Cosmology and Particle Physics

Rogerio Rosenfeld
IFT-UNESP & ICTP-SAIFR & LIneA

Lecture I: The average Universe
Lecture II: Origins
Lecture III: The perturbed Universe

10th CLASHEP

Few recent references:

Baumann’s lectures:
http://www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf
and 1807.03098

Cline’s lectures:
1807.08749

Bauer and Plehn:
1705.01987

Plan:

I.0 – Introduction and motivation

I.1 – Brief review of GR

I.2 – Dynamics of the Universe

I.3 – Thermal history of the Universe

“Our whole universe was in a hot dense state
Then nearly fourteen billion years ago expansion started”

Shameless advertising

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14. Mar 2019

UPCOMING SCHOOLS AND ACTIVITIES (COMPLETE LIST)

Feb. 04 - Feb. 05	2019 Meeting of Scientific Council and Steering Committee
Feb. 11 - Feb. 15	4th Joint Dutch-Brazil School on Theoretical Physics
Feb. 12	ICTP-SAIFR Distinguished Public Lecture by Juan Maldacena
Feb. 25 - Mar. 01	ICTP-SAIFR/FAIR Workshop on Mass Generation in QCD
Mar. 14	Mecânica Quântica: Características e Descaracterização Papos de Física
Mar. 16 - Apr. 13	MInicurso de eletromagnetismo e relatividade para ensino medio Inscrições até 10 de março
Mar. 30 - Mar. 31	Física Moderna para Professores do Ensino Médio Inscrições até 10 de março de 2019
Apr. 01 - Apr. 05	Minicourse on Quantum Gravity from the QFT perspective Application deadline: March 18, 2019
Apr. 27 - May. 25	Minicurso de mecânica quântica para ensino medio Inscrições até 21 de abril
Jun. 01 - Jul. 06	Minicurso de modelagem matematica para ensino medio Inscrições até 26 de maio
Jul. 01 - Jul. 05	Preparatory School for StatPhys 2019 Application deadline: May 5, 2019
Jul. 06 - Jul. 12	2019 IFT-Perimeter-SAIFR Journeys into Theoretical Physics Application deadline: April 28, 2019
Jul. 11	2019 ICTP-SAIFR Competition for Young Physicists Application deadline: June 30, 2019
Jul. 16 - Jul. 19	Conference on Perspectives in Nonlinear Dynamics Registration deadline: May 5, 2019
Jul. 22 - Aug. 02	III Joint ICTP-Trieste/ICTP-SAIFR School on Observational Cosmology Application deadline: May 12, 2019
Aug. 05 - Aug. 16	School on High Energy Astrophysics Application deadline: May 26, 2019
Aug. 19 - Aug. 24	American Monsoons: progress and future plans Deadline for requesting financial support: April 14, 2019

APPLICATIONS FOR...

- Simons-FAPESP Professor Position in Biological Physics
  Application deadline: November 15, 2018
- FAPESP Postdoctoral Positions
  Application deadline: December 1, 2018
- Science journalism fellowship
  Application deadline: December 10, 2018
- Perimeter-FAPESP Postdoctoral Positions
  Application deadline: December 1, 2018
- Scientific Visits
- Proposals to Organize 2020 Activities
  Submission deadline: December 31, 2018

RECENT NEWS

On February 12, Juan Maldacena (IAS Princeton) presented a lecture for the general public entitled "Black Holes and the Structure of Spacetime". Prof. Maldacena is a member of the ICTP-SAIFR steering committee and his awards include the MacArthur Fellowship (1999), the Dirac Medal (2008), the Fundamental Physics Prize (2012), and the Diamond Konex Award (2013) as the most important Argentinian scientist of the last decade.

ICTP-SAIFR BLOG

Oct. 05, 2018 Um matemático no mundo das vacas esféricas
Sep. 26, 2018 O que sabemos que não sabemos?
Sep. 26, 2018 Estranhezas no mundo do muito


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III JOINT ICTP-TRIESTE/ ICTP-SAIFR SCHOOL ON OBSERVATIONAL COSMOLOGY
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In the last two decades, cosmology has become a data driven science. Several observational probes of the Universe, such as the cosmic microwave background, the large scale distribution of galaxies, the weak gravitational lensing of galaxy shapes, the mapping of supernovas and the number of clusters of galaxies are being studied by different experiments to explore fundamental physics describing the nature of dark matter and dark energy.
This is the third edition of a joint ICTP-Trieste/ICTP-SAIFR two-week Cosmology School, aimed at providing students with the necessary tools for understanding the current issues in modern cosmology and to familiarize them with how recent observations can be used to constrain different cosmological models and parameters.
There is no registration fee and limited funds are available for travel and local expenses.
Application deadline: May 12, 2019
Online application and more information:
www.ictp-saifr.org/cosmos2019
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O que é o LIneA

INCT do e-Universo

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Dark Energy Spectroscopic Instrument

Dark Energy Survey

Large Synoptic Survey Telescope

Large Synoptic Survey Telescope

Sloan Digital Sky Survey

Transneptunian Occultation Network

Transneptunian Occultation Network

I.0- Introduction

Why should a particle physicist learn cosmology?

• main evidences from BSM comes from cosmology: dark matter, dark energy, inflation;

• particle physics affect cosmology: eg origin of matter-anti-matter asymmetry, Higgs as inflaton, neutrinos and the formation of structures, phase transitions;

• cosmology affects particle physics: eg evolution of the Universe may be responsible for electroweak symmetry breaking (relaxion idea).

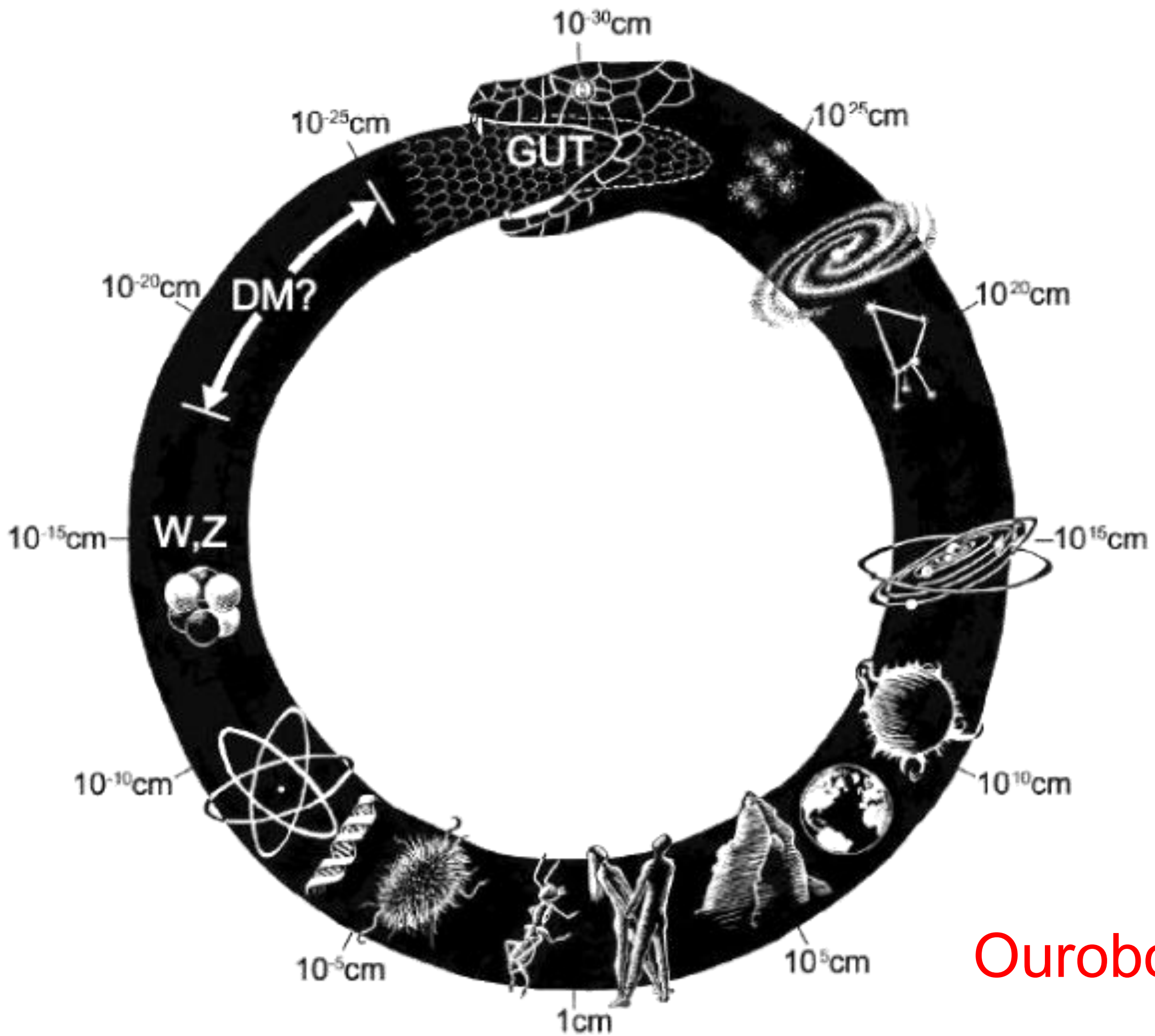
• early Universe is a testbed for SM and BSM: stability or metastability of SM vacuum, new physics tests from CMB, inflation, matter-antimatter asymmetry,...

• gravity (geometry) may play an important role in particle physics: eg models with warped extra dimensions

• new particles from geometry: KK excitations, radion, etc

• models with extra dimensions can change the evolution of the Universe (and hence be tested).

Micro and Macro



Ouroboros symbol

Standard Model of Particle Physics works fine but it is unsatisfactory (neutrino masses, dark matter, hierarchy problem, etc). Beyond SM!

Standard Model of Cosmology (ΛCDM) works fine but it is unsatisfatory (value and nature of Λ). Beyond ΛCDM!

Models abound! We have to see what Nature has chosen...

Cosmology has recently become a data driven science. Era of precision cosmology!

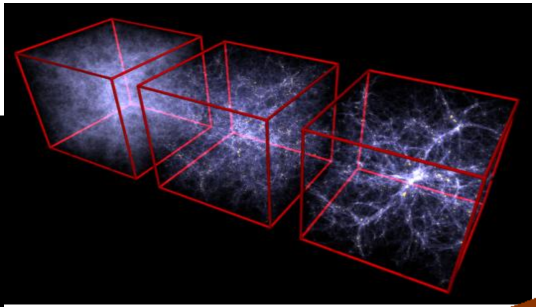
t_U= (13.799±0.021)x10^9 years [used to be $10^{9\pm1}$ years]

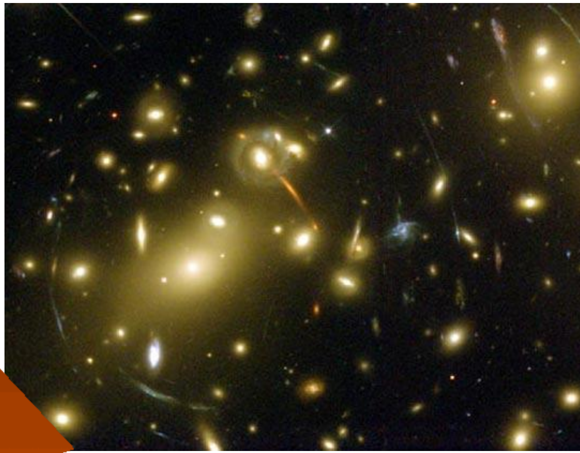
Many experiment are taking a huge amount of data that are being analyzed in order to find out which model best describes the universe.

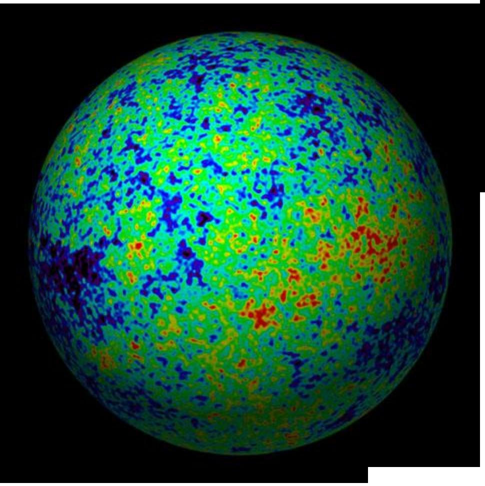
Cosmological probes

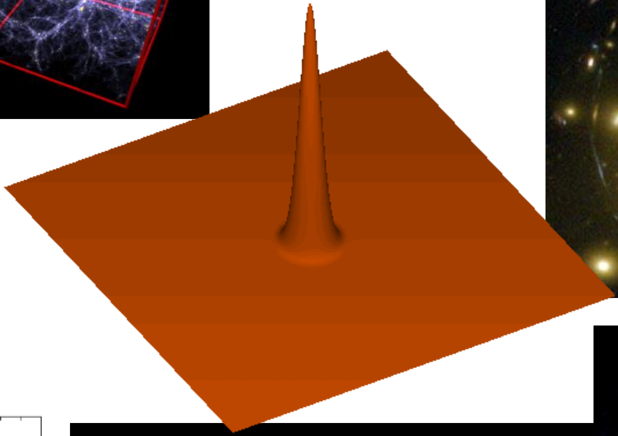
- Cosmic Microwave Background (CMB)
- Big bang nucleosynthesis (BBN)
- Supernovae (type Ia)
- Baryon acoustic oscillation (BAO)
- Gravitational lensing
- Number count of clusters of galaxies

