TESTING GRAVITY WITH GRAVITATIONAL WAVES

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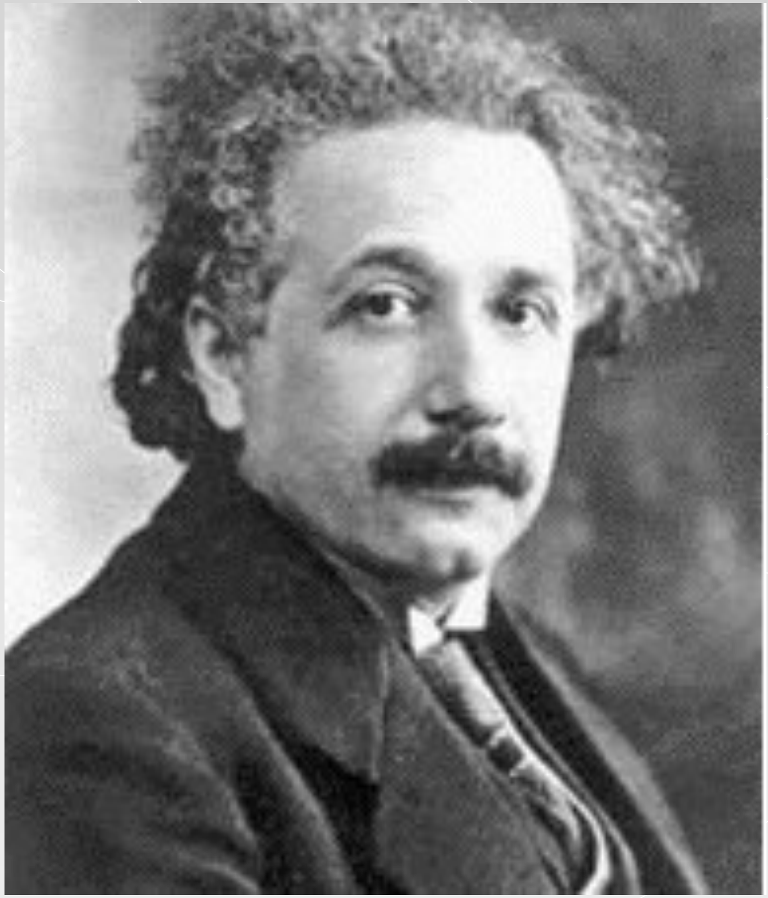
OUTLINE

1. Test of General Relativity
2. Gravitational Waves
3. Polarization Test
4. Propagation Speed Test

TEST OF GENERAL RELATIVITY

GENERAL RELATIVITY

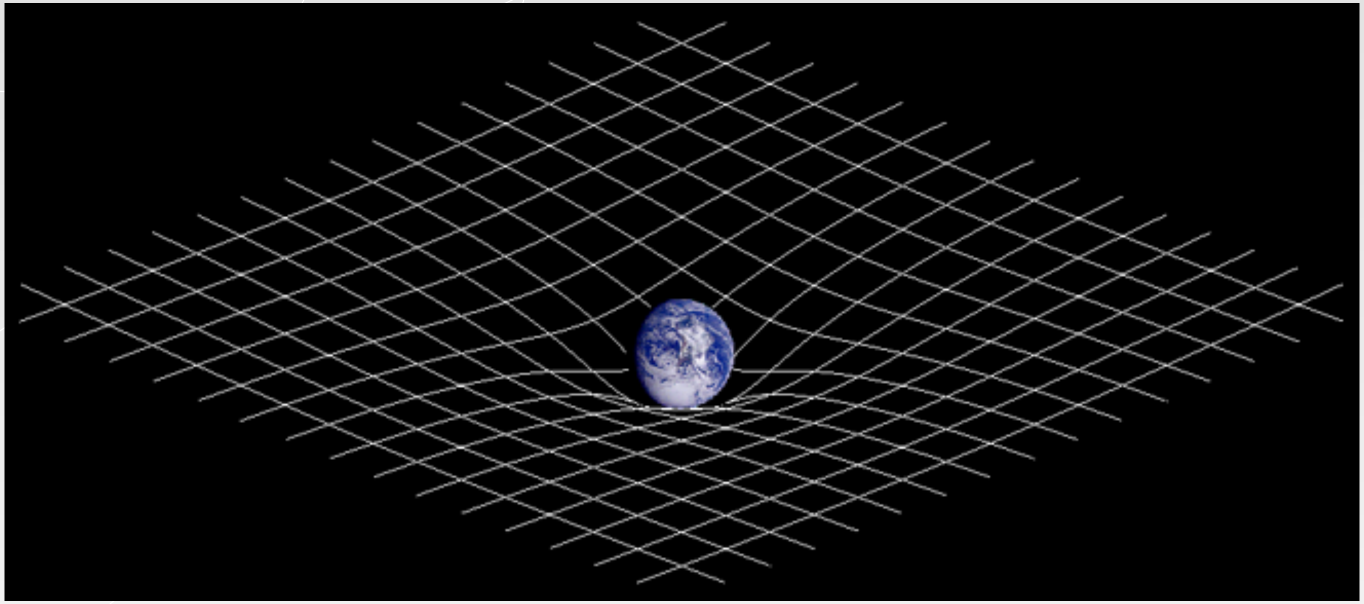
In1915, Einstein proposed.



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

gravity (spacetime) — matter

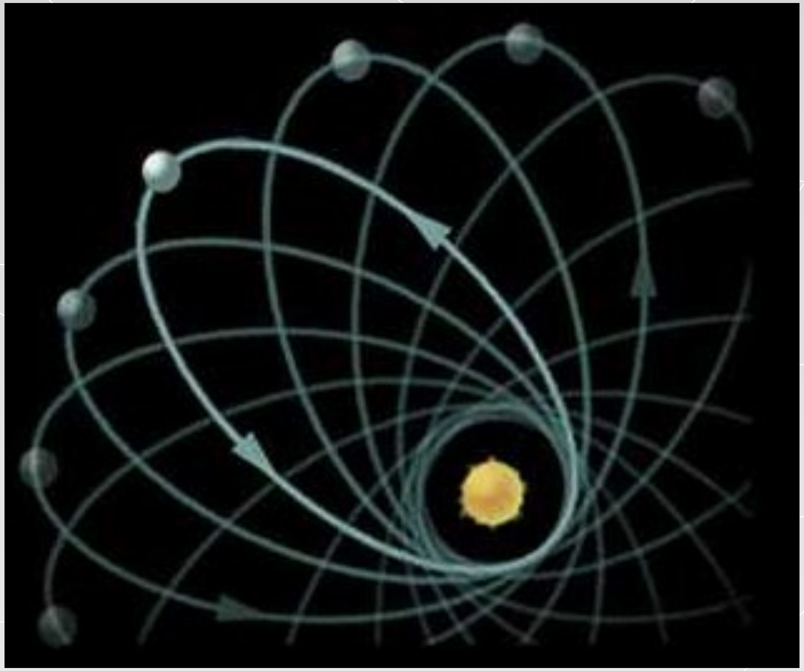
Spacetime is not solid object but dynamical one.



TEST OF GR IN THE SOLAR SYSTEM

perihelion shift of Mercury

[review: Clemence 1947]



prediction in Newtonian

$$5557''.0/\mathrm{century}$$

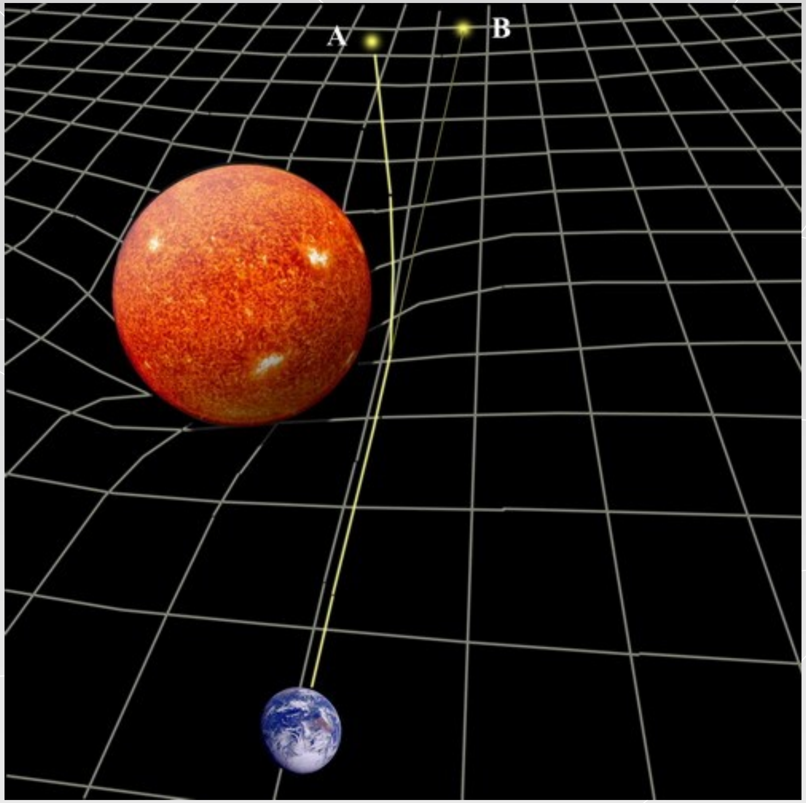
observed value

$$5599''.7/\mathrm{century}$$

GR correctly predicted the observed value.
(correction to Newtonian is $42''.7/\mathrm{century}$)

