Gravitational waves

Ryusuke Jinno (IBS-CTPU)

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SELF INTRODUCTION

- Ryusuke (류스케 / 隆介) Jinno (진노 / 神野)

  - 2016/3 : Ph.D @ Univ. of Tokyo (particle physics group, supervised by Takeo Moroi)

  - 2016/4-8 : JSPS fellow (PD) @ KEK, Japan

  - 2016/9- : Research Fellow @ IBS-CTPU, Korea

SELF INTRODUCTION

- Research interests & recent works

- Machine learning : Application to QFT tunneling problem

- Gravitational waves : Analytic approach to GW production in phase transitions

- (P)reheating : Preheating in Higgs inflation (newly-found main channel: "spike preheating")

- Inflation : Hillcliming inflation (an inflationary attractor)

  Hillclimbing Higgs inflation (new realization of Higgs inflation with hillclimbing)

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    Hillclimbing Higgs inflation (new realization of Higgs inflation with hillclimbing)

Introduction

- What's gravitational waves?
- Some history

astrophysical GWs

- New probe to the Universe

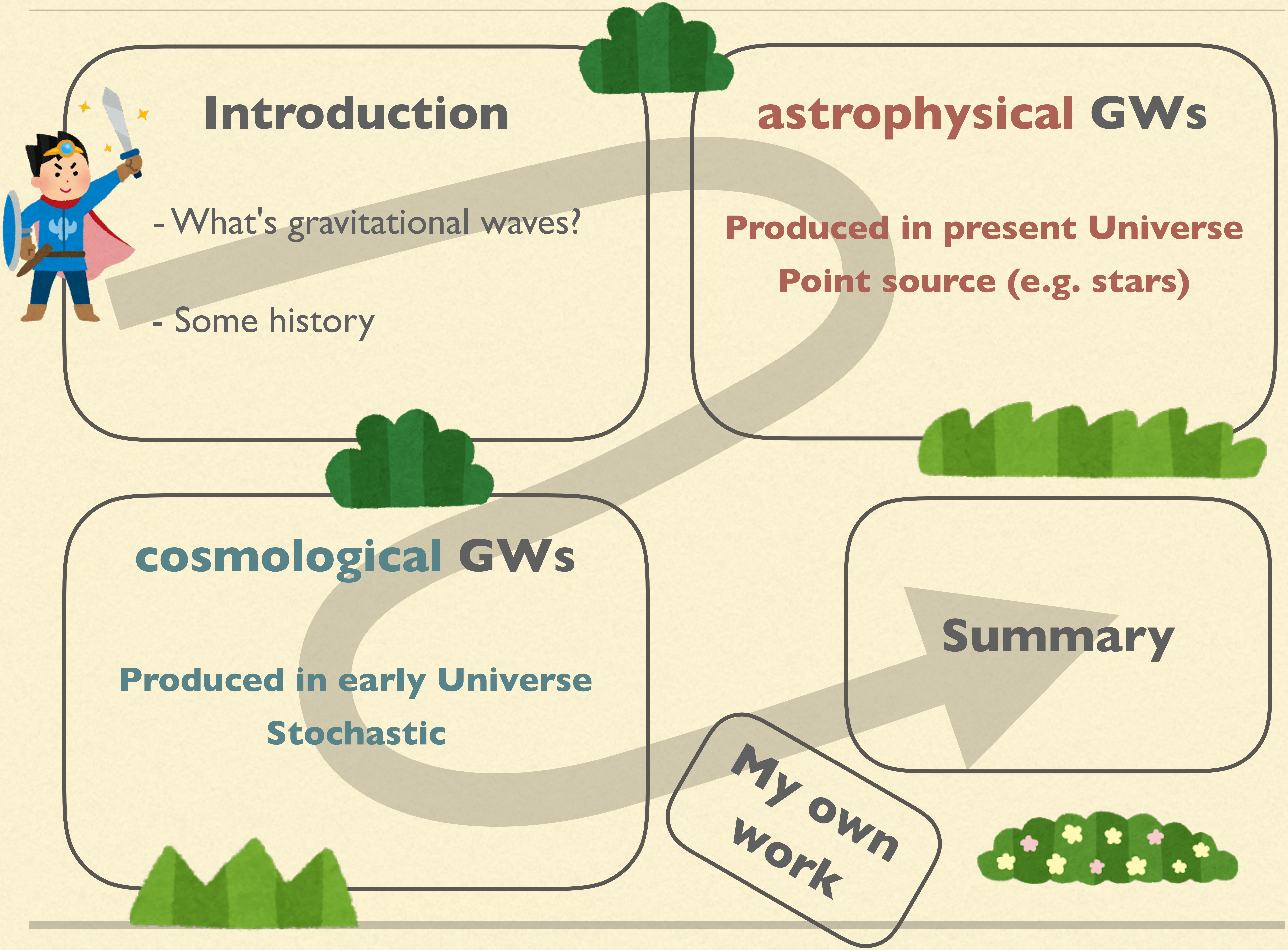
(focussing on recent aLIGO)

cosmological GWs

- What's interesting?
- "Standard" cosmic history
- Various sources

My own work

Summary



Introduction

- What's gravitational waves?
- Some history

astrophysical GWs

Produced in present Universe

Point source (e.g. stars)

cosmological GWs

Produced in early Universe

Stochastic

My own work

Summary

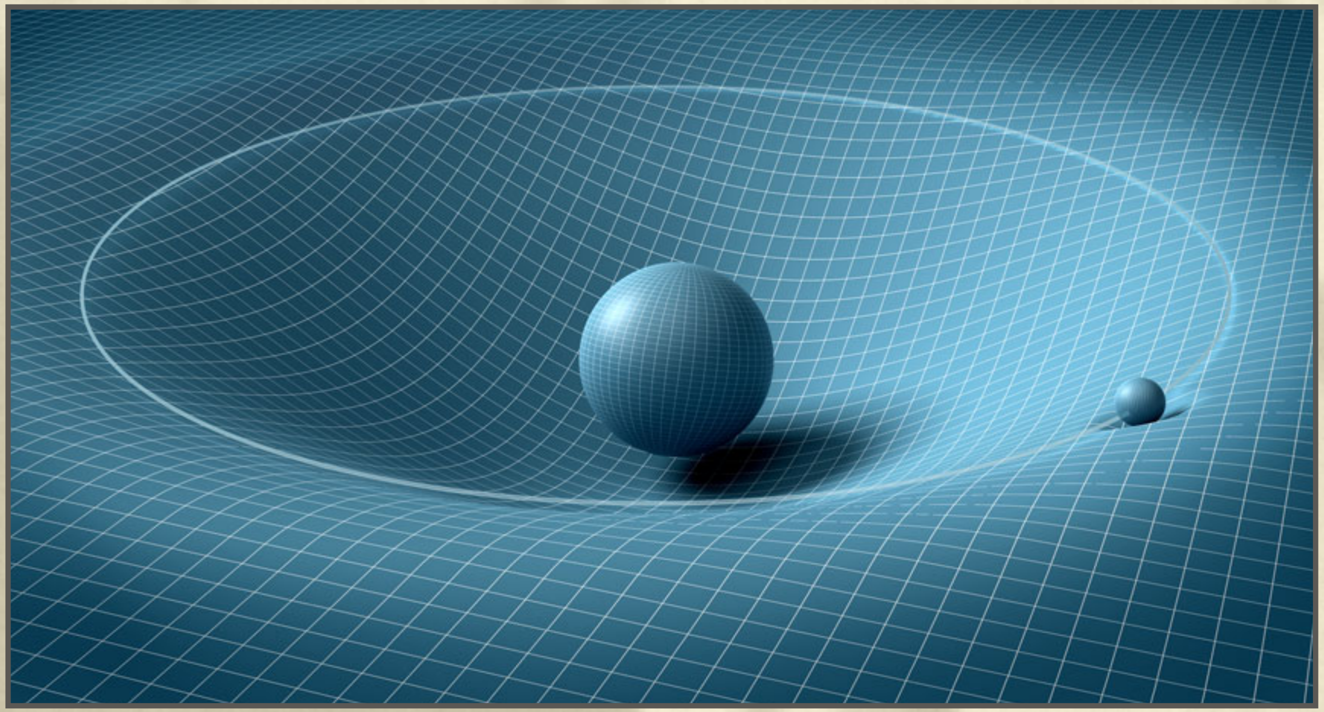
WHAT'S GWS?

- General relativity [A.Einstein, 1916]

  - Theory of gravity

  - Spacetime tells matter how to move, and matter tells spacetime how to curve

[J.A.Wheeler]



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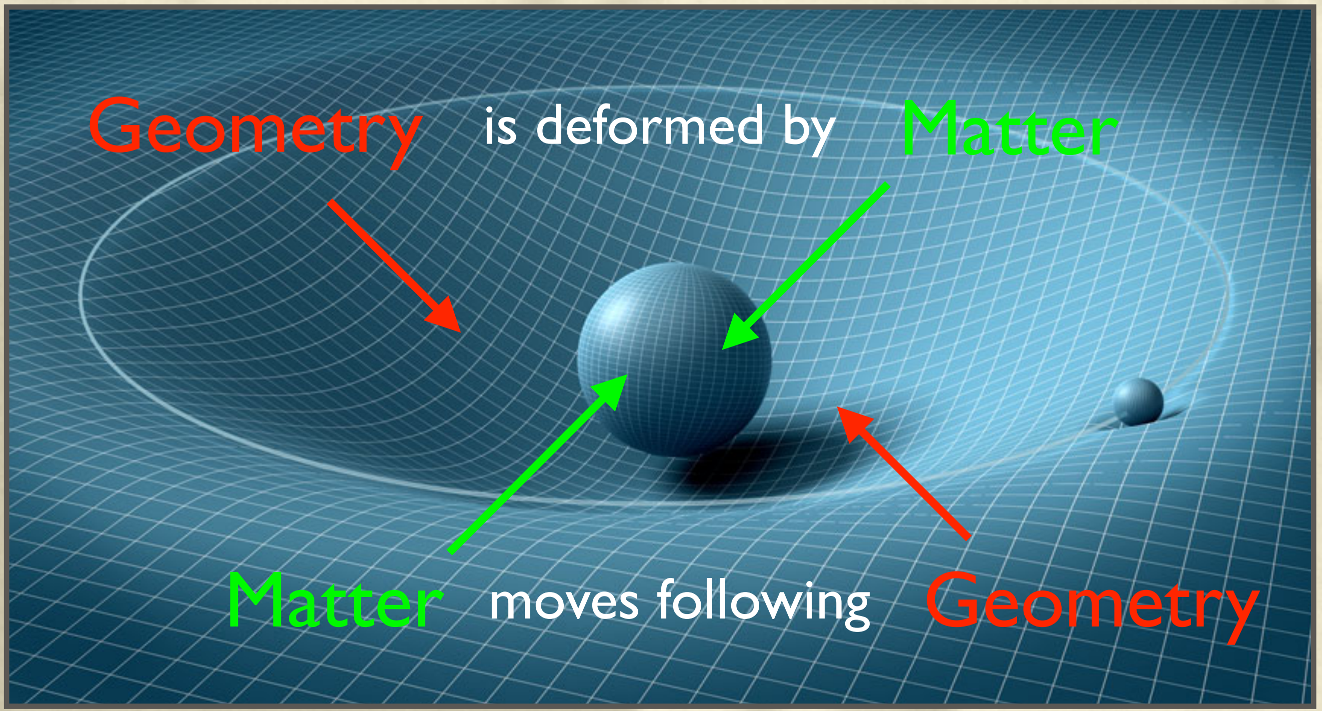

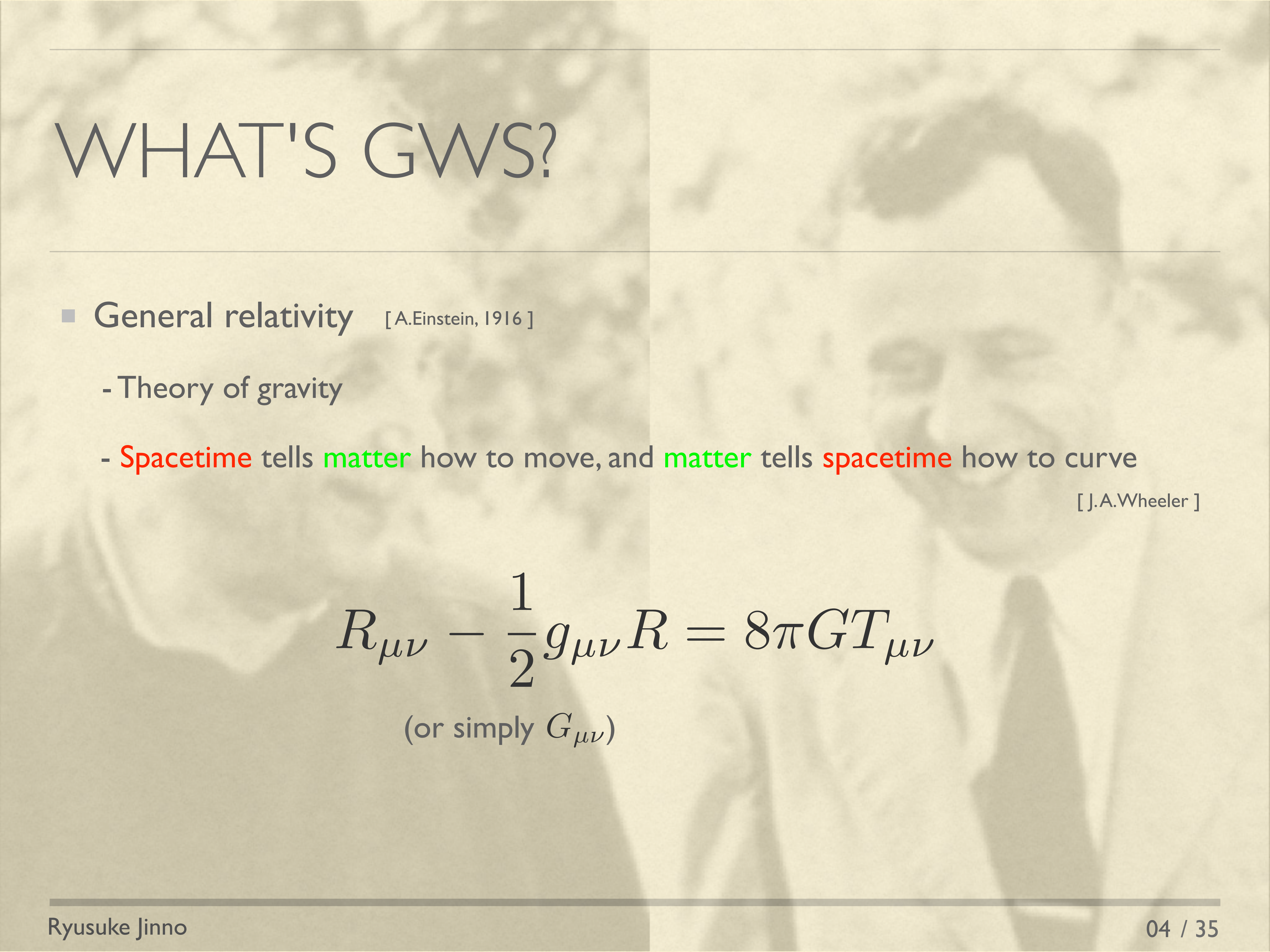

WHAT'S GWS?

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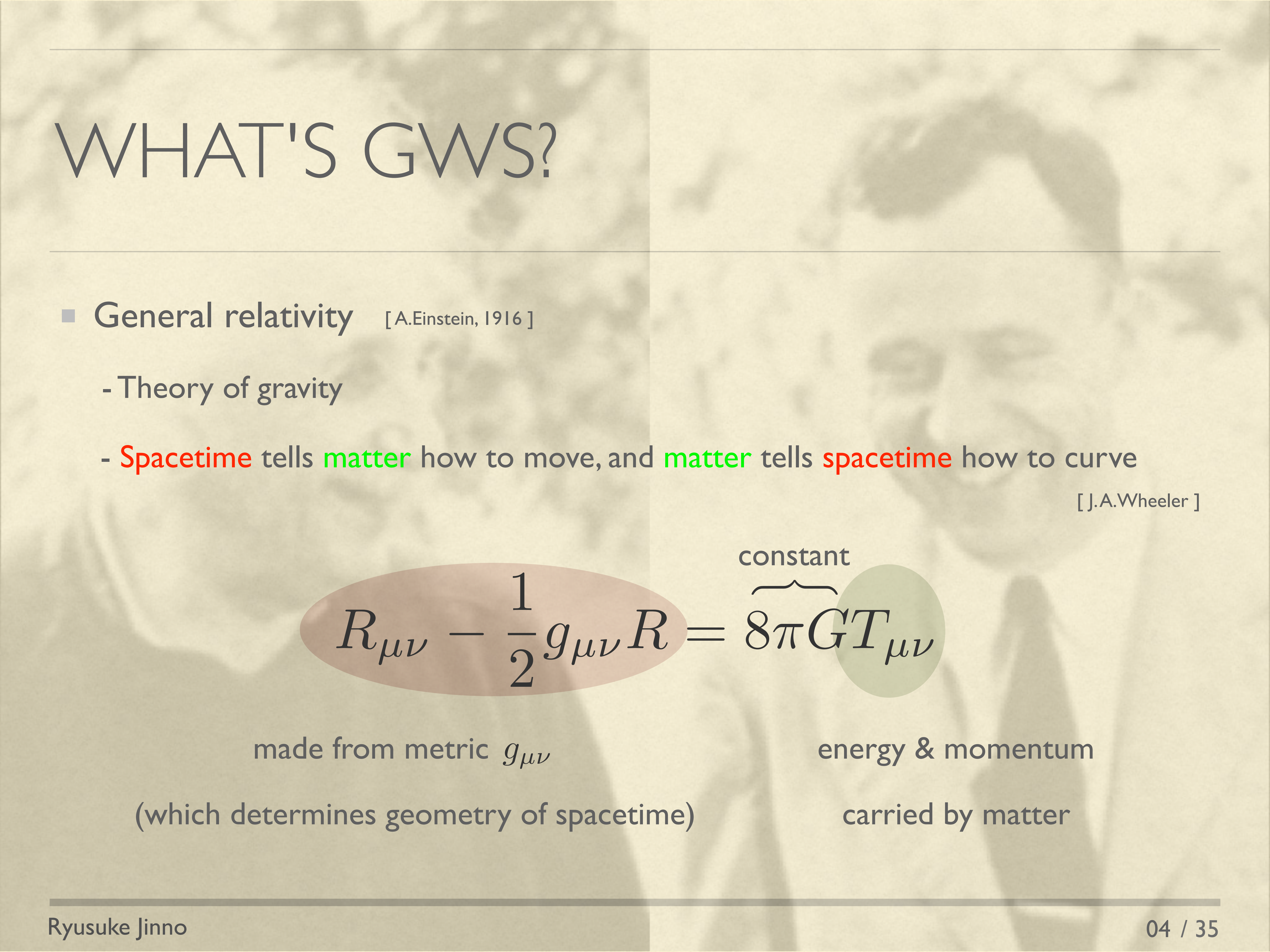
[J.A.Wheeler]

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

(or simply $G_{\mu\nu}$)



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[J.A.Wheeler]

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \overbrace{8\pi G}^{\text{constant}} T_{\mu\nu}$$

made from metric $g_{\mu\nu}$

(which determines geometry of spacetime)

energy & momentum

carried by matter

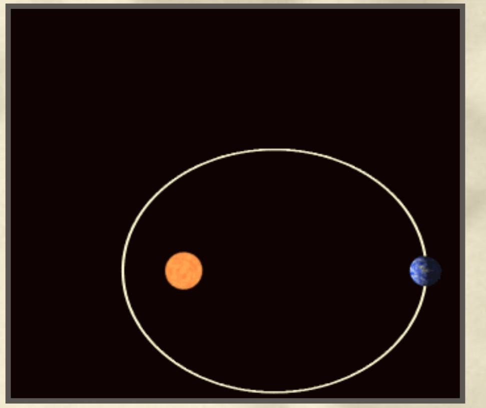
WHAT'S GWS?

