Cosmological implications of gravitational waves

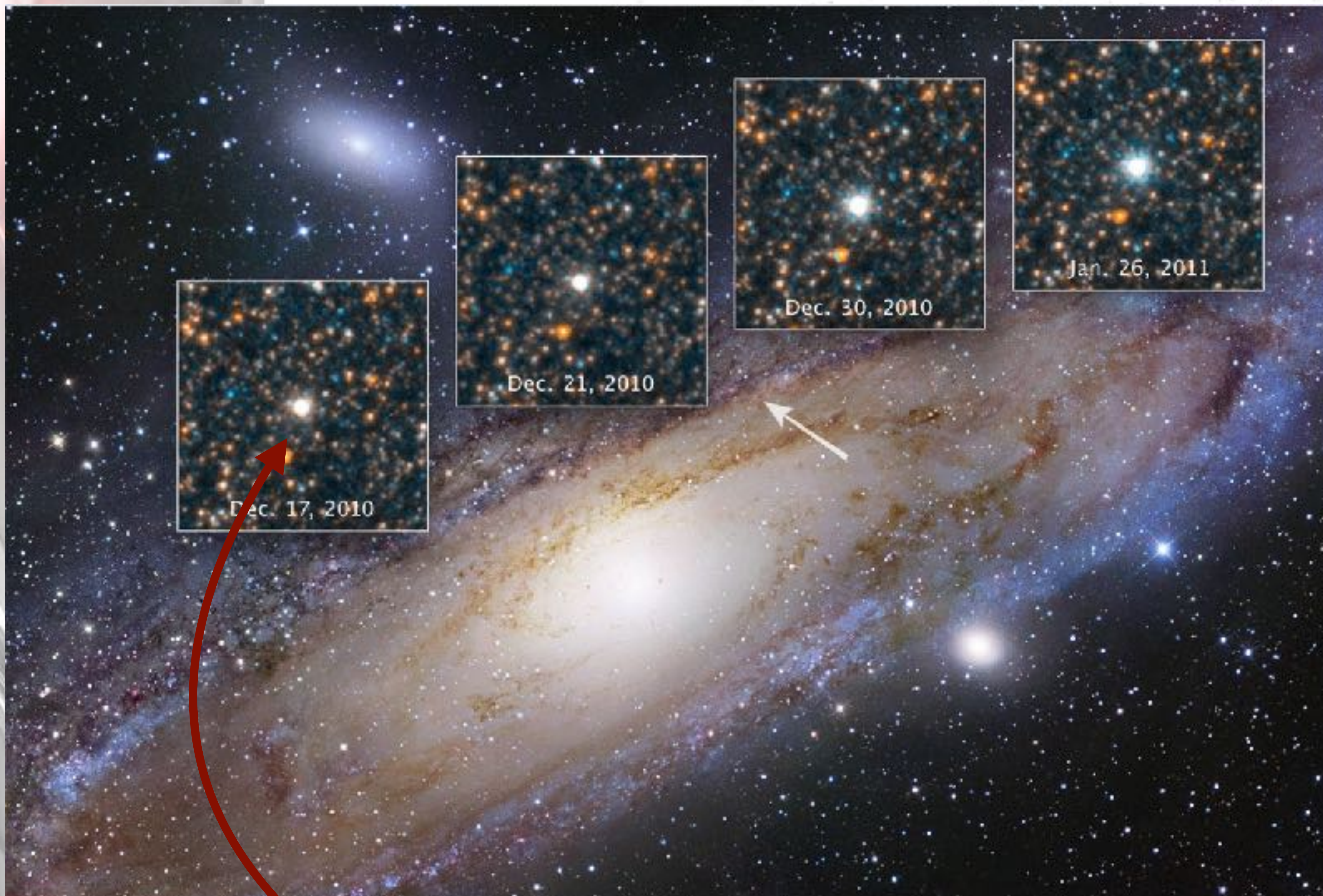
Lavinia Heisenberg
(ETH-ITP)
Institute for Theoretical Physics, Zürich
Lavinia.Heisenberg@phys.ethz.ch

July 22nd 2021, MPIK Colloquium, Heidelberg

The Universe until 1923

The Universe until 1923

The Universe until 1923



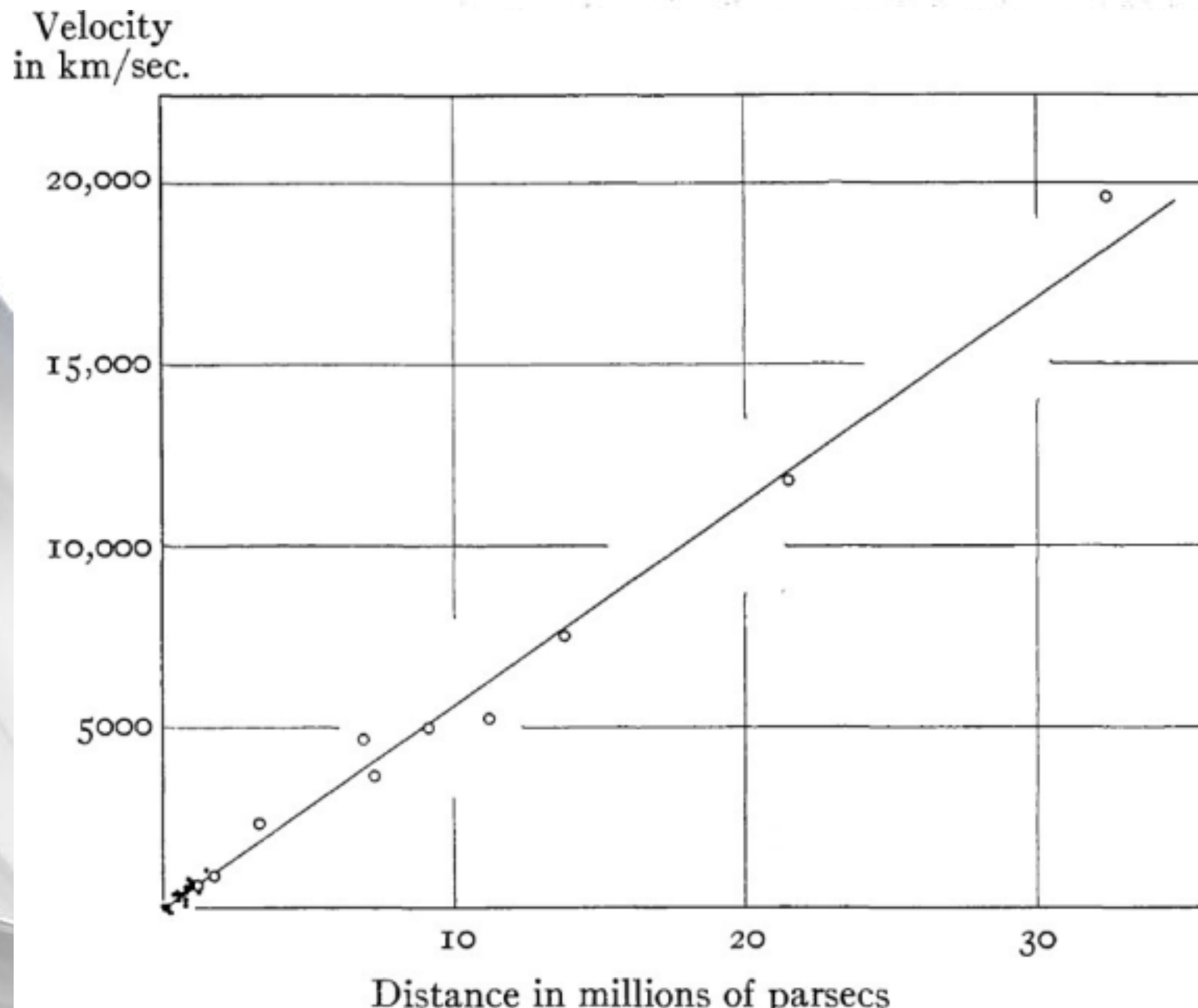
Cepheids

The Universe until 1923

2.2 Mio light-year (~ 10^{12} km)

200 x larger than the diameter of MW

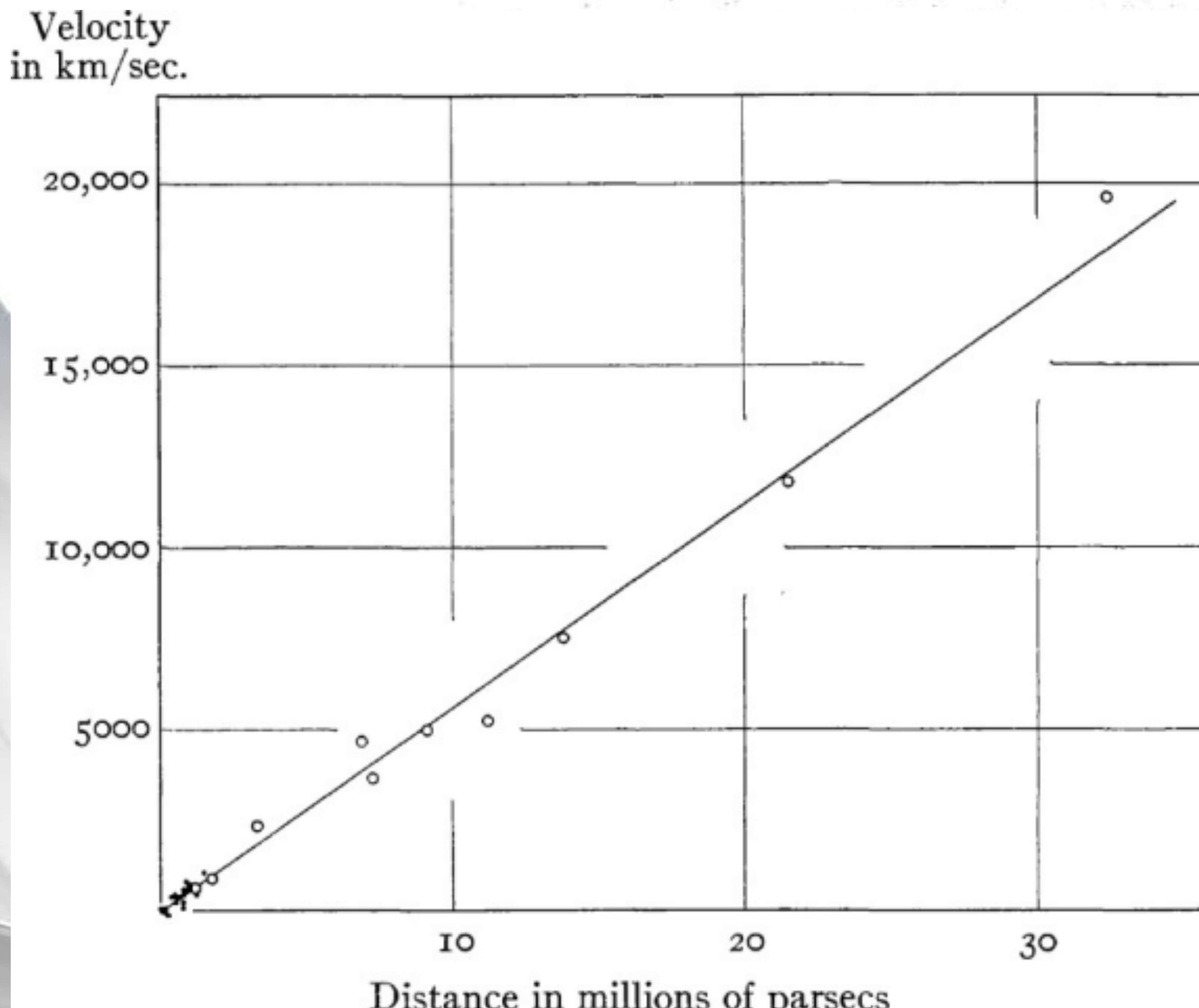
The Universe until 1931



Hubble's law

$$v = H_0 D$$

The Universe until 1931

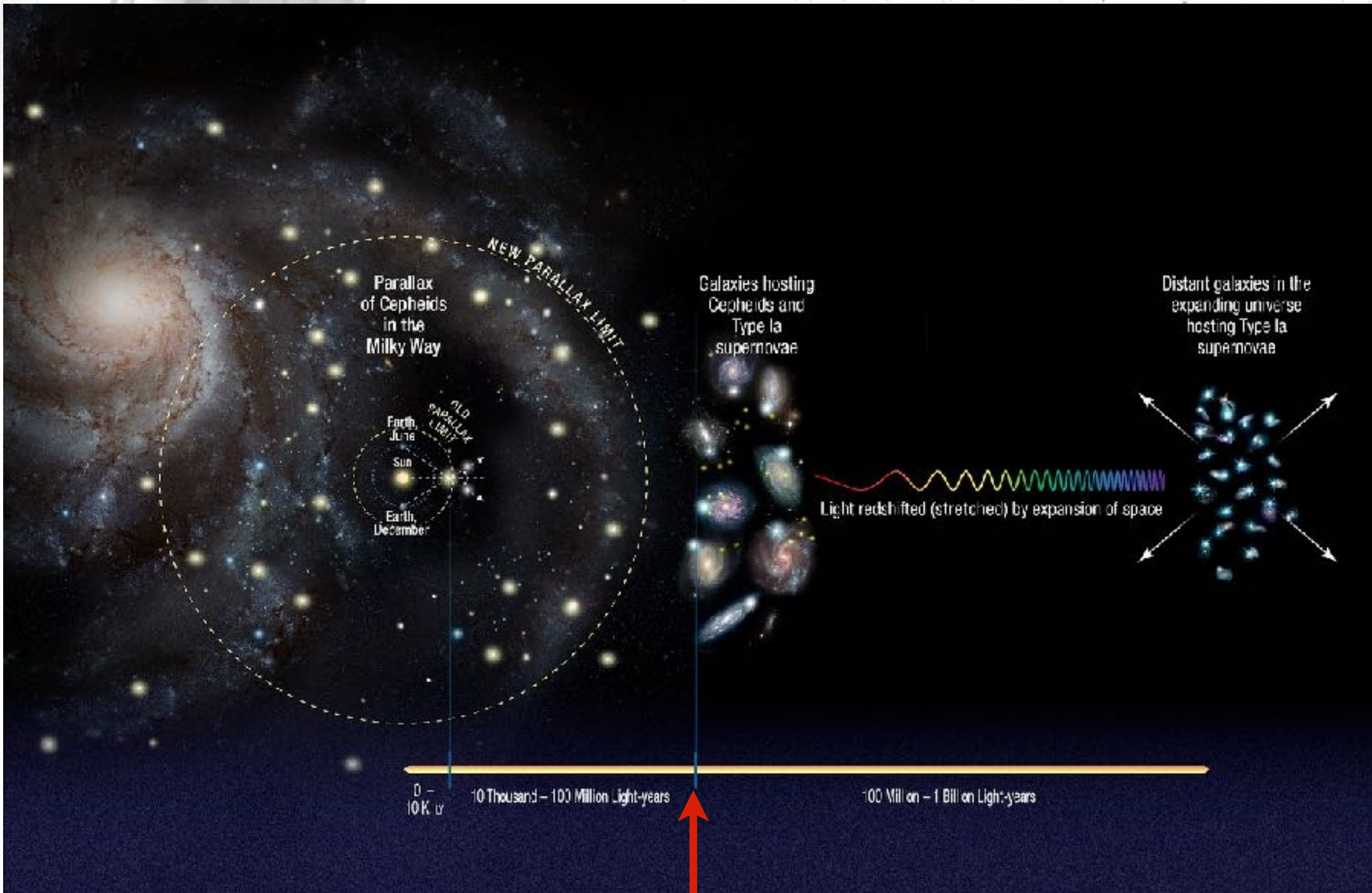


Hubble's law

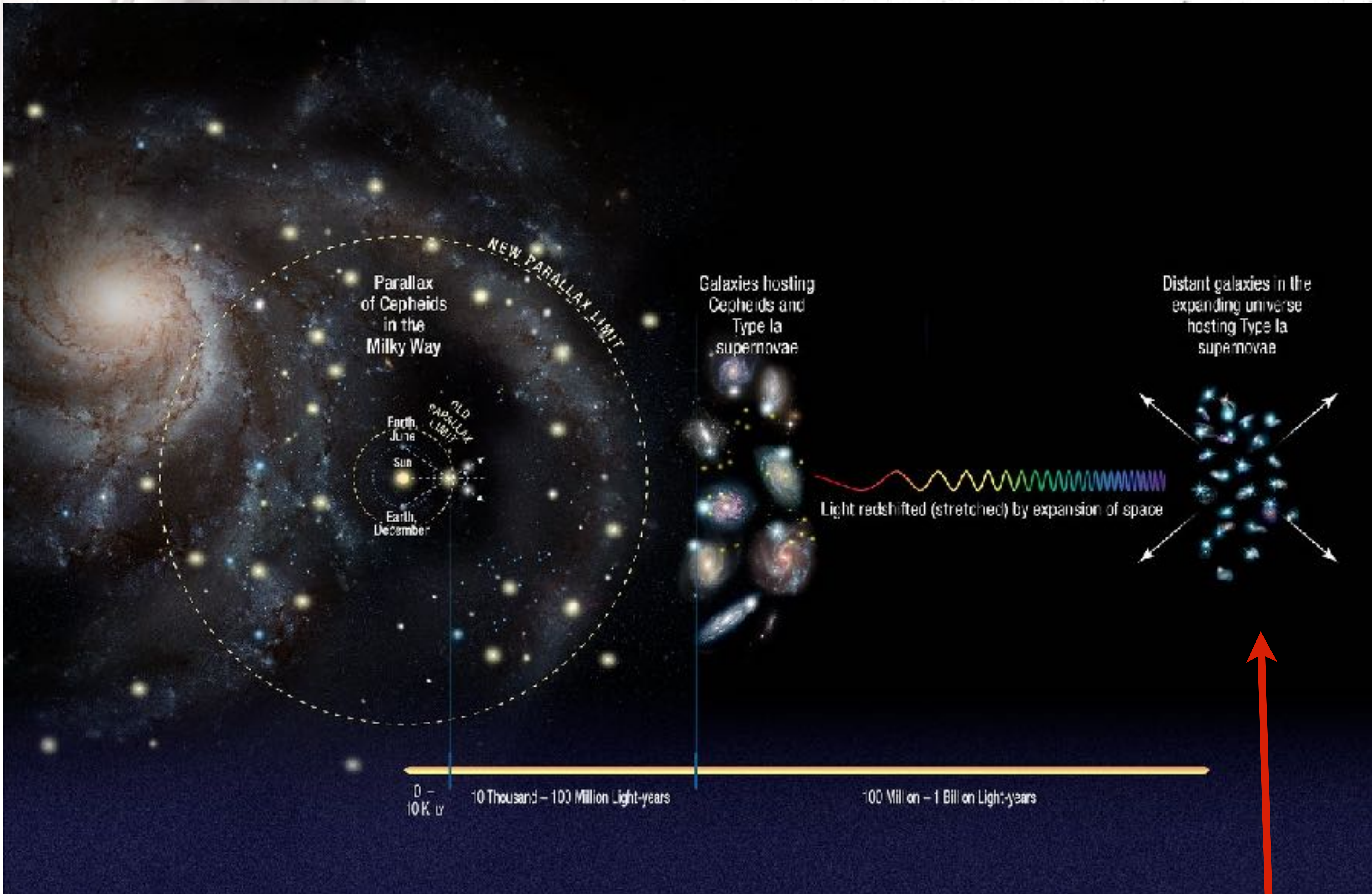
$$v = H_0 D$$

The universe is expanding!

