Dark Matter, Dark Energy & Neutrino Mass

暗物质，暗能量和中微子质量

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理论物理前沿暑期讲习班——暗物质，中微子与粒子物理前沿

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中山大學
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Lecture 1: Introduction to Particle Physics and Cosmology

Lecture 2: Some Basic Backgrounds of the Standard Model of Particle Physics

Lecture 3: Neutrino Mass Generation

Lecture 4: Theoretical Understanding of Dark Matter Detections

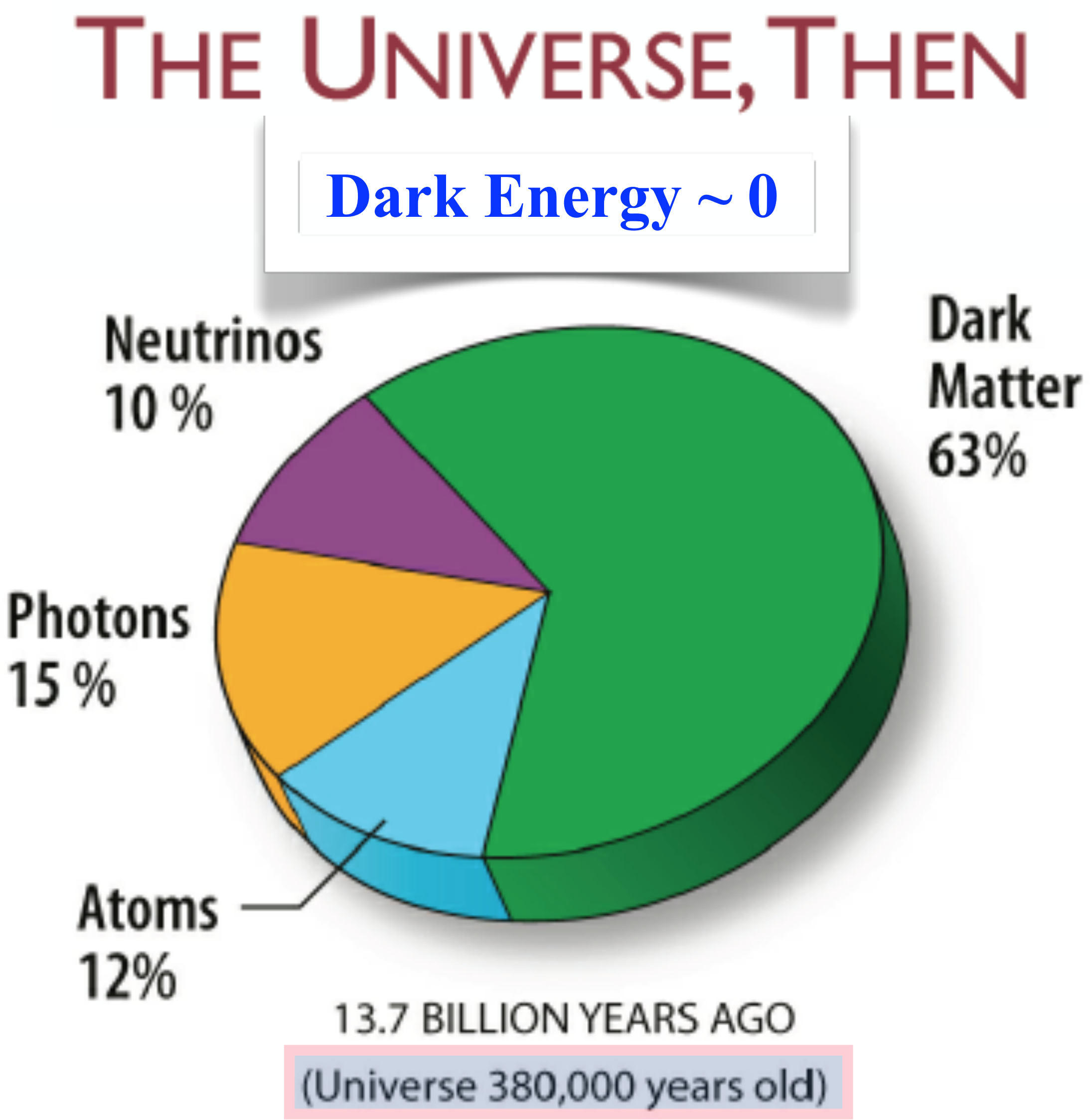
Lecture 5: Dark Energy and Gravitational Waves

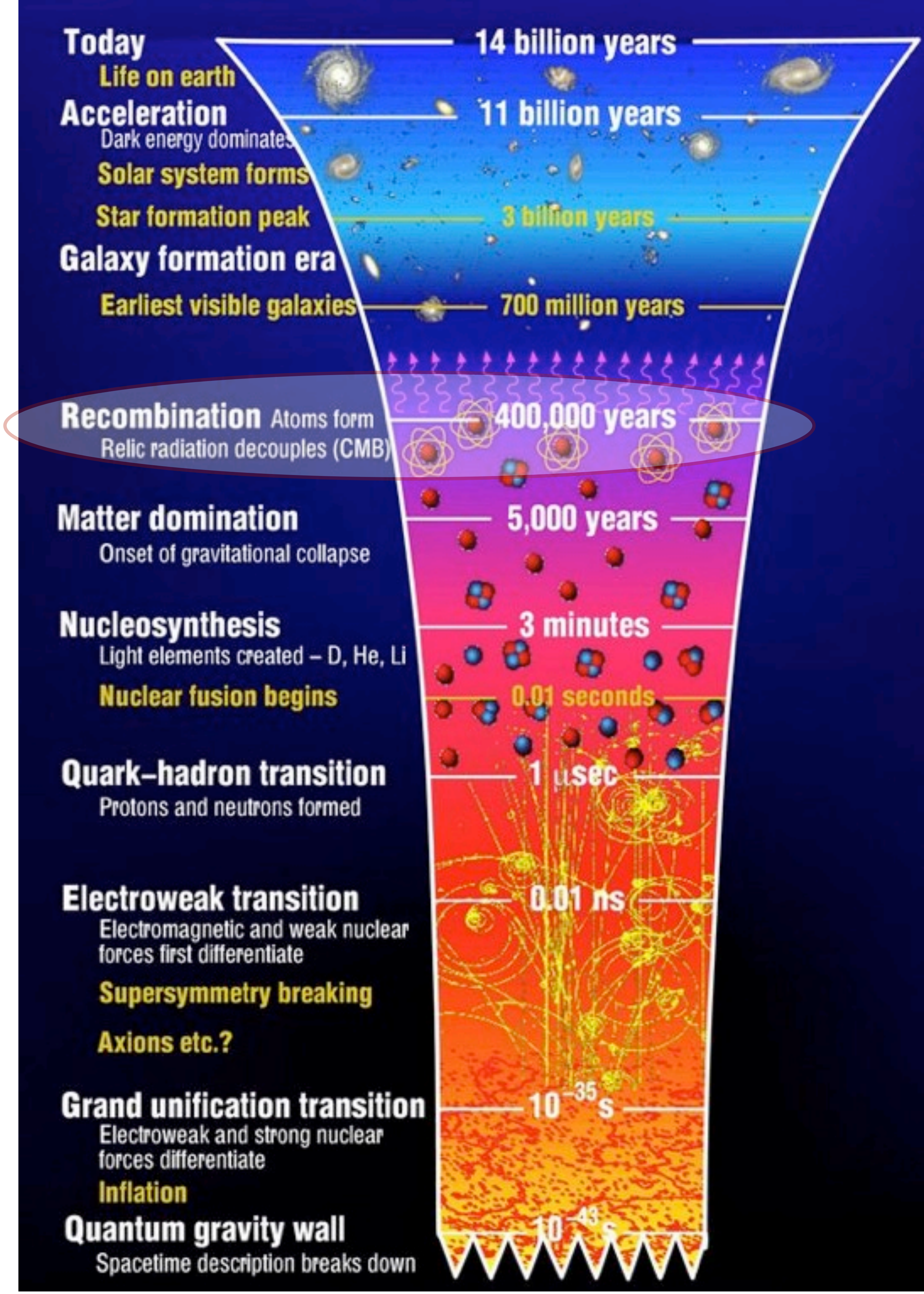
Lecture 5: Dark Energy and Gravitational Waves

Outline

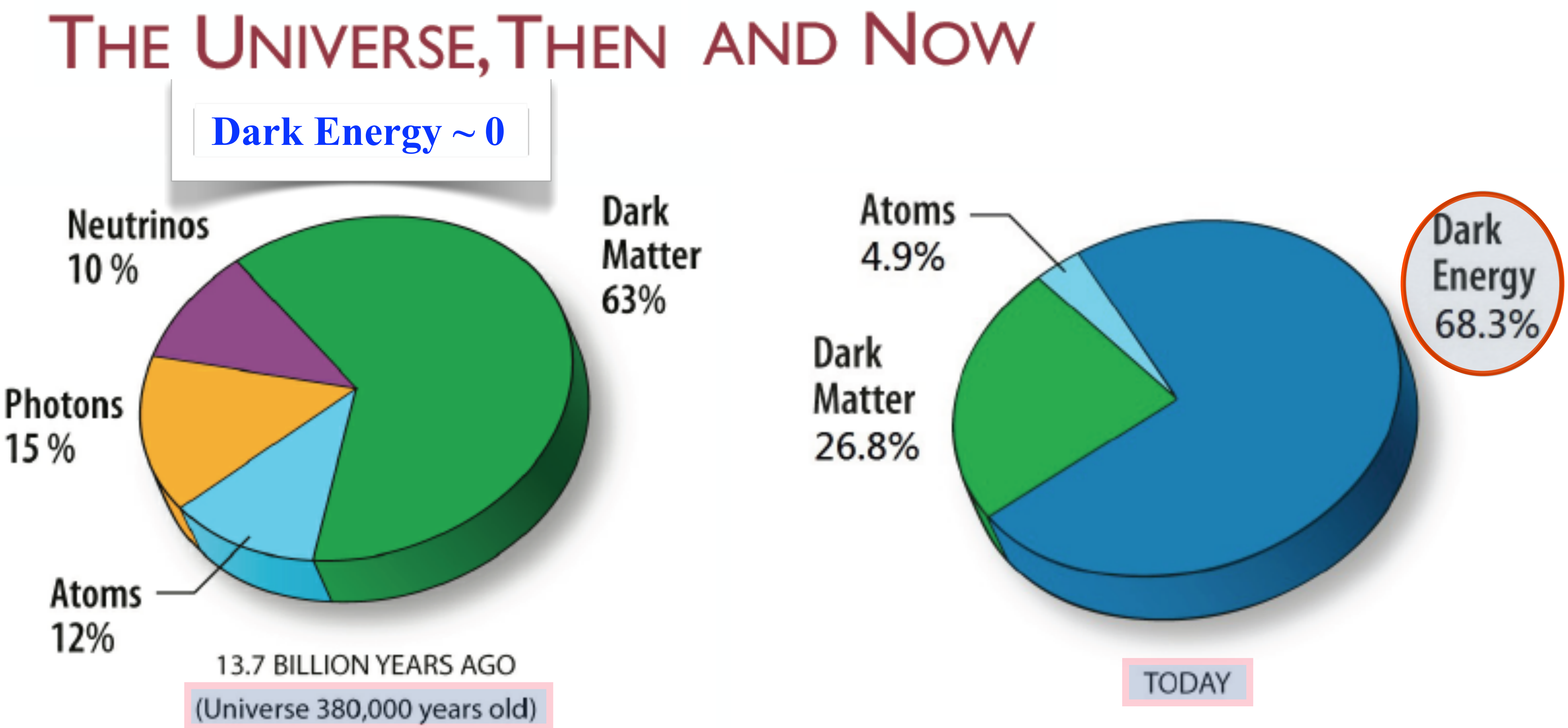
- Introduction
- Some basic concepts in cosmology
- Dark Energy
  - **Equation of state of Dark Energy**
  - **Dynamical Dark Energy models**
  - **Modified gravity theories**
  - **Teleparallel Dark Energy**
- ***Gravitational Waves***

- Introduction





- Introduction



What is the real nature of Dark Energy?

95% of the cosmic matter/energy is a mystery.

暗能量

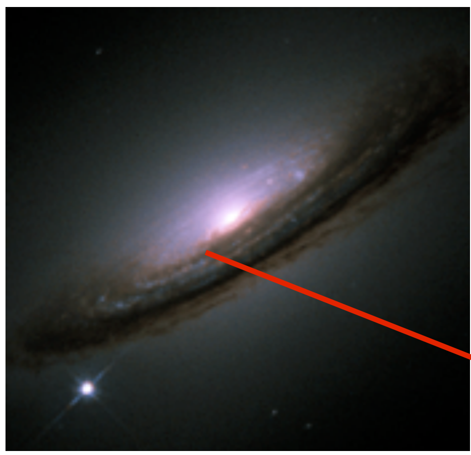
Concordance region:

68% dark energy

27% dark matter

5% atoms

SNe Ia



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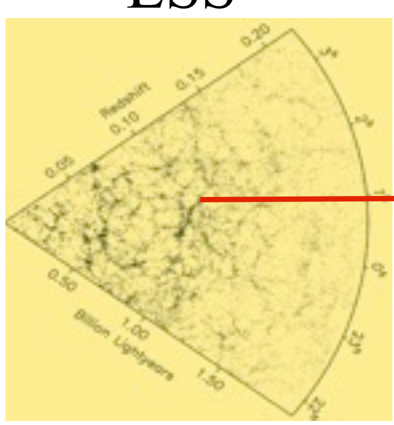
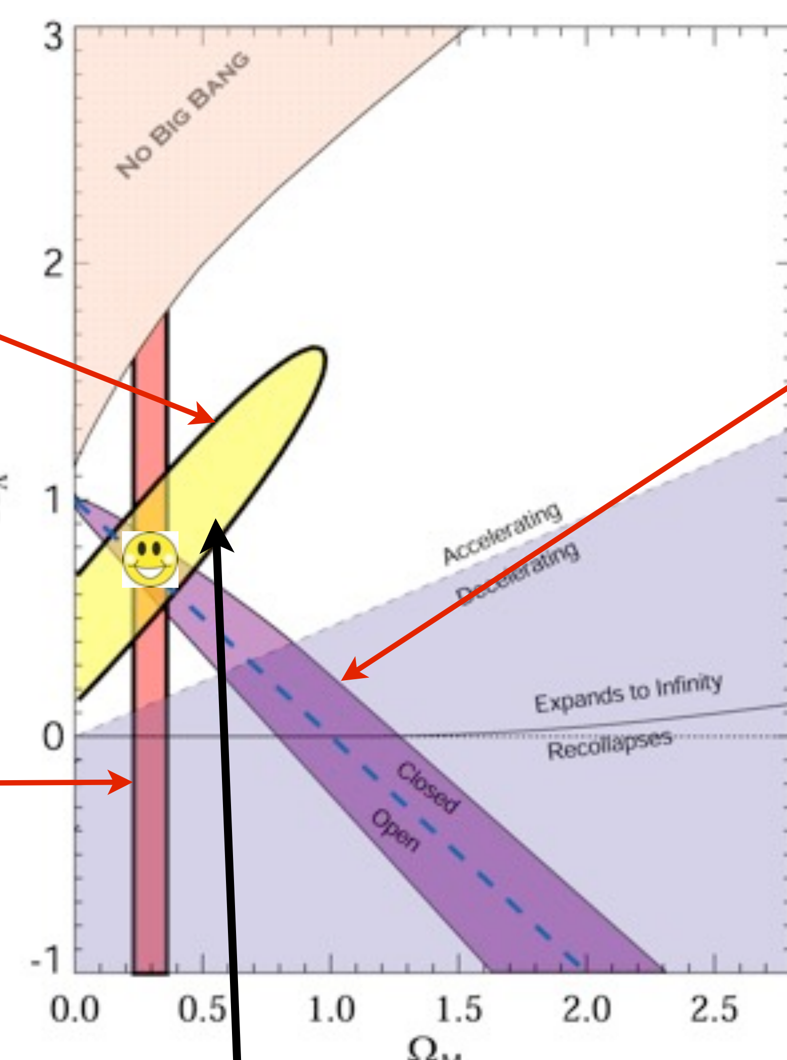


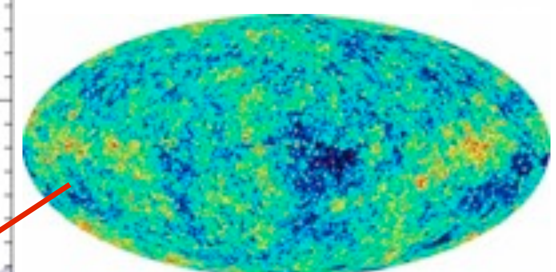
暗能量

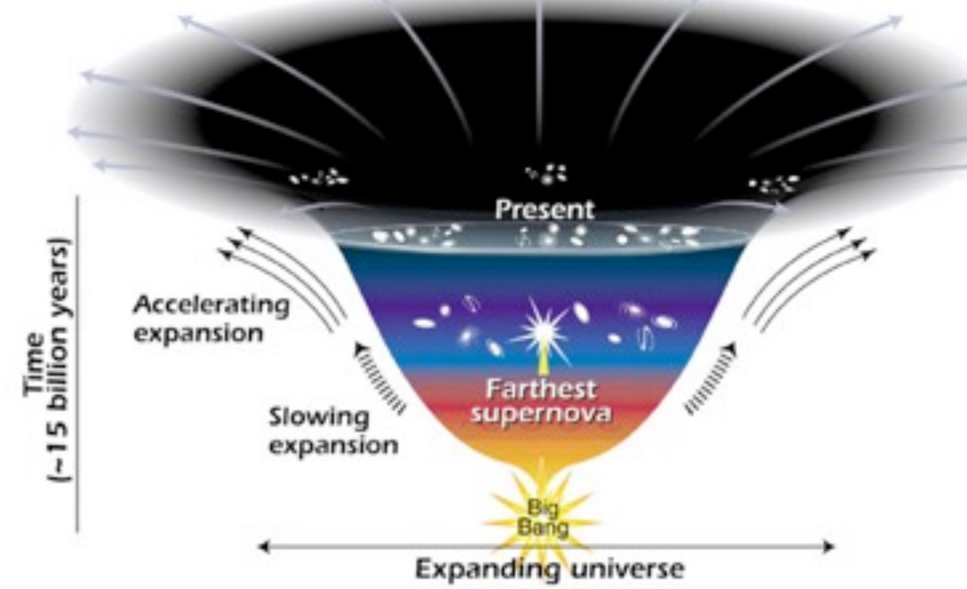


物質

2011 N.P. in Physics

CMB

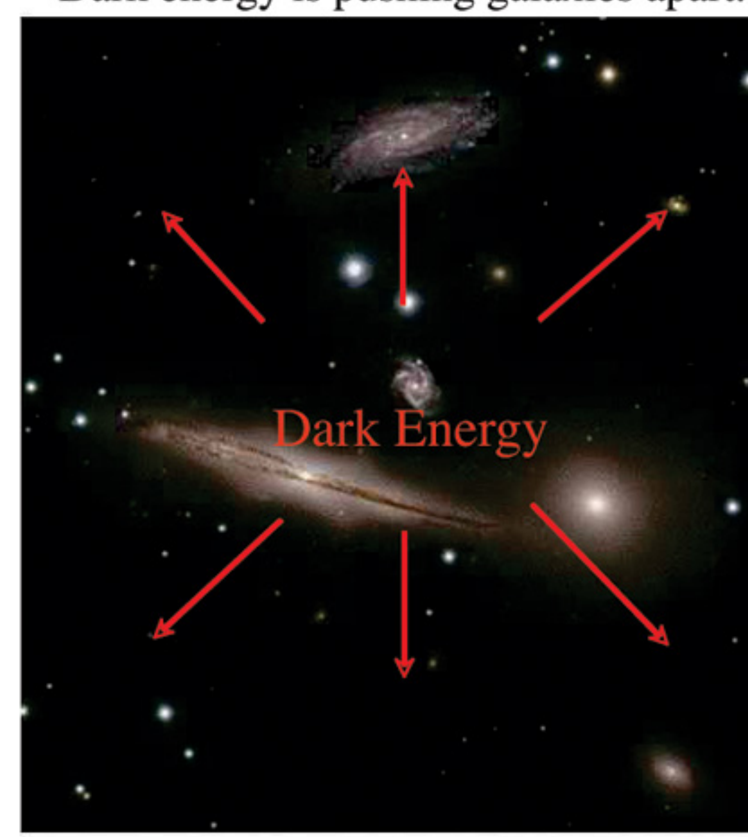


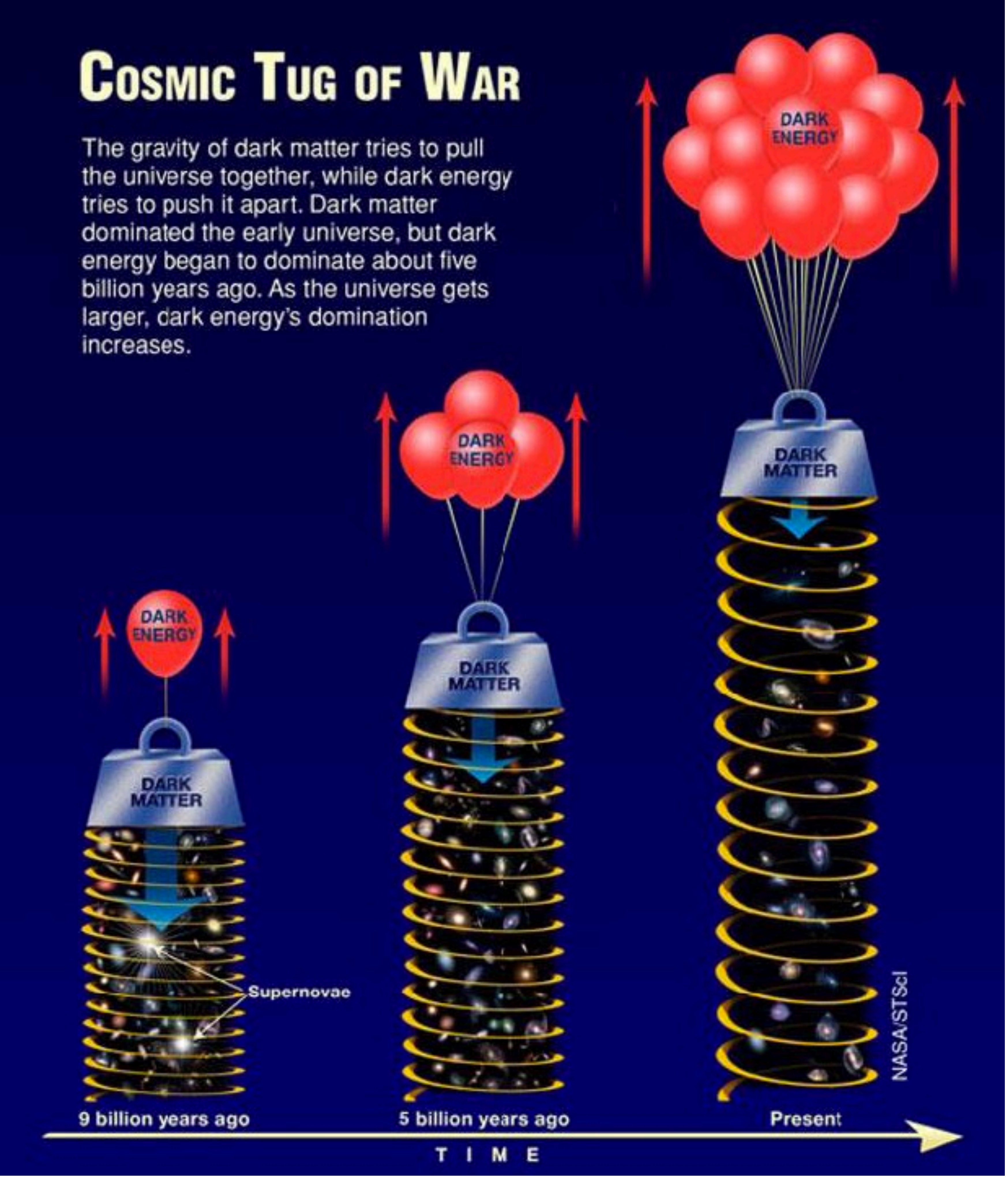


This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

The current universe is accelerating!

Dark energy is pushing galaxies apart.




Cosmic Tug of War
The gravity of dark matter tries to pull the universe together, while dark energy tries to push it apart. Dark matter dominated the early universe, but dark energy began to dominate about five billion years ago. As the universe gets larger, dark energy's domination increases.
DARK ENERGY
DARK MATTER
Supernovae
DARK ENERGY
DARK MATTER
DARK ENERGY
DARK MATTER
NASA/STScI
9 billion years ago
5 billion years ago
Present
TIME

Edward Witten

IAS, Princeton

W语录

W

‘Most embarrassing observation in physics’ – that’s the only quick thing I can say about dark energy that’s also true.”

W

W语录

- Some basic concepts in cosmology

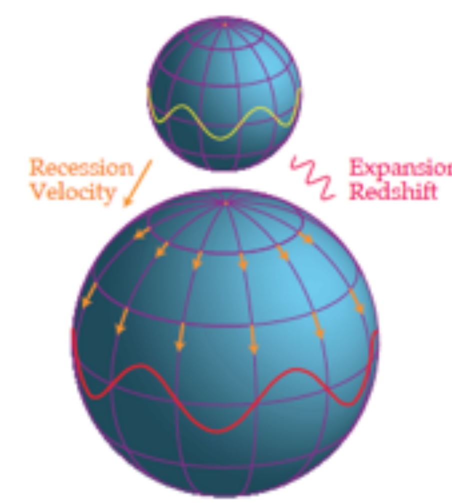
Cosmological principle: the Universe looks the same whoever and wherever you are.

宇宙学原理：宇宙不仅仅没有中心（均匀的），
而且是各向同性的。这个宇宙由FRW模型描述。

Homogeneity and isotropy

Our large-scale Universe possesses two important properties, homogeneity and isotropy.

Homogeneity is the statement that the Universe looks the same at each point, while isotropy states that the Universe looks the same in all directions.



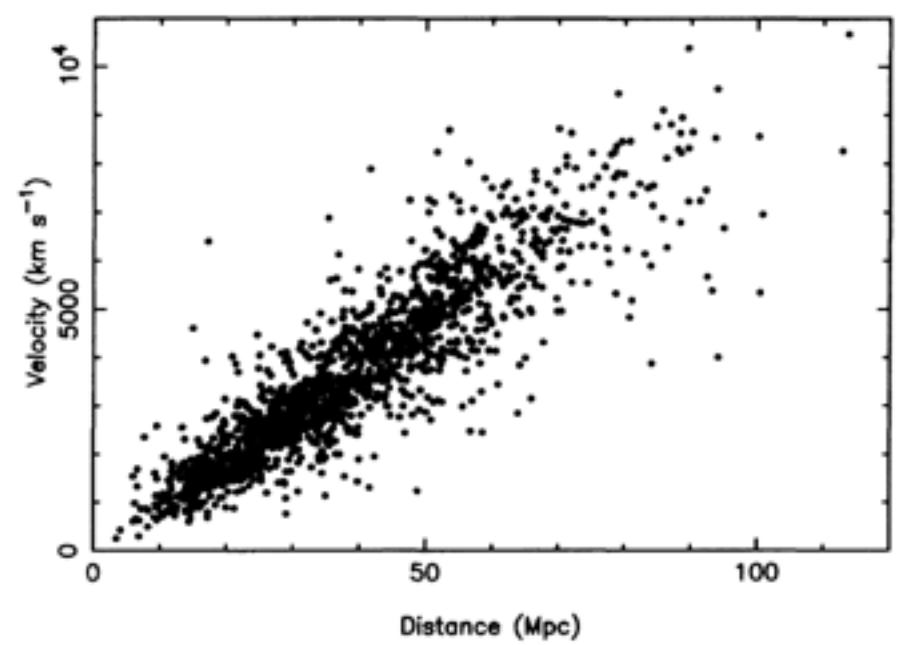
The expansion of the Universe

Redshift z: $$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$ $$z = \frac{v}{c}$$

where λ_{em} and λ_{obs} are the wavelengths of light at the points of emission (the galaxy) and observation (us), v is a speed of a nearby object.

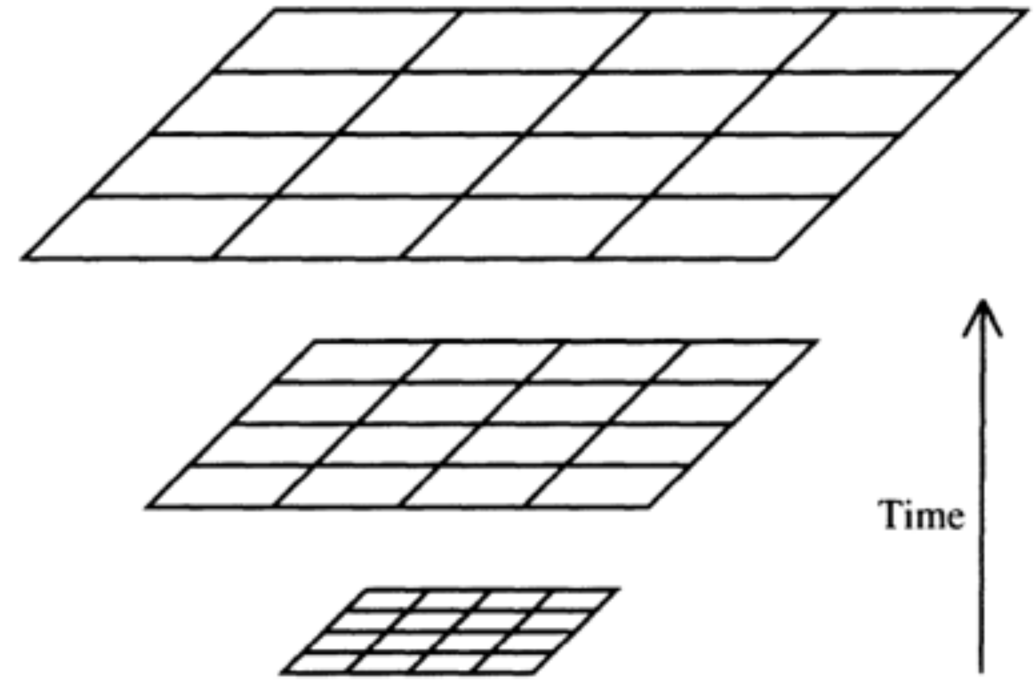
Hubble's law $$\vec{v} = H_0 \vec{r}$$

H_0 is known as Hubble's constant.



Big Bang In the distant past everything in the Universe was much closer together. Indeed, trace the history back far enough and everything comes together. The initial explosion is known as the Big Bang,

A model of the evolution of the Universe from such a beginning is known as the Big Bang Cosmology.



Comoving coordinates

carried along with the expansion.

$$\vec{r} = a(t)\,\vec{x}$$

real distance r and comoving distance x

a(t) is known as the scale factor of the Universe. $a(t_0) = 1$ at present time $t = t_0$.

$$\frac{a(t)}{a(t_0)} = \frac{1}{1+z}$$

$a(t_0) = 1$ ← $a = a(t)$

$z = 0$ $z = z$

The larger the redshift z means the earlier the event.

The Friedmann equation

Newtonian gravity

$$F = \frac{GMm}{r^2} = \frac{4\pi G\rho r m}{3} \qquad V = -\frac{GMm}{r} = -\frac{4\pi G\rho r^2 m}{3}$$

$$U = T + V = \frac{1}{2}m\dot{r}^2 - \frac{4\pi}{3}G\rho r^2 m \longrightarrow U = \frac{1}{2}m\dot{a}^2x^2 - \frac{4\pi}{3}G\rho a^2x^2m$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \longleftarrow \text{Friedmann equation}$$

where $k = -2U/mx^2$

The fluid equation

The first law of thermodynamics $dE + pdV = TdS$ (an expanding volume V of unit comoving radius)

$$E = m = \frac{4\pi}{3}a^3\rho \qquad \frac{dE}{dt} = 4\pi a^2 \rho \frac{da}{dt} + \frac{4\pi}{3}a^3 \frac{d\rho}{dt}$$

Assuming a reversible expansion $dS = 0$ and $\frac{dV}{dt} = 4\pi a^2 \frac{da}{dt}$

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + p\right) = 0$$

← fluid equation — Continuity equation

The equation of state $w = p/\rho$

The acceleration equation

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

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + p\right) = 0$$

$$\rightarrow \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3p\right) \rightarrow \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho\left(1 + 3w\right)$$

Positive acceleration clearly requires

$p < -3\rho$

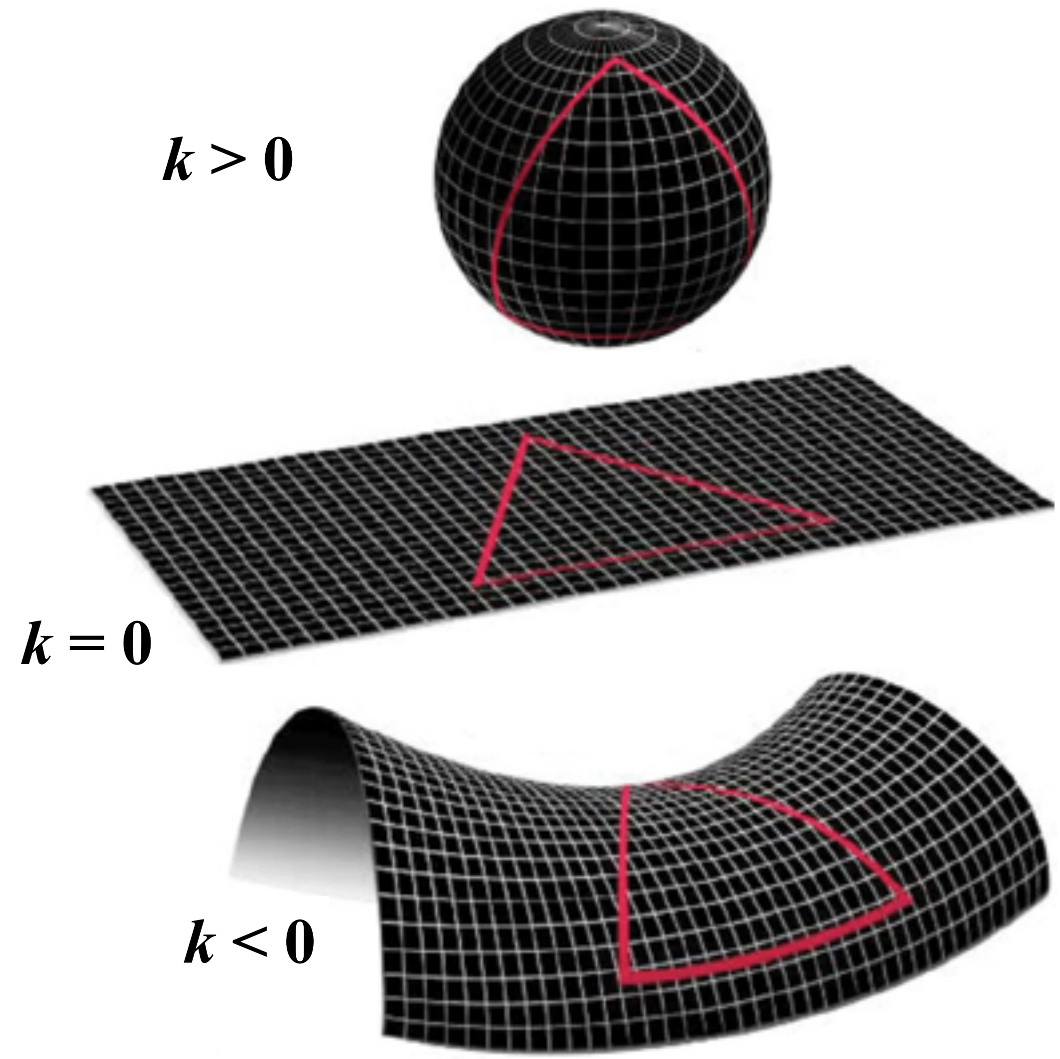
$w \equiv p/\rho < -1/3$

☞ **Negative pressure P of dark energy**

The Geometry of the Universe

A summary of possible geometries.

curvature	geometry	angles of triangle	circumference of circle	type of Universe
$k>0$	spherical	$>180^o$	$c<2\pi r$	Closed
$k=0$	flat	180^o	$c=2\pi r$	Flat
$k<0$	hyperbolic	$<180^o$	$c>2\pi r$	Open



k = -2U/mx^2 = 0

A flat universe can have zero total energy.