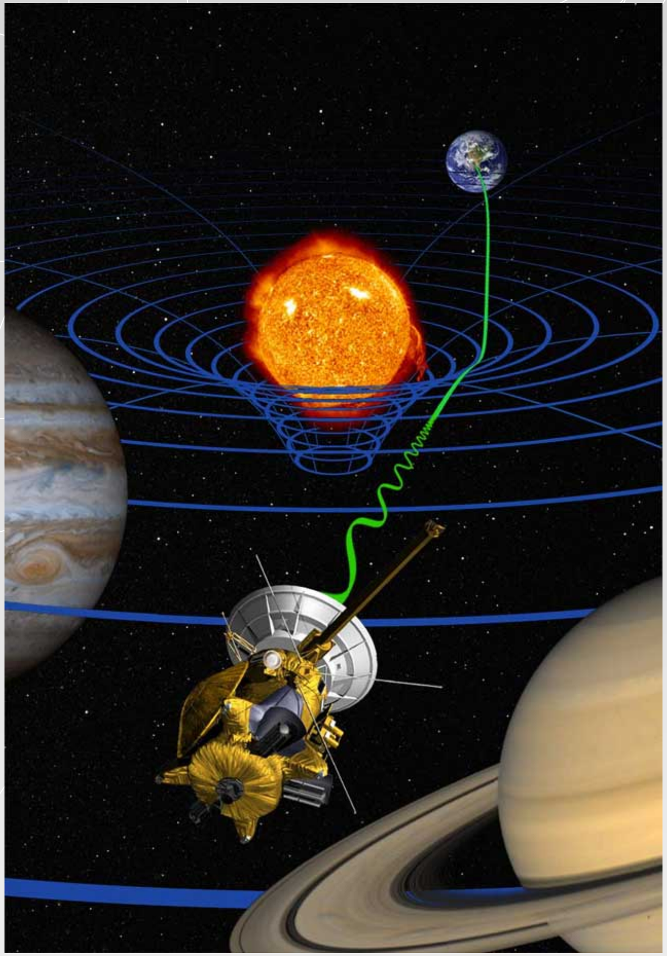
TEST OF GR IN THE SOLAR SYSTEM

deflection of light



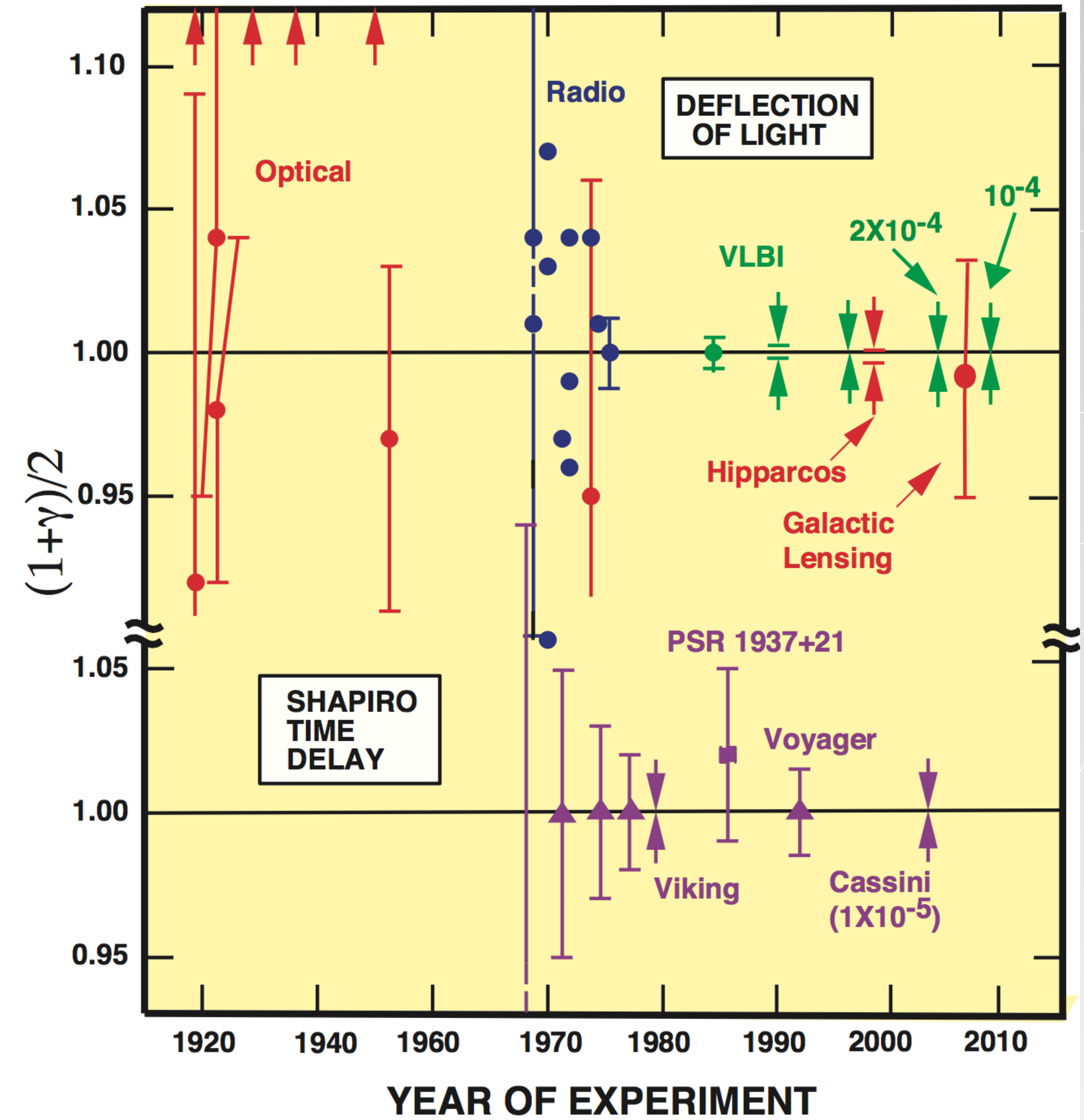
In 1919, firstly observed by Eddinton et al.

Shapiro time delay



In 1968, firstly observed by Shapiro et al.

OBSERVATIONAL CONSTRAINT



deflection angle
(at the rim of Sun)

$$\delta\theta \approx \frac{1}{2}(1+\gamma) \times 1.''75 \cdots$$

$$\boxed{\gamma - 1 \leq 1 \times 10^{-4}}$$

time delay
(Mercury - Earth)

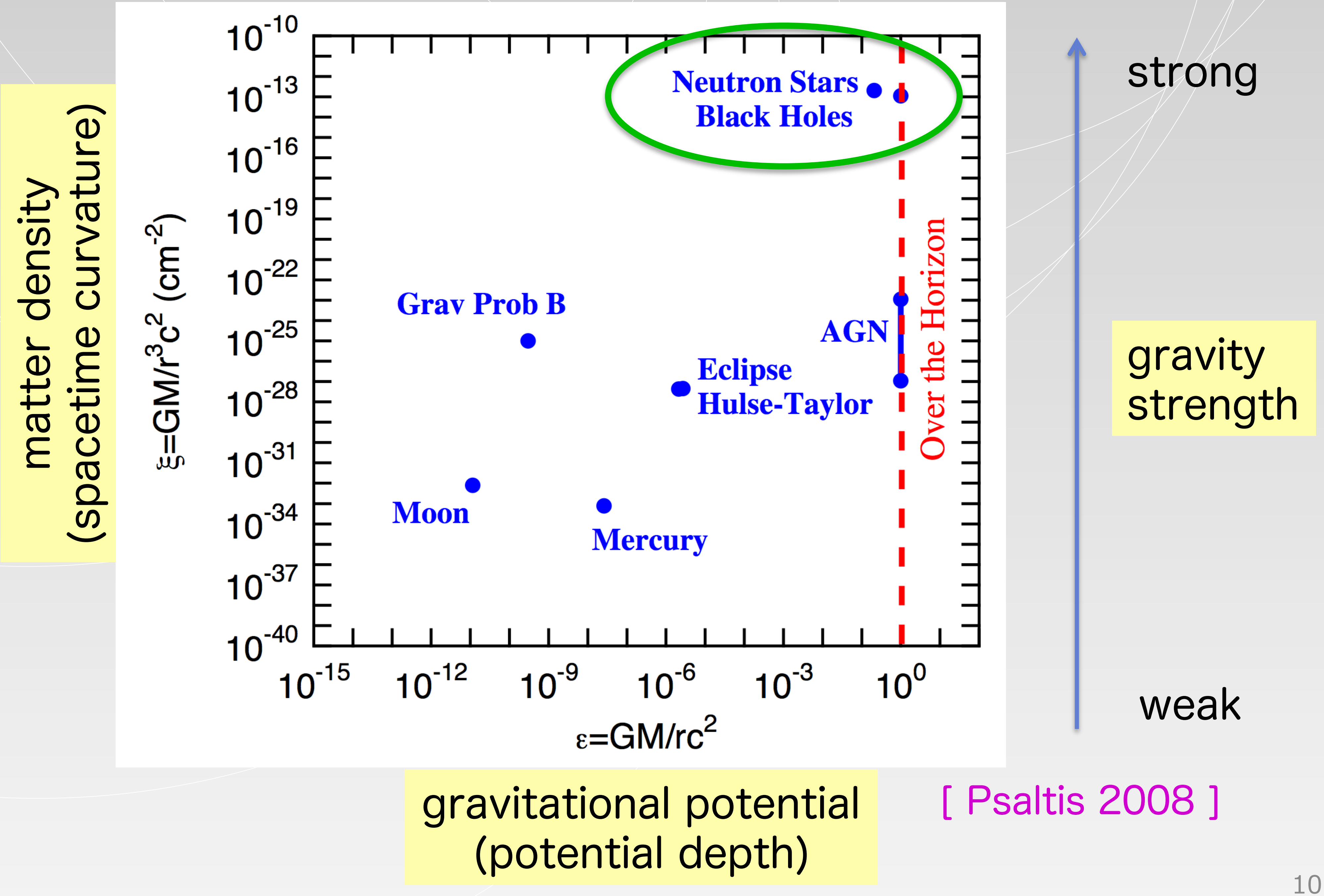
$$\Delta t \approx \frac{1}{2}(1+\gamma) \times 240\,\mu\text{sec} \cdots$$

$$\boxed{\gamma - 1 \leq 1 \times 10^{-5}}$$

In GR $\gamma = 1$

[Will 2014]

GRAVITY IS FULLY TESTED?



[Psaltis 2008]

WHY TESTING GRAVITY IS IMPORTANT?

- strong field regime (neutron star, black hole)
- dynamical property (gravitational waves)
- cosmological scale (dark matter, dark energy)
- quantum gravity theory (modification to gravity)

GRAVITATIONAL WAVES

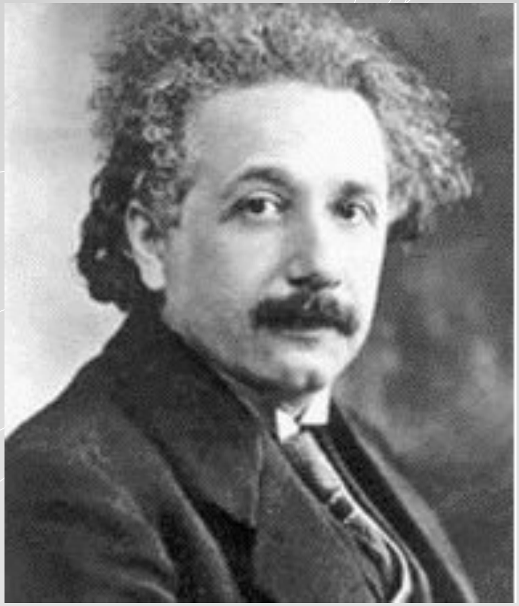
WHAT IS A GRAVITATIONAL WAVE?