Expansion of the Universe

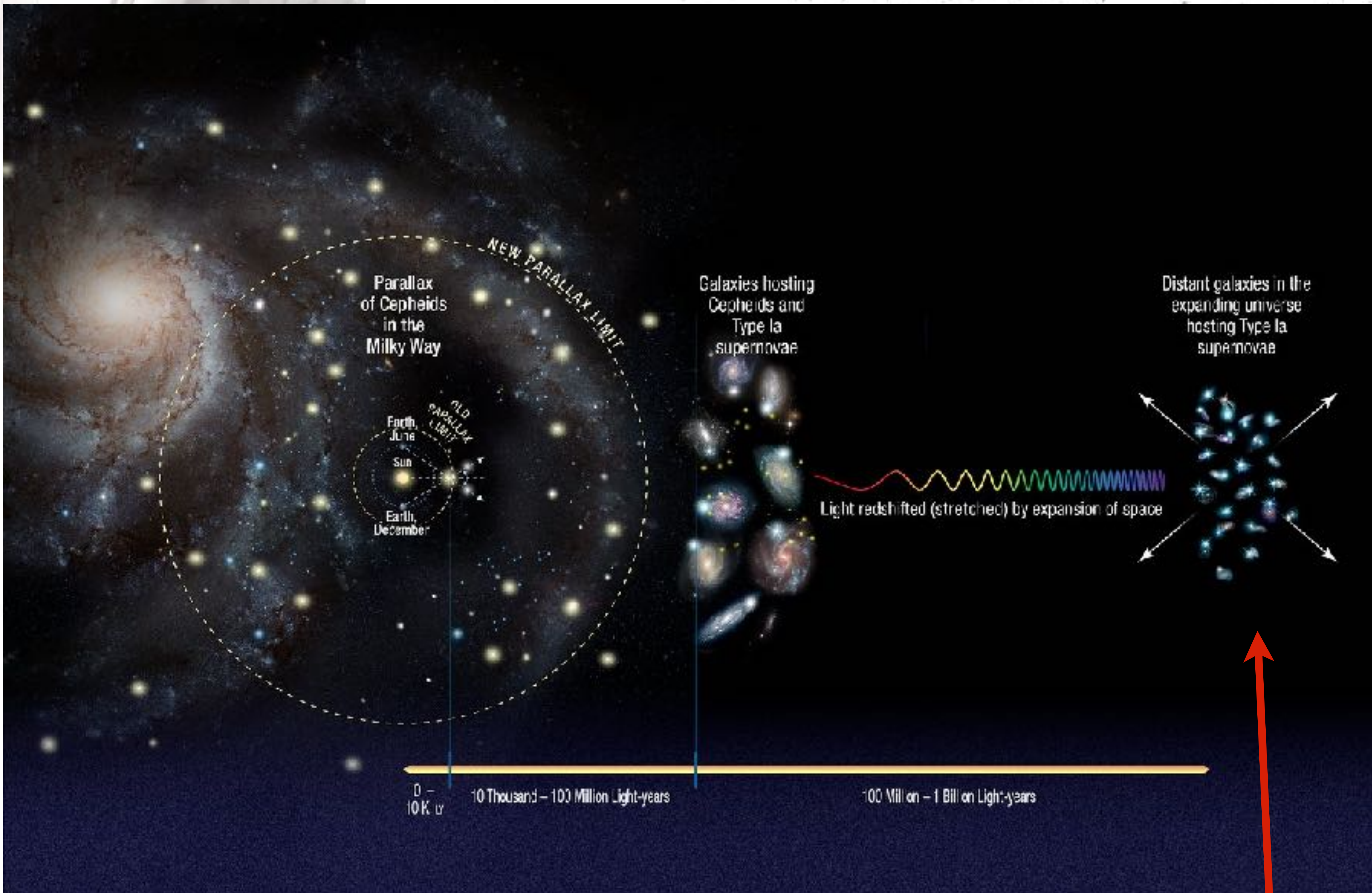

NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Light redshifted (stretched) by expansion of space
Distant galaxies in the expanding universe hosting Type Ia supernovae
0 – 10 K ly
10 Thousand – 100 Million Light-years
100 Million – 1 Billion Light-years

Cepheids



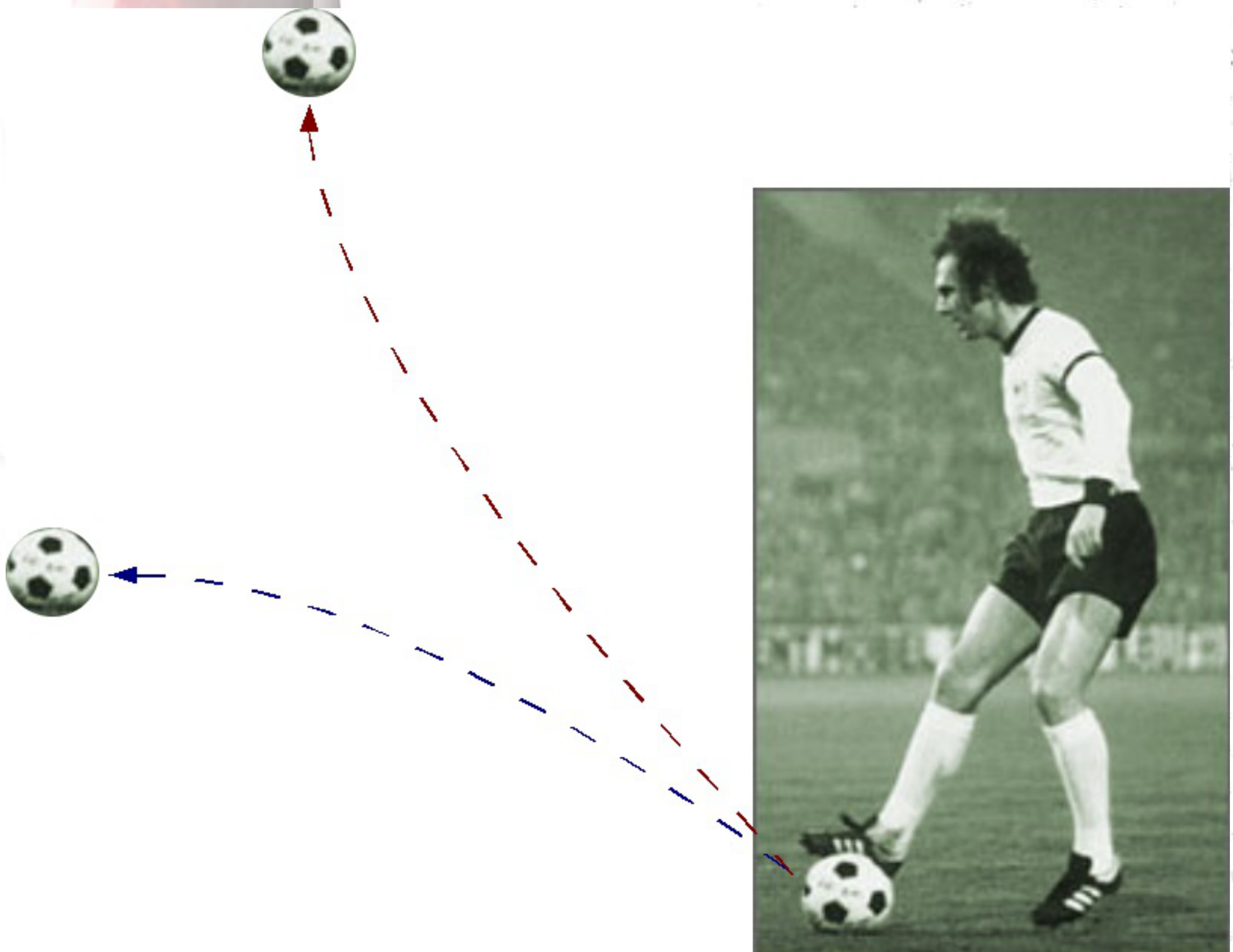
NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Light redshifted (stretched) by expansion of space
Distant galaxies in the expanding universe hosting Type Ia supernovae
0 – 10 K ly
10 Thousand – 100 Million Light-years
100 Million – 1 Billion Light-years

Supernovae

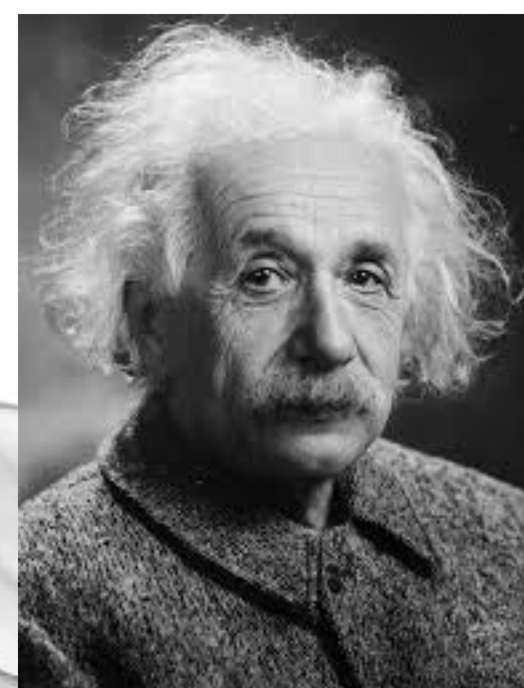


Accelerated Expansion of the Universe!

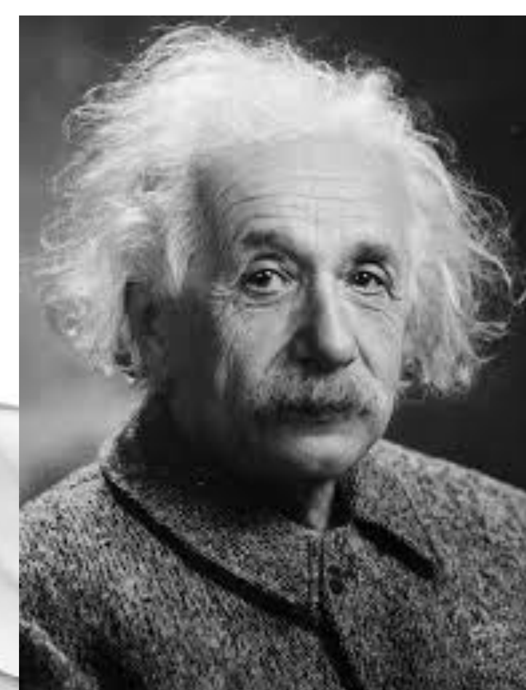
Accelerated Expansion of the Universe



How do we reconcile all these in a theory?

