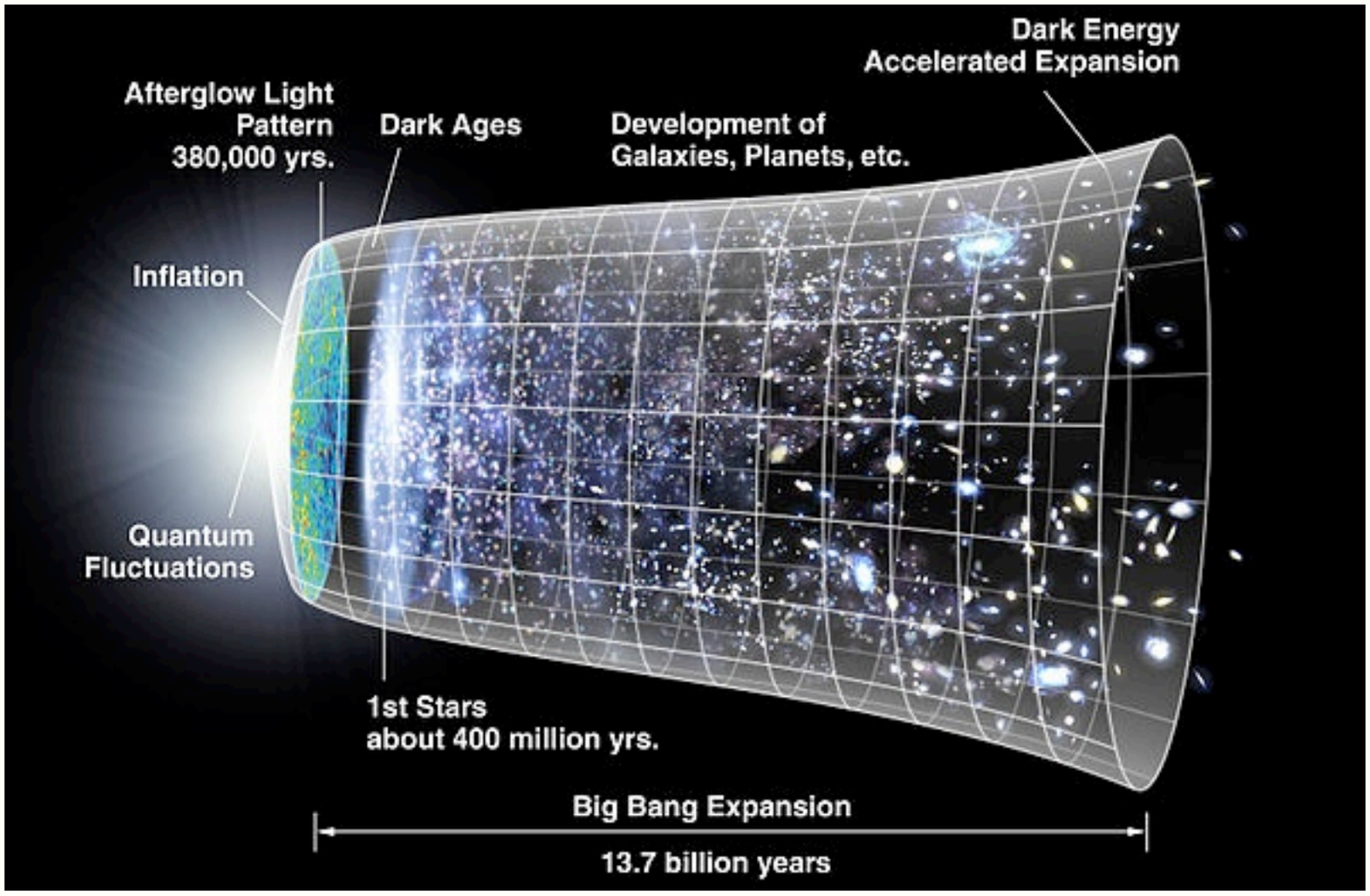
Gravitatie

J.W. van Holten



Teyler Museum, Haarlem
24 april 2012

Equivalentie van zware en trage massa

DE
BEGHINSELEN
DER WEEGHCONST
BESCHREVEN DVER
SIMON STEVIN
van Brugghe.

TOT LEYDEN,
Inde Druckerye van Chriſtoffel Plantijn,
By Françoys van Raphelinghen.
cIↃ. IↃ. LXXXVI.

DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue ſcienze
Attenenti alla
MECANICA & I MOVIMENTI LOCALI,
del Signor
GALILEO GALILEI LINCEO,
Filoſofo e Matematico primario del Sereniſſimo
Grand Duca di Toſcana.
Con vna Appendice del centro di grauità d'alcuni Solidi.

IN LEIDA,
Appreſſo gli Elſevirii. M. D. C. XXXVIII.

Stevin (Weeghconst, 1586)

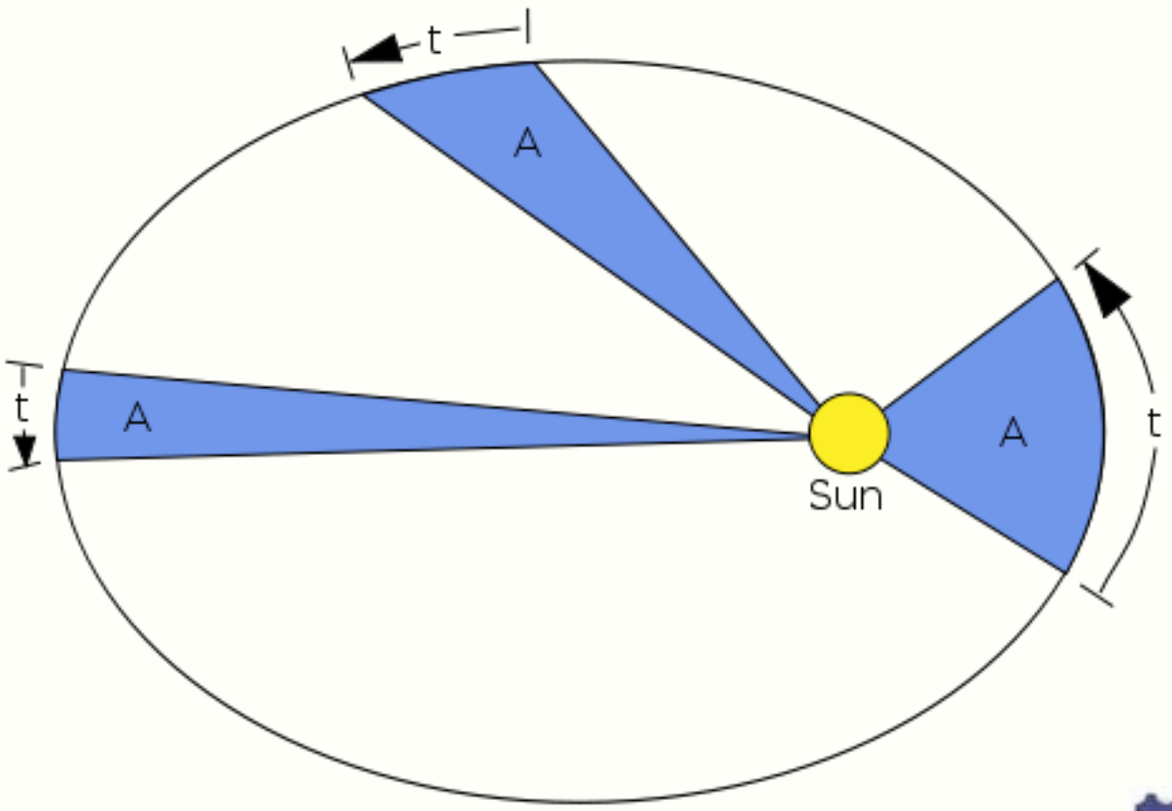
Galilei (Discorsi, 1638)

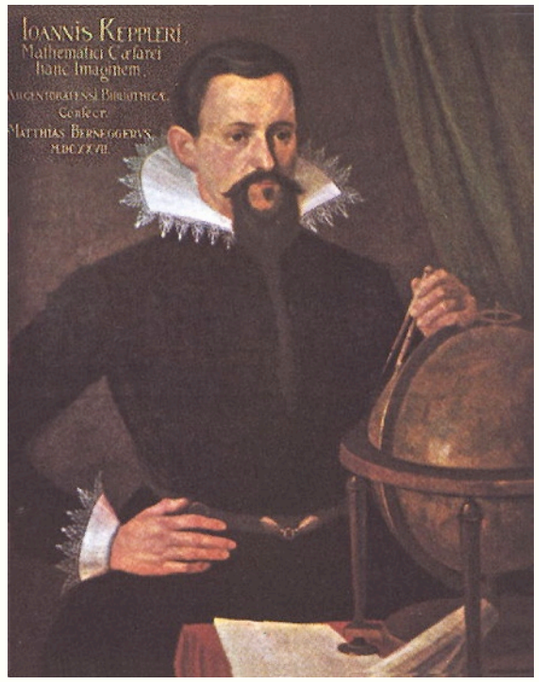
Laet nemen (soo den hoochgheleerden H. IAN CORNETS DE GROOT vlietichste ondersoucker der Naturens verborghentheden, ende ick ghedaen hebben) twee loyen clooten d'een thienmael grooter en swaerder als d'ander, die laet t'samen vallen van 30 voeten hooch, op een bart oft yet daer sy merckelick gheluyt tegen gheuen, ende sal blijcken, dat de lichste gheen thienmael langher op wech en blijft dan de swaerste, maer datse t'samen so ghelijck opt bart vallen, dat haer beyde gheluyden een selue clop schijnt te wesen. S'ghelijcx beuint hem daetlick oock also, met twee euegroote lichamen in thienvoudighe reden der swaerheyt, daerom Aristoteles voornomde eueredenheyt is onrecht.