The Hubble parameter

$$H = \frac{\dot a}{a}$$

$$\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \longrightarrow H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

The Hubble constant

$H_0 \equiv 100$h km s^{-1} Mpc^{-1}

$h \sim 0.7$

The density parameter

$$\Omega(t) \equiv \frac{\rho}{\rho_c}$$

$$\rho_c(t) = \frac{3H^2}{8\pi G}$$

the critical density

$$\rho_c(t_0) = 1.88\,h^2 \times 10^{-26}\,\mathrm{kg\,m^{-3}}$$

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \longrightarrow \Omega - 1 = \frac{k}{a^2H^2}$$

$$\Omega + \Omega_k = 1 \qquad \Omega_k \equiv -\frac{k}{a^2H^2}$$

The Cosmological Constant Λ

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3p\right) + \frac{\Lambda}{3}$$

$$\Omega + \Omega_\Lambda - 1 = \frac{k}{a^2 H^2}$$

$$\Omega_\Lambda \equiv \rho_\Lambda / \rho_c$$

$$\rho_\Lambda \equiv \frac{\Lambda}{8\pi G}$$

Open Universe:	$0 < \Omega + \Omega_\Lambda < 1\,.$
Flat Universe:	$\Omega + \Omega_\Lambda = 1\,.$
Closed Universe:	$\Omega + \Omega_\Lambda > 1\,.$

Comoving Distance d_C

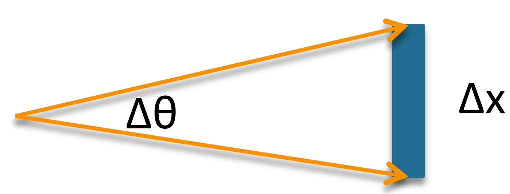
Consider a photon traveling along the r direction to us. $ds^2 = -c^2 dt^2 + a^2(t) dr^2 = 0 \Rightarrow dr = \frac{-c}{a(t)} dt$

$$d_C = r = \int dr = -c\int \frac{dt}{a} = -c\int \frac{da}{a^2 H} = c\int_0^z \frac{dz'}{H(z')}$$

Angular Diameter Distance (physical distance) d_A

$$d_A(z) \equiv \frac{\Delta x}{\Delta \theta}, \qquad \Delta x = a(t) r \Delta\theta$$

(flat universe)



$$d_A(z) = a(t) r = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')}$$

Luminosity distance d_L

$$d_L(z) = (1+z) r(z) = c(1+z)\int_0^z \frac{1}{H(z')} dz'$$

(flat universe)

Cosmological Dynamics

(Einstein, Nov. 25, 1915)

- Einstein equation $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$
- Energy-momentum tensor for isotropic perfect fluid

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

- Continuity equation $T^{\mu}{}_{\nu;\mu} = 0$ (for constant w)

$$\dot{\rho} = -3(\rho + P)H \Rightarrow \dot{\rho} = -3(1+w)\rho\frac{\dot{a}}{a}$$

When w is constant

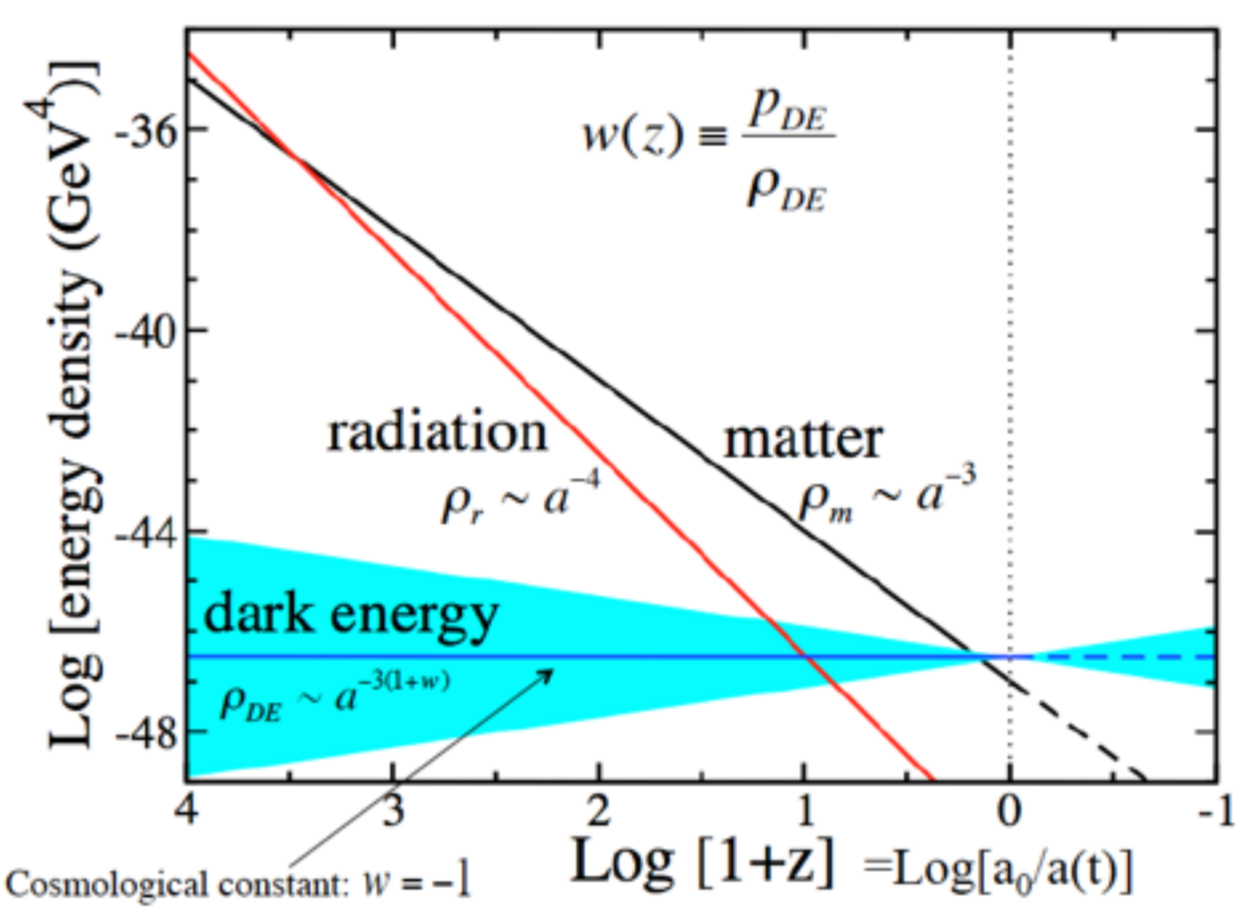
$$a \propto t^{2/3(1+w)} \qquad \rho \propto a^{-3(1+w)}$$

matter $w = 0 \rightarrow \rho \propto a^{-3}$

radiation $w = 1/3 \rightarrow \rho \propto a^{-4}$

Cosmological constant Λ: $w = -1$ → ρ =constant

Dark Energy Equation of State parameter w determines Cosmic Evolution



Radiation dominates at early times (small a), then Matter, and finally Dark Energy.

ΛCDM model

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R - 2\Lambda) + S_m$$

- Einstein equation

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

$$= 8\pi G\left(T_{\mu\nu} + T^{\mathrm{DE}}_{\mu\nu}\right)$$

Friedmann–Lemaître–Robertson–Walker (FLRW) spacetime

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

expansion rate | total energy | curvature

$$H^2 = 8\pi G\,(\rho_M + \rho_{DE})\,/\,3 - k\,/\,a^2$$

$$1 = \Omega_M + \Omega_{DE} - k\,/\,(a^2H^2)$$

G		Newton's constant
a		scale factor or radius
$H \equiv \dot{a}/a$		Hubble parameter
ρ		energy density
p		pressure
k=1, 0, -1		closed, flat, open

$$\Omega \equiv 8\pi G\rho/\,3H^2$$

For the flat universe of k=0:

$$\Omega_{OM} + \Omega_{DM} + \Omega_{DE} = 1$$

$$(\Omega_M = \Omega_{OM} + \Omega_{DM})$$

where $\Omega_{OM} \sim 5\%$, $\Omega_{DM} \sim 27\%$ and $\Omega_{DE} \sim 68\%$

- Dark Energy

  - Equation of state of Dark Energy

$$w = p/\rho$$

What is the value of the equation of state *w* for *Dark Energy*?

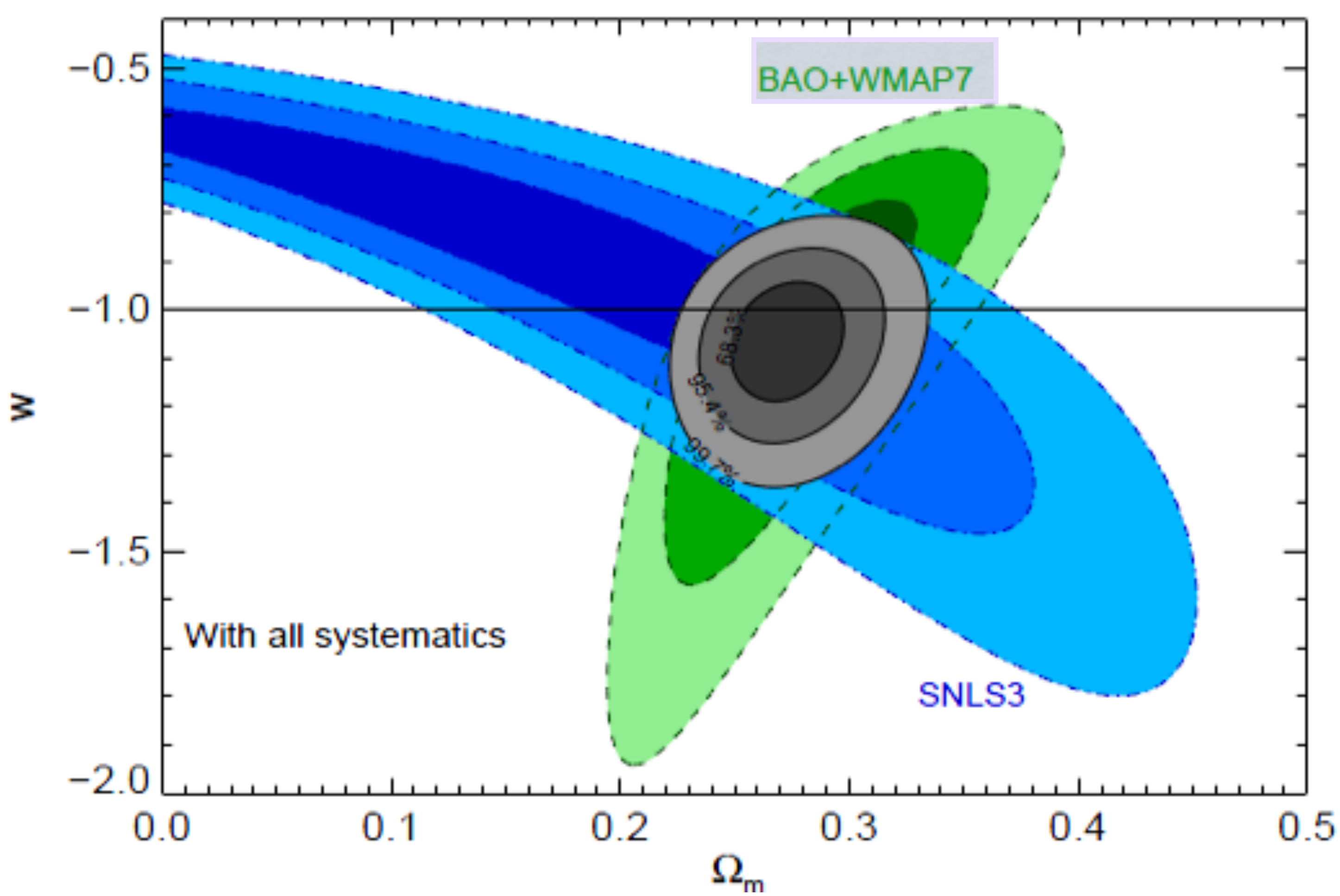
Does *w* vary with time? ☞ **``dynamical" dark energy**

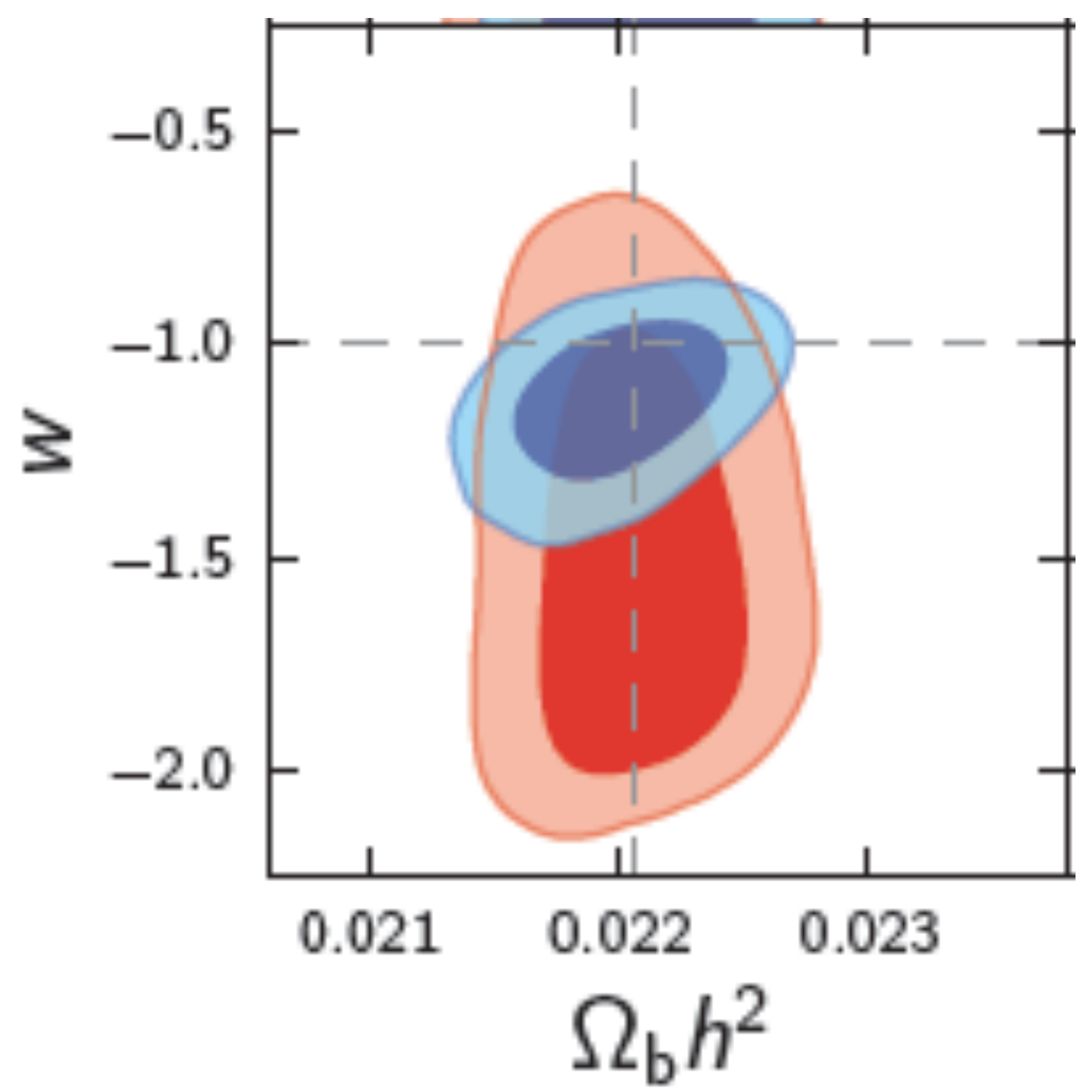
Sullivan et al. (2011) WMAP7

$$\Omega_{DE} = 0.731^{+0.015}_{-0.015}$$

$$w = -1.069^{+0.091}_{-0.092}$$

$w = -1.13^{+0.24}_{-0.25}$ (95%; *Planck*+WP+BAO



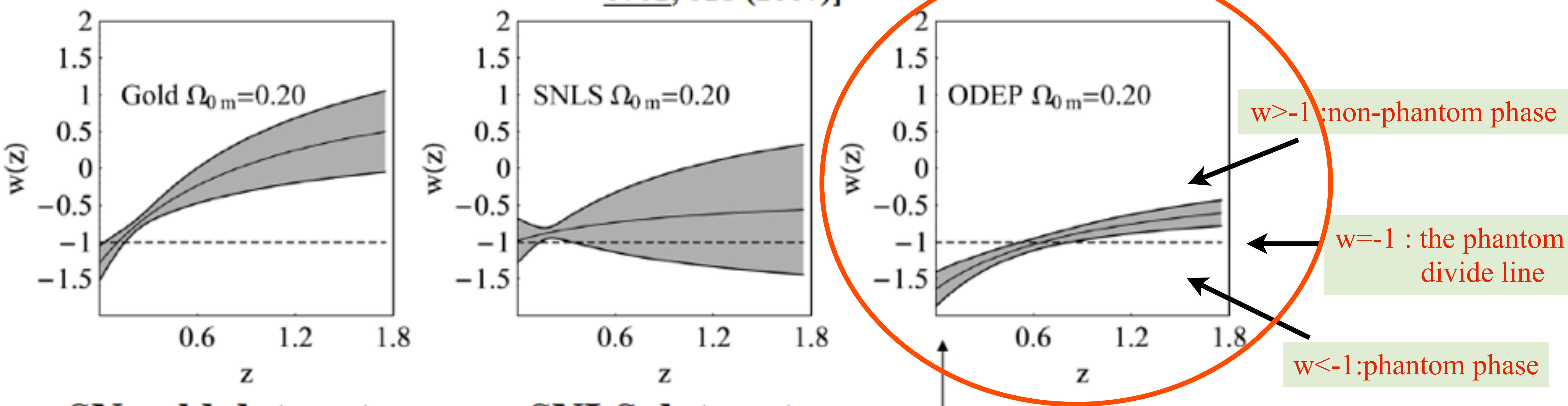


CPL

< Data fitting of $w(z)$ >

$$w(z) = w_0 + w_1 \frac{z}{1+z}$$

From [Nesseris and L. Perivolaropoulos, JCAP 0701, 018 (2007)]



SN gold data set

[Riess *et al.* [Supernova Search Team Collaboration], Astrophys. J. 607, 665 (2004)]

SNLS data set

[Astier *et al.* [The SNLS Collaboration], Astron. Astrophys. 447, 31 (2006)]

Shaded region shows 1σ error.

Cosmic microwave background radiation (CMB) data

[Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. 170, 377 (2007)]

+ SDSS baryon acoustic peak (BAO) data

[Eisenstein *et al.* [SDSS Collaboration], Astrophys. J. 633, 560 (2005)]

- For most observational probes (except the SNLS data), a low Ω_{0m} prior $(0.2 < \Omega_{0m} < 0.25)$ leads to an increased probability (mild trend) for the phantom crossing.

Ω_{0m} : Current density parameter of matter

☞ w(z) increases with z

w<-1 $\xrightarrow{w=-1}$ w>-1

phantom crossing

Physics Landscape Away From The High Energy Frontier

Edward Witten

CERN

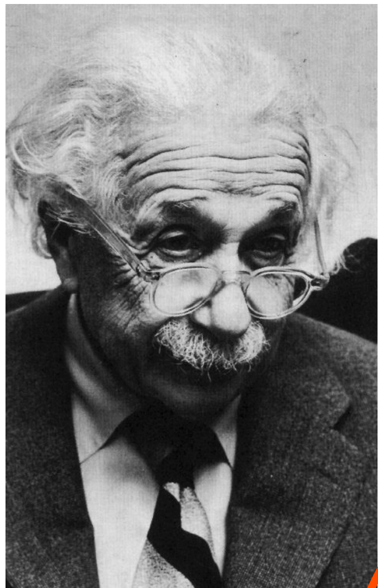
May 11, 2009

W语录

W

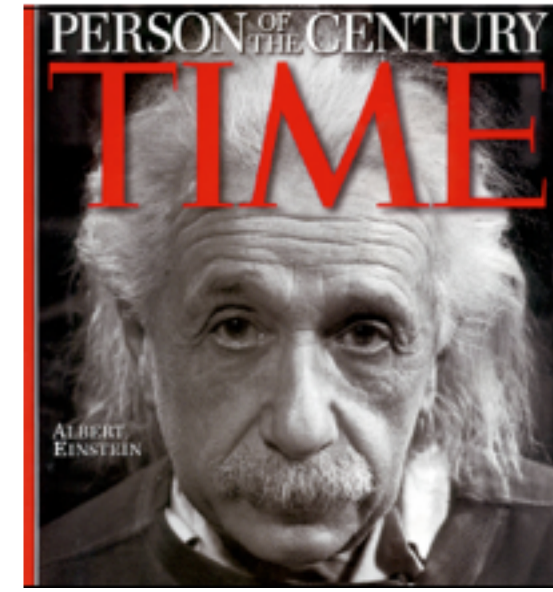
A discovery that the acceleration parameter w is not quite -1 would have almost as big an impact as the original discovery of dark energy.

- Dynamical Dark Energy models



Two main approaches to Dark Energy

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$ **(Einstein equations)**



Modified Gravity

- f(R) gravity
- Scalar-tensor
- DGP
- f(T)
- ....

Modified Matter

- Quintessence
- K-essence
- Quintom or
- Nonsense
- ....

→ $w \neq -1$

→ **The simplest model: cosmological constant Λ** → **ΛCDM**

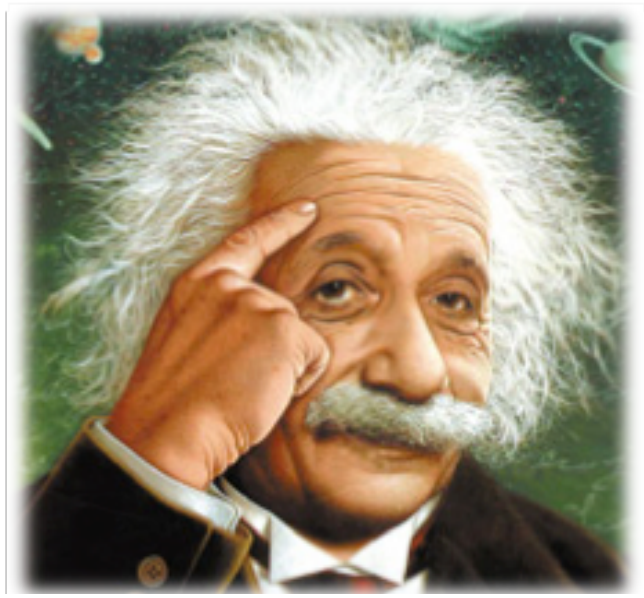
$$w_{\rm DE} \equiv \frac{P_{\rm DE}}{\rho_{\rm DE}} = -1$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

$$R_{uv} - \frac{1}{2} g_{uv} R + \Lambda g_{uv} = 8\pi G T_{uv}^{visible} + T_{uv}^{CDM} + T_{uv}^{DE}$$

The standard cosmology is based upon GR and is consistent with observations

Dynamical DE



Cosmological constant:
``biggest blunder''

Comments on the ΛCDM model:

Cosmological constant Λ causes accelerating expansion.

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R - 2\Lambda) + S_m$$

- Einstein equation

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

$$= 8\pi G\left(T_{\mu\nu} + T_{\mu\nu}^{\mathrm{DE}}\right)$$

- Dark energy $T_{\mu\nu}^{\mathrm{DE}} = -\frac{\Lambda g_{\mu\nu}}{8\pi G}$, $w_{\mathrm{DE}} \equiv \frac{P_{\mathrm{DE}}}{\rho_{\mathrm{DE}}} = -1$

This corresponds to the energy scale $\rho_\Lambda = \frac{3H_0^2}{8\pi G} = 10^{-47}\ GeV^4$

If this originates from vacuum energy in particle physics, $\rho_{vac} \sim m_{pl}^4 = 10^{76}\ GeV^4$

$\frac{\rho^{\mathrm{obs}}}{\rho^{\mathrm{th}}} = 10^{-120}$

A difference of 120 orders of magnitude

S. Weinberg

Cosmological constant problem

Q1: Why so small?

Fine-tuning problem
(known even before the discovery of dark energy)

Q2: Why now?

$\rho_\Lambda^0 \sim \rho_M^0$

Coincidence problem

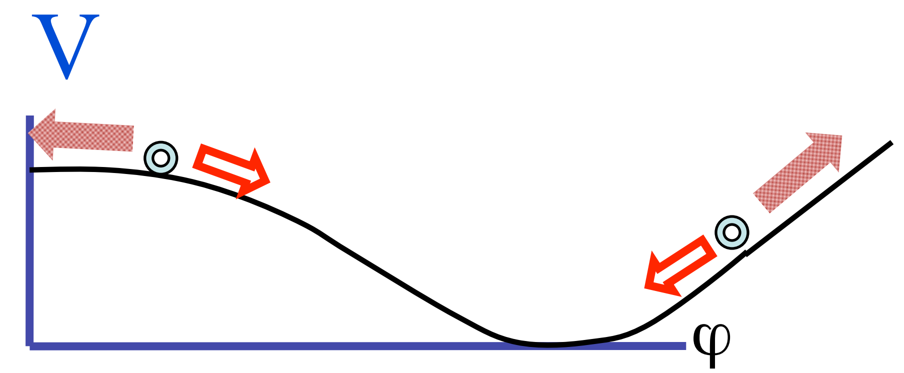
Quintessence

A slowly rolling (nearly) homogeneous scalar field can accelerate the universe

$$\ddot{\phi} + 3H\dot{\phi} = -V'$$

$$w \equiv \frac{p}{\rho} = -1 + \frac{\dot{\phi}^2}{V}$$

Dynamical $\neq 0$



Rolling scalar field dark energy is called "quintessence"

Some quintessence potentials

PNGB aka Axion (Frieman et al)

$$V(\varphi) = V_0(\cos(\varphi / \lambda) + 1)$$

Exponential (Wetterich, Peebles & Ratra)

$$V(\varphi) = V_0 e^{-\lambda\varphi}$$

Exponential with prefactor (AA & Skordis)

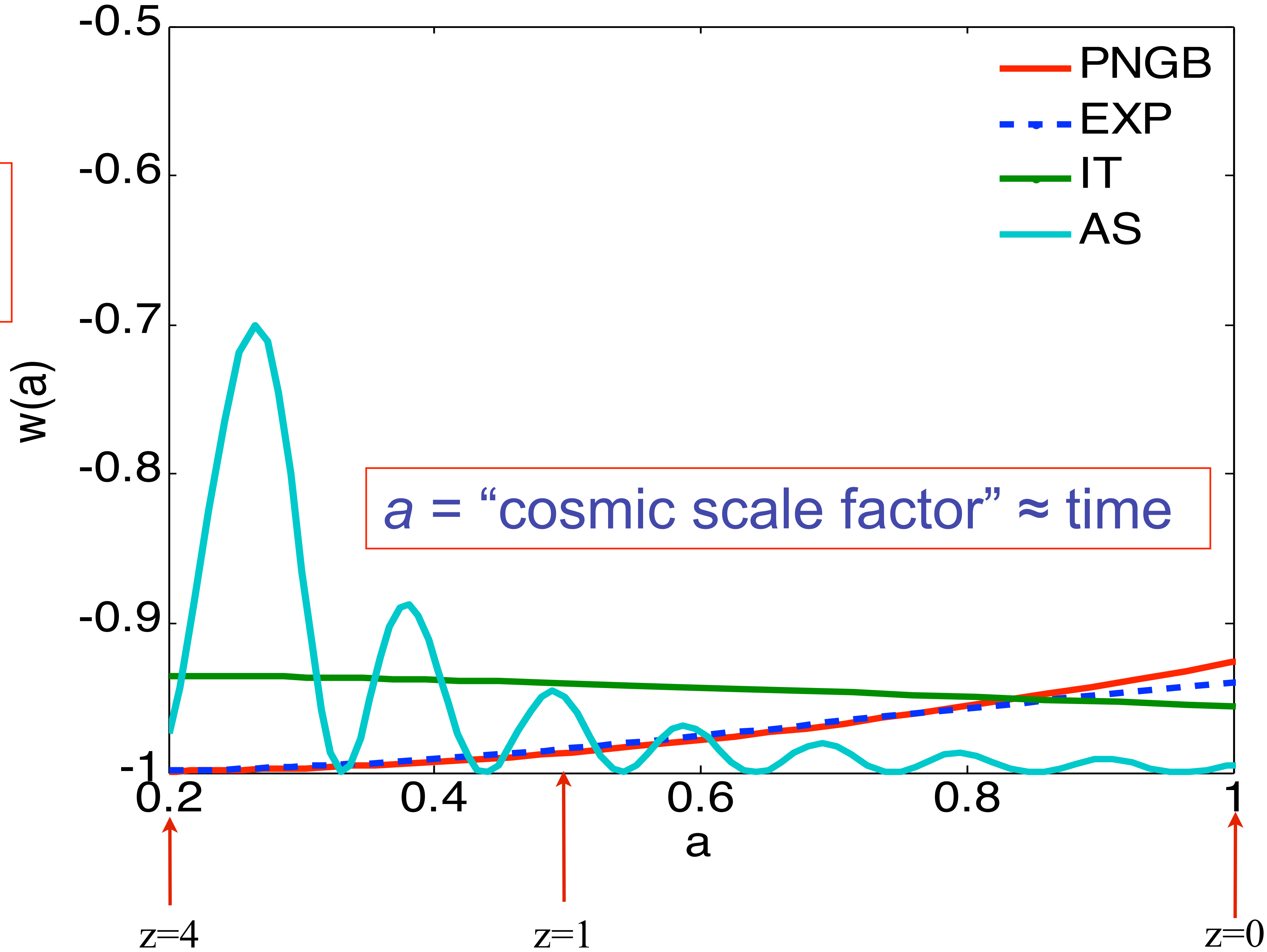
$$V(\varphi) = V_0\left(\chi(\varphi - \beta)^2 + \delta\right)e^{-\lambda\varphi}$$

Inverse Power Law (Ratra & Peebles, Steinhardt et al)

$$V(\varphi) = V_0\left(\frac{m}{\varphi}\right)^{\alpha}$$

…they cover a variety of behavior.

$$w \equiv \frac{p}{\rho}$$



Remarks on Modified Matter Theories:

Quintessence $\mathcal{L} = (1/2)(\partial\phi)^2 - V(\phi)$ $\quad -1 \leq w \leq 1$

Phantom $\mathcal{L} = -(1/2)(\partial\phi)^2 - V(\phi)$

the kinetic energy of the scalar field is negative .

$$-1 \geq w = \frac{p}{\rho} = \frac{-\dot{\phi}^2/2 - V(\phi)}{-\phi^2/2 + V(\phi)}$$

However, it is clearly problematic due to the UV quantum instability.

``The phantom of the OPERA''

K-essence $\mathcal{L} = \mathcal{L}(\phi,\ X), \quad X = (1/2)\partial_\mu\phi\partial^\mu\phi$

$-1 \leq w \leq 1$ or $-1 \geq w$ but no crossing of w= -1

Quintom=Quintessence+Phantom=Hessence ``Nonsense!''

(with the phantom crossing of w= -1)

Is there a gravity theory with phantom crossing without the stability problem?

Modified Gravity Theory

- **Modified gravity theories**

Function $f(R)$ causes accelerating expansion.

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,f(R) + S_m$$

- Field equation $\quad (F = df/dR)$

$$F R_{\mu\nu} - \frac{1}{2} f g_{\mu\nu} - (\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda)F = 8\pi G T_{\mu\nu}$$

i.e.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G\left(T_{\mu\nu} + T^{\mathrm{DE}}_{\mu\nu}\right)$$

$$T^{\mathrm{DE}}_{\mu\nu} = \frac{1}{8\pi G}\Big[(1-F)R_{\mu\nu} - \frac{1}{2}(R-f)g_{\mu\nu} + (\nabla_\mu\nabla_\nu - g_{\mu\nu}\nabla^\lambda\nabla_\lambda)F\Big]$$

$f(R) = R - 2\Lambda$ ☞ the ΛCDM model

f(R) gravity:

The conditions for the cosmological viability of f(R) models

1. $f_{,R} > 0$ → **To avoid ghosts**

2. $f_{,RR} > 0$ → $f(R) = R - \frac{\mu^{2(n+1)}}{R^n}$ **model does not satisfy this condition.**

- **The mass M of a scalar-field degree of freedom needs to be positive for the consistency with local gravity constraints (LGC).**

$$M^2 \approx 1/3f_{,RR} > 0$$ ☞ not a tachyon

- **This condition is also required for the stability of perturbations.**

3. $f(R) \to R - 2\Lambda \quad \text{for} \quad R \gg R_0$

For the presence of the matter era and for the consistency with LGC.

- **Realization of the Λ CDM-like behavior in the large curvature regime**

4. **The presence of a stable late-time de Sitter point**

$$0 < \frac{Rf_{,RR}}{f_{,R}}(r = -2) < 1\,, \quad \text{at} \quad r = -\frac{Rf_{,R}}{f} = -2$$

Others: **constraints from the equivalence principle and solar-system**

TABLE I. Explicit forms of $f(R)$ in (i) Hu-Sawicki, (ii) Starobinsky, (iii) Tsujikawa, and (iv) the exponential gravity models.

model	$f(R)$	Constant parameters
(i)	$R - \frac{c_1 R_{\rm HS}(R/R_{\rm HS})^p}{c_2(R/R_{\rm HS})^p+1}$	c_1, c_2, $p(>0)$, $R_{\rm HS}(>0)$
(ii)	$R + \lambda R_{\rm S} \left[\left(1+\frac{R^2}{R_{\rm S}^2}\right)^{-n} - 1 \right]$	$\lambda(>0)$, $n(>0)$, $R_{\rm S}$
(iii)	$R - \mu R_{\rm T} \tanh\left(\frac{R}{R_{\rm T}}\right)$	$\mu(>0)$, $R_{\rm T}(>0)$
(iv)	$R - \beta R_{\rm E}\left(1 - e^{-R/R_{\rm E}}\right)$	β, $R_{\rm E}$

E. V. Linder, Phys. Rev. D **80**, 123528 (2009)

P. Zhang, Phys. Rev. D **73**, 123504 (2006)

S. Tsujikawa, Phys. Rev. D **77**, 023507 (2008).

For example:

(iv) the exponential gravity

$$f(R) = R - \beta R_s\left(1 - e^{-R/R_s}\right)$$

``**Cosmological evolution in exponential gravity**,''
K. Bamba, **CQG** and C.C. Lee, **JCAP** 1008, 021 (2010);
``**Observational constraints on exponential gravity**,''
L. Yang, C.C. Lee, L.W. Luo, **CQG, PRD82**, 103515 (2010).

1. When $\beta < e^{R/R_s}$, $F(R) = 1 - \beta e^{-R/R_s} > 0$.
2. When $\beta > 0$ and $R_s > 0$, $f''(R) = F'(R) = (\beta/R_s)\, e^{-R/R_s} > 0$.
3. $f(R) - R \to -\beta R_s =$ constant for $R/R_s \gg 1$.
4. When $\beta > 1$, $0 < m(R = R_d) < 1$ where $m \equiv R f''(R)/f'(R) = R F'(R)/F(R)$

The action of f(R) gravity with matter:

$$S = \int d^4x \sqrt{-g}\, f(R) + S_m$$

$$FG_{\mu\nu} = \kappa^2 T^{(\mathrm{matter})}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} (FR - f) + \nabla_\mu \nabla_\nu F - g_{\mu\nu} \Box F$$

where $G_{\mu\nu} = R_{\mu\nu} - (1/2)\, g_{\mu\nu} R$ is the Einstein tensor, $F(R) \equiv df(R)/dR$, ∇_μ is the covariant derivative operator associated with $g_{\mu\nu}$, $\Box \equiv g^{\mu\nu} \nabla_\mu \nabla_\nu$ is the covariant d'Alembertian for a scalar field, and $T^{(\mathrm{matter})}_{\mu\nu}$ is the contribution to the energy-momentum tensor from all perfect fluids of matter.