- distortion of spacetime that propagates with the speed of light

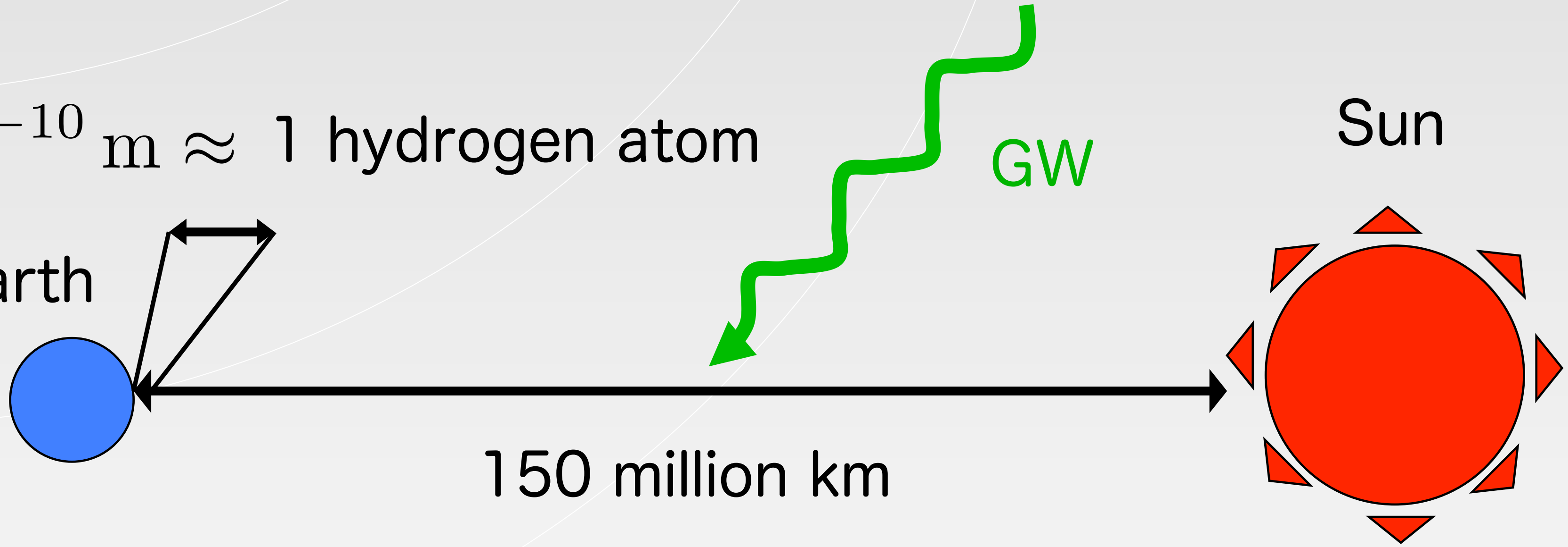
- produced by drastic change of gravitational fields
  (e.g. steller explosion, collision, oscillation)

- expected GW amplitude is extremely small

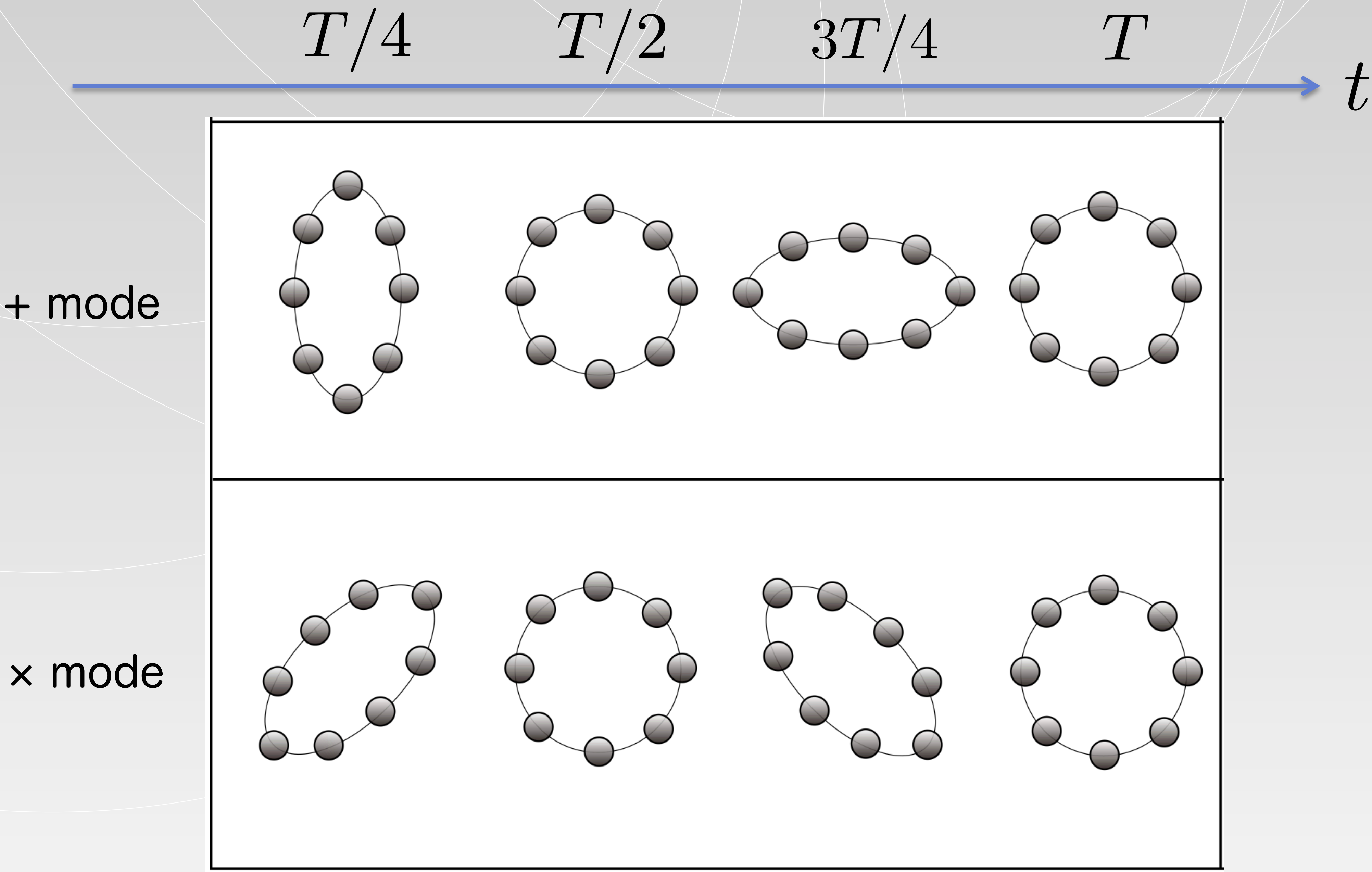
  $h \sim 10^{-21}$ @ ~100Hz



$\sim 10^{-10}\,\mathrm{m} \approx$ 1 hydrogen atom



GW POLARIZATION MODES



INDIRECT EVIDENCE OF GW

- Indirect evidence from binary pulsar (PSR B1913+16)

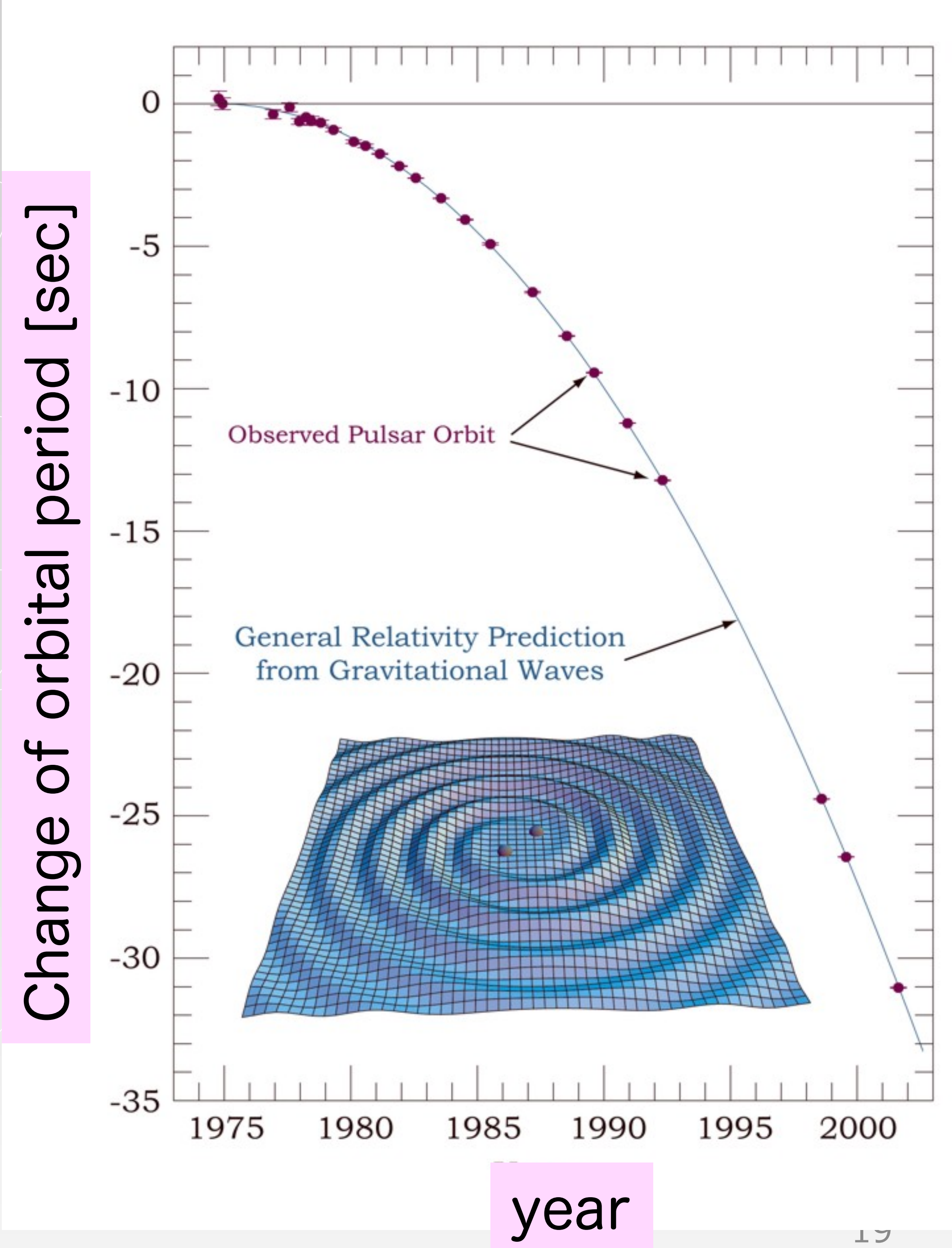
  In 1993, Hulse & Taylor won the Novel prize.

  GWs should exist !!