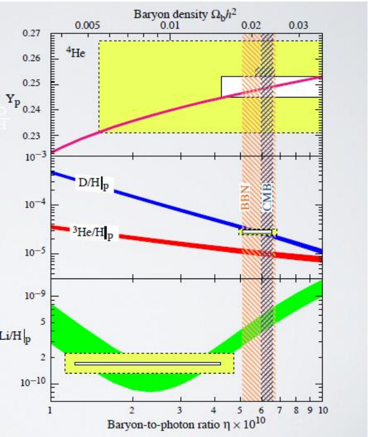
Cosmological probes

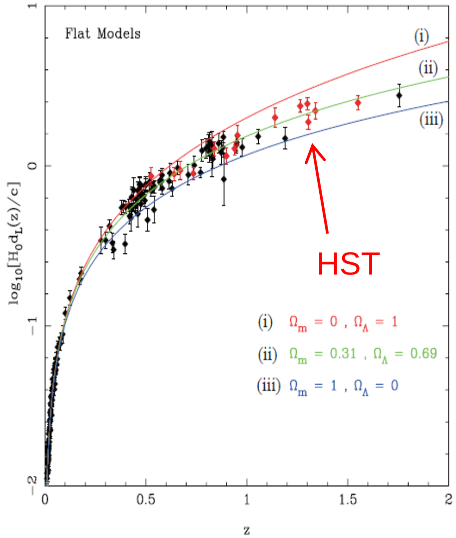


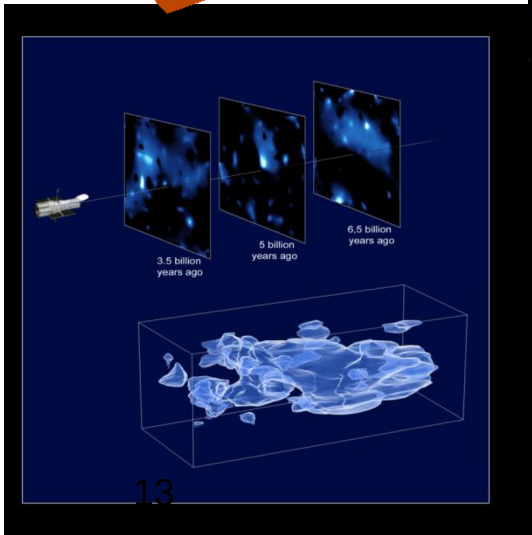


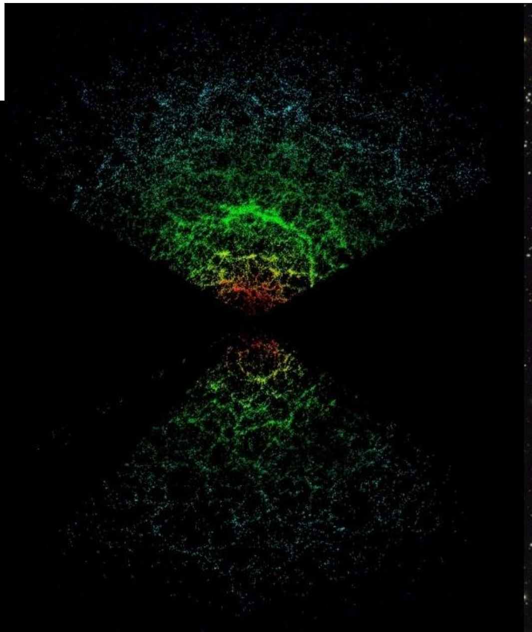












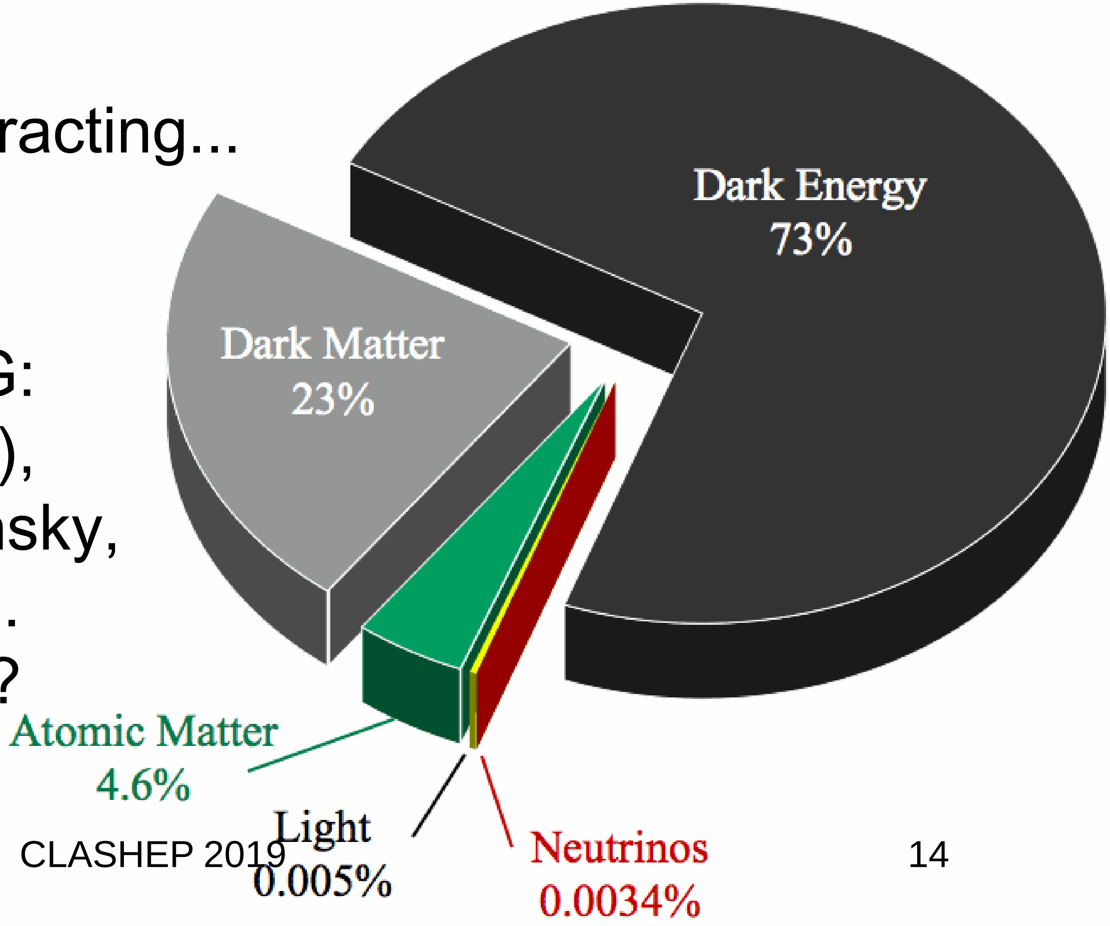
We know that we don't know what 95% of the Universe is made of:

What is dark matter?

Cold, warm, fuzzy, self-interacting...

What is dark energy?

New degree of freedom/MG:
Quintessence, galileon, f(R), Hordensky, beyond Hordensky, massive gravity, EFTofDE...
Does it interact with matter?
Does it cluster?



I.1- Brief Review of GR

General Relativity rules the Universe at large scales!
Classical description is sufficient in most cases.

I.1.0 – Classical field theory in a nutshell

$$\underbrace{\text{Fields}}_{\substack{\text{Fundamental degrees}\\ \text{of freedom}\\ \text{(not always physical)}}} \longrightarrow \underbrace{\text{lagrangian} \longrightarrow \text{action}}_{\substack{\text{Dynamics}\\ \text{(use of symmetries)}}} \longrightarrow \underbrace{\text{equations of motion}}_{\delta S = 0}$$

I.1.1 – Einstein's equation

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

10 nonlinear differential equations. In general it must be solved numerically, eg gravitational waves from coalescence of binary black holes.

Fundamental field of gravity: metric

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

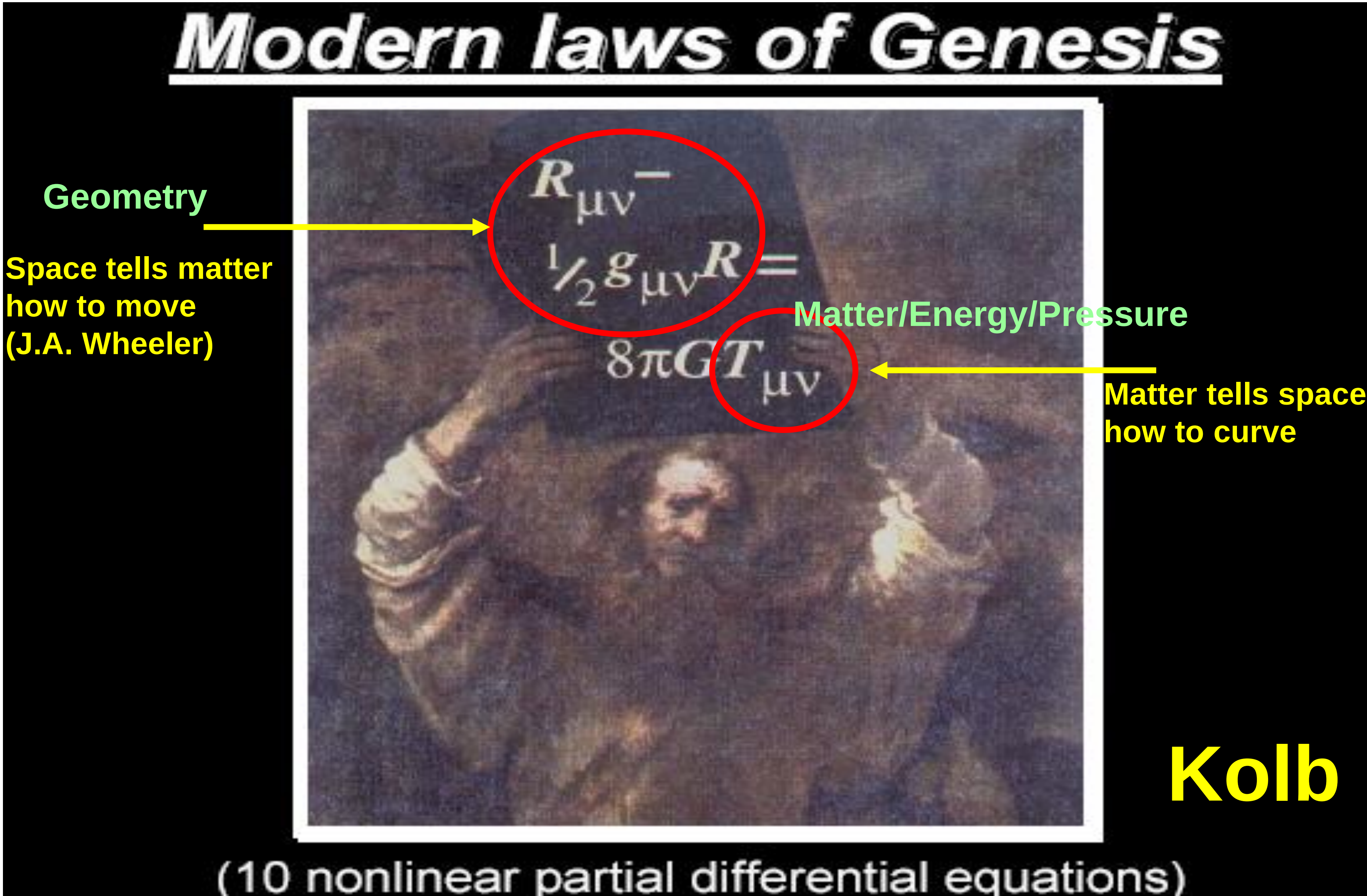
$$g_{\mu\alpha} g^{\alpha\nu} = \delta_\mu^\nu$$
$$g_{\mu\nu} g^{\mu\nu} = 4$$

Flat space-time – Minkwoski metric

$$p_\mu p^\mu = E^2 - (\vec{p})^2$$

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

Standard Cosmological Model



Details of Einstein's equation:

- G: Newton's constant

$$G = \frac{1}{M_{\rm Pl}^2} \quad (\hbar = c = 1)$$

$$M_{\rm Pl} = 1.2 \times 10^{19}\ {\rm GeV}$$

Obs.: sometimes the *reduced* Planck mass is used:

$$\tilde{M}_{\rm Pl} = \frac{M_{\rm Pl}}{\sqrt{8\pi}} = 2.4 \times 10^{18}\ {\rm GeV}$$

Details of Einstein's equation:

• Christoffel symbols (aka metric conection, affine connection) – first derivative of the metric :

$$\Gamma^{\mu}_{\alpha\beta} = \frac{1}{2} g^{\mu\nu} \left\{ \frac{\partial g_{\alpha\nu}}{\partial x^{\beta}} + \frac{\partial g_{\beta\nu}}{\partial x^{\alpha}} - \frac{\partial g_{\alpha\beta}}{\partial x^{\nu}} \right\}$$

• Ricci tensor – second derivative of the metric:

$$R_{\mu\nu} = \frac{\partial}{\partial x^{\alpha}} \Gamma^{\alpha}_{\mu\nu} - \frac{\partial}{\partial x^{\nu}} \Gamma^{\alpha}_{\alpha\mu} + \Gamma^{\alpha}_{\mu\nu} \Gamma^{\beta}_{\alpha\beta} - \Gamma^{\beta}_{\alpha\mu} \Gamma^{\alpha}_{\beta\nu}$$

• Ricci scalar: $R = g^{\mu\nu} R_{\mu\nu}$

19

I.1.2 – Einstein-Hilbert action

$$S_{\mathrm{E-H}}[g_{\mu\nu}] = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,R[g_{\mu\nu}]$$

For the Hilbert-Einstein dispute see:
L. Corry, J. Renn, and J. Stachel, Science 278, 1270 (1997)
F. Winterberg, Z. Naturforsch. **59a,** 715 – 719 (2004)

- Action is invariant under general coordinate transformations:

$$x^\mu \to x'^\mu(x^\mu)$$

- $g = \det(g_{\mu\nu})$

- Dimensional analysis: $(\hbar = c = 1)$

$$[g]:\ \text{dimensionless};\quad [R]:\ E^2$$
$$[d^4x]:E^{-4};\quad [S]:\ \text{dimensionless}$$
$$\Rightarrow \boxed{[G]:E^{-2}}$$
$$G = \frac{1}{M_{\rm Pl}^2}$$

- Einstein equation in vacuum ($T_{\mu\nu}$ = 0) obtained from:

$$\frac{\delta S_{\rm E-H}}{\delta g_{\mu\nu}} = 0$$

I.1.3 – The cosmological constant

February 1917 (~100 years ago): “Cosmological Considerations in the General Theory of Relativity” introduces the cosmological constant in the theory without violating symmetries:
a new constant of Nature!

It has an “anti-gravity” effect (repulsive force) and it was introduced to stabilize the Universe.

$$S_{\mathrm{E-H}} + S_{\Lambda} = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} - \Lambda \right)$$

With the discovery of the expansion of the Universe (Hubble, 1929) it was no longer needed – “my biggest blunder”.

43. "Cosmological Considerations in the General Theory of Relativity"

[*Einstein 1917b*]

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Submitted 8 February 1917
Published 15 February 1917

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \qquad (1)$$

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newtonsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unend-

In: *Königliche Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1917): 142–152.