The Friedmann equations:

$$3FH^2 = \kappa^2 \rho_{\mathrm{M}} + \frac{1}{2}(FR - f) - 3H\dot{F},$$
$$-2F\dot{H} = \kappa^2 (\rho_{\mathrm{M}} + P_{\mathrm{M}}) + \ddot{F} - H\dot{F},$$

$$\dot{\rho}_m + 3H\rho_m = 0$$

The dark energy equation of state:

$$w_{\mathrm{DE}} \equiv P_{\mathrm{DE}}/\rho_{\mathrm{DE}},$$
$$\rho_{\mathrm{DE}} = \frac{1}{\kappa^2}\left[\frac{1}{2}(FR - f) - 3H\dot{F} + 3(1 - F) H^2\right],$$
$$P_{\mathrm{DE}} = \frac{1}{\kappa^2}\left[-\frac{1}{2}(FR - f) + \ddot{F} + 2H\dot{F} - (1 - F)\left(2\dot{H} + 3H^2\right)\right],$$

$$\dot{\rho}_{\mathrm{DE}} + 3H(\rho_{\mathrm{DE}} + P_{\mathrm{DE}}) = 0$$

(i) Hu-Sawicki

W. Hu and I. Sawicki, Phys. Rev. D **76**, 064004 (2007)

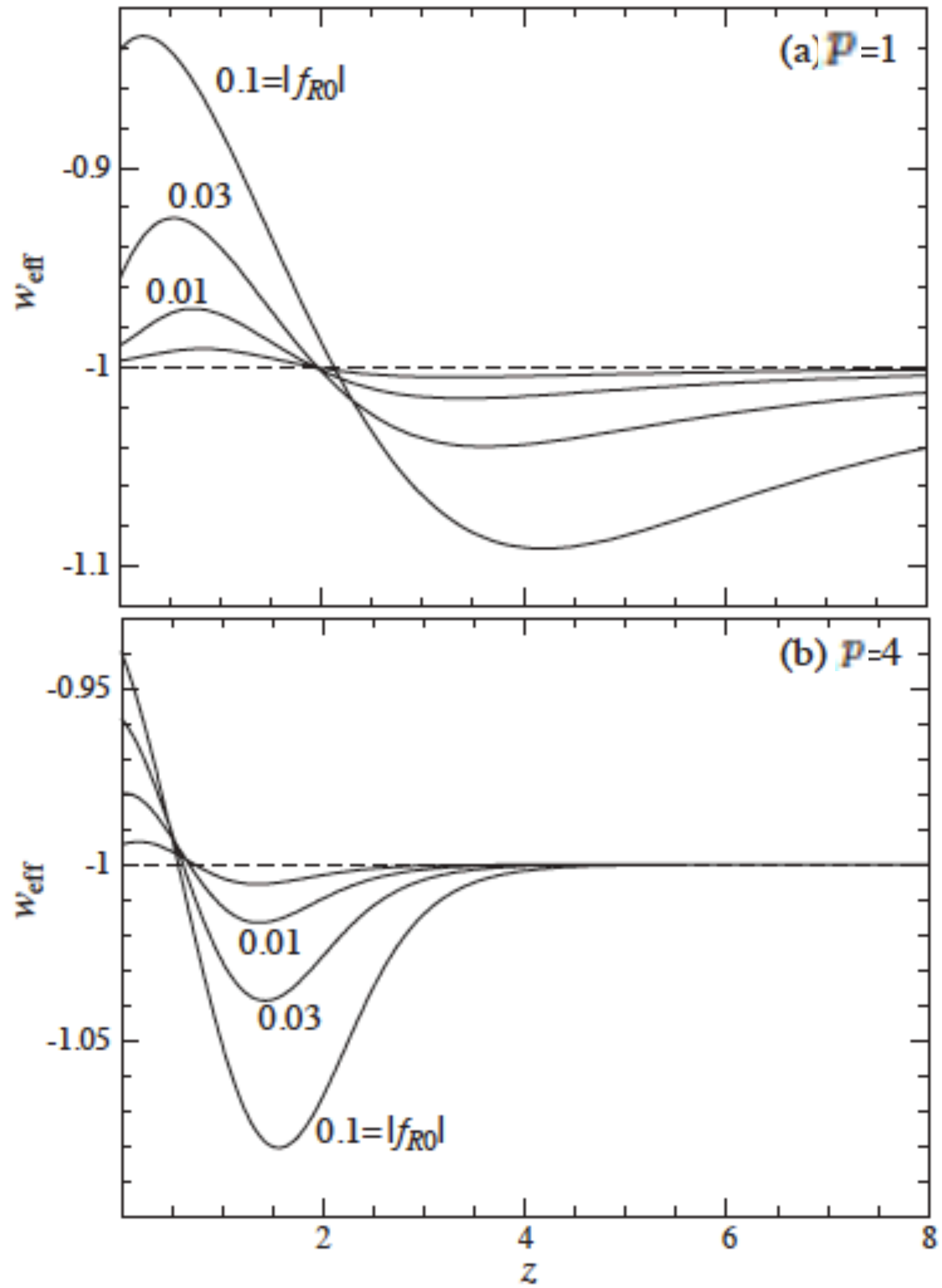
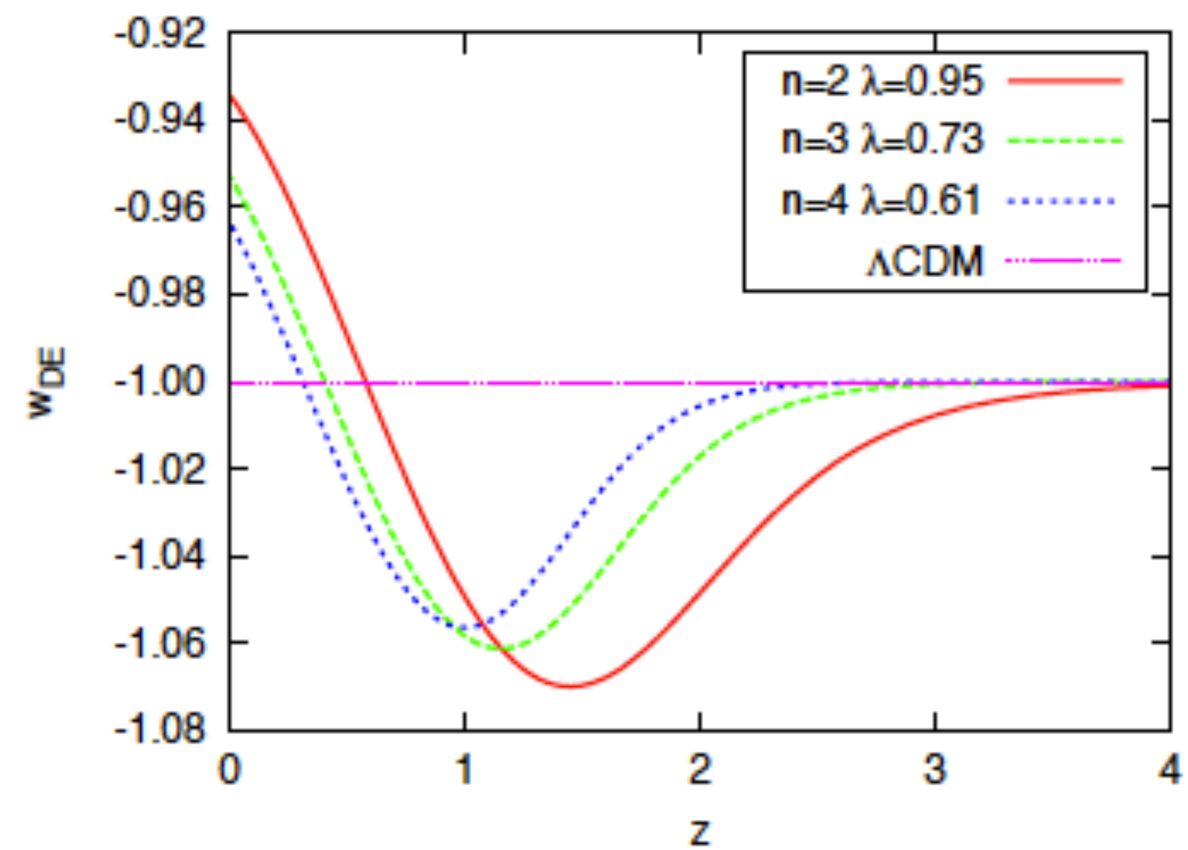


FIG. 3: Evolution of the effective equation of state for $p = 1, 4$ for several values of the cosmological field amplitude today, f_{R0}. The effective equation of state crosses the phantom divide $w_{\rm eff} = -1$ at a redshift that decreases with increasing p leading potentially to a relatively unique observational signature of these models.

(ii) Starobinsky

A. A. Starobinsky, JETP Lett. **86**, 157 (2007)

H. Motohashi, A. A. Starobinsky and J. Yokoyama, arXiv:1002.1141 [astro-ph.CO].



Evolution of $w_{\rm DE}$ for $\lambda_{\rm min}$ for $n = 2, 3$, and 4.

(iv) the exponential gravity

E. V. Linder, Phys. Rev. D **80**, 123528 (2009)

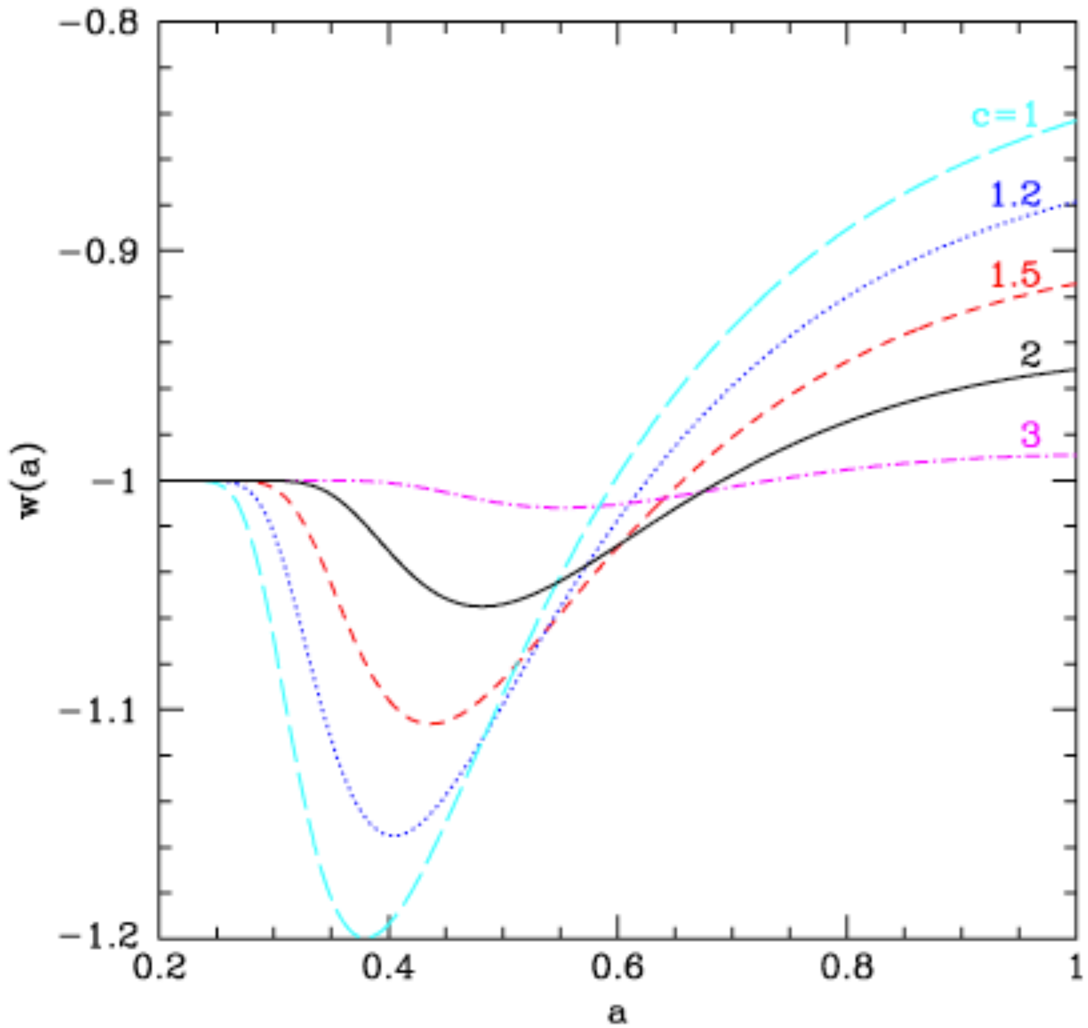
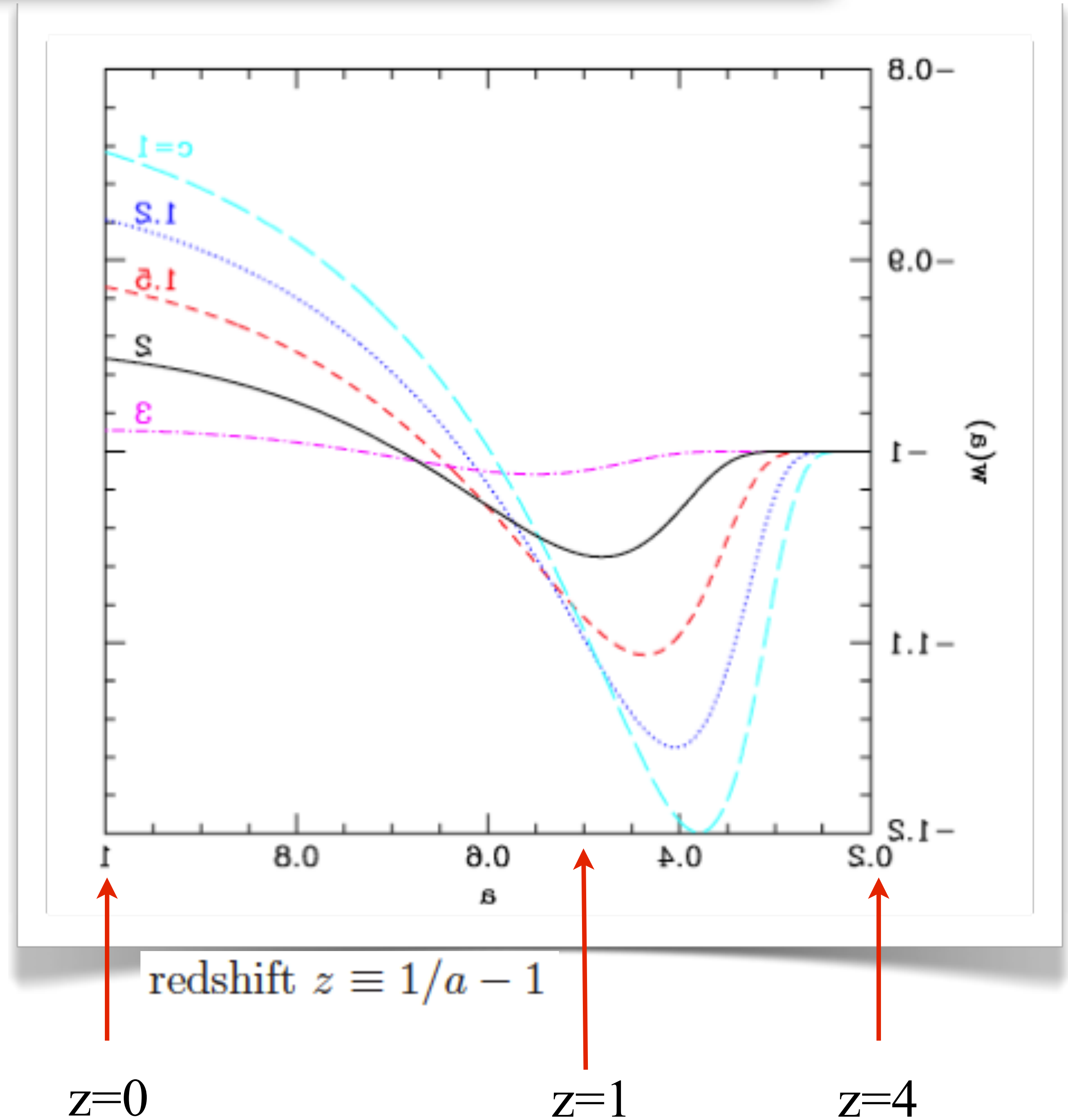


FIG. 3 (color online). The effective dark energy equation of state evolution is shown for various values of c. As c gets large, the expansion history becomes indistinguishable from ΛCDM.



Several Remarks on f(R):

a. In f(R) gravity, the phantom phase of w<-1 is allowed without the stability problem unlike the phantom model.

b. In the past (z>0), the phantom crossing is a generic feature in the popular viable f(R) gravity theories.

c. However, the tendency seems to be opposite to the data, i.e., the crossing is from non-phantom (w>-1) to phantom phase (w<-1) in f(R), whereas the data indicates that it is from phantom to non-phantom phase, as z increases.

d. In the Future: z<0

``Generic feature of future crossing of phantom divide in viable f(R) gravity models,'' K. Bamba, **CQG** and C.C. Lee, JCAP1011, 001 (2010).

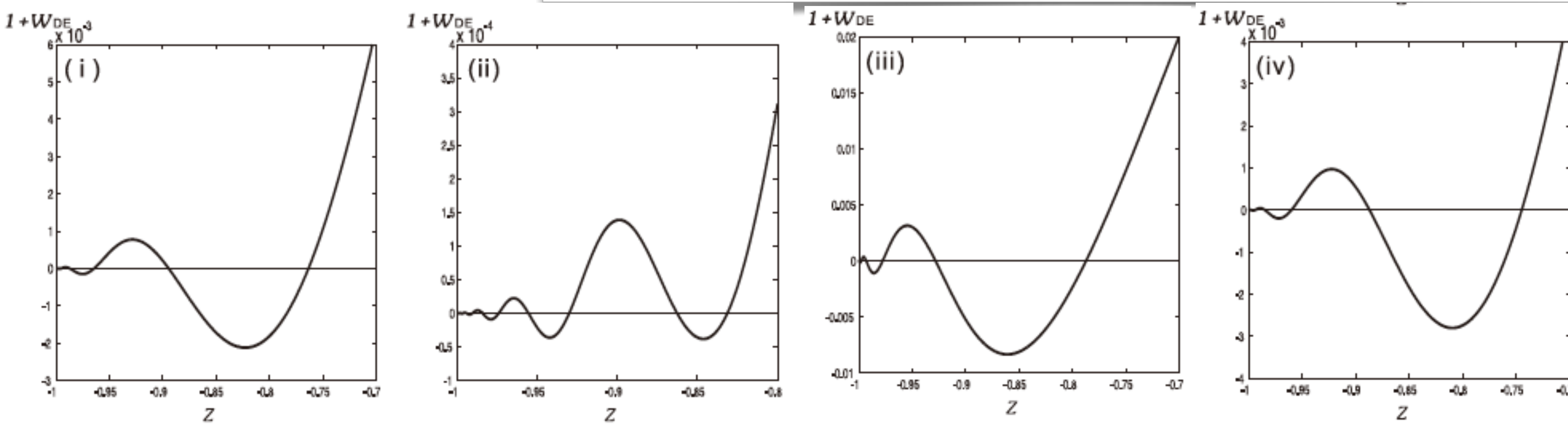


FIG. 1. Future evolutions of $1 + w_{\rm DE}$ as functions of the redshift z in (i) Hu-Sawicki model for $p = 1$, $c_1 = 2$ and $c_2 = 1$, (ii) Starobinsky model for $n = 2$ and $\lambda = 1.5$, (iii) Tsujikawa model for $\mu = 1$ and (iv) the exponential gravity model for $\beta = 1.8$, respectively. The thin solid lines show $1 + w_{\rm DE} = 0$ (cosmological constant).

• Teleparallel Dark Energy

Teleparallel gravity:

<u>Alternative Gravitational Theory</u>

Einstein's unified field theory:
``Riemannian Geometry with Maintaining the Notion of Distant Parallelism”
(Teleparallelism, Einstein 1928)

Torsion scalar (Einstein 1929)

$$\left.\begin{aligned} \mathfrak{J}_1 &= h\,\Lambda^{\alpha}_{\mu\beta}\Lambda^{\beta}_{\underline{\mu}\alpha} \\ \mathfrak{J}_2 &= h\,\Lambda^{\alpha}_{\mu\beta}\Lambda^{\alpha}_{\underline{\mu}\beta} \\ \mathfrak{J}_3 &= h\,\Lambda^{\alpha}_{\mu\alpha}\Lambda^{\beta}_{\underline{\mu}\beta} \end{aligned}\right\}$$

$$\mathfrak{H} = \tfrac{1}{2}\mathfrak{J}_1 + \tfrac{1}{4}\mathfrak{J}_2 - \mathfrak{J}_3 \,.$$

Teleparallel Lagrangian is equivalent to the Riemann scalar (Lanczos 1929)

Generalization: New General Relativity (NGR) (Hayashi & Shirafuji 1979)

$$\left(\frac{1}{4}, \frac{1}{2}, -1\right) \longrightarrow (a, b, c)$$

RIEMANN-Geometrie mit Aufrechterhaltung des Begriffes des Fernparallelismus.

Von A. EINSTEIN.

Die RIEMANNsche Geometrie hat in der allgemeinen Relativitätstheorie zu einer physikalischen Beschreibung des Gravitationsfeldes geführt, sie liefert aber keine Begriffe, die dem elektromagnetischen Felde zugeordnet werden können. Deshalb ist das Bestreben der Theoretiker darauf gerichtet, natürliche Verallgemeinerungen oder Ergänzungen der RIEMANNschen Geometrie aufzufinden, welche begriffsreicher sind als diese, in der Hoffnung, zu einem logischen Gebäude zu gelangen, das alle physikalischen Feldbegriffe unter einem einzigen Gesichtspunkte vereinigt. Solche Bestrebungen haben mich zu einer Theorie geführt, welche ohne jeden Versuch einer physikalischen Deutung mitgeteilt werden möge, weil sie schon wegen der Natürlichkeit der eingeführten Begriffe ein gewisses Interesse beanspruchen kann.

Die RIEMANNsche Geometrie ist dadurch charakterisiert, daß die infinitesimale Umgebung jedes Punktes P eine euklidische Metrik aufweist, sowie dadurch, daß die Beträge zweier Linienelemente, welche den infinitesimalen Umgebungen zweier endlich voneinander entfernter Punkte P und Q angehören, miteinander vergleichbar sind. Dagegen fehlt der Begriff der Parallelität solcher zwei Linienelemente; der Richtungsbegriff existiert nicht für das Endliche. Die im folgenden dargelegte Theorie ist dadurch charakterisiert, daß sie neben der RIEMANNschen Metrik den der »Richtung« bzw. Richtungsgleichheit oder des »Parallelismus« für das Endliche einführt. Dem entspricht es, daß neben den Invarianten und Tensoren der RIEMANNschen Geometrie neue Invarianten und Tensoren auftreten.

Curvature vs Torsion

A general spacetime can, in principle, present two different properties – **curvature** and **torsion**

TORSION AND CURVATURE

CURVATURE

Consider the parallel transport of a vector around a closed curve

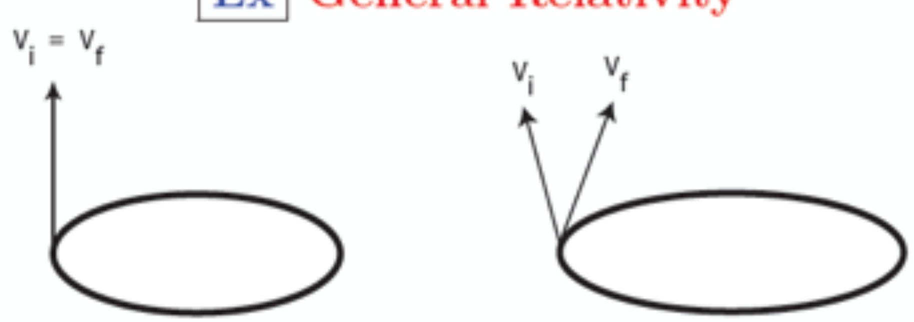
$\Downarrow$

If, when returning to the initial point, there is an angular deficit, the surface is said to be curved

$\Downarrow$

The curvature of the surface is proportional to this angular deficit

Ex General Relativity



TORSION

Consider now the parallel transport of two vectors

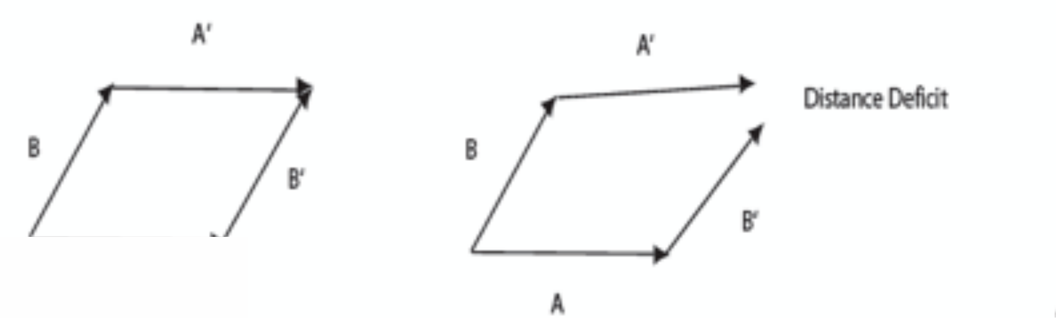
$\Downarrow$

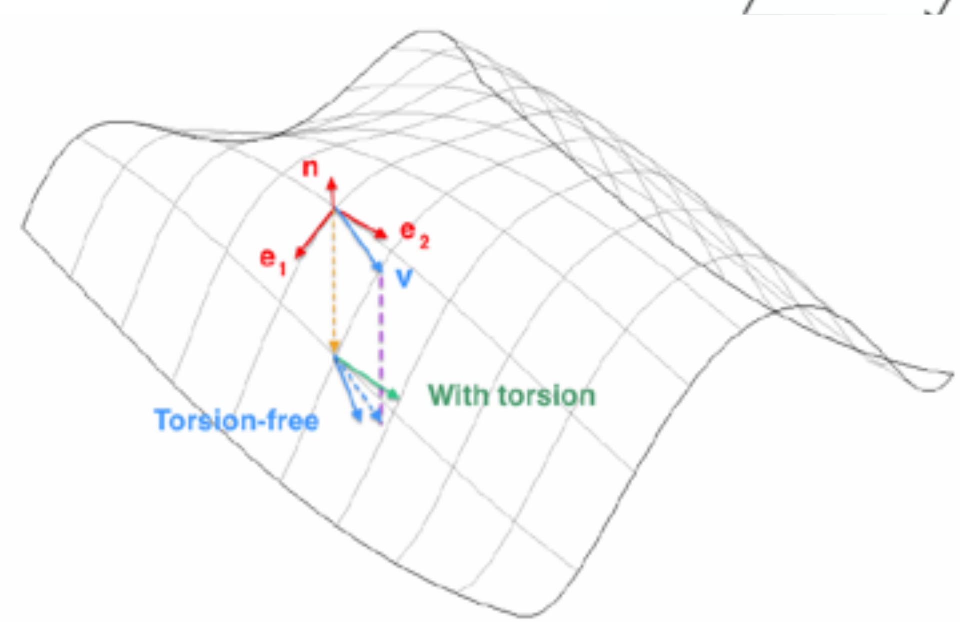
If, when parallel transported one along the other, they do not close a parallelogram the surface is said to present torsion

$\Downarrow$

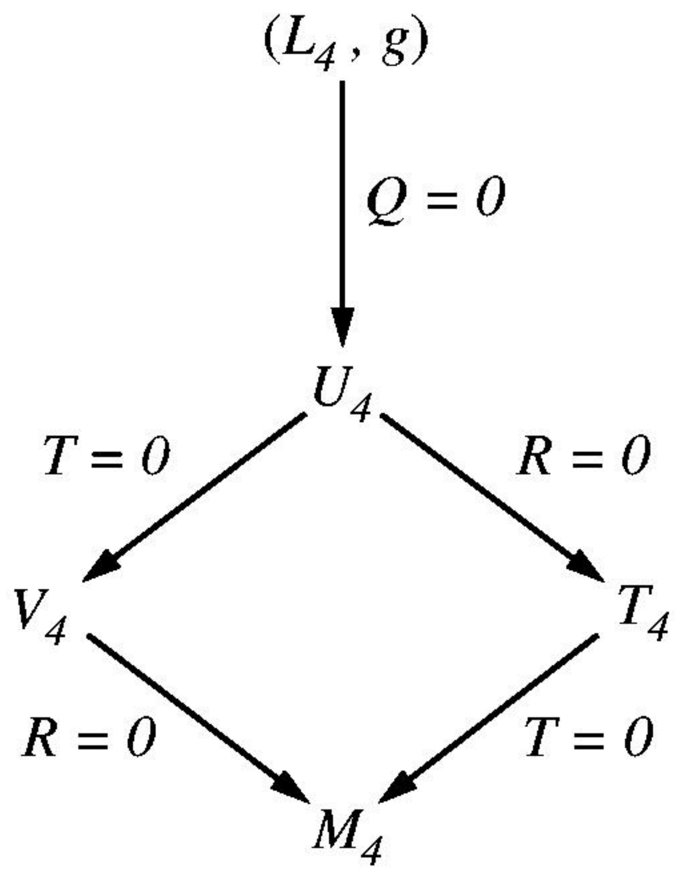
The torsion of the surface is proportional to the gap — or distance deficit

Ex Teleparallel Gravity



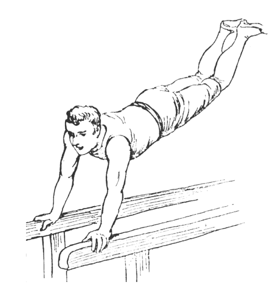


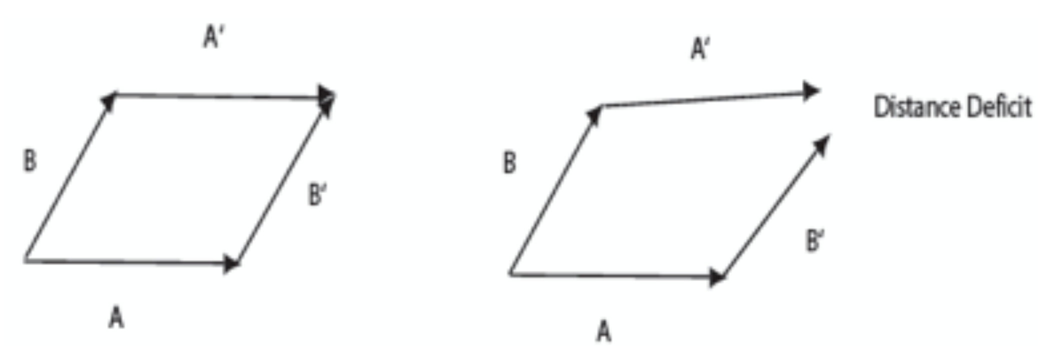
TELE-PARALLEL GEOMETRY



Riemann

Minkowski





Teleparallel gravity:

Teleparallelism

The torsion $T^\rho{}_{\mu\nu}$ and contorsion $K^{\mu\nu}{}_\rho$ tensors are defined by

$$T^\rho{}_{\mu\nu} \equiv e^\rho_A \left(\partial_\mu e^A_\nu - \partial_\nu e^A_\mu\right) ,$$
$$K^{\mu\nu}{}_\rho \equiv -\frac{1}{2}\left(T^{\mu\nu}{}_\rho - T^{\nu\mu}{}_\rho - T_\rho{}^{\mu\nu}\right) .$$

Weitzenböck connection $\overset{w}{\Gamma}{}^\lambda_{\nu\mu} \equiv e^\lambda_A\, \partial_\mu e^A_\nu$

~~Levi Civita~~

e^A_μ is the orthonormal tetrad component

vierbeins : *parallel* vector fields

$$g_{\mu\nu} = \eta_{AB} e^A_\mu e^B_\nu \qquad \mathbf{e}_A \cdot \mathbf{e}_B = \eta_{AB}$$

$$\eta_{AB} = diag(1, -1, -1, -1)$$

parallel : $0 = \overset{w}{\nabla}_\nu e_A^\lambda = \partial_\nu e_A^\lambda + \overset{w}{\Gamma}{}^\lambda_{\mu\nu} e_A^\mu$

coordinate basis: $\mathbf{e}_A = e_A^\mu \partial_\mu$

$$T \equiv S_\rho{}^{\mu\nu} T^\rho{}_{\mu\nu}$$
$$S_\rho{}^{\mu\nu} \equiv \frac{1}{2}\left(K^{\mu\nu}{}_\rho + \delta^\mu_\rho\, T^{\alpha\nu}{}_\alpha - \delta^\nu_\rho\, T^{\alpha\mu}{}_\alpha\right)$$

Torsion scalar: $T = \frac{1}{4} T^{\rho\mu\nu} T_{\rho\mu\nu} + \frac{1}{2} T^{\rho\mu\nu} T_{\nu\mu\rho} - T_{\rho\mu}{}^{\rho} T^{\nu\mu}{}_{\nu}$

$$e^A_\mu = \mathrm{diag}(1, a, a, a), \qquad |e| = \det\left(e^A_\mu\right) = \sqrt{-g}.$$

quadratic form in terms of torsion tensor

Teleparallel gravity: $$S = \int \mathrm{d}^4 x e \left[\frac{T}{2\kappa^2} + \mathcal{L}_m\right]$$

Teleparallel Equivalent of General Relativity (TEGR)

$$S = \int d^4x\, e \left[\frac{T}{2\kappa^2} + \mathcal{L}_m \right]$$

$$e = \det\left(e_\mu^A\right) = \sqrt{-g}$$

" = "

$$T = R + 2\nabla^\mu T^\rho{}_{\rho\mu}$$

$$GR: \quad S = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa^2} + \mathcal{L}_m \right]$$

Scalar field
minimally coupled to
Teleparallel Gravity

" = "

Scalar field
minimally coupled to GR

Scalar field
non-minimally coupled to
Teleparallel Gravity

not eq.

" ≠ "

Scalar field
non-minimally coupled to GR

~ "*scalar-teleparallel theory*"
a simple extension of TEGR

$$S = \int d^4x e \left[\frac{T}{2\kappa^2} + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi + \xi T\phi^2\right) - V(\phi) + \mathcal{L}_m \right]$$

~ *scalar-tensor theory*
a simple extension of GR

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa^2} + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi + \xi R\phi^2\right) - V(\phi) + \mathcal{L}_m \right]$$

Teleparallel Dark Energy

Teleparallel dark energy:

CQG, C.C. Lee, E. N. Saridakis,Y.P. Wu, ``**Teleparallel dark energy,**''
Phys. Lett. B704, 384 (2011) [arXiv:1109.1092 [hep-th]];
CQG, C.C. Lee, E.Saridakis, ``**Observational constraints on teleparallel dark energy**,''
JCAP 1201, 002 (2012) [arXiv:1110.0913 [astro-ph.CO].

$$S = \int d^4x e \left[\frac{T}{2\kappa^2} + \frac{1}{2}\left(\underbrace{\partial_\mu \phi \partial^\mu \phi}_{\text{canonical}} + \xi T \phi^2 \right) - \underbrace{V(\phi)}_{\text{potential}} + \mathcal{L}_m \right]$$

non-minimal coupling to T

Friedmann equations:

$$H^2 = \frac{\kappa^2}{3}\Big(\rho_\phi + \rho_m\Big),$$

$$\dot{H} = -\frac{\kappa^2}{2}\Big(\rho_\phi + p_\phi + \rho_m + p_m\Big)$$

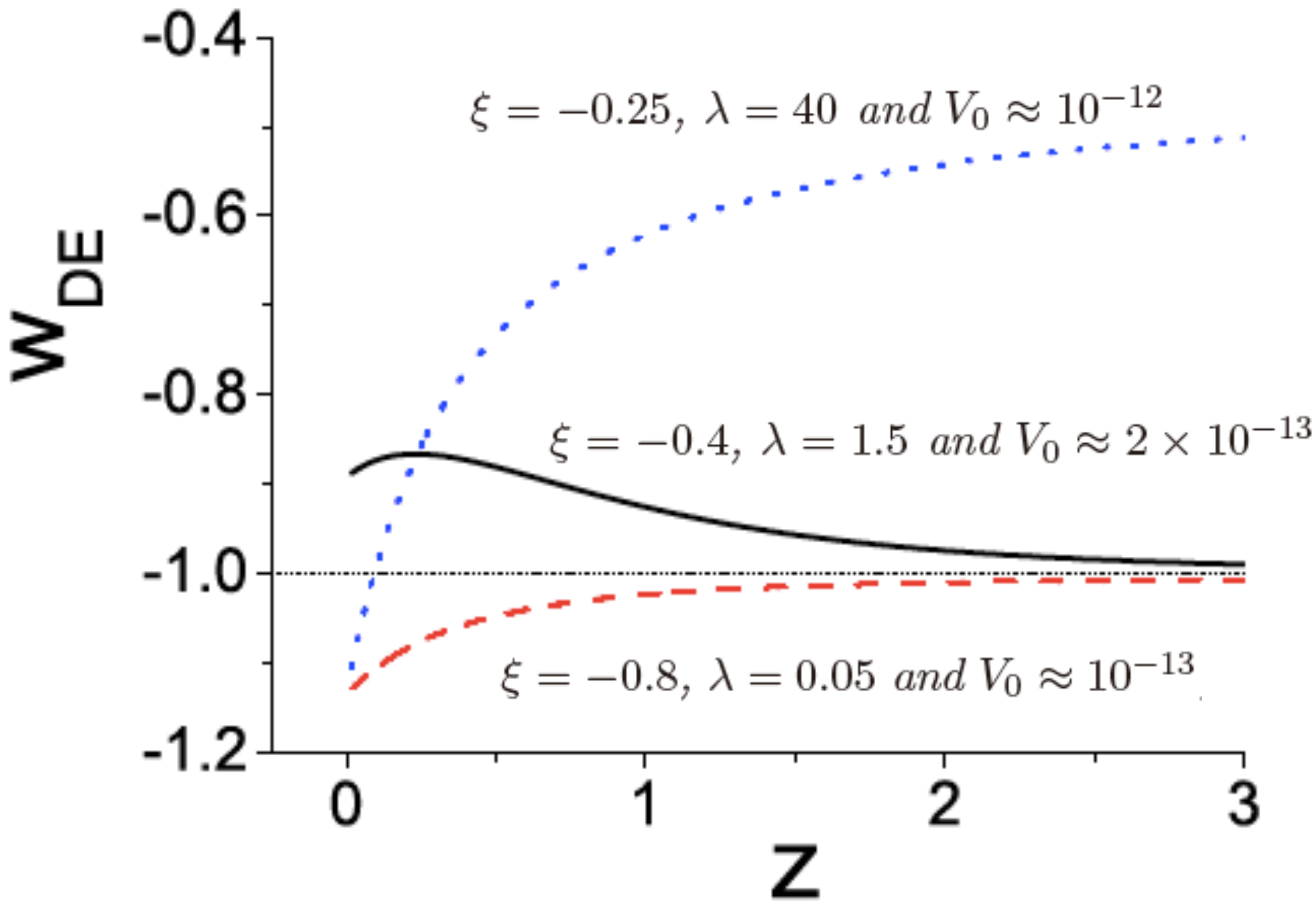
The torsion energy density and pressure:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) - 3\xi H^2 \phi^2,$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) + 4\xi H \phi\dot{\phi} + \xi\left(3H^2 + 2\dot{H}\right)\phi^2$$

Equation of state:

$$w_{DE} \equiv w_\phi = \frac{p_\phi}{\rho_\phi}$$

$$V = V_0 e^{\lambda\phi}$$



Teleparallel Dark Energy with V=0

J.A. Gu, C.C. Lee, **CQG**, ``**Teleparallel dark energy with purely non-minimal coupling to gravity,'' PLB718, 722 (2013)** [arXiv:1204.4048 [astro-ph.CO]].

$$S = \int d^4x\, e \left[\frac{T}{2\kappa^2} + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi + \xi T\phi^2\right) + \mathcal{L}_m \right]$$

← No potential

- Non-minimal term alone can drive cosmic acceleration; need no potential, no non-canonical kinetic term (in contrast to conventional ϕDE models: *quintessence*, *k-essence*, …).