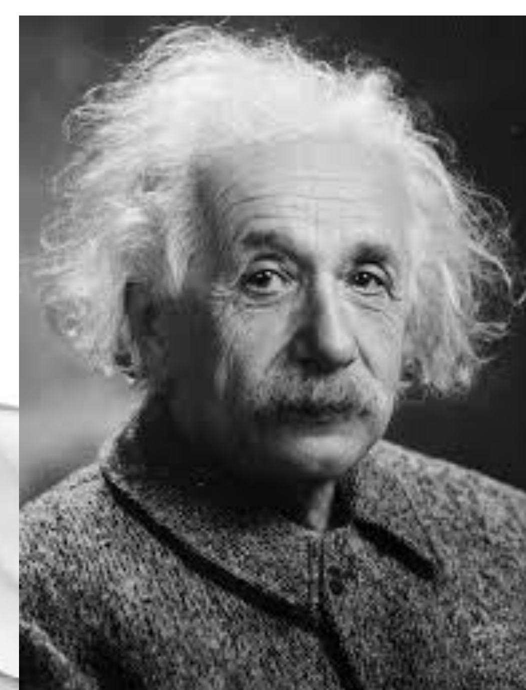


General Relativity



General Relativity

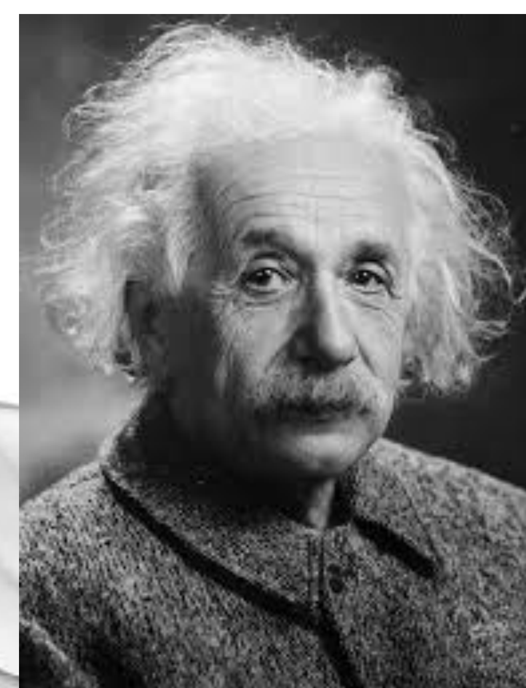
Gravity is



General Relativity

Gravity is

property of
space-time

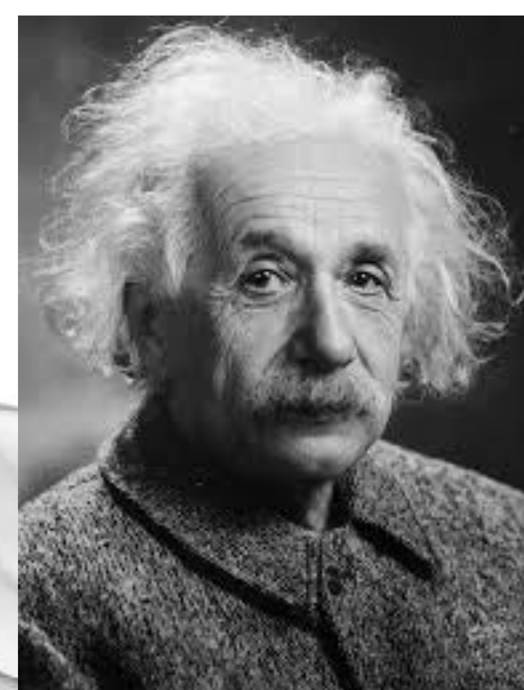


General Relativity

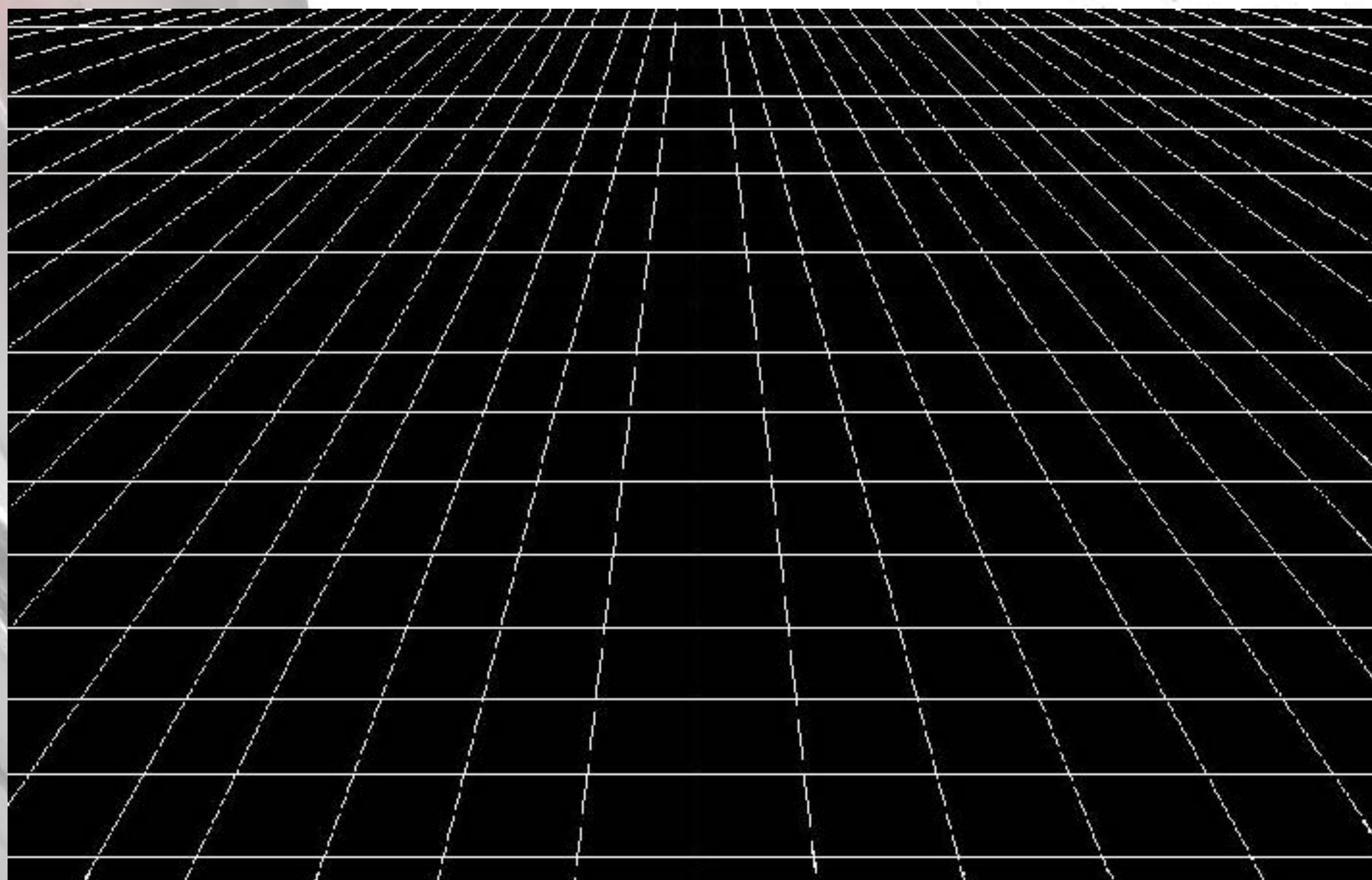
Gravity is

property of space-time

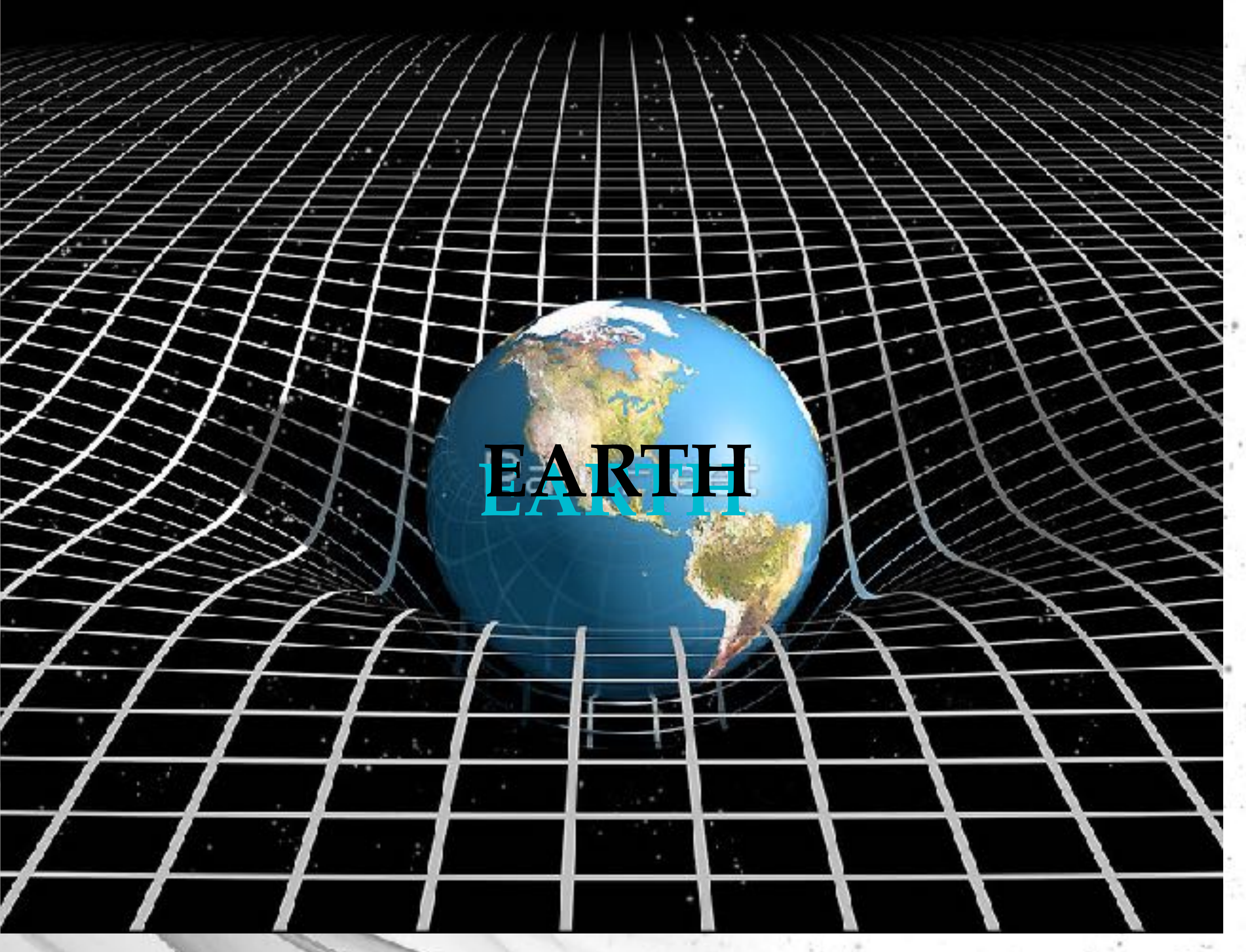
geometry



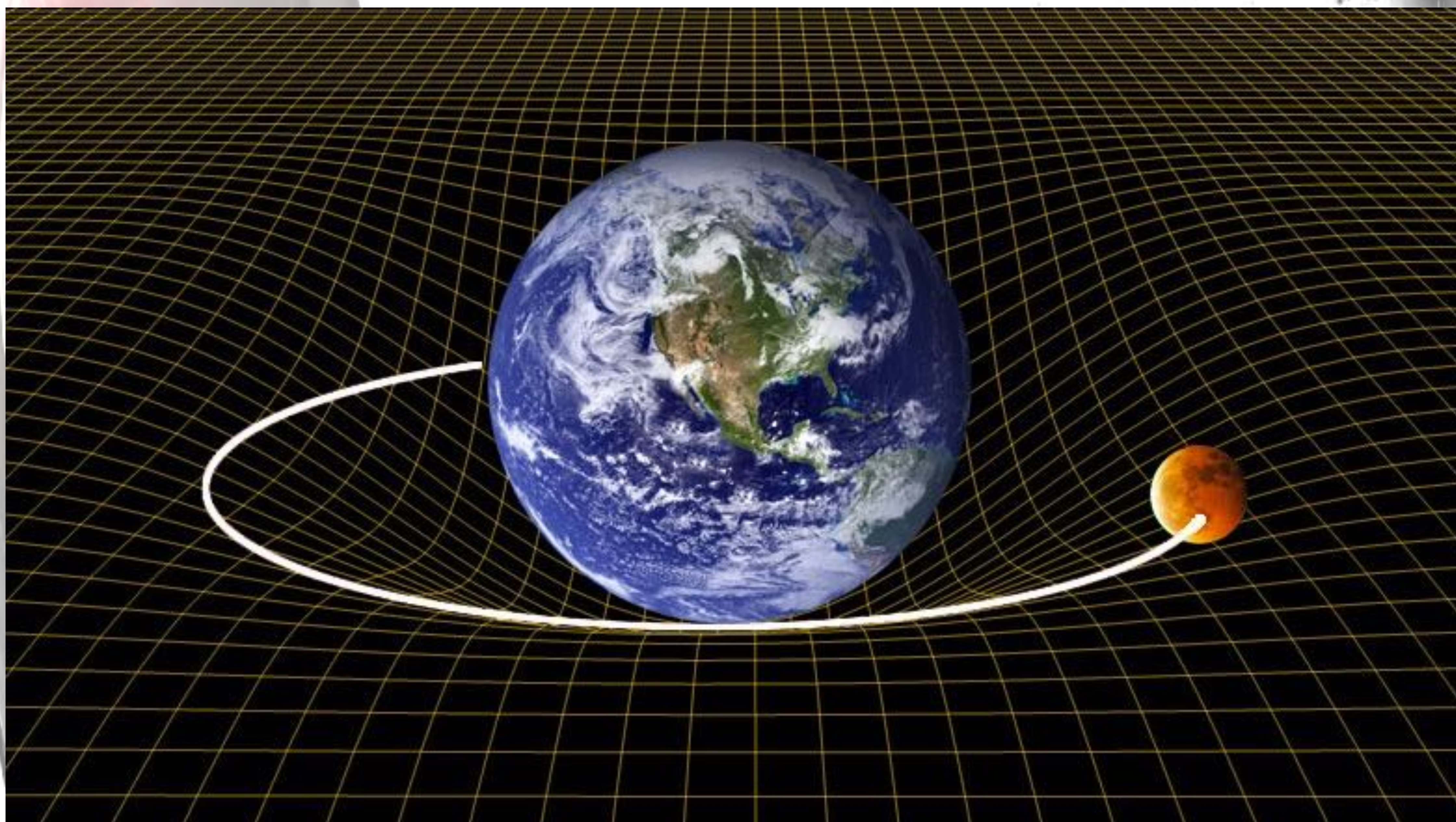
General Relativity (Einsteins perspective)



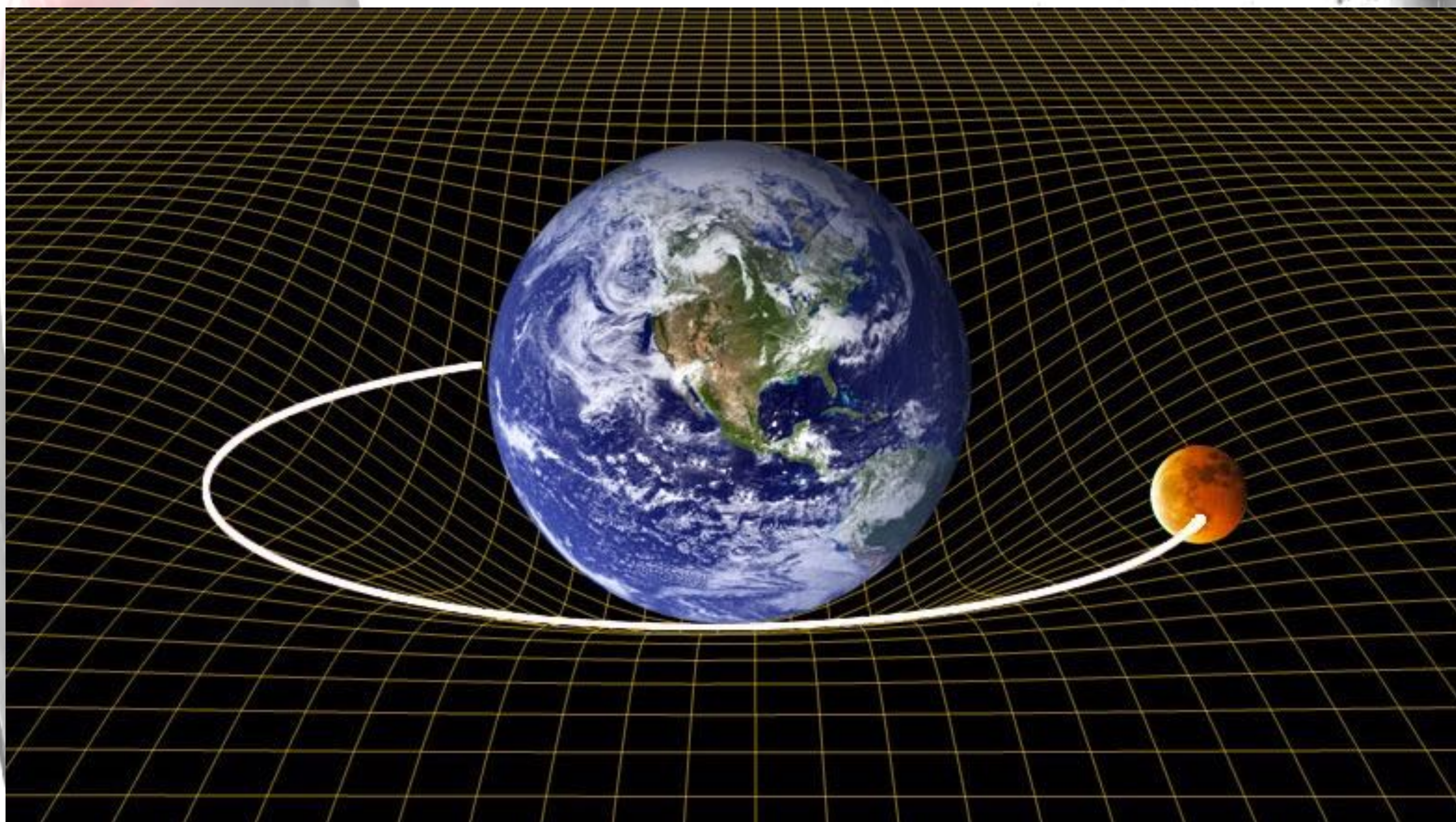
General Relativity (Einsteins perspective)



General Relativity (Einsteins perspective)

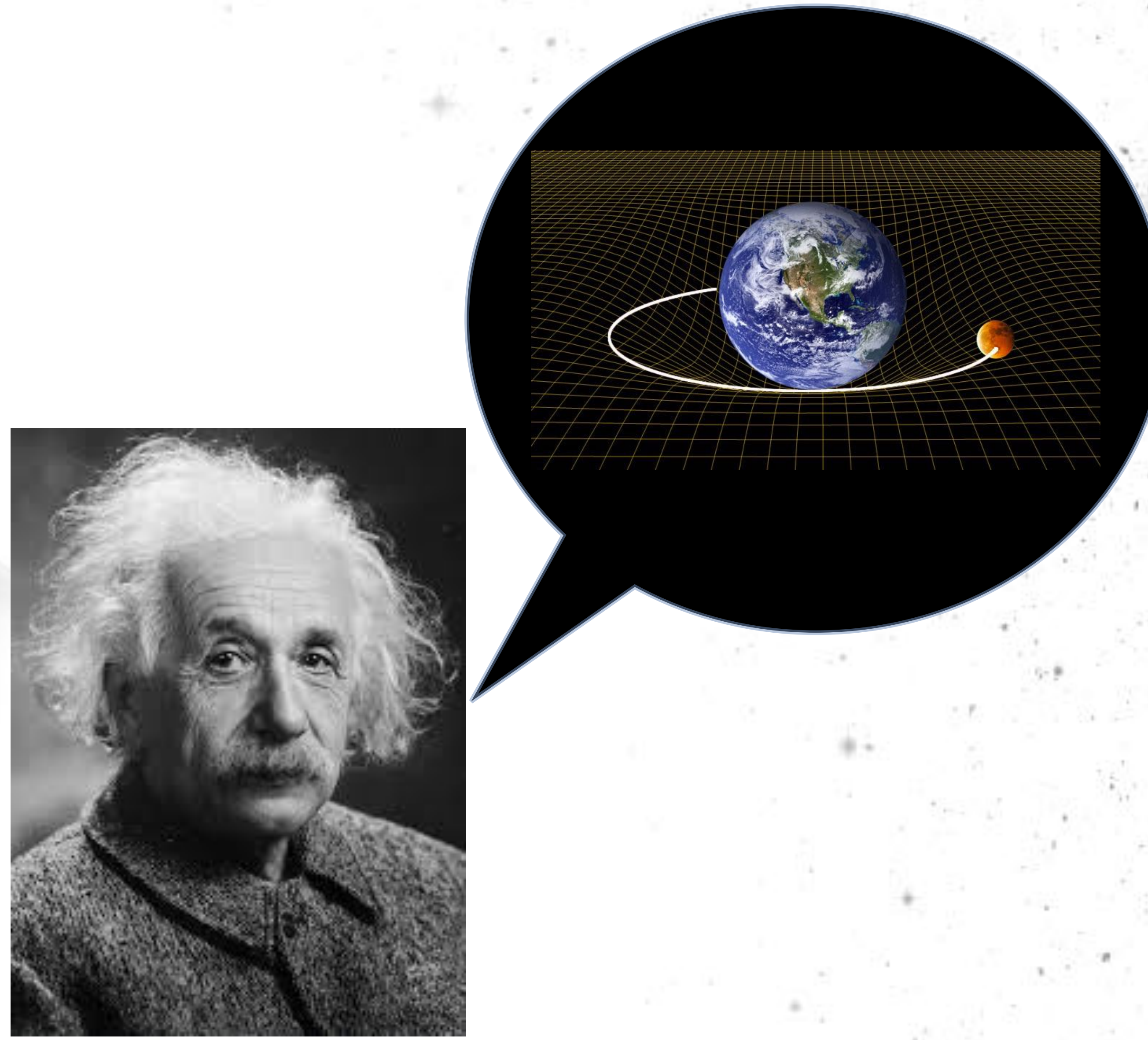


General Relativity (Einsteins perspective)



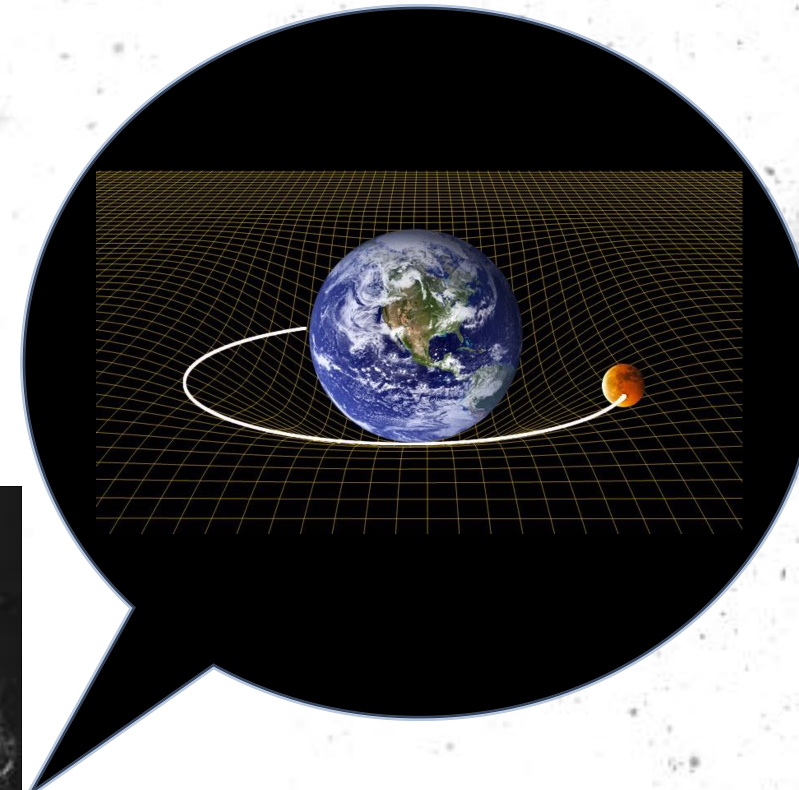
GR = Curvature of space-time

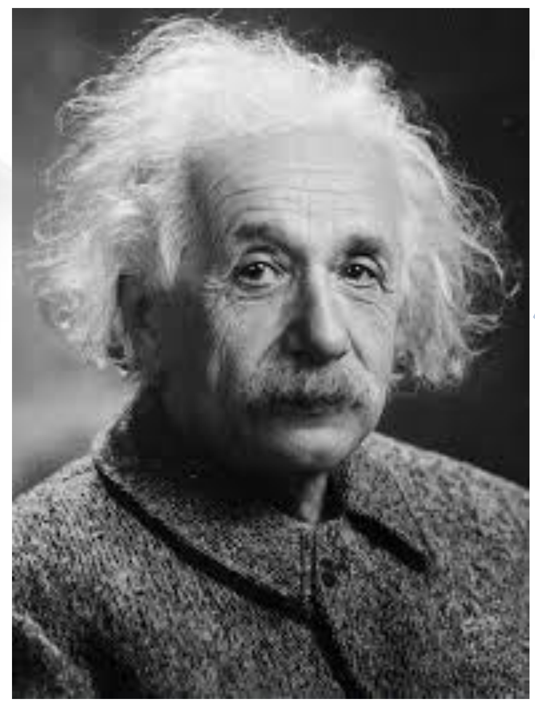
General Relativity (Einsteins perspective)



Is this geometrical description unique?

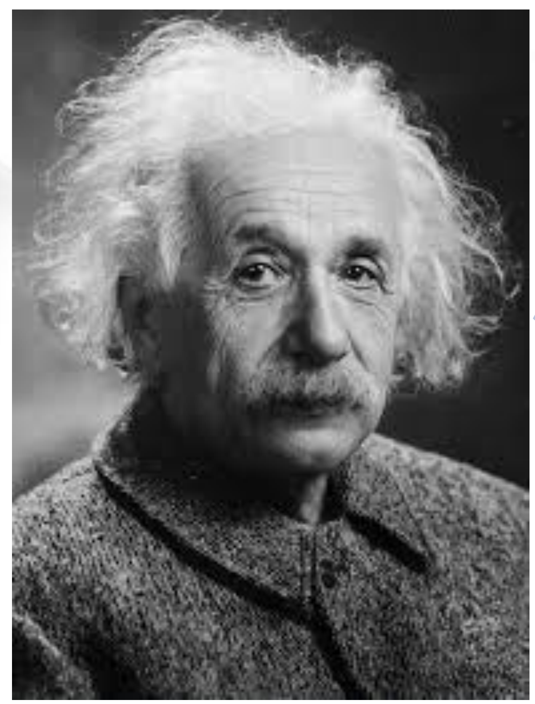
General Relativity (Einsteins perspective)

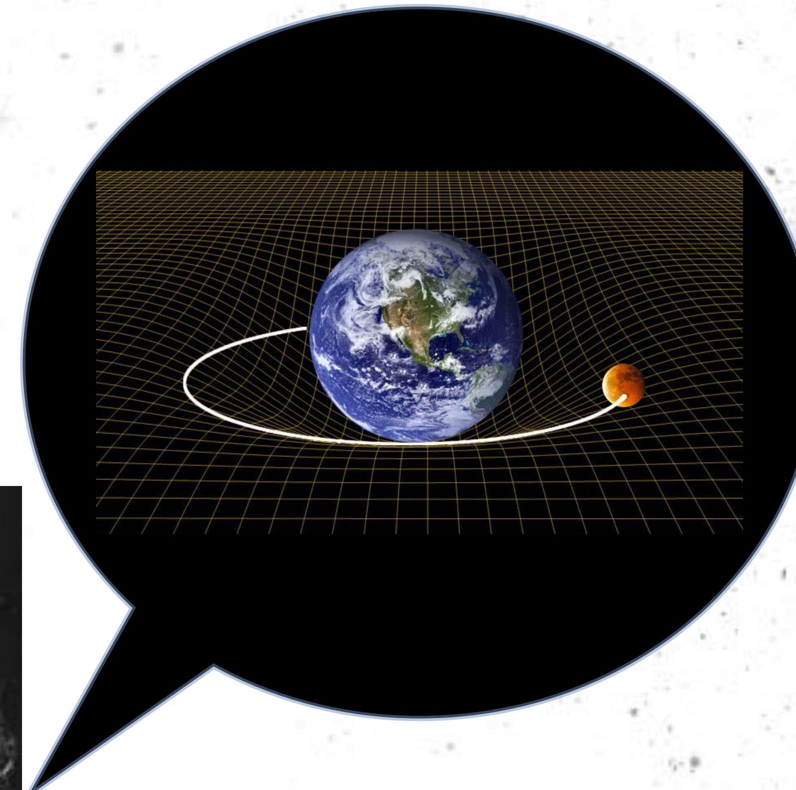




NO!

General Relativity (Einsteins perspective)





NO! ⟶ Trinity!