§ 4. On an Additional Term for the Field Equations of Gravitation

Poisson's equation given by equation (2). For on the left-hand side of field equation (13) we may add the fundamental tensor $g_{\mu\nu}$, multiplied by a universal constant, $-\lambda$, at present unknown, without destroying the general covariance. In place of field equation (13) we write

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T\right) \qquad (13a)$$

George Gamow – My Worldline

correct, and changing it was a mistake. Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life. But this "blunder," rejected by Einstein, is still sometimes used by cosmologists even today, and the cosmological constant denoted by the Greek letter Λ rears its ugly head again and again and again.

I.1.4 – Modified gravity

Modified gravity is anything different from E-H (+ Λ) action (see 1601.06133)

Example: f(R) theories (see 1002.4928)

$$S[g_{\mu\nu}] = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\, f(R)$$

$$f(R) = a_0 + a_1 R + a_2 R^2 + \cdots + \frac{\alpha_1}{R} + \frac{\alpha_2}{R^2} + \cdots$$

cosmological constant

GR

Higher order derivatives

Issues with modified gravity:

• introduces new light degrees of freedom – new forces
Since there are stringent constraints one has to invoke “screening mechanisms” – chameleon, symmetron, Vainshtein, ...

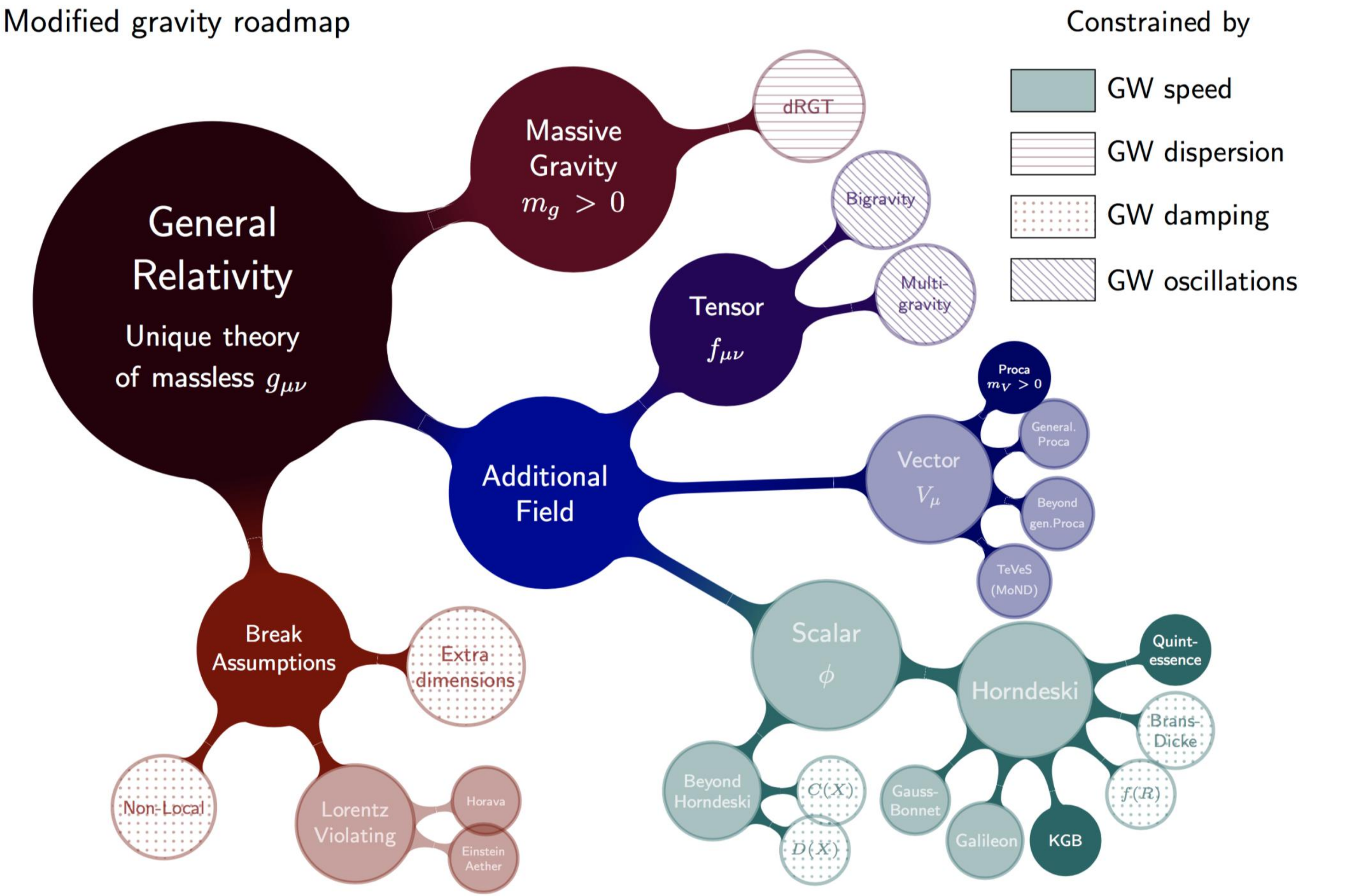
• may have classical instabilities due to higher derivatives in equations of motion (Ostrogradski instabilities)

• may have quantum instabilities – “ghosts”

• may be brought in the form of GR with a suitable change of coordinates (Jordan frame -> Einstein frame) introducing non-standard couplings in the matter sector

• search for MG: use simple parametrizations (more later)

Ezquiaga and Zumalacárregui - 1807.09241

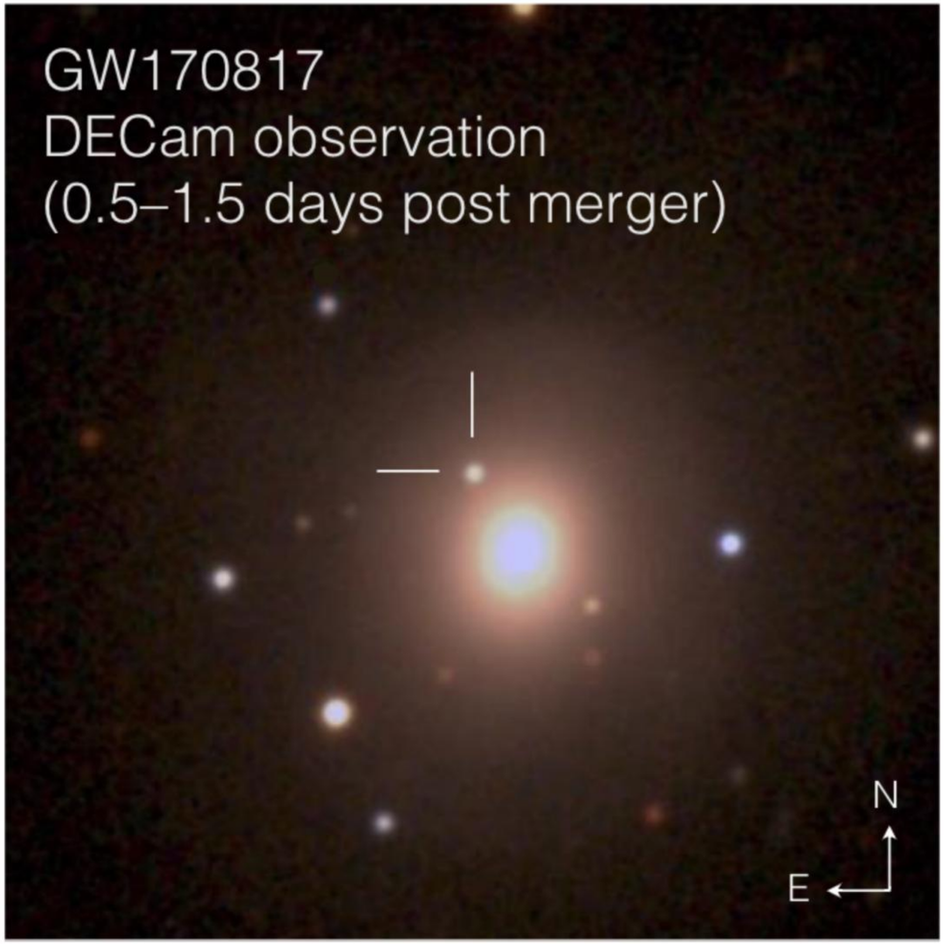


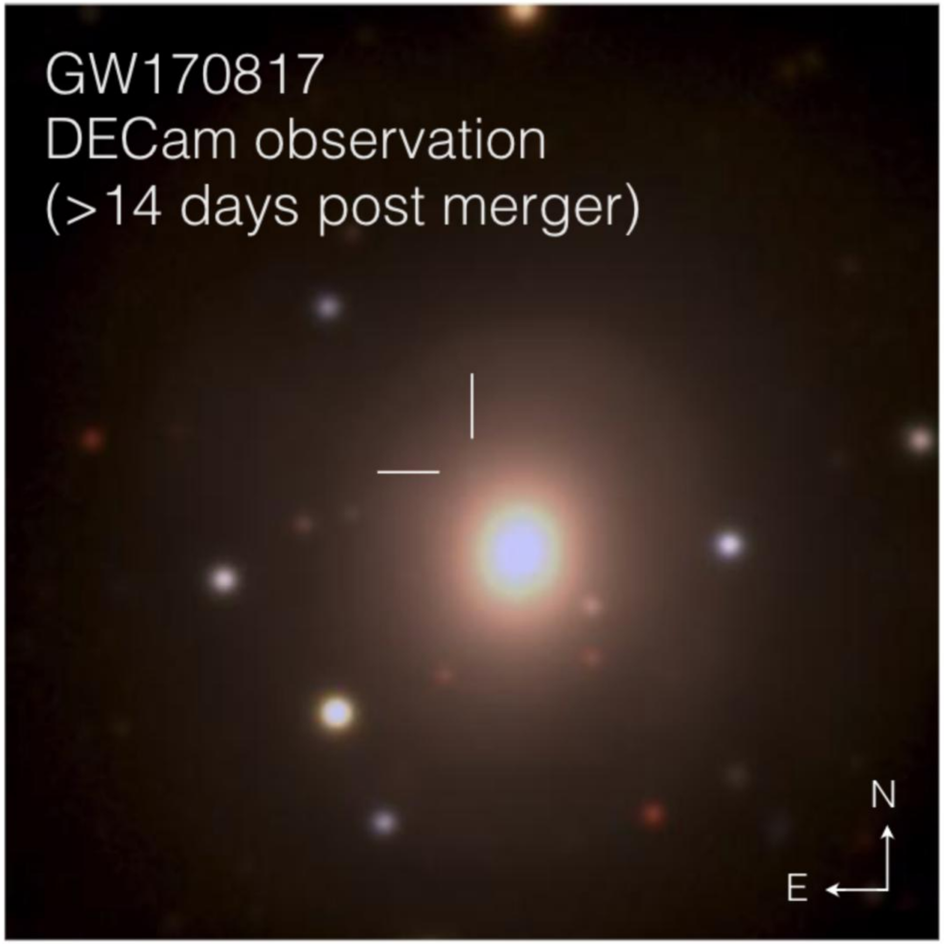
Some modified gravity theories predict that

$$\frac{\Delta c}{c} = \frac{c_g - c}{c} = \mathcal{O}(1)$$

In 2017 GW170817 was detected by LIGO and Virgo: the first detection of a merger of 2 neutron stars at a mere 130 million light-years from Earth.

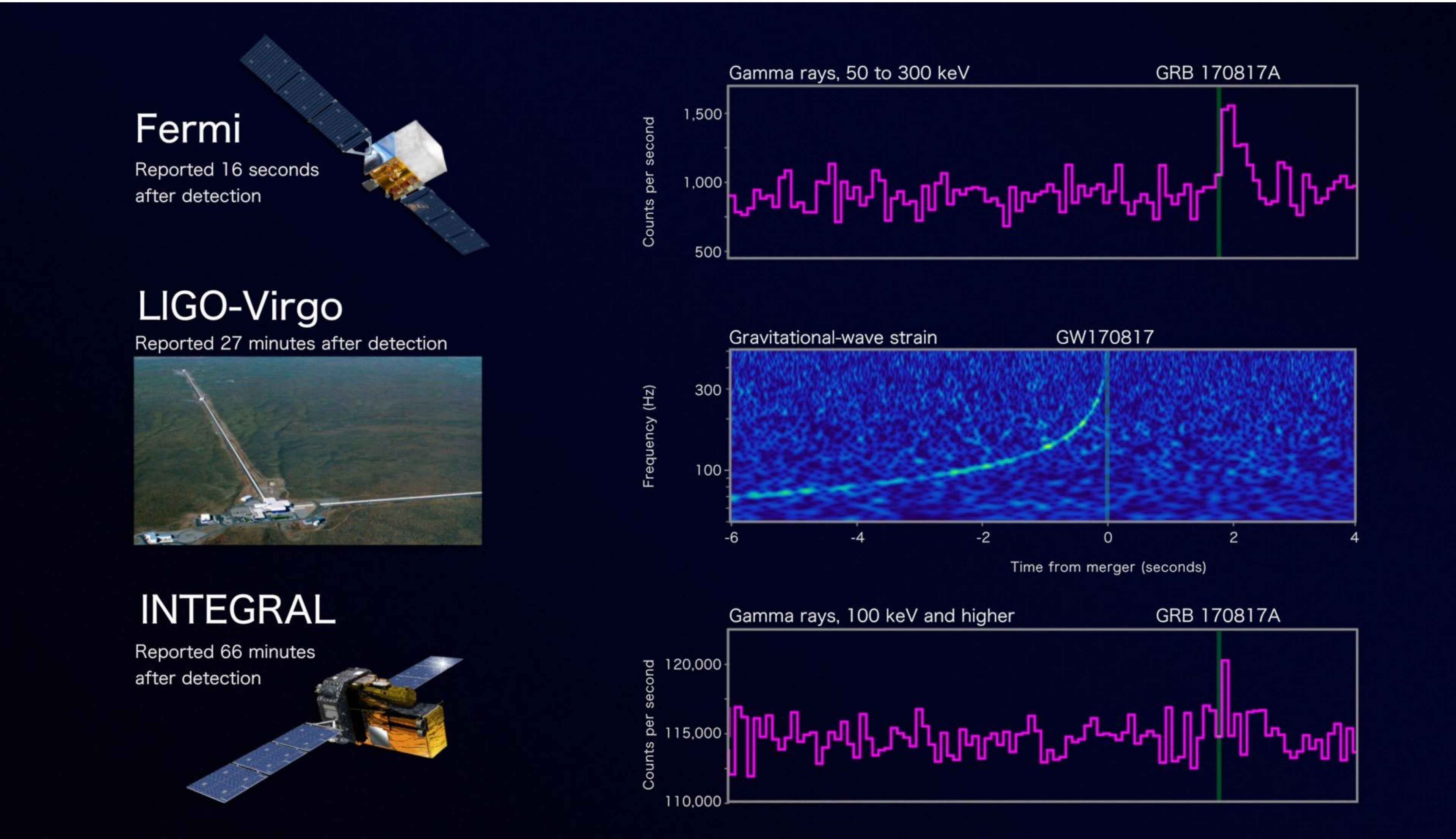
As opposed to black hole mergers, it also emitted light!!