- Important predictions of general relativity

  - Perihelion precession of Mercurie

    575" (Mercurie's perihelion precession for 100 yrs)

    = 532" (perturbations from other planets) + 43" (General relativity)



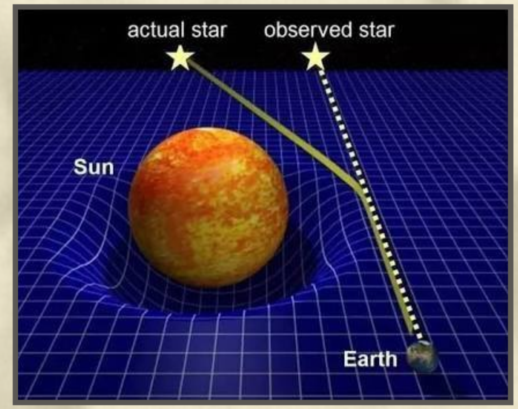
[Wikipedia]

  - Black holes

[NASA/JPL-Caltech]

  - Gravitational lensing (especially the Sun)

    General relativity's prediction = 2 × classical physics prediction



[https://www.quora.com/How-different-is-gravitational-lensing-from-optical-lensing]

  - Gravitational waves

WHAT'S GWS?

- Gravitational waves

  - Let's assume (almost) homogeneous isotropic Universe & small amount of GWs.

    Then we have metric $$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

    scale factor
    = "size of the Universe"

    GWs
    We assume << 1

  - Note : in some cases other perturbations are important (e.g. around BHs)

  - GWs $h_{ij}(t, \vec{x})$ satisfy traceless cond. $h_{ii} = 0$ & transverse cond. $\frac{\partial}{\partial x^i} h_{ij} = 0$

    and obey the equation of motion $$\boxed{\Box h_{ij}(t, \vec{x}) = -16\pi G P_{ij,kl} T_{kl}(t, \vec{x})}$$

WHAT'S GWS?

$$\boxed{\Box h_{ij}(t,\vec{x}) = -16\pi G P_{ij,kl} T_{kl}(t,\vec{x})}$$

- Rough picture

  - In the absence of matter (i.e. $T_{ij} = 0$), GWs are just waves: $\Box h_{ij} = 0$

  - Energy-momentum tensor T_{ij} acts as a source,

    and projection $P_{ij,kl}$ picks up some component of T_{ij}

  - Newton constant part: $8\pi G \sim \dfrac{1}{(10^{18}\ \mathrm{GeV})^2} \sim \dfrac{1}{(\text{Huge energy scale})^2}$

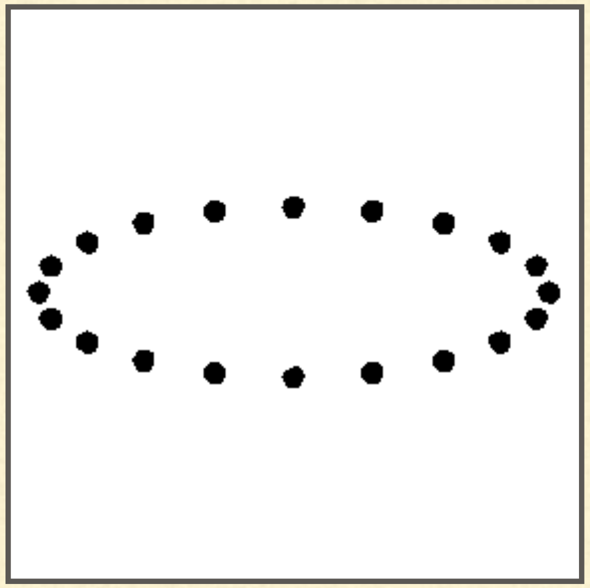
WHAT'S GWS?

$$\boxed{\Box h_{ij}(t,\vec{x}) \sim T_{ij}(t,\vec{x})}$$

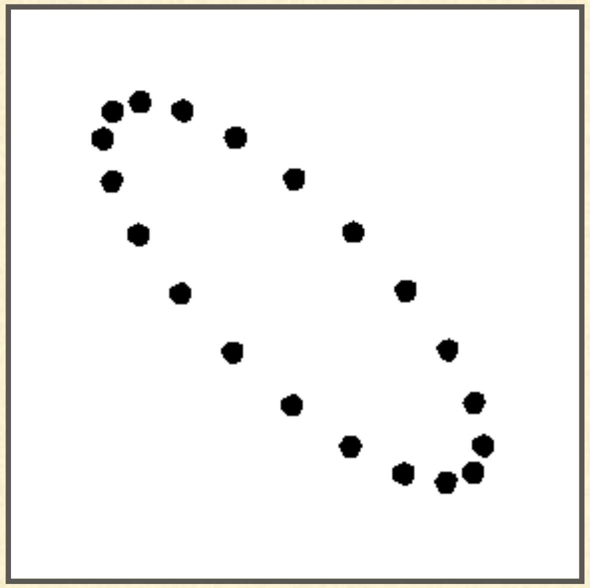
- 2 modes of GWs

- 2 dof: 6 (3×3 symmetric matrix) - 1 (traceless $h_{ii} = 0$) - 3 (transverse $\partial_i h_{ij} = 0$)

Mode +



Mode ×



WHAT'S GWS?

$$\boxed{\Box h_{ij}(t,\vec{x}) \sim T_{ij}(t,\vec{x})}$$

- 2 modes of GWs

- 2 dof: 6 (3×3 symmetric matrix) - 1 (traceless $h_{ii}=0$) - 3 (transverse $\partial_i h_{ij}=0$)

- Decomposition into various $\vec{k}$ makes it easier: $h_{ij}(t,\vec{x}) \sim \int d^3k\ e^{i\vec{k}\cdot\vec{x}} h_{ij}(t,\vec{k})$

- Traceless ($h_{ii}(t,\vec{k})=0$) & transverse ($k_i h_{ij}(t,\vec{k})=0$)

waves ($\sim \sin(kt)$, in the absence of matter) in $\vec{k} \propto \hat{z}$ direction has the form:

$$h_{ij}(t,\vec{k}) = h_+ \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \sin(kt+\delta_+) + h_\times \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \sin(kt+\delta_\times)$$

WHAT'S GWS?

- 2 mo

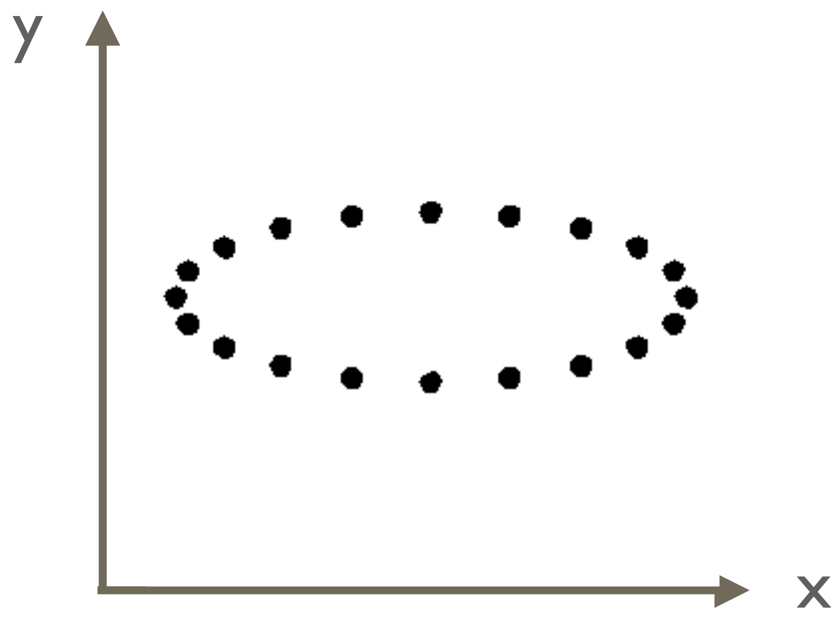
  - 2 do $_j = 0)$

  - Dec $(t, \vec{k})$

  - Trac

  wave n:

Spacial metric $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} h_+ & 0 & 0 \\ 0 & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix} \sin(kt + \delta_+)$



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WHAT'S GWS?

$\Box h \quad (t, \vec{x}) \quad T \quad (t, \vec{x})$

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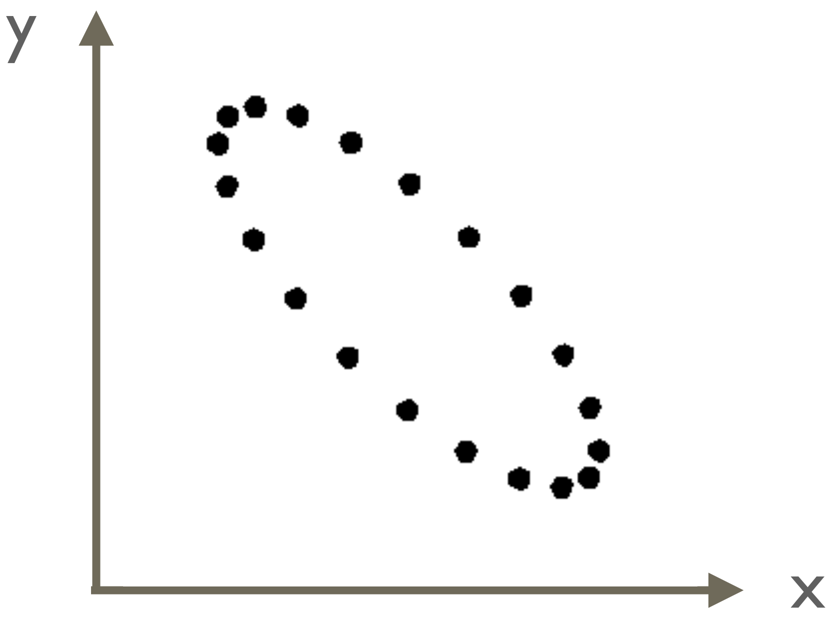

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BRIEF HISTORY OF GWS

[Wikipedia]

- 1893, Heaviside: Analogy of electromagnetism applied to gravity

  [Heaviside, *Electromagnetic Theory*, 1893, p.281-282,359]

- 1905, Poincare: Proposal of gravitational waves emitted from accelerating body

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- 1916, Einstein: General theory of relativity → prediction of GWs

  (note : at that time, 3 types are proposed: LL, LT, TT)

- 1922, Doubt on the existence of GWs

  (e.g. Eddington: they "propagate at the speed of thought")

- 1936, Einstein & Rosen wrote a paper saying that GWs do not exist

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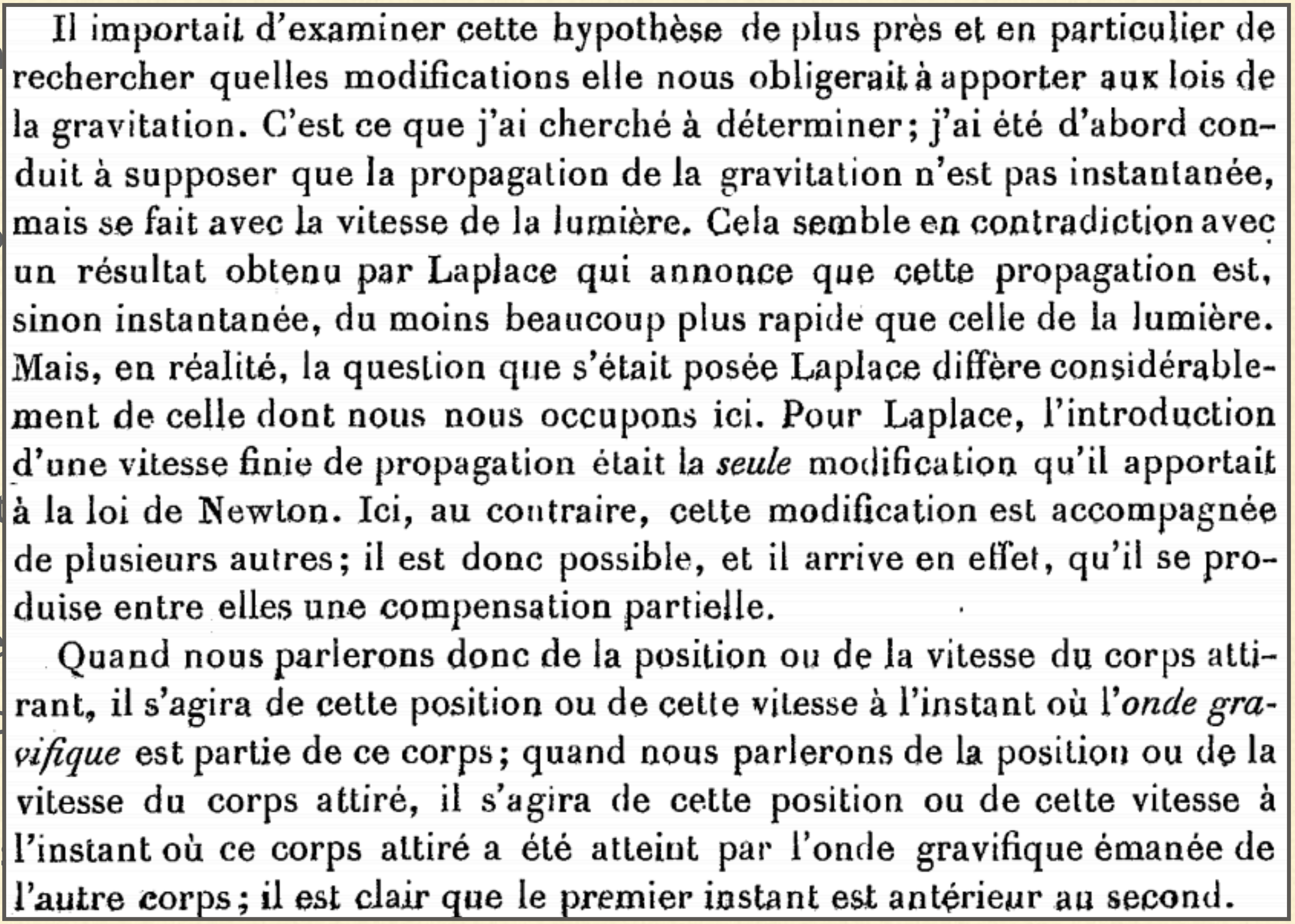

Il importait d'examiner cette hypothèse de plus près et en particulier de rechercher quelles modifications elle nous obligerait à apporter aux lois de la gravitation. C'est ce que j'ai cherché à déterminer; j'ai été d'abord conduit à supposer que la propagation de la gravitation n'est pas instantanée, mais se fait avec la vitesse de la lumière. Cela semble en contradiction avec un résultat obtenu par Laplace qui annonce que cette propagation est, sinon instantanée, du moins beaucoup plus rapide que celle de la lumière. Mais, en réalité, la question que s'était posée Laplace diffère considérablement de celle dont nous nous occupons ici. Pour Laplace, l'introduction d'une vitesse finie de propagation était la *seule* modification qu'il apportait à la loi de Newton. Ici, au contraire, cette modification est accompagnée de plusieurs autres; il est donc possible, et il arrive en effet, qu'il se produise entre elles une compensation partielle.

Quand nous parlerons donc de la position ou de la vitesse du corps attirant, il s'agira de cette position ou de cette vitesse à l'instant où l'*onde gravifique* est partie de ce corps; quand nous parlerons de la position ou de la vitesse du corps attiré, il s'agira de cette position ou de cette vitesse à l'instant où ce corps attiré a été atteint par l'onde gravifique émanée de l'autre corps; il est clair que le premier instant est antérieur au second.

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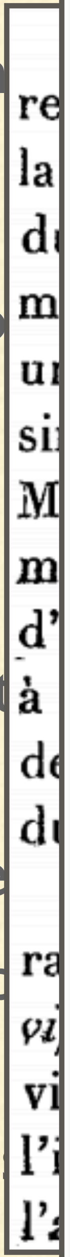

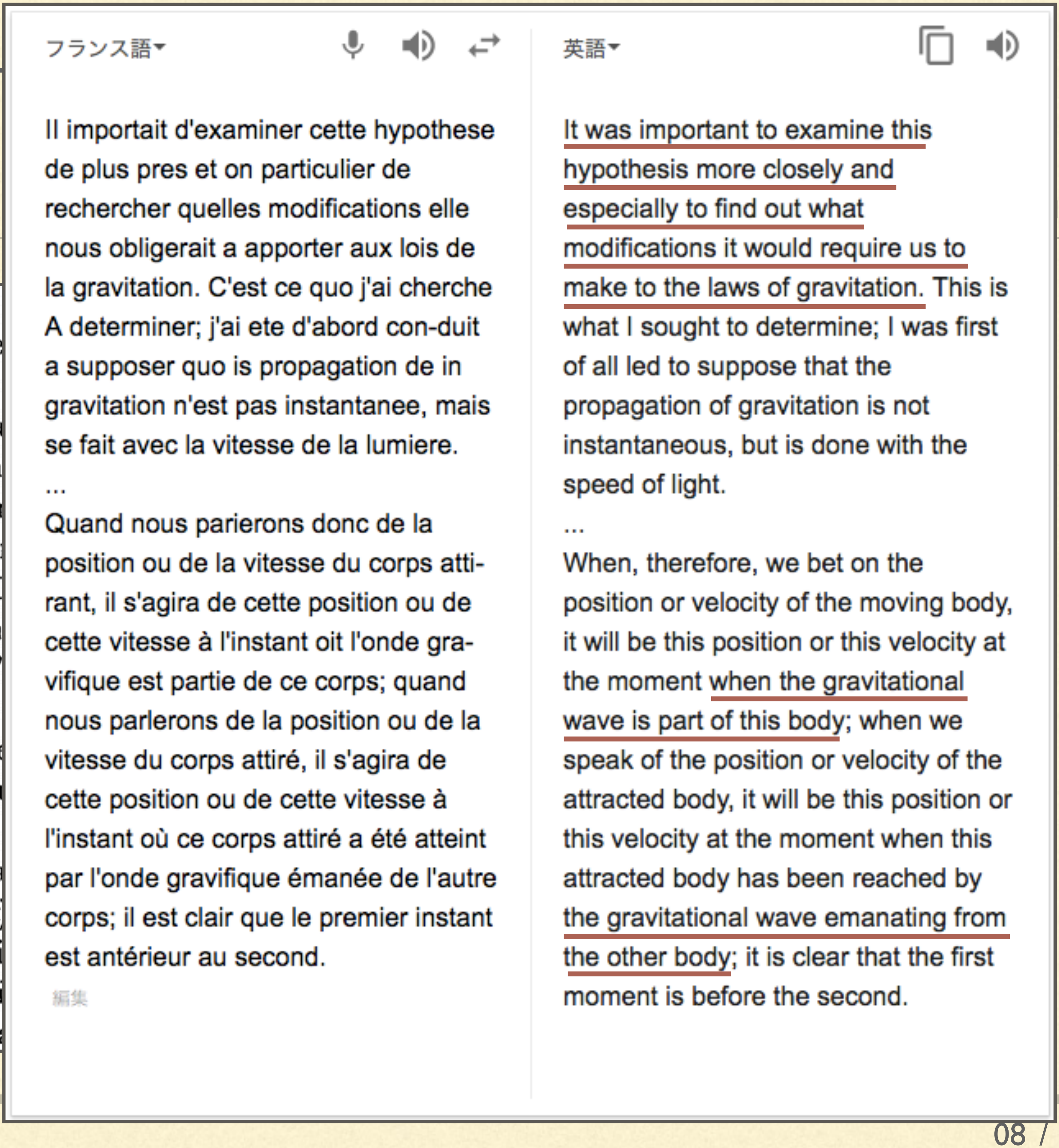

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...

Quand nous parierons donc de la position ou de la vitesse du corps atti-rant, il s'agira de cette position ou de cette vitesse à l'instant oit l'onde gra-vifique est partie de ce corps; quand nous parlerons de la position ou de la vitesse du corps attiré, il s'agira de cette position ou de cette vitesse à l'instant où ce corps attiré a été atteint par l'onde gravifique émanée de l'autre corps; il est clair que le premier instant est antérieur au second.