L.H & J.Beltran,
T.Koivisto
Universe 5 (2019) 7, 173,
arXiv:1903.06830

Geometrical Trinity of General Relativity

L.H & J.Beltran, T.Koivisto

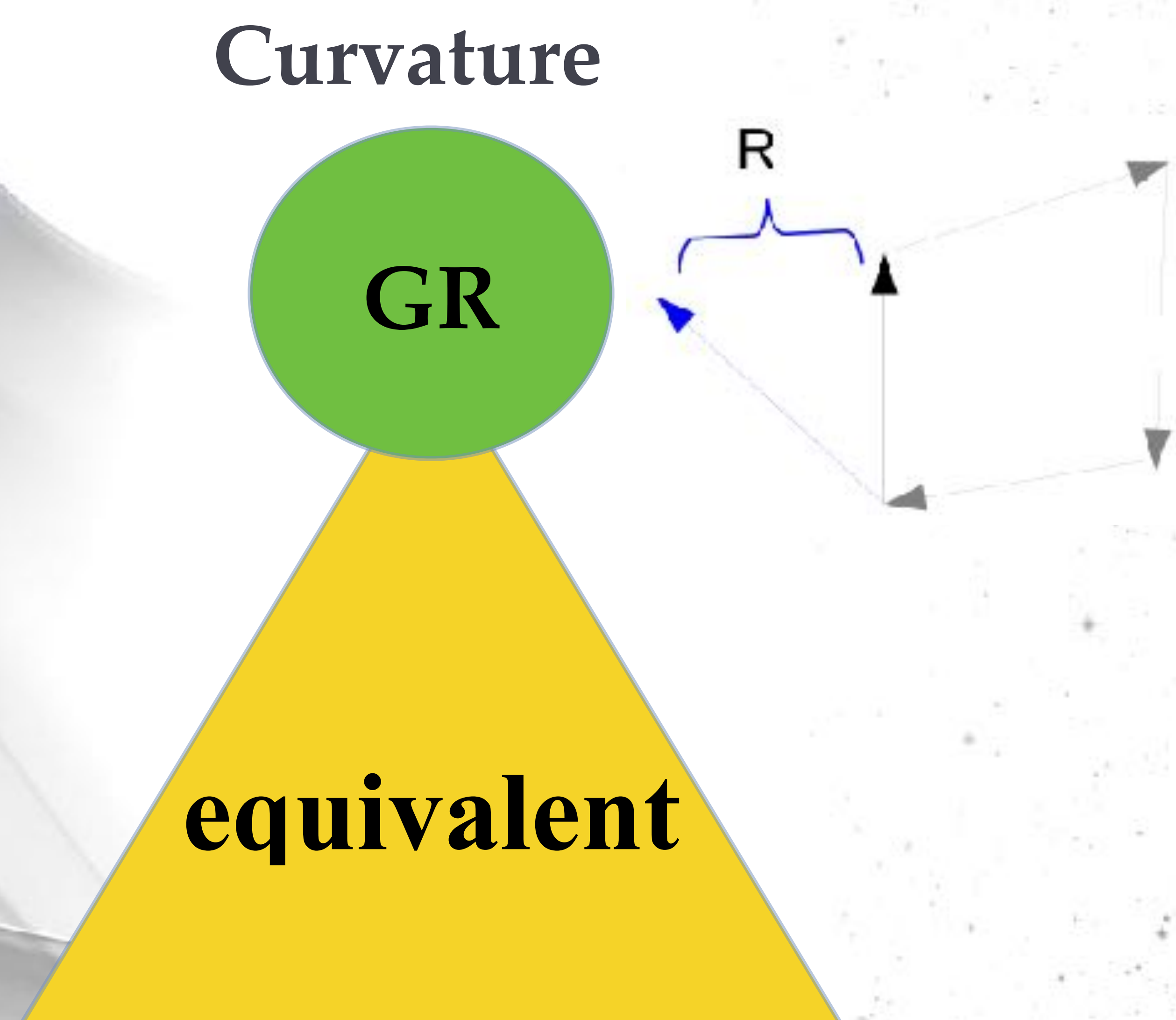
Universe 5 (2019) 7, 173,

arXiv:1903.06830

equivalent

Geometrical Trinity of General Relativity

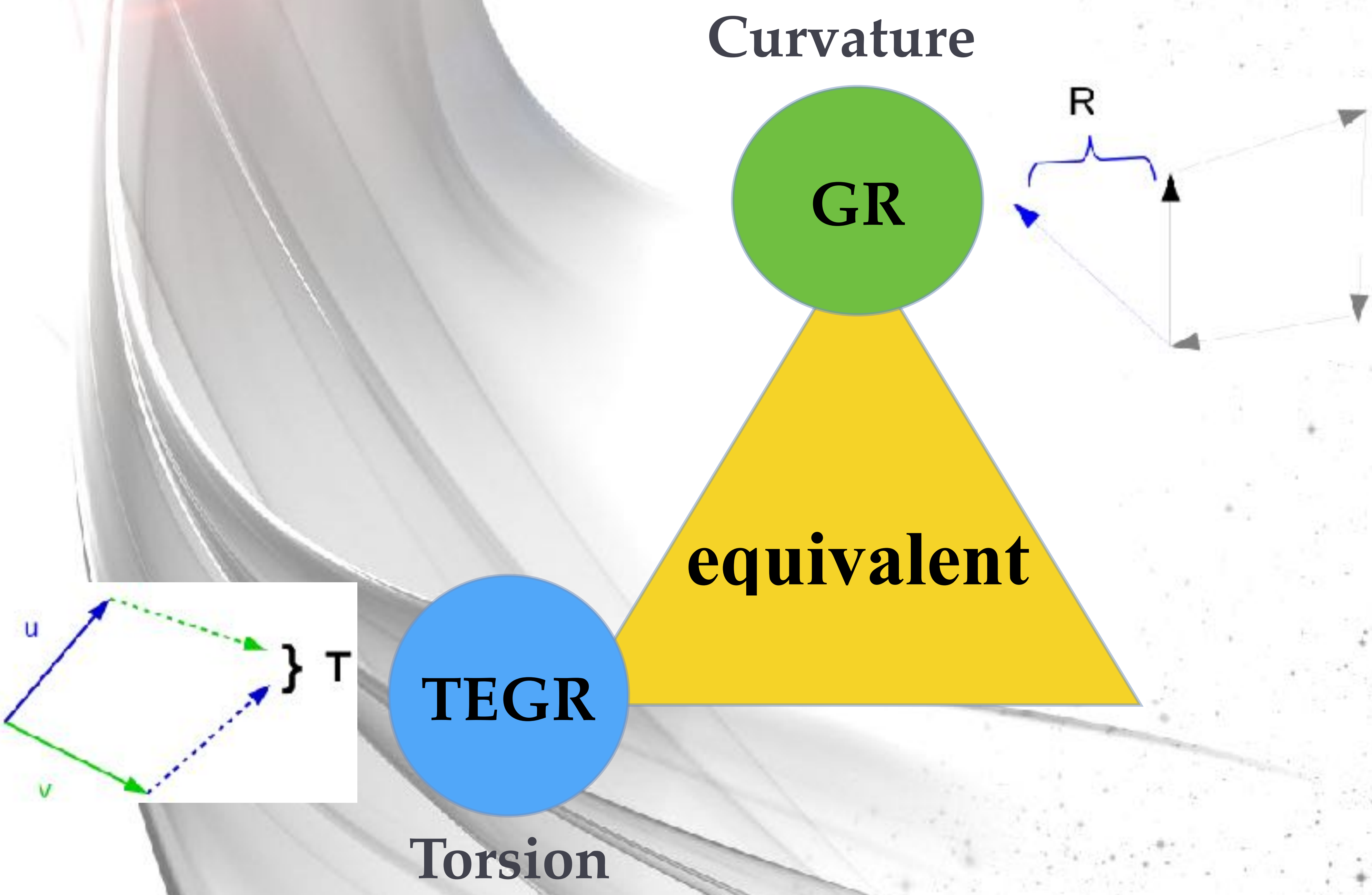
L.H & J.Beltran, T.Koivisto
Universe 5 (2019) 7, 173,
arXiv:1903.06830



Geometrical Trinity of General Relativity

L.H & J.Beltran, T.Koivisto

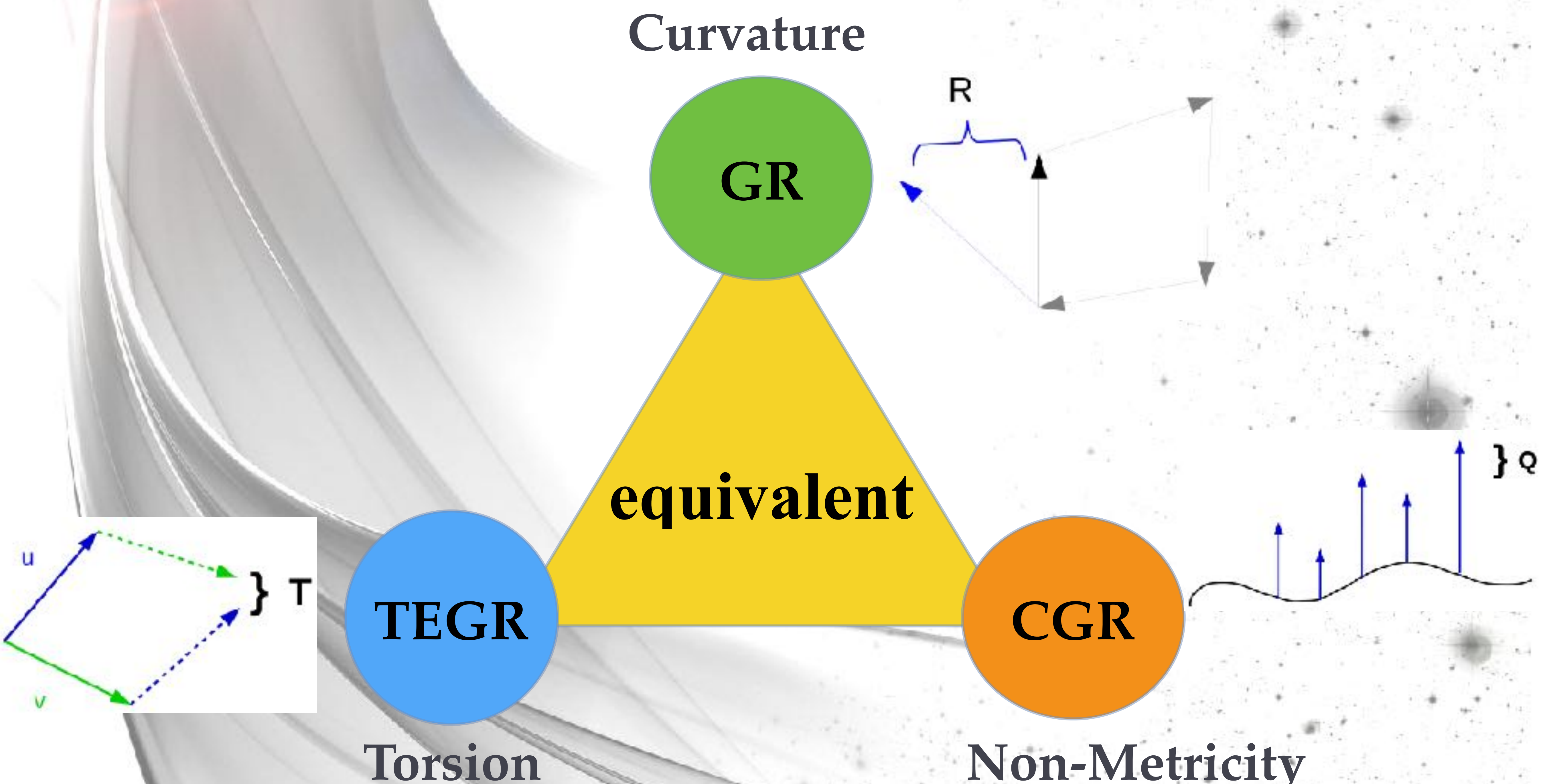
Universe 5 (2019) 7, 173,
arXiv:1903.06830



Geometrical Trinity of General Relativity

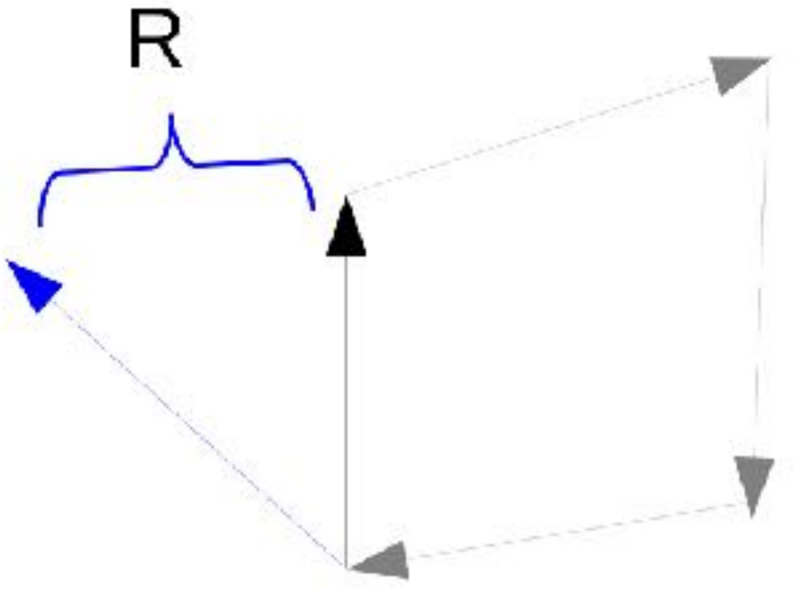
L.H & J.Beltran, T.Koivisto

Universe 5 (2019) 7, 173,
arXiv:1903.06830



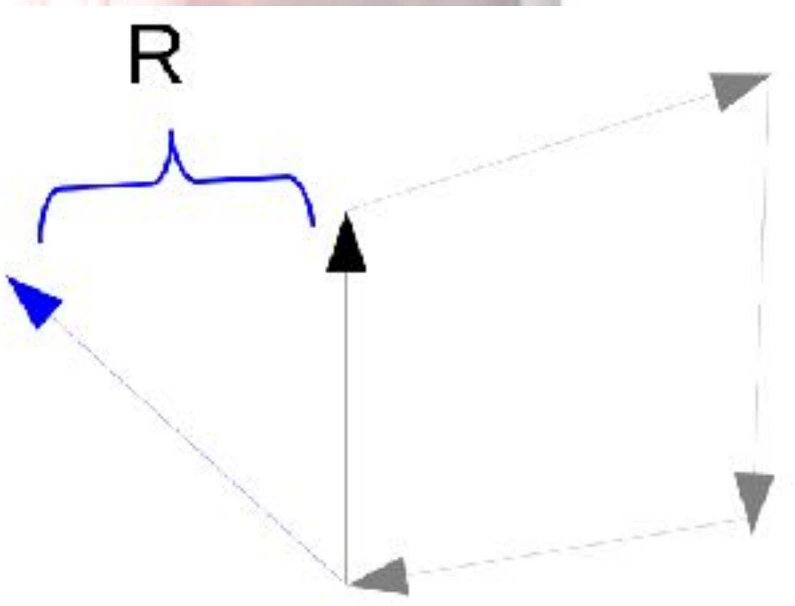
Geometrical objects

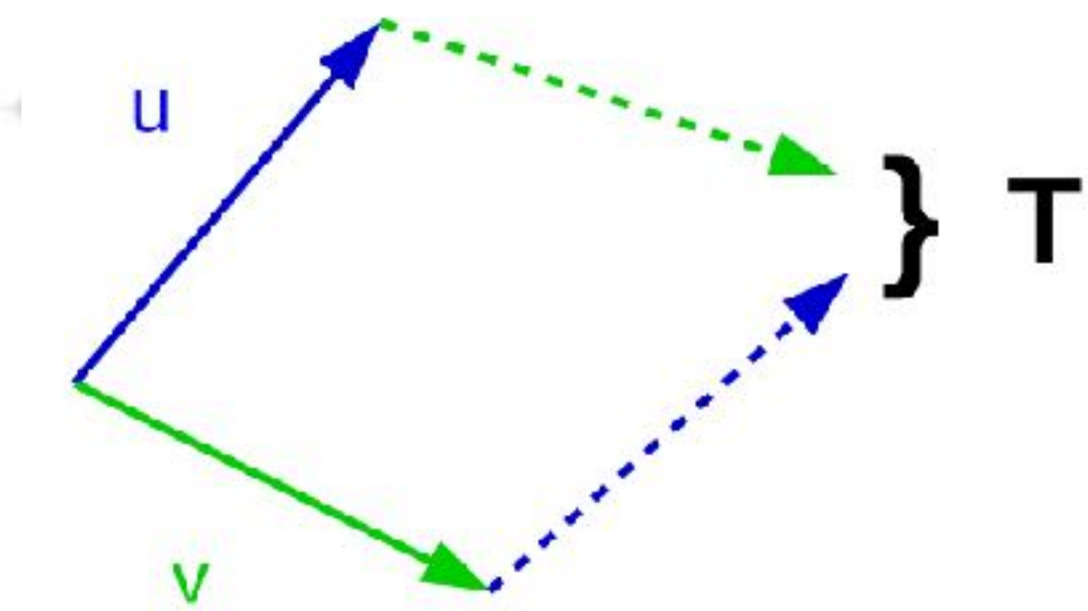
Geometrical objects



- **Curvature:** $R^{\alpha}_{\beta\mu\nu} \neq 0$

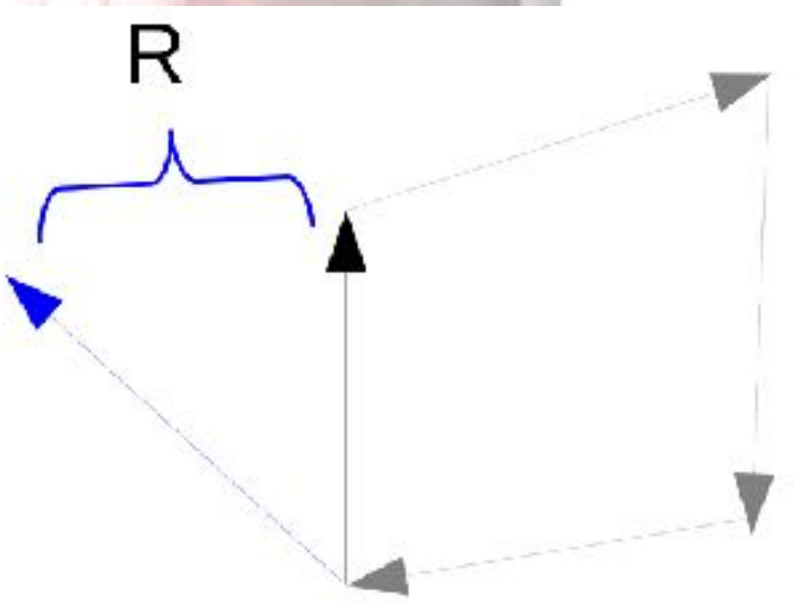
Geometrical objects

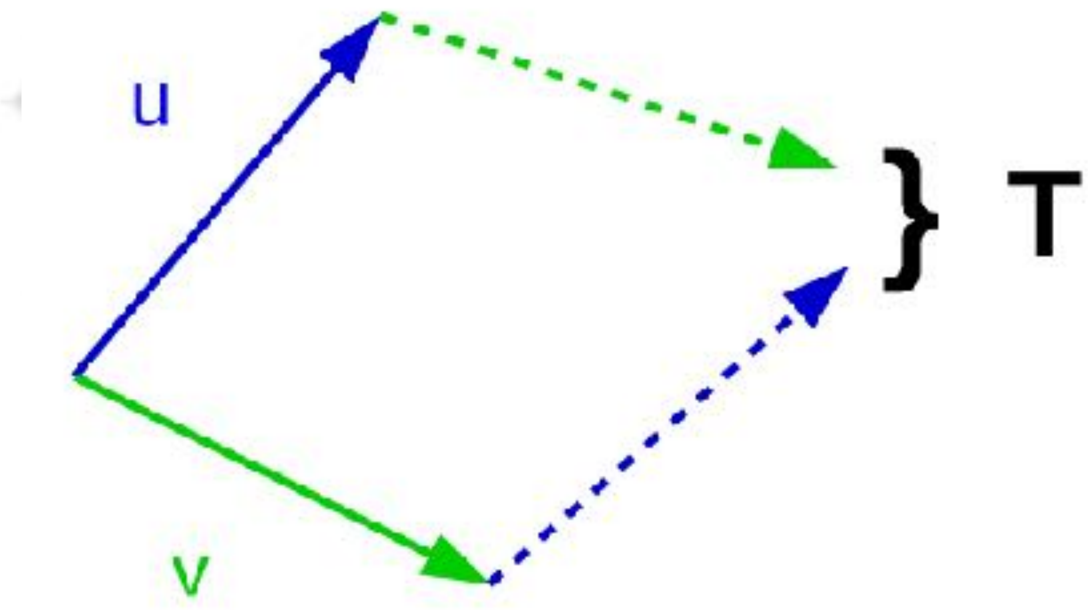




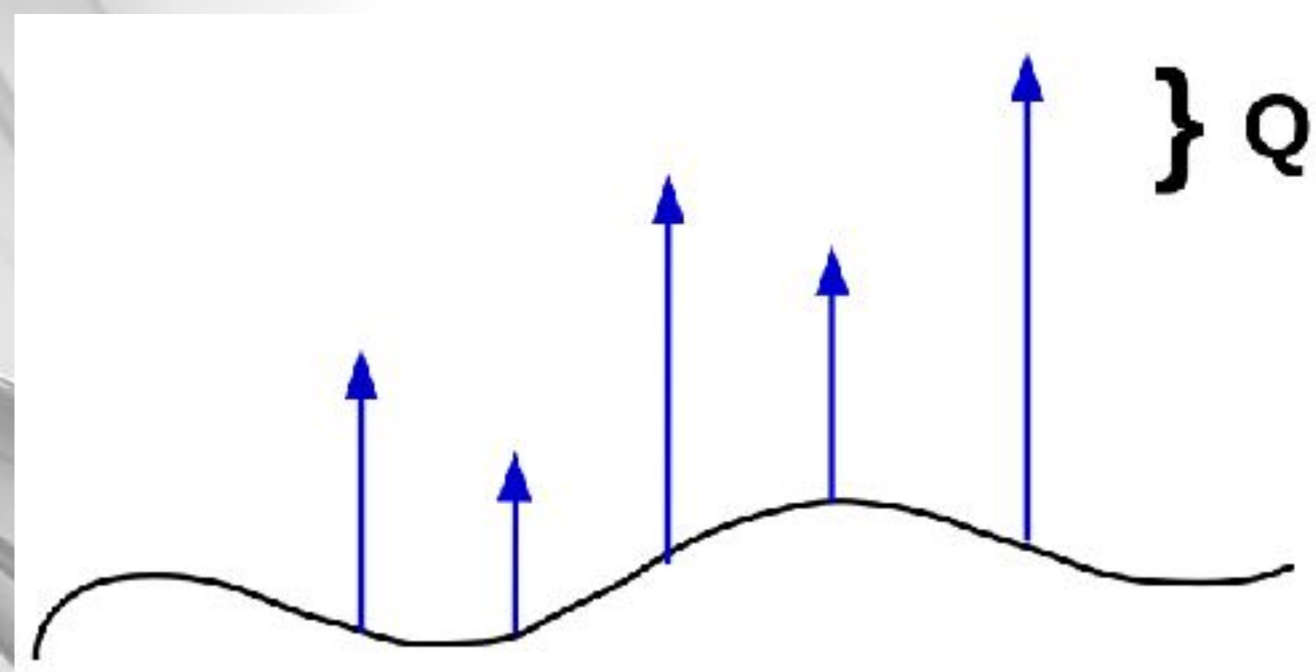
- **Curvature:** $R^{\alpha}_{\beta\mu\nu} \neq 0$
- **Torsion:** $T^{\alpha}_{\mu\nu} \neq 0$