- Not directly detected yet

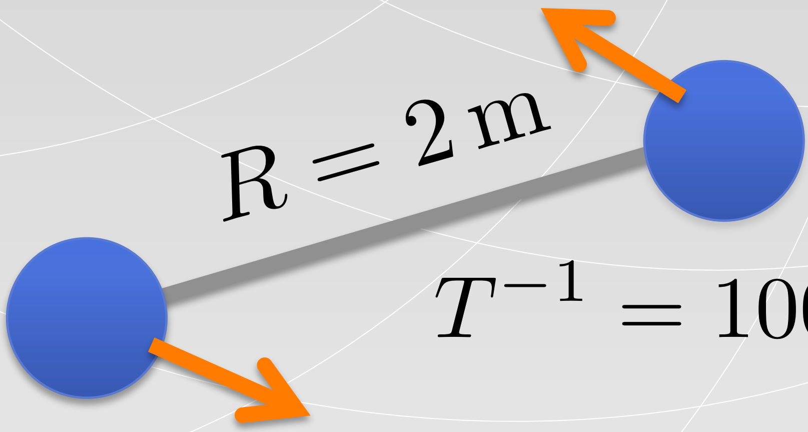
  ⇓

  GW detectors



GW GENERATION IN LAB ??

$$L_{gw} = \frac{G}{5c^5}\langle \dddot{I}_{ij}\dddot{I}^{ij}\rangle \sim \frac{G}{5c^5}\frac{M^2R^4}{T^6}$$



$\mathrm{R} = 2\,\mathrm{m}$

$M = 100\,\mathrm{kg}$

$T^{-1} = 100\,\mathrm{Hz}$

$$L_{gw} \sim 4 \times 10^{-27}\,\mathrm{erg\,s^{-1}} \longrightarrow h \lesssim 10^{-43}$$

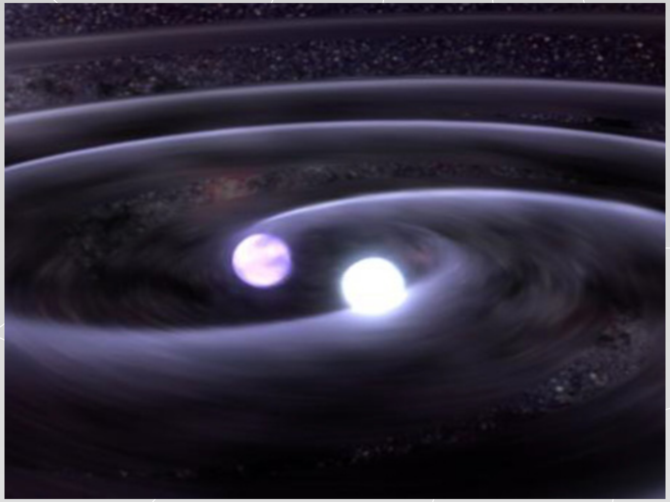
at 1500 km away

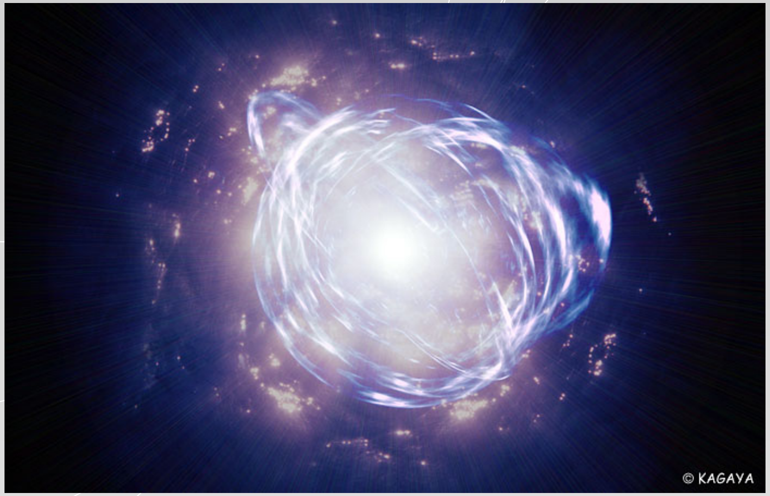
Too small !! Impossible to detect.

GRAVITATIONAL WAVE SOURCES

Astrophysical

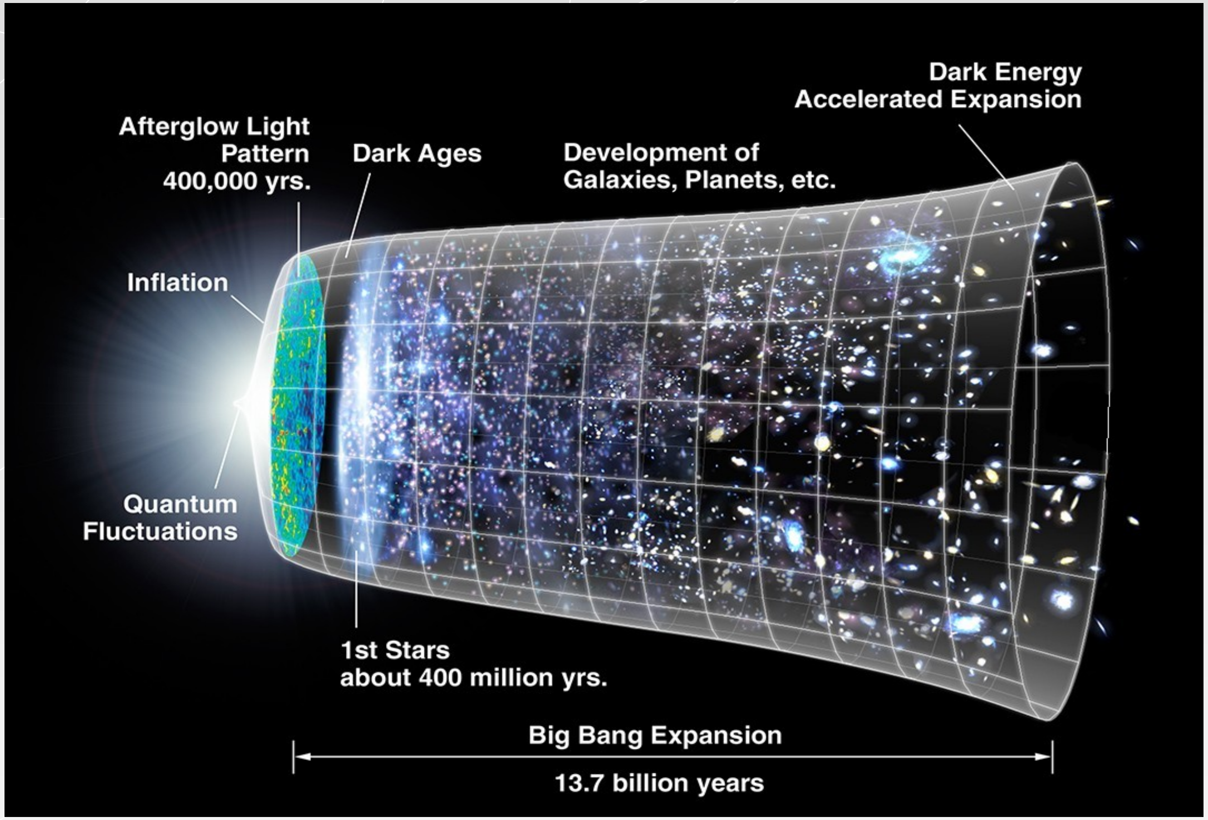
- NS binary
- BH binary
- supernova
- gamma-ray burst





Cosmological

- inflation
- phase transition
- cosmic string



GW DETECTORS (2015~)

WHAT GRAVITATIONAL WAVES CAN PROBE?

Various modified gravity theories have been suggested.
Those theories predict the properties of GWs different from GR.

- different phase evolution of GWs (different eq. of motion)
- additional GW polarizations (scalar & vector pols.)
- GW propagation speed different from c (massive graviton)

⇓

GW observation can be utilized for

- direct test of general relativity
- probe for the extended theories beyond GR

In the absence of detailed knowledge about correct gravity theory, a model-independent test is crucial.