Field equations:

$$\ddot{\phi} + 3H\dot{\phi} + 6\xi H^2\phi = 0$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa^2}{3}\left(\rho_\phi + \rho_\mathrm{m} + \rho_\mathrm{r}\right)$$

$$\dot{H} = -\frac{\kappa^2}{2}\left(\rho_\phi + p_\phi + \rho_\mathrm{m} + 4\rho_\mathrm{r}/3\right)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 - 3\xi H^2\phi^2\,,$$

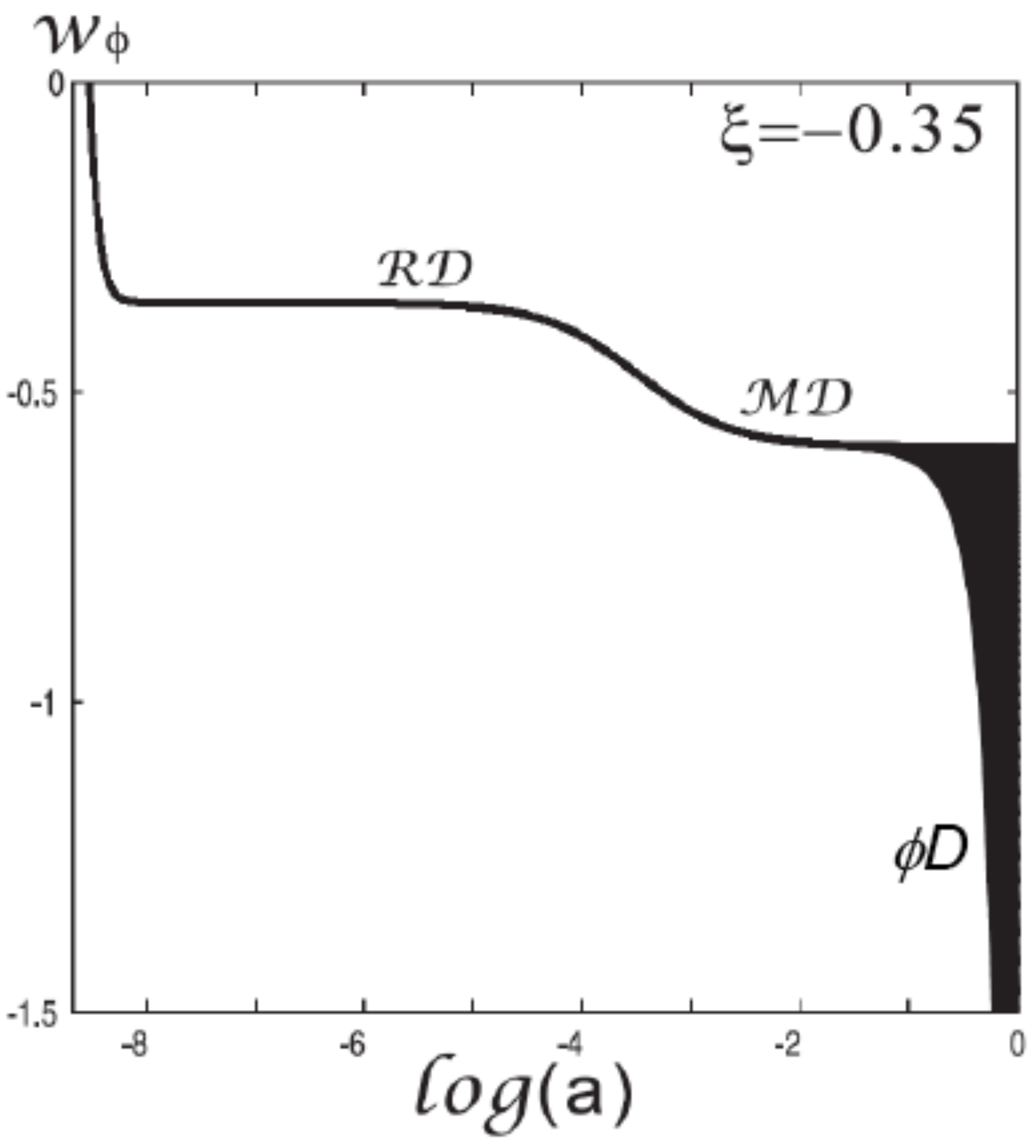
$$p_\phi = \frac{1}{2}\dot{\phi}^2 + 3\xi H^2\phi^2 + 2\xi\frac{d}{dt}\left(H\phi^2\right)$$

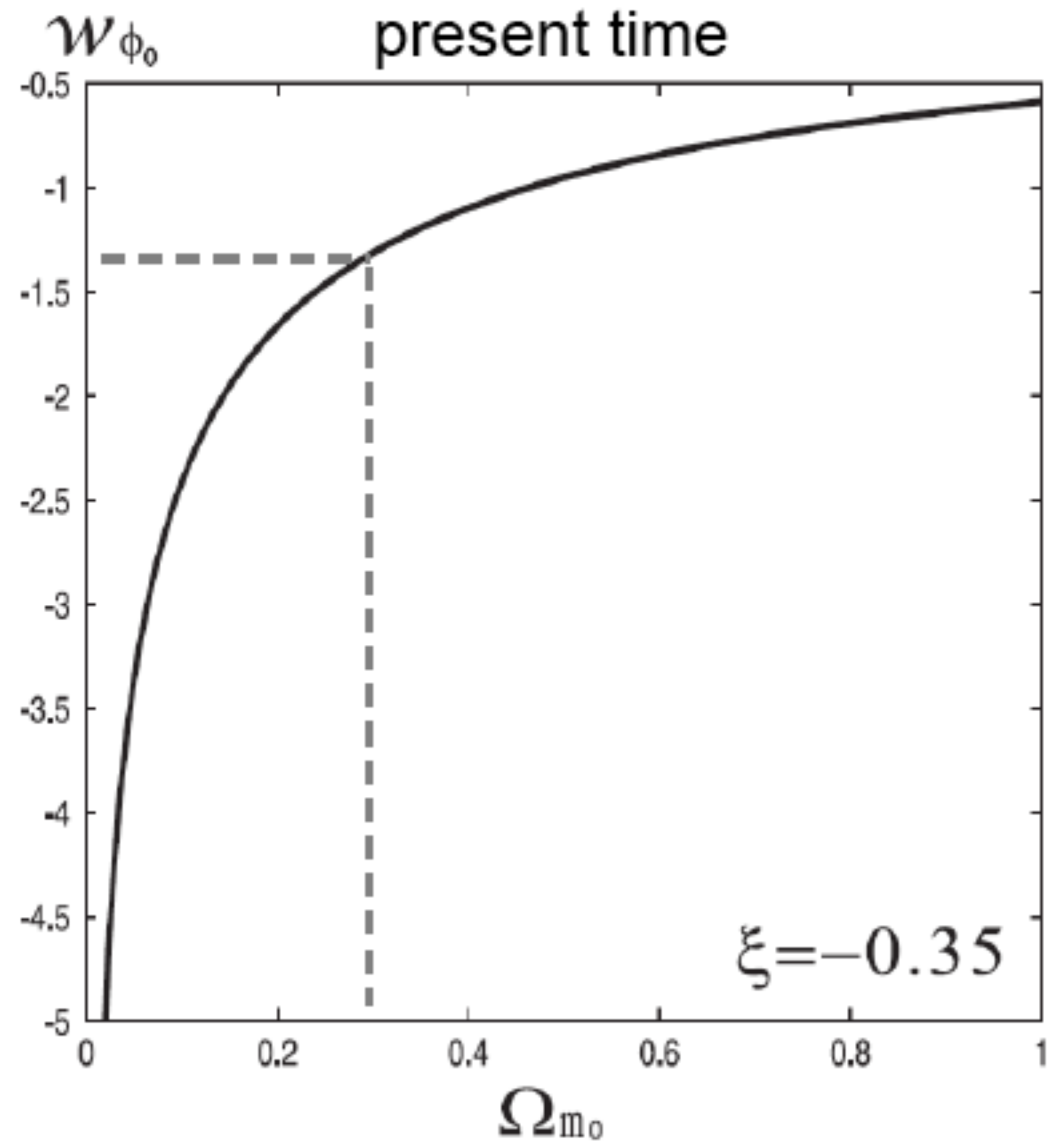
→ We consider $\xi < 0$ to guarantee *positive* ρ_ϕ and for having *negative* p_ϕ

$\rho_\mathrm{m} \propto a^{-3}$ $\rho_\mathrm{r} \propto a^{-4}$

Eff. EoS:	**+1**	**-1**	**NA**	**0**	**1/3**

Behavior of w_ϕ with various initial conditions (IC)

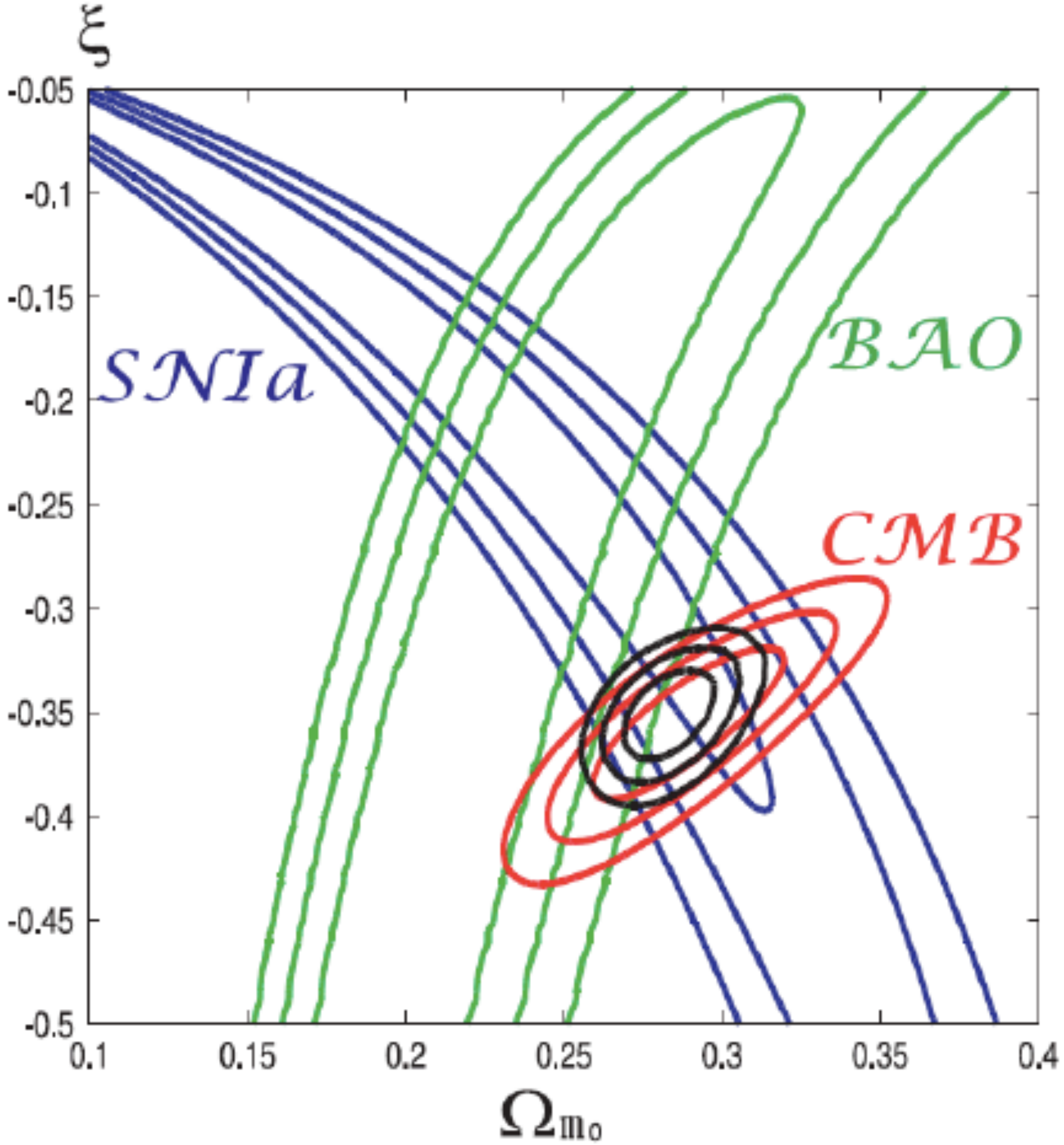


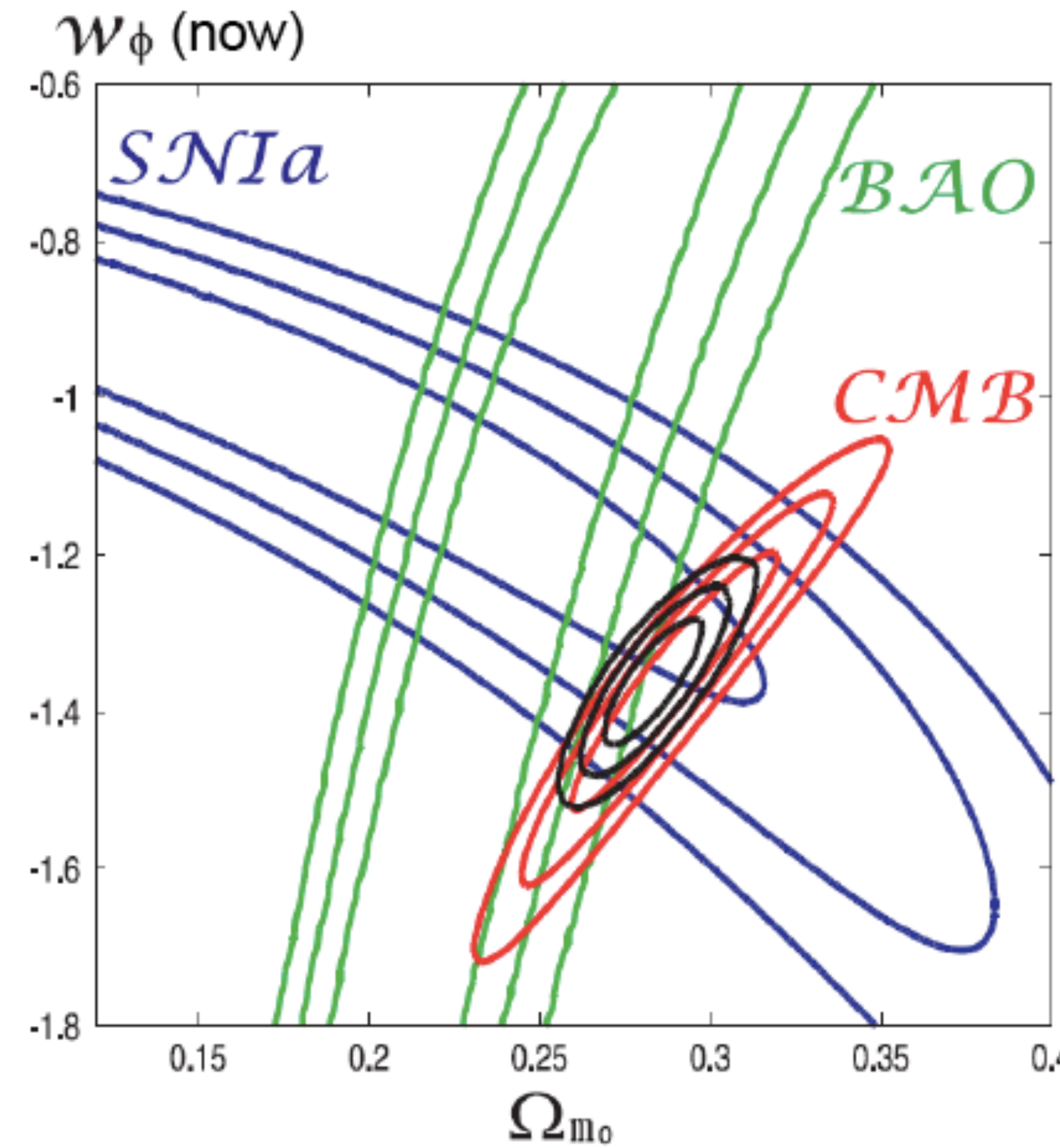


RD & *MD* — *φD*

w_ϕ : insensitive to *IC* — sensitive to *IC*

Data Fitting with SNIa, BAO, CMB





Best fit: $\xi \cong -0.35\,,\ \Omega_{m0} \cong 0.28$

From the Dark Energy Task Force report (2006)

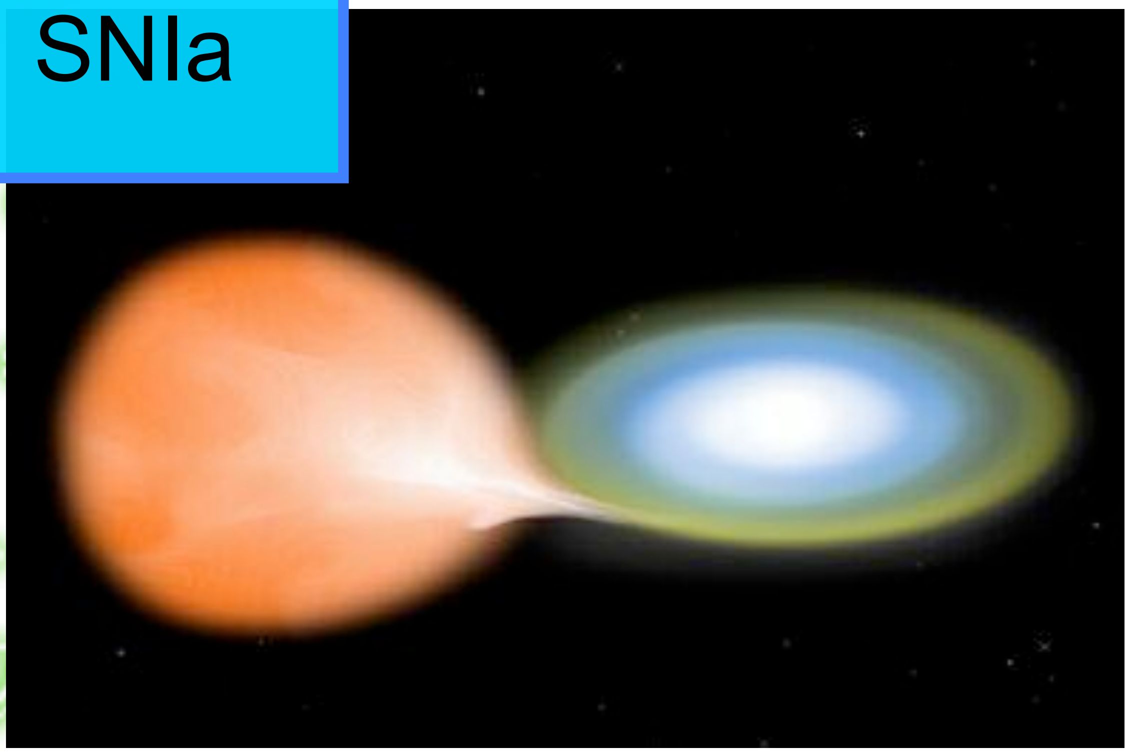
www.nsf.gov/mps/ast/detf.jsp (astro-ph/0690591)

Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation. The acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our fundamental theories of particles and gravity are either incorrect or incomplete. Most experts believe that nothing short of <u>a revolution in our understanding of fundamental physics</u> will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. It demands an ambitious observational program to determine the dark energy properties as soon as possible.

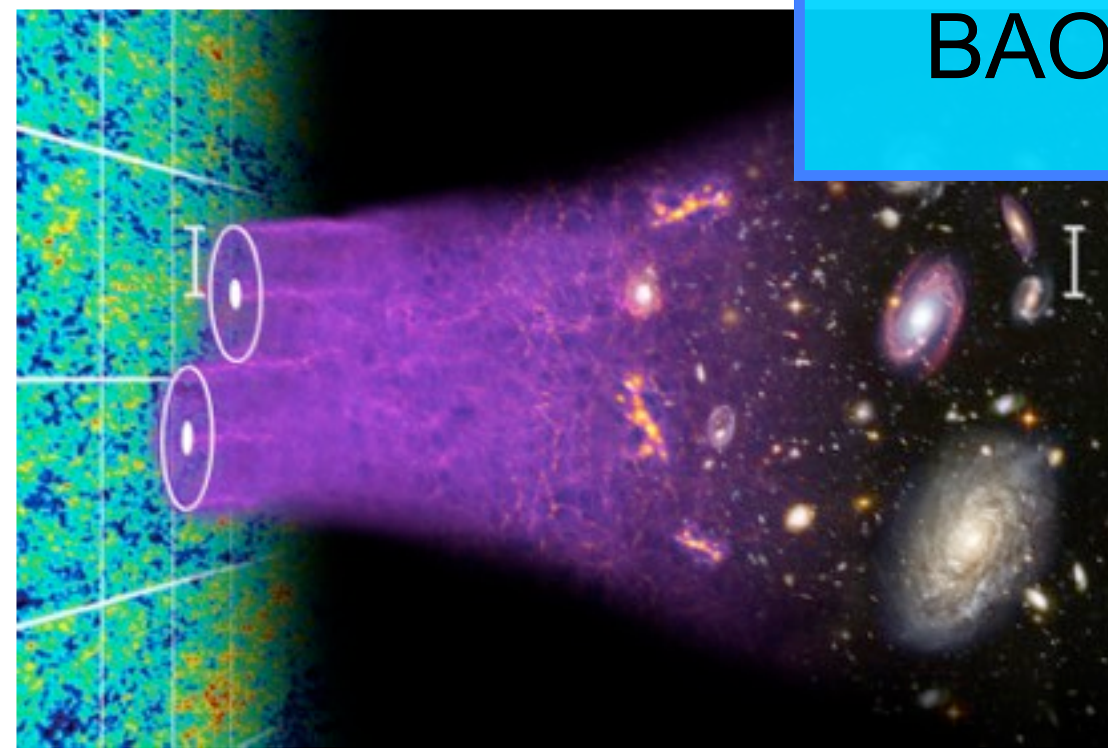
- Type Ia Supernovae (SNIa)
- Baryon Acoustic Oscillation (BAO)
- Weak Lensing (WL)
- Galaxy Cluster (CL)

Four Major Observational Techniques

SNIa

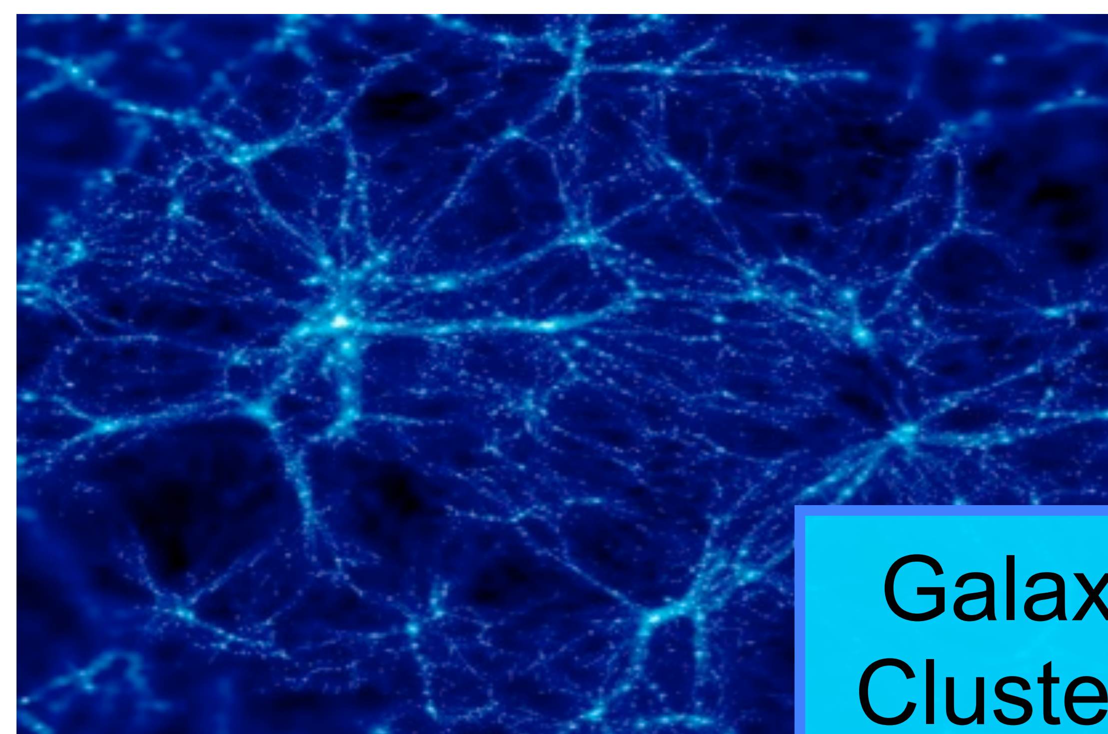


BAO



Weak Lensing

Galaxy Clusters



4 methods, 4 stages.

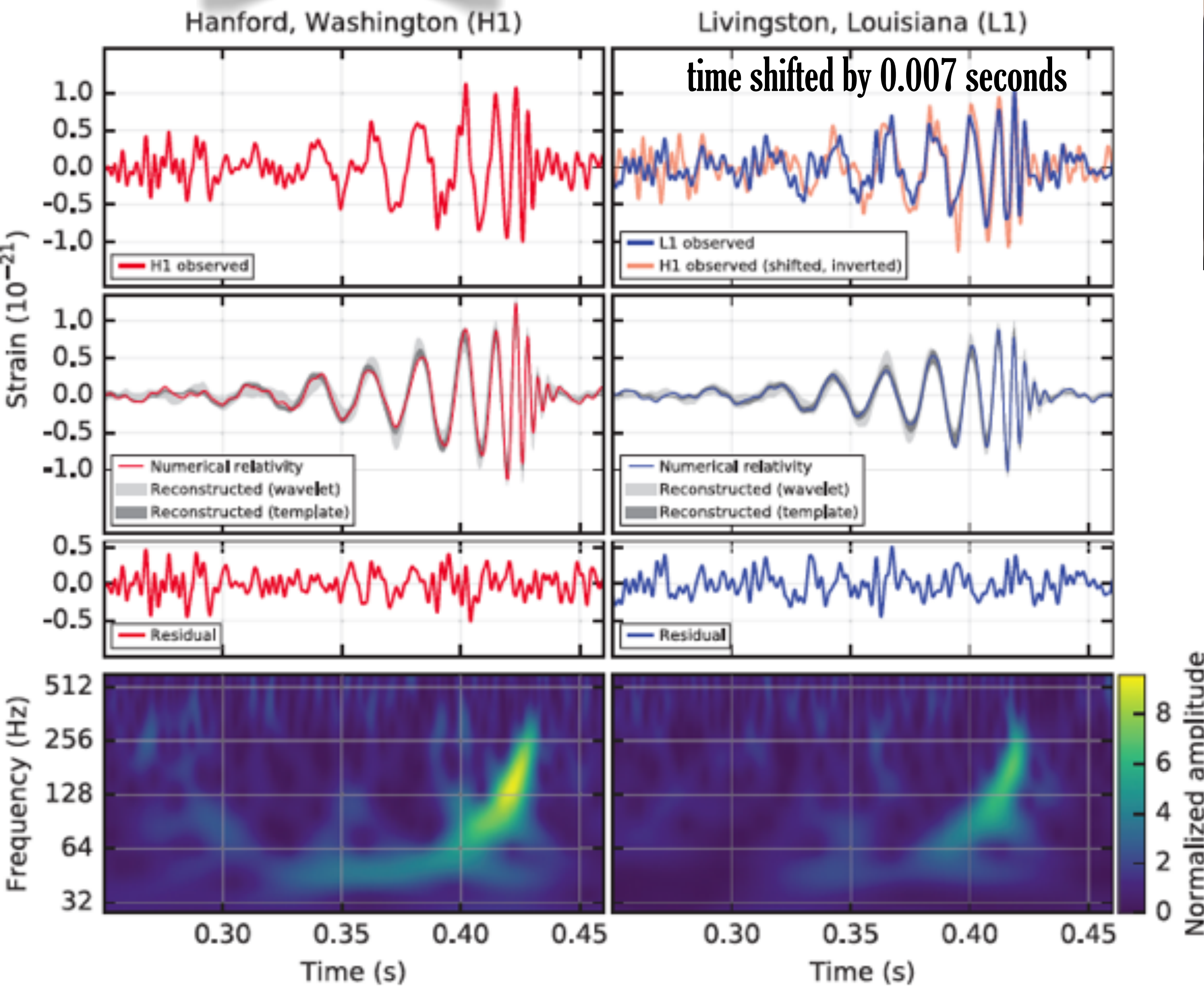
	Finished (now) D(z), H(z),g(z) 5% accuracy	Near-future (~2018) 1% accuracy FoM x3	Distant future (~2025) 0.1% accuracy FoM x10 ~20000 deg^2
Baryon Acoustic Oscillation (BAO)	SDSS BOSS Wiggle Z VIPERS	Subaru PFS(1400deg^2) DESI HETDEX	LSST SKA Euclid WFIRST
Type Ia supernovae (SN)	CFHTLS	SNLS	LSST WFIRST
Cluster counts (CL)	SDSS RSCS ROSAT	SPT ACT	eROSITA
Weak lensing (WL)	CFHTLS	Subaru HSC (1400deg^2) DES (5000deg^2)	Euclid WFIRST

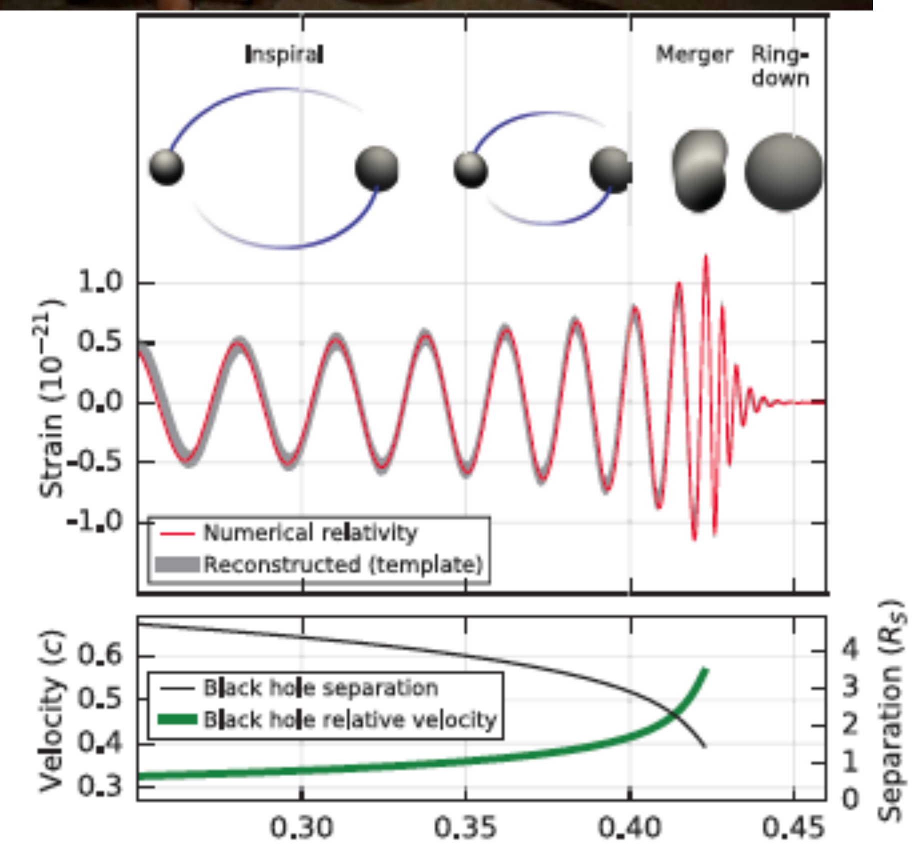
- *Gravitational Waves* 引力波

Feb. 11, 2016

Sept. 15, 2015

GW150914

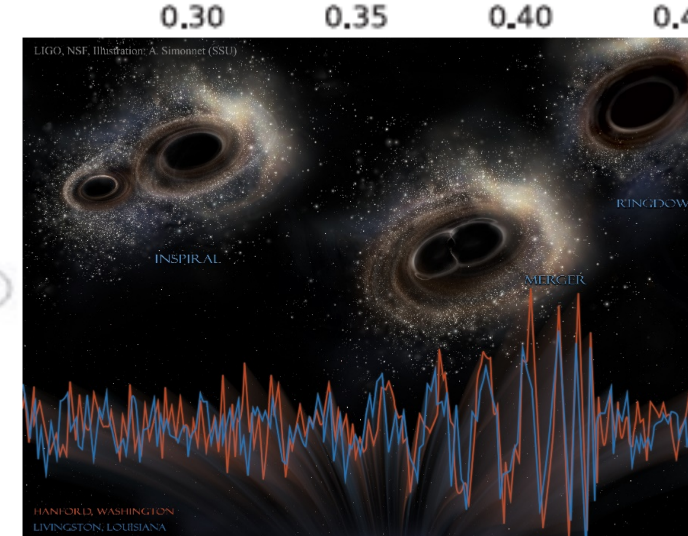


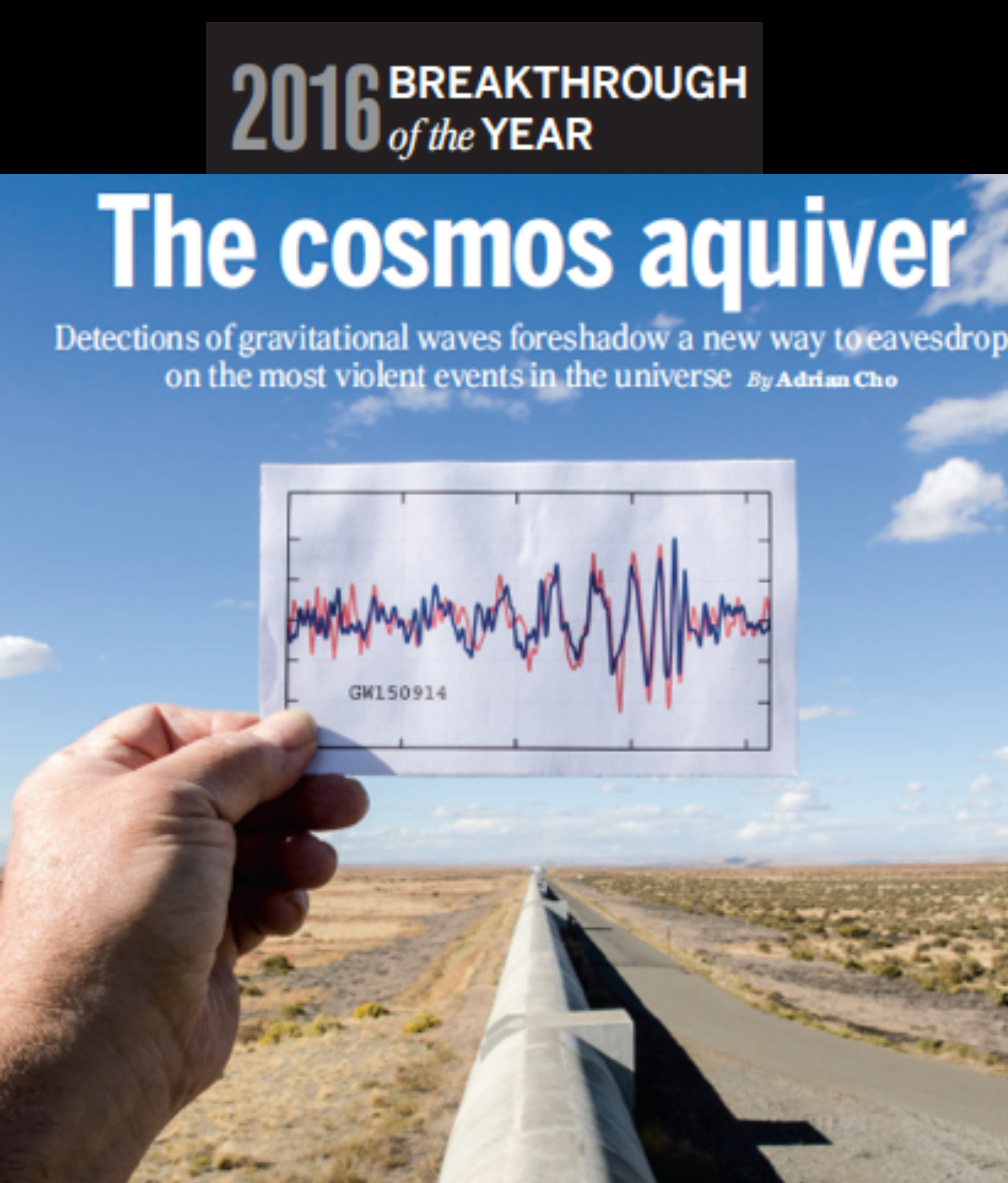


GW150914: What was seen?