Geometrical objects





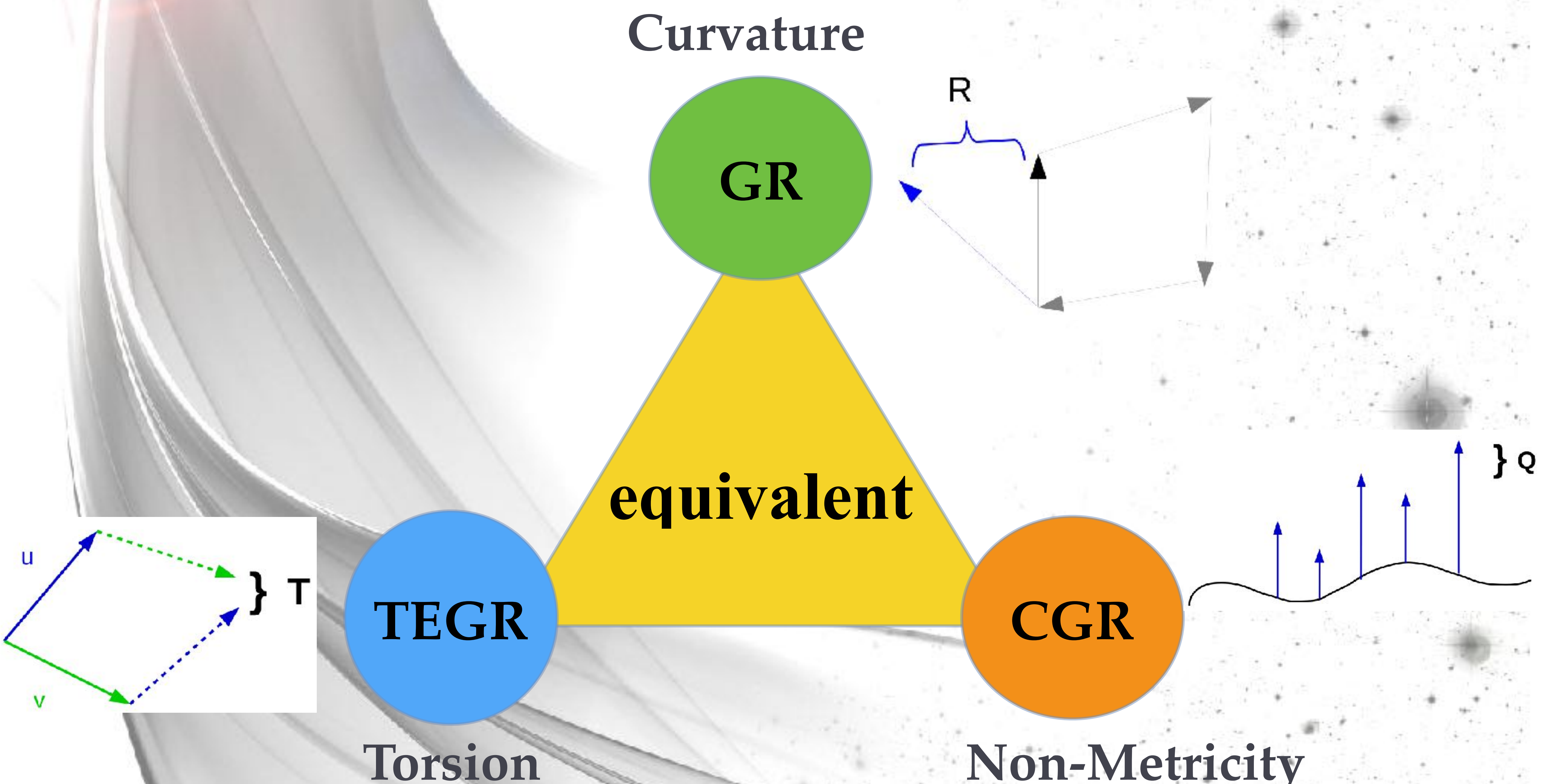
- **Curvature:** $R^{\alpha}_{\beta\mu\nu} \neq 0$
- **Torsion:** $T^{\alpha}_{\mu\nu} \neq 0$



- **Non-metricity:** $Q^{\alpha}_{\mu\nu} \neq 0$

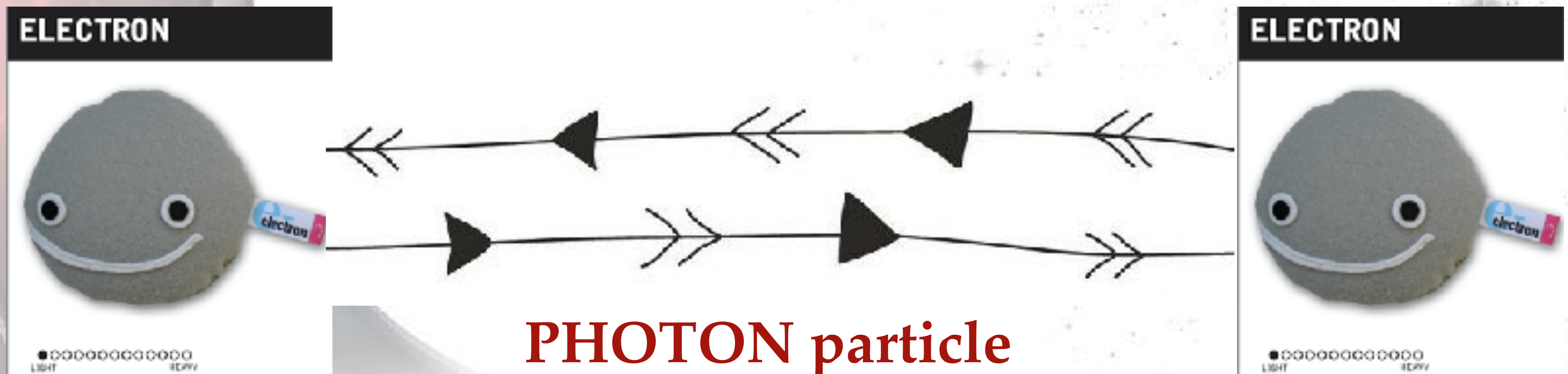
Geometrical Trinity of General Relativity

L.H & J.Beltran, T.Koivisto
Universe 5 (2019) 7, 173,
arXiv:1903.06830



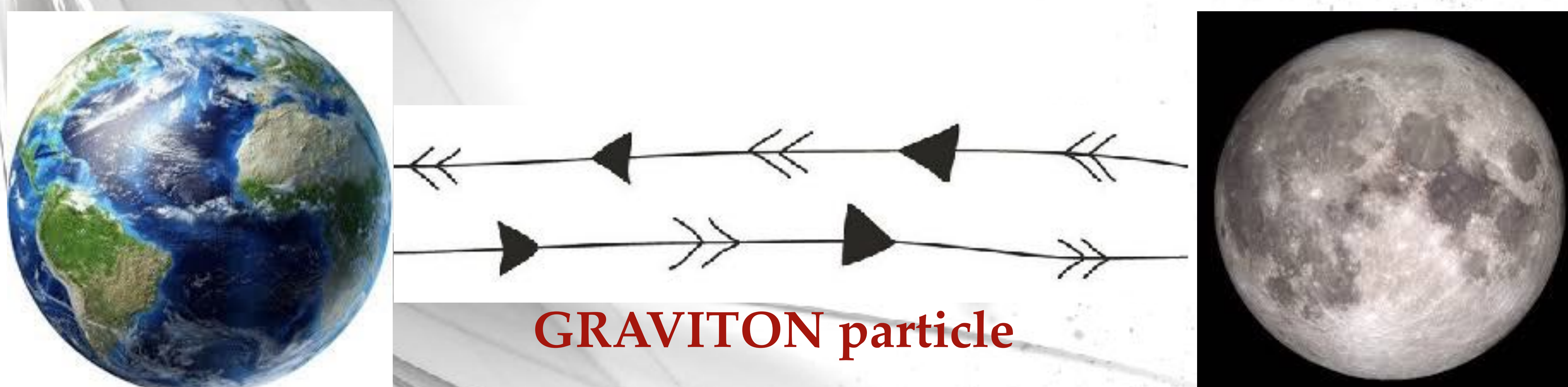
Particle Physics Perspective

- Electromagnetic interactions



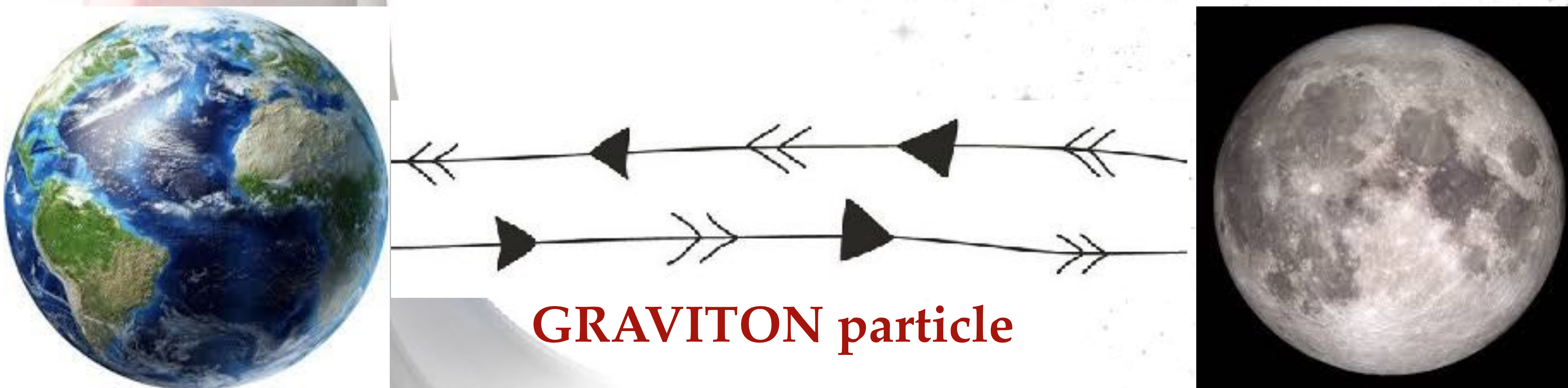
PHOTON particle

- Gravitational interactions



GRAVITON particle

Particle Physics Perspective



What is the most natural candidate for the GRAVITON particle?

Facts that we know about gravity:

Gravity

- is long-range ⟶ particle is massless

Facts that we know about gravity:

Gravity

- is long-range $\longrightarrow$ particle is massless
- exists as a classical theory $\longrightarrow$ no fermionic particle (only bosonic, spin=0,1,2..)

Facts that we know about gravity:

Gravity

- is long-range $\longrightarrow$ particle is massless
- exists as a classical theory $\longrightarrow$ no fermionic particle (only bosonic, spin=0,1,2..)
- is attractive $\longrightarrow$ not photon-like (no spin=1)

Facts that we know about gravity:

Gravity

- is long-range ⟶ particle is massless
- exists as a classical theory ⟶ no fermionic particle (only bosonic, spin=0,1,2..)
- is attractive ⟶ not photon-like (no spin=1)
- interacts with light ⟶ not Higgs boson-like (no spin=0)

Facts that we know about gravity:

Gravity

- is long-range $\longrightarrow$ particle is massless
- exists as a classical theory $\longrightarrow$ no fermionic particle (only bosonic, spin=0,1,2..)
- is attractive $\longrightarrow$ not photon-like (no spin=1)
- interacts with light $\longrightarrow$ not Higgs boson-like (no spin=0)

This leaves massless spin-2 particle as a natural candidate!

$\longrightarrow$ **General Relativity**

We can describe the Universe with 2 fundamental pillars

We can describe the Universe with 2 fundamental pillars

GR **General Relativity**

We can describe the Universe with 2 fundamental pillars

GR — **General Relativity**

CP — **Cosmological Principle**

We can describe the Universe with 2 fundamental pillars

GR General Relativity

CP Cosmological Principle → Homogeneity & Isotropy

We can describe the Universe with 2 fundamental pillars

GR

General Relativity

CP

Cosmological Principle → Homogeneity & Isotropy

spherically symmetric for every observer

(FLRW model)

Budget of the Universe

$$G_{\mu\nu} = \frac{T_{\mu\nu}}{M_{\rm Pl}^2}$$

Budget of the Universe

Observations indicate

- $\sim 27\%$ **with** $p \sim 0$

$$G_{\mu\nu} = \frac{T_{\mu\nu}}{M_{\rm Pl}^2}$$

DM

- **Cold Dark Matter: non-relativistic weakly interacting matter**

Budget of the Universe

Observations indicate

- $\sim 4.9\%$ **baryons**
- $\sim 27\%$ **with** $p \sim 0$

$$G_{\mu\nu} = \frac{T_{\mu\nu}}{M_{\rm Pl}^2}$$

DM

- **Cold Dark Matter: non-relativistic weakly interacting matter**

Budget of the Universe

Observations indicate

$$G_{\mu\nu} = \frac{T_{\mu\nu}}{M_{\rm Pl}^2}$$

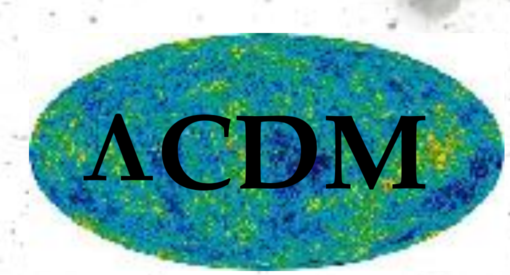
DM **DE**

- $\sim 4.9\%$ **baryons**
- $\sim 27\%$ **with** $p \sim 0$
- $\sim 68\%$ **with** $p < -\frac{1}{3}\rho$

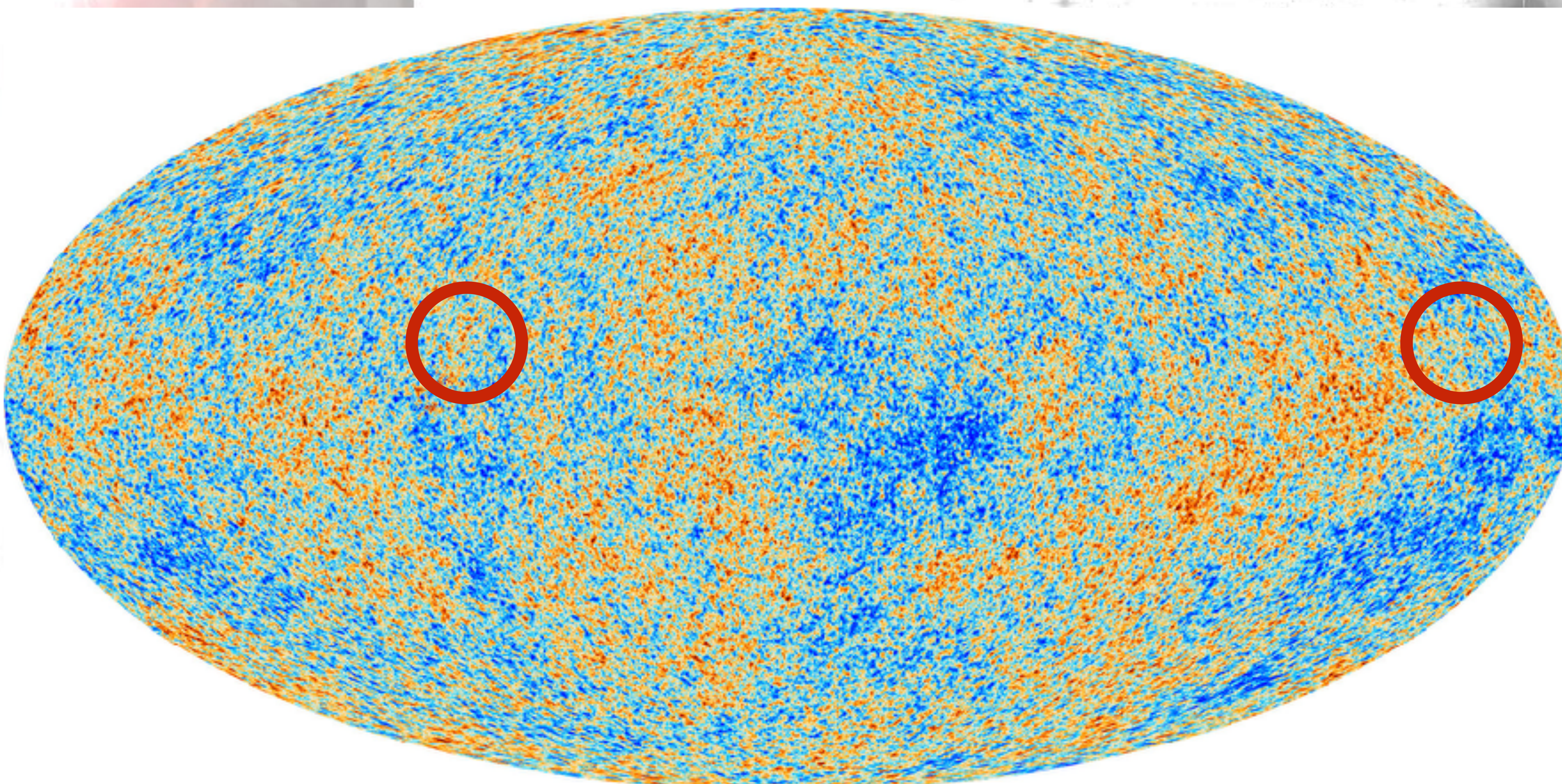
- **Cold Dark Matter: non-relativistic weakly interacting matter**
- **Dark Energy: energy with negative pressure** $\longrightarrow$ **accelerating universe**