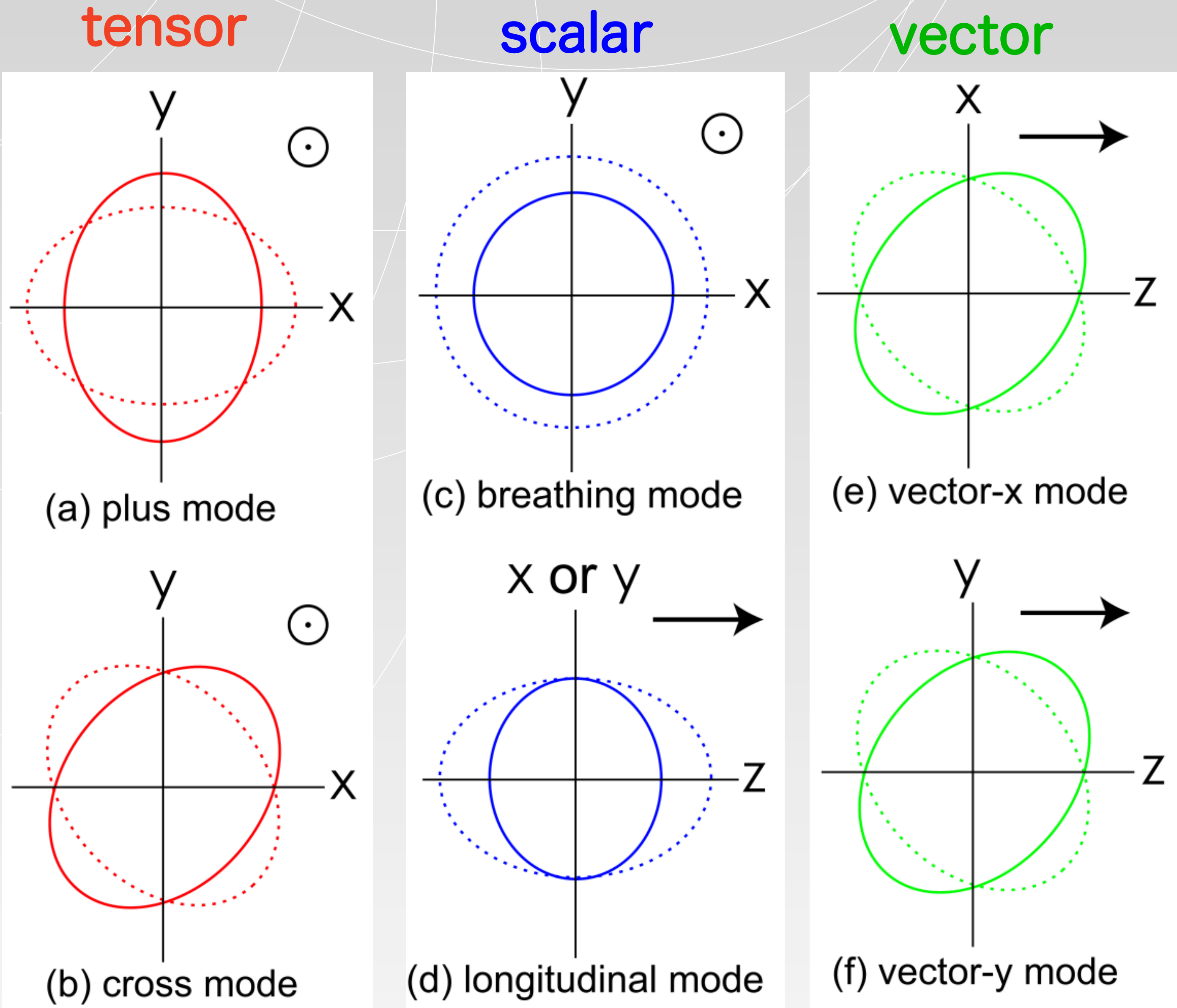
POLARIZATION TEST

GW POLARIZATIONS

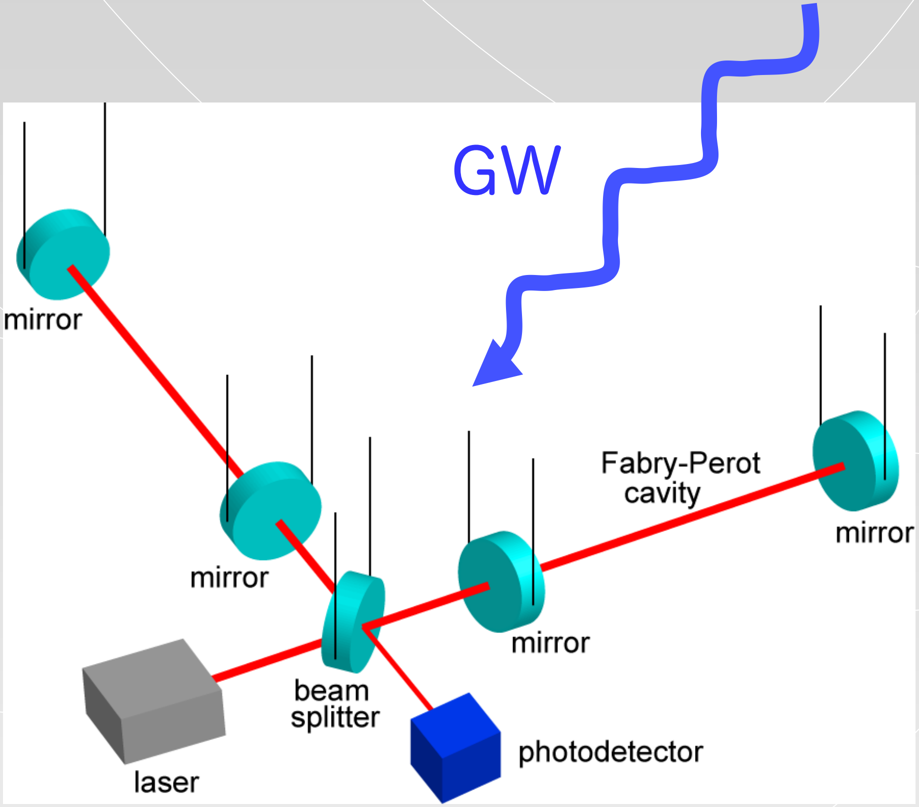
In general metric theory of gravity, 6 polarizations are allowed.
[Eardley et al. 1973, Will 1993]

GW is propagating in the z direction.

6 pols. are classified into tensor, vector, and scalar modes, depending on the rotational symmetry about the propagation axis.



ANTENNA PATTERN FUNCTION



Response of a detector to GW propagating in a direction.

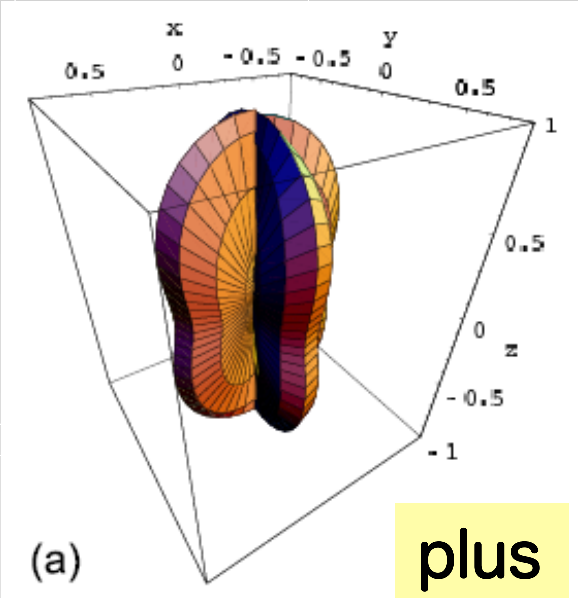
Definition of antenna pattern func.

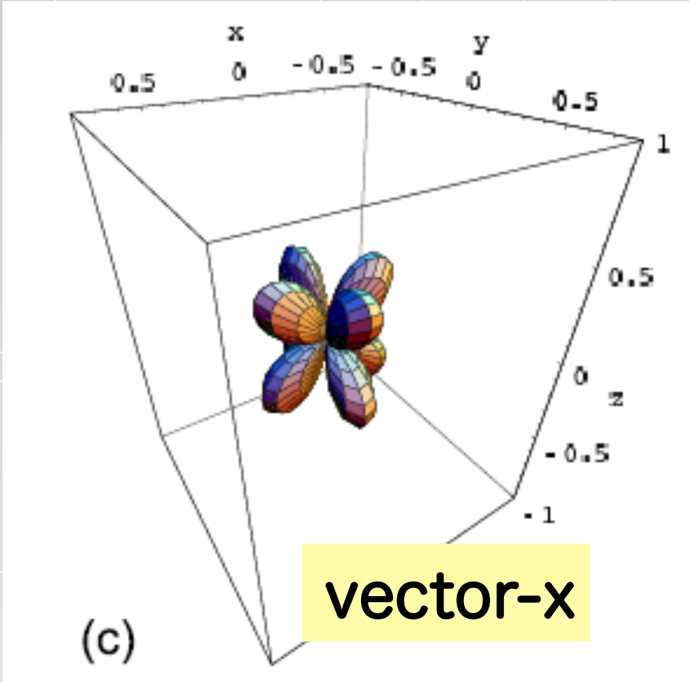
$$F_A(\hat{\Omega}) = D_{ij}\, e_A^{ij}(\hat{\Omega})$$

D_{ij} : detector tensor

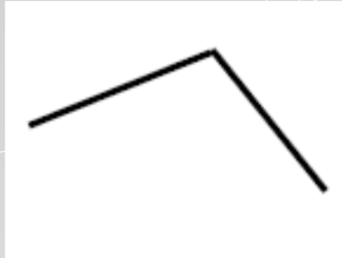
e_A^{ij} : GW polarization tensor

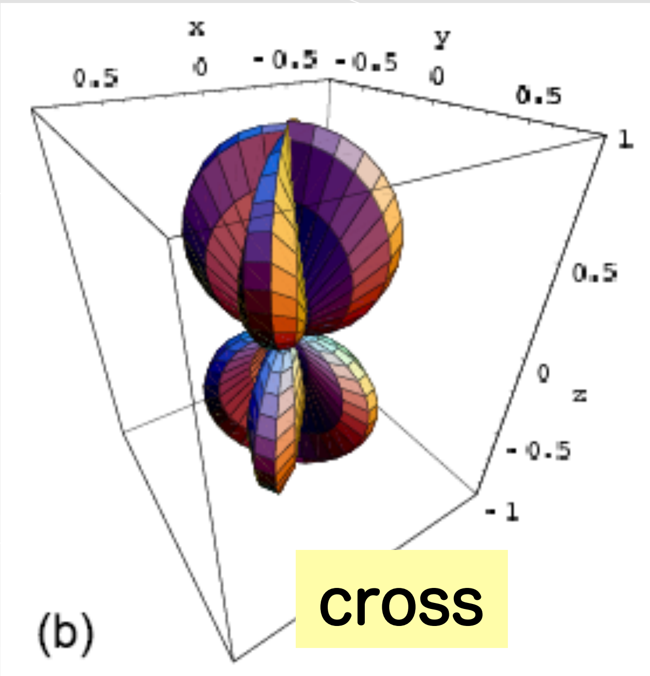
ANTENNA PATTERN FUNCTION

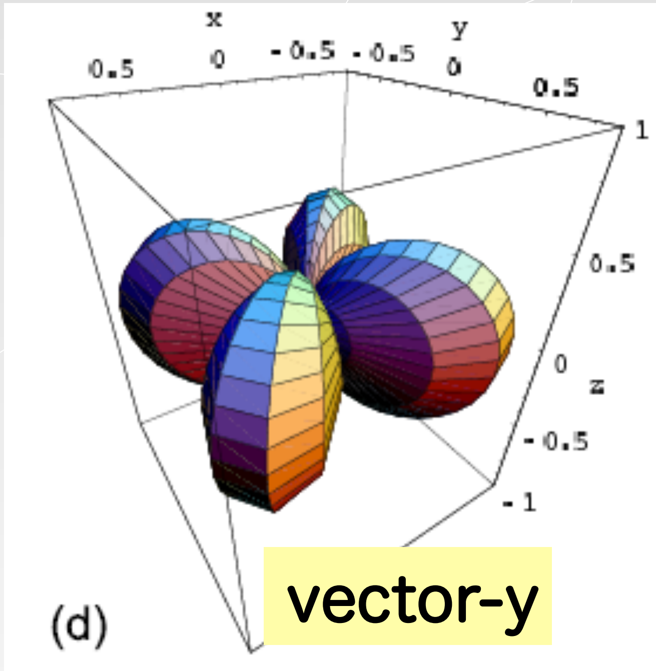


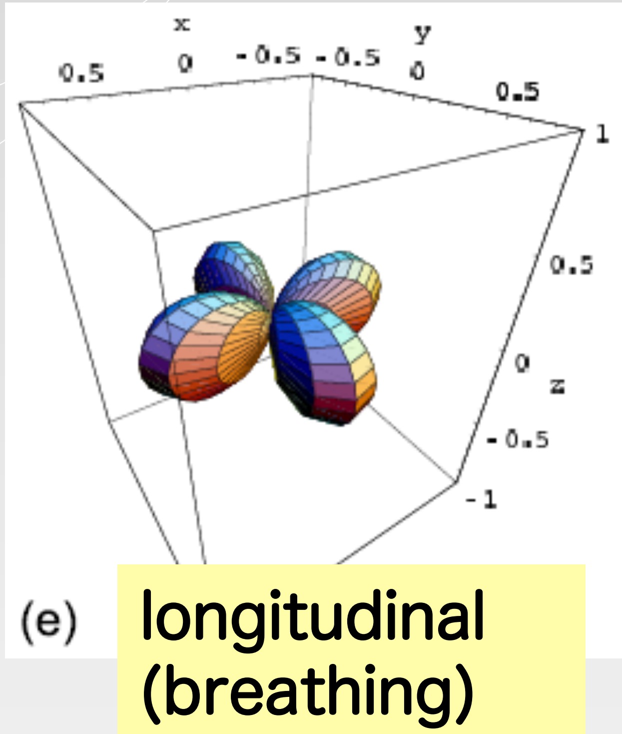


interferometer









POLARIZATION DECOMPOSITION

[AN+ 2009, Hayama & AN 2013]

simple case

3 detectors & 3 polarization modes (+, ×, ○)