It was important to examine this hypothesis more closely and especially to find out what modifications it would require us to make to the laws of gravitation. This is what I sought to determine; I was first of all led to suppose that the propagation of gravitation is not instantaneous, but is done with the speed of light.

...

When, therefore, we bet on the position or velocity of the moving body, it will be this position or this velocity at the moment when the gravitational wave is part of this body; when we speak of the position or velocity of the attracted body, it will be this position or this velocity at the moment when this attracted body has been reached by the gravitational wave emanating from the other body; it is clear that the first moment is before the second.

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BRIEF HISTORY OF GWS

[Wikipedia]

- 1956, Pirani remedied the confusion caused by various coordinate systems

- 1950's, Discussions on whether GWs carry energy

  → settled by Feynman, "sticky bead" thought experiment

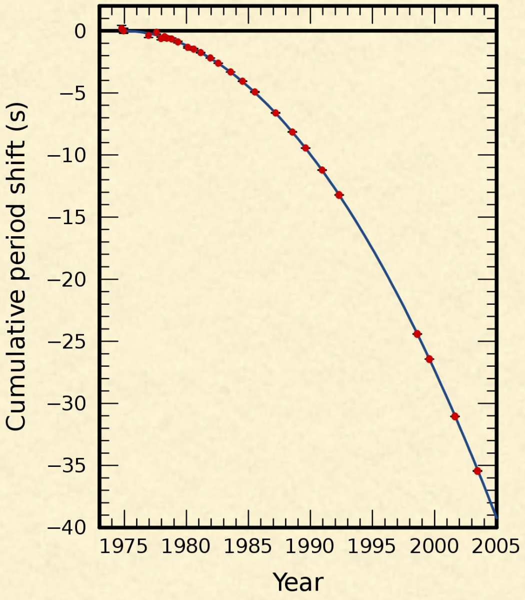
- 1969, First detection announced by Joseph Weber

→ though not confirmed by others,

experimentally this was an important step

- 1974, Hulse & Taylor confirmed the existence of GWs

  (though indirectly) by orbital decay of binary pulsar



SUMMARY SO FAR

- In General Relativity, there are degrees of freedom

  propagating with speed of light: Gravitational Waves

Introduction

- What's gravitational waves?
- Some history

astrophysical GWs

- New probe to the Universe

(focussing on recent aLIGO)

cosmological GWs

- What's interesting?
- "Standard" cosmic history
- Various sources

My own work

Summary

FIRST GW DETECTION

- Advanced LIGO announced

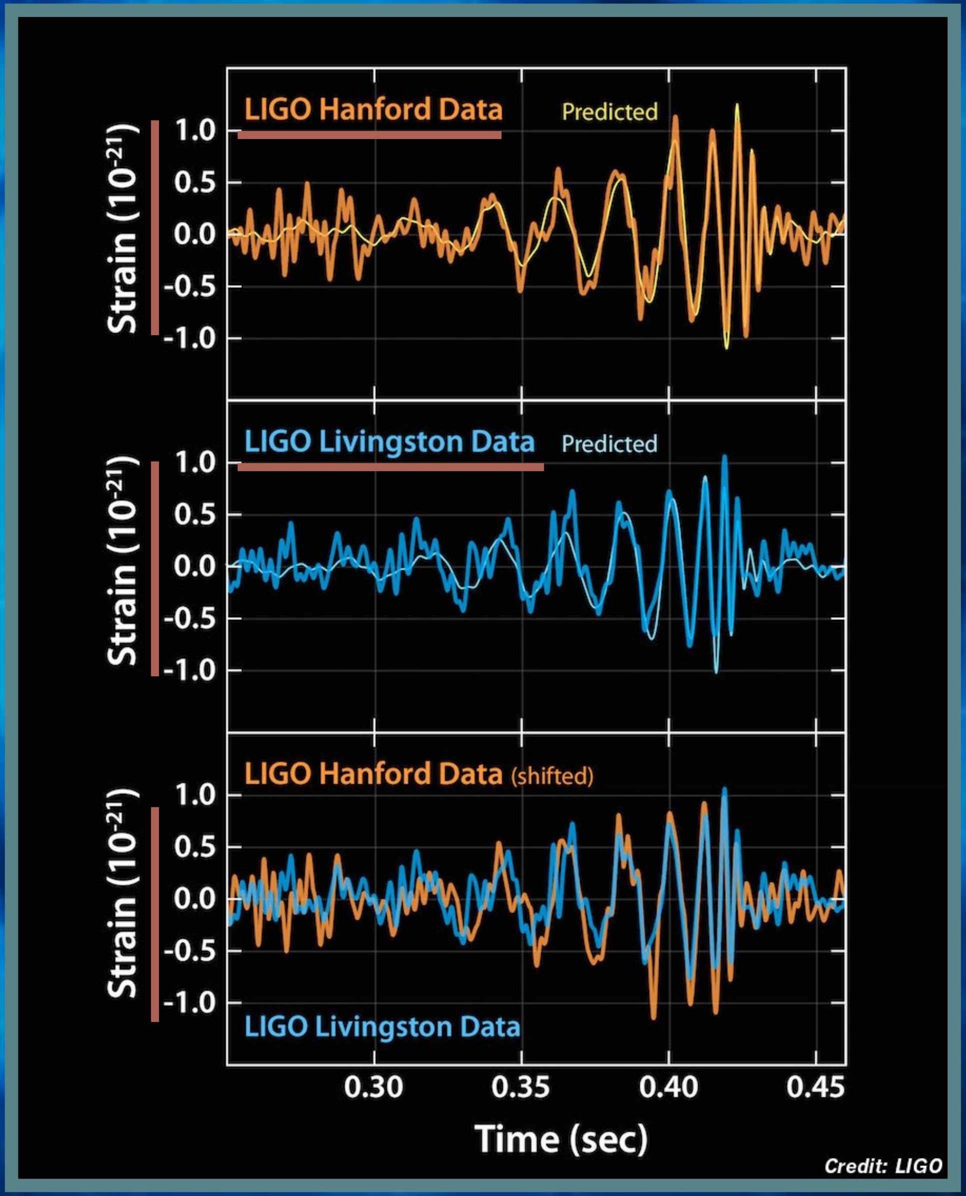
  first detection of GWs in 2016/2

- Event itself was in 2015/9/14

- Black hole binary 36M⊙ + 29M⊙ →62M⊙

  (3M⊙ radiatied as GWs)

- Strain ~ 10^{-21} , Frequency ~ 250Hz

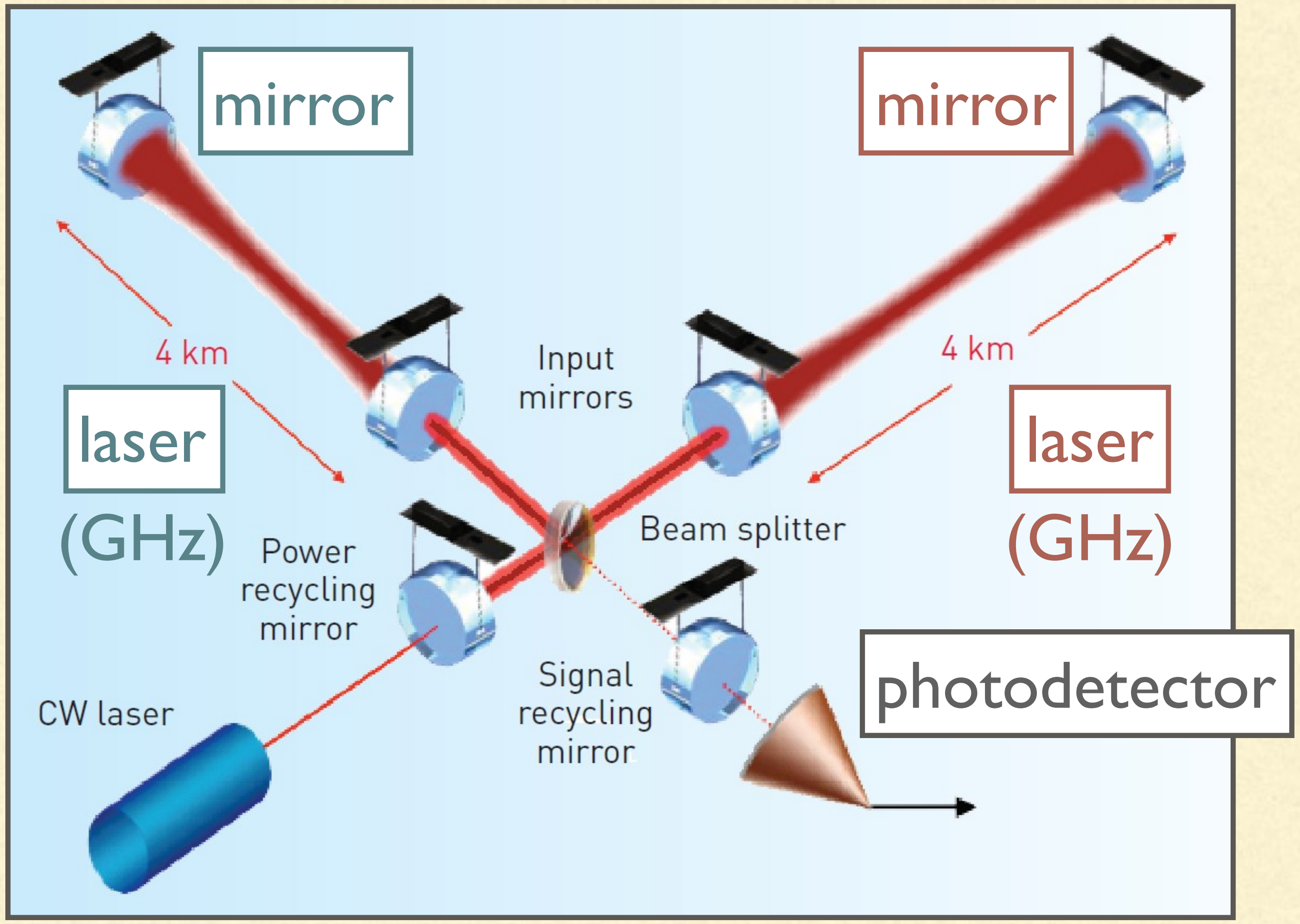


Credit: LIGO

FIRST GW DETECTION

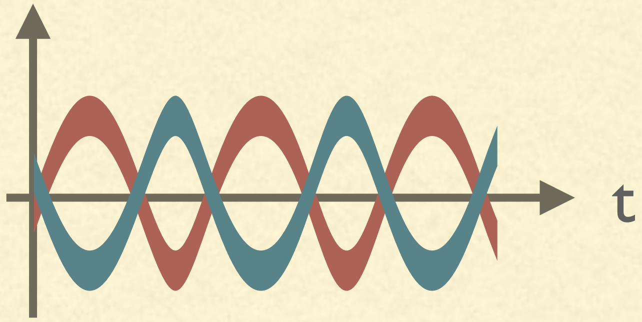
- Advanced LIGO?

  - Ground interferometer experiment in US



Total power ~ electric field^2

Electric field



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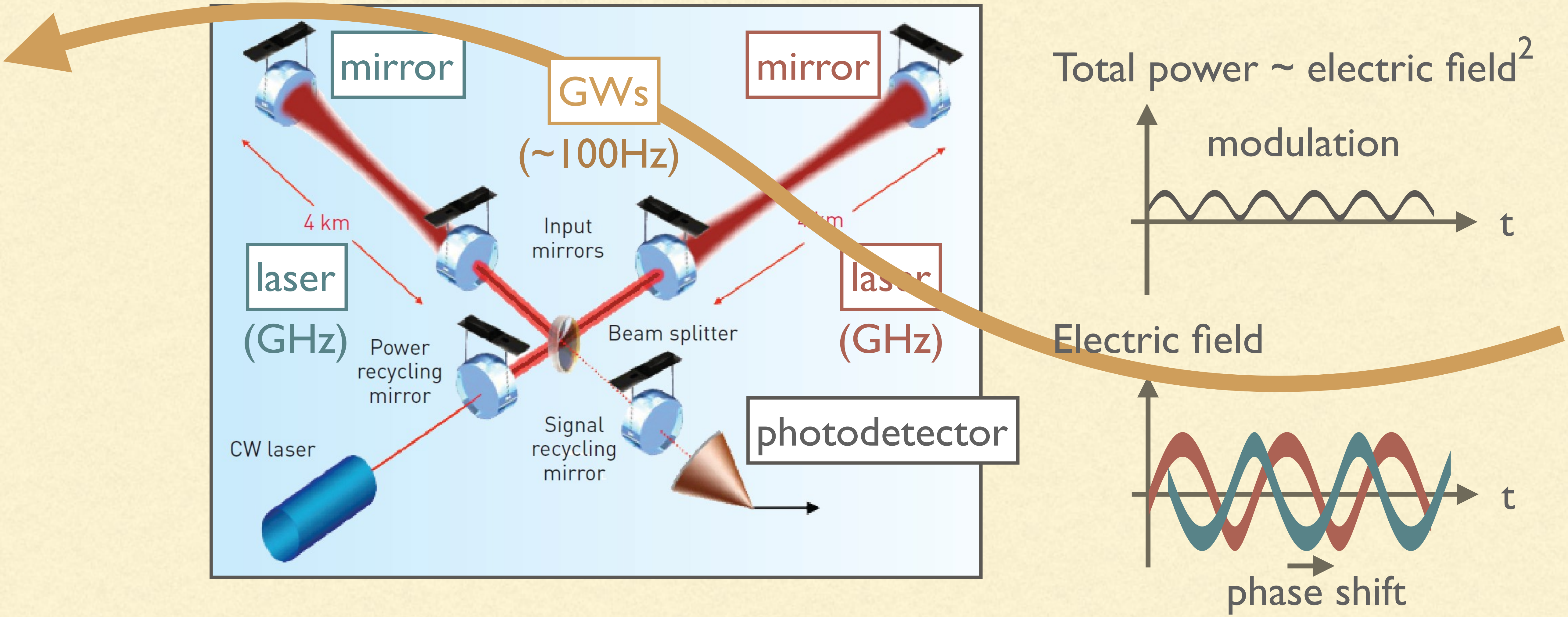


mirror

mirror

GWs (~100Hz)

laser (GHz)

laser (GHz)

photodetector

Total power ~ electric field^2

modulation

Electric field

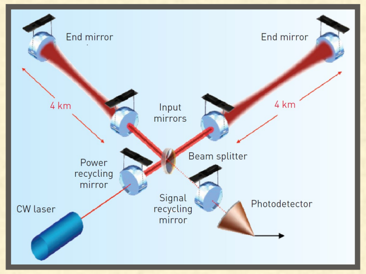
phase shift

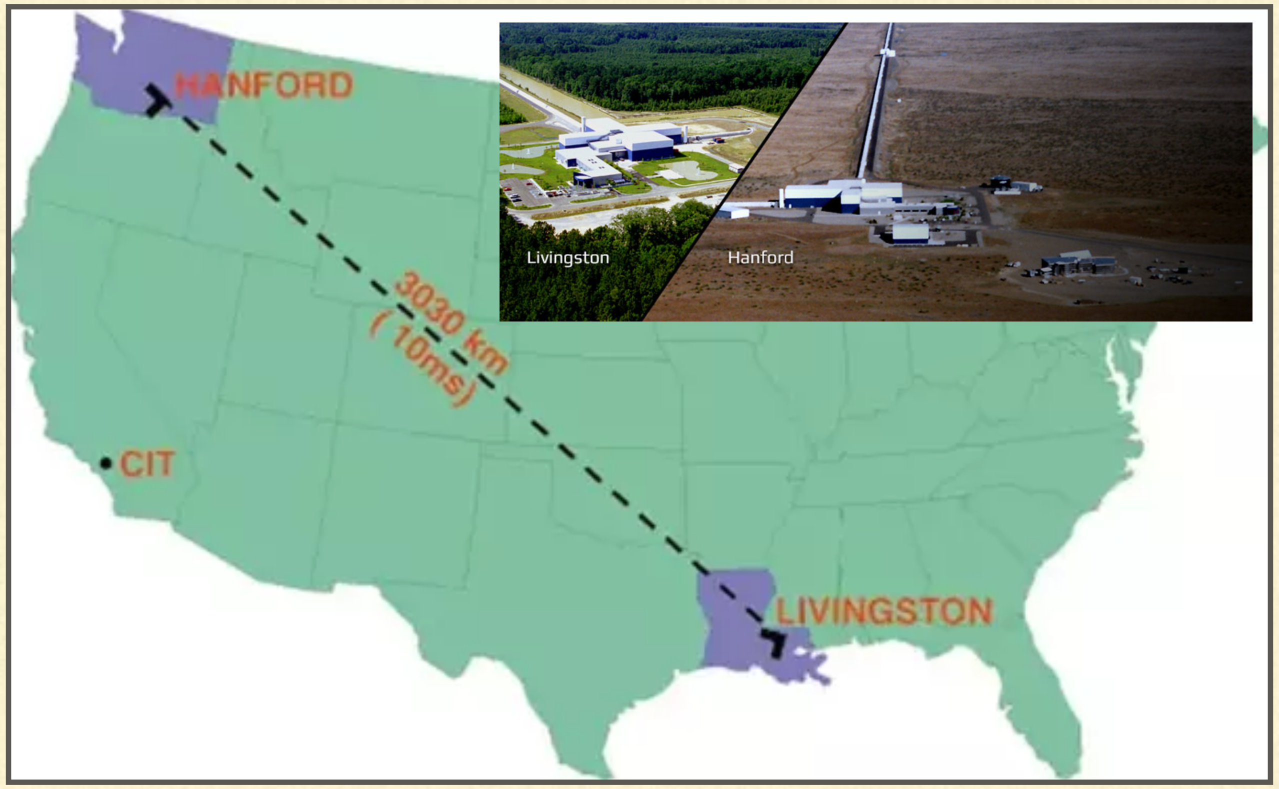
FIRST GW DETECTION

- Advanced LIGO?

  - Ground interferometer experiment in US

  - 2 interferometers: Hanford & Livingston





FIRST GW DETECTION

- Advanced LIGO?

  - Ground interferometer experiment in US

  - 2 interferometers: Hanford & Livingston

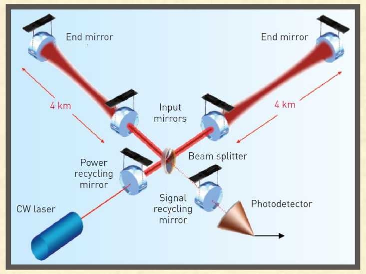
  - Brief history

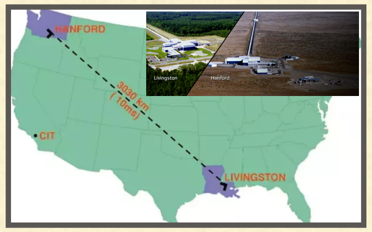
    2002-2010 : data collection by LIGO → no detection

    2010- : major update to Advanced LIGO

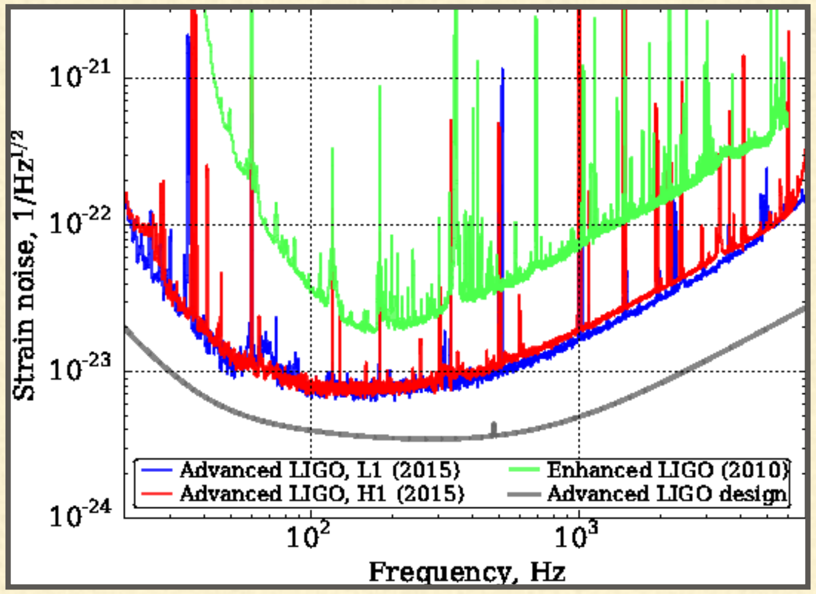
    2015- : first detection of GWs from BH binary

    → announced in 2016

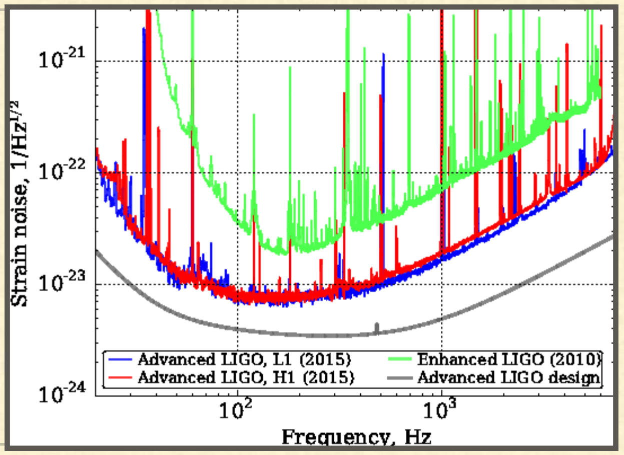




[LIGO, 1604.00439]



FIRST GW DETECTION



- Strain?