GW170817
DECam observation
(0.5–1.5 days post merger)
N
E


GW170817
DECam observation
(>14 days post merger)
N
E

Also seen in gamma rays by Fermi and Integral with less than 2 seconds difference!!

Exercise 0: From this data estimate a bound on $\dfrac{\Delta c}{c} = \dfrac{c_g - c}{c}$



I.1.5 – Adding matter to the action

$$S_{\mathrm{matter}} = \int d^4x \sqrt{-g}\, \mathcal{L}_{\mathrm{matter}}$$

Examples:

Electromagnetism: $$S_{\mathrm{EM}} = -\frac{1}{4} \int d^4x \sqrt{-g}\, g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta}$$

Real scalar field: $$S_\phi = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi - V(\phi) \right]$$

I.1.6 – Energy-momentum tensor

Definition:

$$\delta S_{\mathrm{matter}} = \frac{1}{2}\int d^4x\sqrt{-g}\, T^{\mu\nu}(x)\delta g_{\mu\nu}$$

which implies

$$T^{\mu\nu}(x) = \frac{2}{\sqrt{-g}}\frac{\delta S_{\mathrm{matter}}}{\delta g_{\mu\nu}}$$

Exercise 1: Show that for a real scalar field

$$T_\phi^{\mu\nu} = \partial^\mu \phi \partial^\nu \phi - \mathcal{L}_\phi g^{\mu\nu}$$

Exercise 2: Show that for a cosmological constant

$$T_\Lambda^{\mu\nu} = \Lambda g^{\mu\nu}$$

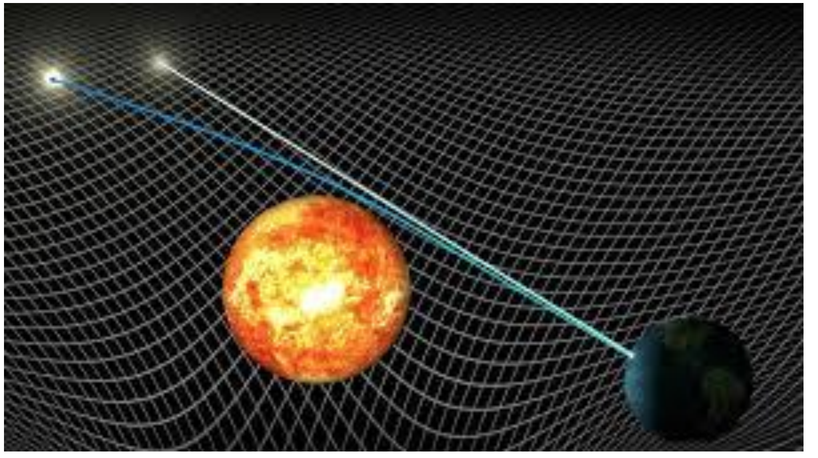
Finally, Einstein equation for GR is obtained from the requirement:

$$\delta\left(S_{\mathrm{total}}\right) = \delta\left(S_{\mathrm{E-H}} + S_{\Lambda} + S_{\mathrm{matter}}\right) = 0$$

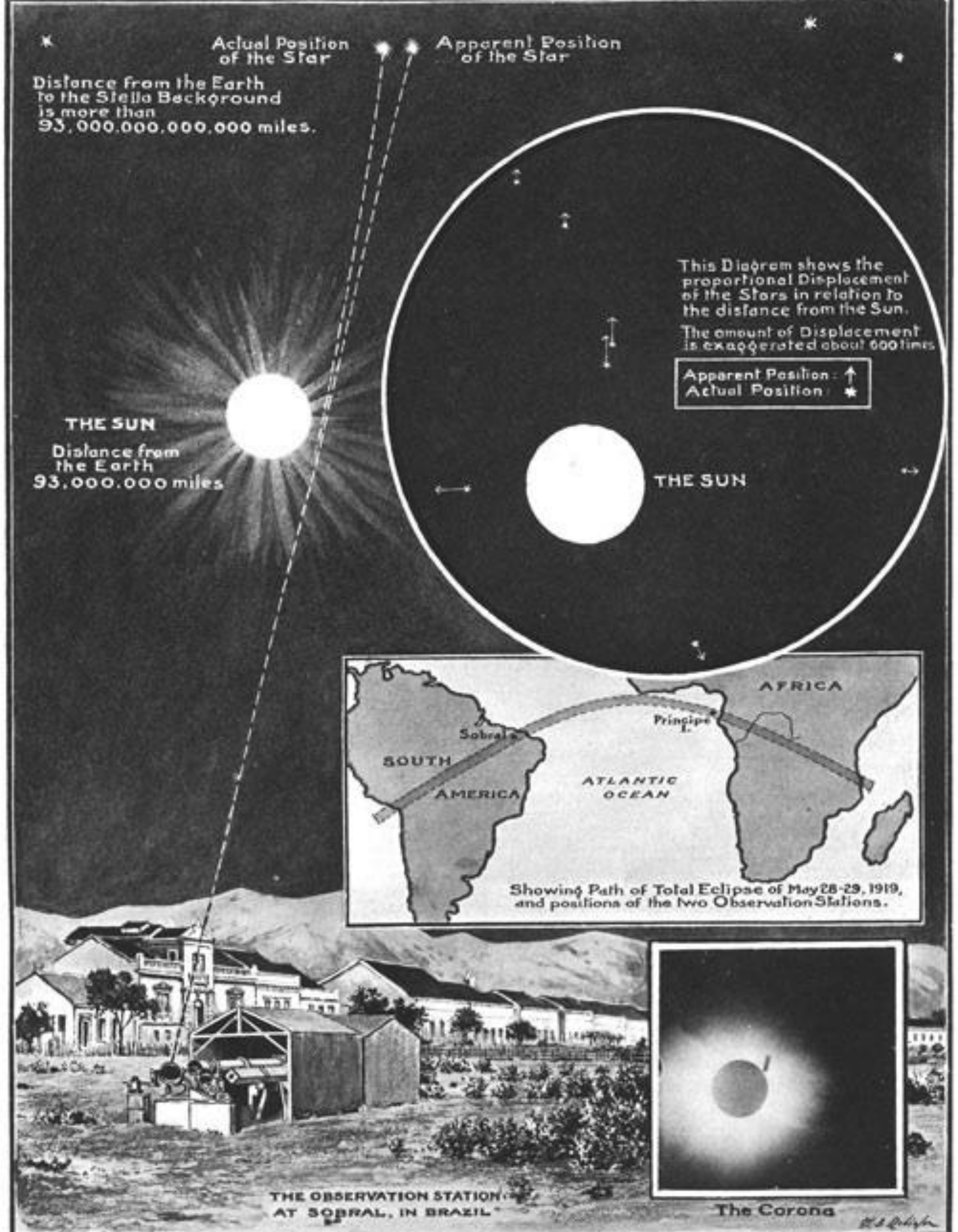
Historical interlude

100 years of the eclipse that confirmed GR

First test of GR: the solar eclipse in May 29, 1919



Two expeditions organized by the Royal Society:
Principe Island in Africa (Eddington)
Sobral in Brazil (Crommelin)



Actual Position of the Star
Apparent Position of the Star
Distance from the Earth to the Stella Background is more than 93,000,000,000,000 miles.
THE SUN
Distance from the Earth 93,000,000 miles
This Diagram shows the proportional Displacement of the Stars in relation to the distance from the Sun.
The amount of Displacement is exaggerated about 600 times
Apparent Position :
Actual Position :
THE SUN
AFRICA
Principe I.
Sobral
SOUTH AMERICA
ATLANTIC OCEAN
Showing Path of Total Eclipse of May 28-29, 1919, and positions of the two Observation Stations.
THE OBSERVATION STATION AT SOBRAL, IN BRAZIL
The Corona

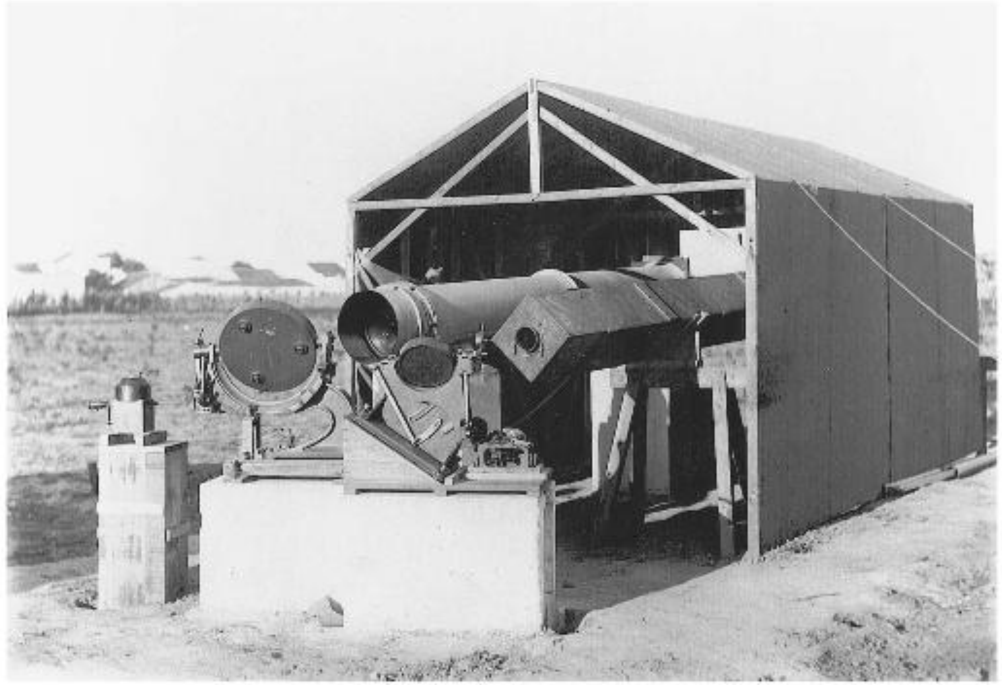
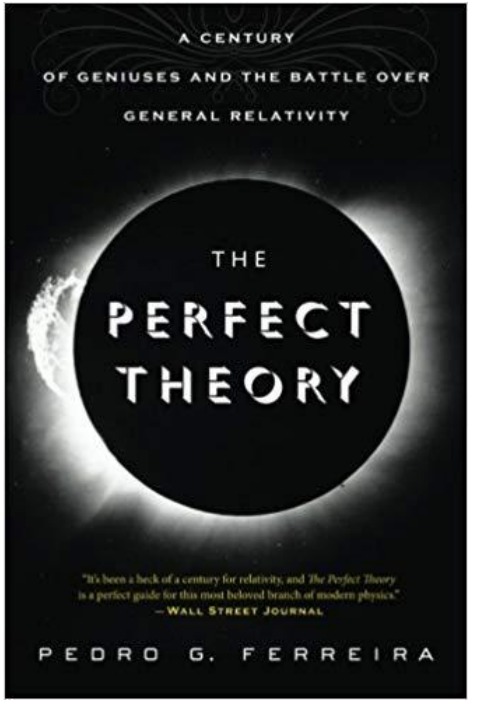


Figure 1. *The eclipse observation equipment at Sobral. The troublesome coelostats can be seen in the foreground. Copyright Science Museum/Science and Society Picture Library. Inventory no. 1922-0277.*

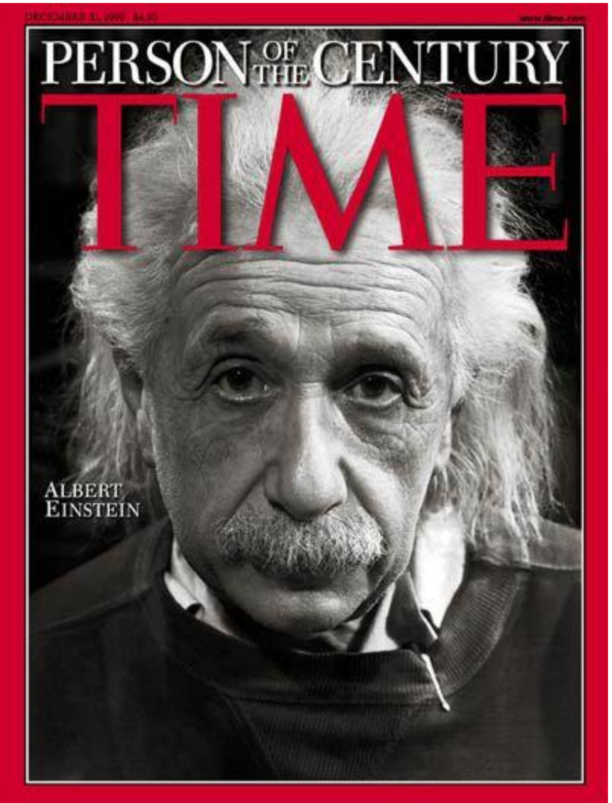
Equipes brasileira e inglesa em Sobral, entre outras pessoas. Henrique Morize é o quarto, em pé, da esquerda para a direita. Os astrônomos ingleses estão sentados: A.C.D. Crommelin é o quarto da esquerda para a direita; C.R. Davidson é o quinto (Observatório Nacional/ MCT).