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} F_1^+ & F_1^\times & F_1^\circ \\ F_2^+ & F_2^\times & F_2^\circ \\ F_3^+ & F_3^\times & F_3^\circ \end{pmatrix} \begin{pmatrix} h_+ \\ h_\times \\ h_\circ \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix}$$

detector data | response functions | GW amp. | noise

$$\Rightarrow \begin{pmatrix} h_+ \\ h_\times \\ h_\circ \end{pmatrix} \approx \begin{pmatrix} F_1^+ & F_1^\times & F_1^\circ \\ F_2^+ & F_2^\times & F_2^\circ \\ F_3^+ & F_3^\times & F_3^\circ \end{pmatrix}^{-1} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

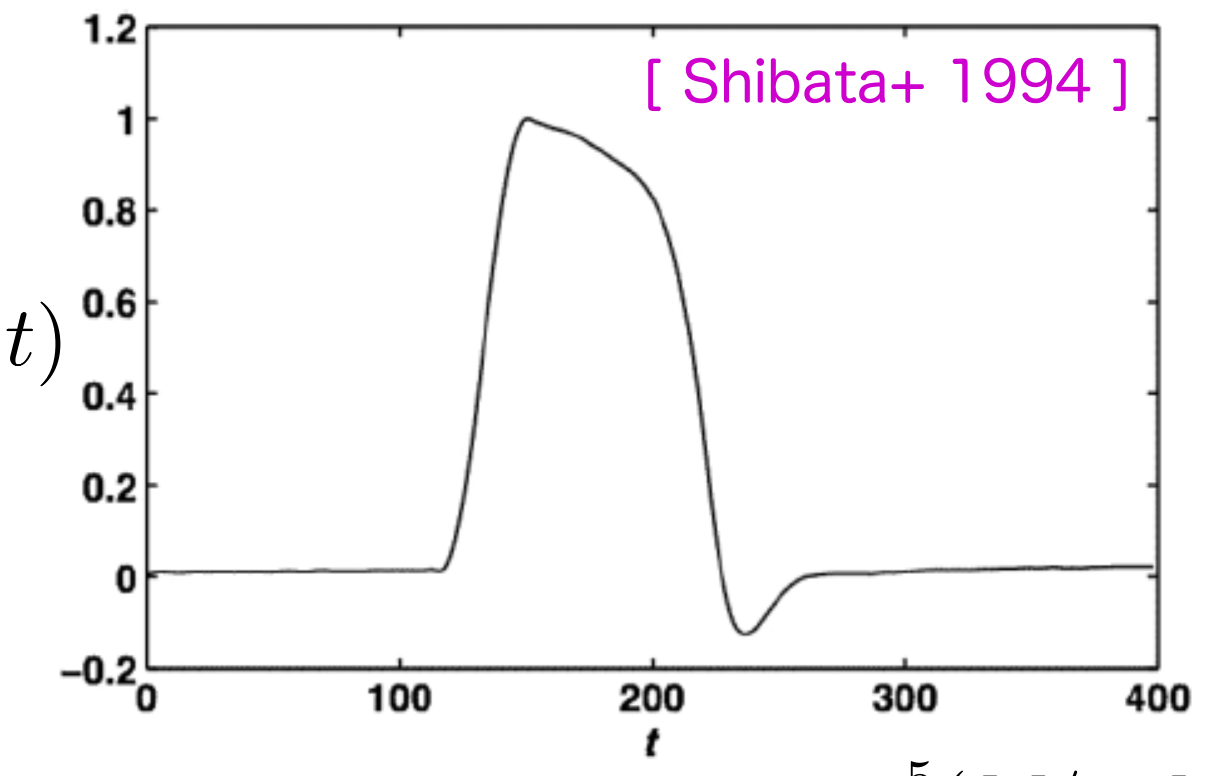
SPHERICALLY SYMMETRIC CORE COLLAPSE

There are many studies of simulation of spherically symmetric core collapse in the scalar-tensor theory
[Shibata+ 1994, Saijo+ 1997, Harada+ 1997, Novak 1998]

scalar GW

$$h(t) = 1.25 \times 10^{-21}\left(\frac{M}{10M_\odot}\right)\left(\frac{10\ \mathrm{kpc}}{R}\right)\left(\frac{40000}{\omega_{\mathrm{BD}}}\right)\Phi(t)$$

$\Phi(t)$



~ several msec duration

Time in the unit of $4.93 \times 10^{-5}(M/10M_\odot)$

POLARIZATION DECOMPOSITION

[Hayama & AN 2013]

$$\boldsymbol{h}_A = \boldsymbol{H}_A \cdot \boldsymbol{x},$$

$$\boldsymbol{M} := \boldsymbol{F}^T \boldsymbol{F}.$$

$$\begin{aligned}\boldsymbol{H}_+ = \frac{1}{\det(\boldsymbol{M})}[&(\boldsymbol{F}_\times \times \boldsymbol{F}_\circ)\cdot(\boldsymbol{F}_\times \times \boldsymbol{F}_\circ)\boldsymbol{F}_+ \\ &- (\boldsymbol{F}_\times \times \boldsymbol{F}_\circ)\cdot(\boldsymbol{F}_+ \times \boldsymbol{F}_\circ)\boldsymbol{F}_\times \\ &+ (\boldsymbol{F}_\times \times \boldsymbol{F}_\circ)\cdot(\boldsymbol{F}_+ \times \boldsymbol{F}_\times)\boldsymbol{F}_\circ],\end{aligned}$$

$$\begin{aligned}\boldsymbol{H}_\times = \frac{1}{\det(\boldsymbol{M})}[&-(\boldsymbol{F}_+ \times \boldsymbol{F}_\circ)\cdot(\boldsymbol{F}_\times \times \boldsymbol{F}_\circ)\boldsymbol{F}_+ \\ &+ (\boldsymbol{F}_+ \times \boldsymbol{F}_\circ)\cdot(\boldsymbol{F}_+ \times \boldsymbol{F}_\circ)\boldsymbol{F}_\times \\ &- (\boldsymbol{F}_+ \times \boldsymbol{F}_\circ)\cdot(\boldsymbol{F}_+ \times \boldsymbol{F}_\times)\boldsymbol{F}_\circ],\end{aligned}$$

$$\begin{aligned}\boldsymbol{H}_\circ = \frac{1}{\det(\boldsymbol{M})}[&(\boldsymbol{F}_+ \times \boldsymbol{F}_\times)\cdot(\boldsymbol{F}_\times \times \boldsymbol{F}_\circ)\boldsymbol{F}_+ \\ &- (\boldsymbol{F}_+ \times \boldsymbol{F}_\times)\cdot(\boldsymbol{F}_+ \times \boldsymbol{F}_\circ)\boldsymbol{F}_\times \\ &+ (\boldsymbol{F}_+ \times \boldsymbol{F}_\times)\cdot(\boldsymbol{F}_+ \times \boldsymbol{F}_\times)\boldsymbol{F}_\circ].\end{aligned}$$

In general,
# of detectors
> # of polarizations.

↓

overdetermined & complicated inverse problem

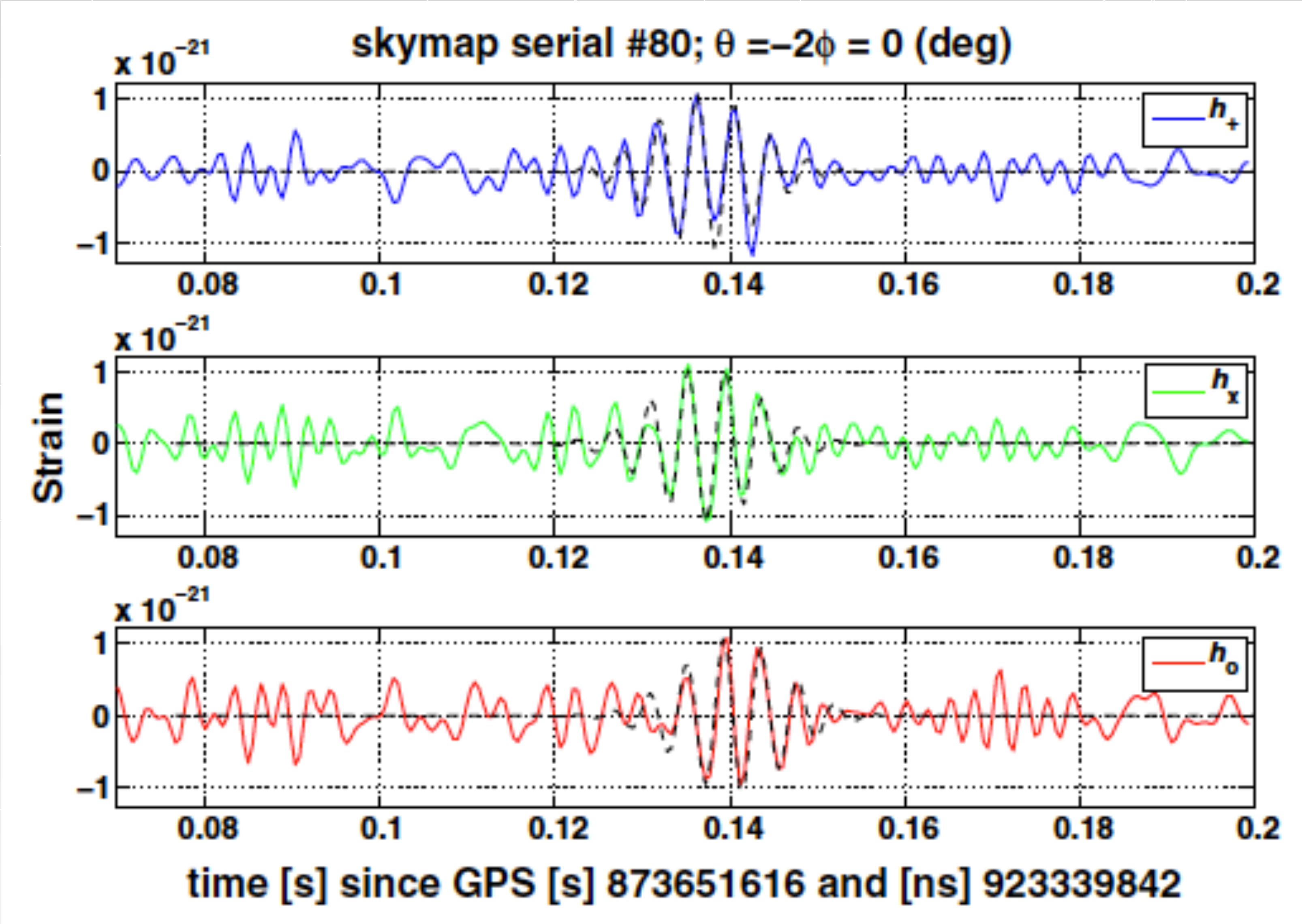
RECONSTRUCTION OF GW WAVEFORM

black dashed : injected GW signal, colored : reconstructed signal
(SNR=6〜27)

