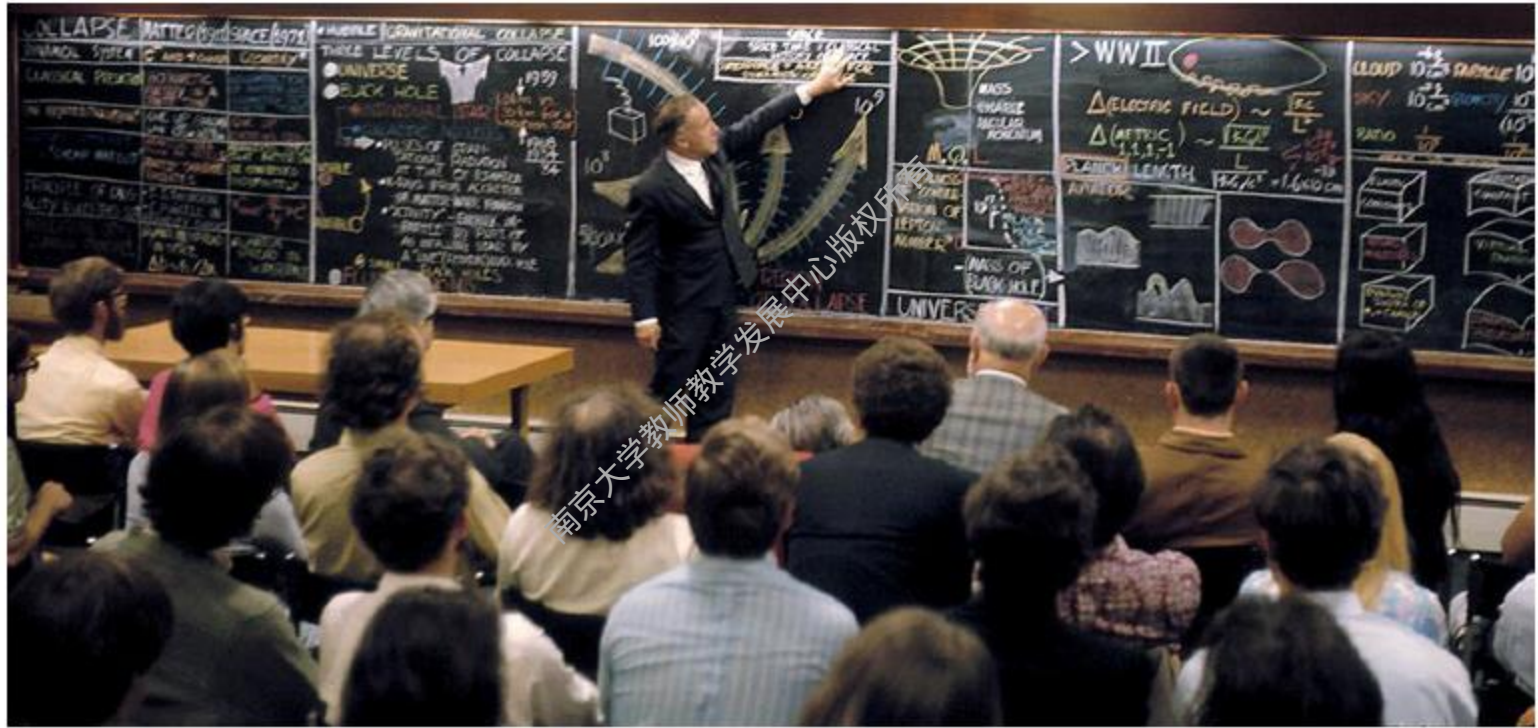


Fig. 26.5. John Wheeler in 1971, lecturing about singularities, black holes, and the universe.



I 教师



MITOPENCOURSEWARE 15 YEARS
 MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Subscribe to the OCW Newsletter

Find Courses | About | Donate | Featured Sites

MITOPENCOURSEWARE 15 YEARS
 MASSACHUSETTS INSTITUTE OF TECHNOLOGY
 Celebrating a new milestone in open education

Learn more

I am contributing to a great project that will help many others improve their lives, materially, intellectually and spiritually.

Carlos Independent Learner Italy

DONATE NOW

麻省理工学院

麻省理工学院 (Massachusetts Institute of Technology, 缩写: MIT) 是一所私立大学, 有“世界理工大学之冠”美誉, 位于麻省剑桥的查尔斯河 (Charles River) 畔, 其麻省理工的“麻省理工”精神, 今天MIT仍然是在美国乃至世界都有非常重要的影响力, 培养了众多对世界产生重大影响的人士, 也是世界理工科最高的所在地。