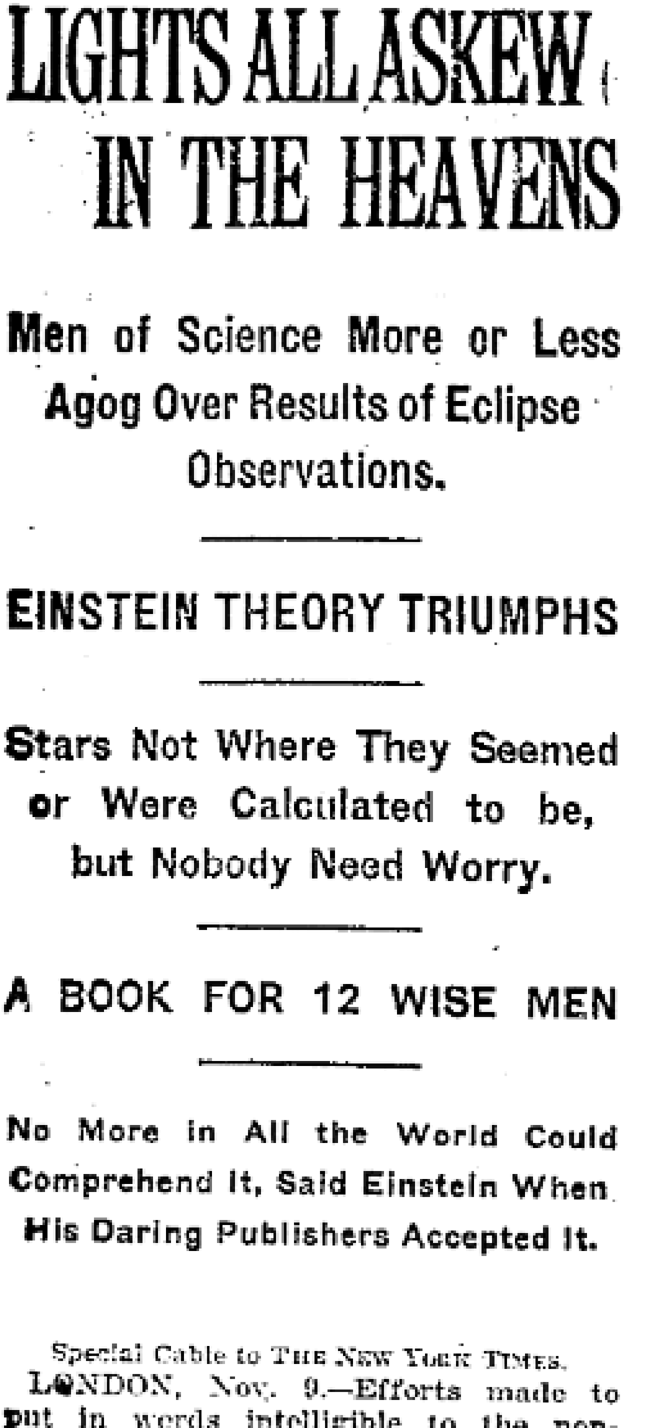
The astronomers were unable to return home quickly, and it was only in late July that the various photographic plates began to be analyzed. Of the sixteen plates that Eddington had recorded, only two had enough stars to measure the deflection properly. The value they got was 1.61 arcseconds with an error of 0.3 arcseconds, consistent with Einstein's prediction of 1.7 arcseconds. When the plates from Sobral were analyzed, the results were worrying. The value measured was 0.93 arcseconds, far from the relativistic prediction and very close to the Newtonian prediction, but these were the same plates that had been deformed by the heat. When the backup observations from Sobral, undertaken on the smaller telescope, were analyzed, the deflection came out at 1.98 arcseconds with a very small error of 0.12 arcseconds. Einstein's prediction, again.

See also Clifford Will, 1409.7812



"After a careful study of the plates I am prepared to say that there can be no doubt that they confirm Einstein's prediction. A very definite result has been obtained that light is deflected in accordance with Einstein's law of gravitation." 06/11/1919





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.

Special Cable to THE NEW YORK TIMES.

LONDON, Nov. 9.—Efforts made to put in words intelligible to the non-

Einstein visit to South America – March 21 – May 12 1925

Einstein left Hamburg on March 5 aboard the ship Cap Polonio. The ship arrived in Rio de Janeiro on March 21, and Einstein was received by a special commission, composed by scientists, journalists and members of the Jewish community. He stayed one day in the city, during a technical stop of the ship. He reached Buenos Aires on March 24, after a stay of a few hours in Uruguay.[19] In Buenos Aires, Einstein had an exhaustive agenda. He took part in receptions organized by scientists, the Jewish community and the German Ambassador. He was received by the President and State Ministers and visited a newspaper office and Jewish institutions. He gave eight conferences at the Faculty of Exact, Physical and Natural Sciences, a speech on "Positivism and Idealism: the geometry and the finite and infinite space of the General Theory" at the Philosophy and Literature Faculty, and a conference entitled "Some thoughts on the Jews situation" at the Hebrew Association.

Einstein traveled also to La Plata and Córdoba, and attended conferences in both places. He had a reception at the National Academy of Exact Sciences where he answered several questions on relativity and quantum physics.[20] But, generally, his scientific activity in Argentina was restricted to the diffusion and explanation of the relativistic ideas. Einstein left Argentina on April 24 and reached Montevideo on the same day. He had three conferences at the Engineering Faculty of the University and, as in Argentina, took part in many receptions and visited the President of the country and State Ministers. He stayed a week in Montevideo, and left on May 1, headed for Rio de Janeiro.

https://www.researchgate.net/publication/27271119_Einstein_in_Brazil_The_communication_to_the_Brazilian_Academy_of_Science_on_the_constituti

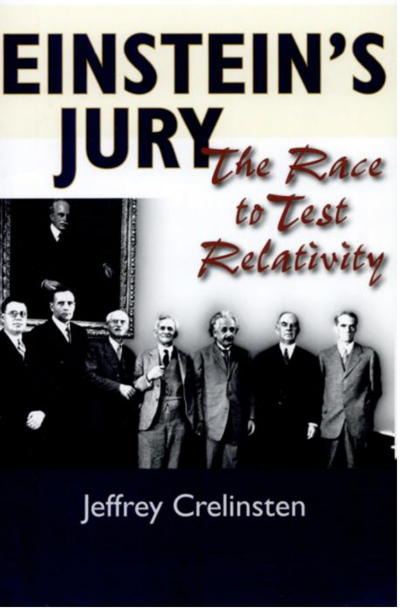
When Einstein visited Brazil in 1925, he declared to the local newspapers: "The idea that my mind conceived was proven in the sunny sky of Brazil."

Freundlich wrote Einstein that same night, offering to help develop ways to look for light bending near the Sun or the planet Jupiter. Back in Prague, Pollak told Einstein about the young Berlin astronomer, and Einstein gave him permission to send Freundlich proofs of his article. "Prof. Einstein has given me strict orders," wrote Pollak, "to inform you that he himself very much doubts that the experiments could be done successfully with anything except the Sun." He urged Freundlich "to send further reports to me, or perhaps to Prof. Einstein, about your views on an astronomical verification."[18]

Early attempt to test GR in 1912

As luck would have it, a visitor to the Berlin Observatory in November of that year opened for Freundlich another avenue of research on the problem. Charles Dillon Perrine, who had successfully resolved the "Vulcan problem" while at Lick Observatory, had left Lick in 1909 to become director of the Southern Hemisphere observatory in Cordoba. When Freundlich told him about Einstein's light-bending prediction, Perrine suggested that he write to various astronomers who might have old eclipse plates on which star images might be measured for deflection. Naturally, he mentioned the Lick Vulcan plates. Freundlich immediately drafted a circular letter, which he sent to several observatories, including Lick, asking for "support of astronomers, who possess eclipse-plates" to test Einstein's predicted light deflection by the Sun.[21]

In view of the likely unsuitability of the Vulcan plates for the task at hand, Campbell offered to lend the Vulcan cameras to Perrine to try Freundlich's problem at the eclipse in Brazil on October 9–10, 1912.



Perrine agreed to enlarge his eclipse program to include Freundlich's investigation and to take the photographs himself. Campbell sent the lenses down via the astronomer William Joseph Hussey. Perrine left Bue-

nos Aires on September 13, 1912, and the eclipse took place on October 10. A few days later Campbell received a telegram from Edward C. Pickering of Harvard, the communication center for American astronomy: "Perrine cables from Brazil, rain."[31]

End of historical interlude

I.2- Dynamics of the Universe

I.2.1 – Friedmann-Lemaître-Robertson-Walker

Universe is spatially homogeneous and isotropic on average.

It is described by the FLRW metric (for a spatially flat universe):

$$ds^2 = dt^2 - a(t)^2 \left[dx^2 + dy^2 + dz^2 \right]$$

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -a^2 & 0 & 0 \\ 0 & 0 & -a^2 & 0 \\ 0 & 0 & 0 & -a^2 \end{pmatrix}$$

FLRW metric is determined by one time-dependent function:
the so-called scale factor a(t).
Distances in the universe are set by the scale factor.

Scale factor is the key function to study how the average universe evolves with time.

convention: a=1 today
physical distances: $d(t) = a(t)\, d_0$

Average evolution of the universe

- specified by one function: scale factor a(t)
- determines measurement of large scale distances, velocities and acceleration

$$a(t) \qquad \dot{a}(t) \qquad \ddot{a}(t)$$

- measured through standard candles (SNIa's) and standard rulers (position of CMB peak, BAO peak,...)

Redshift z: $$a(t) = \frac{1}{1+z}$$ z=0 today.

Expansion of the universe

Hubble parameter:

Expansion rate of the universe

$$H = \frac{\dot{a}(t)}{a(t)}$$

Hubble constant: Hubble parameter today (H_0)

Analogy of the expansion of the universe with a balloon:

Space itself expands and galaxies get a free “ride”.

Exercise 3: Show that for a spatially flat FLRW metric the Ricci tensor and the Ricci scalar are given by:

$$R_{00} = -3\frac{\ddot{a}}{a}; \;\; R_{ii} = a\ddot{a} + 2a^2;$$

$$R = -6\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2}\right)$$

I.2.2 – The right-hand side of Einstein equation: the energy-momentum tensor simplified

It is usually assumed that one can describe the components of the Universe as “perfect fluids”: at every point in the medium there is a locally inertial frame (rest frame) in which the fluid is homogeneous and isotropic (consistent with FLRW metric):

$$T^{00} = \rho(t); \; T^{ij} = \delta^{ij} P(t); \; T^{0i} = 0$$

density pressure isotropy

Homegeneity: density and pressure depend only on time.

Energy-momentum in the rest frame (indices are important):

$$T^{\mu}_{\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -P & 0 & 0 \\ 0 & 0 & -P & 0 \\ 0 & 0 & 0 & -P \end{pmatrix}$$

In a frame with a given 4-velocity:

$$T^{\mu\nu} = -Pg^{\mu\nu} + (\rho + P)u^{\mu}u^{\nu}$$

$$u^{\mu} = \gamma\,(1, \vec{v})$$

[Imperfect fluids: anisotropic stress, dissipation, etc.]

I.2.3 – Solving Einstein equation for the average Universe: Friedmann's equations

00 component:

$$R_{00} - \frac{1}{2} g_{00} R = 8\pi G T_{00} \implies$$

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho}$$

1st Friedmann equation

ii component:

$$R_{ii} - \frac{1}{2} g_{ii} R = 8\pi G T_{ii} \implies$$

$$\left(\frac{\dot{a}}{a}\right)^2 + 2\frac{\ddot{a}}{a} = -8\pi G P \implies$$

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)}$$

2nd Friedmann equation

I.2.4 – Evolution of different fluids

Exercise 4: Take a time derivative of 1st Friedmann equation to derive the “continuity”equation :

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = 0$$

Also follows from the conservation of the energy-momentum tensor and also from the 1st law of thermodynamics:

$$dU = -PdV,\ U = \rho V,\ V \propto a^{-3}$$

In order to study the evolution of a fluid we need to postulate a relation between density and pressure: the equation of state

Assume a simple relation:

$$P = \omega \rho$$

ω is called the equation of state parameter.

Examples:

- Non-relativistic matter (dust): $P \ll \rho \longrightarrow \omega = 0$
- Relativistic matter (radiation): $\omega = 1/3$

- Cosmological constant: $\omega = -1$

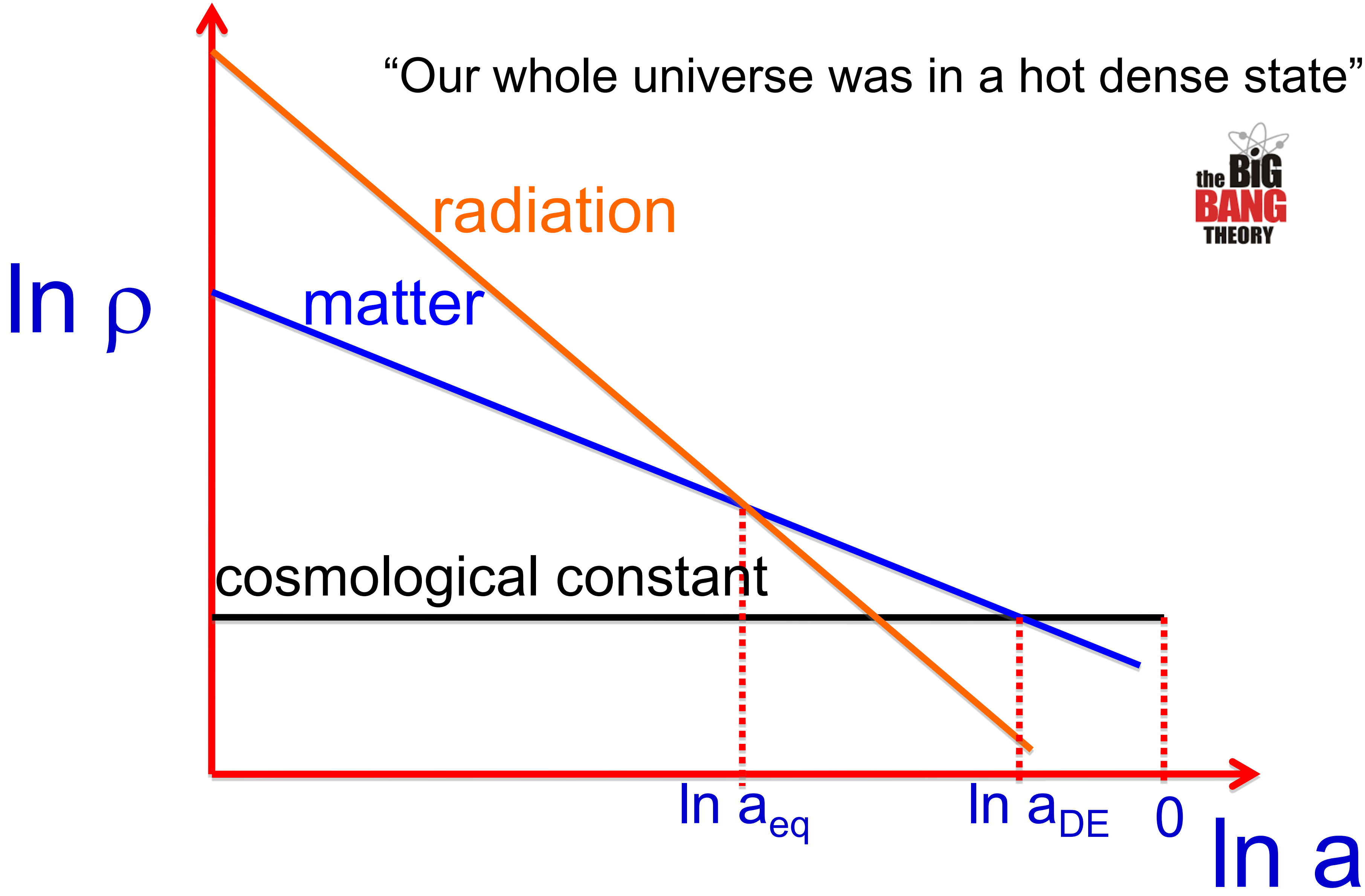
$$T^{\mu}_{\nu,\Lambda} = \begin{pmatrix} \Lambda & 0 & 0 & 0 \\ 0 & \Lambda & 0 & 0 \\ 0 & 0 & \Lambda & 0 \\ 0 & 0 & 0 & \Lambda \end{pmatrix} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -P & 0 & 0 \\ 0 & 0 & -P & 0 \\ 0 & 0 & 0 & -P \end{pmatrix}$$