+ mode

× mode

○ mode



RECONSTRUCTION OF GW WAVEFORM

SNR of injected signal in each detector

	Reconstructed	H	L	V	K
h_+	23.3	8.3	9.6	26.7	24.5
$h_\times$	20.2	15.4	18.0	15.4	10.8
$h_\circ$	16.3	13.3	20.4	10.0	6.2

SNR after reconstruction with a detector network

- SNRs of each detector depend on the source sky position and antenna patter functions.
- After the reconstruction, SNR is slightly degraded due to less sensitive detector, but not much.

SUMMARY FOR POLARIZATION TEST

- GW polarizations can be used for the model-independent test of modified gravity theories.
- When N pols. signal exist in GW data from a point source, N detectors can reconstruct N pol. modes.
- Sensitivities to extra pols. are almost the same as those to ordinary tensor pols even if the polarization decomposition is done.
- Stochastic GW backgrounds with 3 pol. modes (tensor, vector, scalar) can be separated by, at least, 3 detectors.

PROPAGATION SPEED TEST

MOTIVATION

In GR, GW propagates with the speed of light.

GW propagation speed could be changed due to

- modification of gravity (e.g. graviton mass, etc.)
- spacetime structure (e.g. Lorentz violation, extra dimensions, quantized spacetime, etc.)

The propagation speed test of GW is important because the GW speed has not ever been measured.

We proposed the method to measure GW propagation speed and show how precisely we can measure it.

CURRENT CONSTRAINT

[Moore & Nelson 2001]

From the observations of ultra-high energy cosmic rays (UHECR)

Graviton looses its energy due to gravitational Cherenkov radiation if the propagation speed of graviton is less than the speed of light. Then UHECR cannot reach the Earth.

However, such UHECR have been observed.

Assuming the sources of UHECR are in the Galaxy,

$$\delta_g \equiv 1 - \frac{v_g}{c} < 2 \times 10^{-15}$$

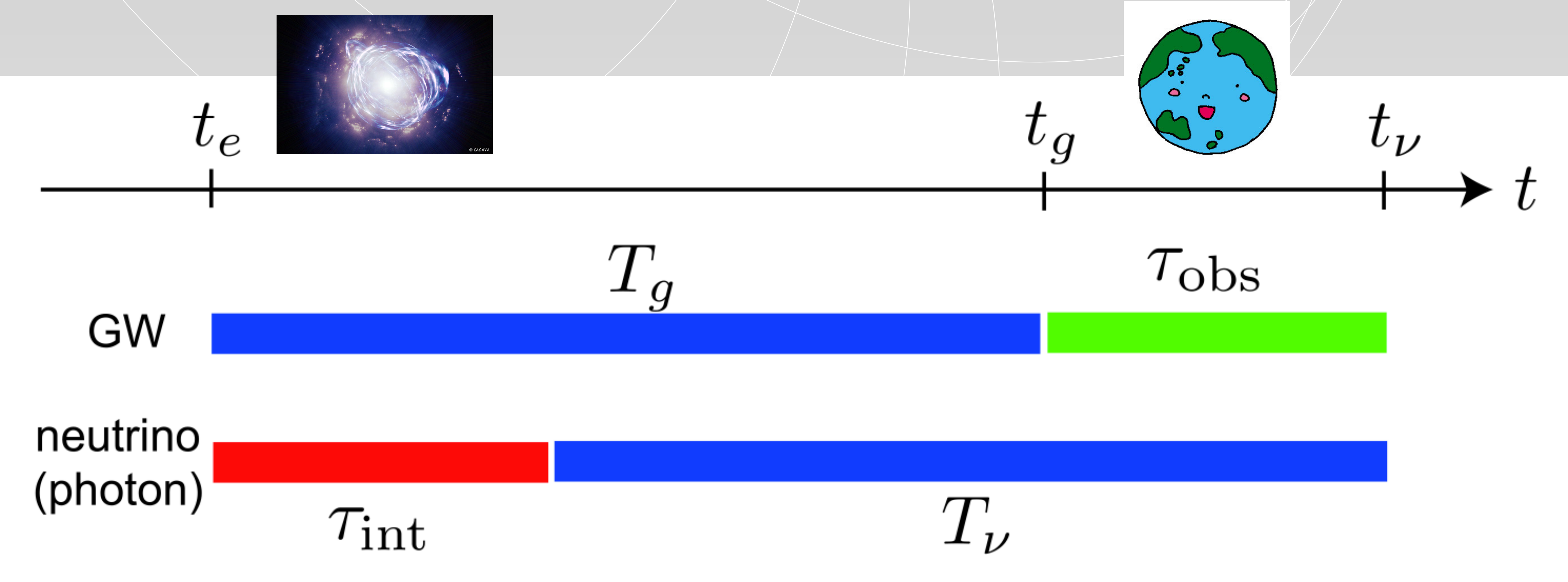
(applied only to subluminal propagation of graviton)

The problem is that this constraint is indirect one and depends on the above assumption.

OUR METHOD

Direct measurement of propagation speed of GW

[AN & Nakamura 2014]



$T_g \neq T_\nu$?

- neutrino mass
- graviton mass ?
- Lorentz violation?
- other spacetime effects ?

DETECTABLE DERIVATION OF GW SPEED

$$\tau_{\mathrm{obs}} = \Delta T + \tau_{\mathrm{int}} \qquad \Delta T = T_\nu - T_g$$

Uncertainties are in T_ν (from neutrino mass uncertainty) and τ_{int} (from the emission model of a source).

↓

Detectable δ_g is

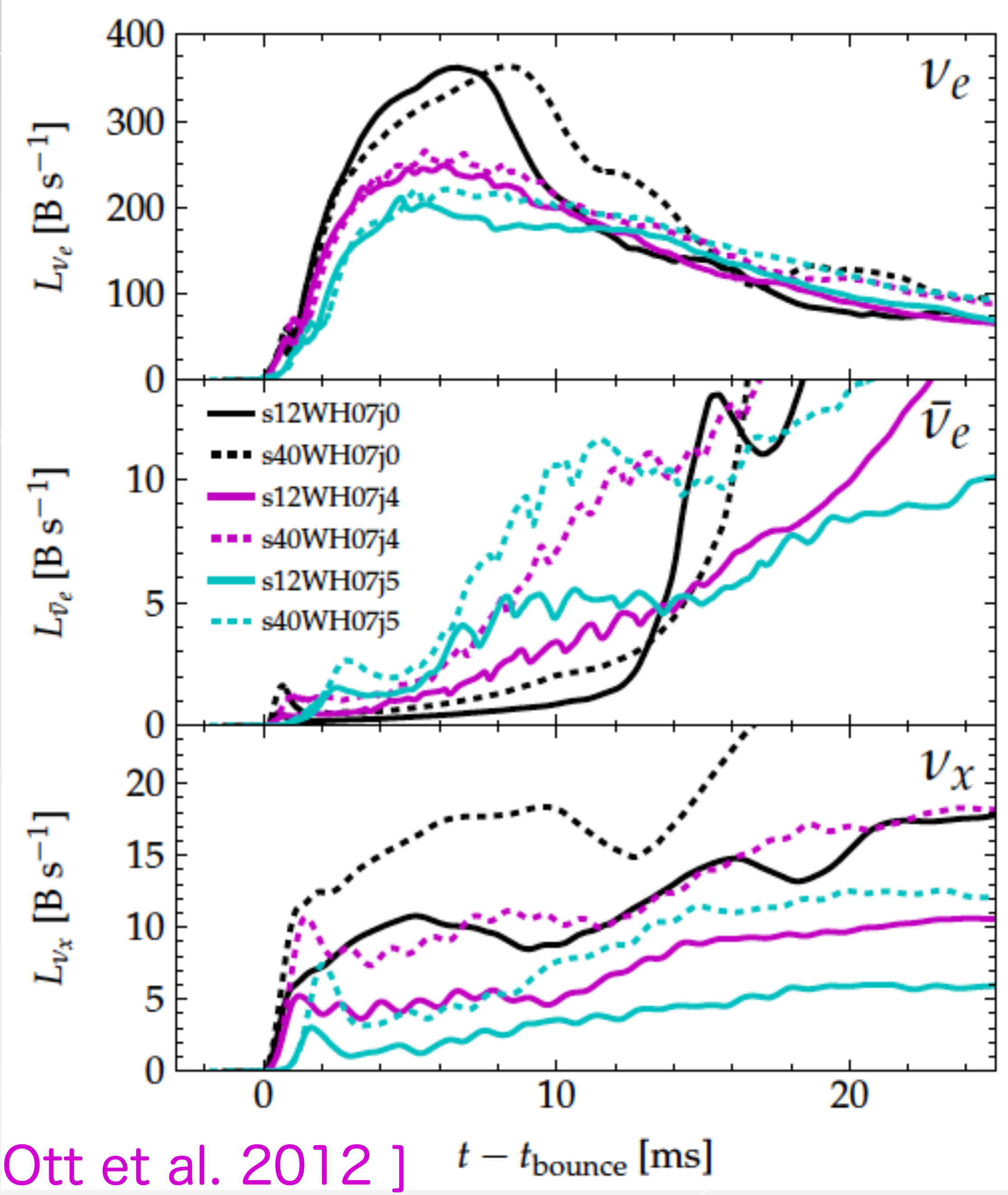
$$\Delta\tau_{\mathrm{int}} < T_0|\delta_\nu - \delta_g|$$

L : Distance to a source

$T_0 \equiv L/c$

$$\delta_g \equiv \frac{c - v_g}{c} \qquad \delta_\nu \equiv \frac{c - v_\nu}{c}$$

SUPERNOVA SIMULATION



[Ott et al. 2012]

neutrinos start to be emitted within several msec after the core bounce.