Cosmological Constant $p = -\rho$

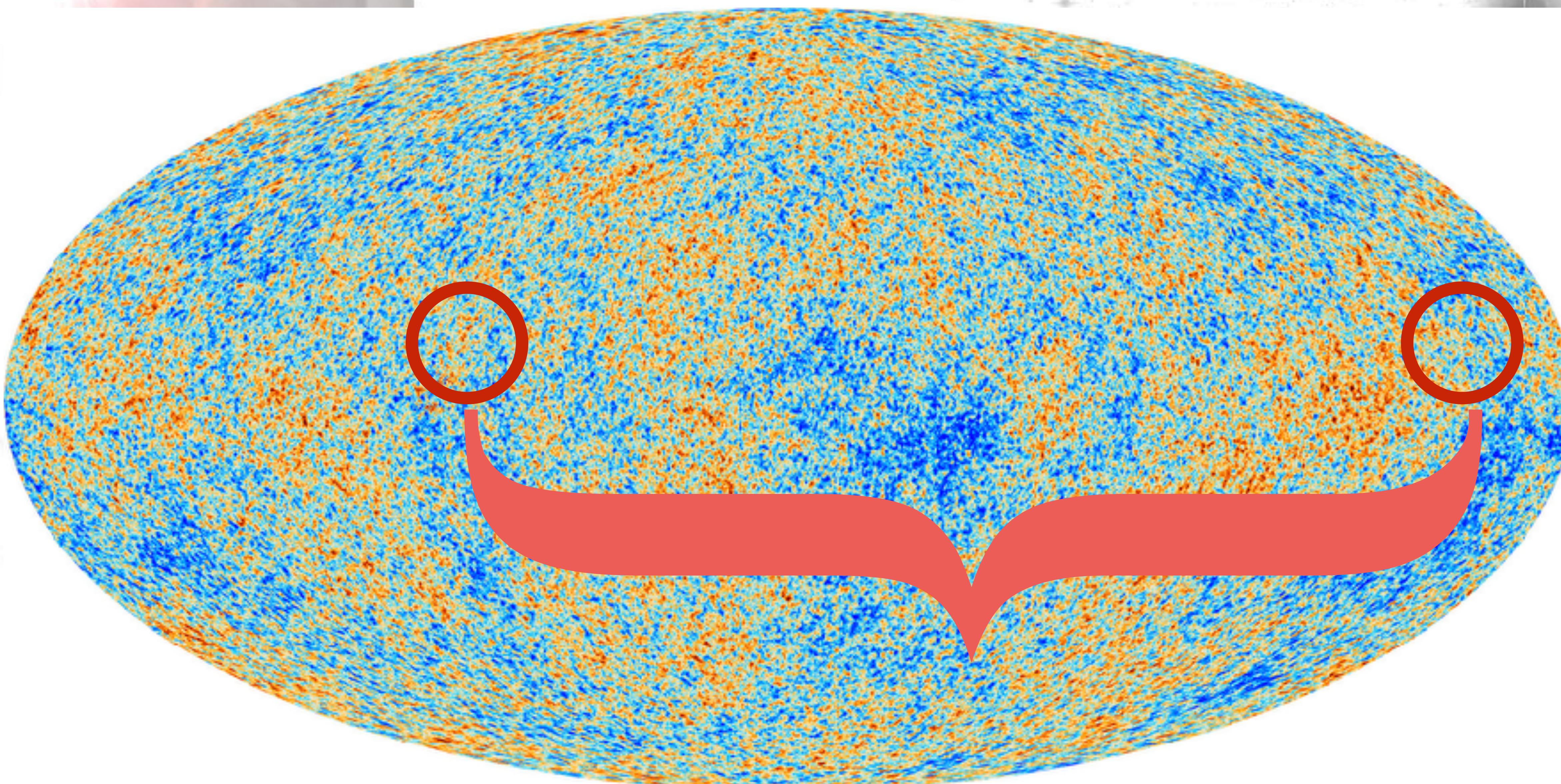
Λ



CMB

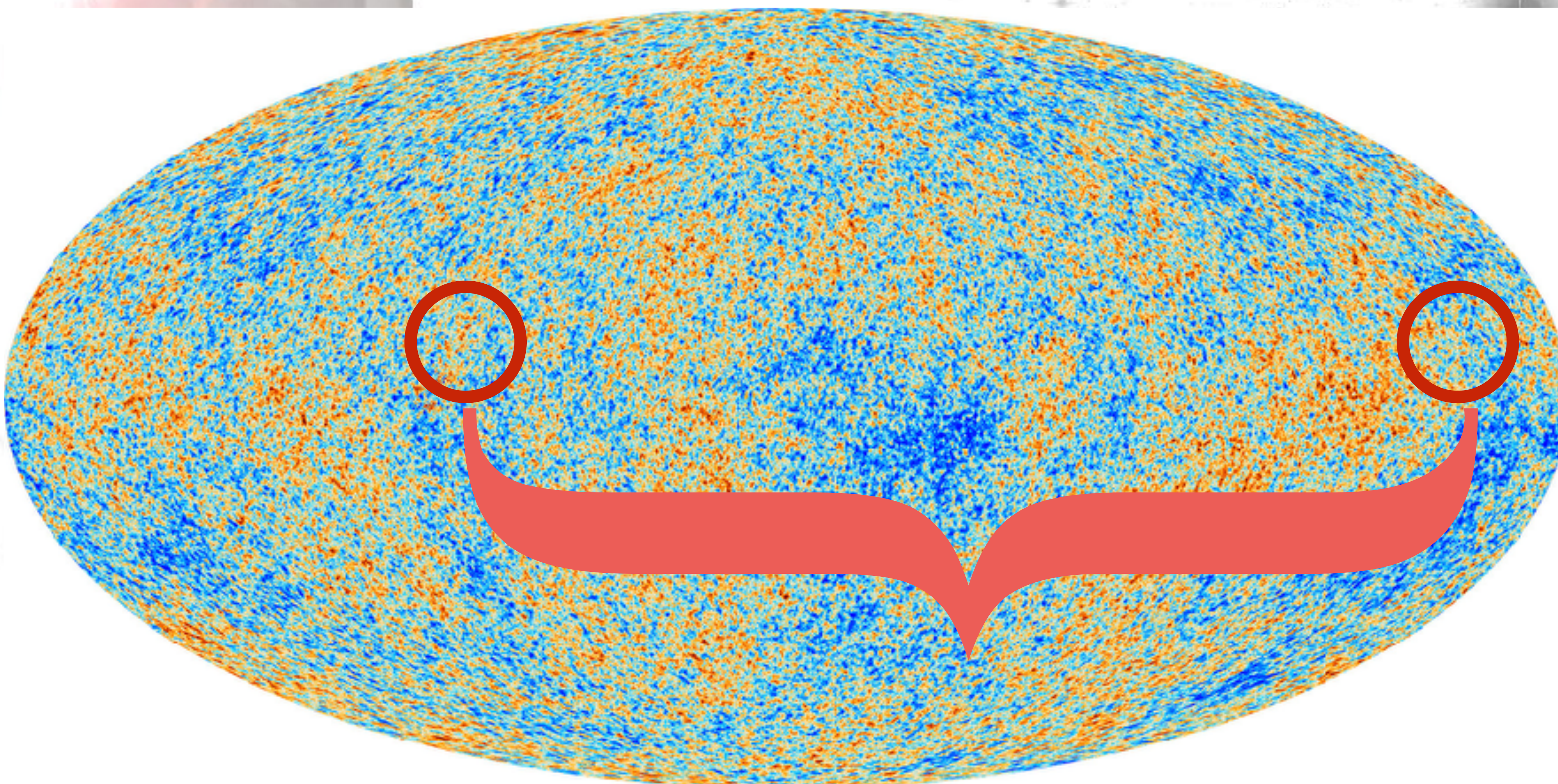


CMB



How can causally not connected regions have the same fluctuations?

CMB



INFLATON: early phase of accelerated expansion!

GR + DM + DE + Inflaton

GR + DM + DE + Inflaton

What is the quantum nature of GR?

GR + DM + DE + Inflaton

What is the quantum nature of GR?

What is the origin of DM?

GR + DM + DE + Inflaton

What is the quantum nature of GR?

What is the origin of DM?

What causes these two accelerated expansion phases of the universe?

GR + DM + DE + Inflaton

What is the quantum nature of GR?

What is the origin of DM?

What causes these two accelerated expansion phases of the universe?

Is DE just a cosmological constant or a field evolving in time like the inflaton?

particle 1

particle 2

particle 3

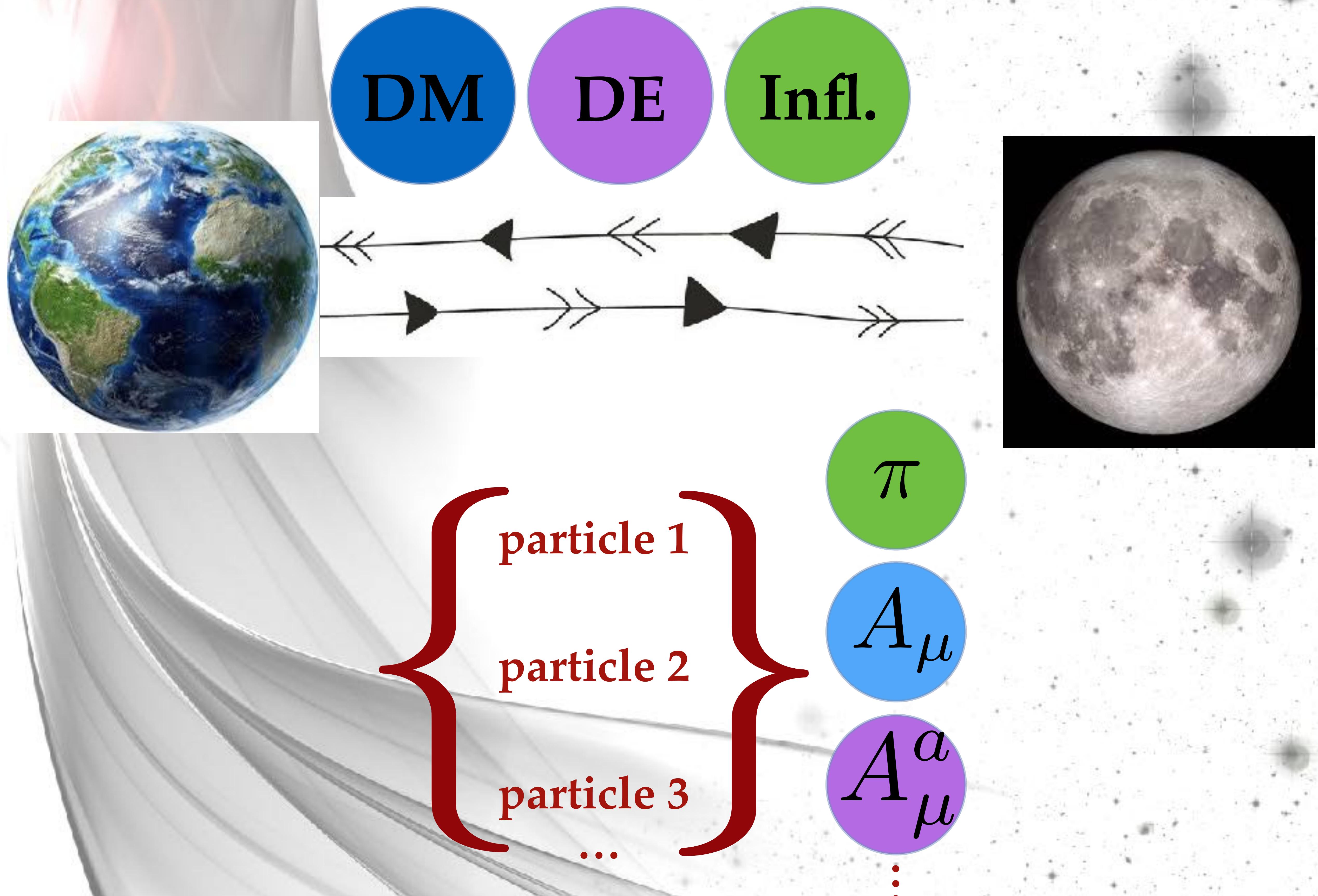
...

π

A_μ

A^a_μ

$\vdots$


DM
DE
Infl.
particle 1
particle 2
particle 3
...
π
A_μ
A_μ^a
⋮

π Scalar Field (Galileons)

π Scalar Field (Galileons)

- second order equations of motion
- Lorentz invariant and local
- shift and galileon symmetry $\pi \to \pi + c + x_\mu b^\mu$

Scalar Field (Galileons)

π

- second order equations of motion
- Lorentz invariant and local
- shift and galileon symmetry $\pi \to \pi + c + x_\mu b^\mu$

Galileon interactions

Nicolis, Rattazzi, Trincherini
Phys.Rev.D79 064036, 2009

$$\mathcal{L}_2 = (\partial\pi)^2$$
$$\mathcal{L}_3 = (\partial\pi)^2[\Pi]$$
$$\mathcal{L}_4 = (\partial\pi)^2([\Pi]^2 - [\Pi^2])$$
$$\mathcal{L}_5 = (\partial\pi)^2([\Pi]^3 - 3[\Pi][\Pi^2] + 2[\Pi^3])$$

$$\Pi_{\mu\nu} = \partial_\mu\partial_\nu\pi$$
$$[\Pi] = \Box\pi$$

Scalar-Tensor-interactions

The generalisation to curved space-time yield the rediscovery of Horndeski interactions

Scalar-Tensor-interactions

The generalisation to curved space-time yield the rediscovery of Horndeski interactions

G.W.Horndeski Int. J. Theo.Phys. 10, 363-384 (1974)
C.Deffayet, Esposito-Farese,Vikman
Phys. Rev.D (79), 084003 (2009)
T. Kobayashi, M. Yamaguchi, J. Yokoyama,
Prog. Theor. Phys. 126 (2011),511-529

$$\Pi_{\mu\nu} = \nabla_\mu \partial_\nu \pi$$

$$X = -\frac{1}{2}(\partial\pi)^2$$

$$\mathcal{L}_2 = K(\pi, X)$$

$$\mathcal{L}_3 = G_3(\pi, X)[\Pi]$$

$$\mathcal{L}_4 = G_4(\pi, X)R + G_{4,X}([\Pi]^2 - [\Pi^2])$$

$$\mathcal{L}_5 = G_5(\pi, X)G_{\mu\nu}\Pi^{\mu\nu} - \frac{G_{5,X}}{6}([\Pi]^3 - 3[\Pi][\Pi^2] + 2[\Pi^2])$$

Scalar-Tensor-interactions

The generalisation to curved space-time yield the rediscovery of Horndeski interactions

G.W.Horndeski Int. J. Theo.Phys. 10, 363-384 (1974)
C.Deffayet, Esposito-Farese,Vikman
Phys. Rev.D (79), 084003 (2009)
T. Kobayashi, M. Yamaguchi, J. Yokoyama,
Prog. Theor. Phys. 126 (2011),511-529

$$\Pi_{\mu\nu} = \nabla_\mu \partial_\nu \pi$$

$$X = -\frac{1}{2}(\partial\pi)^2$$

$$\mathcal{L}_2 = K(\pi, X)$$

$$\mathcal{L}_3 = G_3(\pi, X)[\Pi]$$

$$\mathcal{L}_4 = G_4(\pi, X)R + G_{4,X}([\Pi]^2 - [\Pi^2])$$

$$\mathcal{L}_5 = G_5(\pi, X)G_{\mu\nu}\Pi^{\mu\nu} - \frac{G_{5,X}}{6}([\Pi]^3 - 3[\Pi][\Pi^2] + 2[\Pi^2])$$

Non-minimal couplings modifying the gravity sector

Scalar Field (Galileons)

π

Realization of the

CP

Cosmological Principle $\rightarrow$ Homogeneity & Isotropy

is very simple: $\pi = \pi(t)$

A_μ Vector Field (Generalized Proca)

A_μ Vector Field (Generalized Proca)

- second order equations of motion
- Lorentz invariant and local
- 3 propagating degrees of freedom

A_μ Vector Field (Generalized Proca)

- second order equations of motion
- Lorentz invariant and local
- 3 propagating degrees of freedom

L. H., JCAP 1405, 015 (2014), arXiv:1402.7026
G.Tasinato JHEP 1404 (2014)067 arXiv:1402.6450
Allys, Peter, Rodriguez, JCAP 1602 (2016) 02, 004

L.H & J.Beltran, Phys.Lett.B757 (2016) 405-411, arXiv:1602.03410

$$\mathcal{L}_2 = f_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$
$$\mathcal{L}_3 = f_3(A^2)\ \ \partial\cdot A$$
$$\mathcal{L}_4 = f_4(A^2)\ \ \left[(\partial\cdot A)^2 - \partial_\rho A_\sigma \partial^\sigma A^\rho\right]$$
$$\mathcal{L}_5 = f_5(A^2)\ \ \left[(\partial\cdot A)^3 - 3(\partial\cdot A)\partial_\rho A_\sigma \partial^\sigma A^\rho + 2\partial_\rho A_\sigma \partial^\gamma A^\rho \partial^\sigma A_\gamma\right] + \tilde{f}_5(A^2)\tilde{F}^{\alpha\mu}\tilde{F}^{\beta}{}_{\mu}\partial_\alpha A_\beta$$
$$\mathcal{L}_6 = f_6(A^2)\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\partial_\alpha A_\mu \partial_\beta A_\nu$$

Vector-Tensor Theories

L. H., JCAP 1405, 015 (2014), arXiv:1402.7026

G.Tasinato JHEP 1404 (2014)067 arXiv:1402.6450

L.H & J.Beltran, Phys.Lett.B757 (2016) 405-411, arXiv:1602.03410

Allys, Peter, Rodriguez, JCAP 1602 (2016) 02, 004

$$Y = -\frac{1}{2} A_\mu A^\mu$$

$$\mathcal{L}_2 = G_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$

$$\mathcal{L}_3 = G_3(Y)\nabla_\mu A^\mu$$

$$\mathcal{L}_4 = G_4(Y)R + G_{4,Y}\left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]$$

$$\mathcal{L}_5 = G_5(Y)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,Y}\Big[(\nabla\cdot A)^3 + 2\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma - 3(\nabla\cdot A)\nabla_\rho A_\sigma \nabla^\sigma A^\rho\Big] - \tilde{G}_5(Y)\tilde{F}^{\alpha\mu}\tilde{F}^\beta{}_\mu \nabla_\alpha A_\beta$$

$$\mathcal{L}_6 = G_6(Y)L^{\mu\nu\alpha\beta}\nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{G_{6,Y}}{2}\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu \nabla_\beta A_\nu$$

Vector-Tensor Theories

Non-minimal couplings modifying the gravity sector

L. H., JCAP 1405, 015 (2014), arXiv:1402.7026

L.H & J.Beltran, Phys.Lett.B757 (2016) 405-411, arXiv:1602.03410

G.Tasinato JHEP 1404 (2014)067 arXiv:1402.6450

Allys, Peter, Rodriguez, JCAP 1602 (2016) 02, 004

$$Y = -\frac{1}{2}A_\mu A^\mu$$

$$\mathcal{L}_2 = G_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$

$$\mathcal{L}_3 = G_3(Y)\nabla_\mu A^\mu$$

$$\mathcal{L}_4 = G_4(Y)R + G_{4,Y}\left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]$$

$$\begin{aligned}\mathcal{L}_5 = {} & G_5(Y)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,Y}\Big[(\nabla\cdot A)^3 \\ & + 2\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma - 3(\nabla\cdot A)\nabla_\rho A_\sigma \nabla^\sigma A^\rho\Big] \\ & - \tilde{G}_5(Y)\tilde{F}^{\alpha\mu}\tilde{F}^\beta{}_\mu \nabla_\alpha A_\beta\end{aligned}$$

$$\mathcal{L}_6 = G_6(Y)L^{\mu\nu\alpha\beta}\nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{G_{6,Y}}{2}\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu \nabla_\beta A_\nu$$

Vector-Tensor Theories

L. H., JCAP 1405, 015 (2014), arXiv:1402.7026

G.Tasinato JHEP 1404 (2014)067 arXiv:1402.6450

L.H & J.Beltran, Phys.Lett.B757 (2016) 405-411, arXiv:1602.03410

Allys, Peter, Rodriguez, JCAP 1602 (2016) 02, 004

$$Y = -\frac{1}{2}A_\mu A^\mu$$

$$\mathcal{L}_2 = G_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$

$$\mathcal{L}_3 = G_3(Y)\nabla_\mu A^\mu$$

$$\mathcal{L}_4 = G_4(Y)R + G_{4,Y}\left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]$$

$$\mathcal{L}_5 = G_5(Y)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,Y}\Big[(\nabla \cdot A)^3 + 2\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma - 3(\nabla \cdot A)\nabla_\rho A_\sigma \nabla^\sigma A^\rho\Big] - \tilde{G}_5(Y)\tilde{F}^{\alpha\mu}\tilde{F}^\beta{}_\mu \nabla_\alpha A_\beta$$

$$\mathcal{L}_6 = G_6(Y)L^{\mu\nu\alpha\beta}\nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{G_{6,Y}}{2}\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu \nabla_\beta A_\nu$$

A_μ Vector Field (Generalized Proca)

It was believed that a single vector field is in tension with

A_μ Vector Field (Generalized Proca)

It was believed that a single vector field is in tension with

CP Cosmological Principle → Homogeneity & Isotropy

A_μ Vector Field (Generalized Proca)

It was believed that a single vector field is in tension with

CP Cosmological Principle → Homogeneity & Isotropy

and therefore not appropriate for dark energy applications.

Vector Field (Generalized Proca)

- **Generalized Proca iniated a radiacal change of view!**

Vector Field (Generalized Proca)

Generalized Proca iniated a radiacal change of view!

$$A_\mu = (A_0(t), 0, 0, 0)$$

Vector Field (Generalized Proca)

→ **Generalized Proca iniated a radiacal change of view!**

GR + $$\boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha}$$

Vector Field (Generalized Proca)

Generalized Proca iniated a radiacal change of view!

GR + $$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$$

G.Tasinato JHEP 1404 (2014)067
arXiv:1402.6450

L.H. & de Felice,Kase,Mukohyama,
Tsujikawa,Zhang, JCAP
1606,2016,06,048, arXiv:1603.05806

- Dark Energy fixed point

Vector Field (Generalized Proca)

Generalized Proca iniated a radiacal change of view!