- Chirp: 35 Hz to 250 Hz
- Initial masses: $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$
- Final mass: $62^{+4}_{-4} M_\odot$
- Energy output: $3^{+0.5}_{-0.5} M_\odot$

1.3 billion light year away (10^{17}m)




2016 BREAKTHROUGH of the YEAR
The cosmos aquiver
Detections of gravitational waves foreshadow a new way to eavesdrop on the most violent events in the universe By Adrian Cho
GW150914


Watching bacteriorhodopsin pump protons
Boron nitride paves a path to propylene
Trillions of insects migrate over our heads
Science
$15
23 DECEMBER 2016
AAAS
2016
BREAKTHROUGH of the YEAR

May 2, 2016 (San Francisco)

SPECIAL BREAKTHROUGH PRIZE IN FUNDAMENTAL PHYSICS AWARDED

$3 million prize shared between LIGO founders Ronald W. P. Drever, Kip S. Thorne and Rainer Weiss + 1012 contributors to the discovery

Rainer Weiss
Professor Emeritus in Physics, Massachusetts Institute of Technology, USA

Ronald W P Drever
Professor of Physics, Emeritus, California Institute of Technology, USA

Kip S Thorne
Feynman Professor of Theoretical Physics, Emeritus, California Institute of Technology, USA

May 2, 2016 (San Francisco)

SPECIAL BREAKTHROUGH PRIZE IN FUNDAMENTAL PHYSICS AWARDED

$3 million prize shared between LIGO founders Ronald W. P. Drever, Kip S. Thorne and Rainer Weiss + 1012 contributors to the discovery

FOR DETECTION OF GRAVITATIONAL WAVES 100 YEARS AFTER ALBERT EINSTEIN PREDICTED THEIR EXISTENCE

Opening new horizons in astronomy and physics

2016 Gruber Cosmology Prize

May 4, 2016, New Haven, CT

USD: 0.5 million

Ronald W. P. Drever

Kip Thorne

Rainer Weiss

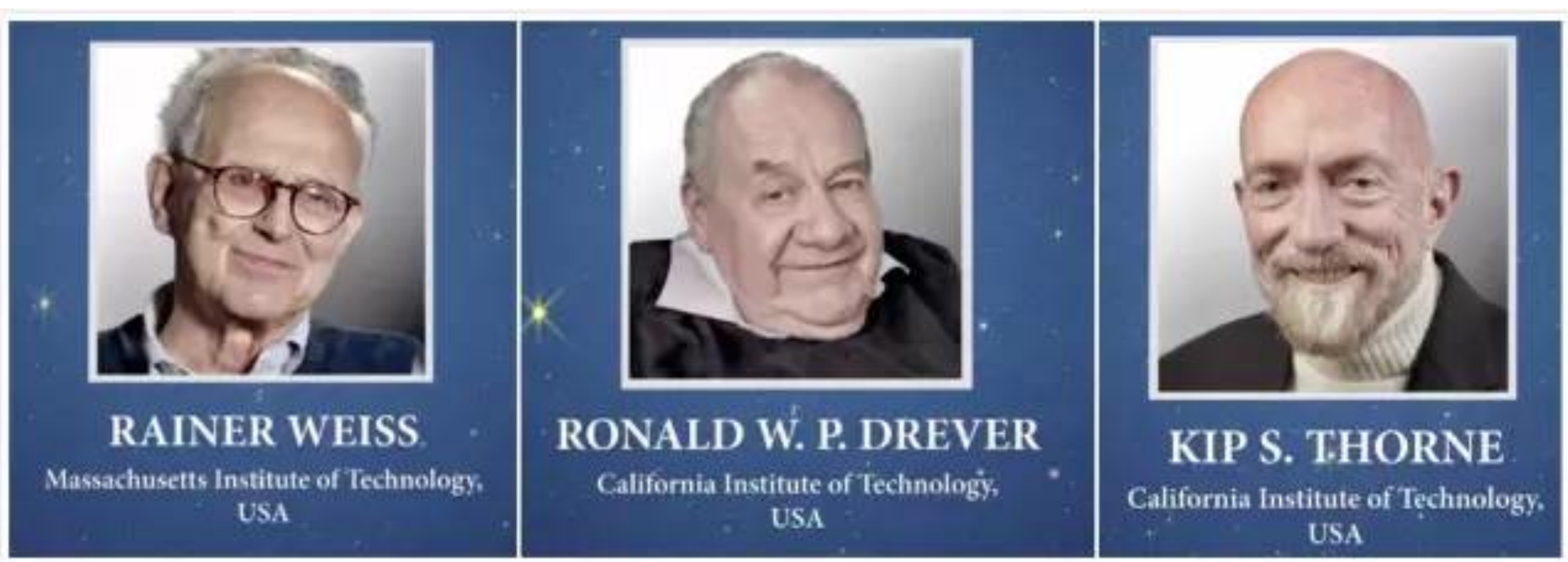
pursuing a vision to observe the universe in gravitational waves, leading to a first detection

THE SHAW PRIZE 邵逸夫獎

The Shaw Prize in Astronomy (香港May 31, 2016)

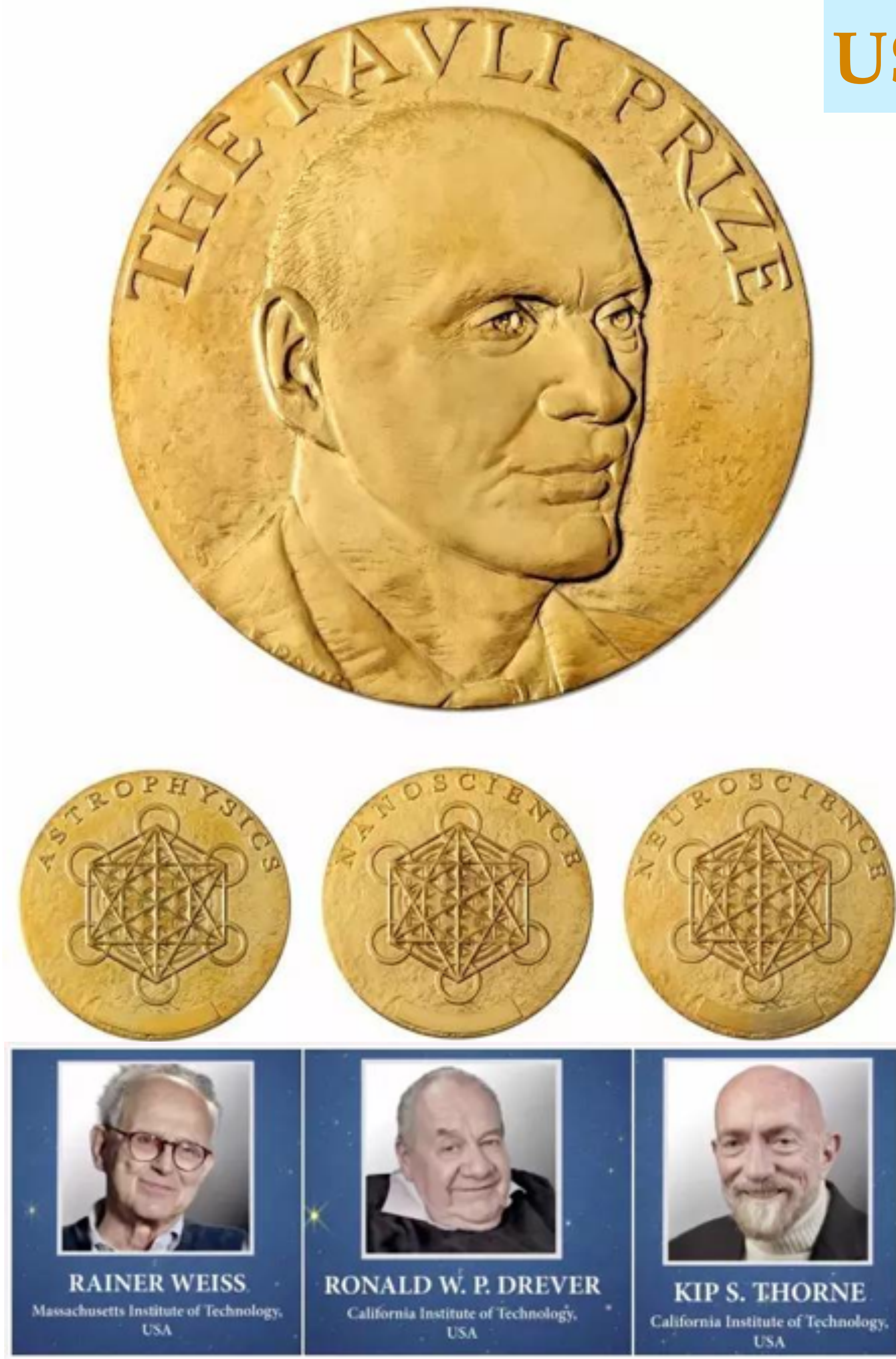
US$1.2 million

for conceiving and designing the Laser Interferometer Gravitational-Wave Observatory (LIGO), whose recent direct detection of gravitational waves opens a new window in astronomy, with the first remarkable discovery being the merger of a pair of stellar mass black holes.



2016年卡弗里(Kavli)奖在挪威揭晓(2016.06.02)

USD:1million



美国加州理工学院的罗奈尔特·德雷弗（Ronald W.P. Drever）、基普·索恩（Kip S. Thorne），以及美国麻省理工学院的雷纳·韦斯（Rainer Weiss）因为“直接探测到引力波”而共同获得了第五届卡弗里天体物理学奖。

2015年9月14日，美国激光干涉引力波天文台（LIGO）所探测到的信号只持續了1/5秒的时间，但是却終结了一場长达数十年的直接探測时空涟漪——引力波的探索历程。它同时也為天文探索開辟了一种全新的方法，讓科学家可以利用引力辐射而非电磁辐射來研究宇宙中某些最极端和剧烈的现象。

这次探测首次验证了在强场情况下的爱因斯坦广义相对论，确立了引力波的性质，证实了30倍于太阳质量黑洞的存在。引力波的发现，打开了探索宇宙的新窗口。

Smithsonian, American Ingenuity Award

Dec. 2016

Rainer Weiss, Kip Thorne, Barry Barish and Ronald Drever

Scientists whose work led to the detection of gravitational waves

2016 Nobel Prize in Physics?

2016 Nobel Prize in Physics?

Barish became the principal investigator of the Laser Interferometer Gravitational-wave Observatory (LIGO) in 1994 and director in 1997. He led the effort through the approval of funding by the NSF National Science Board in 1994, the construction and commissioning of the LIGO interferometers in Livingston, LA and Hanford, WA in 1997.

But some influential physicists, including previous Nobel laureates, say the prize, which can be split three ways at most, should include somebody else: Barry Barish.

2017 Nobel Prize in Physics?

Oct. 2017

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deceased at age 86
(Oct. 26, 1931-Mar. 7, 2017)

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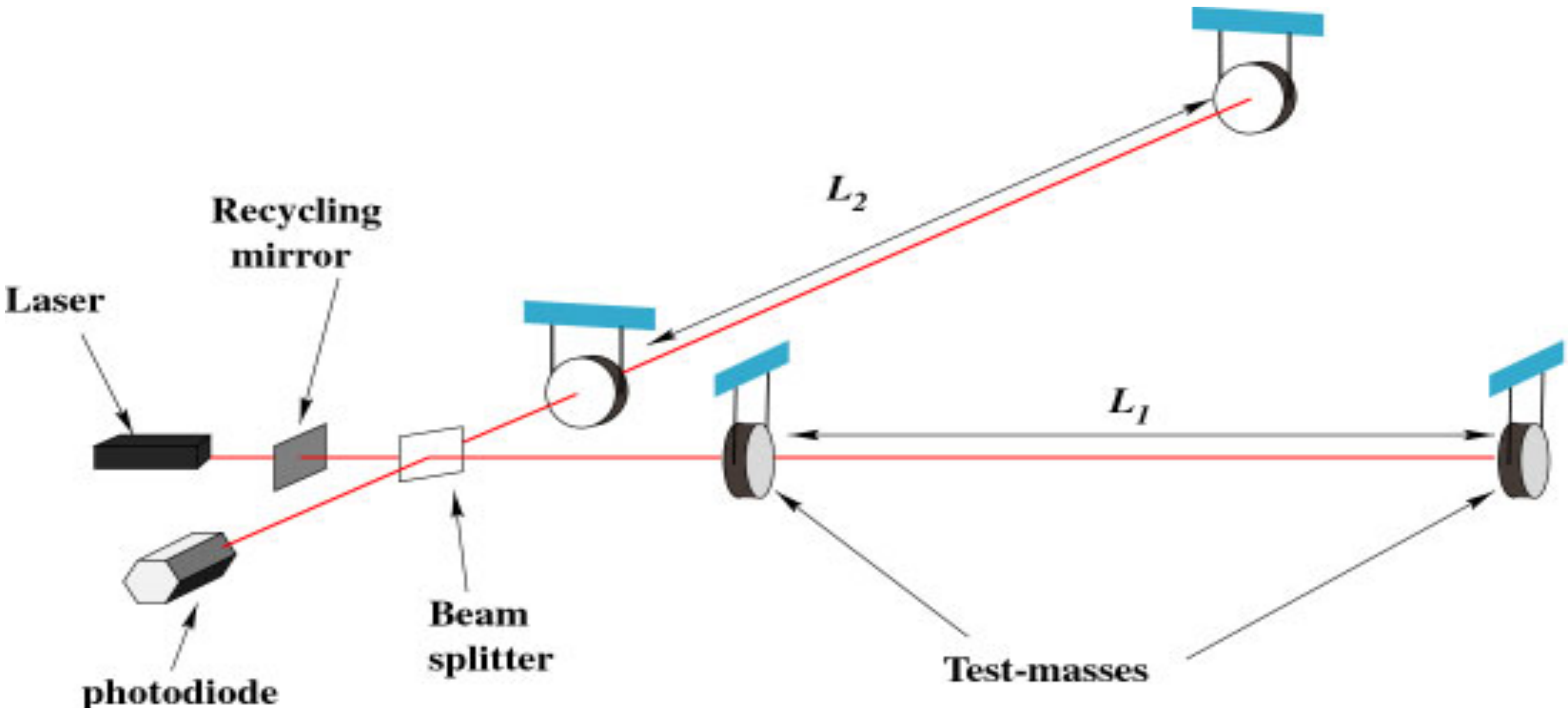
Rainer Weiss Kip Thorne Barry Barish

LIGO Interferometer Concept

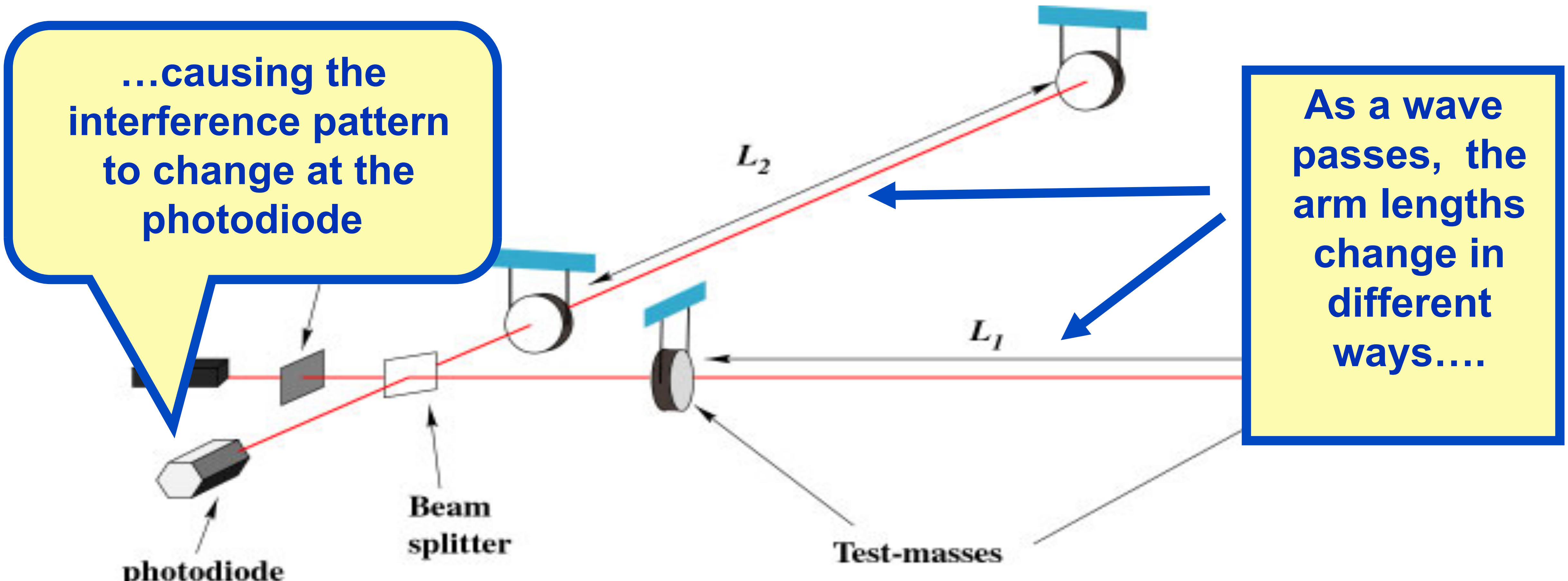


所用仪器是和1887年迈克耳逊的干涉仪基本相同的原理。干涉仪向不同方向发出两束激光，在两个长臂中来回后进行干涉，从干涉图像可以测量出两臂的微小差异

LIGO Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

- Arms in LIGO are 4km
- Measure difference in length to one part in 10^{21} or 10^{-18} meters



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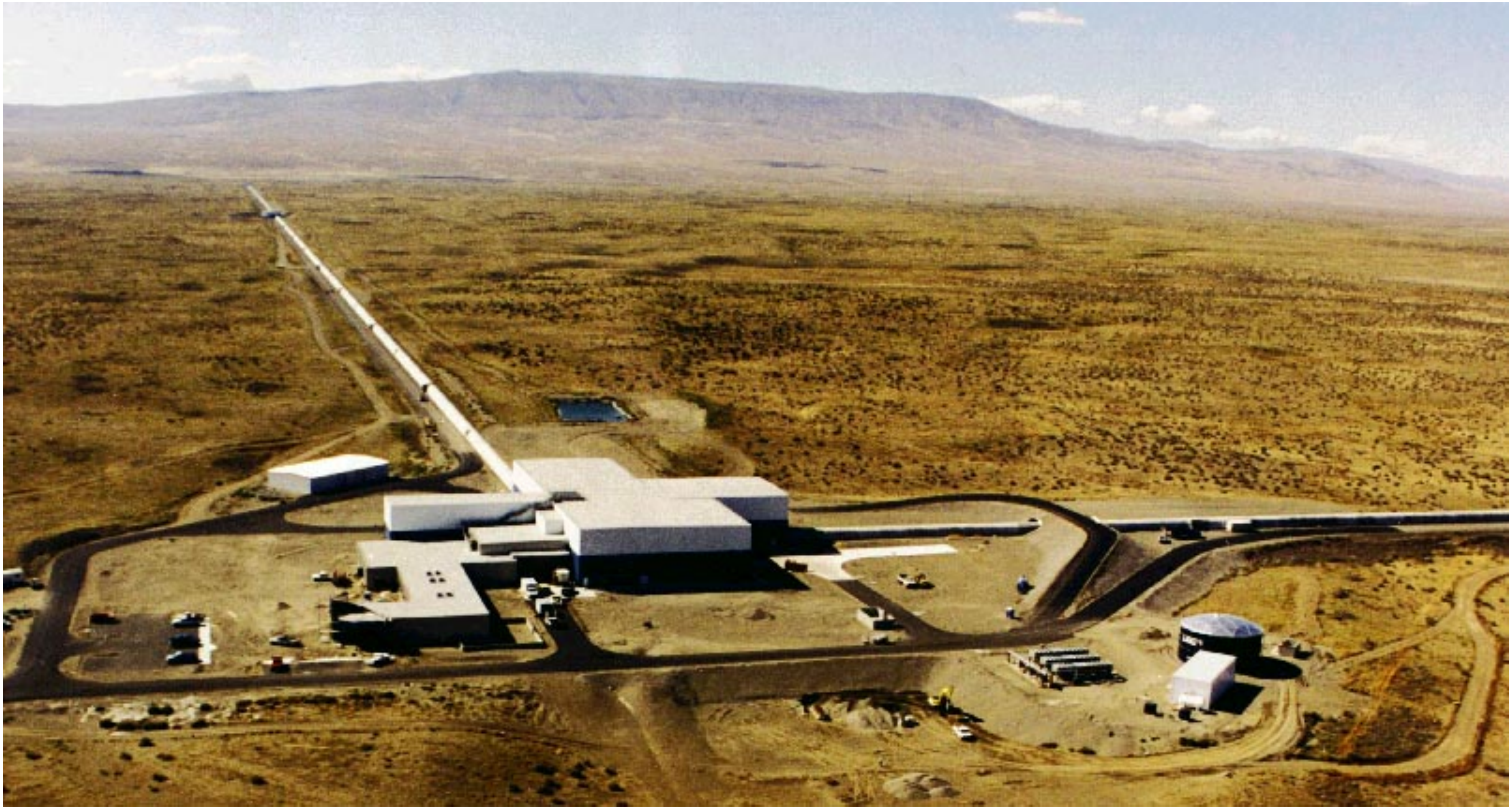
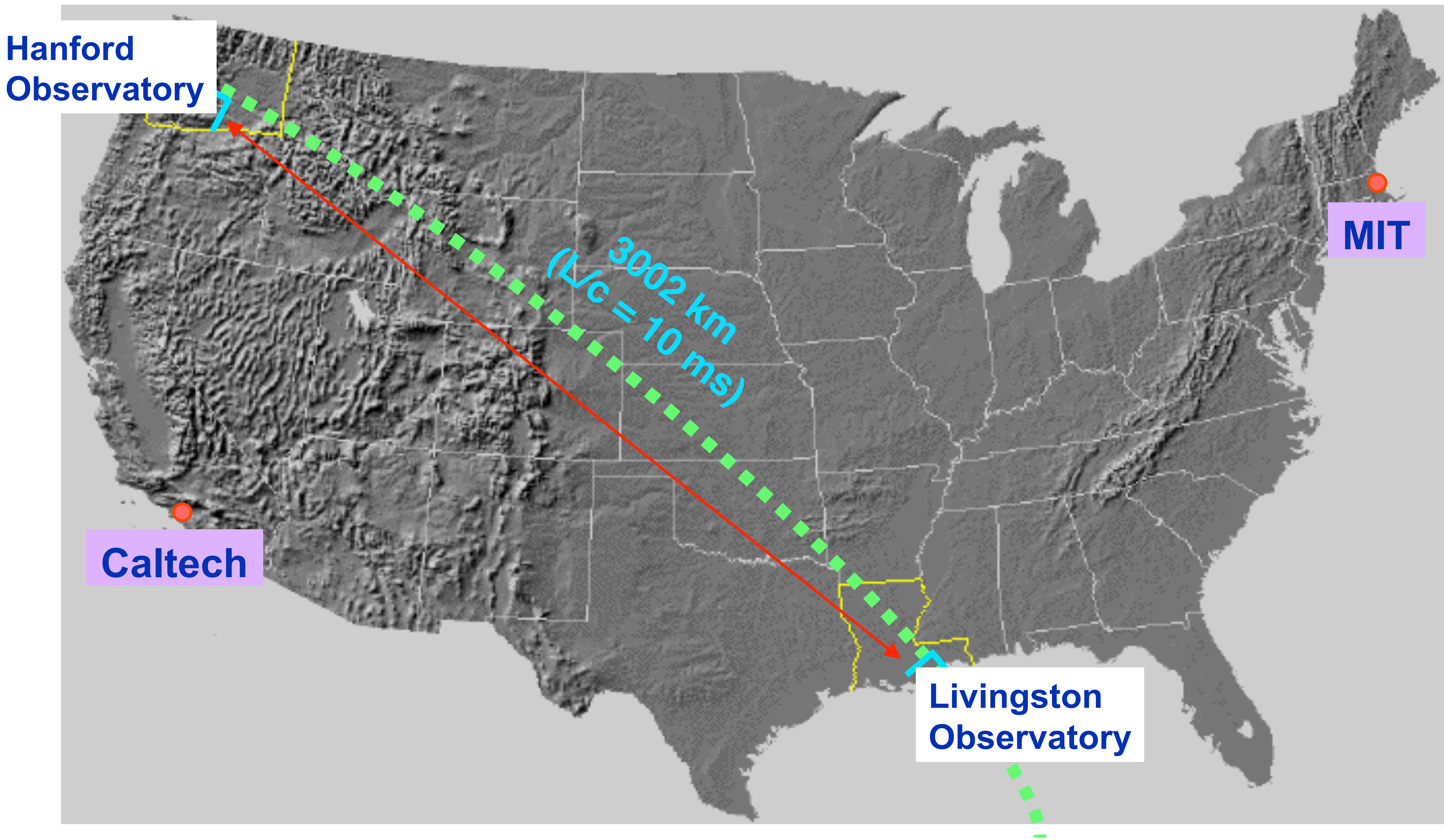
LIGO Livingston Observatory

LIGO Hanford Observatory



LIGO

Simultaneous Detection



LIGO
beam tube

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

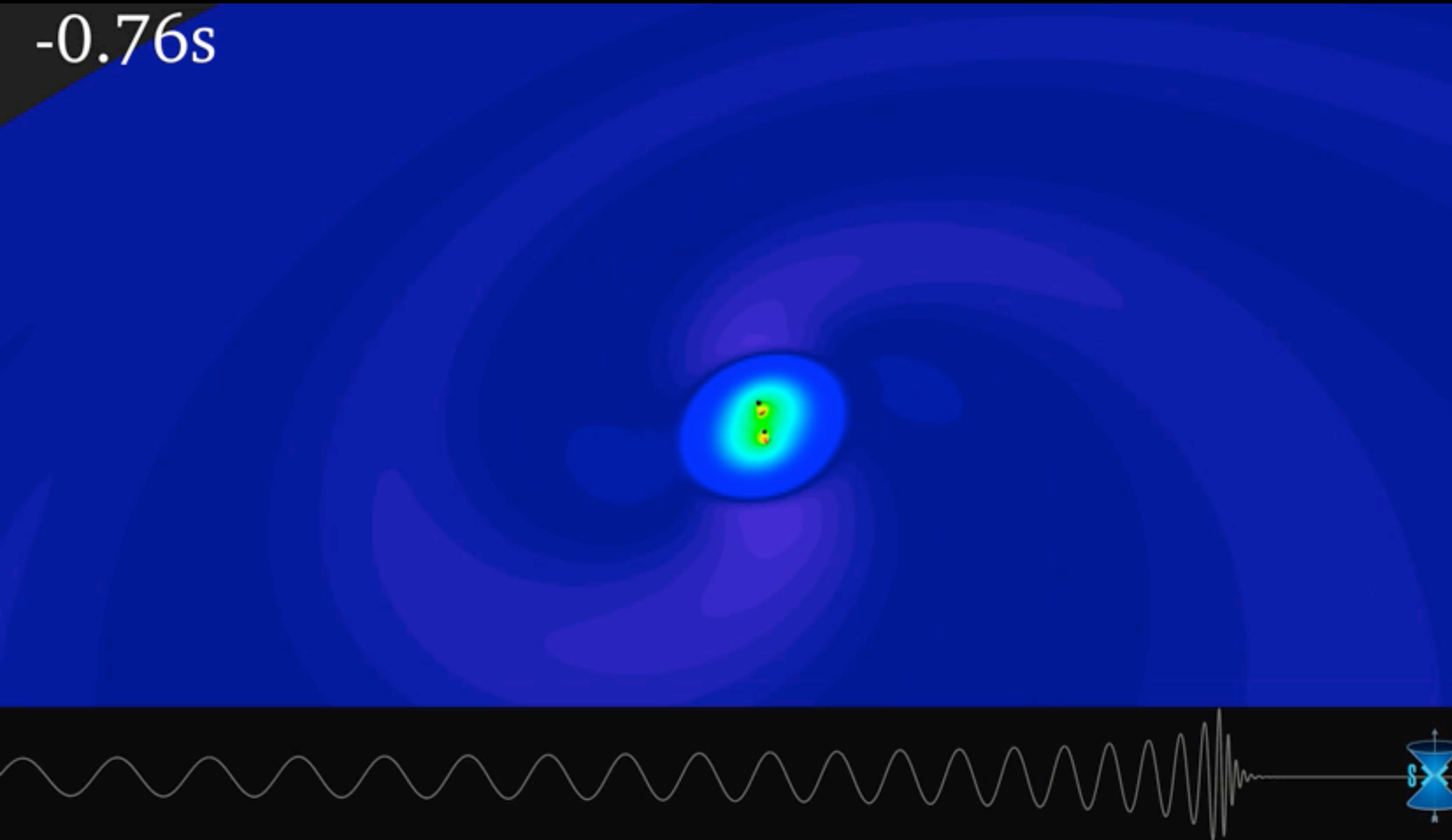
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

LIGO

Detection Paper Factoids

"the stat that really struck me was that in the first 24 hrs., not only was the page for your PRL abstract hit 380K times, but the PDF of the paper was downloaded from that page 230K times. This is far more hits than any PRL ever, and the fraction of times that it resulted in a download was unusually high. Hundreds of thousands of people actually wanted to read the whole paper! That is just remarkable." Robert Garistro (PRL editor)


-0.76s

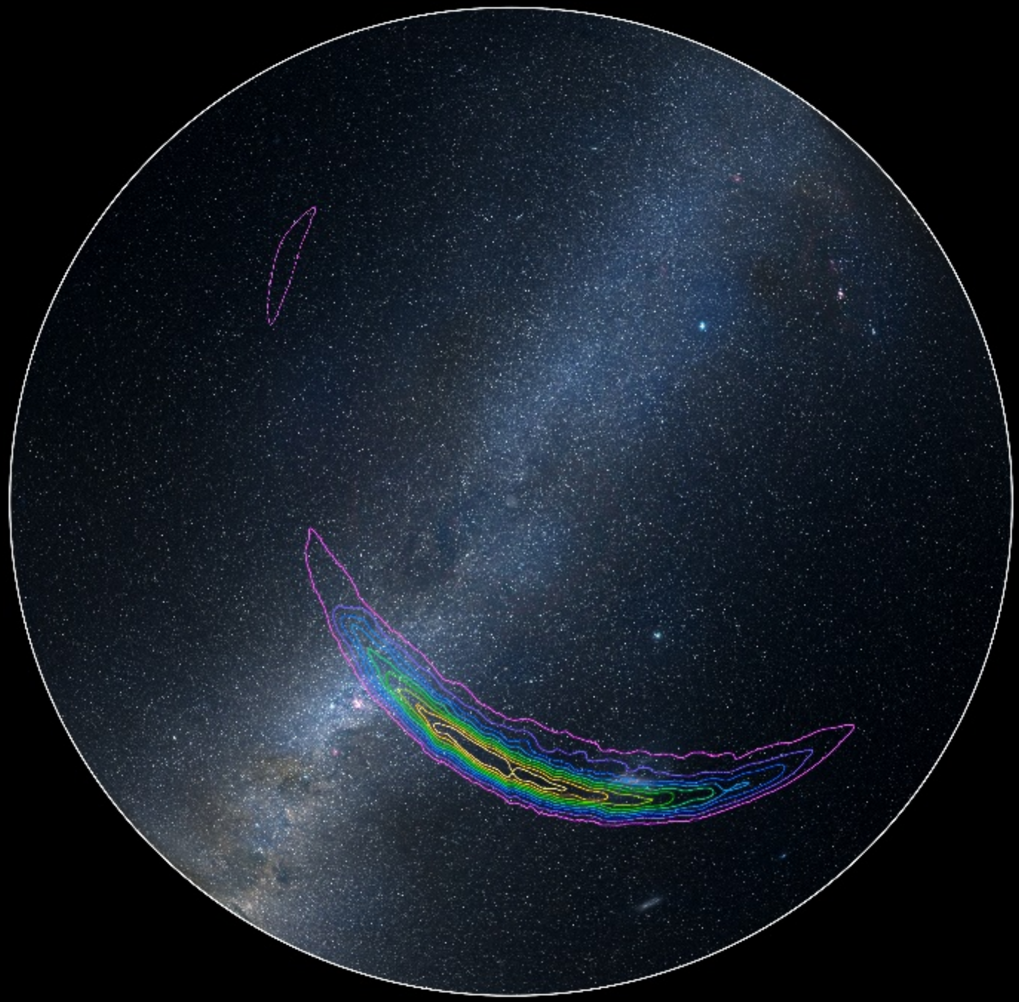
first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