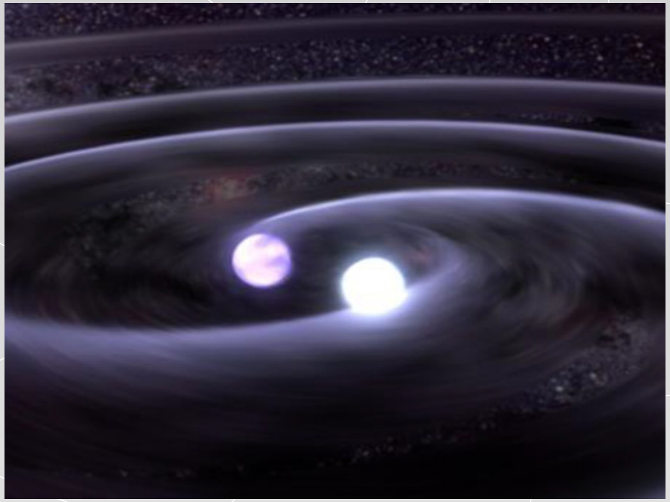
$$\Delta\tau_{\rm int} < 10\,{\rm msec}$$

$$E = 10\,{\rm MeV}$$

$$L = 100\,{\rm kpc}$$

with aLIGO

NEUTRON STAR BINARY MERGER



Taking into account a broad range of emission mechanism for SGRB leads to conservative limits on emission time delay,

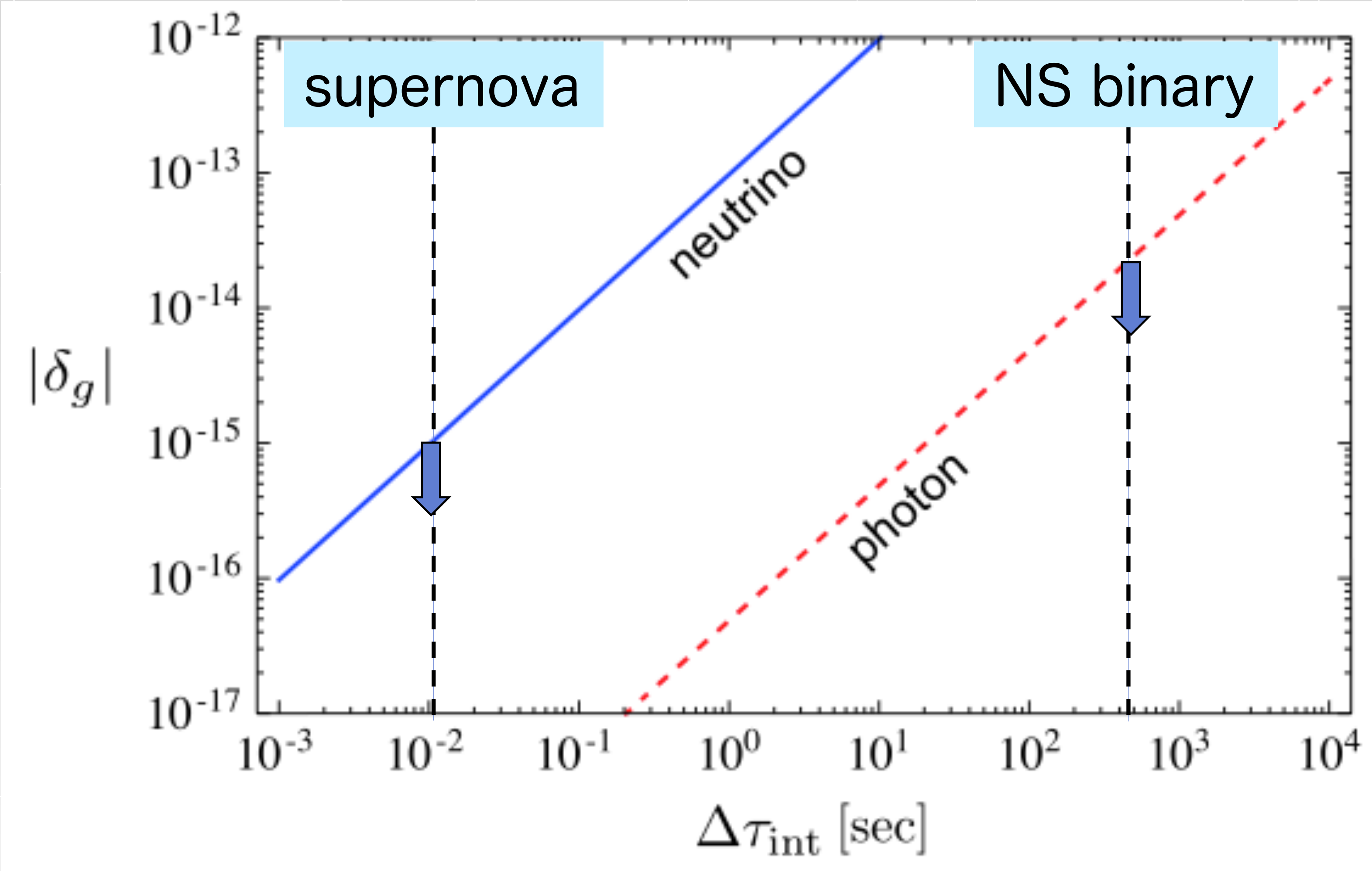
[Baret et al. 2011]

$$\Delta\tau_{\rm int} = 500\,{\rm sec}$$

$$L = 200\,{\rm Mpc}$$ with aLIGO

POSSIBLE CONSTRAINTS ON GW PROPAGATION SPEED

If there is no deviation of GW speed from c, δ_g is constrained.
[AN & Nakamura 2014]



COMPARISON WITH OTHER METHOD

GW Rømer time delay [Finn & Romano 2013]

Rømer time delay [O. Rømer 1676]

・・・The period of occultations of the Galilean satellite Io is modulated by Earth's revolution.

→ Propagation speed of light is finite.

GW amplitude and phase also experience the modulations due to Earth's spin and revolution.

With rapidly rotating NS detected by aLIGO (SNR=10)

→ $\delta_g \lesssim 10^{-6}$

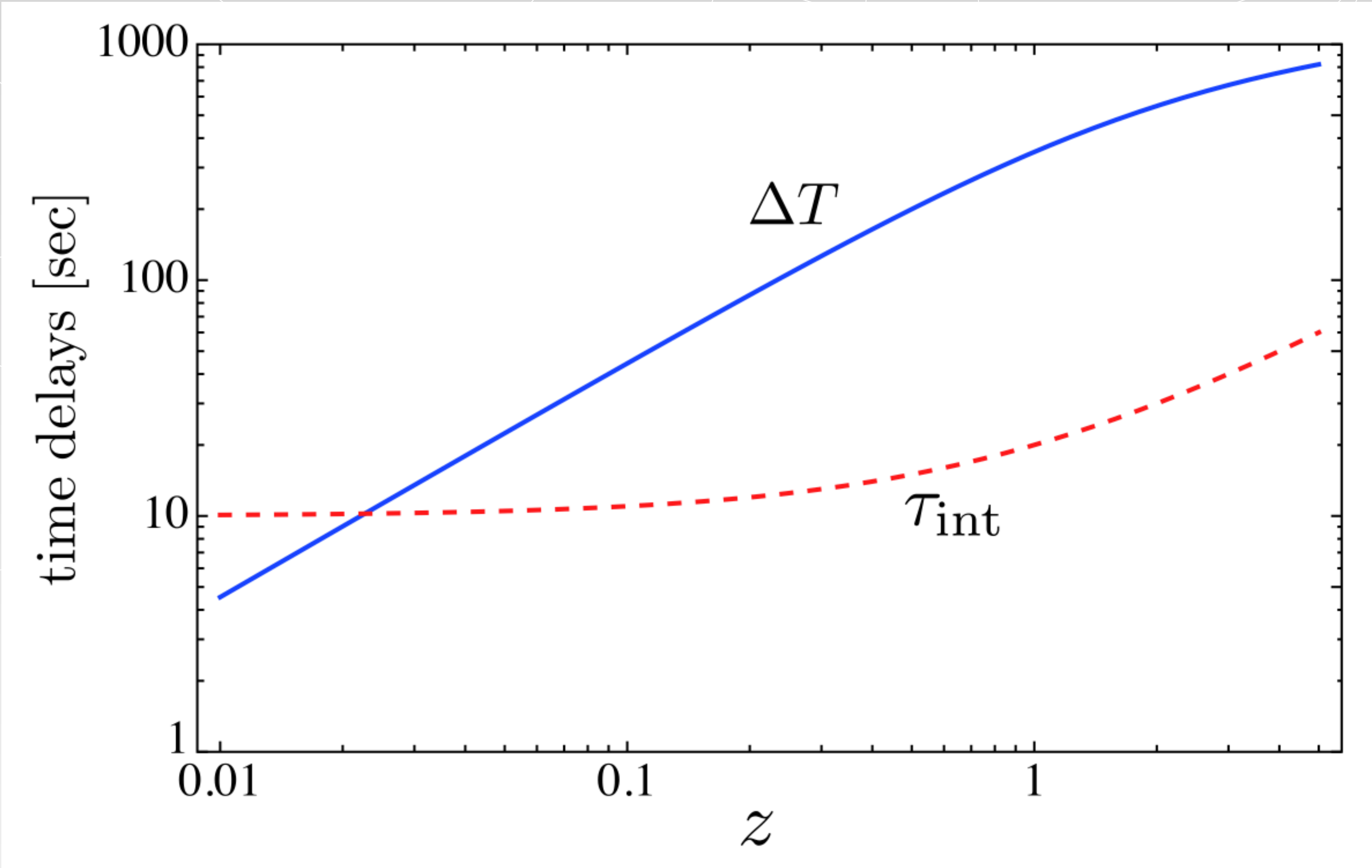
GW & SN neutrino $\delta_g \lesssim 10^{-15}$

GW & GRB photon $\delta_g \lesssim 10^{-14}$

8-9 orders of magnitude stronger !!

USING MULTIPLE BINARIES

With a next-generation GW detector (Einstein Telescope), many binaries at cosmological distance will be observed.



We can distinguish between true signal and intrinsic time error.

SUMMARY

SUMMARY

- General Relativity is well tested and has passed all tests in a weak field regime.
- A gravitational wave will be detected for the first time in a couple of years by ground-based GW detectors.
- Gravitational waves bring new opportunities to test gravity in strong & dynamical regimes.
- Measuring the polarization modes and the propagation speed of GW is fundamental model-independent tests of gravity.
- We would finally confirm all predictions of GR by Einstein in the centennial year of GR !!