Exercise 5: From the continuity equation show that the evolution of the density for a constant equation of state is:

$$\rho(t) = \rho(t_i) \left(\frac{a(t)}{a(t_i)} \right)^{-3(1+\omega)}$$

- Non-relativistic matter (dust): $\rho \propto a^{-3}$
- Relativistic matter (radiation): $\rho \propto a^{-4}$
- Cosmological constant: $\rho \propto a^{0}$

“Our whole universe was in a hot dense state”



I.2.5 – Evolution of the scale factor

Exercise 6: Using 1st Friedmann equation and the result from last section:

$$\frac{\dot{a}}{a} \propto \sqrt{\rho}, \;\; \rho \propto a^{-3(1+\omega)}$$

show that:

$$a(t) \propto t^{\frac{2}{3(1+\omega)}} = \begin{cases} t^{2/3} \; (\mathrm{matter}) \\ t^{1/2} \; (\mathrm{radiation}) \end{cases}$$

but for the cosmological constant one has an **exponential growth**:

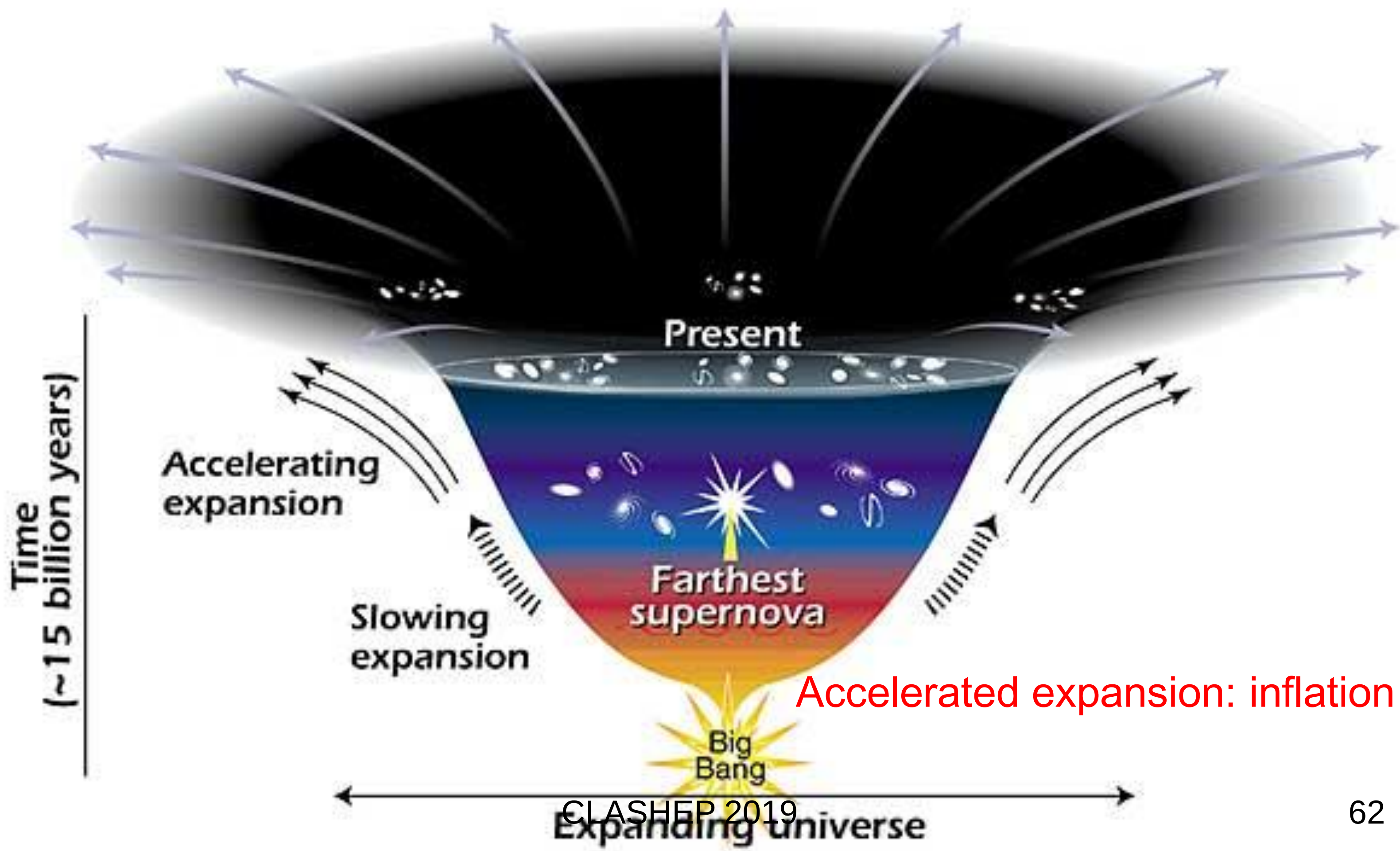
$$\frac{\dot{a}}{a} = \mathrm{const.} = H \rightarrow a(t) \propto e^{Ht}$$

Exponential growth: universe is accelerating!

2nd Friedmann equation is (for w=-1):

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) = \frac{8\pi G}{3}\rho > 0$$

The Universe started to accelerate a couple of billion years ago. Before that there was a period of normal decelerated expansion, essential for the formation of galaxies.



Accelerated expansion: inflation

Curiosity: what happens if w<-1 (“phantom” dark energy)?

$$\omega = -1 - \delta \to \rho_{\text{phantom}} \propto a^{-3(1+\omega)} = a^{3\delta}$$

Density increases with time. It can be shown that there is a singularity where $a \to \infty$ at finite time: the “big rip” [see astro-ph/0302506]

I.2.6 – Recipe of the Universe

Critical density: density at which the Universe is spatially flat.

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

Hubble constant today has been measured with some precision and there is a mild tension:

$$H_0 = (67.8 \pm 0.9)\ \mathrm{km/s/Mpc}\ (\mathrm{Planck})$$
$$H_0 = (72.0 \pm 3)\ \mathrm{km/s/Mpc}\ (\mathrm{HST})$$

Exercise 6: estimate the critical density in units of protons/m^3

Different contributions to the energy density budget of the Universe

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

Spatially flat universe:

$$\sum_i \Omega_i = 1$$

1st Friedmann equation:

$$\frac{H(t)^2}{H_0^2} = \sum_i \Omega_i^{(0)} a^{-3(1+\omega_i)}$$

Exercise 7: given a Universe with

$$\Omega_{\Lambda}^{(0)} = 0.7,\ \Omega_{\rm matter}^{(0)} = 0.3,\ \Omega_{\rm rad}^{(0)} = 5 \times 10^{-5}$$

compute:

a. H_0^{-1} in units of years
b. the age of the Universe
c. $(\rho_c)^{1/4}$ in units of eV – energy scale associated with the cosmological constant
d. H_0 in units of eV
e. the redshift z_{eq}
f. the redshift z_{Λ}

I.2.7 – Beyond Λ: dynamical dark energy

For a real homogeneous scalar field the energy-momentum tensor gives:

$$T_\phi^{00} = \rho = \frac{1}{2}\dot{\phi}^2 + V(\phi);$$

$$T_\phi^{ii} = -g^{ii}P = -\left(\frac{1}{2}\dot{\phi}^2 - V(\phi)\right)g^{ii}$$

and therefore the time-dependent equation of state in this case is:

$$\omega(t) = \frac{P}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \Rightarrow -1 \leq \omega \leq 1$$

If potential energy dominates w~-1 and scalar field resembles a cosmological constant: quintessence field. Can be ultralight (~H_0)!

Some examples of dark energy models:

Cosmological Constant $p_\Lambda = -\rho_\Lambda$

Canonical Scalar Field: Quintessence $\mathcal{L}_Q = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - V(\varphi)$

Perfect Fluid $p_0 = w\rho_0$ $\delta p = c_{\text{eff}}^2\delta\rho$

Chaplygin Gas $\rho_{Ch} = -A\rho_{Ch}^{-\alpha}$

K-essence $\mathcal{L} = F(X,\varphi)$ $X = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi$

e.g. Tachyon, Born-Infeld $\mathcal{L}_T = V(\varphi)\sqrt{1 - \partial^\mu\varphi\partial_\mu\varphi}$

I.2.8 – Vacuum energy: the elephant in the room

Quantum mechanics – zero point energy of a harmonic oscillator:

$$E = \hbar\omega(n + 1/2)$$

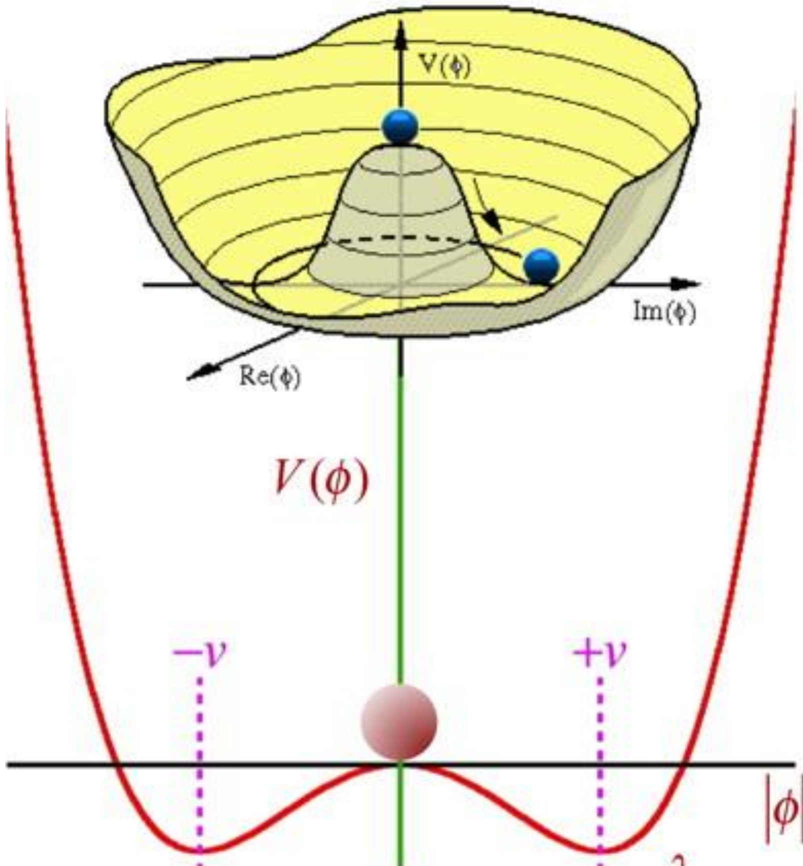
In Quantum Field Theory, the energy density of the vacuum is (free scalar field of mass m):

$$\rho_{vac} = \int \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2}$$

and is infinite! Integral must be cut-off at some physical energy scale - goes as (cut-off)^4.

If integral is cutoff at the Planck scale, disagreement of ~ 10^{120} with data. This is know as the cosmological constant problem.

The Higgs field and the vacuum energy:



$$V(\phi) = \tfrac{1}{2}\mu^2\phi^\dagger\phi + \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

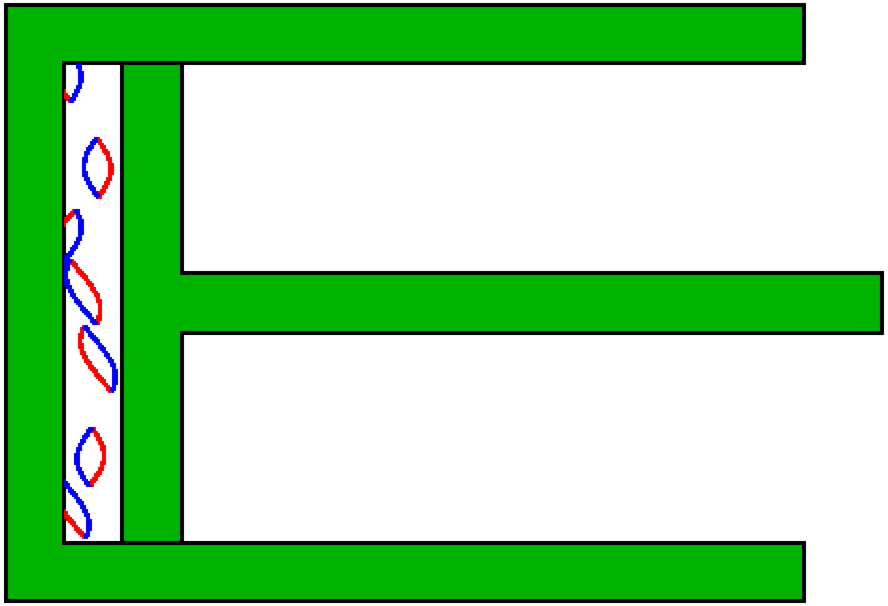
Groundstate at $|\phi_0| = \sqrt{\dfrac{-\mu^2}{\lambda}} \equiv \upsilon$

$$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$$

$$V(\phi_0) = -\frac{\lambda}{4}\upsilon^4$$

Vacuum energy

$$\rho_\Lambda \propto \text{constan}$$



E. L. Wright

$$dE = -pdV \Rightarrow p_\Lambda < 0$$

I.2.9 – Distances in the Universe

There are 2 ways to measure large distances in the Universe:
from known luminosities (standard candles – eg SNIa) or
from known scales (standard rulers – eg BAO).