GR + $$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$$

- **Dark Energy fixed point**

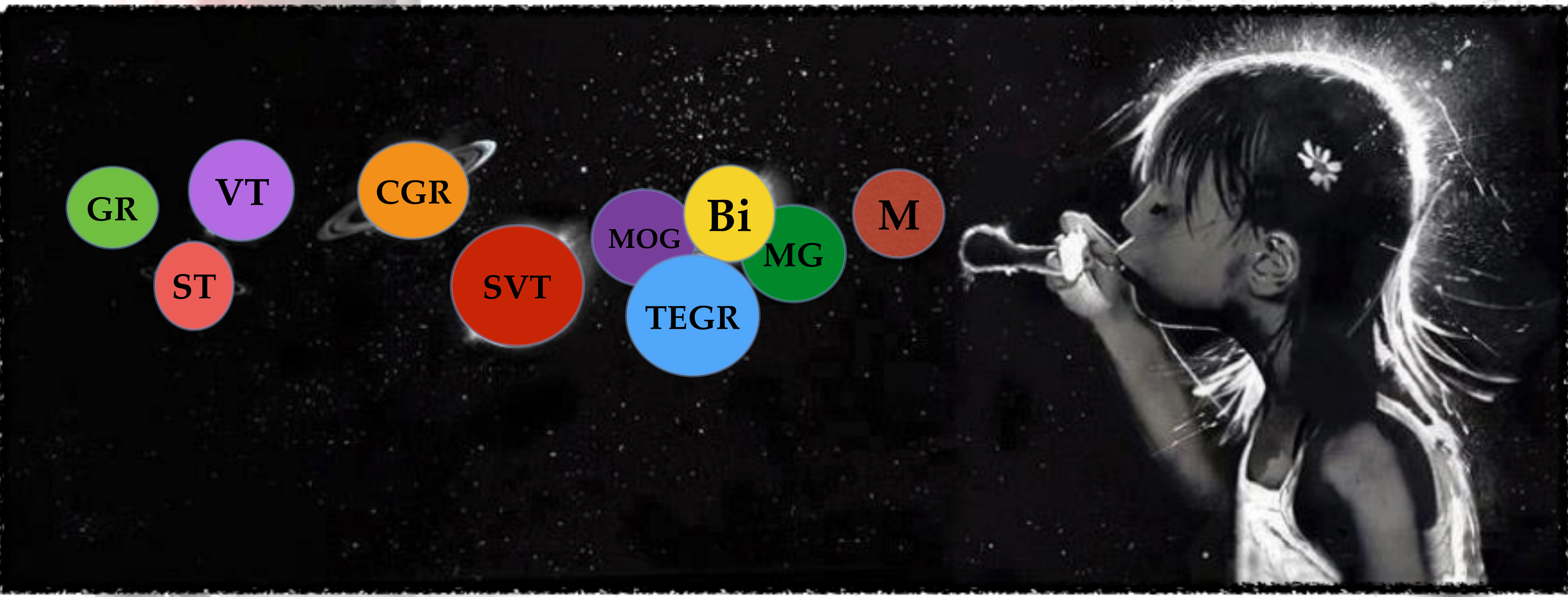
G.Tasinato JHEP 1404 (2014)067 arXiv:1402.6450

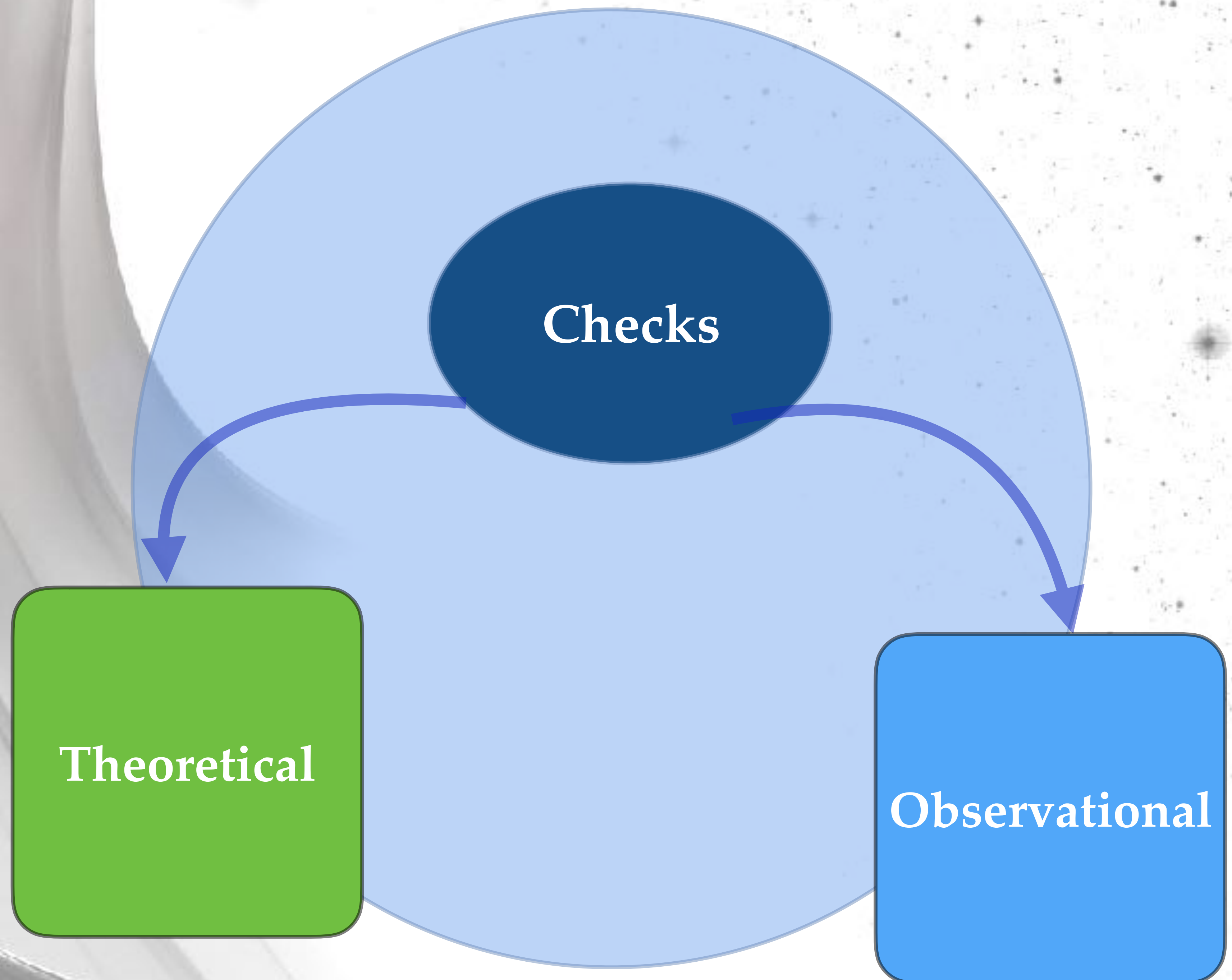
L.H. & de Felice,Kase,Mukohyama, Tsujikawa,Zhang, JCAP 1606,2016,06,048, arXiv:1603.05806

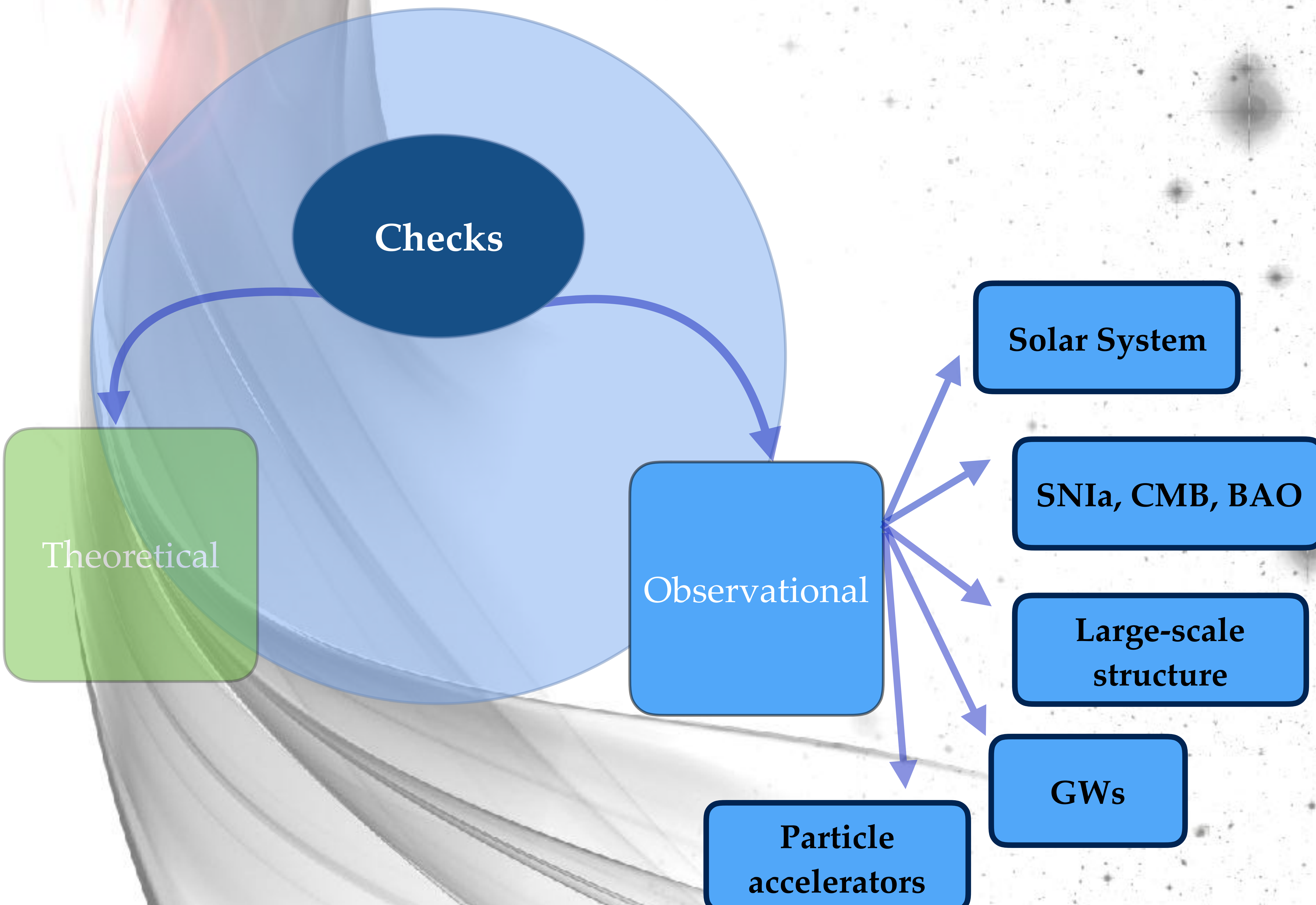
- **Reduces the H_0 tension and delivers a better fit to data**

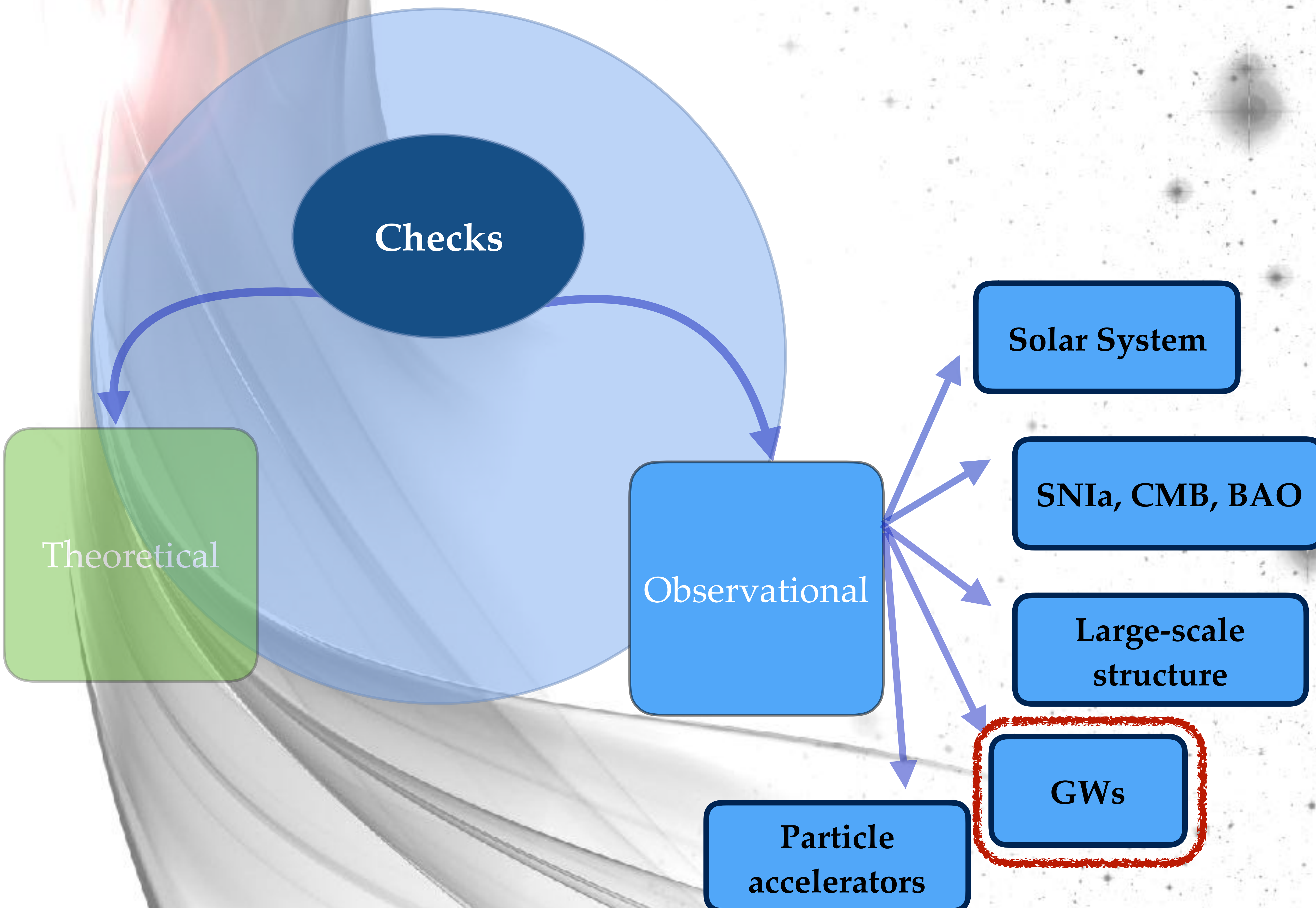
L.H. & de Felice,Tsujikawa, PRD95 (2017)12, 123540, arXiv:1703.09573

Cosmological Models




Checks
Theoretical
Observational


Checks
Theoretical
Observational
Solar System
SNIa, CMB, BAO
Large-scale structure
GWs
Particle accelerators


Checks
Theoretical
Observational
Solar System
SNIa, CMB, BAO
Large-scale structure
GWs
Particle accelerators

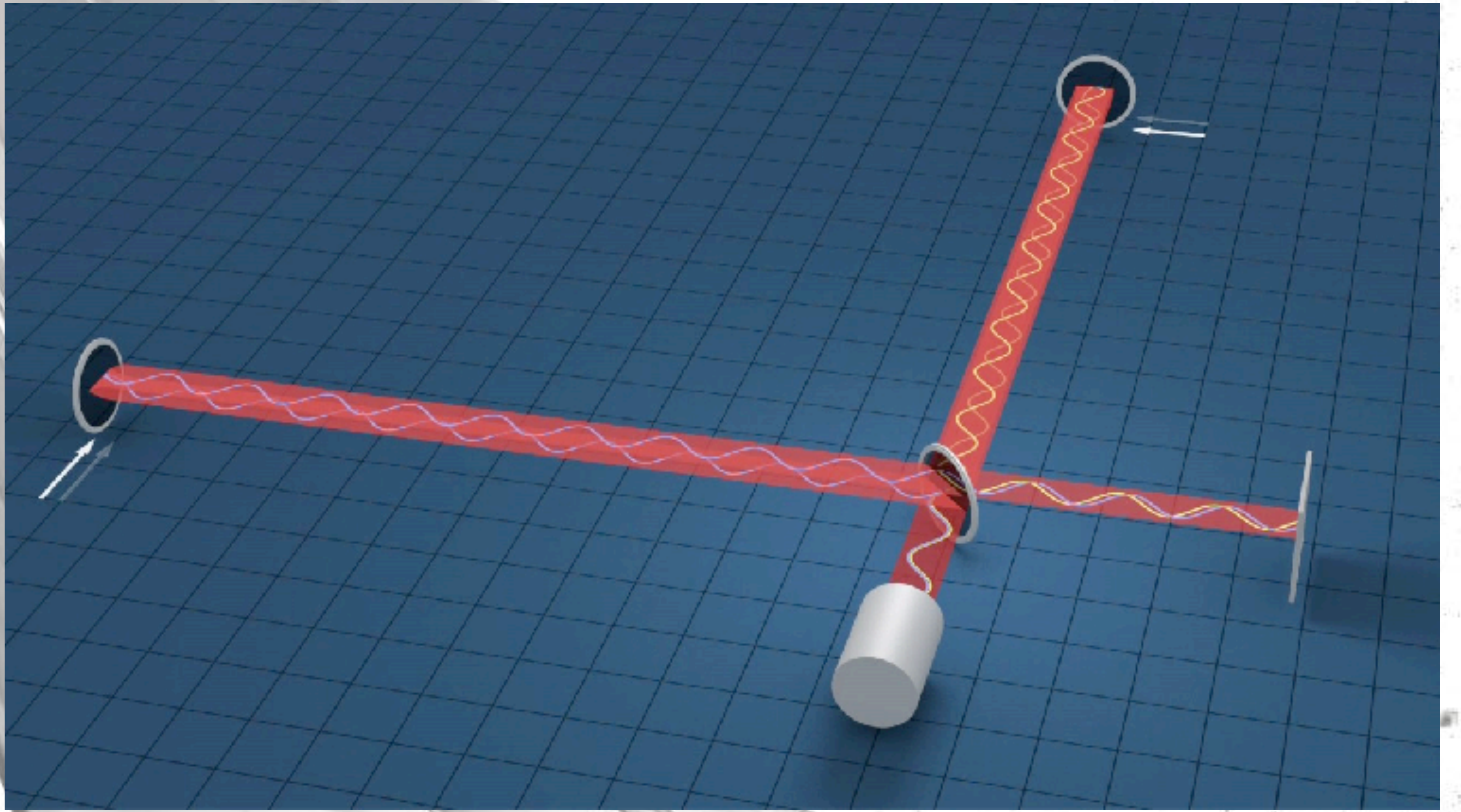
What is a Gravitational Wave?

GWs are ripples of space-time

Giving rise to changes in the lengths and shapes

GWs are ripples of space-time

Giving rise to changes in the lengths and shapes



GWs are ripples of space-time

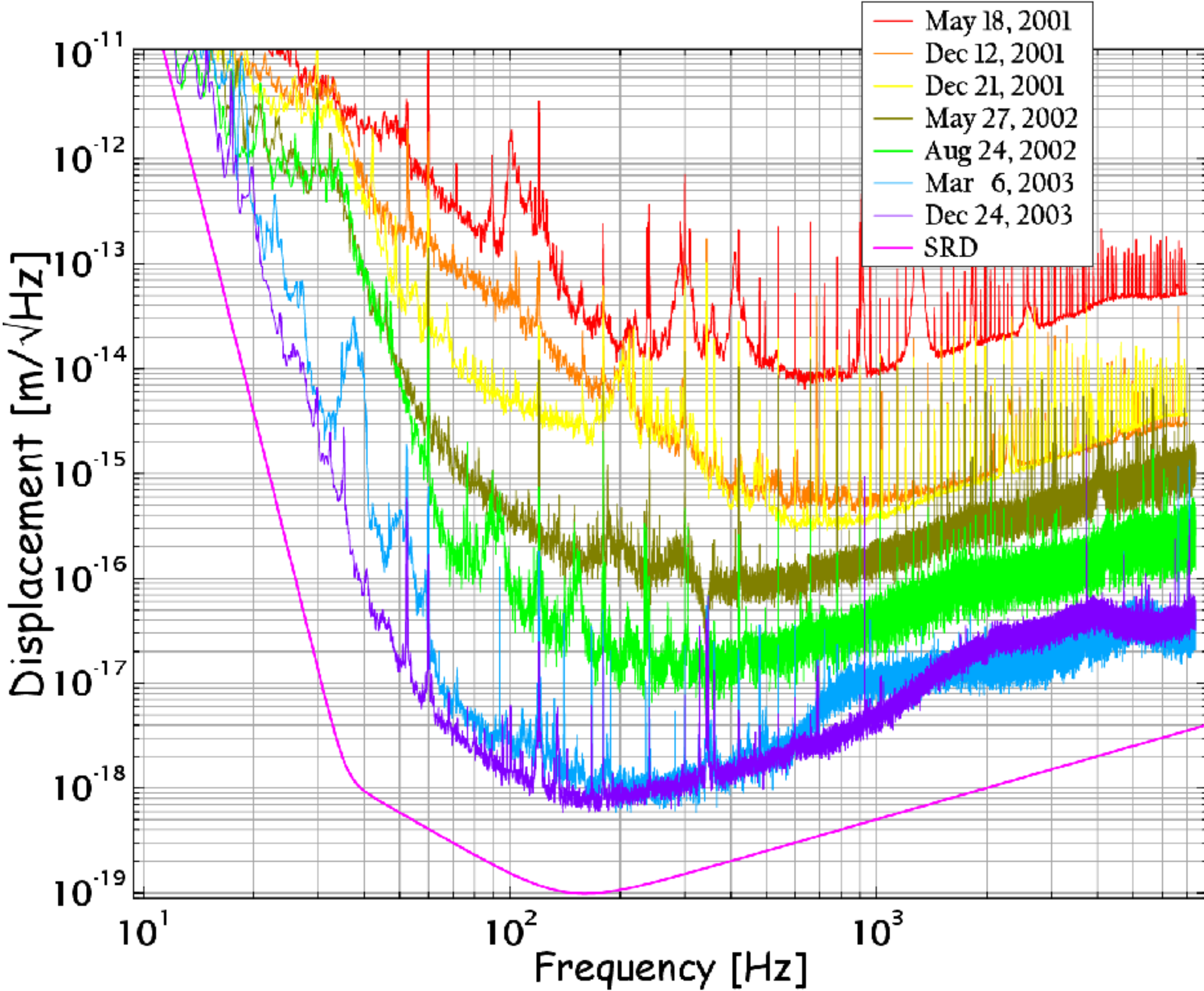
Giving rise to changes in the lengths and shapes