Newton:
universele aantrekking

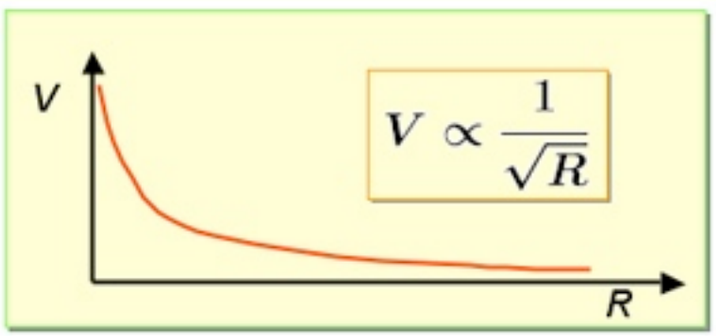
$$F = \frac{GMm}{r^2} = ma$$

Planetenbanen

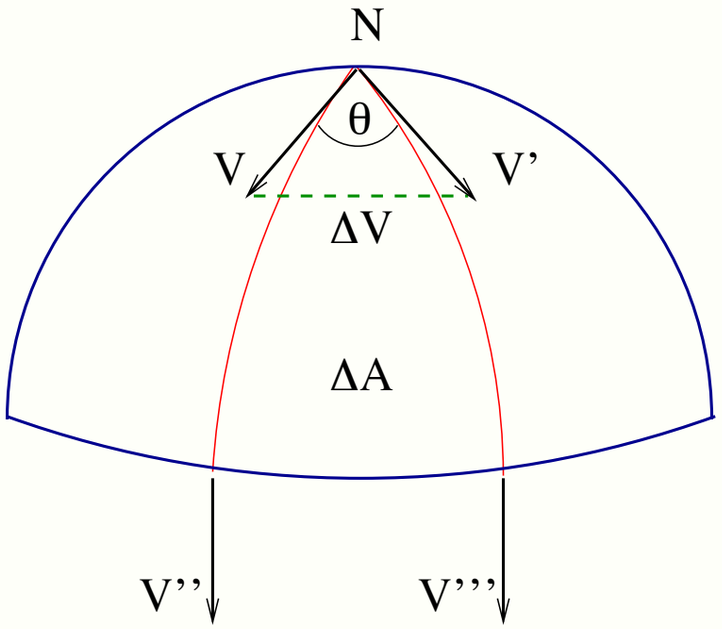




Johannes Kepler



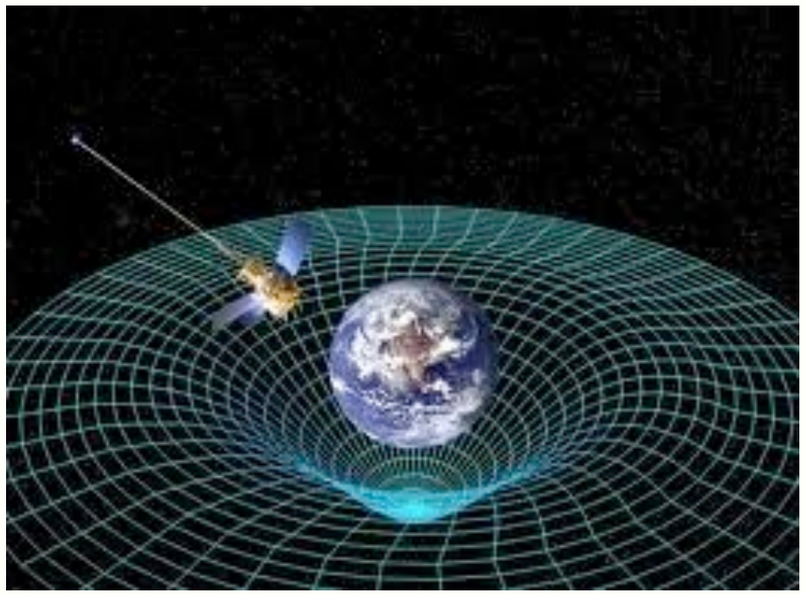
Gravitatie als meetkunde van ruimte en tijd