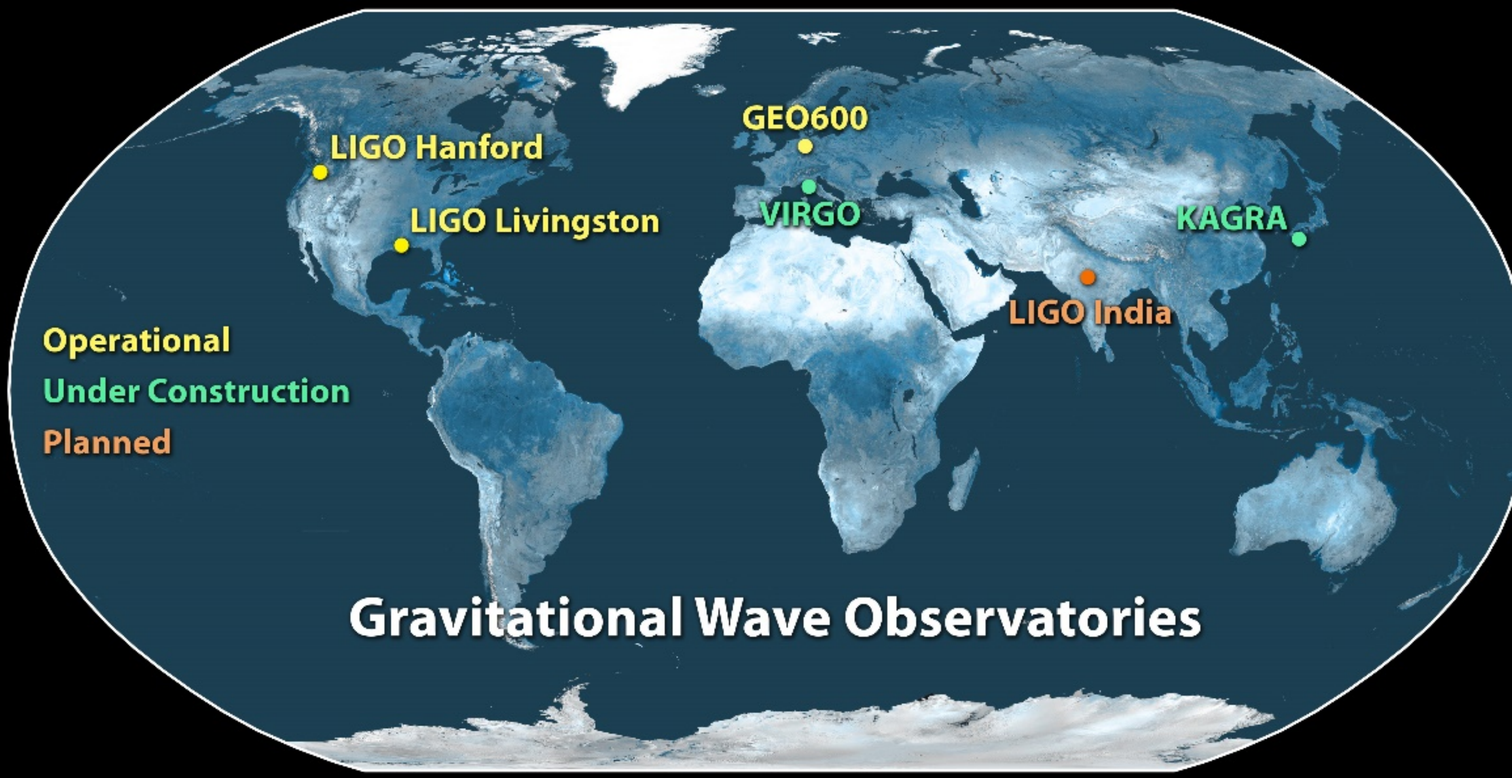
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV

mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

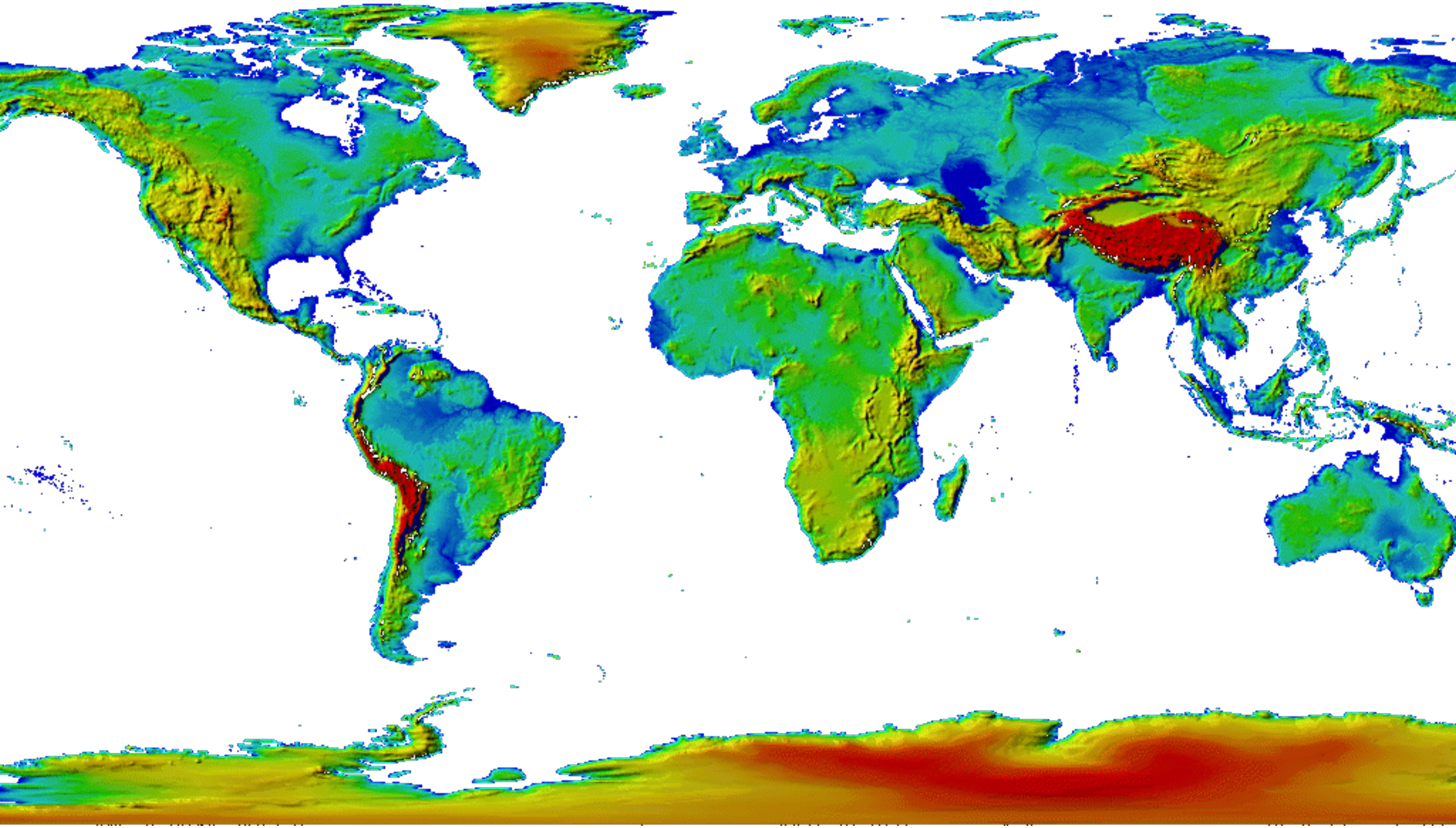
coalescence rate of binary black holes	2 to 400 $Gpc^{-3} yr^{-1}$
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries



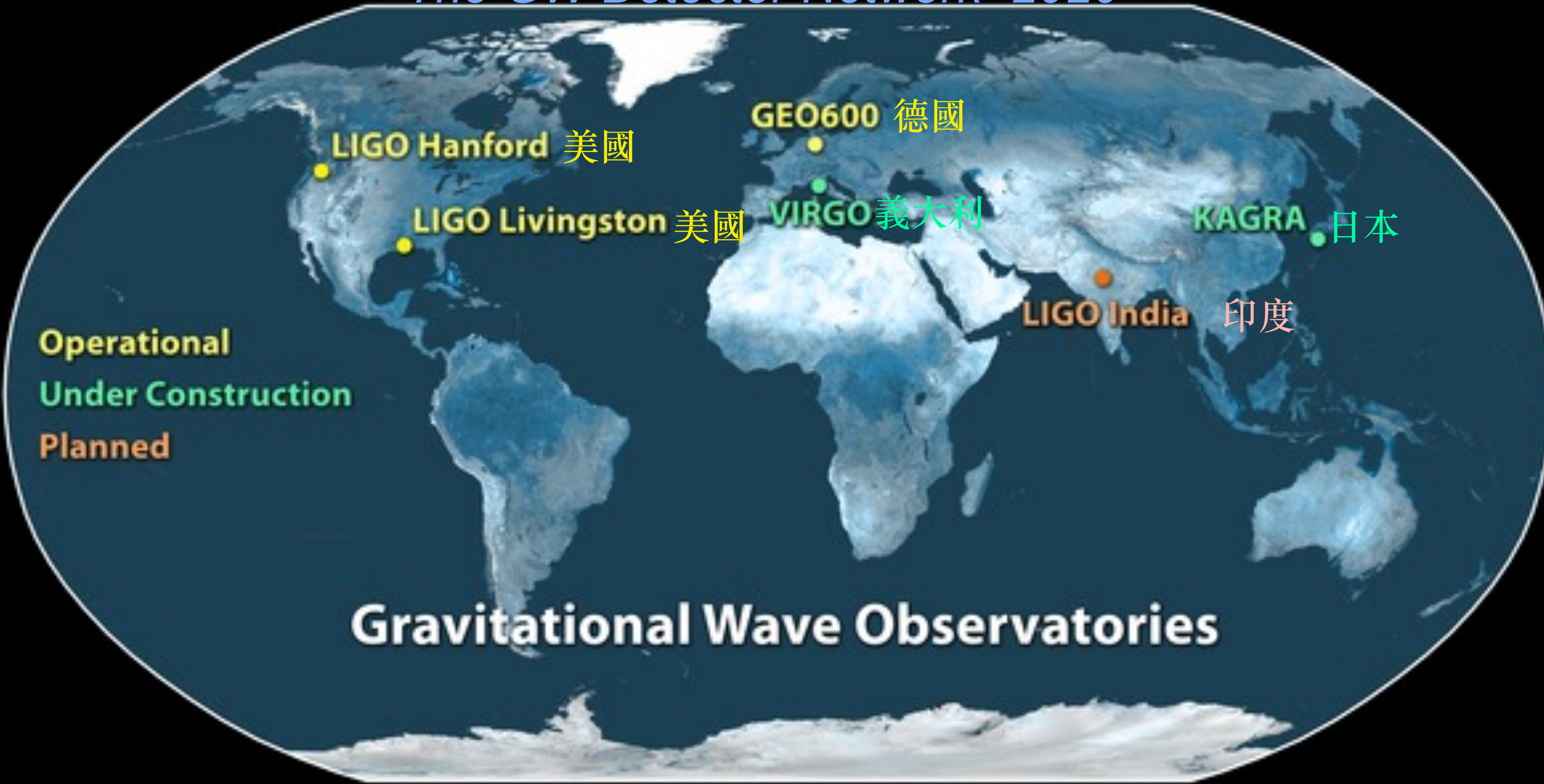


LIGO Scientific Collaboration

- 1500+ members, 85+ institutions, 16+ countries



The GW Detector Network~2020



Current operating facilities in the global network include the twin LIGO detectors—in Hanford, Washington, and Livingston, Louisiana—and GEO600 in Germany. The Virgo detector in Italy and the Kamioka Gravitational Wave Detector (KAGRA) in Japan are undergoing upgrades and are expected to begin operations in 2016 and 2018, respectively. A sixth observatory is being planned in India.


Virgo 義大利

New Astrophysics

Stellar binary black holes do exist!

Form and merge in time scales accessible to us
Predictions previously encompassed [0 – 10^3] / Gpc^3 / yr
Now we exclude lowest end: rate > 1 Gpc^3 / yr

Masses ($M > 20\, M_\odot$) are large compared with *known* stellar mass BHs

Testing GR

Most relativistic binary know today :
J0737-3039

Orbital velocity $v/c \sim 2 \times 10^{-3}$

GW150914 : Highly disturbed black holes

Non-linear dynamics

Access to the properties of space-time

$v/c \sim 0.6$

Confirms predictions of General Relativity

If $v_{GW} < c$, gravitational waves then have a modified dispersion relation. We see no evidence of modified inspiral

LIMIT 90% Confidence

$m_g < 1.2 \times 10^{-22}\ \mathrm{eV}/c^2$

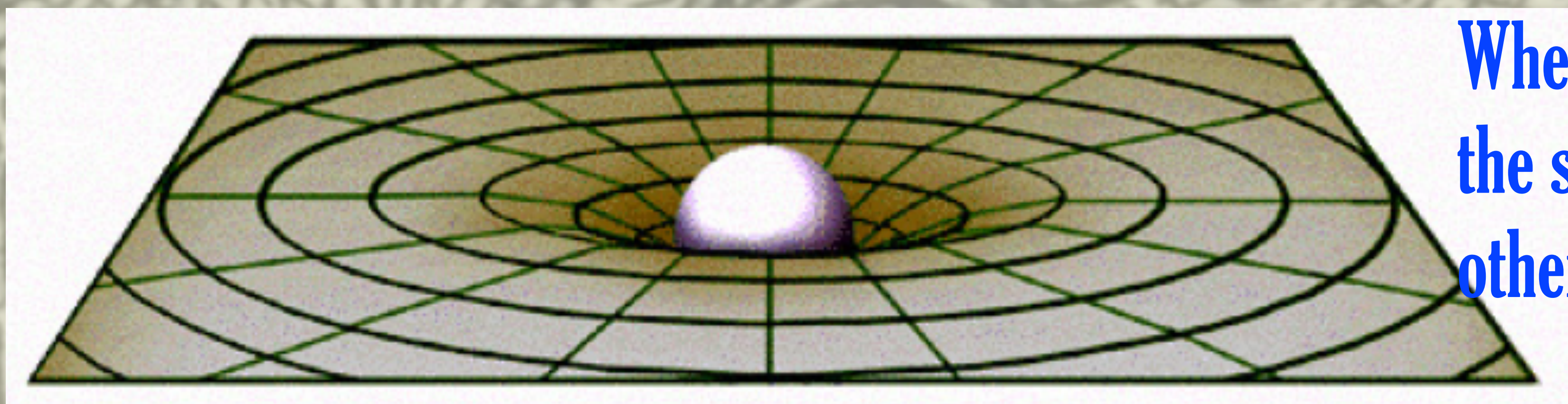
1915 General Relativity

(Einstein, Nov. 25, 1915)
(Einstein equations)

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

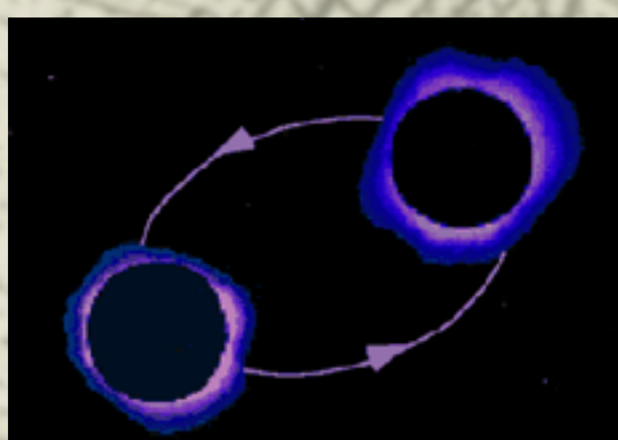
Space and Time: Spacetime!

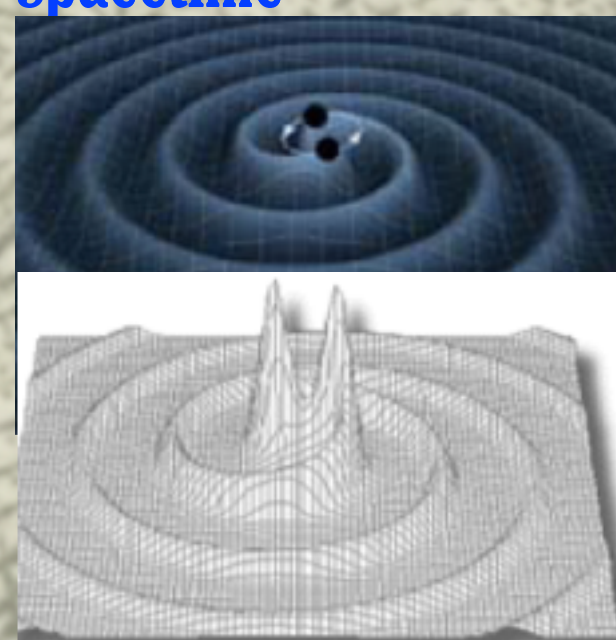
Spacetime tells matter how to move, and matter tells spacetime how to curve — John Wheeler



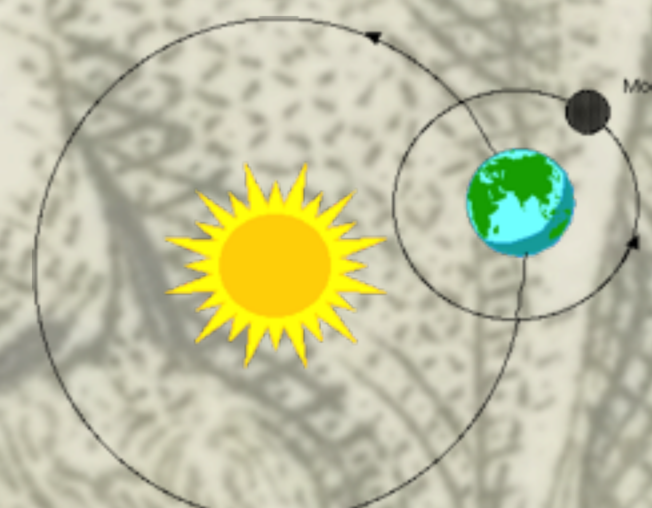
When masses move, they wrinkle the spacetime fabric, making other masses move ...

June 1916 Eienstein ``Gravitational Wave"
ripple in the curvature of spacetime



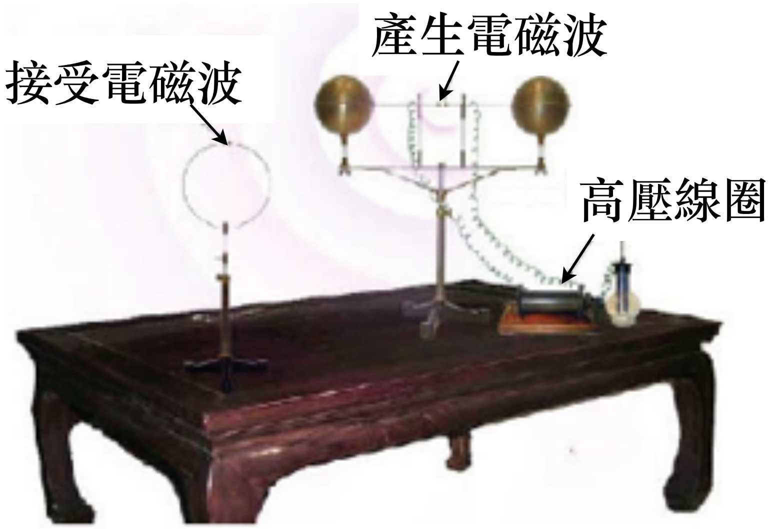


Explains just as well as Newton's why things fall and planetary motion...



The last prediction of General Relativity!

- 電磁波 Maxwell 1865 ⟶ Hertz 1887 : 23 年
- 引力波 Einstein 1916 ⟶ LIGO 2016 : 100 年



電磁波產生和探測

引力波探測：LIGO臂長4公里

電磁場
Vector Field

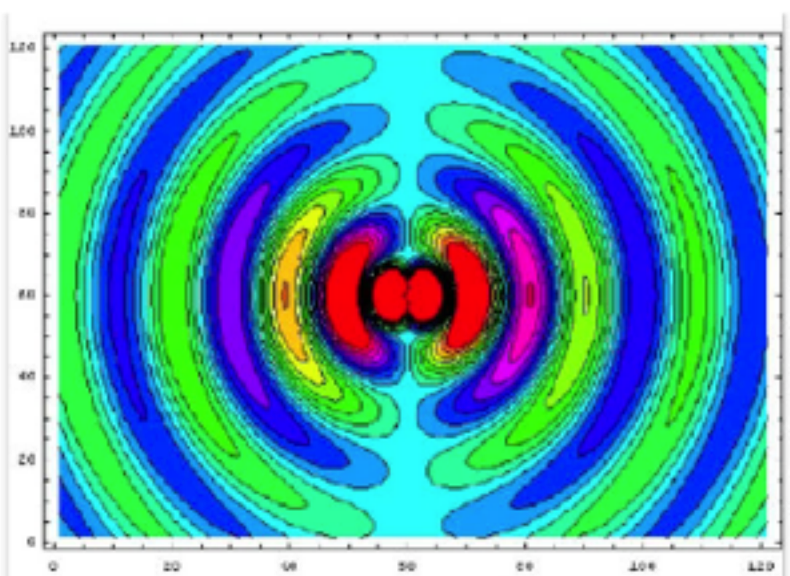
$$\Box A^\mu = -\frac{4\pi}{c} J^\mu$$

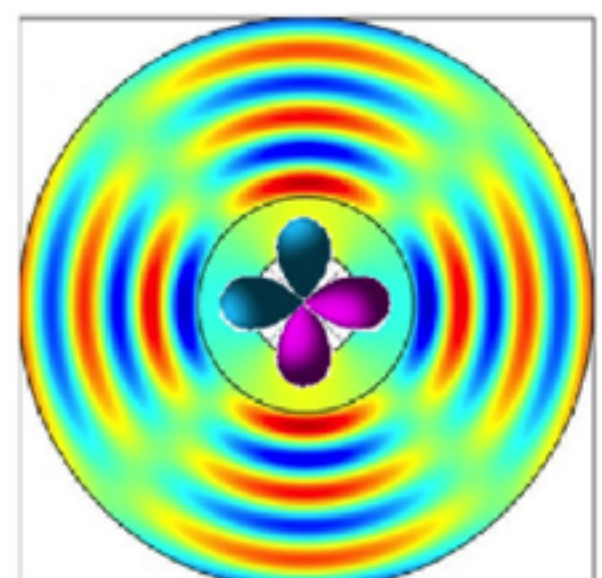
重力場
Tensor Field

$$\Box \mathbf{h}^\mu_k = -\frac{16\pi G}{c^4} \mathbf{T}^\mu_k$$

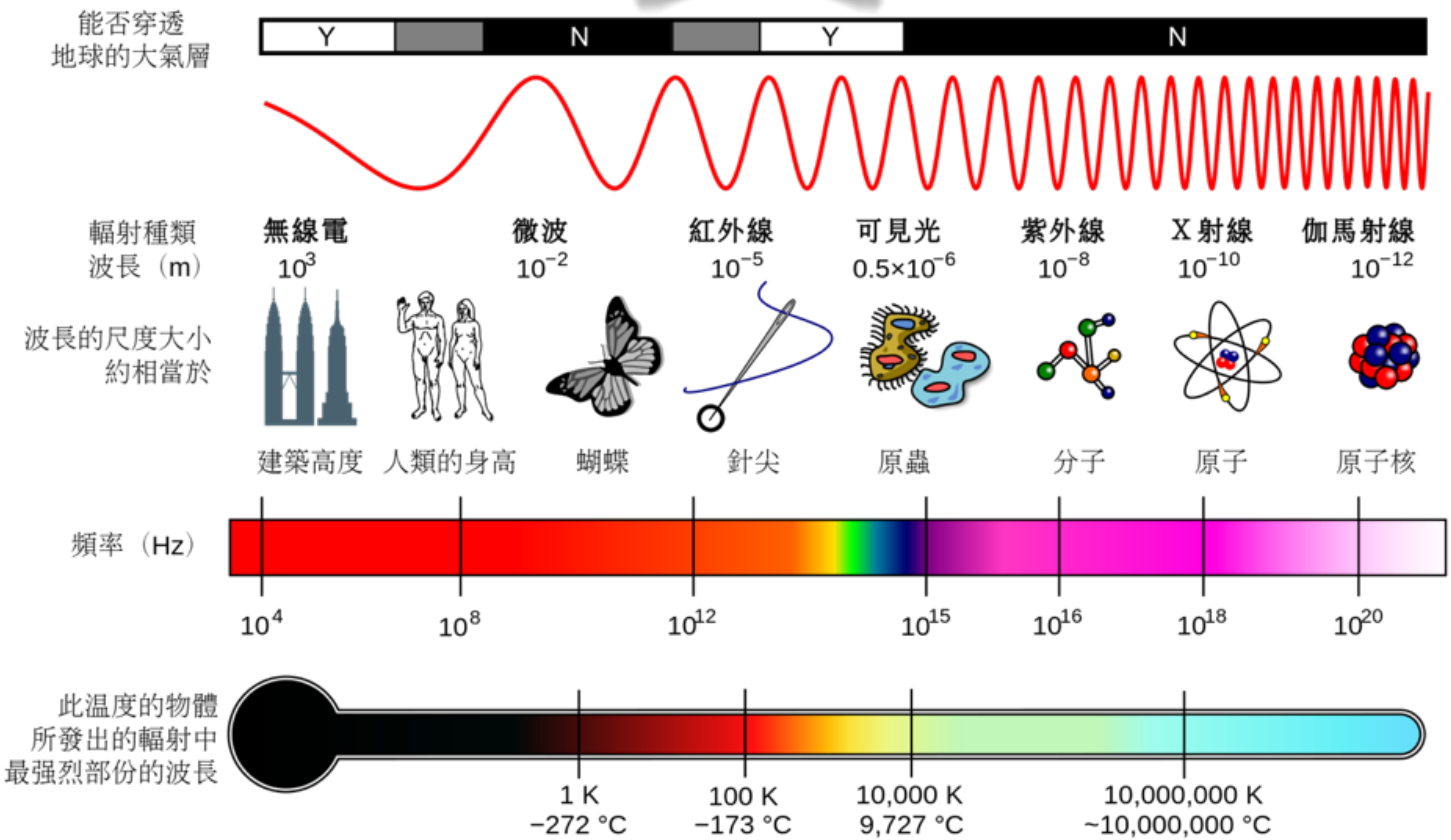
偶極子輻射
Dipole Radiation

四極子輻射
Quadrupole Radiation





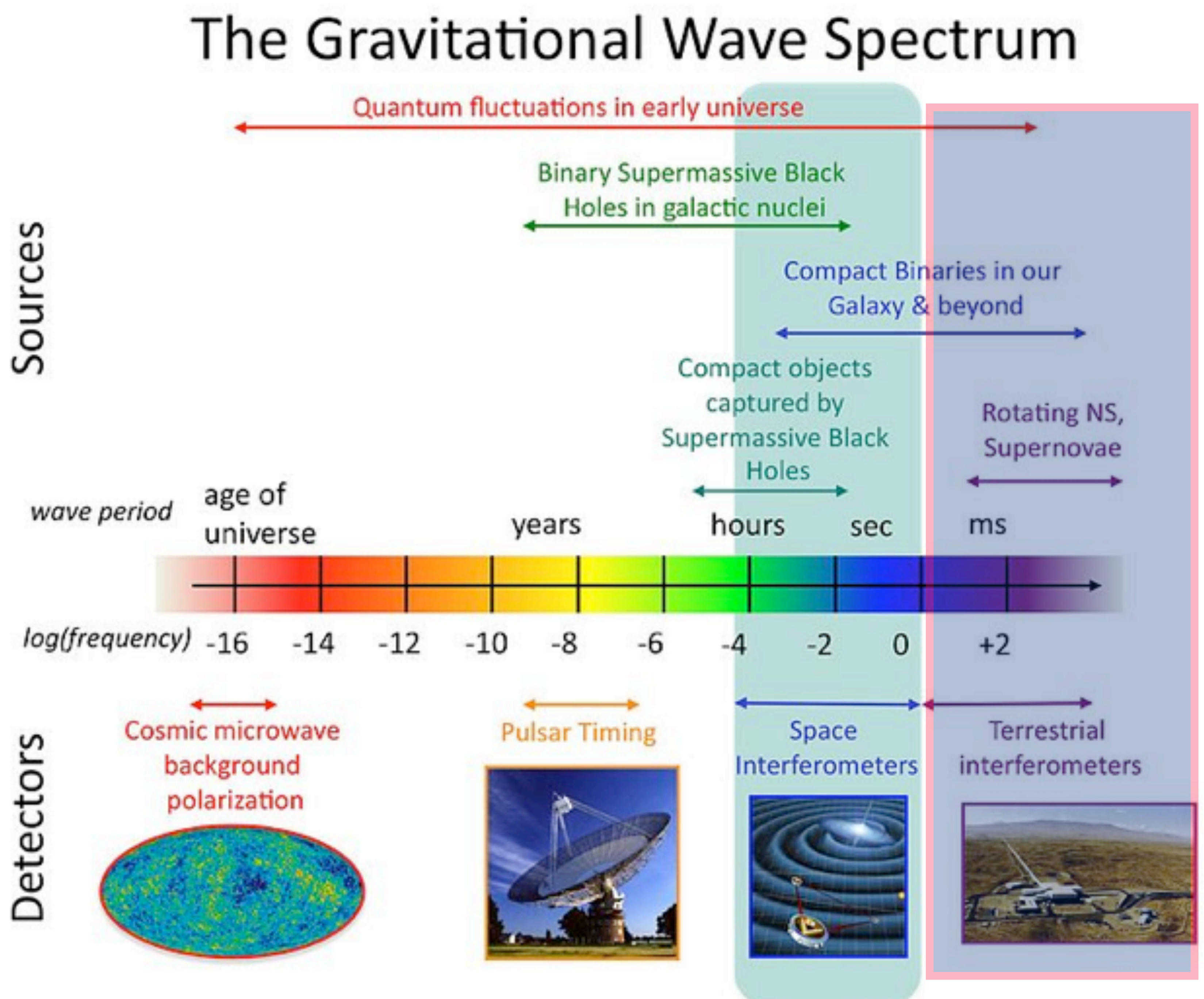
電磁波



能否穿透
地球的大氣層
Y
N
Y
N
輻射種類
波長（m）
無線電
10^3
微波
10^{-2}
紅外線
10^{-5}
可見光
0.5×10^{-6}
紫外線
10^{-8}
X 射線
10^{-10}
伽馬射線
10^{-12}
波長的尺度大小
約相當於
建築高度
人類的身高
蝴蝶
針尖
原蟲
分子
原子
原子核
頻率（Hz）
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
此溫度的物體
所發出的輻射中
最强烈部份的波長
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

Big Picture

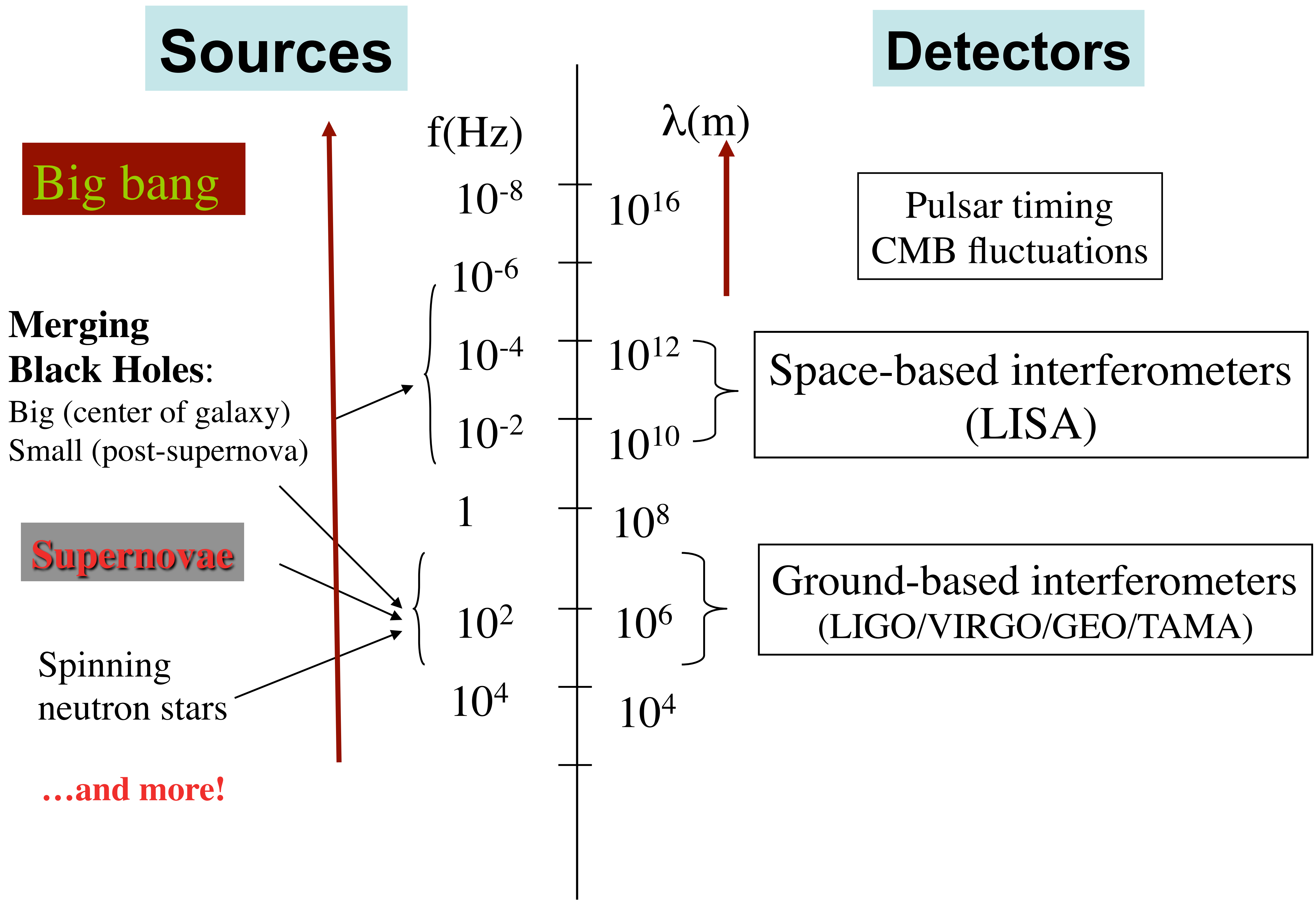
Gravitational Waves	EM Waves
Source:	Source:
~ any accelerating matter	~any accelerating charge
Weak coupling:	Strong coupling:
Imaging impractical:	Imaging often practical:
(strong sources)	(common sources)
<~ wavelength	>> wavelength
• **Hard** to make & detect	• Easy to make & detect
• Hard to obscure	• Easy to **obscure**



- **Gravitational Waves** are far more radical than **Radio or X-rays**

Completely new form of radiation!

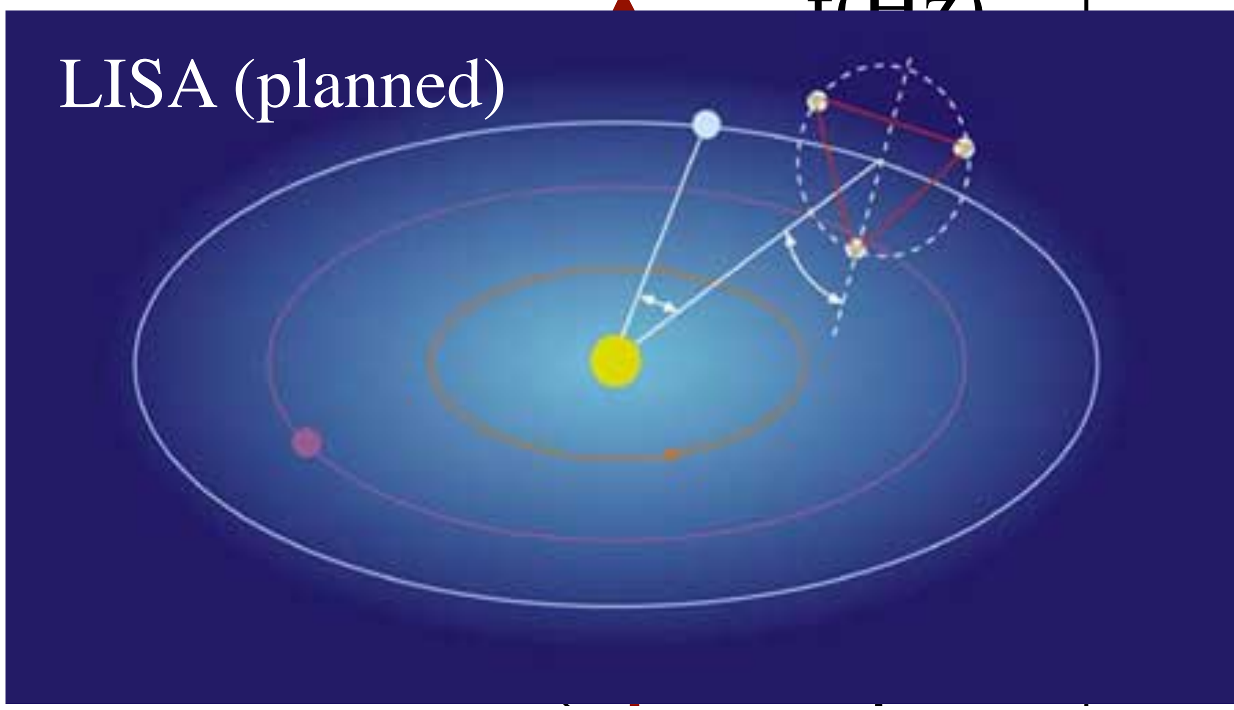
Frequencies to be opened span 22 decades
$f_{HF} / f_{ELF} \sim 10^{22}$


Sources
Detectors
f(Hz)
λ(m)
Big bang
10^{-8}
10^{16}
Pulsar timing
CMB fluctuations
10^{-6}
Merging
Black Holes:
Big (center of galaxy)
Small (post-supernova)
10^{-4}
10^{12}
Space-based interferometers
(LISA)
10^{-2}
10^{10}
1
10^{8}
Supernovae
Ground-based interferometers
(LIGO/VIRGO/GEO/TAMA)
10^{2}
10^{6}
Spinning
neutron stars
10^{4}
10^{4}
…and more!