  - Typically shown in unit $\mathrm{Hz}^{-1/2}$, as a function of frequency f

  - Rough meaning: typical contribution to $h_{ij}(t,\vec{x})$ caused by GWs of frequency f

  - More rigorously, ...

$$\langle h_{ij}^2(t,\vec{x})\rangle_{\text{long time average}} \sim \int df \ \mathrm{Strain}(f)^2$$

  - So, strain 10^{-22} $\mathrm{Hz}^{-1/2}$ around frequency 100Hz means...

$$\text{typical } h_{ij} \sim \sqrt{(\text{freq. band } \Delta f) \times (\text{typical strain})^2} \sim 10^{-21}$$

  - How crazy? spacial metric ~ $\delta_{ij} + h_{ij}$ → distance ~ 4km ± 10^{-18}m

ADVANCED LIGO: DETECTION SO FAR

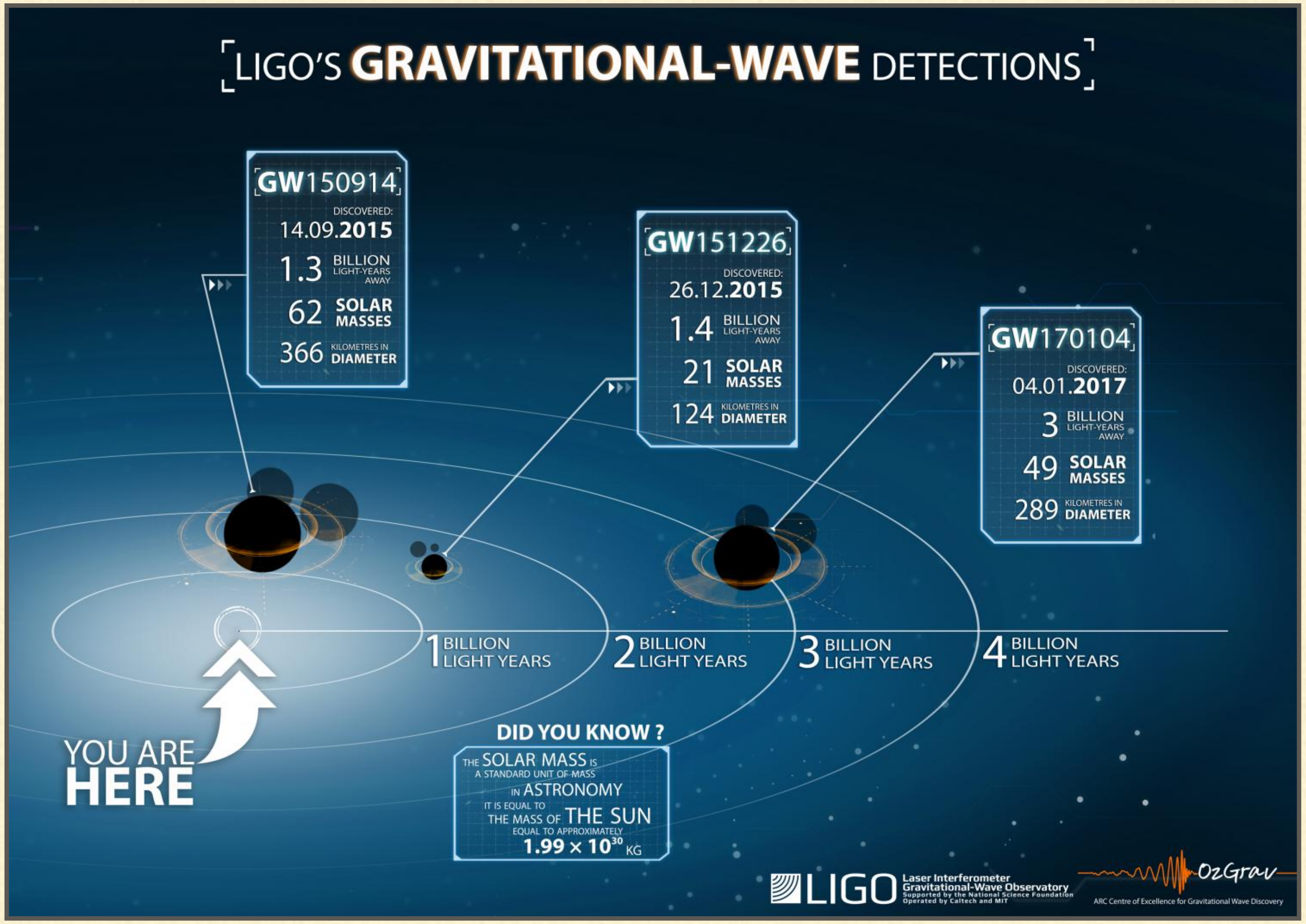
- Advanced LIGO results so far

  \- 6 detections:

  5 BH binaries, 1 NS binary

BH
- GW150914
- GW151226
- GW170104
- GW170608
- GW170814

NS
- GW170817

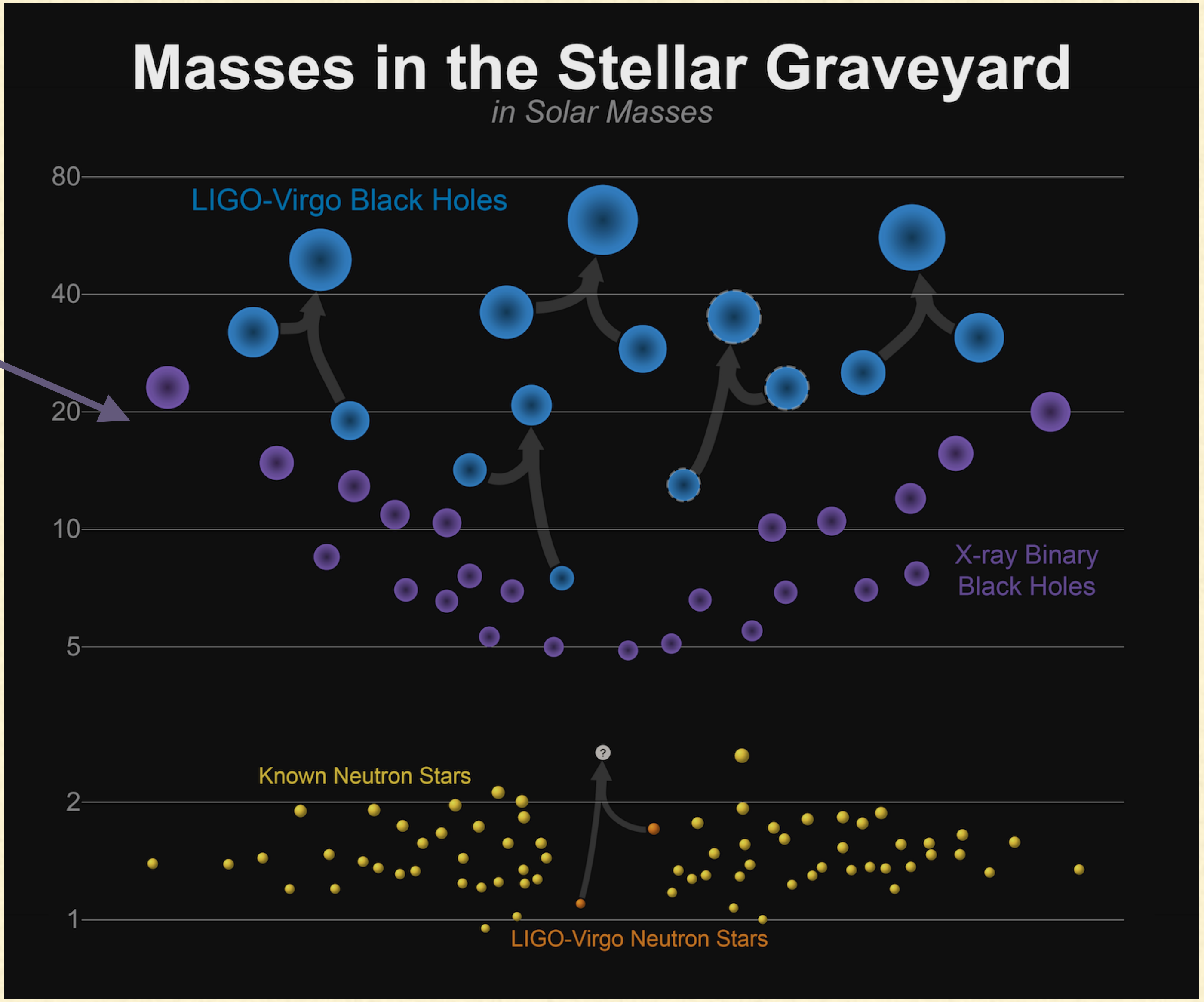


ADVANCED LIGO: NEW POPULATION OF BHS

- Black holes

  - Smaller mass ($\lesssim$ 10-20 $M_\odot$) BHs already found by X-ray studies

  - GWs revealed new population of BHs ($\gtrsim$ 20 $M_\odot$)



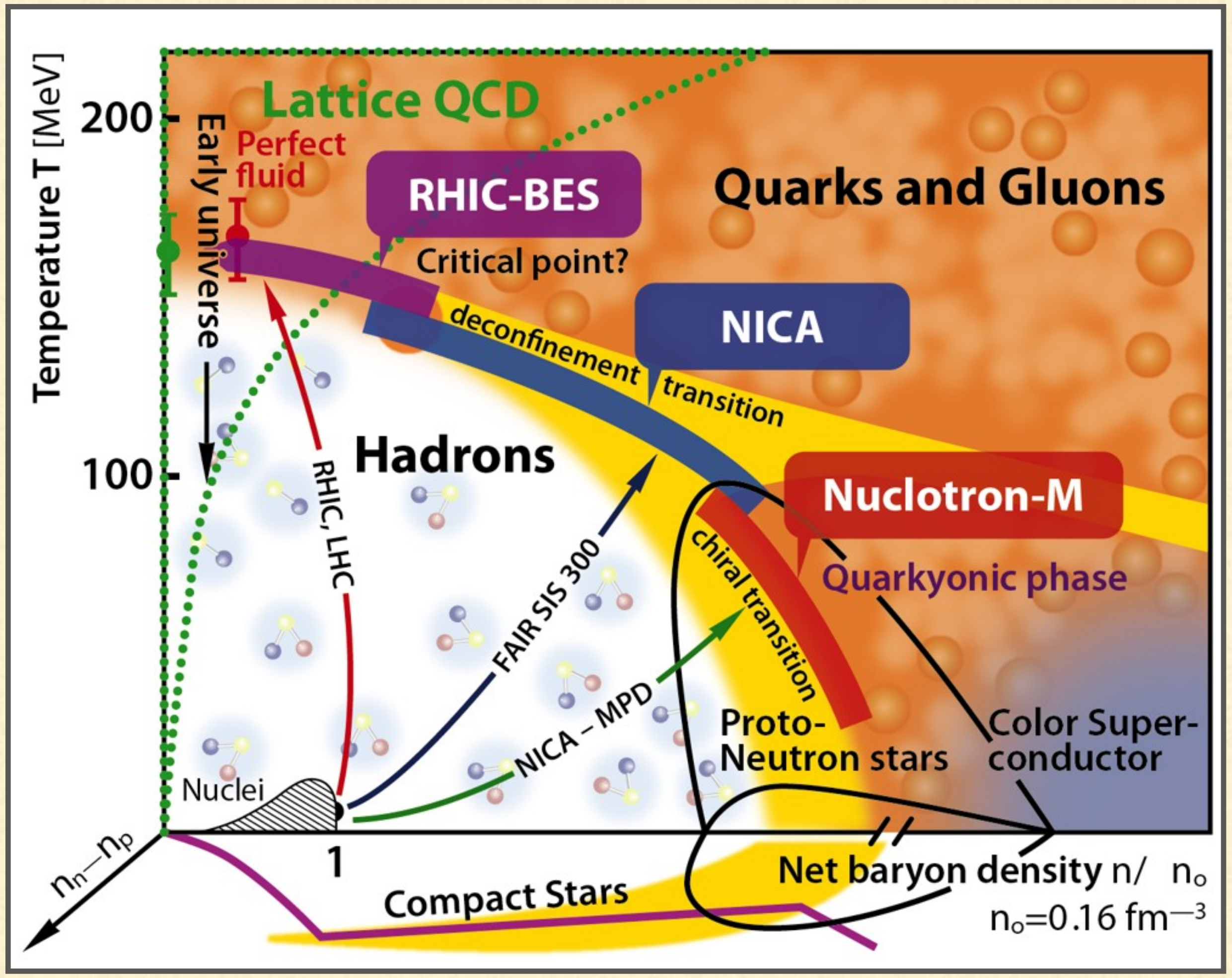
[LIGO]

ADVANCED LIGO: NEUTRON STAR EOS

- Neutron star equation of state p = p(ρ)

  - QCD phase diagram: colliders cannot access high μ (chemical potential) regions

Temperature



Chemical potential

[http://nica.jinr.ru/physics.php]

ADVANCED LIGO: NEUTRON STAR EOS

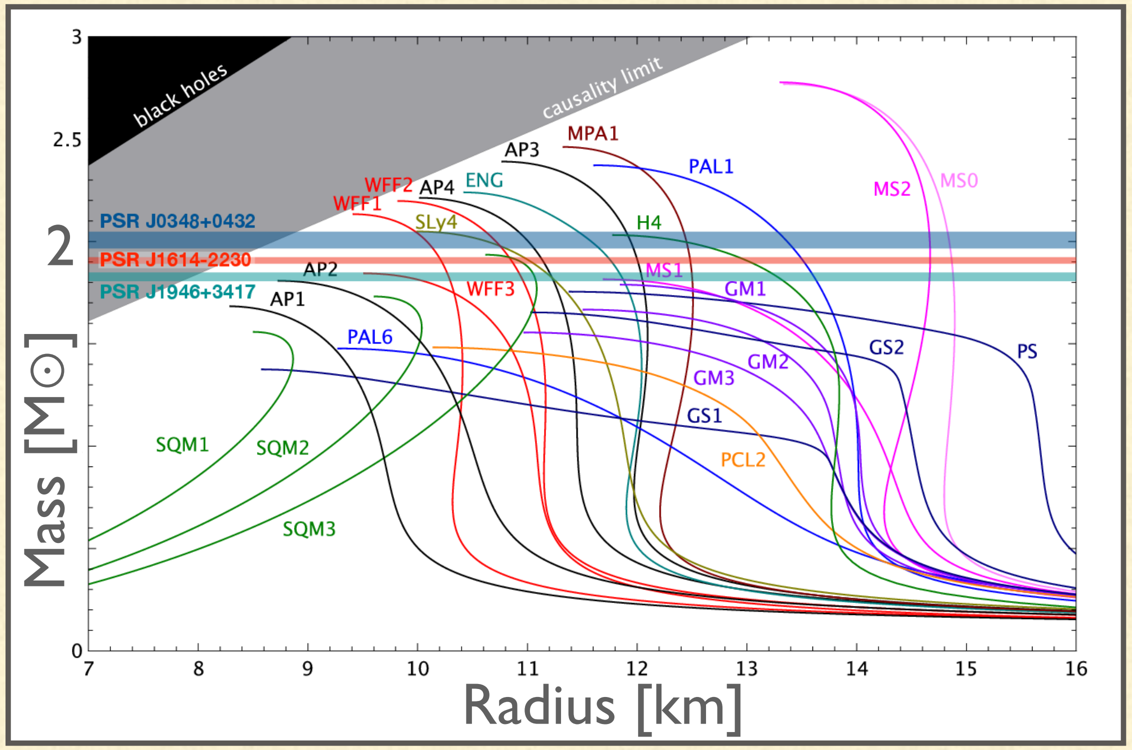
- Neutron star equation of state p = p(ρ)

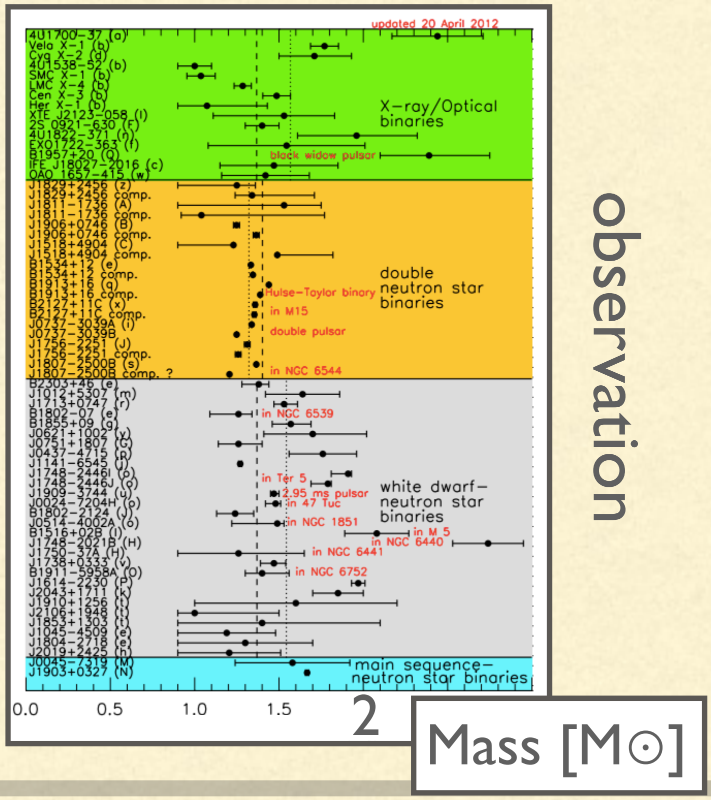
  - QCD phase diagram: colliders cannot access high μ (chemical potential) regions

  - Different eos predicts different mass-radius relation

  - NS with mass > 2M⊙ found → some eos models dead already

prediction





observation

[https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html]

[Lattimer, 1305.3510]