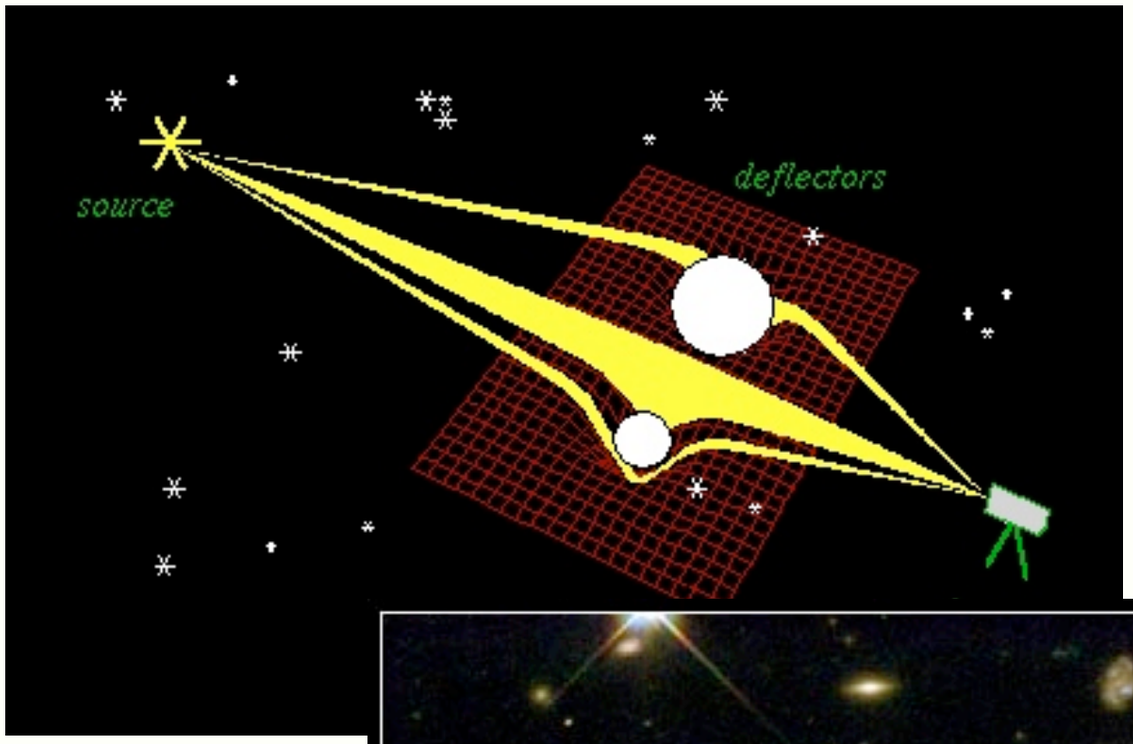


A. Einstein

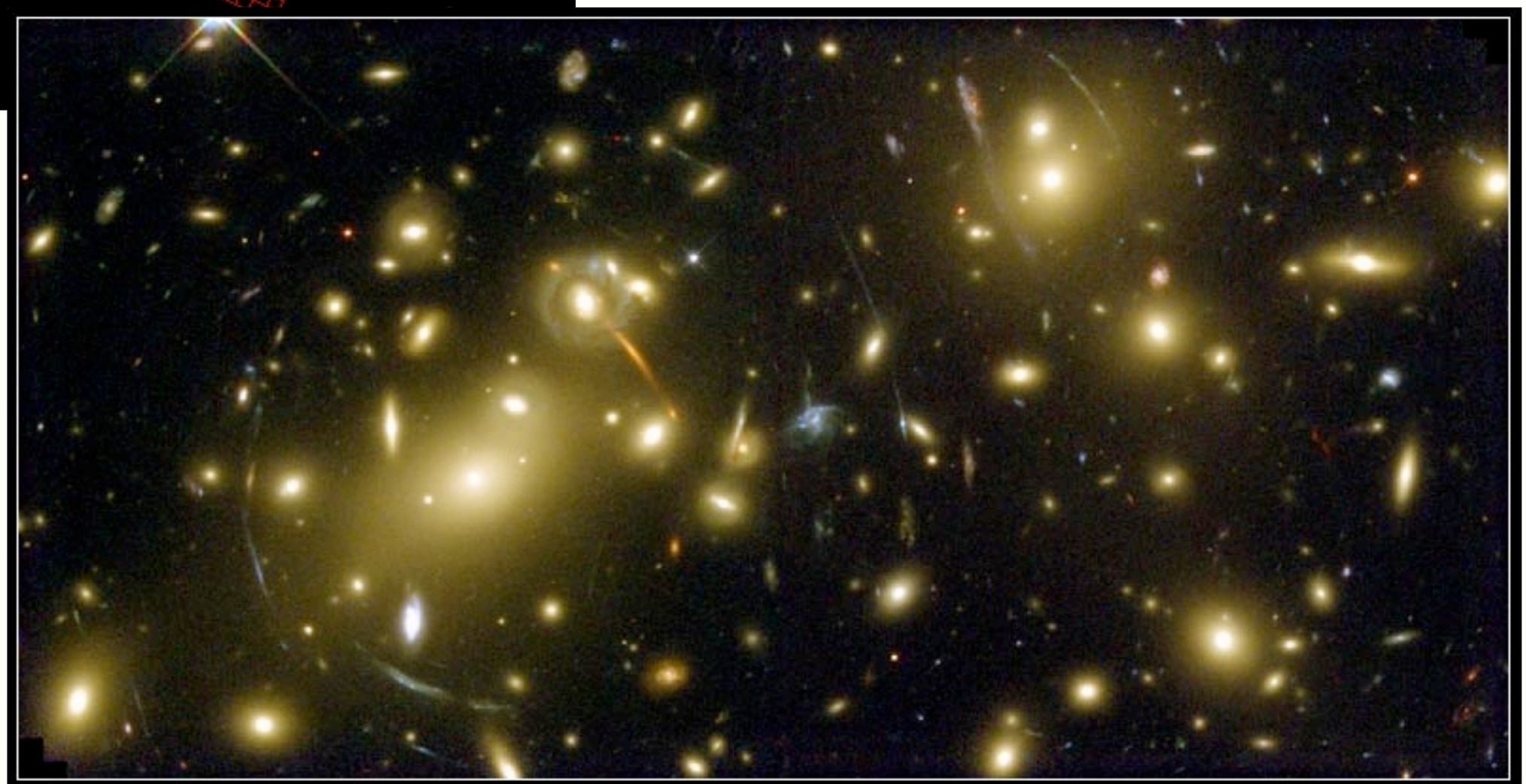
Massa ⟶ kromming

kromming ⟶ afbuiging





Gravitatielenzen

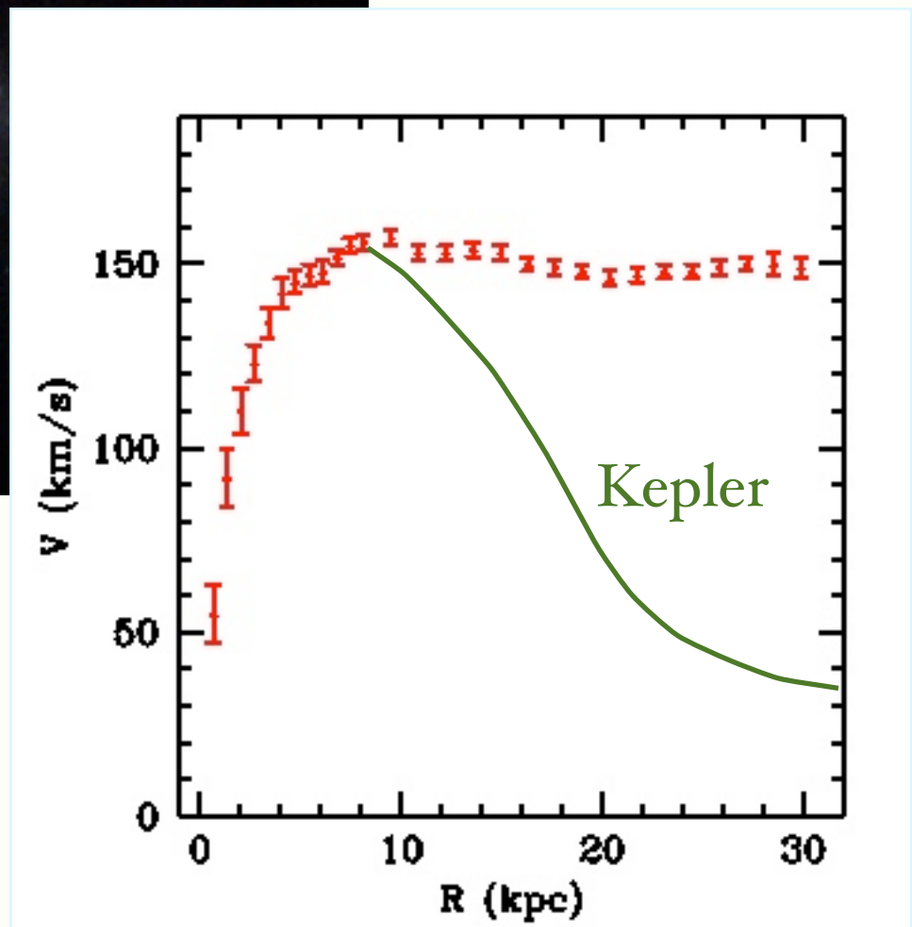


Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

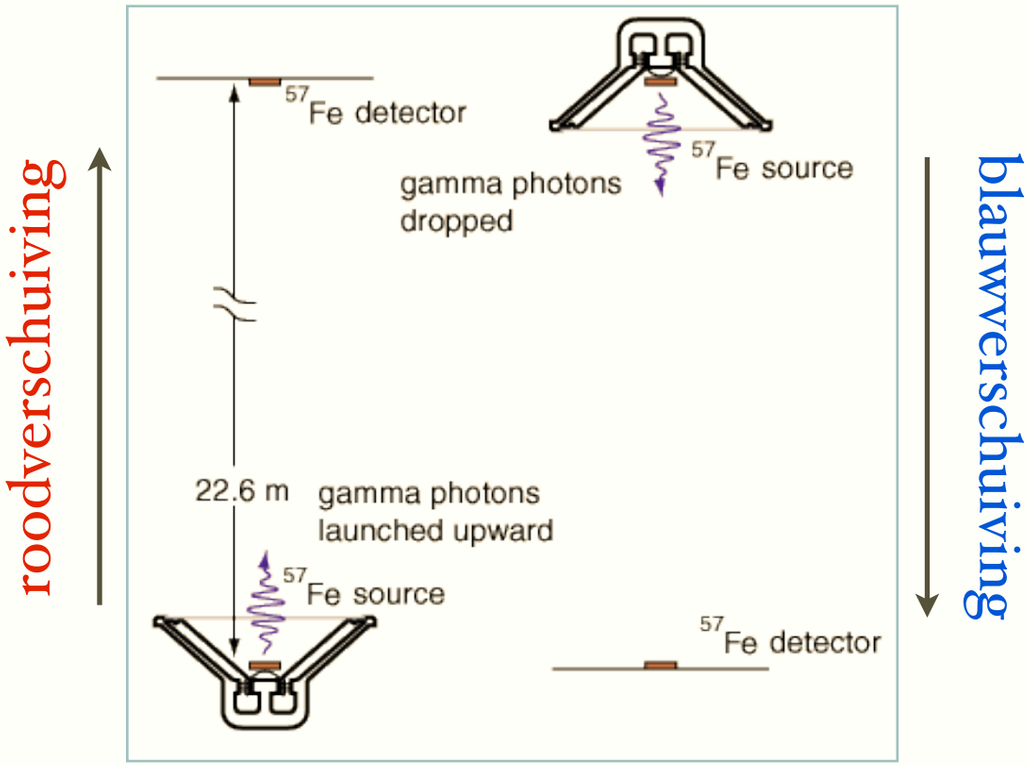
Galactische rotatie

NGC 3198



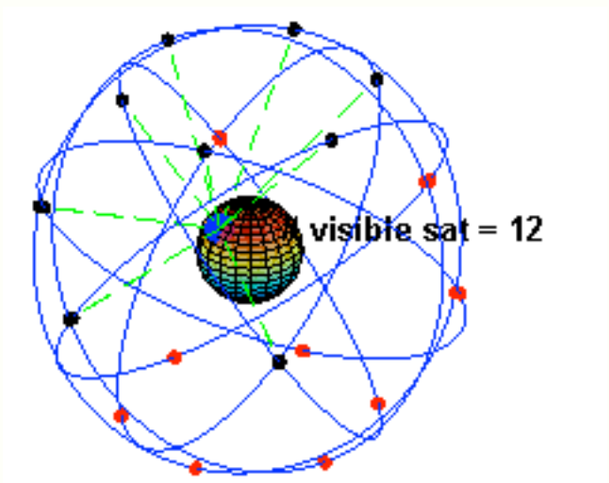
Donkere materie

Frequentieverandering o.i.v. zwaartekracht



Experiment van Pound en Rebka (1960)

GPS



Tijddilatatie:

klokken vertragen
in een zwaartekrachtveld

Hubble expansie

E. Hubble

toename expansiesnelheid:

$H_0 = 72$ km/s/Mpc

(1 pc = 3.08 ljr)

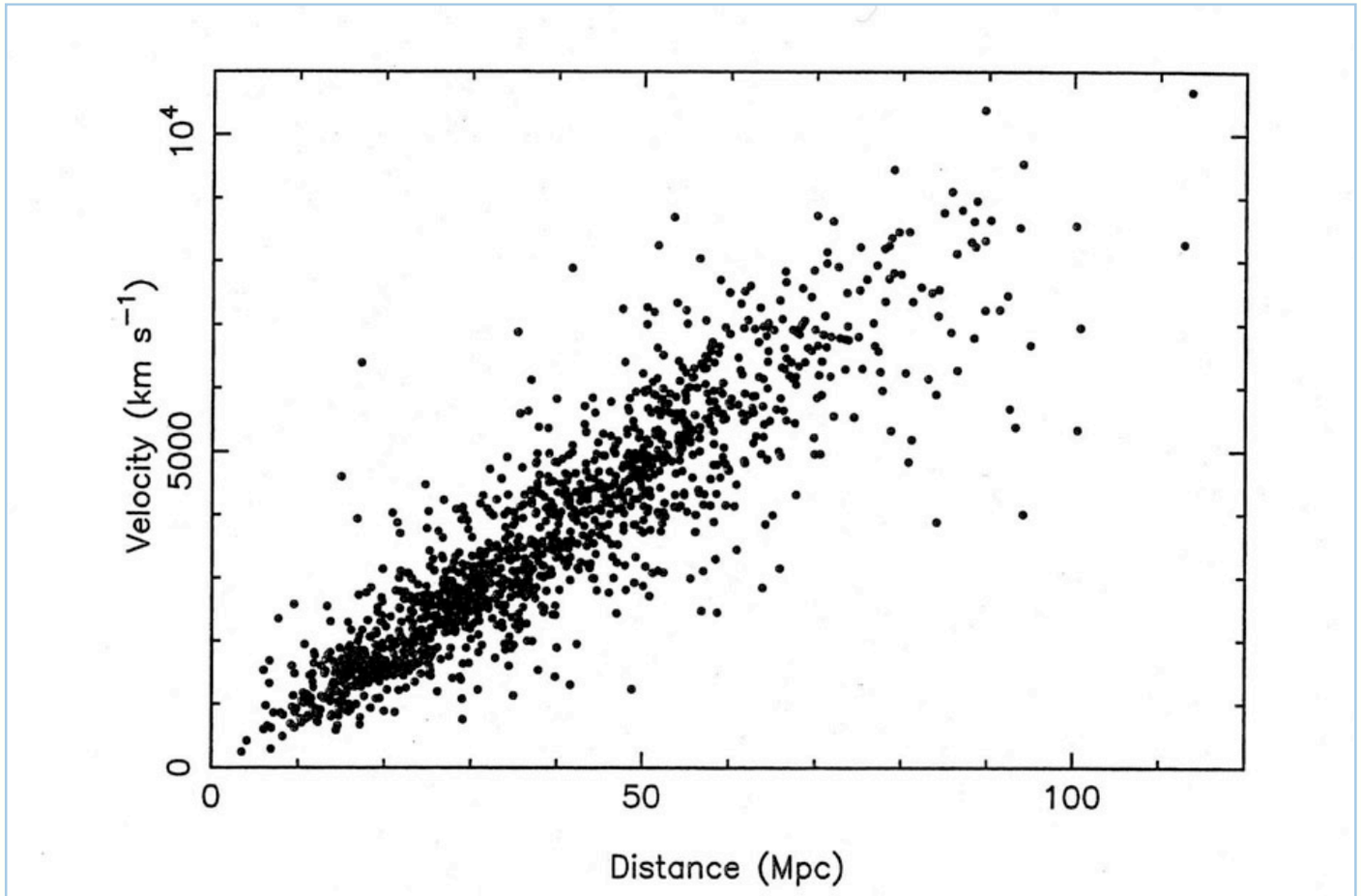
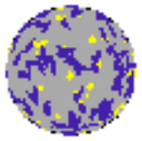
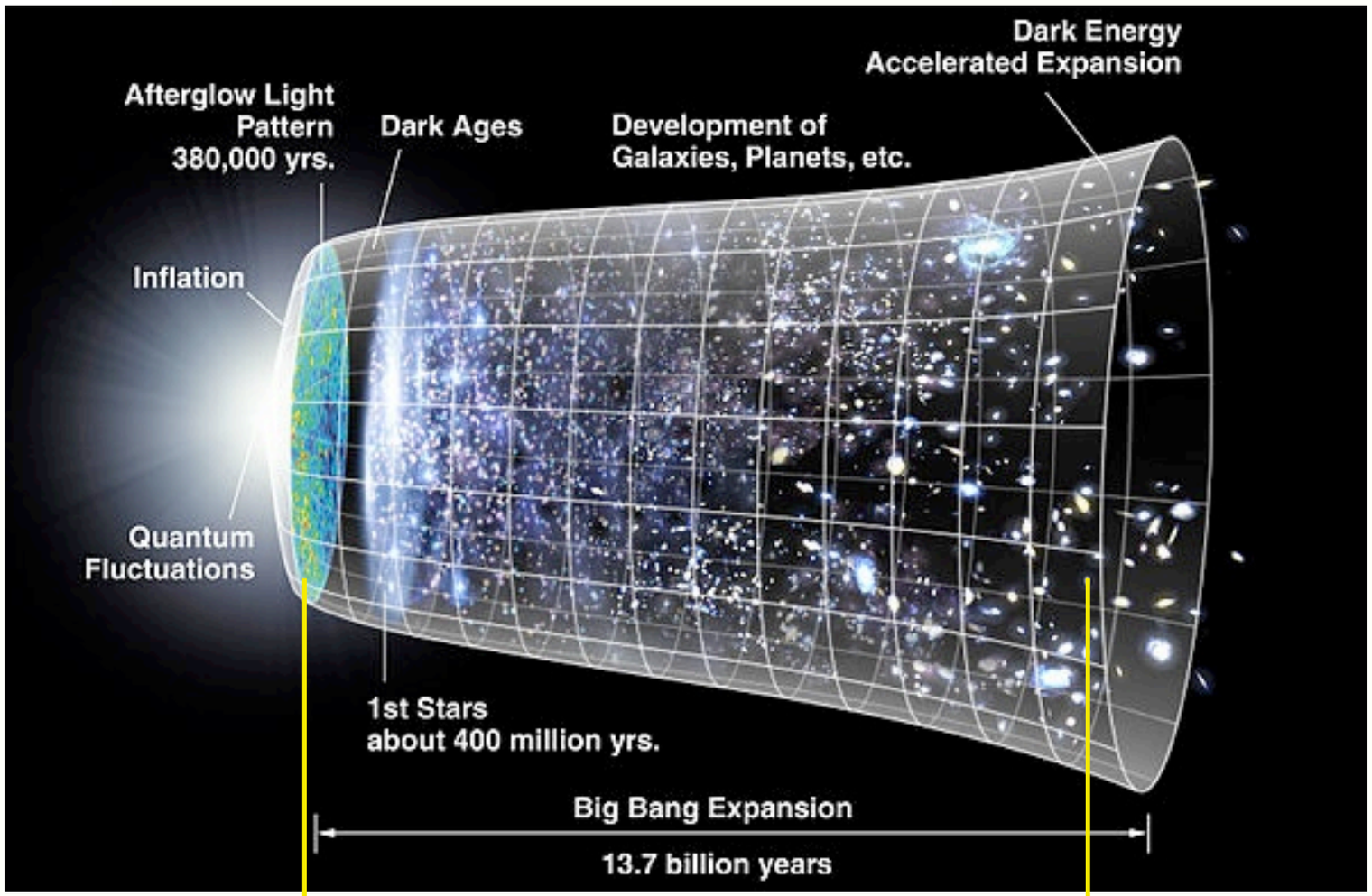


Figure 2.5 A plot of velocity versus estimated distance for a set of 1355 galaxies. A straight-line relation implies Hubble's law. The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law. [The x-axis scale assumes a particular value of H_0.]