Let's recall that
physical distance = a(t) comoving distance
and discuss some other typical distances in the Universe.

a. Comoving distance between us (z=0) and an object at redshift z:

$$ds^2 = 0 \Rightarrow dt^2 = a(t)^2 d\chi^2 \Rightarrow$$

$$\boxed{\chi(z) = \int_0^z \frac{dz'}{H(z')}}$$

b. Comoving particle horizon: largest region in causal contact since the Big Bang:

$$\chi(z)_{\mathrm{phys}} = \int_0^t \frac{dt'}{a(t')}$$

c. Luminosity distance (d_L):

$$F = \frac{L}{4\pi d_L^2}$$

Flux of photons

Known luminosity of the source

In FLRW there are 2 extra source of dilution of the flux:
- redshift of photons (1/(1+z))
- rate of arrival decrease by (1/(1+z)) – time dilation

Therefore: $$\boxed{d_L = (1+z)\chi(z)}$$

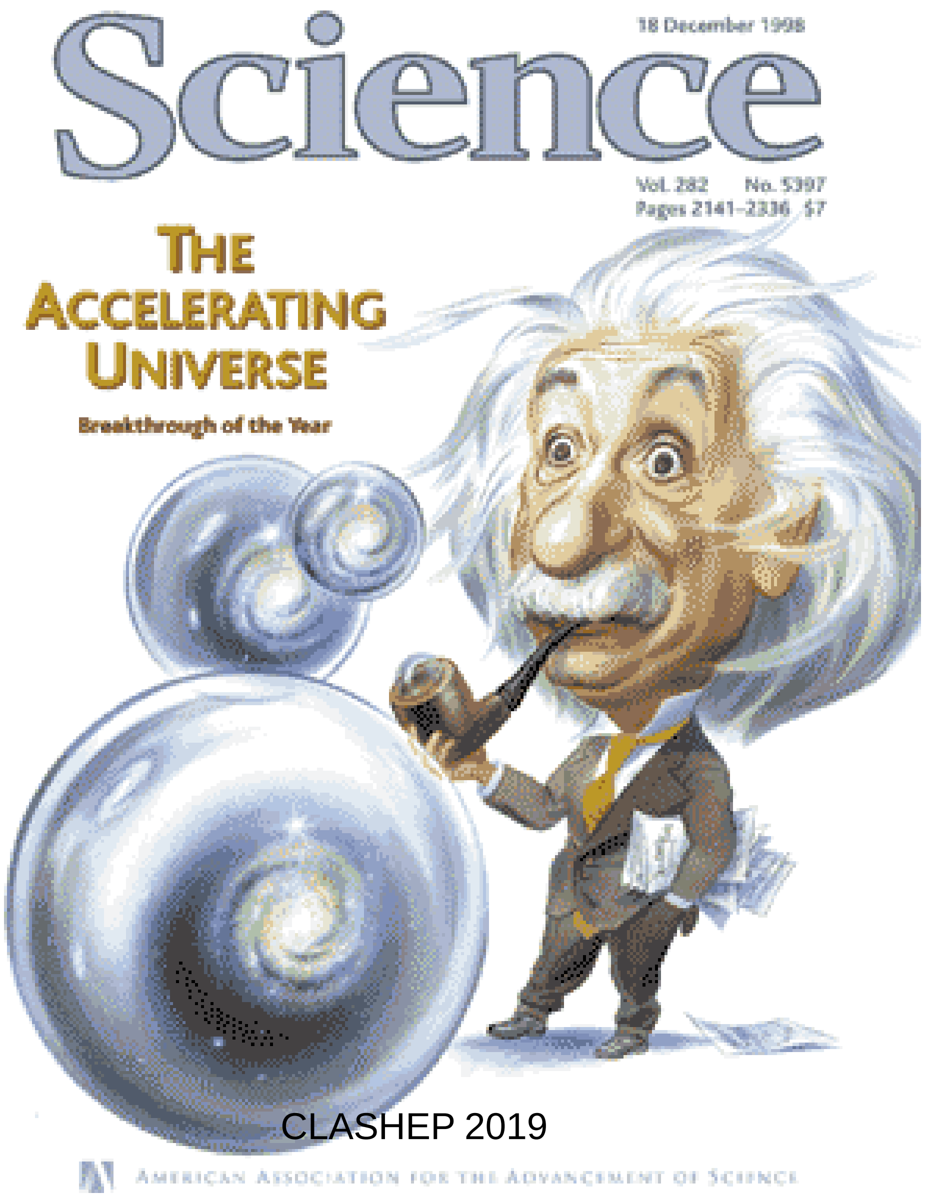
Exercise 8: plot $d_L(z)$ for $0<z<2$ for a flat Universe with

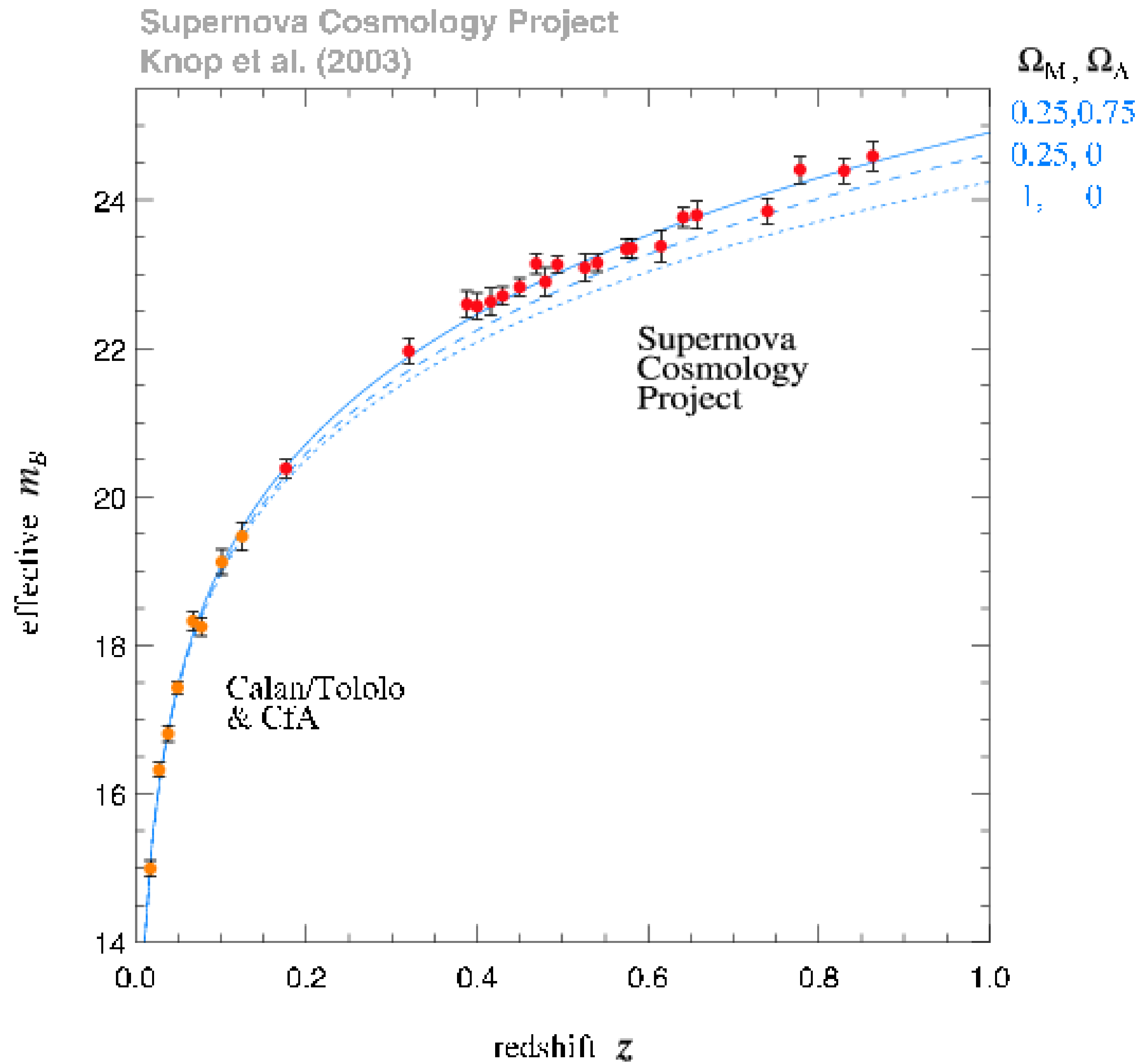
α. $\Omega_m = 1$ and $\Omega_\Lambda = 0$
β. $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$

d_L is larger for a Universe with Λ -> objects with same z look fainter

This is how the accelerated expansion of the Universe was discovered in 1998 using SNIa

The big surprise in 1998:





Supernova Cosmology Project
Knop et al. (2003)
Ω_M, Ω_Λ
0.25,0.75
0.25, 0
1, 0
Supernova
Cosmology
Project
Calan/Tololo
& CfA
effective m_B
redshift z
24
22
20
18
16
14
0.0
0.2
0.4
0.6
0.8
1.0

The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

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The Nobel Prize in Physics 2011

Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

Photo: U. Montan

Brian P. Schmidt

Prize share: 1/4

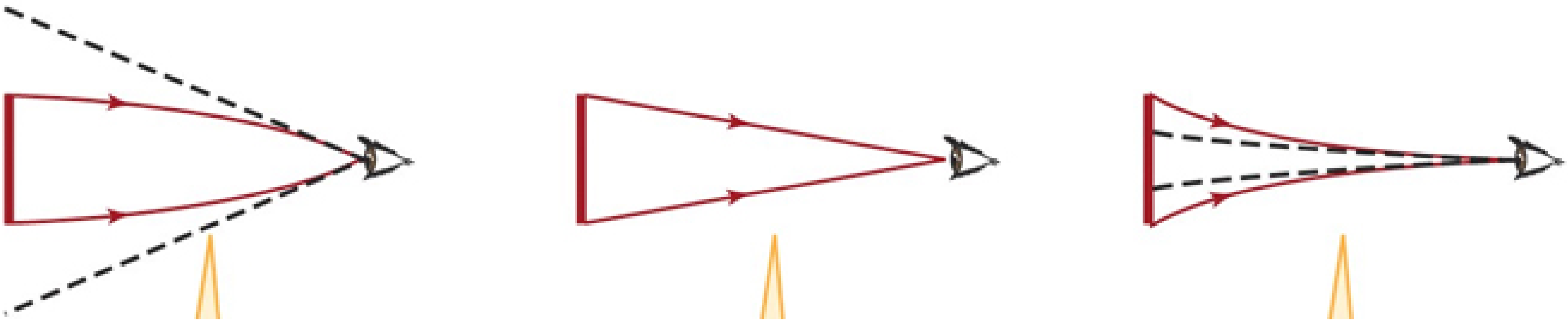
Photo: U. Montan

Adam G. Riess

Prize share: 1/4

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

d. Angular diameter distance (d_A):
related to the angle subentended by a physical lenght (l)



Closed Universe

Flat Universe

Open Universe

$$d_A = \frac{l}{\delta\theta},\ l = a\chi\delta\theta \Rightarrow$$

$$\boxed{d_A = \frac{1}{1+z}\chi(z)}$$

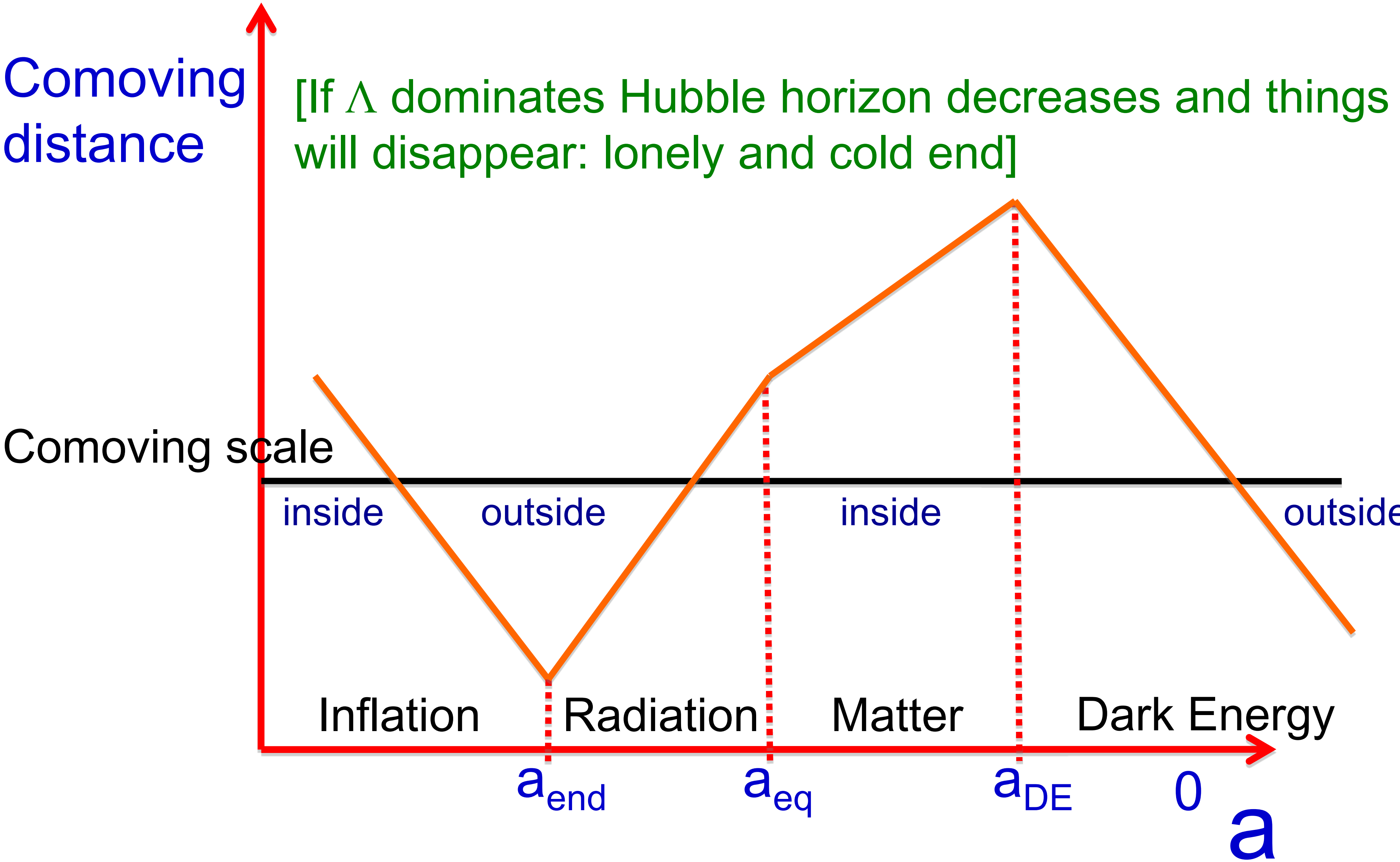
e. Hubble radius: distance particles can travel in a Hubble time

$$R_H = \frac{1}{H(t)}$$

Comoving Hubble radius: $$r_H = \frac{1}{aH} = \frac{1}{\dot{a}}$$

- Radiation dominated $\quad r_H \propto a$
- Matter dominated $\quad r_H \propto a^{1/2}$
- Λ dominated $\quad r_H \propto 1/a$

Comoving Hubble radius during the evolution of the Universe



I.3- Thermal history of the Universe

I.3.1 – Brief review of thermodynamics

Quick way to derive relation between temperature and scale factor:

$$\rho_r \propto T^4; \; \rho_r \propto a^{-4} \Rightarrow a \propto T^{-1}$$

Stefan-Boltzmann law

More formally the number density and energy density are:

$$n = \frac{g}{(2\pi)^3} \int d^3p \; f(\vec{p})$$

$$\rho = \frac{g}{(2\pi)^3} \int d^3p \; E(\vec{p}) f(\vec{p})$$

$$E = \sqrt{|\vec{p}|^2 + m^2}$$

E is the energy of a state, f(p) is the phase-space distribution and g is number of internal degrees of freedom (eg g=2 for photons, g=8 for gluons, g=12 for quarks, etc).