Sources

Detectors

λ(m)



Pulsar timing
CMB fluctuations

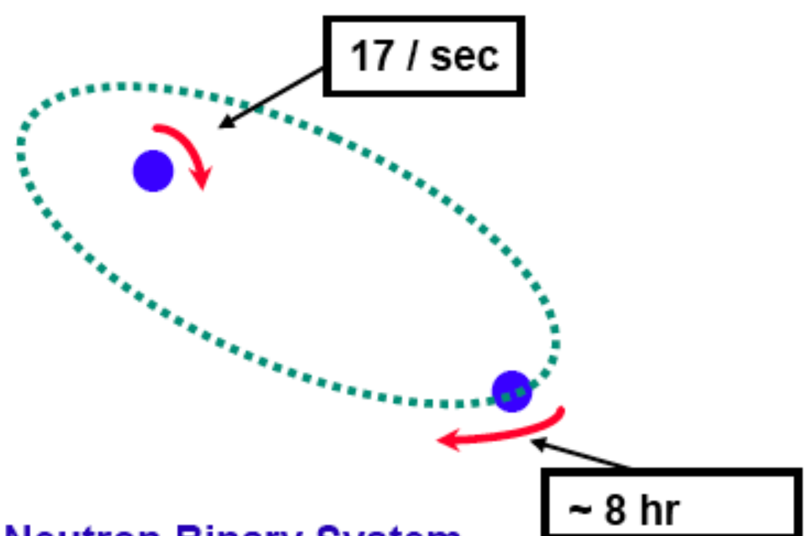
Space-based interferometers
(LISA)

Ground-based interferometers
(LIGO/VIRGO/GEO/TAMA)

Indirect Detecting Gravitational Waves (1974)

Observed pulsar binaries

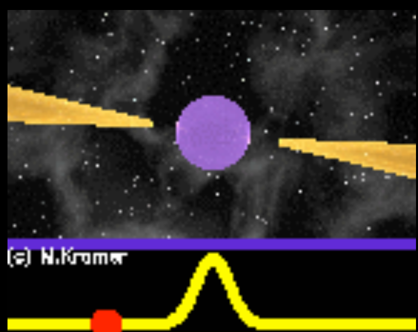
PSR 1913 + 16 -- Timing of pulsars

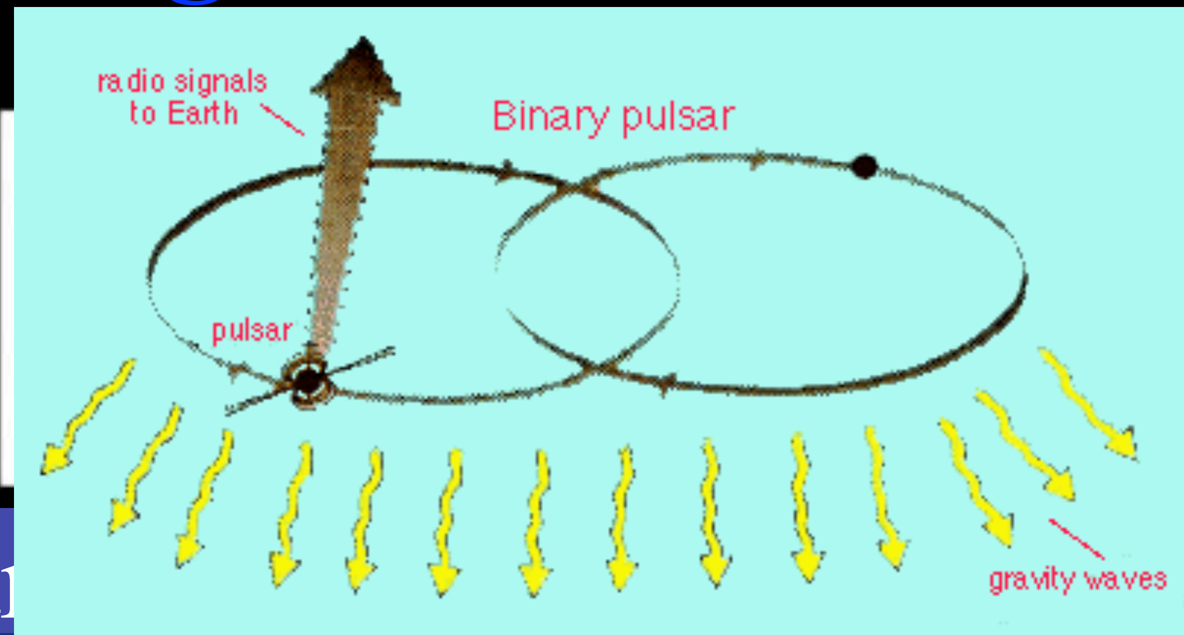


Neutron Binary System
- separated by 10^6 miles
- $m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity
- spiral in by 3 mm/orbit
- rate of change orbital period

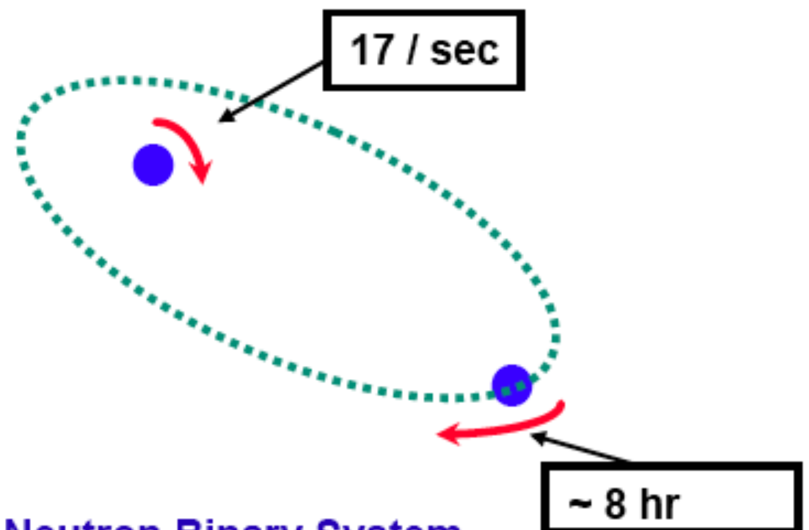
Indirect Detecting Gravitational Waves (1974)





Observed pulsar

PSR 1913 + 16 -- Timing of pulsars



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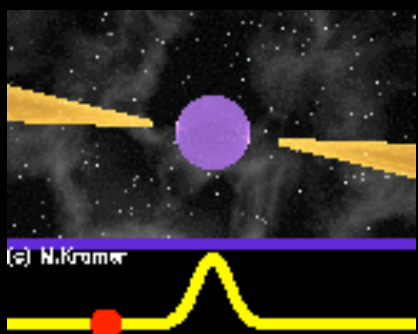
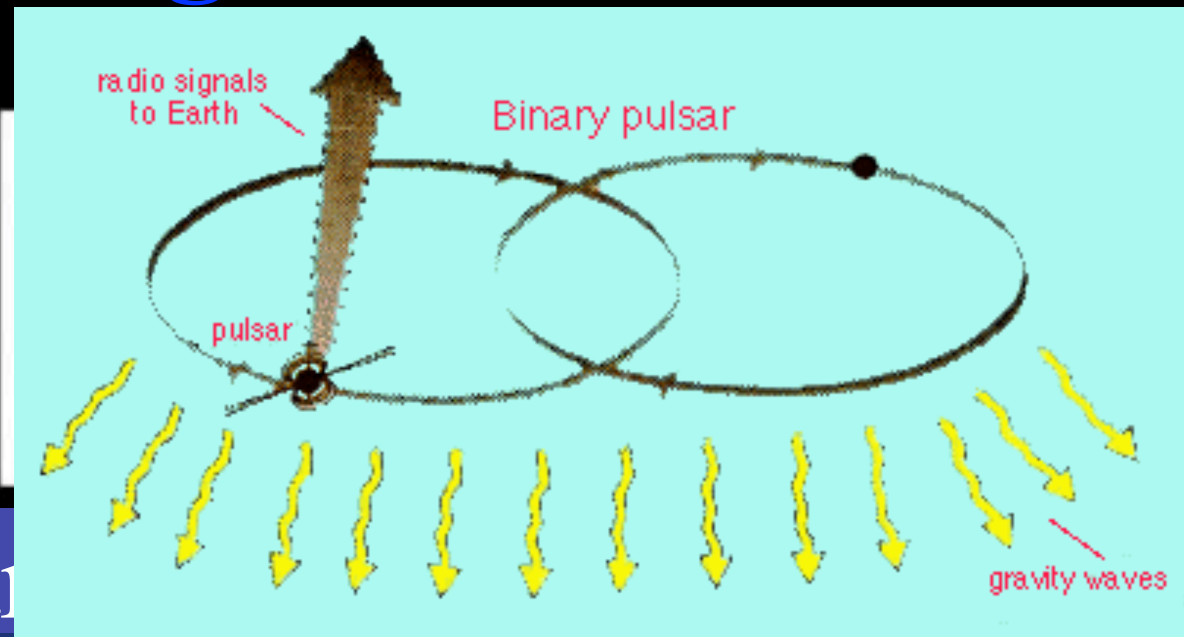
Indirect Detecting Gravitational Waves (1974)

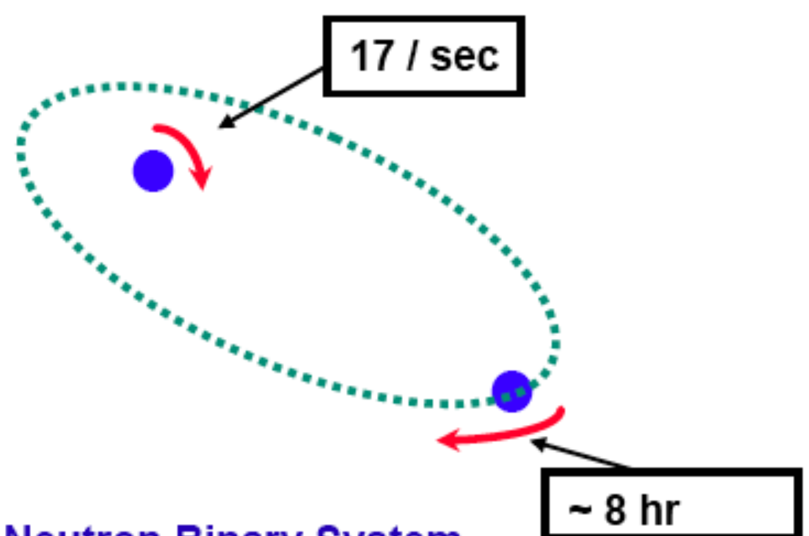
英雄歲月





Observed pulsar

PSR 1913 + 16 -- Timing of pulsars



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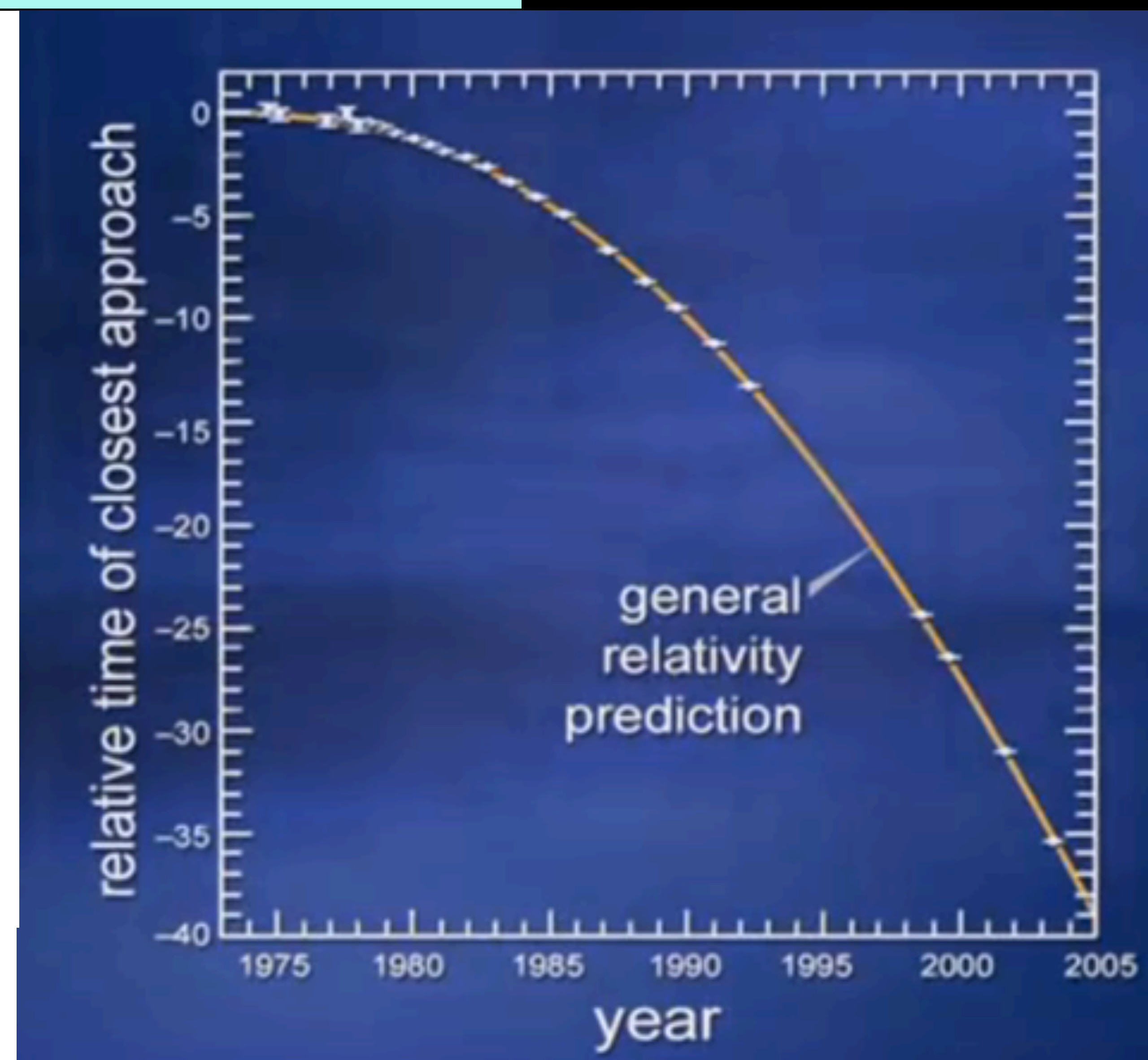


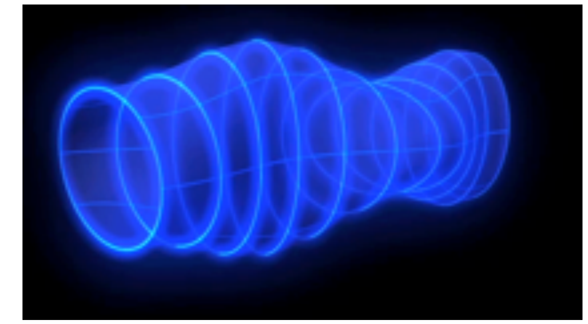
(Nobel Prize, 1993)

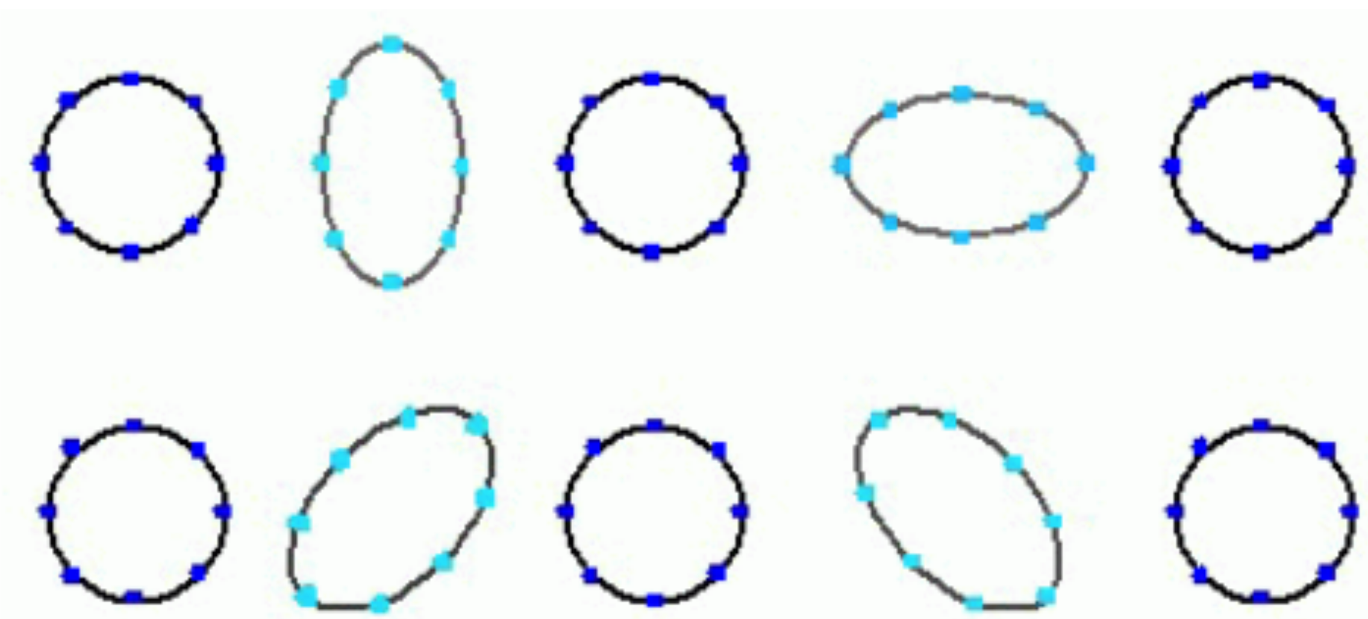
Gravitational Waves: $$\frac{\delta L}{L} \approx h_{ij} n^i n^j$$

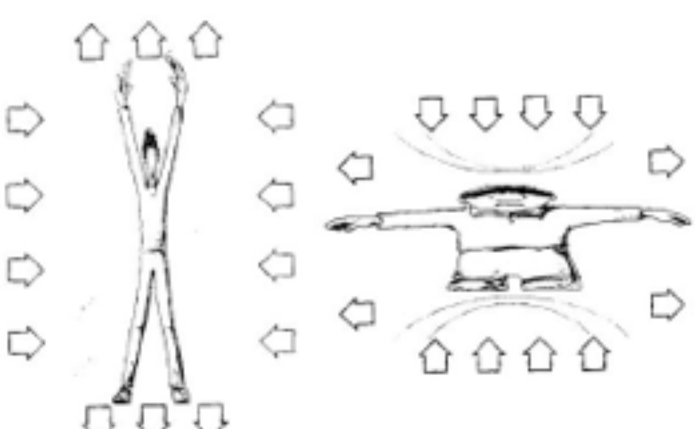
Quadrupole NOT dipole
Spacetime itself is what ``Waves”

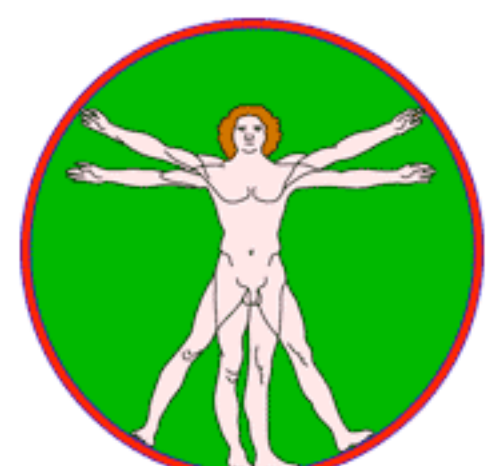
Massless, two helicity states s=±2,
i.e. two Transverse-Traceless (TT) tensor polarizations propagating at v=c

$$h_{ij} = h_+(x_i x_j - y_i y_j) + h_\times(x_i y_j + y_i x_j)$$









Direct Detecting Gravitational Waves in 1966?

Weber Bar (50 Years ago)

``OBSERVATION OF THE THERMAL FLUCTUATIONS OF A GRAVITATIONAL-WAVE DETECTOR"
J. Weber, PRL 1966 (Received 3 October 1966)

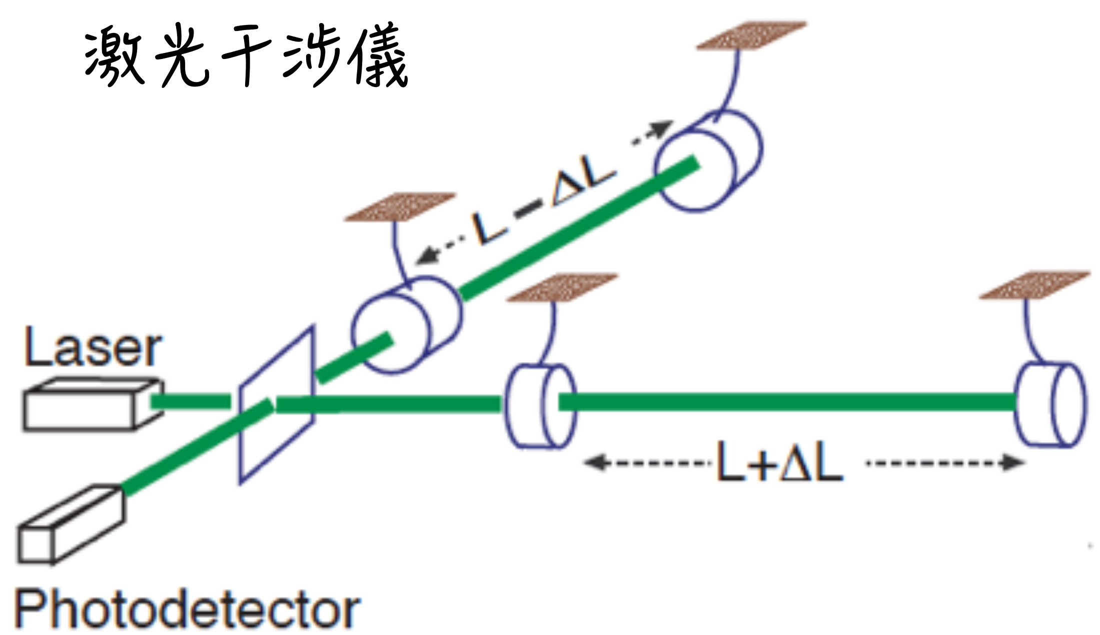
Strains as small as a few parts in 10^{16} are observable for a compressional mode of a large cylinder.

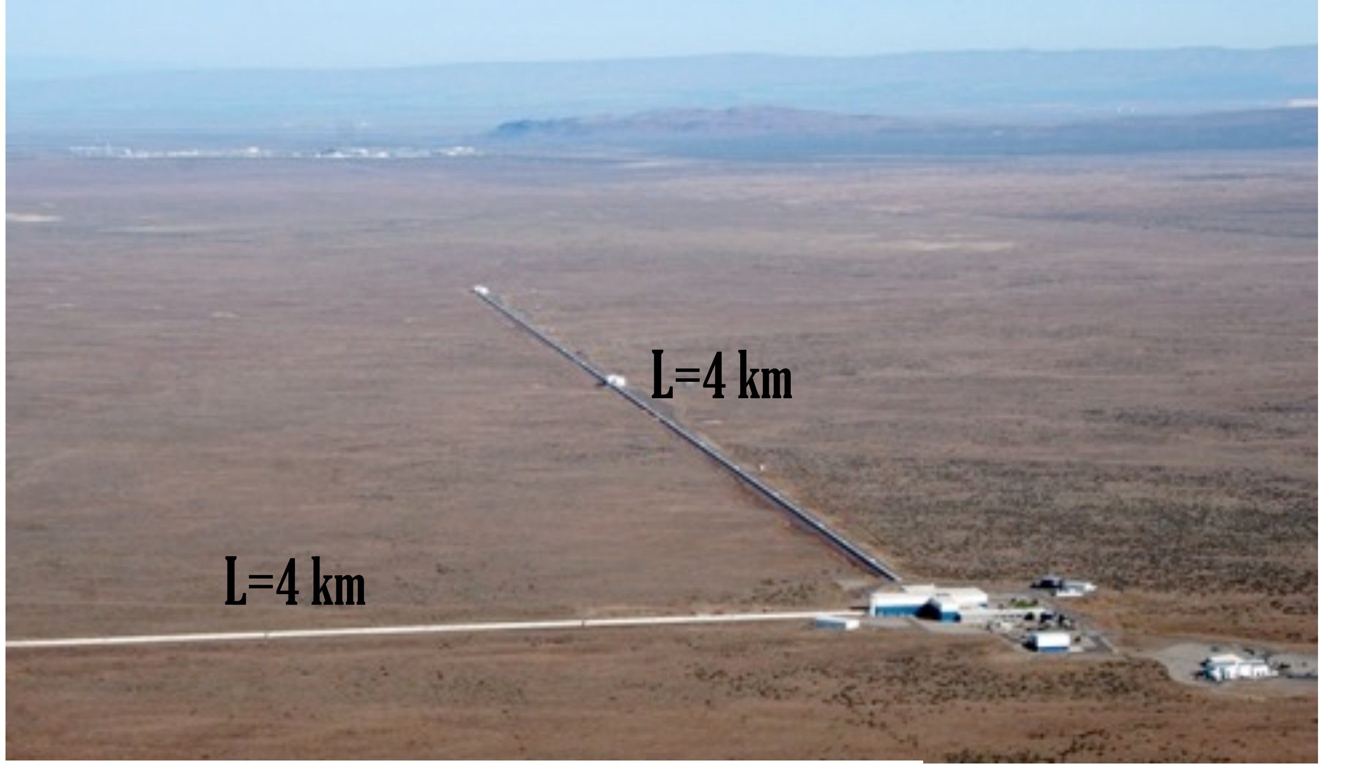
``GRAVITATIONAL RADIATION"
J. Weber, PRL 1967 (Received 8 February 1967)

The results of two years of operation of a 1660-cps gravitational-wave detector are reviewed. The possibility that some gravitational signals may have been observed cannot completely be ruled out. New gravimeter-noise data enable us to place low limits on gravitational radiation in the vicinity of the earth's normal modes near one cycle per hour, implying an energy-density limit over a given detection mode smaller than that needed to provide a closed universe.

Direct Detecting Gravitational Waves 20150914

Laser Interferometer Gravitational wave Observatory: LIGO





Bounce laser beams off mirrors

$\Longrightarrow$ measure change in mirror movement as small as 1/1000 of proton diameter!

<u>Sensitivity needed? (LIGO)</u>

$\Delta L \sim h\,L \sim 10^{-21}$ 4km

$\sim 4 \times 10^{-16}$ cm

laser light	$\sim 10^{-4}$cm
atom	$\sim 10^{-8}$cm
proton	$\sim 10^{-13}$cm

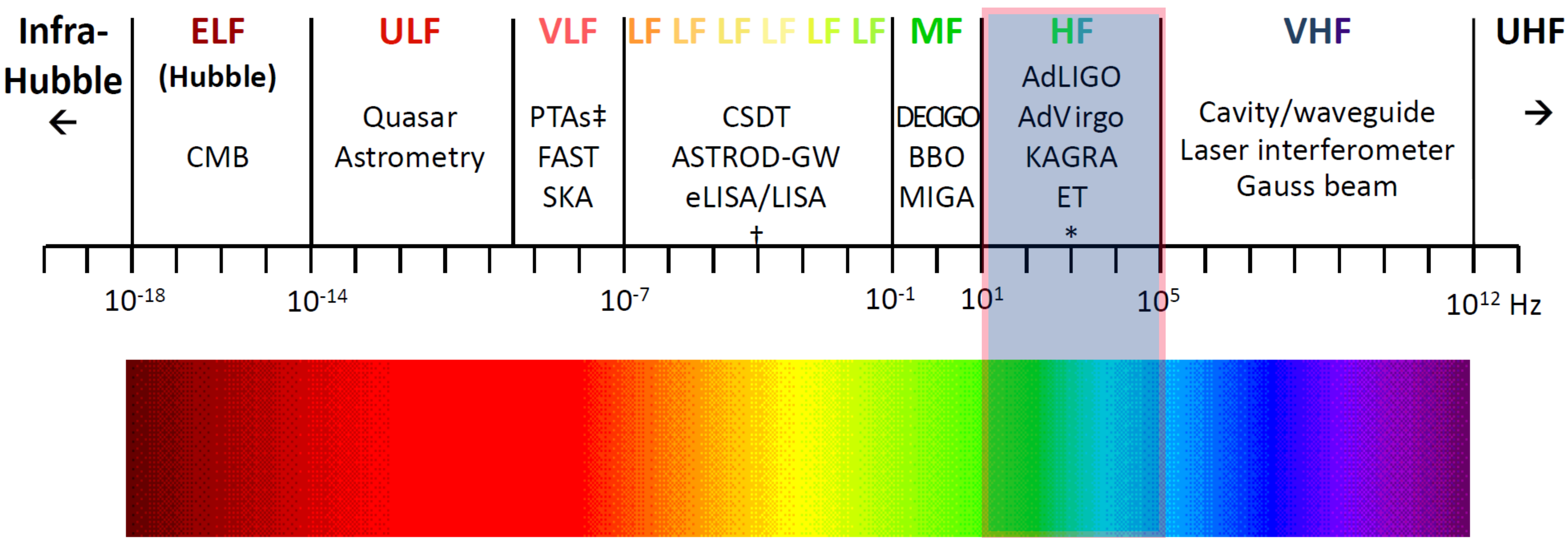
What will we learn from Gravitational Waves?

- *"Warped side of the universe"*
  - our first glimpses, then in-depth studies
- *The nonlinear dynamics of curved spacetime*
- *Answers to astrophysical & cosmological puzzles:*
  - How are supernovae powered?
  - How are gamma-ray bursts powered?
  - What was the energy scale of inflation? ...
- *Surprises*

重力波是完全新的波形式，不受屏蔽，直接印證早期宇宙

從一百多年電磁波的經驗，期待重力波今後的進展！

The Gravitation-Wave (GW) Spectrum Classification

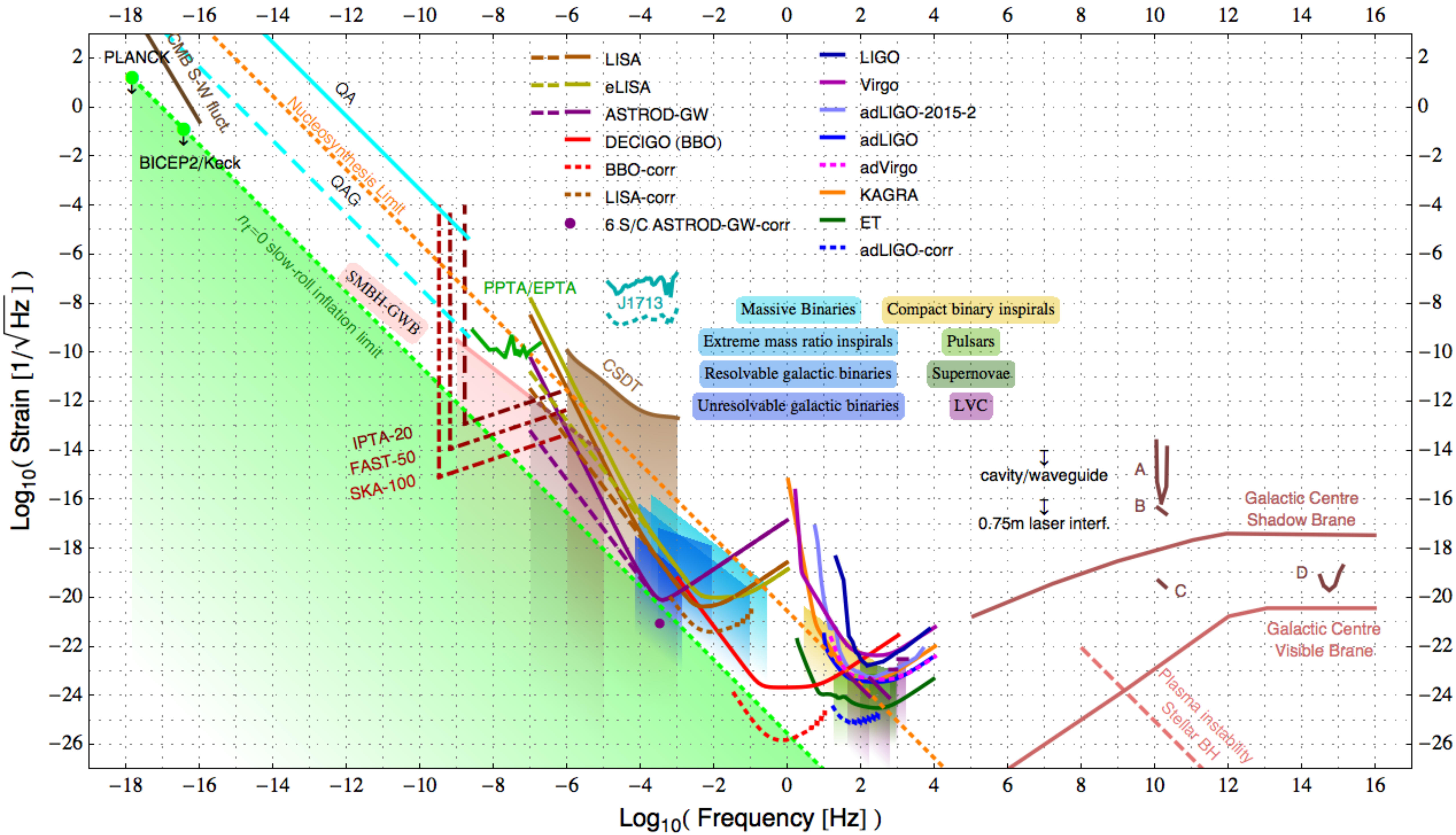


* AIGO, AURIGA, EXPLORER, GEO, NAUTILUS, MiniGRAIL, Schenberg.

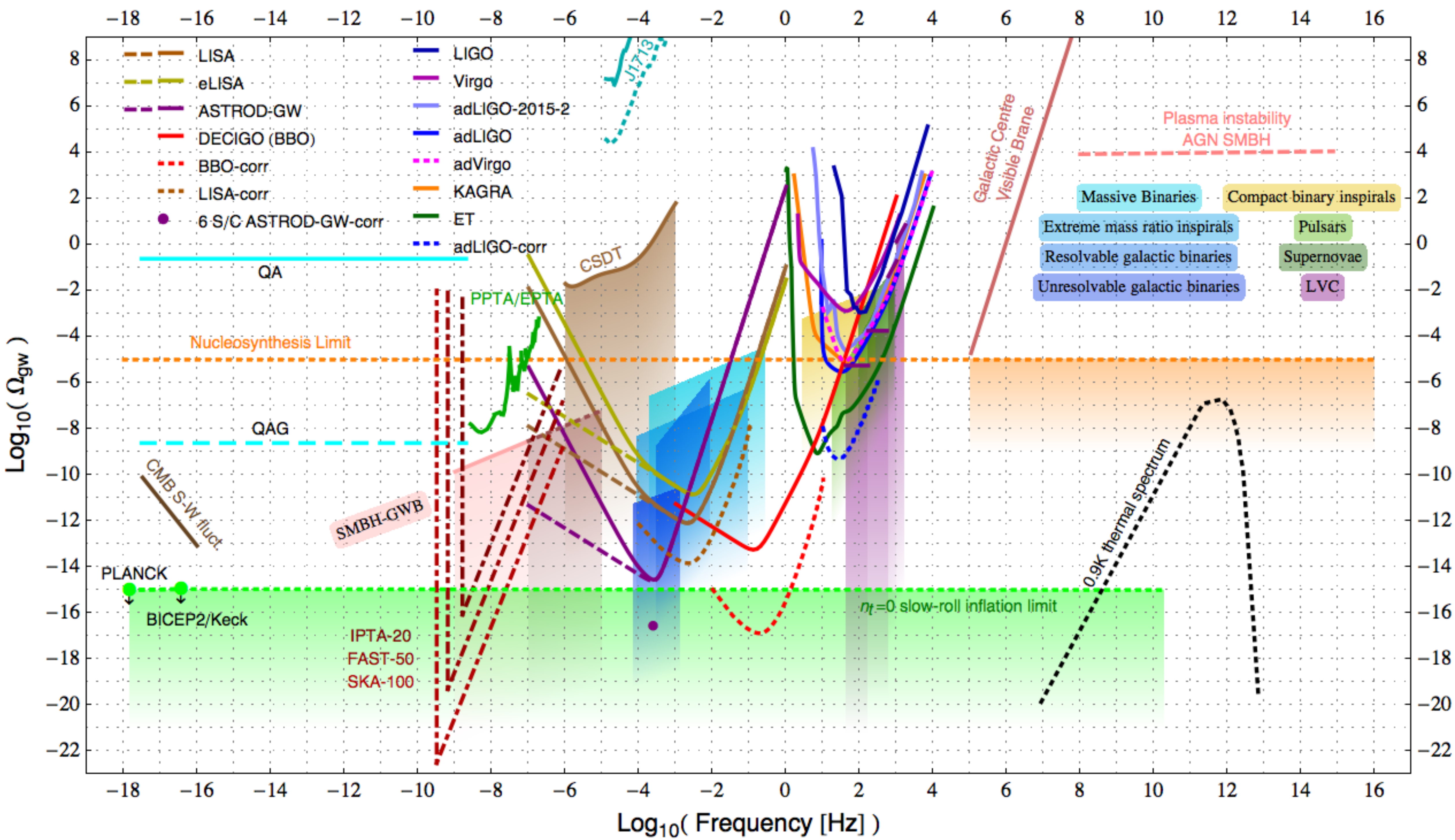
† OMEGA, gLISA/GEOGRAWI, GADFLI, TIANQIN, ASTROD-EM, LAGRANGE, ALIA, ALIA-descope.