Type Ia supernovae



Het uitdijend heelal

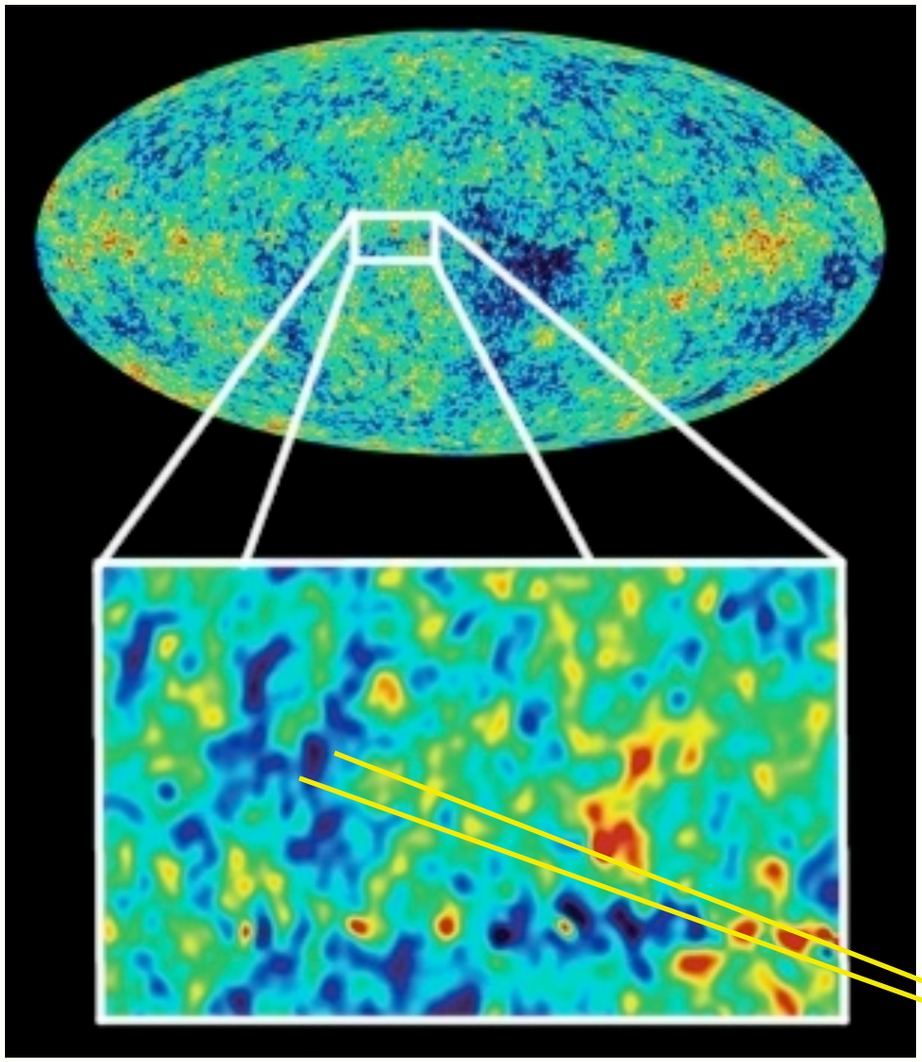


Expansiesnelheid

T = 3000 K

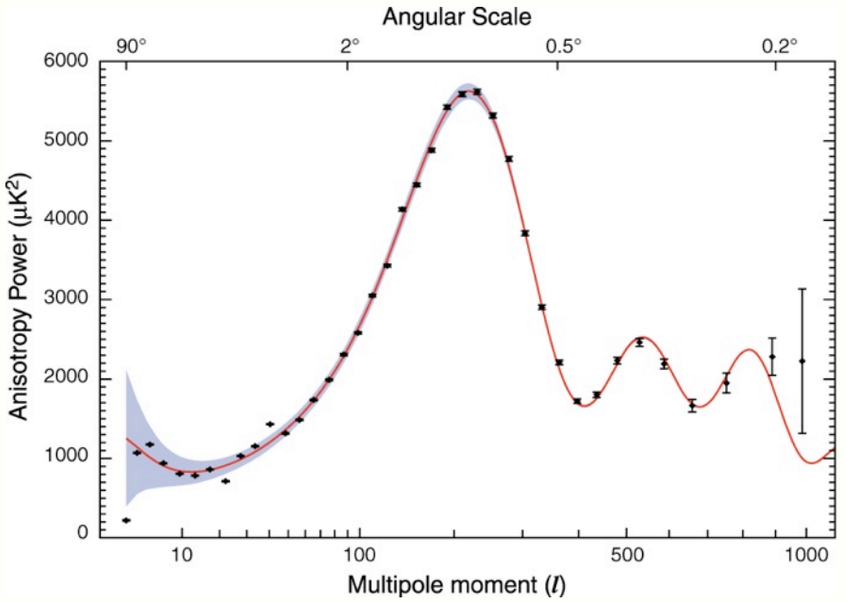
T = 3 K

WMAP

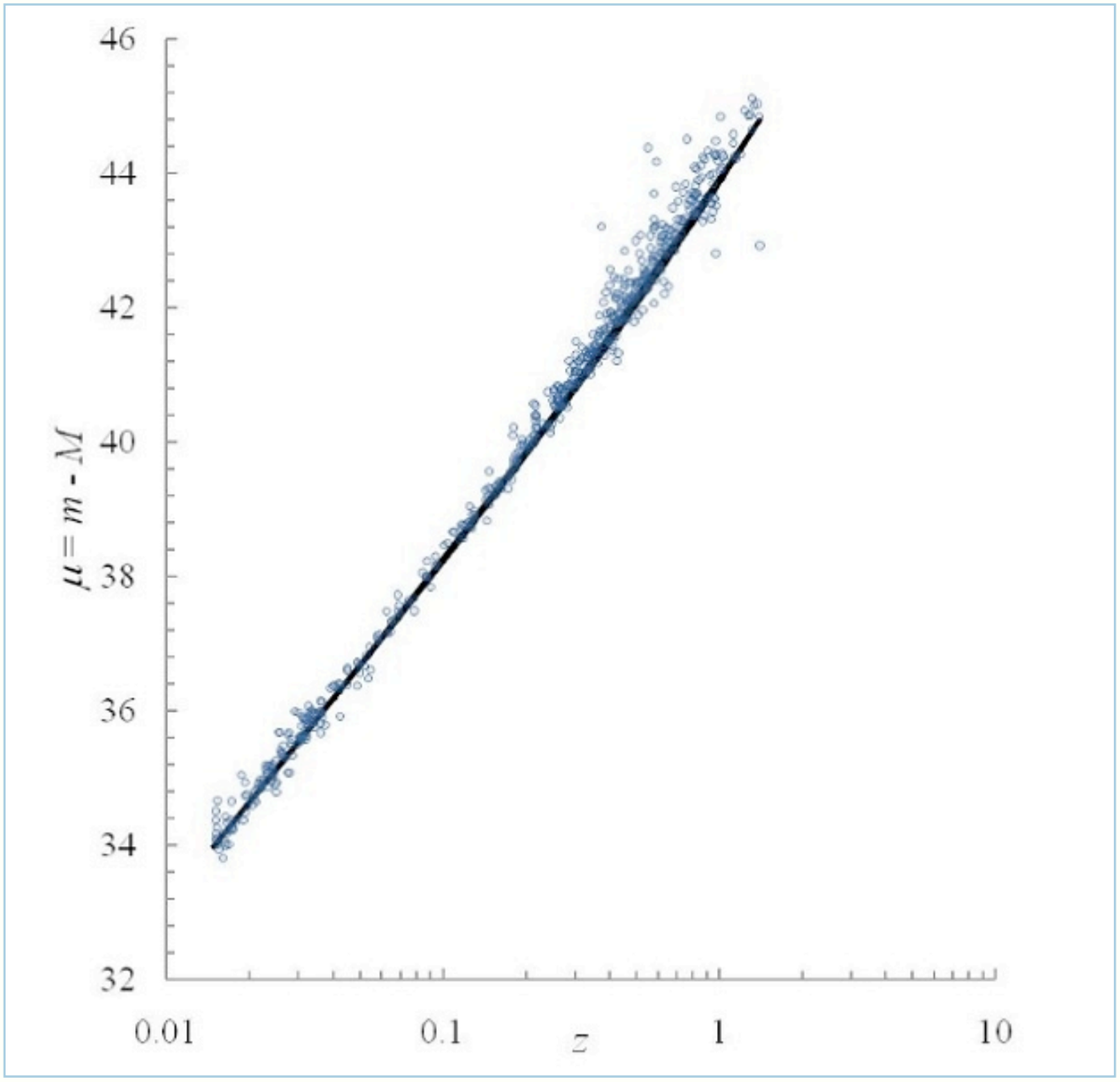


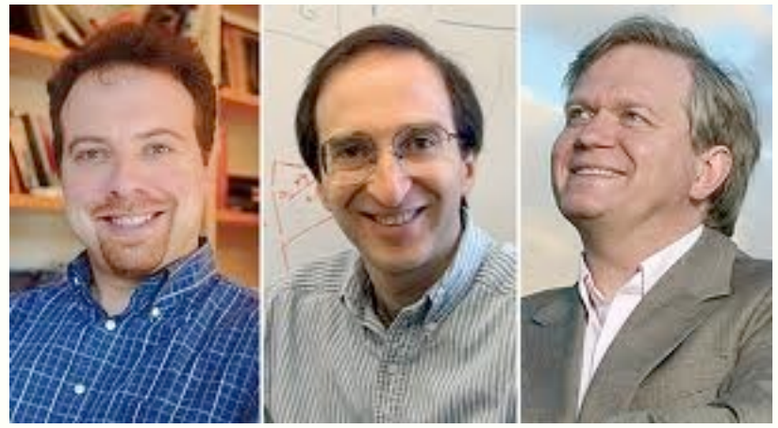
kosmische
achtergrondstraling

t = 350 000 jaar



Versnelde expansie



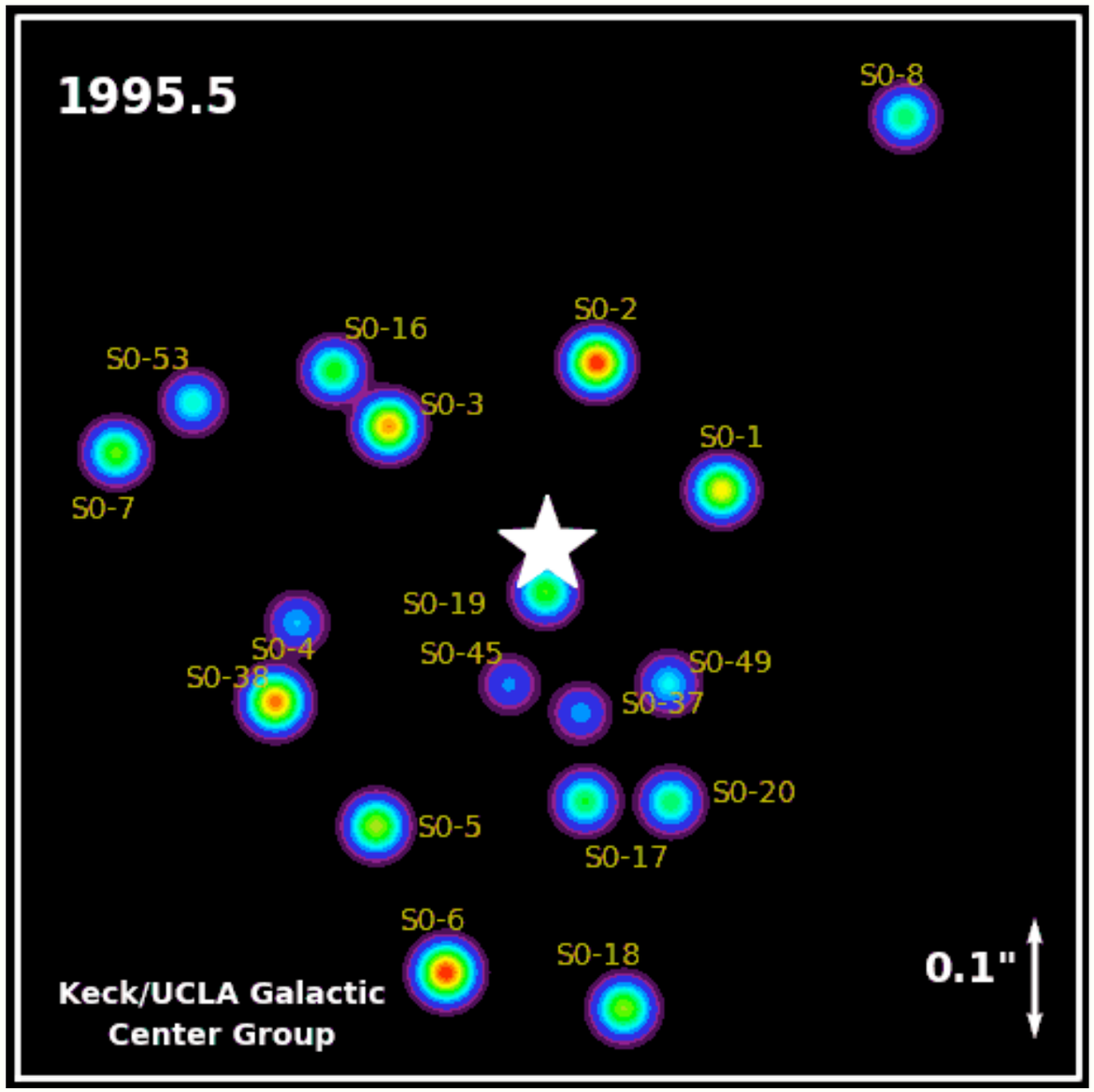


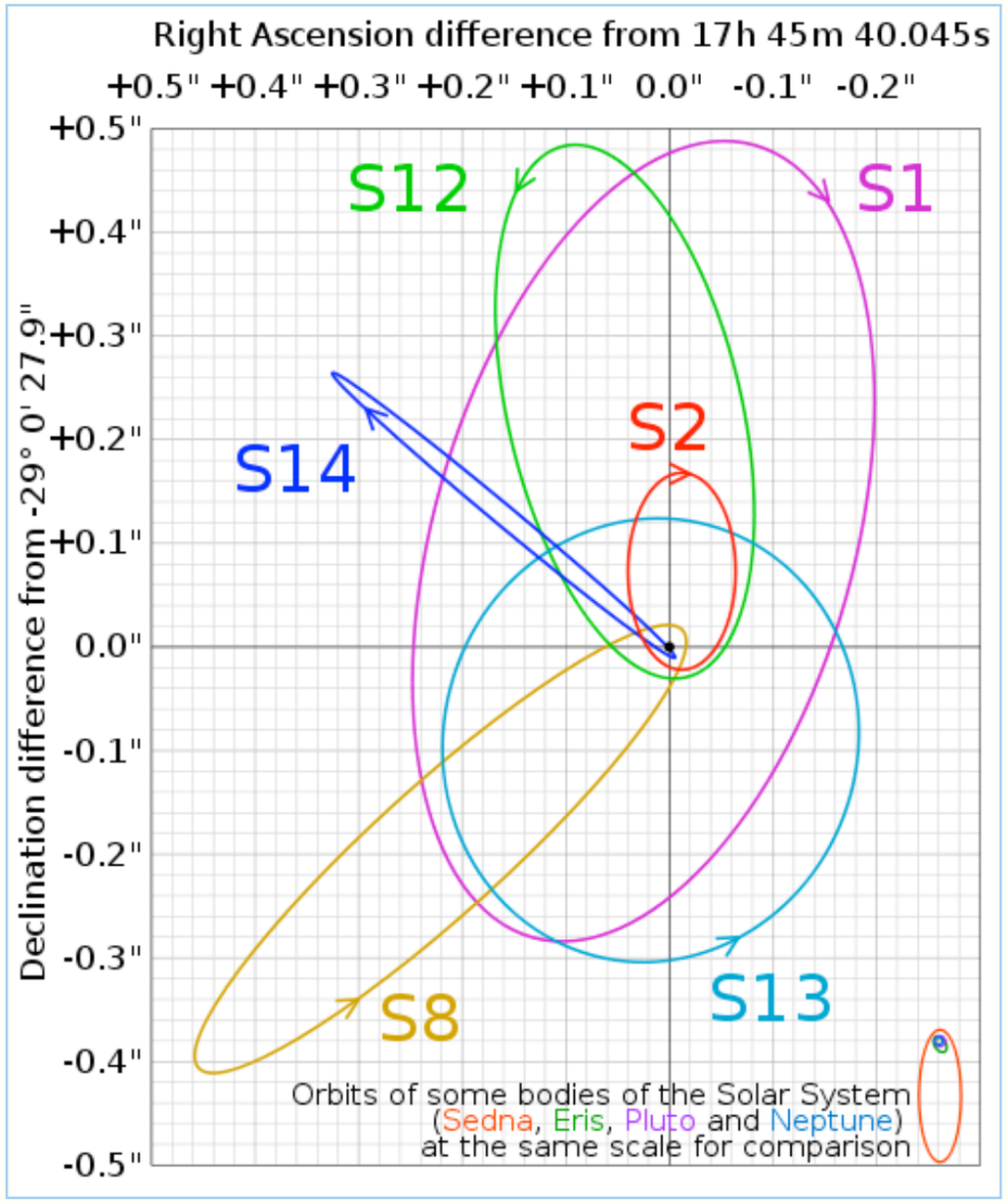
A.Riess B.Schmidt
S.Perlmutter

Type Ia supernovae

Negatieve druk:
donkere energie

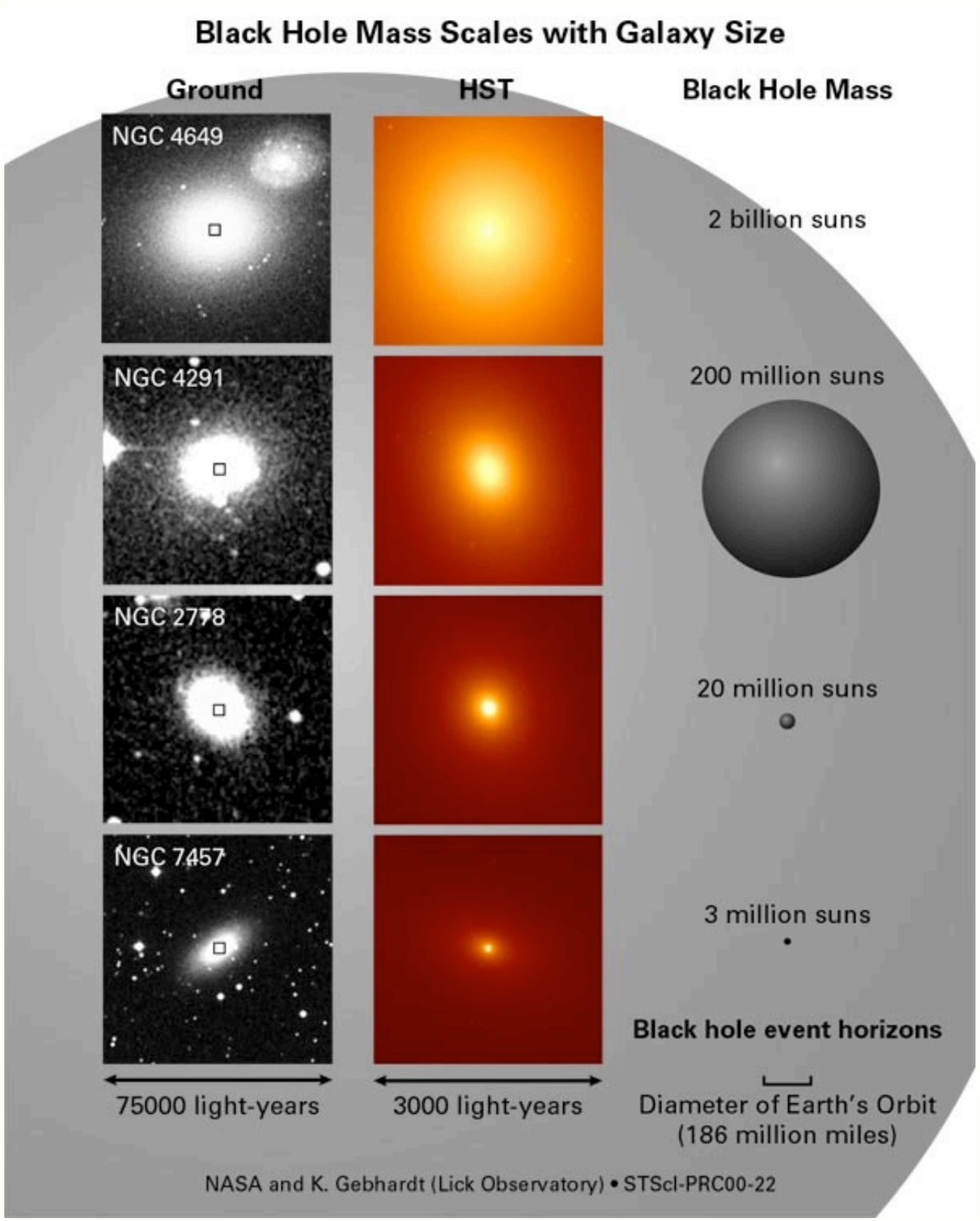
Galactisch centrum

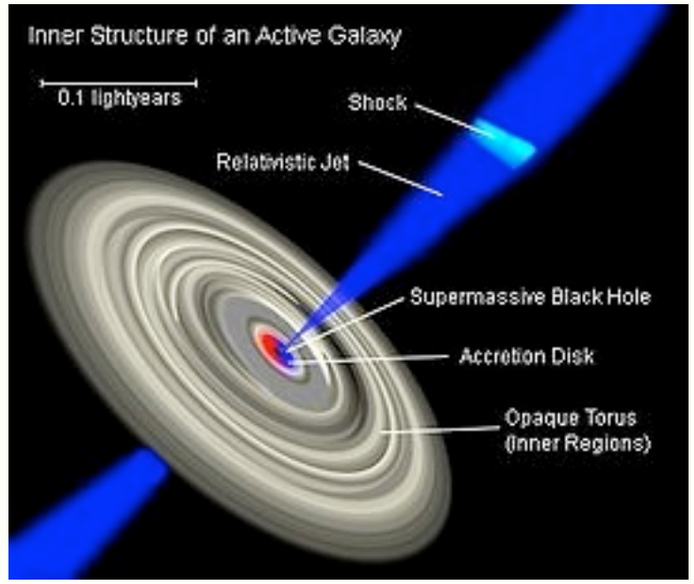




$$M_{centrum} = 4 \times 10^6 M_{zon}$$

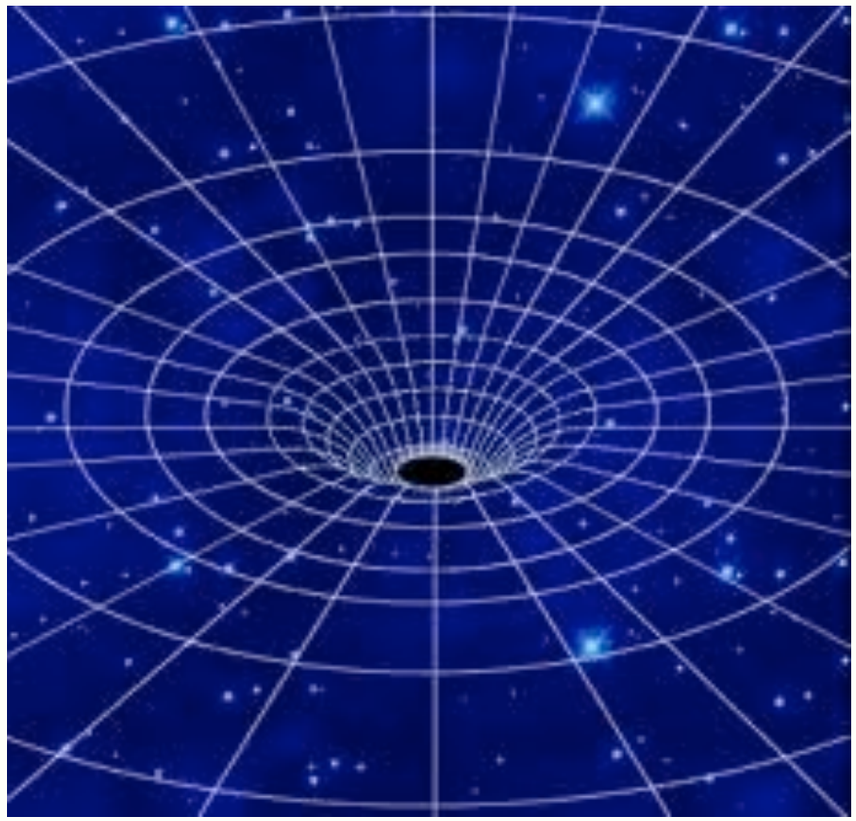