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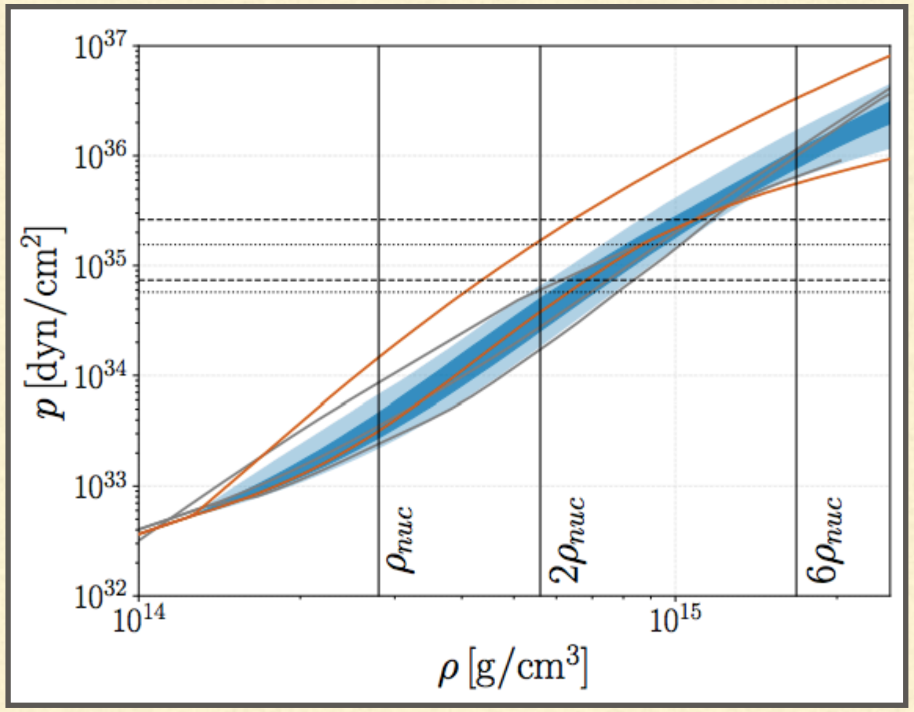
  - NS with mass > 2M⊙ found → some eos models dead already

  - GWs already start to constrain eos

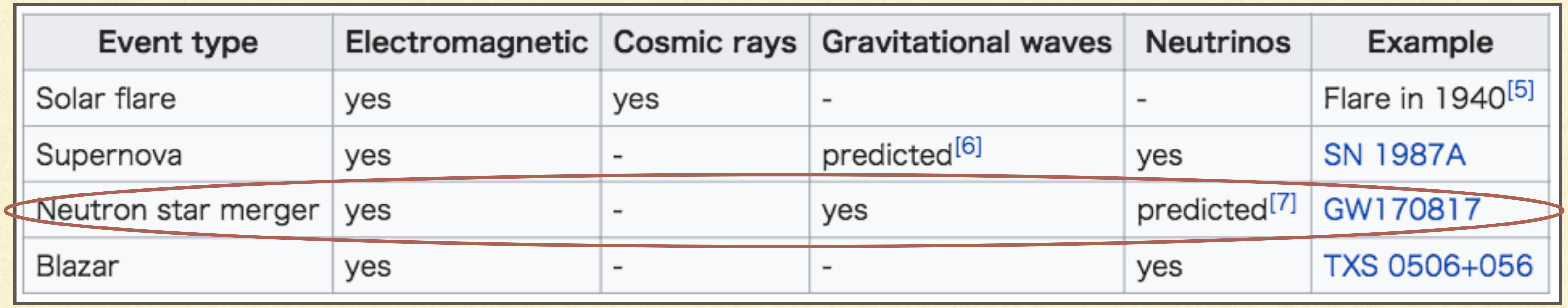


[LIGO, 1805.11581]

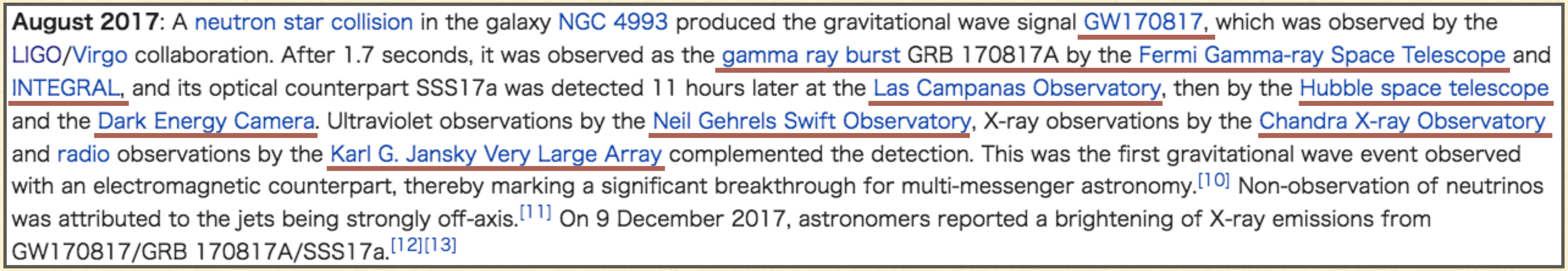
MULTI-MESSENGER ASTRONOMY

- Era of multi-messenger astronomy: EM, CR, GWs, Neutrinos

[Wikipedia]



Event type	Electromagnetic	Cosmic rays	Gravitational waves	Neutrinos	Example
Solar flare	yes	yes	-	-	Flare in 1940[5]
Supernova	yes	-	predicted[6]	yes	SN 1987A
Neutron star merger	yes	-	yes	predicted[7]	GW170817
Blazar	yes	-	-	yes	TXS 0506+056



August 2017: A neutron star collision in the galaxy NGC 4993 produced the gravitational wave signal GW170817, which was observed by the LIGO/Virgo collaboration. After 1.7 seconds, it was observed as the gamma ray burst GRB 170817A by the Fermi Gamma-ray Space Telescope and INTEGRAL, and its optical counterpart SSS17a was detected 11 hours later at the Las Campanas Observatory, then by the Hubble space telescope and the Dark Energy Camera. Ultraviolet observations by the Neil Gehrels Swift Observatory, X-ray observations by the Chandra X-ray Observatory and radio observations by the Karl G. Jansky Very Large Array complemented the detection. This was the first gravitational wave event observed with an electromagnetic counterpart, thereby marking a significant breakthrough for multi-messenger astronomy.[10] Non-observation of neutrinos was attributed to the jets being strongly off-axis.[11] On 9 December 2017, astronomers reported a brightening of X-ray emissions from GW170817/GRB 170817A/SSS17a.[12][13]

STANDARD "SIREN"

Skipped due to time constraint

Please google it m(_ _)m

ASTROPHYSICAL GWS: SUMMARY

- GW detection opens up a new era of GW astronomy:

  - New population of black holes

  - Neutron star equation of state

  - Multi-messenger astronomy

  - Standard "siren" ...

Introduction

- What's gravitational waves?
- Some history

astrophysical GWs

- New probe to the Universe

(focussing on recent aLIGO)

cosmological GWs

- What's interesting?
- "Standard" cosmic history
- Various sources

My own work

Summary

COSMOLOGICAL GWS: SUMMARY

- Early Universe = High energy physics

- GWs are good probe to the early Universe

  because of their suppressed interaction with other particles

- GWs with different frequencies have information on different energy scales:

  Frequency-Energy scale correspondence

EARLY UNIVERSE & HIGH-ENERGY PHYSICS

- Observed / strongly suggested "Beyond the Standard Model" in particle physics

- Baryon asymmetry
- Dark energy
- Dark matter
- Grand unification
- Hierarchy problem
- Inflation
- Neutrino mass
- Strong CP

...

...alphabetical order,
to avoid religious conflict

EARLY UNIVERSE & HIGH-ENERGY PHYSICS

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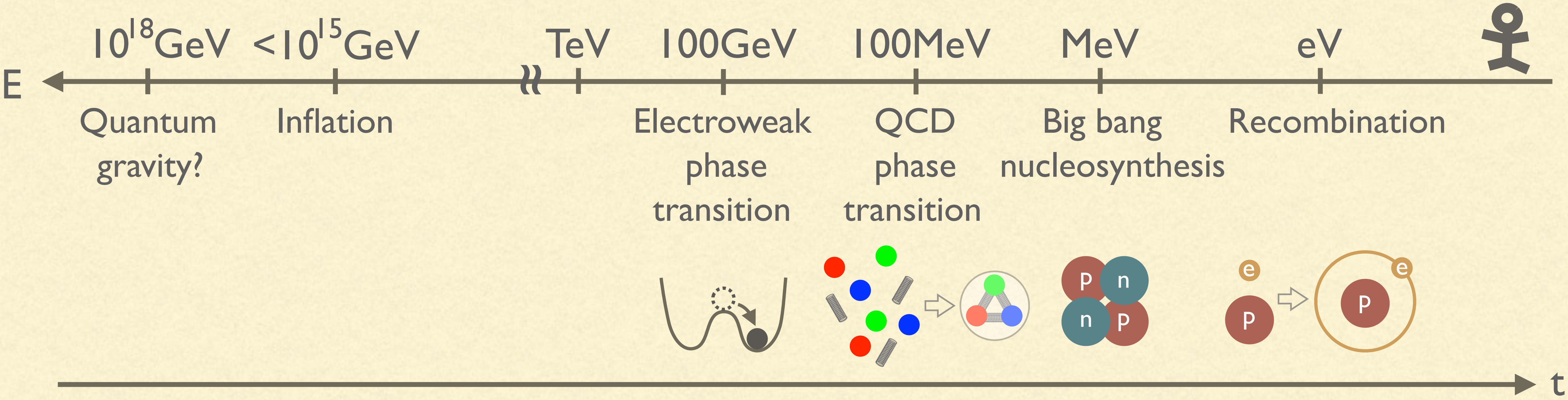

E

10^{18}GeV Quantum gravity?

$<10^{15}$GeV Inflation

TeV

100GeV Electroweak phase transition

100MeV QCD phase transition

MeV Big bang nucleosynthesis

eV Recombination

t

EARLY UNIVERSE & HIGH-ENERGY PHYSICS

- Observed / strongly suggested "Beyond the Standard Model" in particle physics

...alphabetical order, to avoid religious conflict

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- Dark energy	- Inflation
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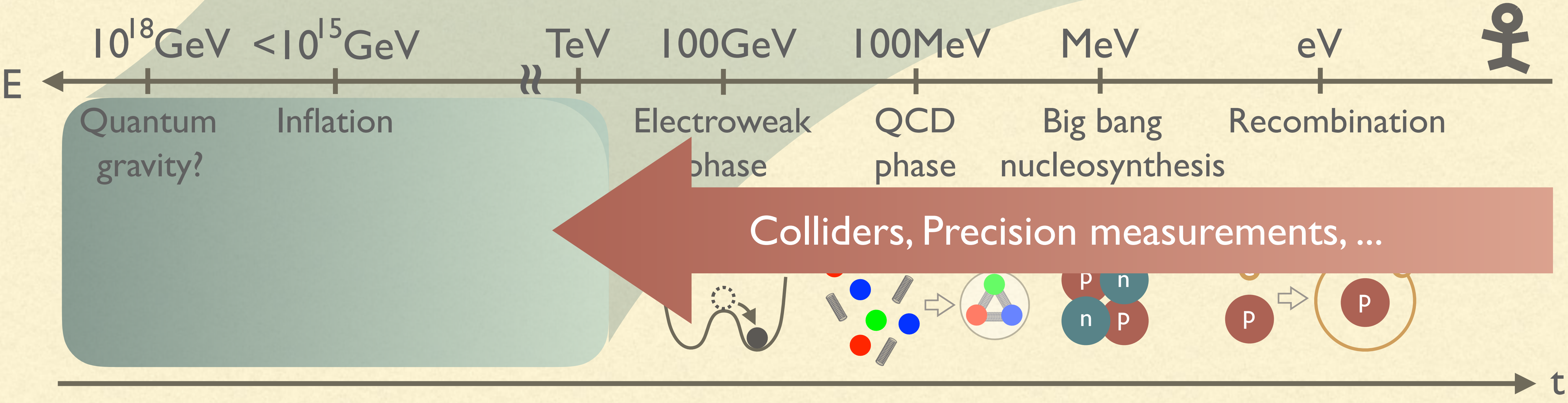


Colliders, Precision measurements, ...

EARLY UNIVERSE
& HIGH-ENERGY PHYSICS

- Early Universe = High energy thermal plasma

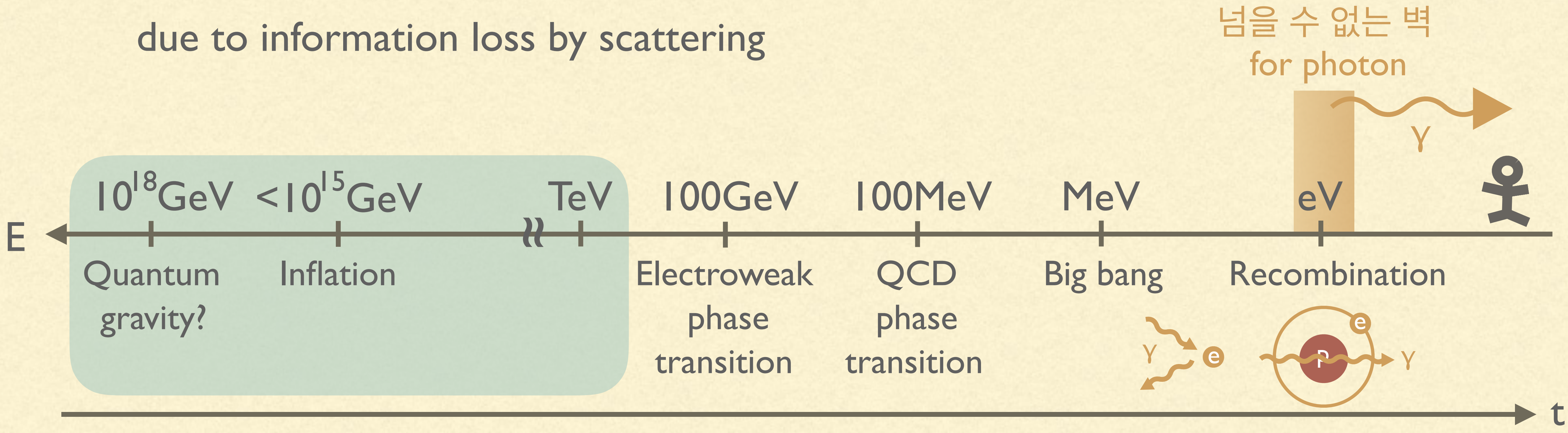
  → Cosmic relics are clues to unknown high-energy physics

- The most well-known relic is CMB (cosmic microwave background)

  → However, CMB basically probes only up to O(eV) causal Universe

  due to information loss by scattering

[Note: inflationary physics
by CMB is exceptional,
due to over-horizon
conservation of ζ]



넘을 수 없는 벽
for photon

E

10^{18}GeV — Quantum gravity?

$<10^{15}$GeV — Inflation

TeV

100GeV — Electroweak phase transition

100MeV — QCD phase transition

MeV — Big bang

eV — Recombination

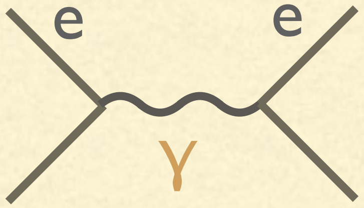
t

EARLY UNIVERSE & HIGH-ENERGY PHYSICS

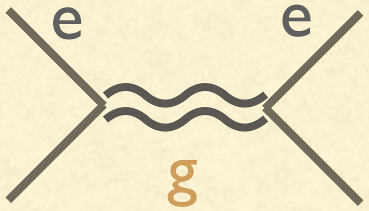
- Gravitational waves

  - All possible interactions suppressed by $M_P \equiv 1/\sqrt{8\pi G} \sim 10^{18}\ \text{GeV}$:

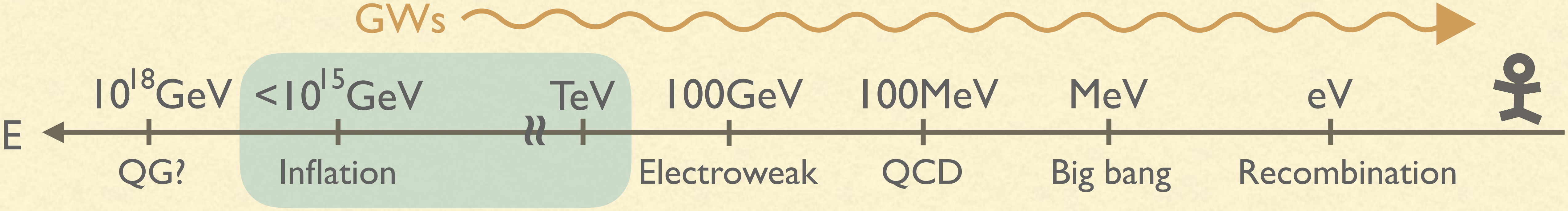
    EM interaction between electrons: $F \sim \dfrac{\alpha}{r^2} \sim \dfrac{1/137}{r^2}$



    Gravitational interaction between electrons: $F \sim \dfrac{Gm_e^2}{r^2} \sim \dfrac{10^{-42}}{r^2}$



  - As a result, GWs propagate until present ***without being scattered,*** if produced



GWs

E

10^{18}GeV QG?

$<10^{15}$GeV Inflation

TeV

100GeV Electroweak

100MeV QCD

MeV Big bang

eV Recombination

FREQUENCY-ENERGY CORRESPONDENCE

- Hubble horizon?

- Hubble parameter $H \equiv \frac{\dot{a}}{a}$ ← Remember $ds^2 = -dt^2 + a^2(t)dx^i dx^i$

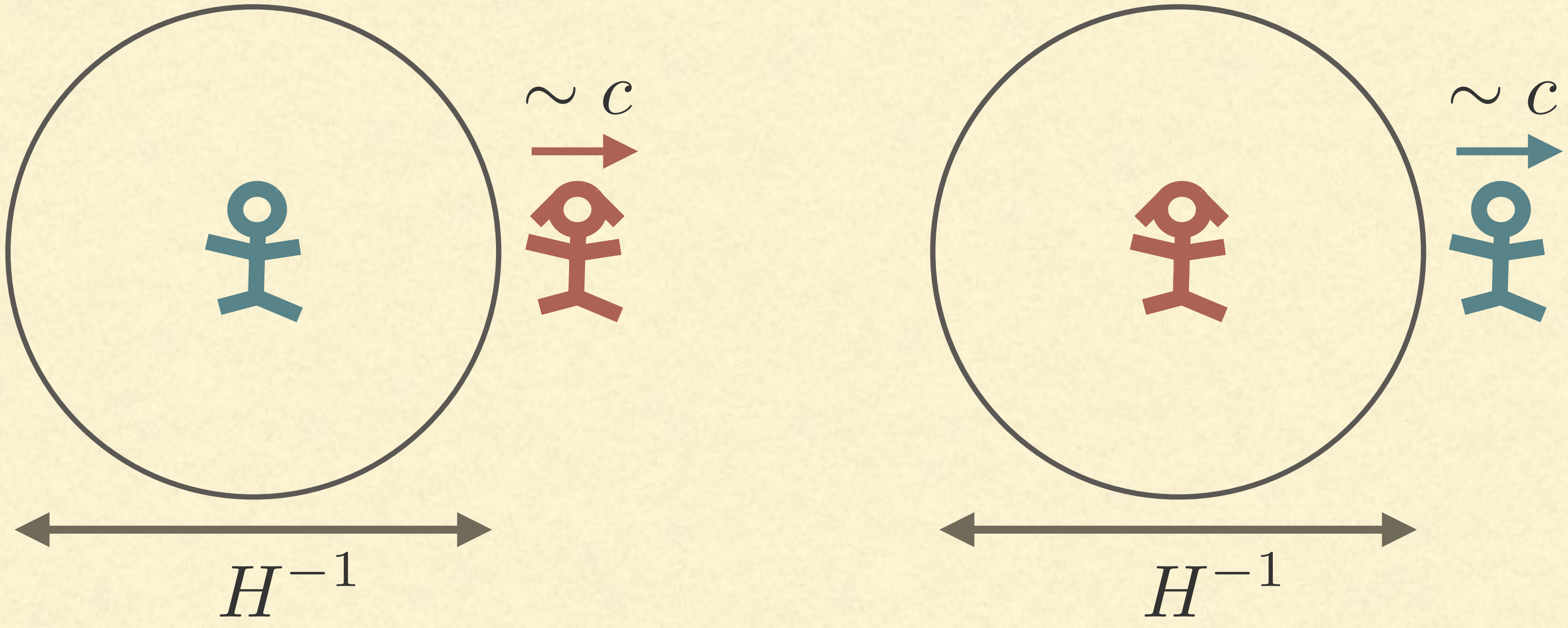
"scale factor"

~ size of the Universe

- Inverse Hubble parameter H^{-1} determines

typical size of causally accessible region at that time

- Why?