麻省理工学院公开课: 信息与确
 类型: 物理

麻省理工学院公开课: 单变函数微积分
 类型: 数学

麻省理工公开课: 公共政策学
 类型: 社会管理

麻省理工公开课: 通过摄影感受世界
 类型: 艺术

麻省理工公开课: 媒体
 类型: 社会管理

麻省理工公开课: 创新与发明
 类型: 计算机

麻省理工公开课: 电路和电子学
 类型: 物理

麻省理工学院公开课: 供应链管理专题
 类型: 管理

coursera

一个教育平台

udacity

尝试打破高等教育现状

edx

中国大学MOOC

学堂在线

网络开放课程平台

好大学在线 CNMOOC

首页 Home | 课程 Courses | 院校 Universities

大学物理
 COLLEGE PHYSICS

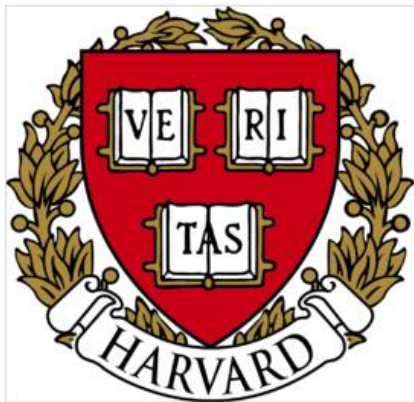
IBM《Water Analytics基础课程》
 主讲人: 胡其国 教授 开罗大学的数据分析

华文慕课
 CHINESE MOOCs



II

学生



校训

拉丁原文: **Amicus Plato, Amicus Aristotle, Sed Magis Amicus VERITAS.**

"要与柏拉图为友, 要与亚里士多德为友, 更要与真理为友"。

哈佛校训是什么

浏览 10460 次

分享 | 2013-12-18 21:53

网友采纳

2013-12-21 13:50

热心网友

1. This moment will nap, you will have a dream; but this moment study, you will interpret a dream.
此刻打盹, 你将做梦; 而此刻学习, 你将圆梦。
2. I leave uncultivated today, was precisely yesterday perishes tomorrow which person of the body implored.
我荒废的今日, 正是昨日殒身之人祈求的明日。
3. Thought is already late, exactly is the earliest time.
觉得为时已晚的时候, 恰恰是最早的时候。
4. Not matter of the today will drag tomorrow.
勿将今日之事拖到明日。
5. Time the study pain is temporary, has not learned the pain is life-long.
学习时的苦痛是暂时的, 未学到的痛苦是终生的。
6. Studies this matter, lacks the time, but is lacks diligently.
学习这件事, 不是缺乏时间, 而是缺乏努力。
7. Perhaps happiness does not arrange the position, but succeeds must arrange the position.
幸福或许不排名次, 但成功必排名次。
8. The study certainly is not the life complete. But, since continually life part of - studies also are unable to conquer, what but also can make?
学习并不是人生的全部。但, 既然连人生的一部分——学习也无法征服, 还能做什么呢?



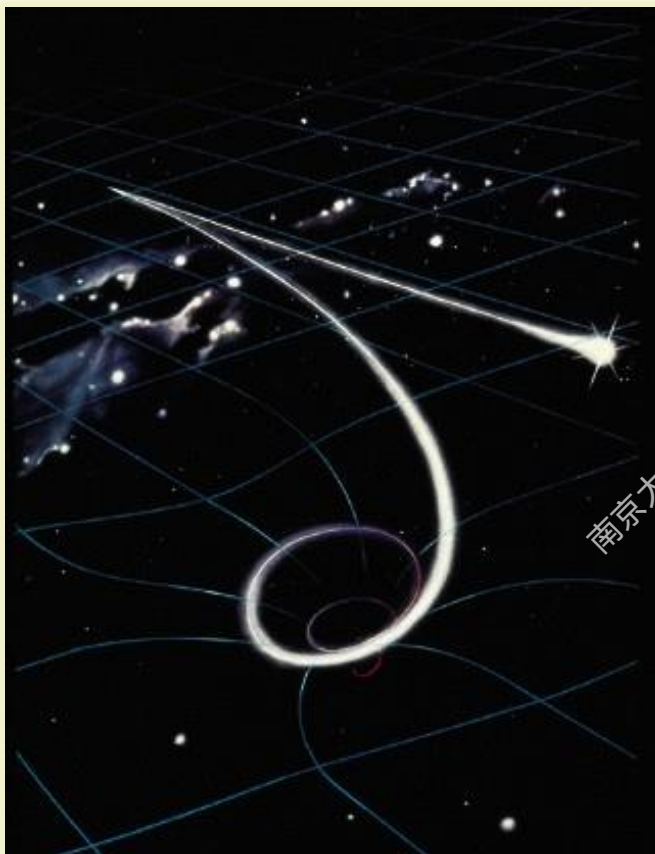
请严肃地告诉孩子: 学习肯定是辛苦的

无限风光在险峰





内容



黑洞—时空中的无限深渊

For **Freshmen**

For **Sophomores**

For **Juniors/Seniors**

Discussion

南京大学教师教学发展中心版权所有

坚守！

谢谢

南京大学教师教学发展中心版权所有

星空依旧灿烂

©Stéphane Guisard
UNAM / INAH