‡ EPTA, NANOGrav, PPTA, IPTA.

Strain power spectral density (psd) amplitude vs. frequency for various GW detectors and GW sources



Normalized GW spectral energy density Ω_{gw} vs. frequency for GW detector sensitivities and GW sources



- **Future Prospectives □ □ □ □**

Three Kinds of GW Researchers in future

Experimentalists (Experimental Astronomers/Physicists):

Working on detectors and data

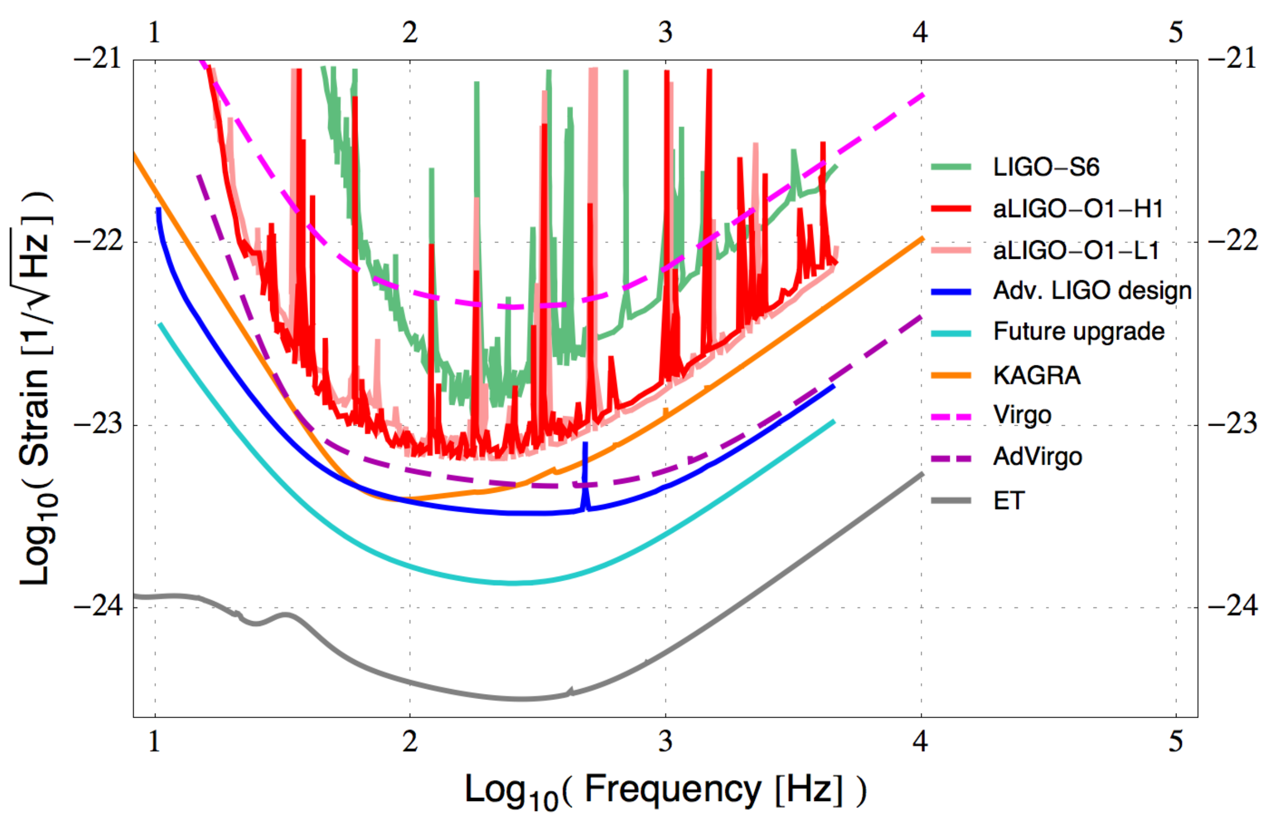
Multi-Messenger Astronomers:

Working on astrophysics

Theoretical Physicists/Cosmologists:

Working on fundamental and theoretical physics

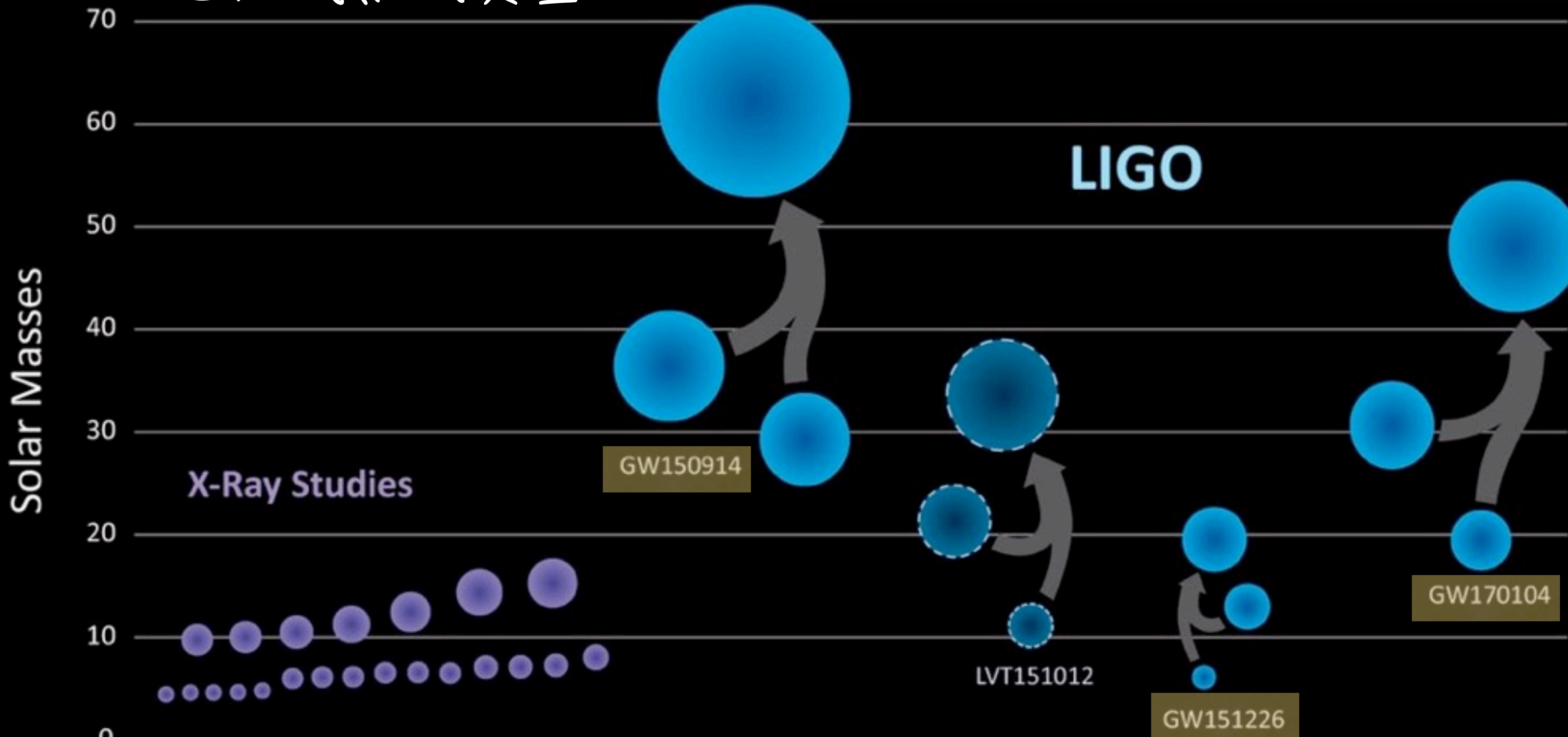
Advanced LIGO has detected GWs from stellar-mass binary black hole mergers. We will see a global network of second generation km-size interferometers for GW detection soon. Scaling with the achieved detection, third generation detectors would be to detect more than 100,000 5σ-GW events per year.



- Present aLIGO sensitivity: ~ one 5-σ event per 3 months.
- Goal second generation sensitivity: 100 5-σ events per year
- Improved 2nd gen.: x2, 800-1000 events/yr
- First generation sensitivity: several 3-σ events per year → one should look at the past data and try to search for them with better efforts and methods
- Third generation sensitivity → 100,000 or more 5-σ events per year Plenty compared to some other branches of physics and astronomy

已知的黑洞質量

Black Holes of Known Mass

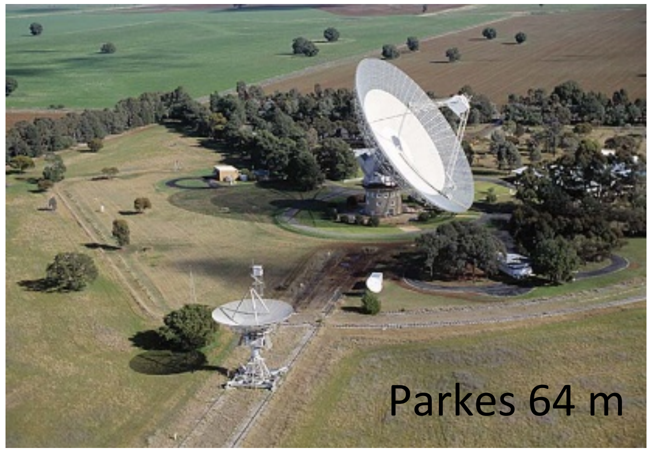


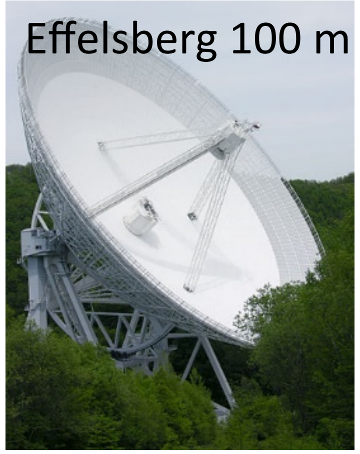
	Event #1: GW150914	Event #2: GW151226 (Boxing Day)	Event #3: GW170104
Type	Black Hole + Black Hole	Black Hole + Black Hole	Black Hole + Black Hole
Mass 1	36 solar masses	14 solar masses	31 solar masses
Mass 2	29 solar masses	8 solar masses	20 solar masses
Final Mass	62 solar masses	21 solar masses	49 solar masses
Energy	3 solar masses radiated	1.1 solar masses radiated	2 solar masses radiated
Distance	400 Mpc (1.3 billion lyr)	440 Mpc (1.4 billion lyr)	880 Mpc (~3 billion lyr)
Duration	~ 0.2 seconds	~ 1 second	~ 0.3 seconds

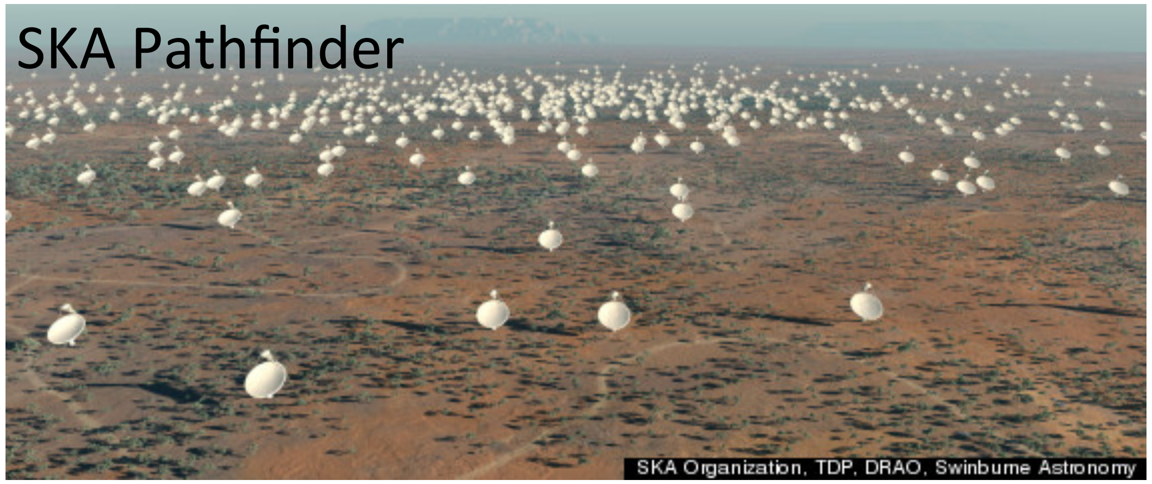
Another avenue for real-time direct detection is from the PTAs. The PTA bound on stochastic GW background already excludes most theoretical models; this may mean we could detect very low frequency GWs anytime soon with a longer time scale.

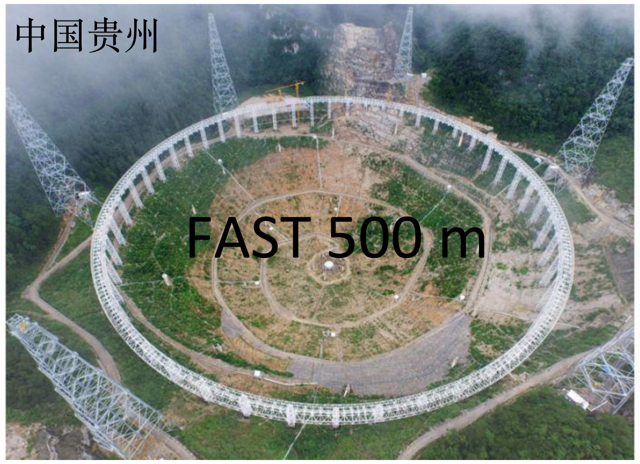
Pulsar Timing Arrays (PTAs)

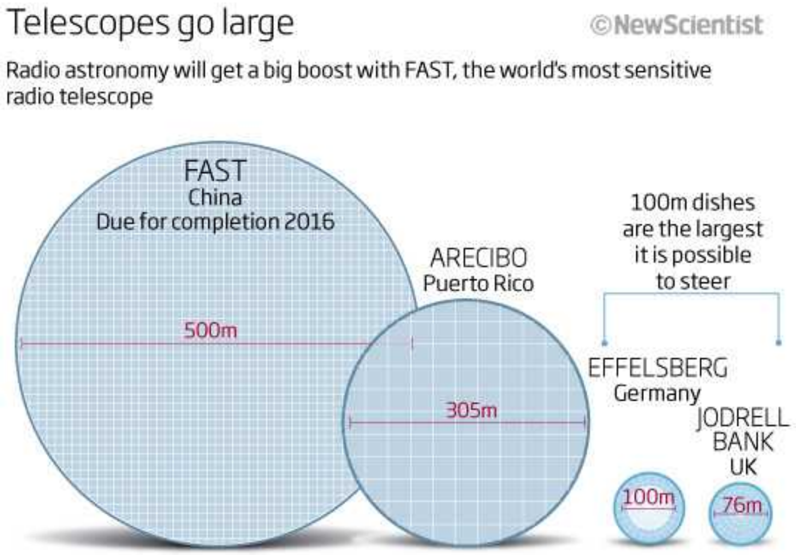
PPTA, NANOGrav, EPTA, IPTA,FAST, SKA





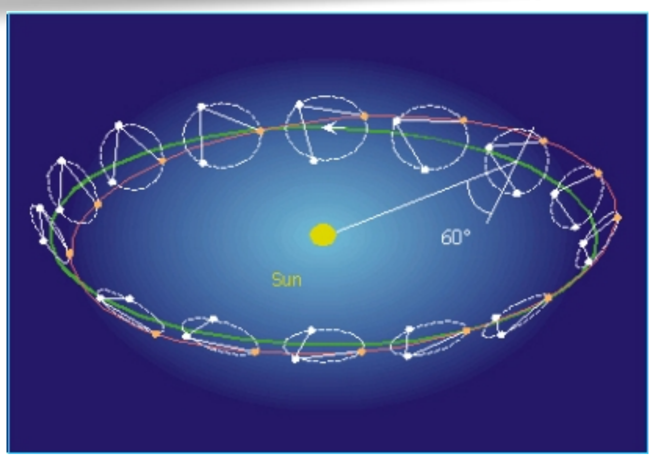




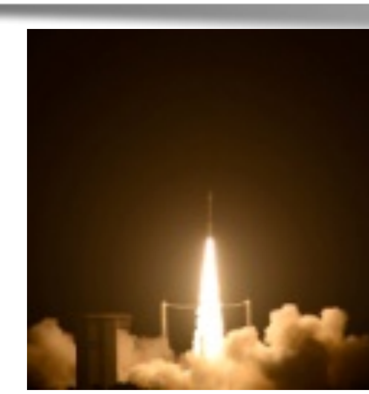


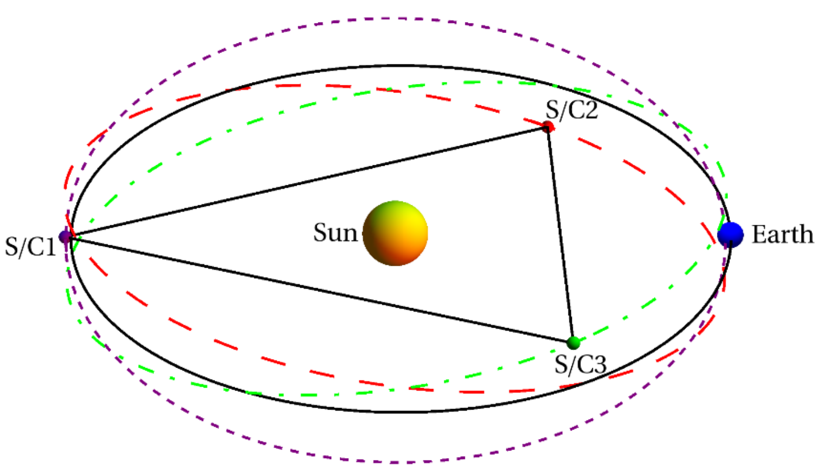
Although the prospect of a launch of space GW is only expected in about 20 years, the detection in the low frequency band may have the largest signal to noise ratios. This will enable the detailed study of black hole co-evolution with galaxies and with the dark energy issue. LISA Pathfinder has been launched on December 3, 2015. This will pave the technology road for GW space missions.

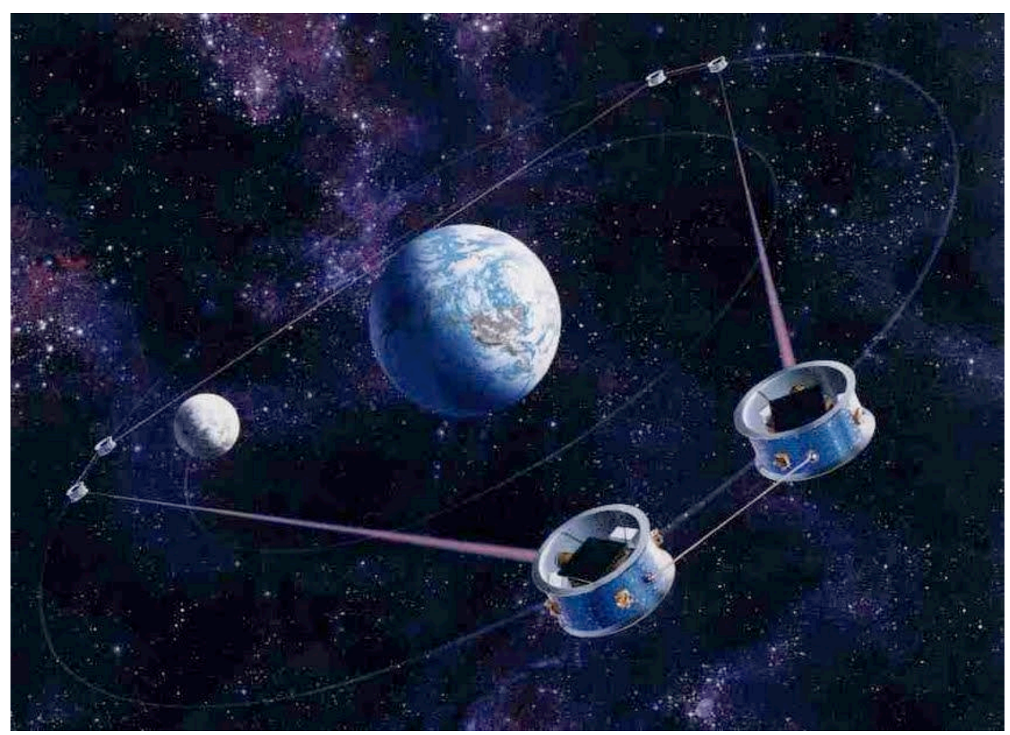
LISA

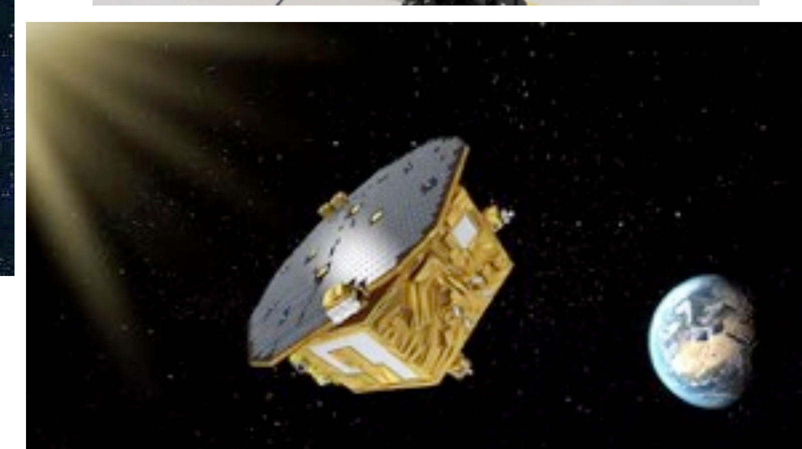


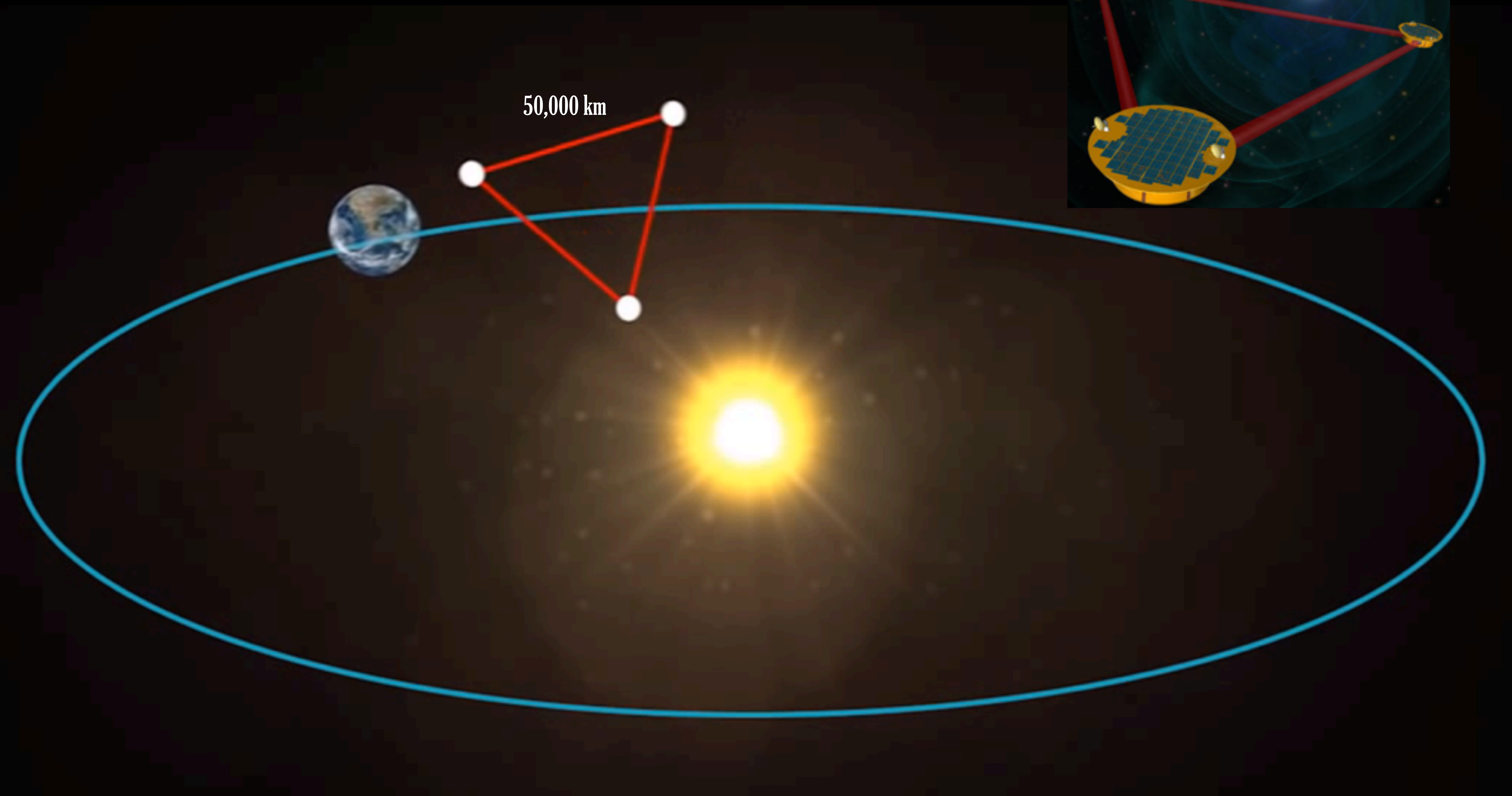
A Compilation of GW Mission Proposals LISA Pathfinder Launched on December 3, 2015





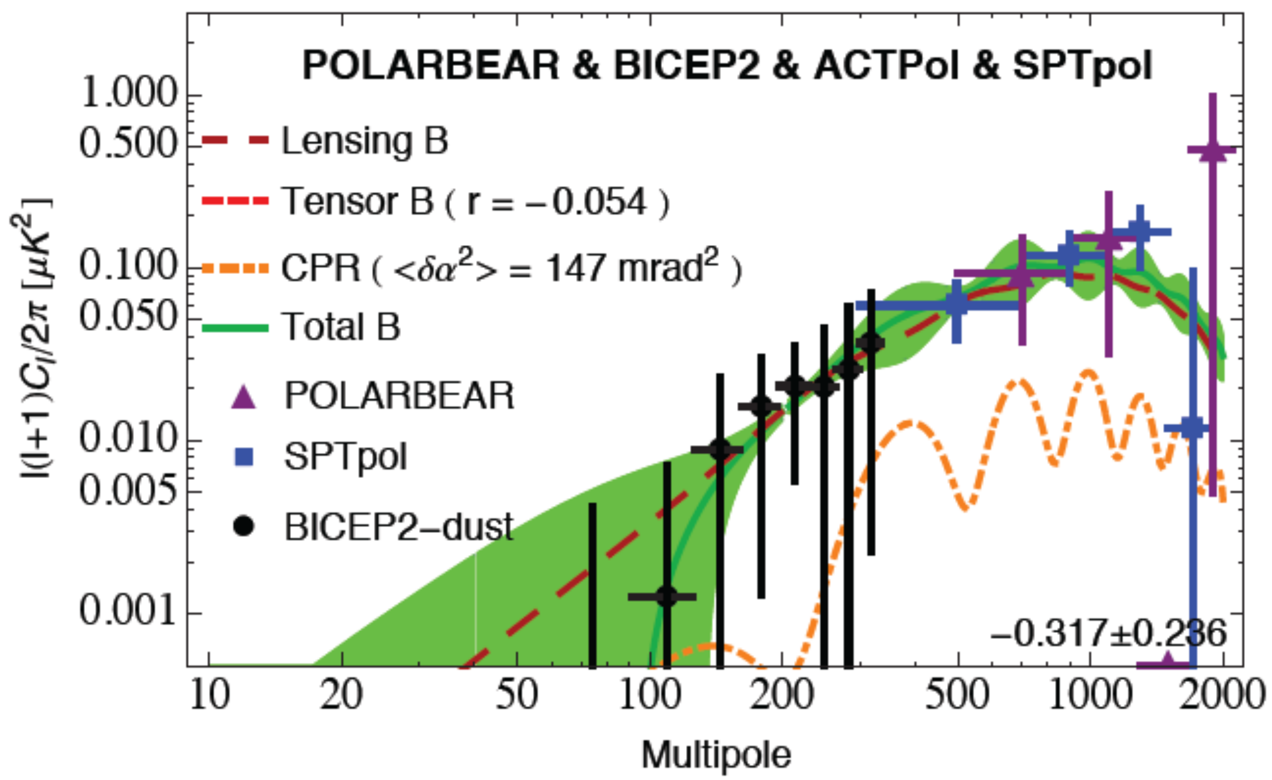


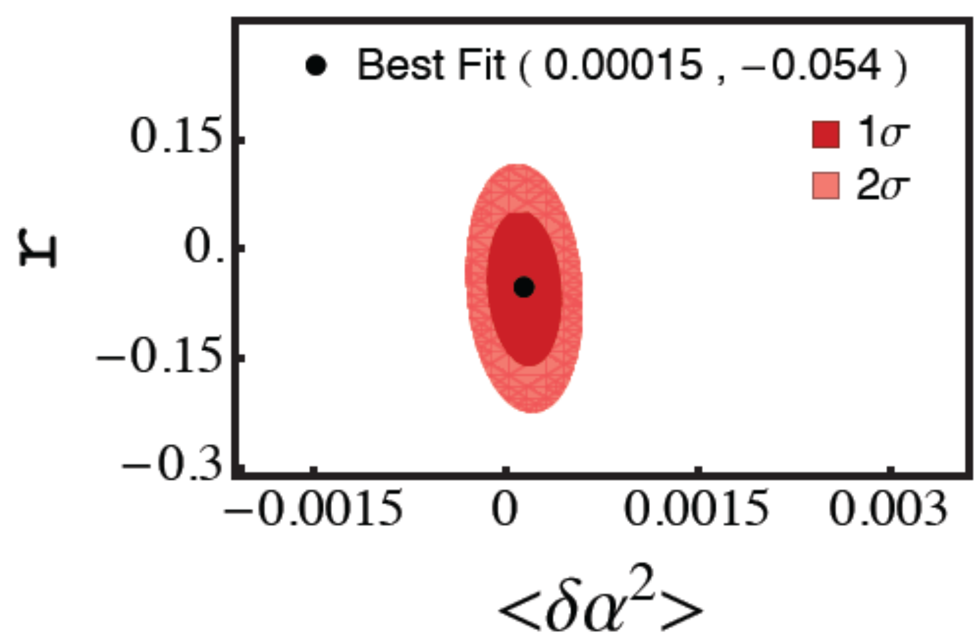




In the future, there will also be gravitational wave detectors in space, like LISA.

Foreground separation and correlation detection method need to be investigated to achieve the sensitivities 10^{-16}-10^{-17} or beyond in Ω_{gw} to study the primordial GW background for exploring very early universe and possibly quantum gravity regimes.





中國的四個引力波探測實驗計劃：

太極（中國科學院）

天琴（中山大學）

阿里（中國科學院）

FAST（中國科學院）

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2016—2020年进行预研和关键技术突破;

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2025—2033年进行测试和发射。

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Taiji Program in Space
Gravitational wave physics
空间太极计划

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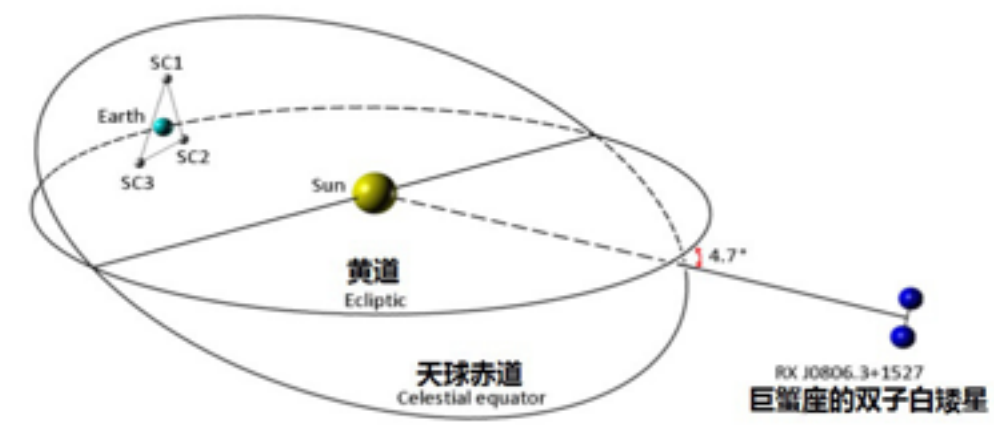

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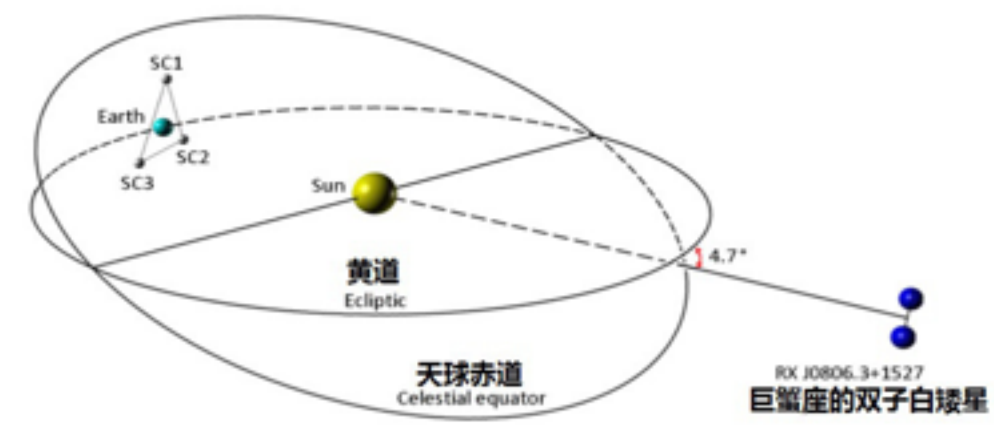

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阿里（中國科學院）

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Search for low-f primordial GW

原初引力波

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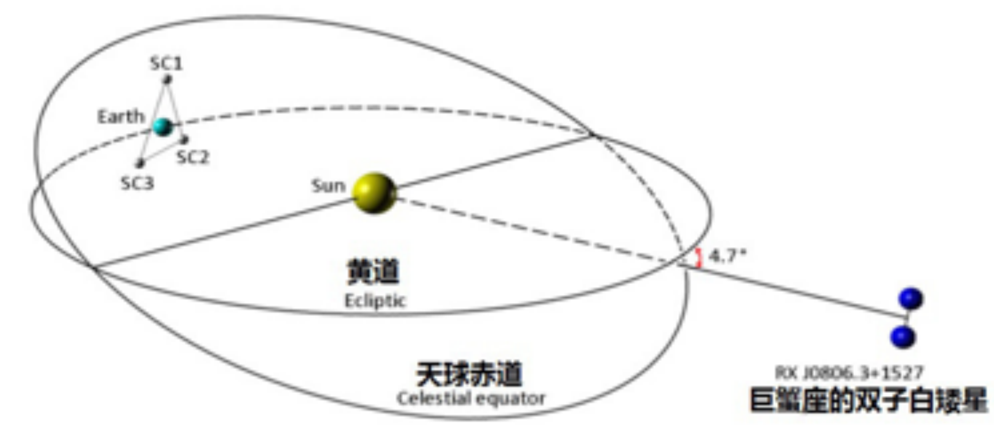

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FAST（中國科學院）

Five hundred meter Aperture Spherical Telescope

在中國貴州省平塘縣 大窩凼窪地，2016年9月建成

观测到全天的脉冲星或者某一方向上的多个脉冲星周期发生变化，探测到引力波。

謝謝！