FREQUENCY-ENERGY CORRESPONDENCE

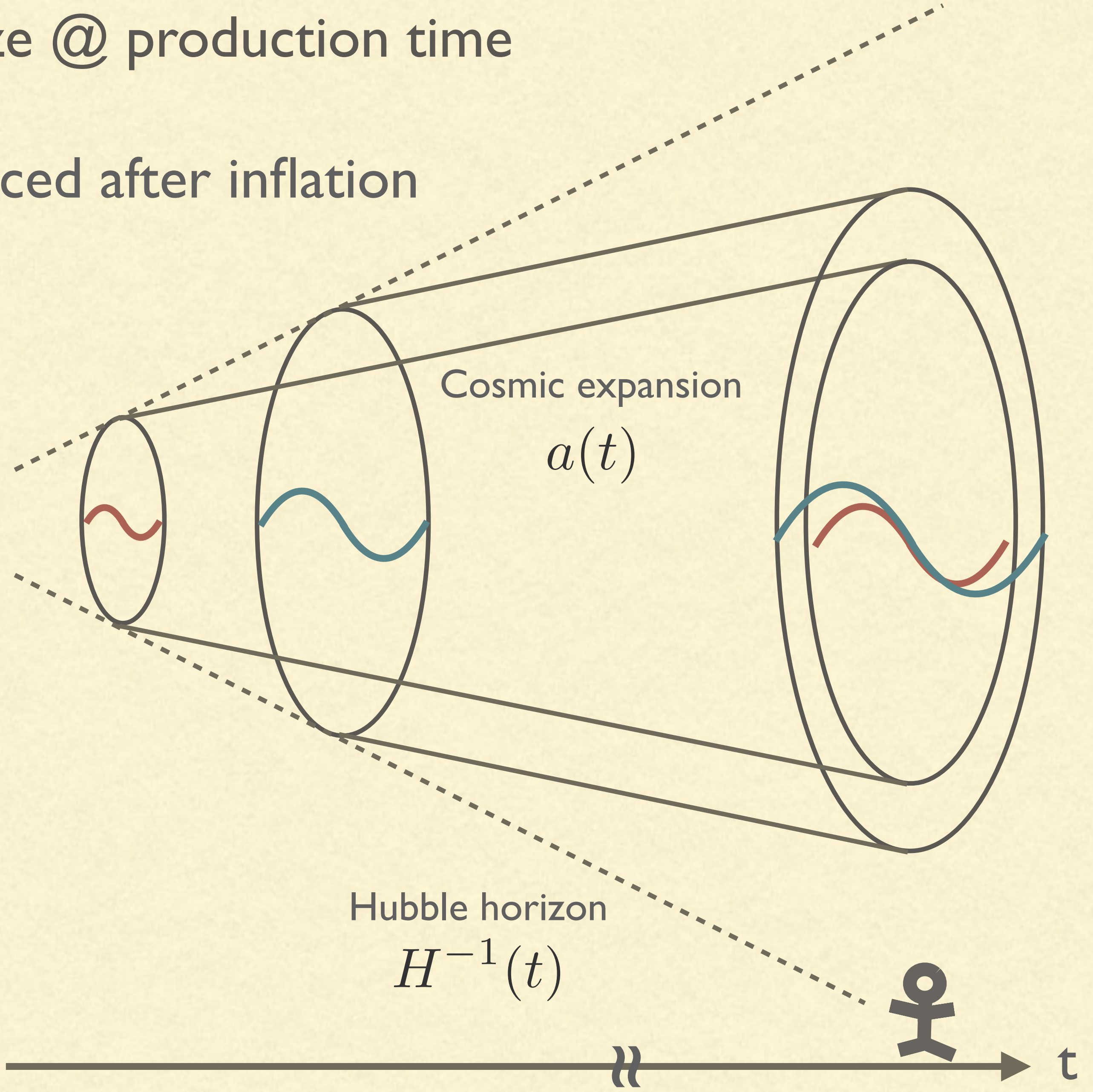
- GW present frequency vs. Horizon size @ production time

  - Suppose horizon-size GWs are produced after inflation

  - GWs are stretched in proportion to $a(t)$ (redshift)

  - Hubble horizon expand faster than $a(t)$

  - As a result, GWs produced earlier has shorter wavelength (higher freq.)



FREQUENCY-ENERGY CORRESPONDENCE

- GW present frequency vs. Energy scale of the Universe @ production time

  - Energy of the Universe is higher at earlier times

  - As a result : GW present frequency ⇆ Energy scale of the Universe @ prod.

$$\boxed{f_0 \sim 1 \text{ Hz} \times \left(\frac{T}{10^7 \text{ GeV}} \right)}$$

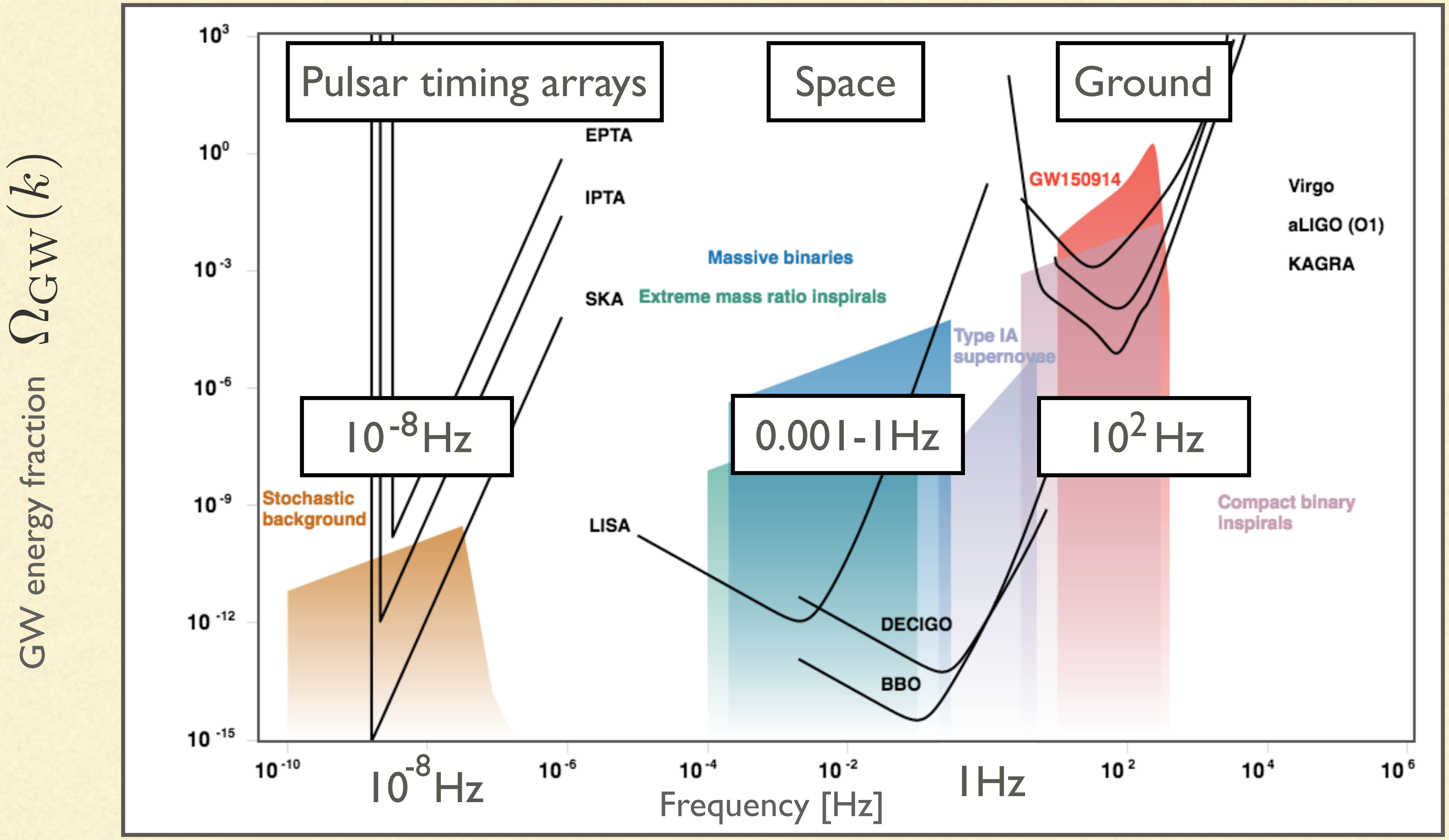
  - If sub-horizon GWs are produced, they shift toward higher frequency accordingly:

$$\boxed{f_0 \sim 1 \text{ Hz} \times \frac{1}{R} \times \left(\frac{T}{10^7 \text{ GeV}} \right)}$$

R : (GW wavelength) / (Horizon size) @ prod.

VARIOUS GW EXPERIMENTS

[http://rhcole.com/apps/GWplotter/]



100 MeV

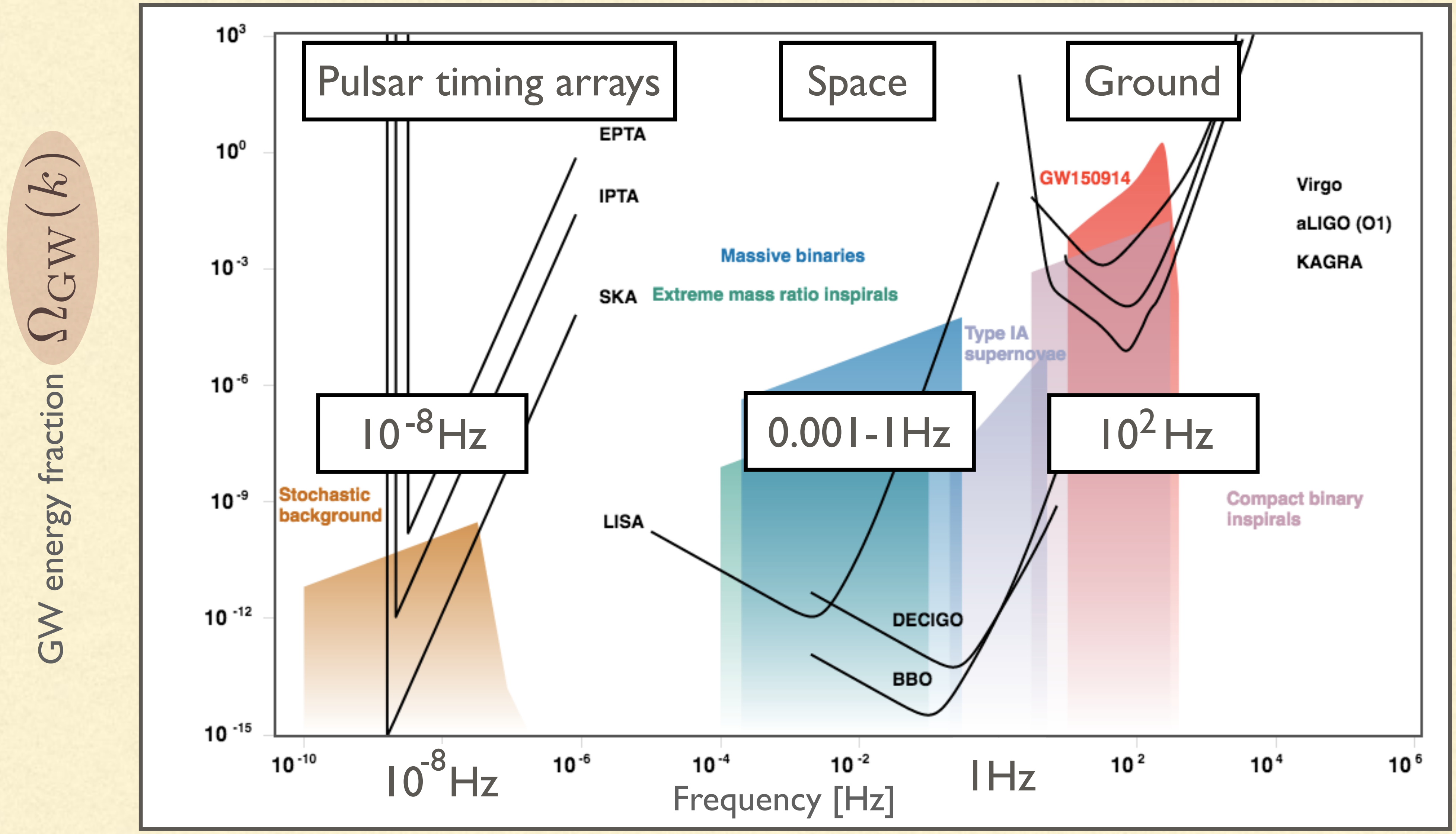
10^7GeV

→ T

If produced
with horizon size

VARIOUS GW EXPERIMENTS

[http://rhcole.com/apps/GWplotter/]



100 MeV

10^7 GeV

T

If produced
with horizon size

ENERGY DENSITY OF GWS

- Energy density of GWs

  - Quadratic action of GWs

FRW background

Up to quadratic

$$S_{\text{grav}} = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R\right] \overset{\downarrow}{\simeq} \frac{M_P^2}{4}\int d^4x\ a^3\left[\frac{1}{2}(\dot{h}_{ij})^2 - \frac{1}{2}(\partial_k h_{ij})^2\right]$$

  - Looks similar to canonical scalar field, if we identify $(M_P/2)h_{ij}$ as canonical field

  - Energy density $\rho_{\text{GW}} = \frac{M_P^2}{4}\left[\frac{1}{2}(\dot{h}_{ij})^2 + \frac{1}{2}(\partial_k h_{ij})^2\right]$

Abuse of notation

$\Omega_{\text{GW}}(t,k)$

- Energy density of GWs compare to the total energy density

$$\boxed{\Omega_{\text{GW}}(t) \equiv \frac{\rho_{\text{GW}}(t)}{\rho_{\text{tot}}(t)} \underset{\text{various ln k contributions}}{\overset{\text{Decomposition into}}{=}} \int d\ln k\ \frac{d\Omega_{\text{GW}}(t,k)}{d\ln k}}$$

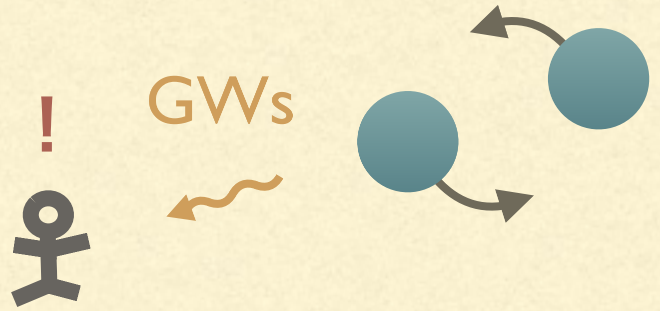
POINT SOURCE VS. STOCHASTIC

- Main difference between astrophysical & cosmological GWs

Astrophysical GWs : point-source

- Event-by-event

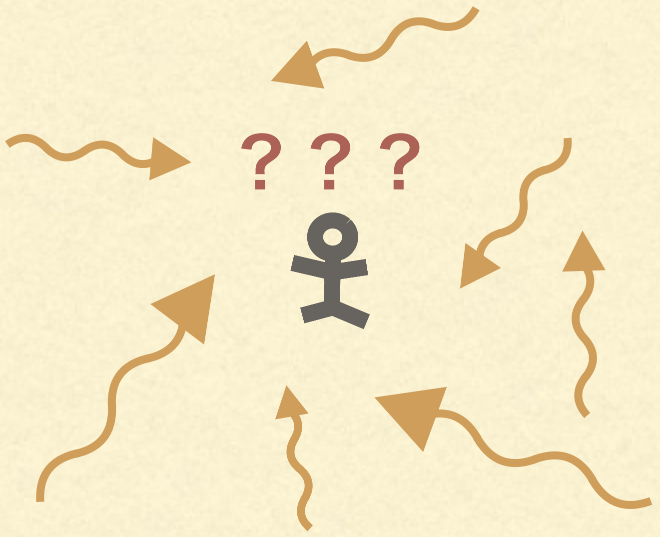
- Definite direction & frequency



Cosmological GWs : stochastic

- Cannot identify "event"

- Various directions & frequencies mixed up



VARIOUS GW EXPERIMENTS

- Pulsar timing array

  - Millisecond pulsar : pulsar with rotational period 1-10 milliseconds

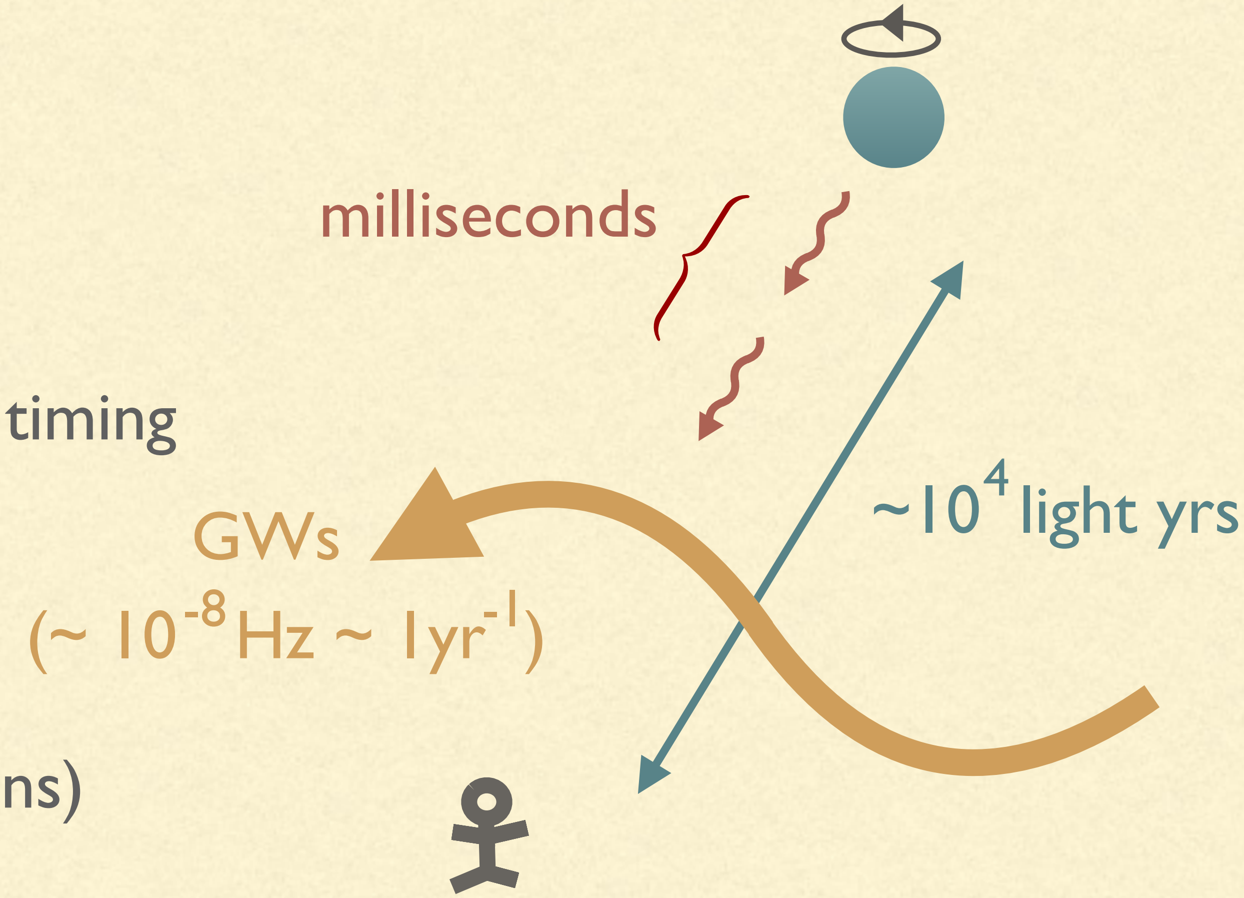
    (presumably, old & rapidly rotating NS)