Zwarte gaten





Jet M87

Zwarte gaten



Horizon:

$$\frac{GMm}{R_S} = \frac{1}{2} m c^2$$

$$R_S = \frac{2GM}{c^2}$$

Gravitatie

$$R_{zon} = 2{,}95 \times 10^{3}\ m$$
$$R_{aarde} = 8{,}87 \times 10^{-3}\ m$$
$$R_{elektron} = 1{,}35 \times 10^{-57}\ m$$

Schwarzschildstraal

$R_S = 2GM/c^2$

Quantumtheorie

$$\lambda_{zon} = 1{,}11 \times 10^{-72}\ m$$
$$\lambda_{aarde} = 0{,}37 \times 10^{-66}\ m$$
$$\lambda_{elektron} = 0{,}39 \times 10^{-13}\ m$$

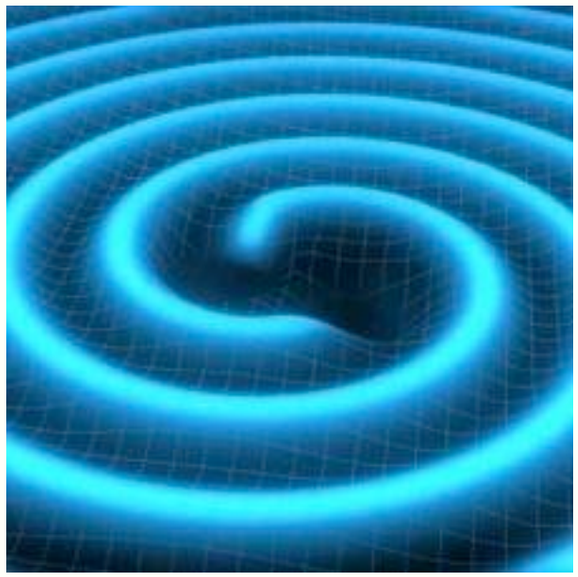
Comptongolflengte

$\lambda_C = h/Mc$

Planck massa: $R_S = \lambda_C$

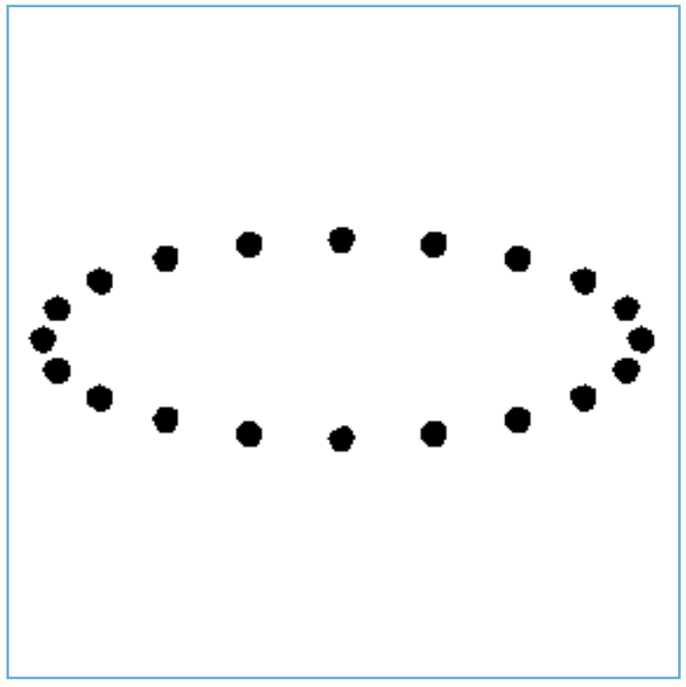
$$M_{Planck} = 5{,}5 \times 10^{-8}\ kg = 3 \times 10^{19}\ GeV/c^2$$