Phase-space distribution (+ for FD, - for BE), k_B=1,
μ chemical potential:

$$f(\vec{p}) = \frac{1}{e^{(E-\mu)/T} \pm 1}$$

Relativistic limit (T>>m) and T>>μ

$$\rho = \left(\frac{\pi^2}{30}\right) g T^4 \begin{cases} 1 \; (\mathrm{Bose-Einstein}) \\ \frac{7}{8} \; (\mathrm{Fermi-Dirac}) \end{cases}$$

$$n = \frac{\zeta(3)}{\pi^2} g T^3 \begin{cases} 1 \; (\mathrm{Bose-Einstein}) \\ \frac{3}{4} \; (\mathrm{Fermi-Dirac}) \end{cases} \qquad \zeta(3) = 1.202\cdots$$

Exercise 9: compute the number of CMB photons (T=2.73 K) in a cm^3

Non-relativistic limit (T<<m) and $\mu=0$ [same for B-E and F-D]

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\rho = mn$$

Exponential Boltzmann suppression

Density of relativistic particles in the Universe is set by the effective number of relativistic degrees of freedom g_*:

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$

$$g_* = \sum_{\mathrm{bosons}} g_i \left(\frac{T_i}{T}\right)^4 + \sum_{\mathrm{fermions}} \frac{7}{8} g_i \left(\frac{T_i}{T}\right)^4$$

$g_*(T)$ changes when mass thresholds are crossed as T decreases.
At high T (>200 GeV) $g_*^{(SM)} \sim 100$.

http://www.damtp.cam.ac.uk/user/db275/Cosmology/Lectures.pdf

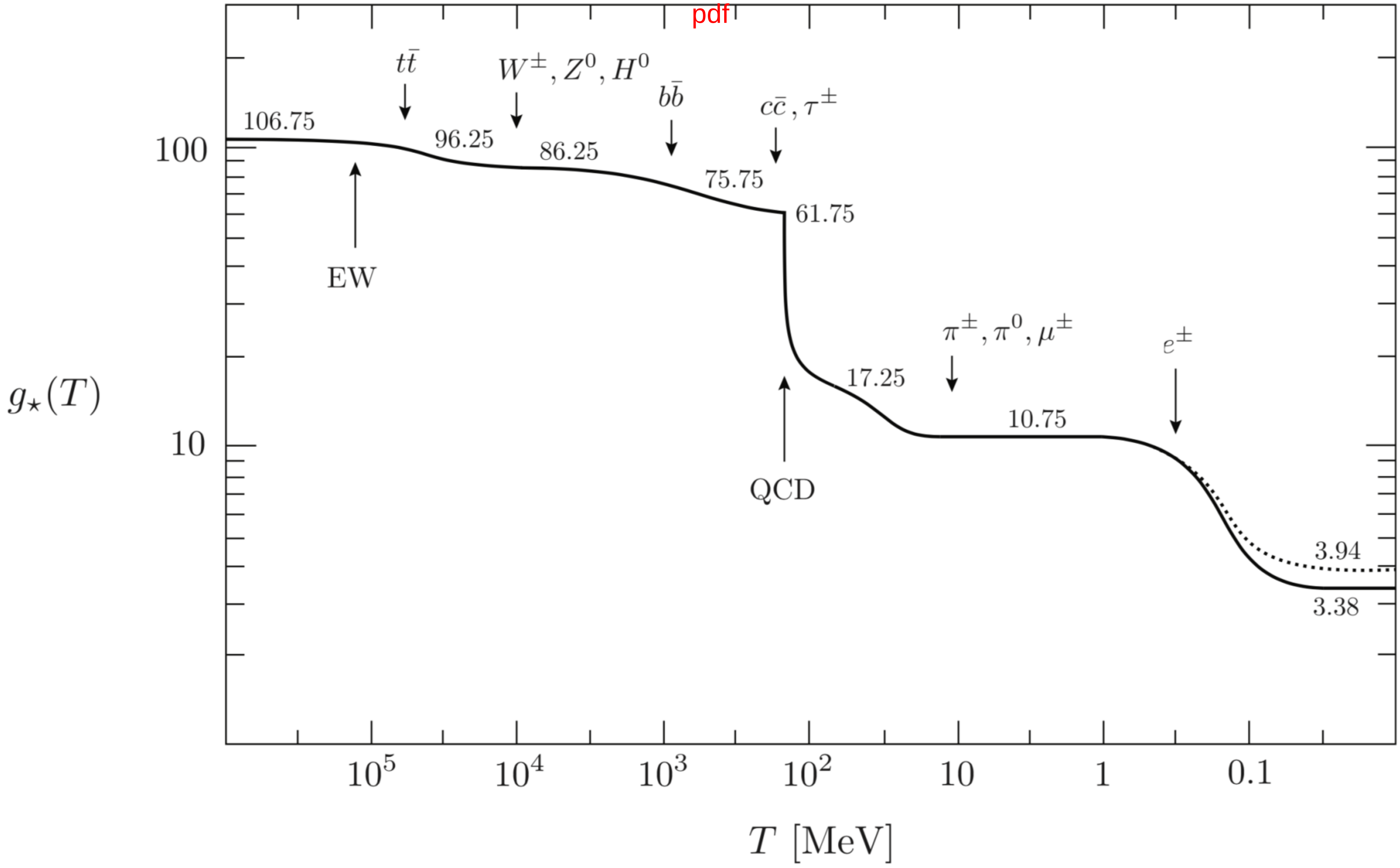


Figure 3.4: *Evolution of relativistic degrees of freedom $g_\star(T)$ assuming the Standard Model particle content. The dotted line stands for the number of effective degrees of freedom in entropy $g_{\star S}(T)$.*

I.3.2 – Temperature-time relationship

From Friedmann's 1st equation for a radiation-dominated era:

$$H = \sqrt{\frac{\rho_r}{3\tilde{M}_{\rm Pl}^2}} \sim \frac{T^2}{M_{\rm Pl}}$$

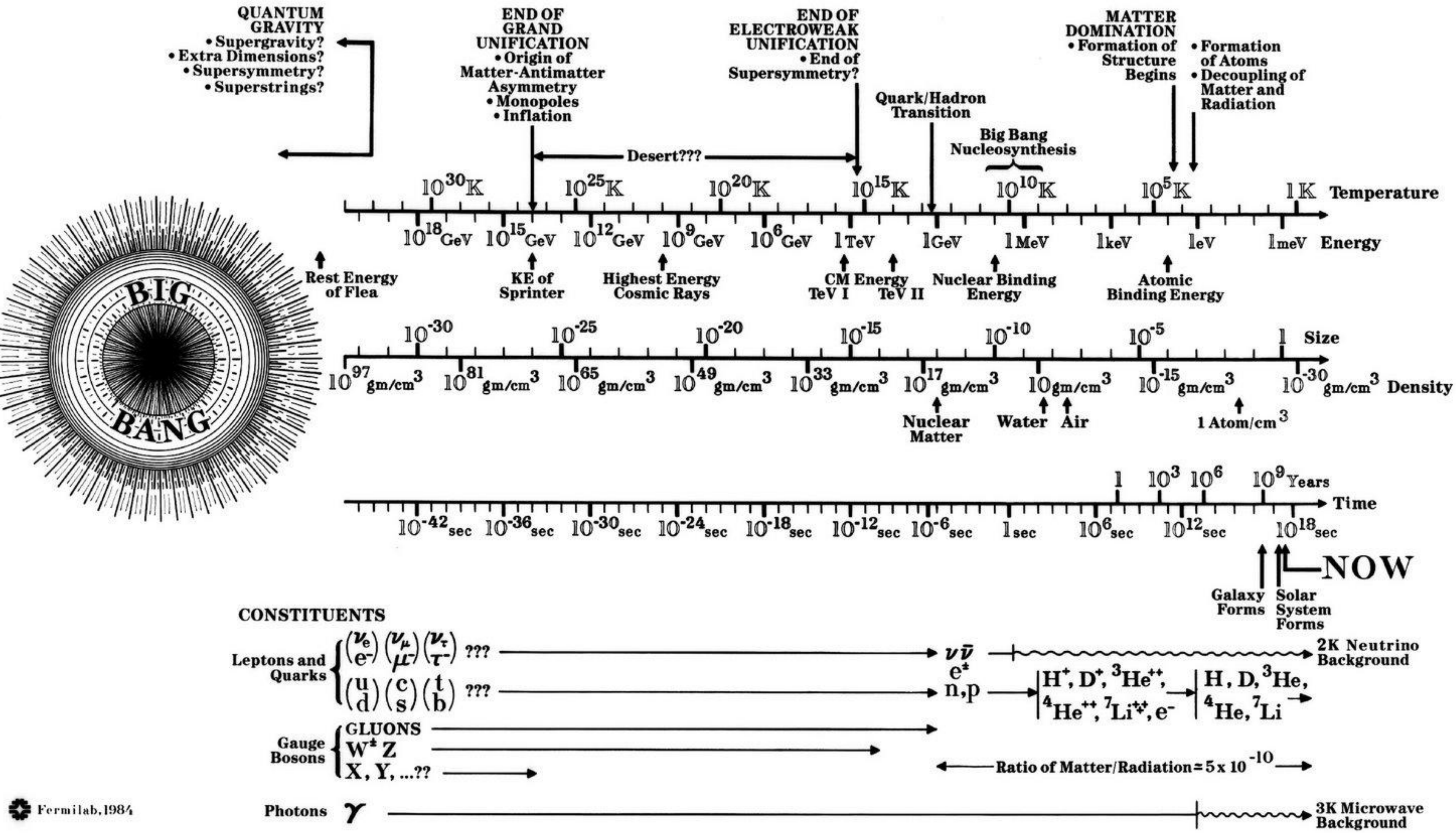
and $$H = \frac{\dot{a}}{a} \propto t^{-1}$$

one finds: $$T \propto t^{-1/2}$$

Putting numbers: $$T(\mathrm{MeV}) \simeq 1.5 g_*^{-1/4} t(\mathrm{s})^{-1/2}$$

Thermal history of the Universe

Kolb & Turner



I.3.3 – Decoupling of species

Different particles are in thermal equilibrium when they can interact efficiently. There are 2 typical rates that can be compared:

• rate of particle interactions:

$$\Gamma(T) = n\langle\sigma v\rangle$$

Number density

Thermal averaged cross section x velocity

• expansion rate of the Universe:

$$H(T)$$

When

$$\Gamma(T) \gg H(T)$$

particles are in thermal equilibrium.

As a first estimate particles decouple when $\Gamma(T) \sim H(T)$

More precise estimate requires solving a Boltzmann equation (more later)

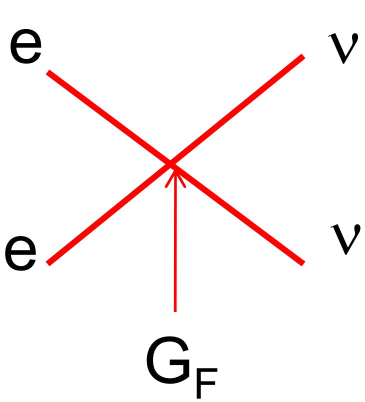
Example: decoupling of neutrinos from the thermal bath

Weak interactions:

$$\nu_e + \bar{\nu}_e \leftrightarrow e^+ + e^-$$

$$e^- + \bar{\nu}_e \leftrightarrow e^- + \bar{\nu}_e$$

Low energy cross section (4-fermi interaction):



$G_F = 10^{-5}$ GeV^{-2}: Fermi constant

$$\sigma \sim G_F^2 T^2;\ n_\nu \sim T^3 \Rightarrow \Gamma_\nu(T) \sim G_F^2 T^5$$

$$H(T) \sim T^2/M_{\rm Pl}$$

$$\boxed{T_{\nu,\rm dec} = \left(\frac{1}{G_F^2 M_{\rm Pl}}\right)^{1/3} \sim 1\ \rm MeV}$$

After decoupling neutrinos cool down as $T \propto 1/a$.

They would have the same temperature as photons except for the fact that photons get heated up by the annihilation of e^+e^- at around $T \sim 0.5$ MeV. Hence neutrinos are a bit cooler ($T_\nu = 1.95$ K)

Obs.1: In SM ν's are massless and only ν_L exist. Now we know that this is incorrect. Some extensions of the SM postulate the existence of ν_R to explain ν masses. This is a new degree of freedom and is gauge singlet under SM interactions [eg 1303.6912].

Obs.2: Today there is a cosmic ν background which is very difficult to detect – experiment Ptolomy is being designed for this search.

Obs.3: Experiments such as Planck are sensitive to the number of relativistic degrees of freedom present at the time of CMB. This is characterized by the so-called N_{eff} parameter. In the SM, N_{eff} = 3.046 (some ν□s are heated by e^+e^- annihilation). There were some measurements giving a larger N_{eff} which prompted many papers postulating new relativistic degrees of freedom dubbed **"dark radiation"**.

In 2015 Planck measured N_{eff} = 3.15 +/- 0.23 and most people are now happy.

Obs.4: If massless $\rho_\nu \sim \rho_\gamma$. If massive:

$$\rho_\nu \simeq \sum_i m_{\nu,i} n_{\nu,i} \Rightarrow \Omega_\nu^{(0)} = \frac{\sum_i m_{\nu,i}}{94\mathrm{eV}}$$

Obs.5: Most stringent bounds on ν masses comes from cosmology.
More later.