  - If GWs ~ 10^{-8} Hz pass through,

    they cause modurations in pulse arrival timing

    with a period of O(months)

  - Pulse arrival timing measurable with O(ns)



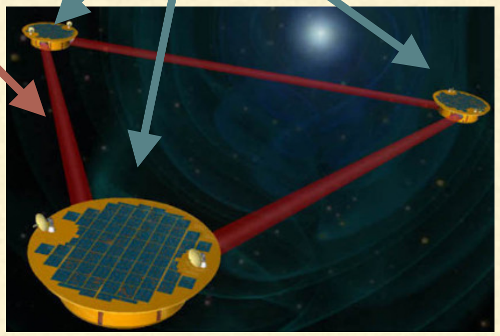
VARIOUS GW EXPERIMENTS

- Space interferometer

  - Interferometers launched in space

    e.g. LISA = Laser Interferometer Space Antenna (ESA & NASA)

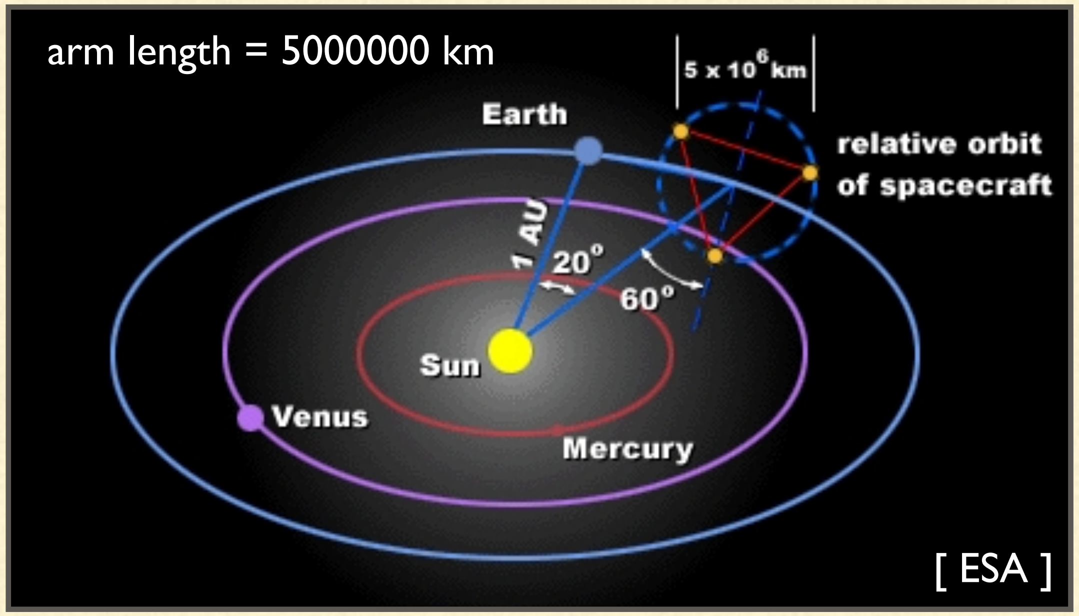
    Launch scheduled in 2034



    e.g. DECIGO = DECiherz Interferometer Gravitational wave Observatory (Japan)

    e.g. Taiji, TianQin (China)

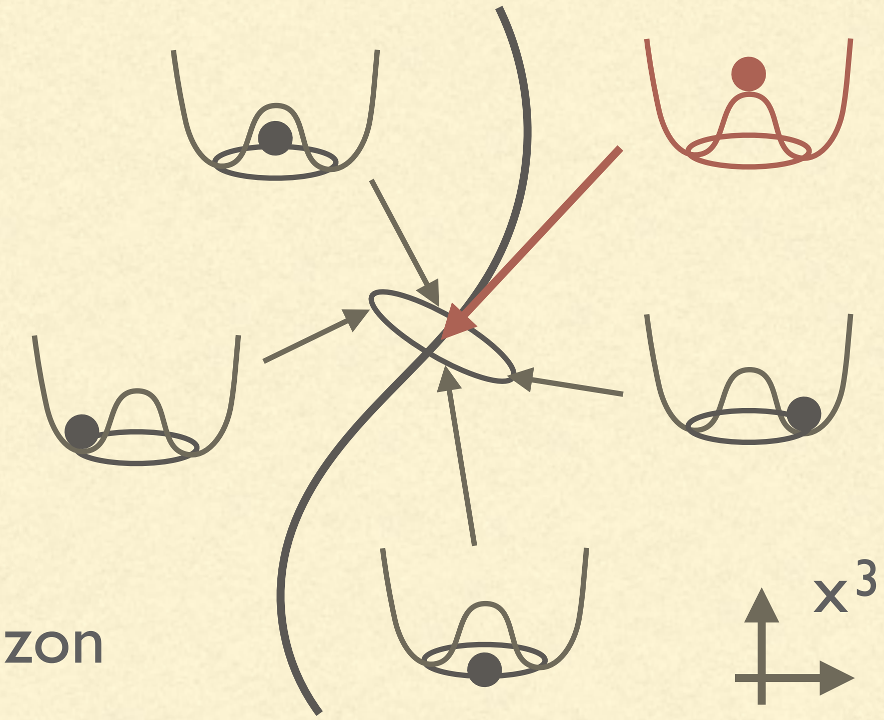
  - "Arm" length corresponds to observable GW frequency



[ESA]

COSMOLOGICAL GW SOURCES

- Cosmic string



- Remnant of U(1) symmetry breaking

- Known to follow scaling law :

After production, O(1) strings per one Hubble horizon

at any time in radiation-dominated Universe

- Cusps and loops continuously emit GWs

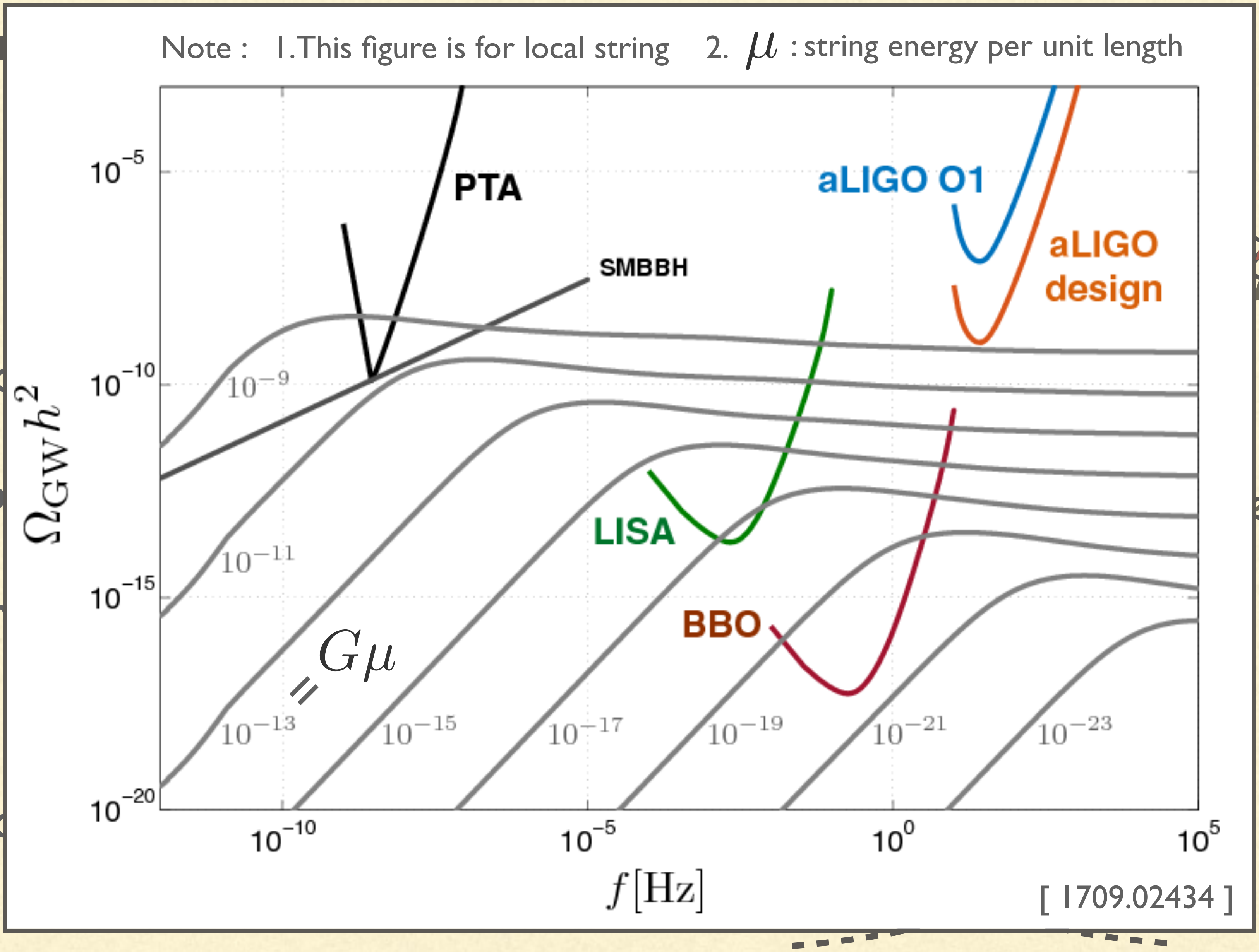
COSMOLOGICAL GW SOURCES

- Cosmic st
  - Remnant
  - Known t

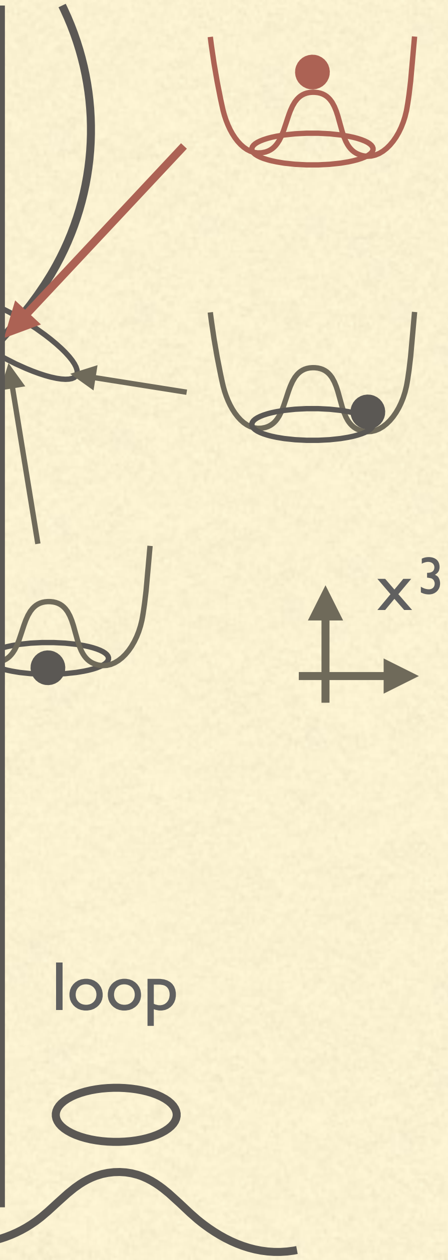
    After pro

    at any tim
  - Cusps and

Note : 1.This figure is for local string 2. μ : string energy per unit length



[1709.02434]



COSMOLOGICAL GW SOURCES

- Cosmi

- Remn

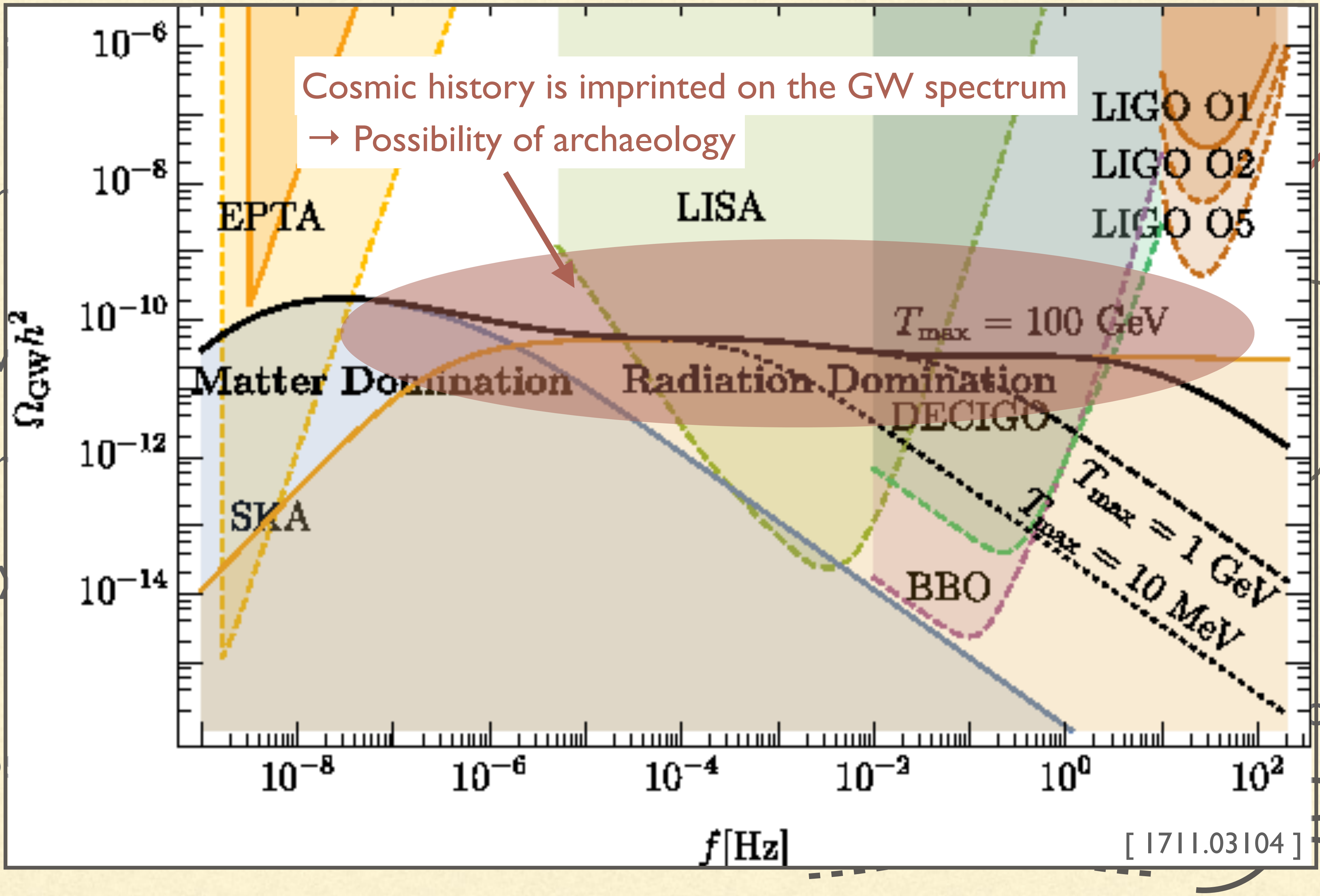
- Know

After

at any

op

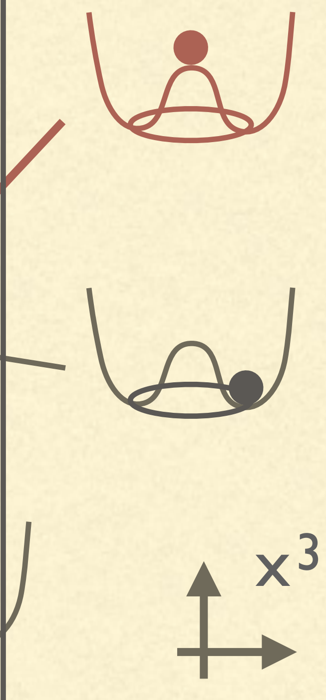
- Cusp



Cosmic history is imprinted on the GW spectrum

→ Possibility of archaeology

[1711.03104]



COSMOLOGICAL GW SOURCES

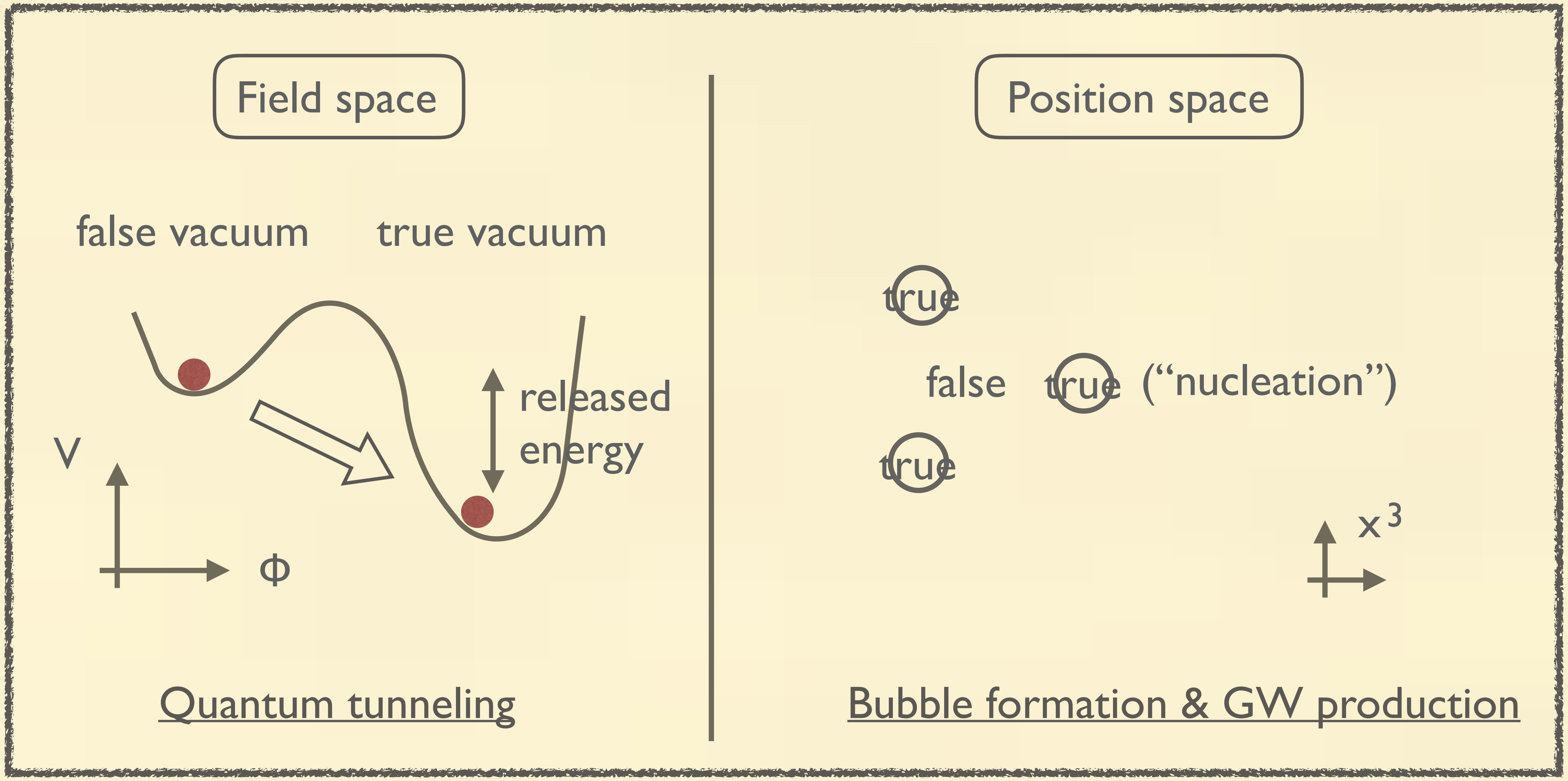
- First-order phase transition

  - In some particle physics models (including extensions of EW sector), quantum tunneling of scalar field occurs in the history of the Universe