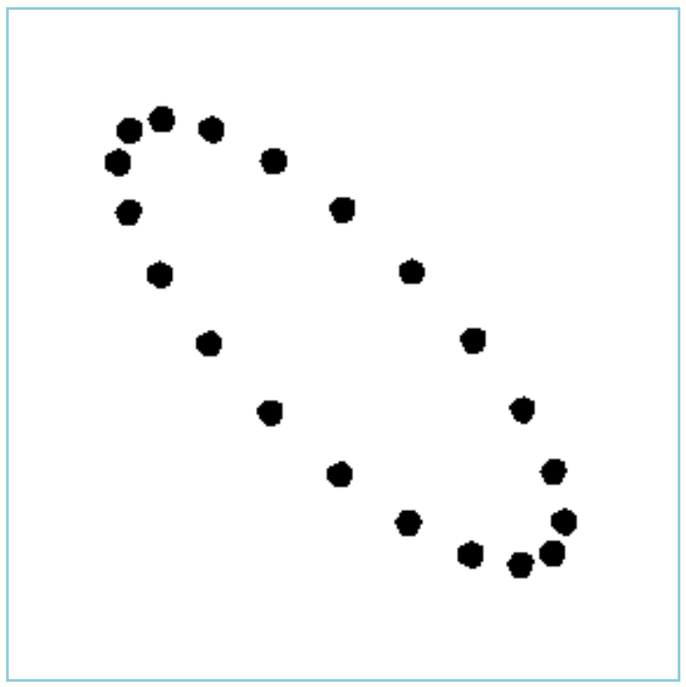
$$R_{Planck} = 4 \times 10^{-35}\ m$$

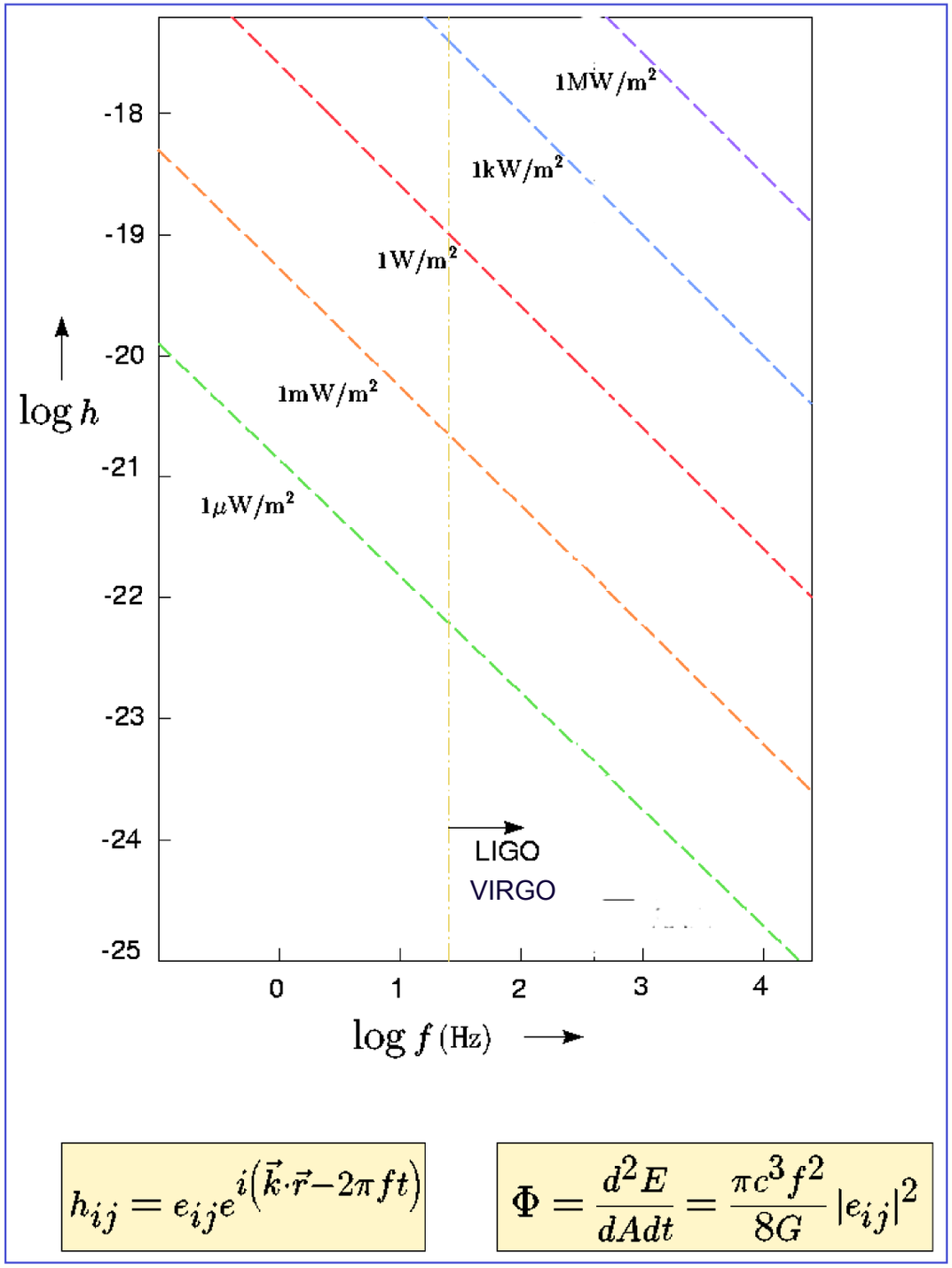


Gravitatiegolven

- rimpels in de ruimte-tijd
- voortplanting met de lichtsnelheid
- 2 polarisaties
- quadrupoolnatuur







$$h_{ij} = e_{ij} e^{i\left(\vec{k}\cdot\vec{r} - 2\pi f t\right)}$$

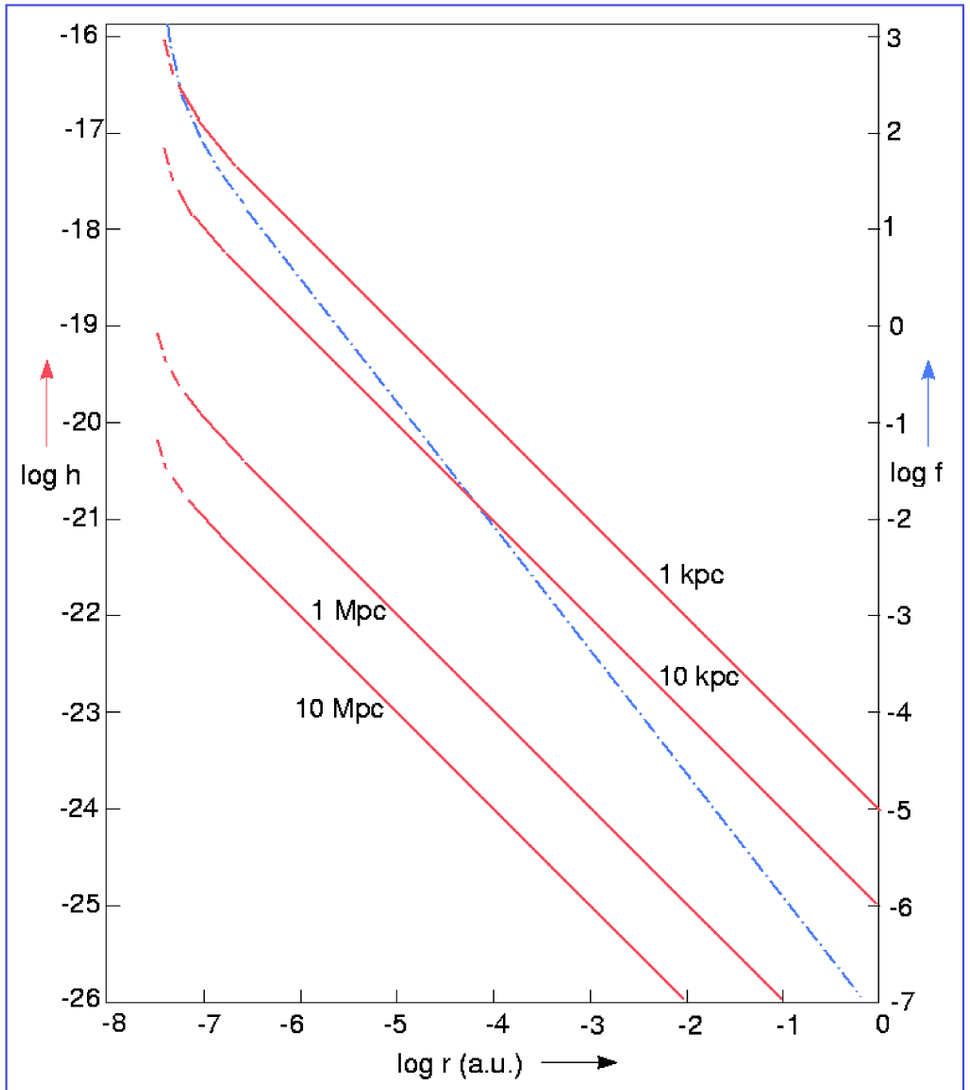
$$\Phi = \frac{d^2E}{dAdt} = \frac{\pi c^3 f^2}{8G} |e_{ij}|^2$$

Intensiteit van gravitatiegolven:

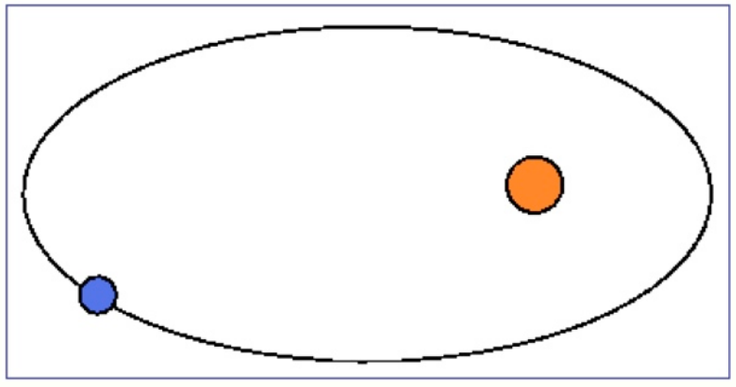
amplitude en flux

als functie van frequentie

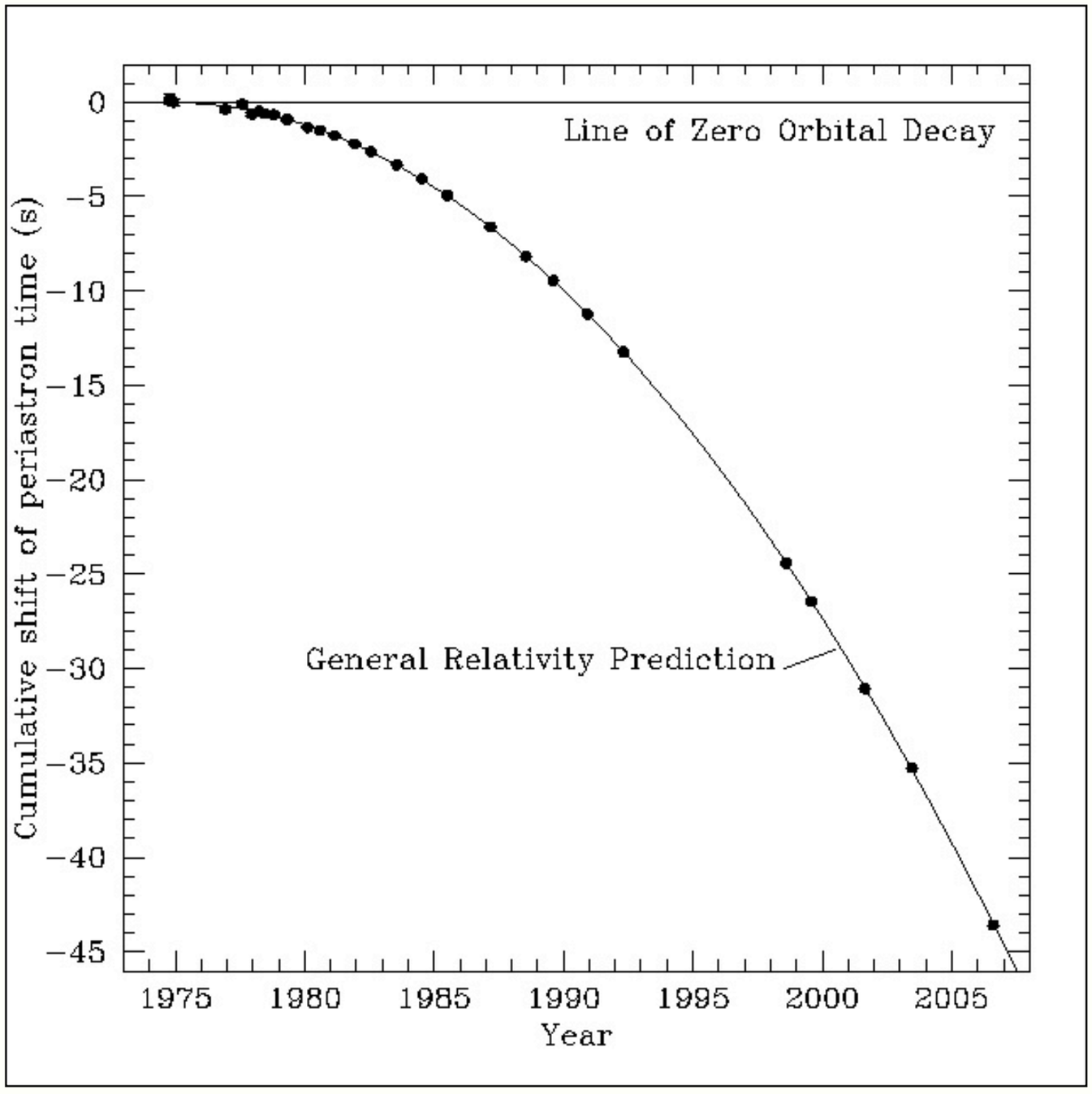
Binary stars



$$f = 0.6 \times 10^{-7} \frac{\sqrt{(M_1 + M_2)/M_\odot}}{(r/[1\,\mathrm{a.u.}])^{3/2}}\ \mathrm{Hz}$$

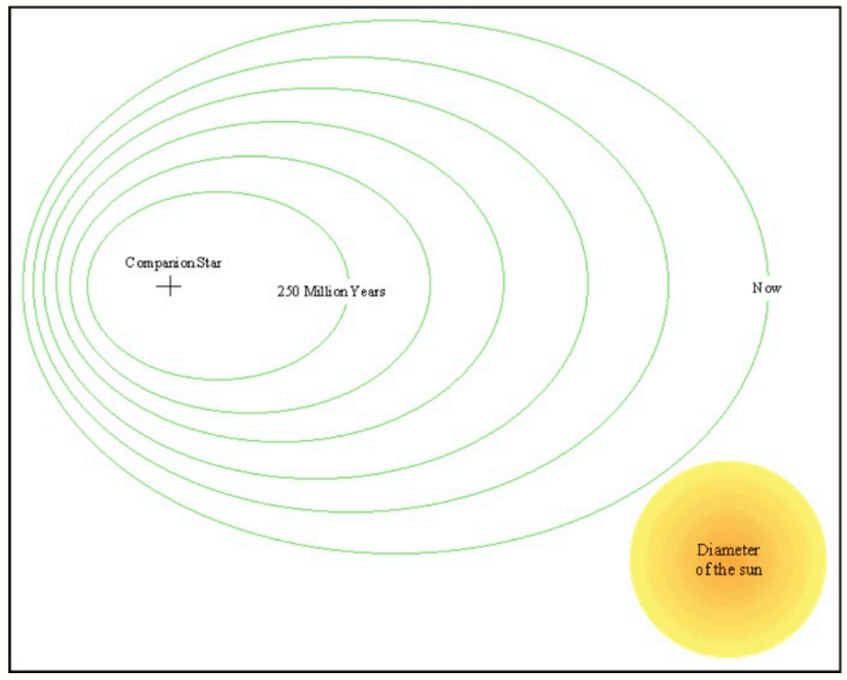


PSR 1913+16

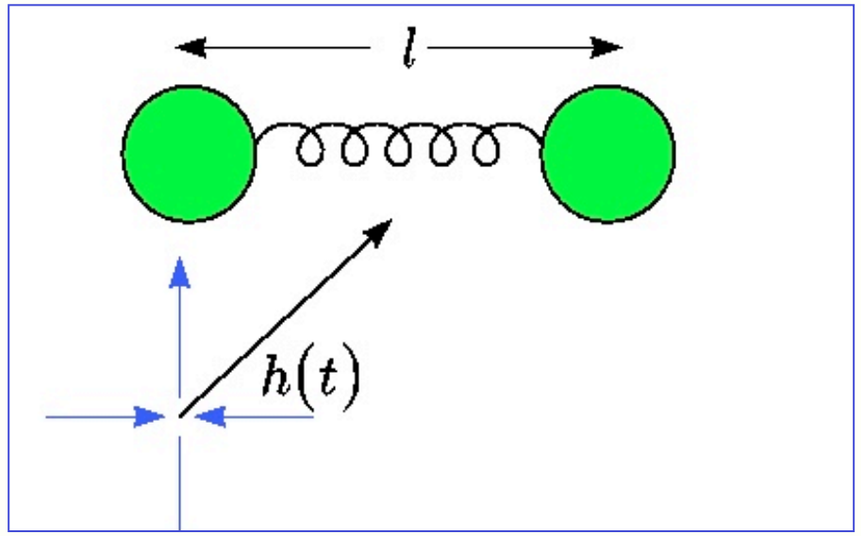


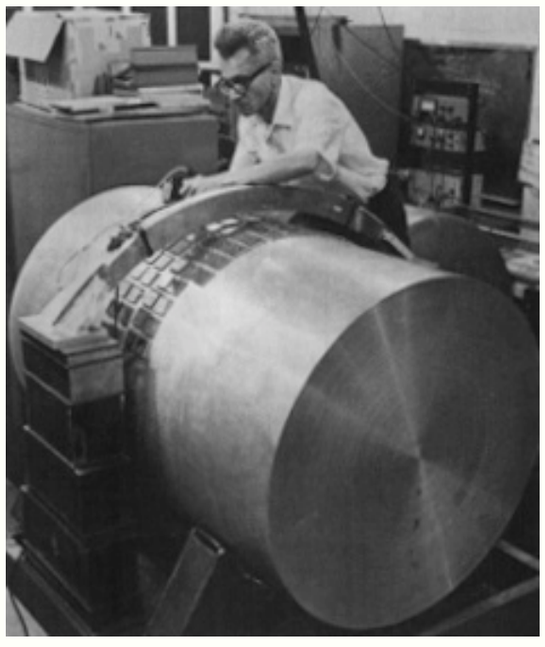
J.Taylor

Dubbel-pulsar (Hulse-Taylor, 1975)



Detectie I

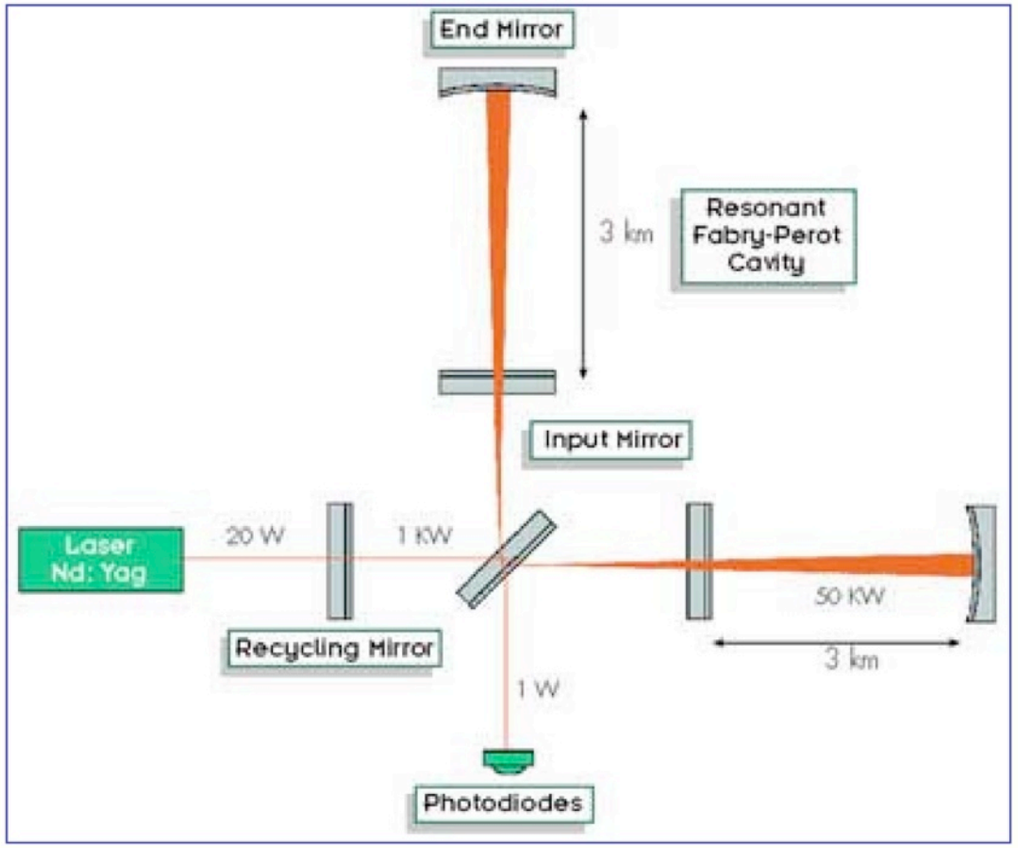




Joe Weber
(1960)

Minigrail
(2012)

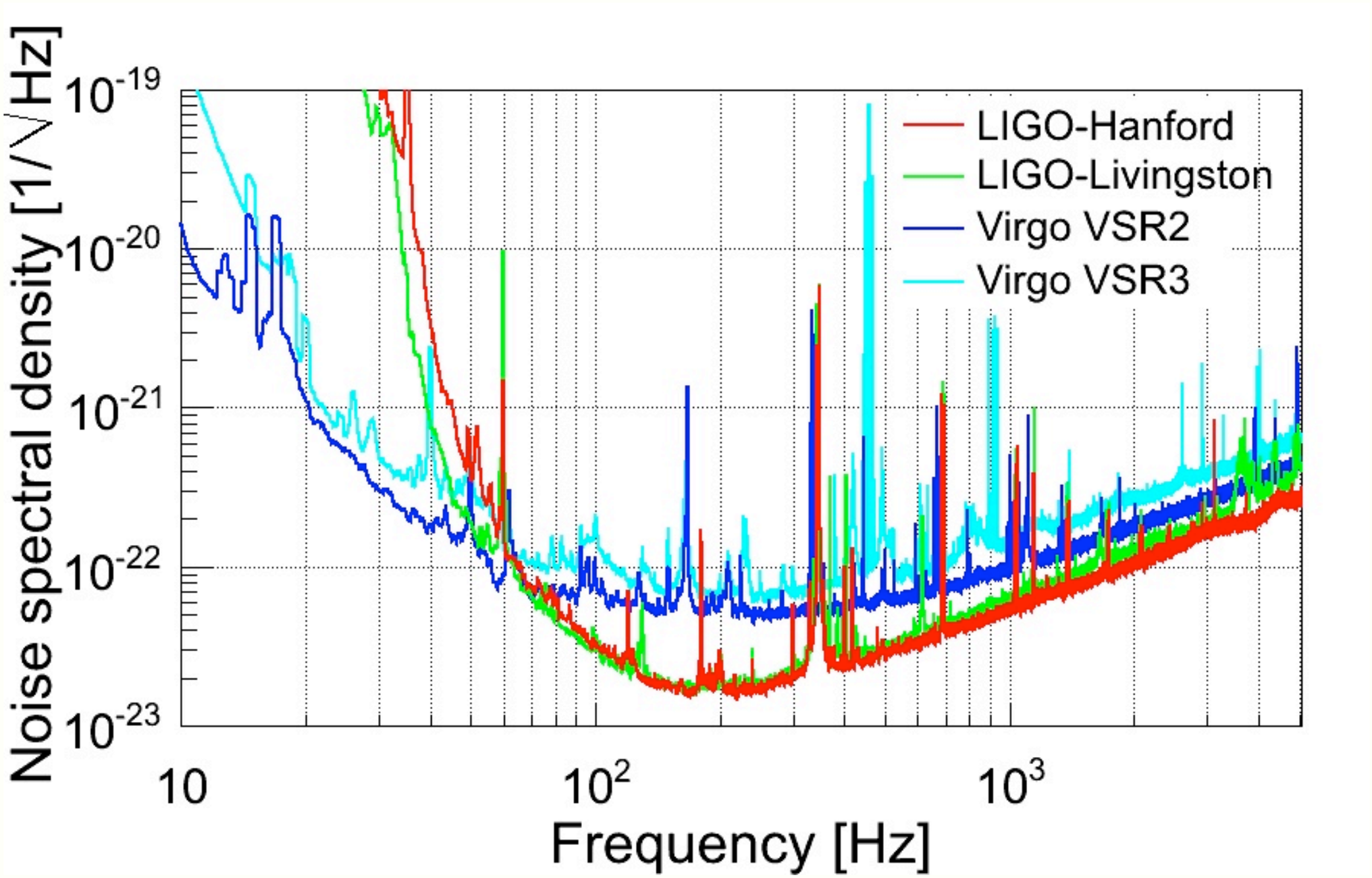
Detectie II



Interferometer

Virgo (Italië)

LIGO-VIRGO
gevoeligheid



The Gravitational Wave Spectrum