  - The transition proceeds with bubble formation and expansion

COSMOLOGICAL GW SOURCES

- First-order phase transition



Field space

false vacuum

true vacuum

released energy

V

ϕ

Quantum tunneling

Position space

true

false

true ("nucleation")

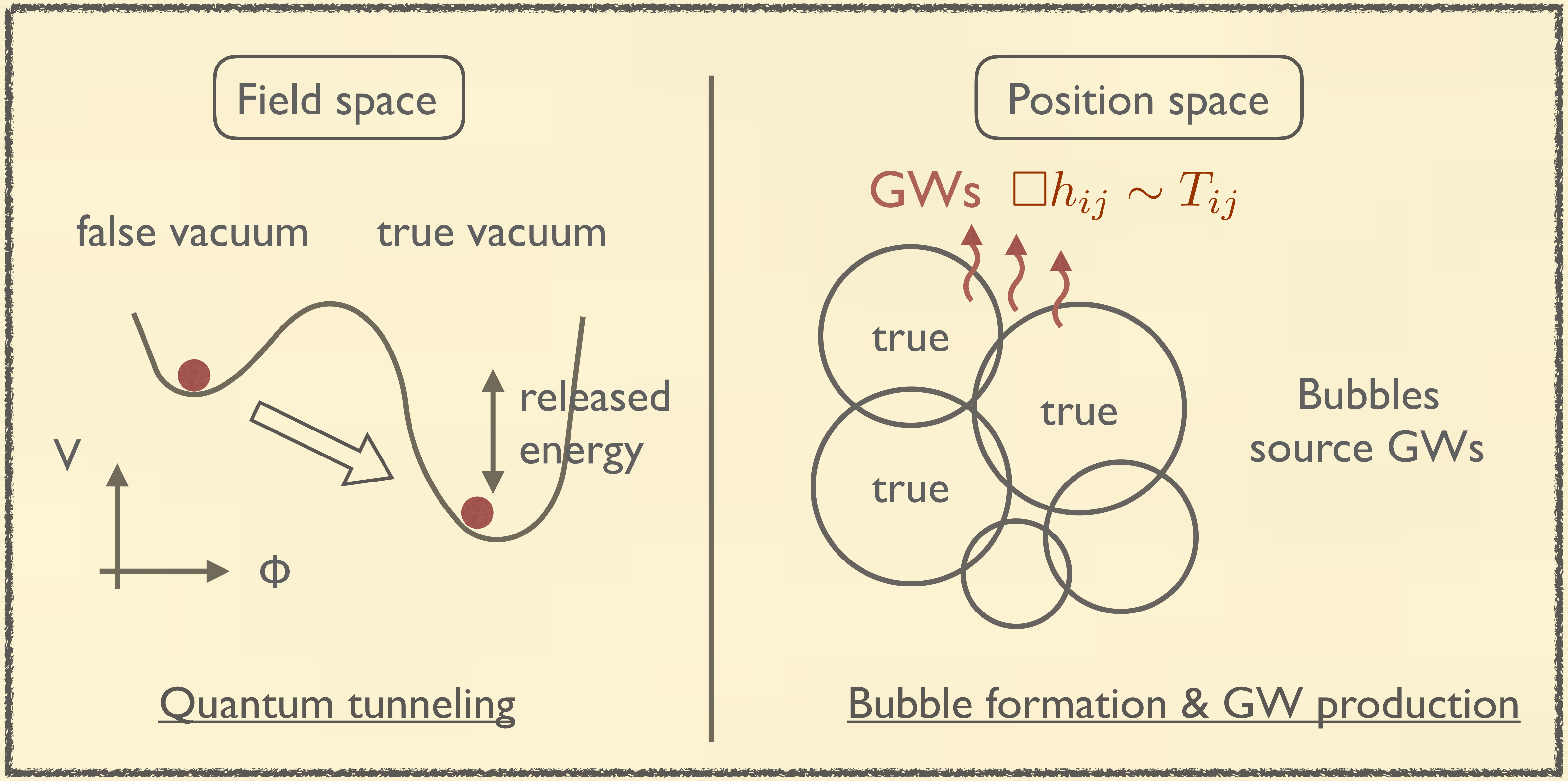
true

x^3

Bubble formation & GW production

COSMOLOGICAL GW SOURCES

- First-order phase transition



Field space

false vacuum

true vacuum

released energy

V

Φ

Quantum tunneling

Position space

GWs $\Box h_{ij} \sim T_{ij}$

true

true

true

Bubbles source GWs

Bubble formation & GW production

COSMOLOGICAL GW SOURCES

- First-order phase transition

  - In some particle physics models (including extensions of EW sector), quantum tunneling of scalar field occurs in the history of the Universe

  - The transition proceeds with bubble formation and expansion

  - GWs are produced by the scalar field bubbles and surrounding plasma bulk motion

  - GW frequency roughly corresponds to the bubble size, which is typically 1/100 ~ 1/1000 of the Hubble horizon

    → EW scale transition corresponds to sub-1 Hz

COSMOLOGICAL GW SOURCES

- First-ord

  - In some

  quantum e

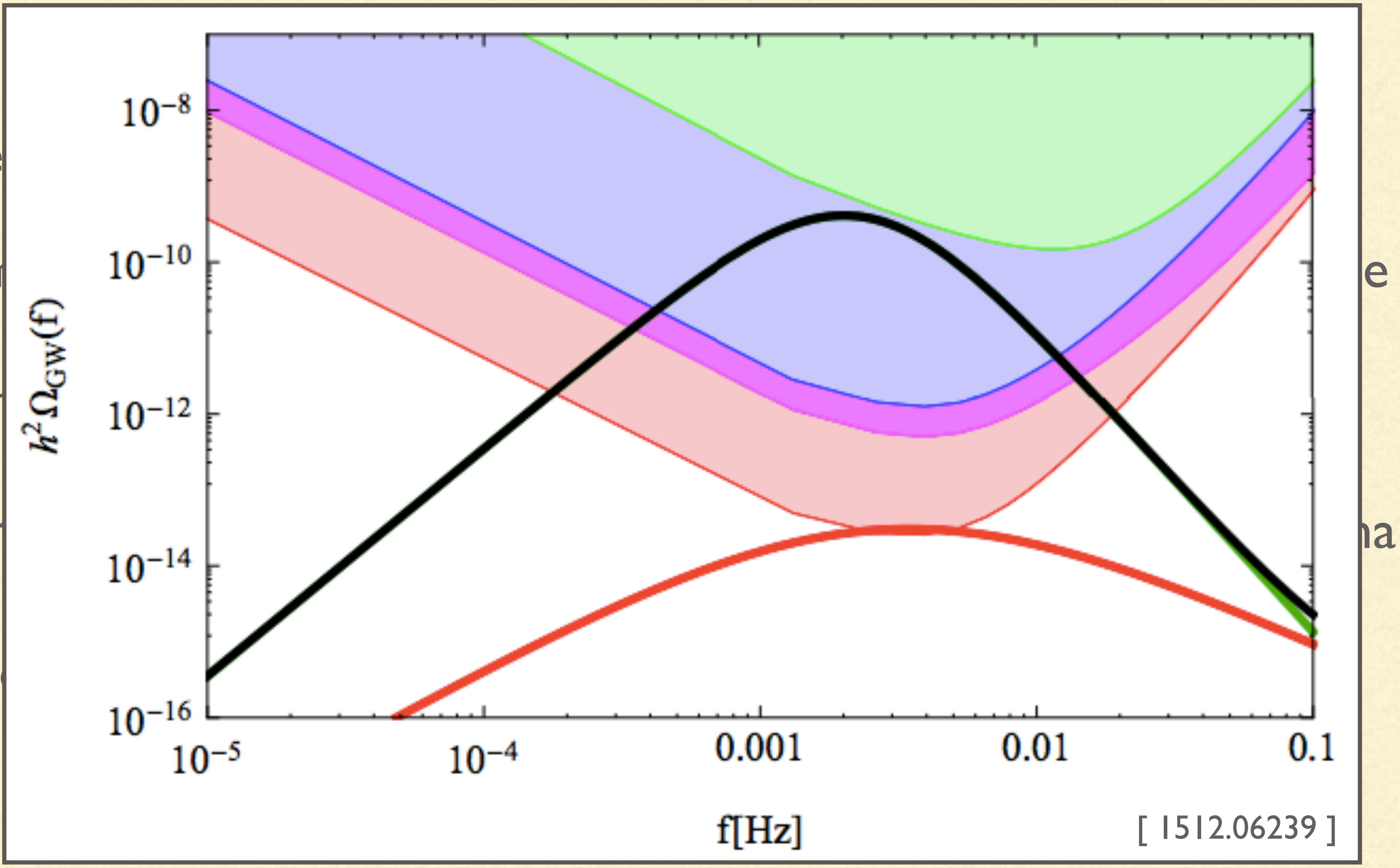
  - The tra

  - GWs a a bulk motion

  - GW fre

  which i

  → EW scale transition corresponds to sub-1 Hz



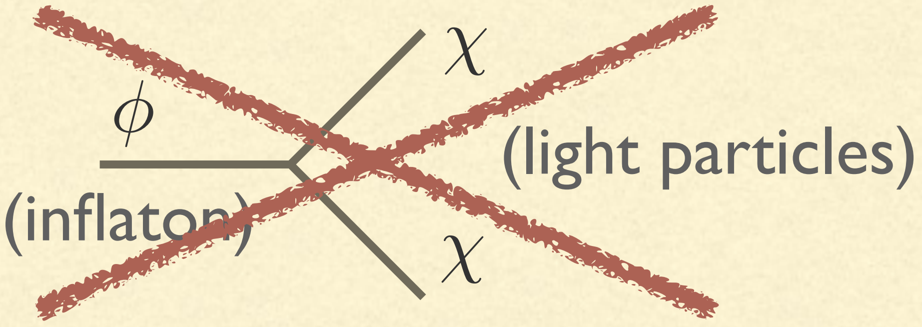
[1512.06239]

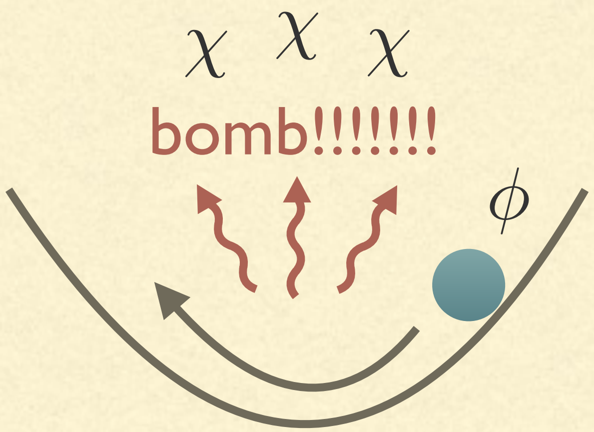
COSMOLOGICAL GW SOURCES

- Preheating = dynamics before reheating

- At the end of inflation (= accelerated expansion of the Universe at very early stage), inflaton (= scalar field which drives inflation) decays into light particles, and light particles eventually thermalize (= reheating)

- This decay process is explosive : not like perturbative decay





- This explosive dynamics produces GWs typically at high frequencies

COSMOLOGICAL GW SOURCES

- Inflation

  - Accelerated expansion of the Universe at very early stage, driven by some scalar field (called inflaton)

  - Not only solves notorious horizon & flatness problems, but also produces late-time seeds of galaxies → consistent with observations

  - People expect that the same mechanism as this seed generation also produces GWs (called "primordial GWs")

COSMOLOGICAL GW SOURCES

- Inflation

  - Acceler

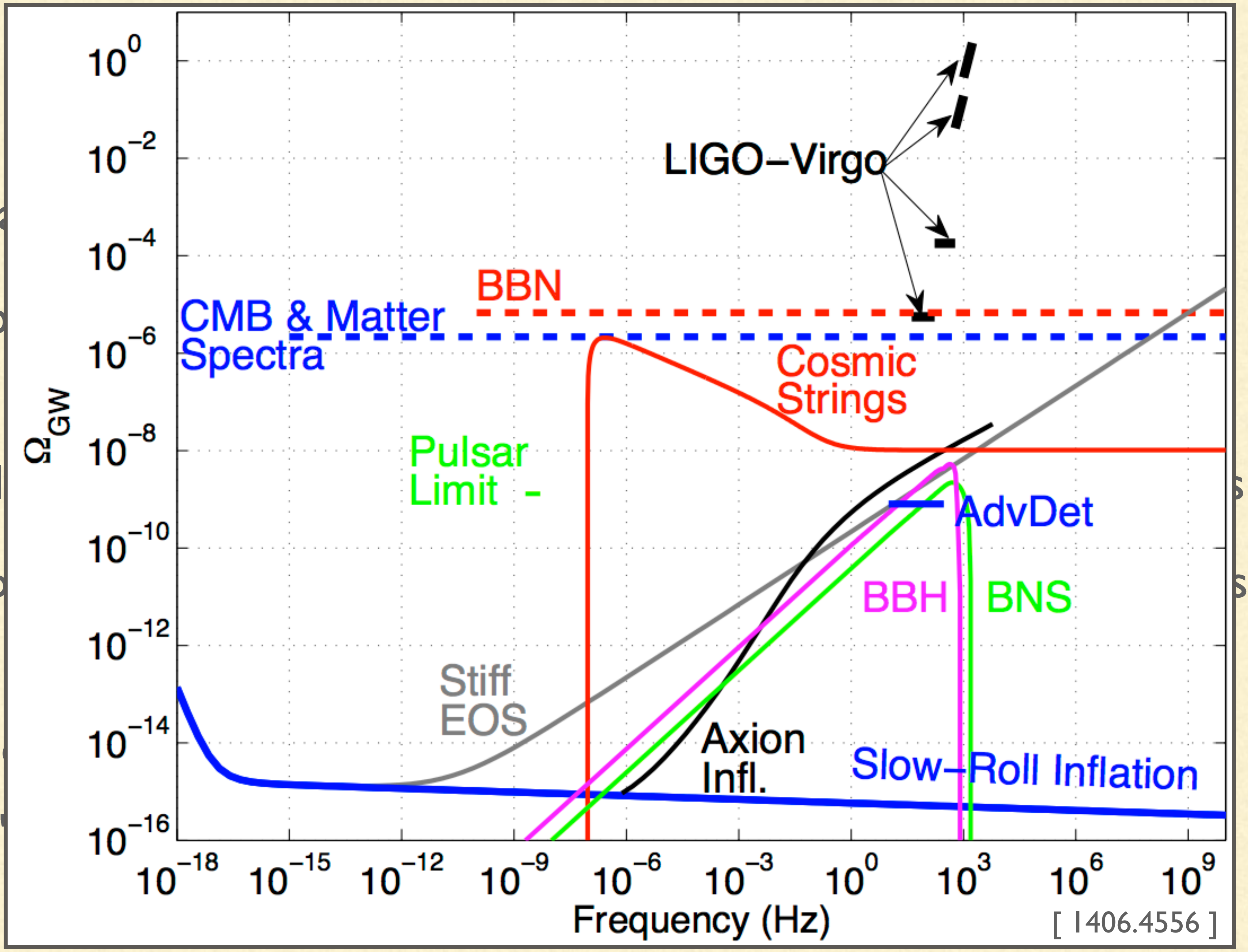
    driven b

  - Not onl sistent with

    but also servations

  - People produces GWs

    (called '



[1406.4556]

SUMMARY

- In General Relativity, there are degrees of freedom

  propagating with speed of light : Gravitational Waves

- Detection of GWs opened up new era of **GW astronomy**

- **GW cosmology** may play a key role to explore

  unknown high-energy physics

Back up

COSMOLOGICAL GW SOURCES

- Cosmological GW production : Rules of thumb

Integration over

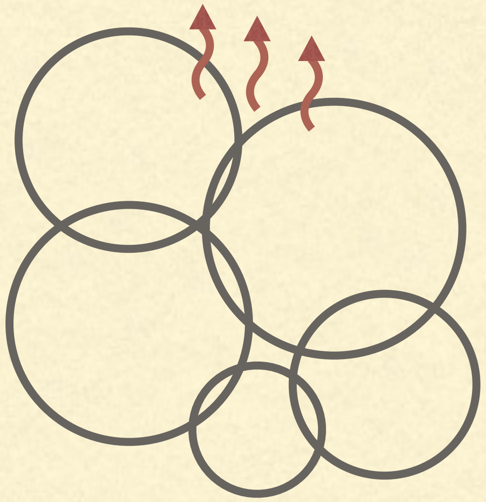
Source duration time

$$\Box h \sim GT \quad \rightarrow \quad \dot{h} \sim GT\Delta t$$

$$\rho_{\rm GW} \sim M_P^2 \dot{h}^2 \sim \frac{T^2}{M_P^2} \Delta t^2$$

Cosmological 1st-order phase transition

GWs $\Box h_{ij} \sim T_{ij}$



bubbles expanding with $\sim c$

→ momentum

- T means T_{ij} : Energy density only does not produce GWs.

  We need (quadrupole of) momentum.

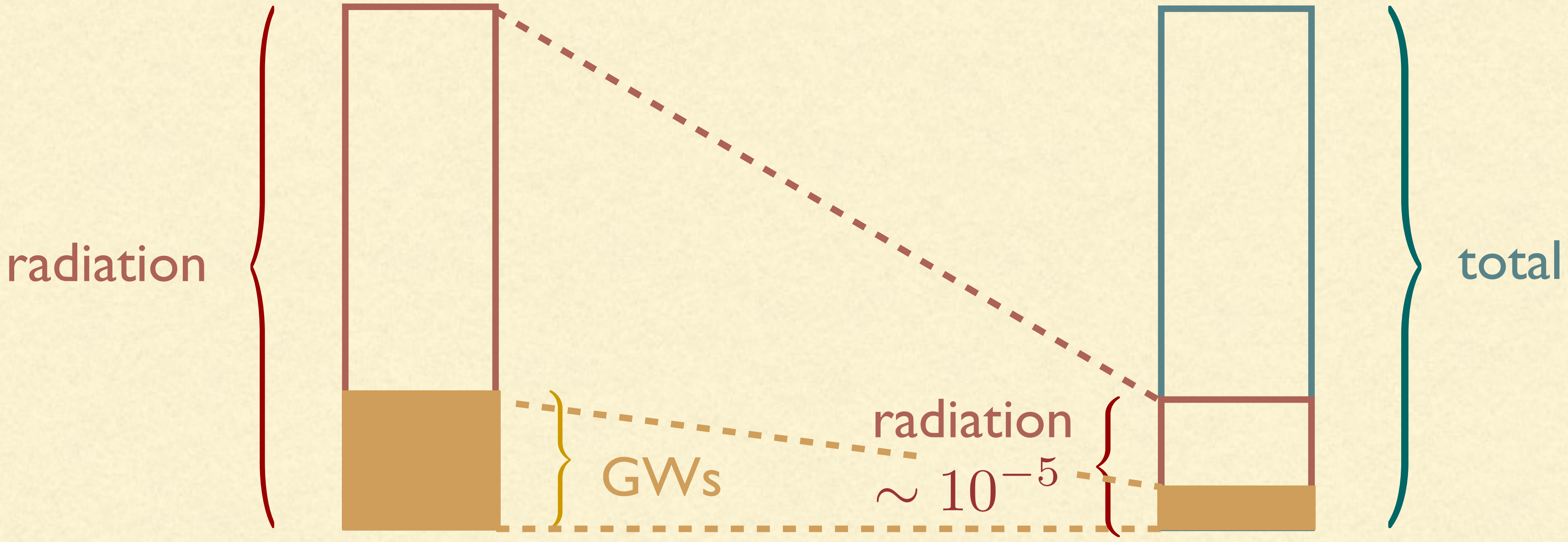
- Long-lasting souces are favored for GW production

Note: 1. This does not apply to inflationary GWs! 2. This applies only to $\Delta t \lesssim$ typical length scale of the source

COSMOLOGICAL GW SOURCES

- Cosmological GW evolution

- Roughly : Just redshifted as radiation component Note: except for g_*



Production time

(Radiation-dominated assumed)

Present