The measurement challenge

$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

$$L = 4\mathrm{km}$$

$$\Delta L = 4 \times 10^{-18} \text{ meters}$$



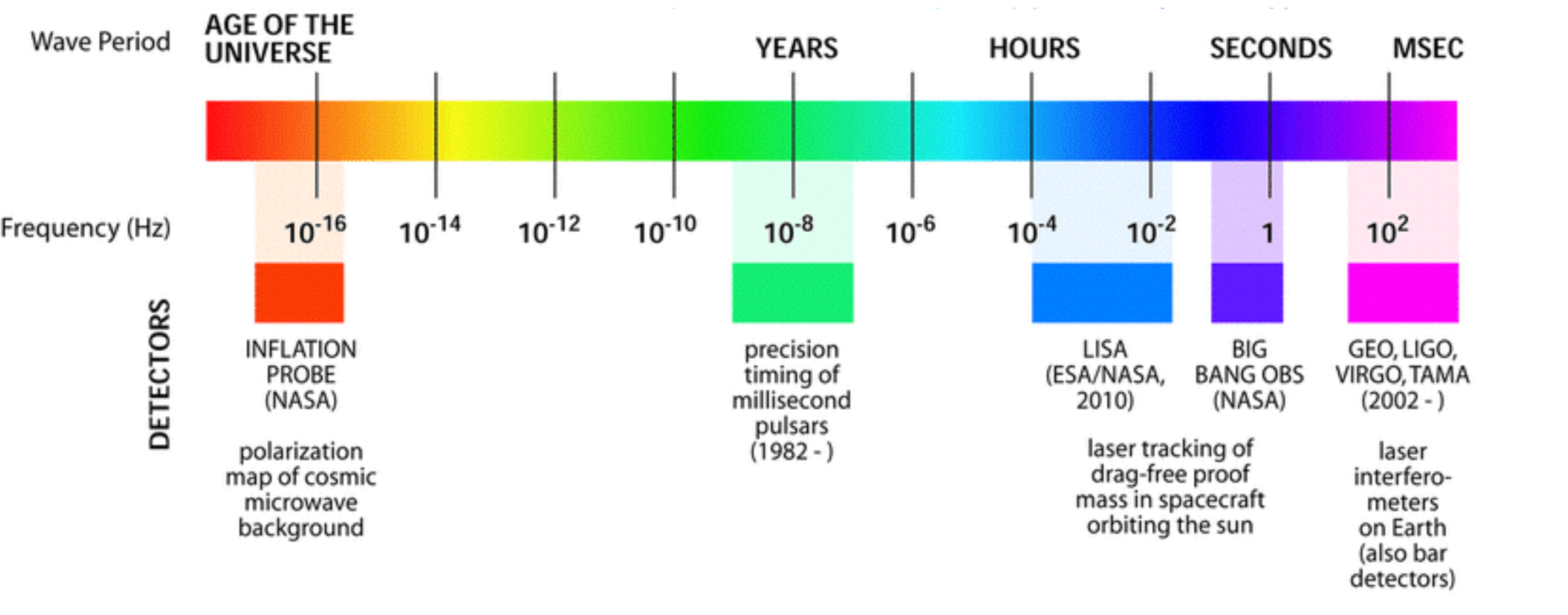
May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
SRD
Displacement [m/√Hz]
Frequency [Hz]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{1}
10^{2}
10^{3}

GWs are ripples of space-time

Giving rise to changes in the lengths and shapes

Like the electromagnetic spectrum there is the GW spectrum

THE GRAVITATIONAL WAVE SPECTRUM



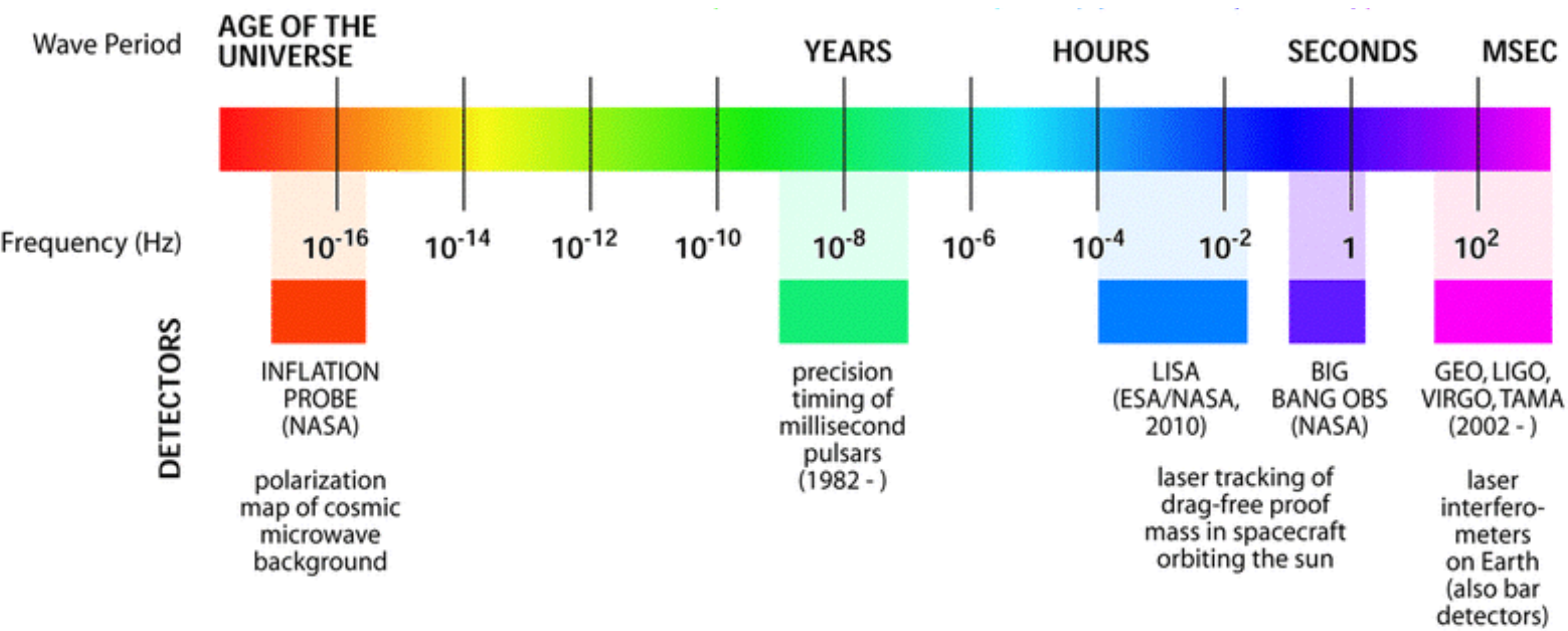
Pulsar Timing Array

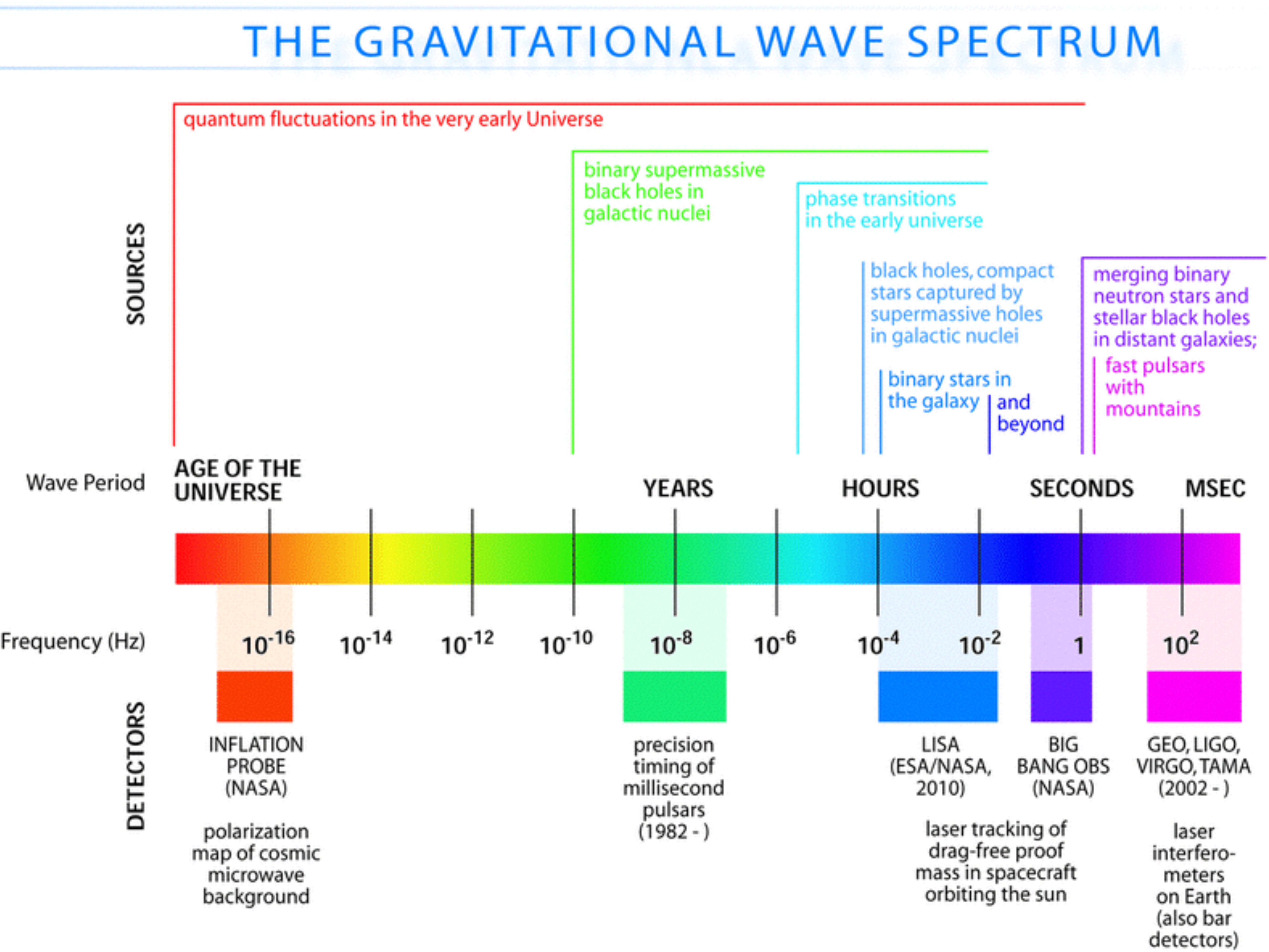
a set of pulsars is analysed to search for correlated signatures in the pulse arrival times

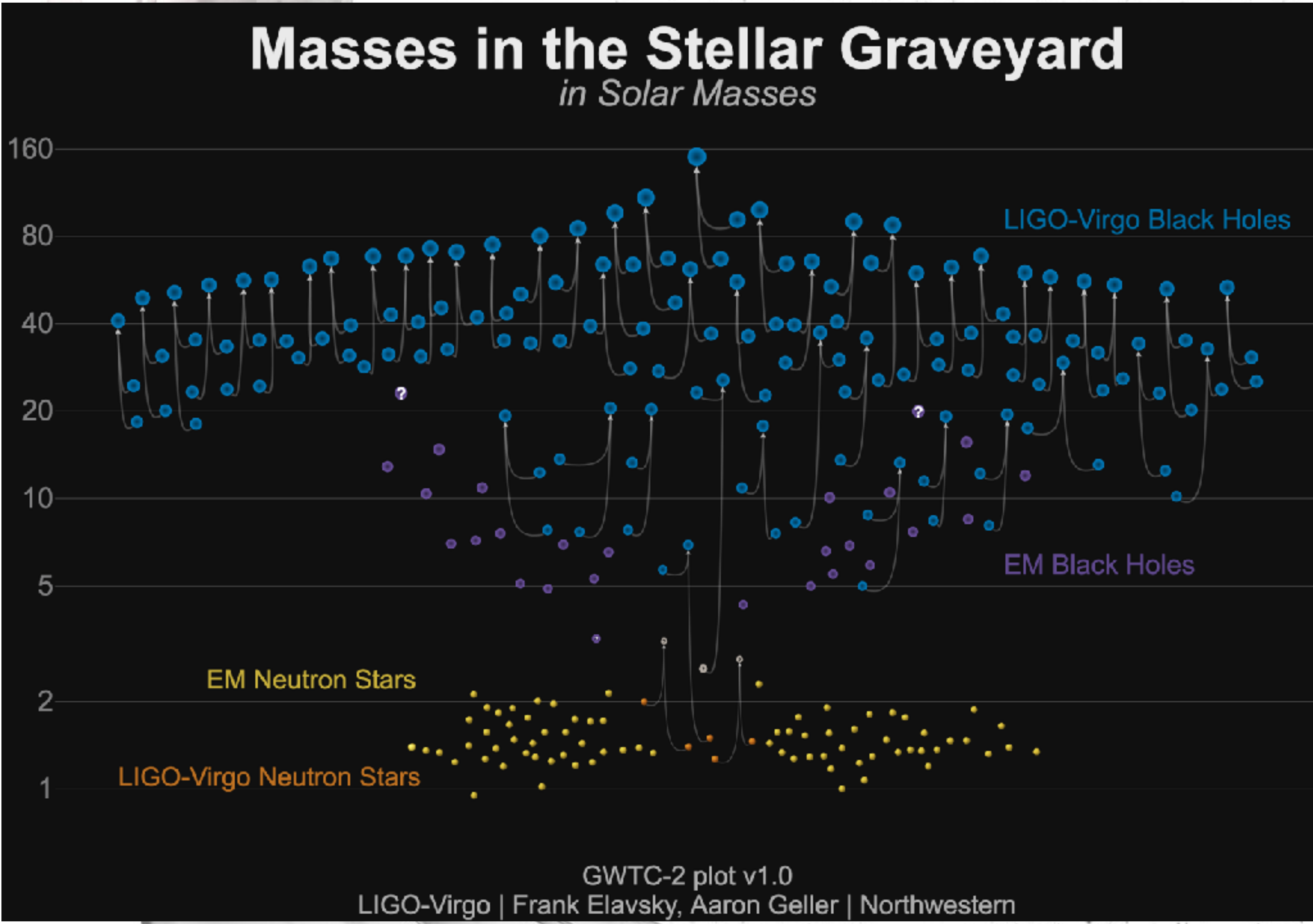
THE GRAVITATIONAL WAVE SPECTRUM

Different wavelengths probe BHs of different sizes

Neutron stars and BHs at different separation and lifetimes




THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
BIG BANG OBS (NASA)
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interfero-meters on Earth (also bar detectors)


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Gravitational Waveform

We test gravity by the shapes of the gravitational waveform

Gravitational Waveform

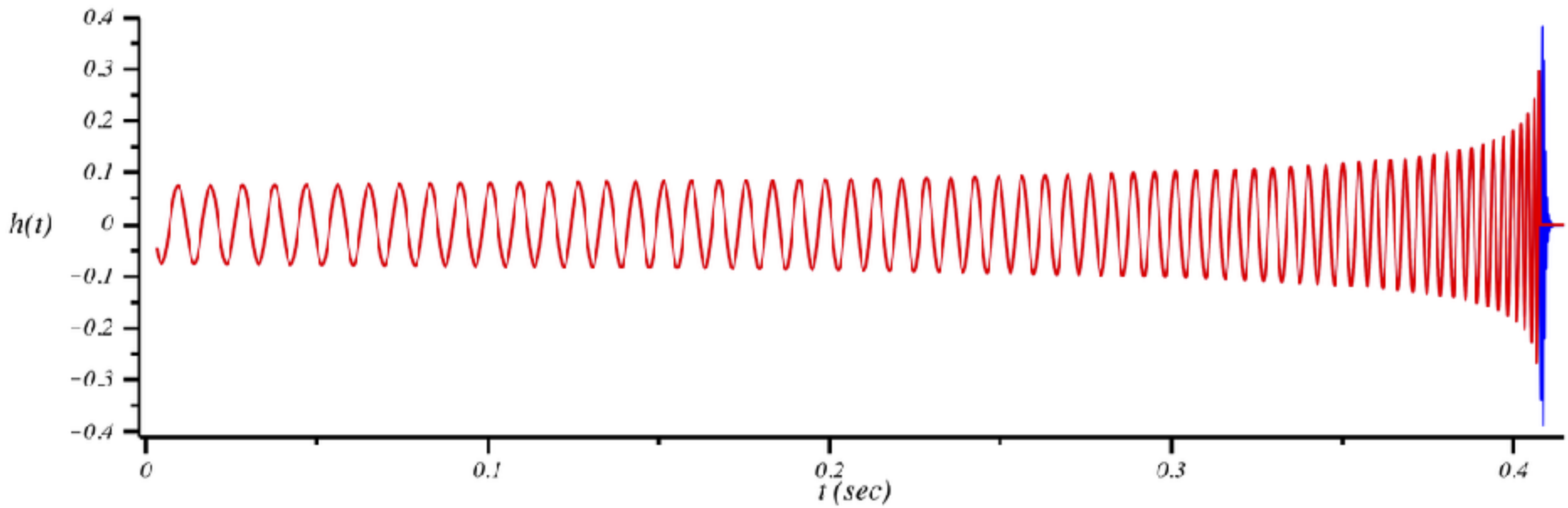
Different wavelengths probe BHs of different sizes
Neutron stars and BHs at different separation and lifetimes

$$w = \sqrt{\frac{GM}{r^3}}$$

$$f_{\mathrm{GW}} = \frac{w}{\pi}$$

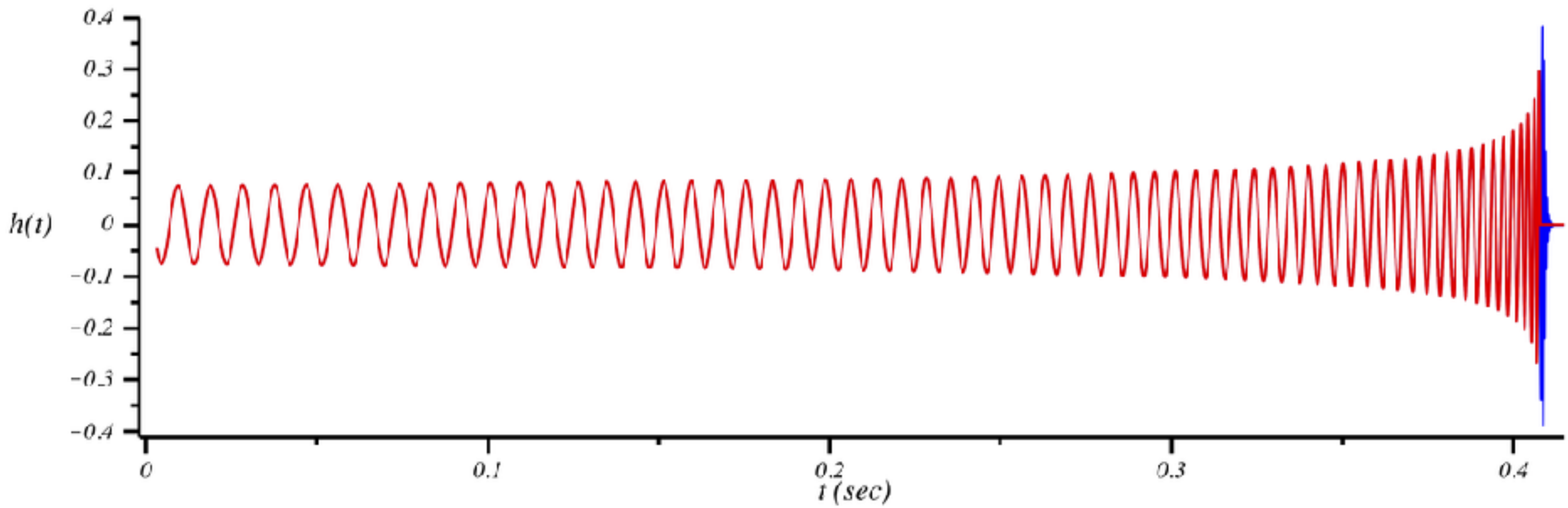
Gravitational Waveform

From frequency evolution one can infer masses



Gravitational Waveform

From frequency evolution one can infer masses

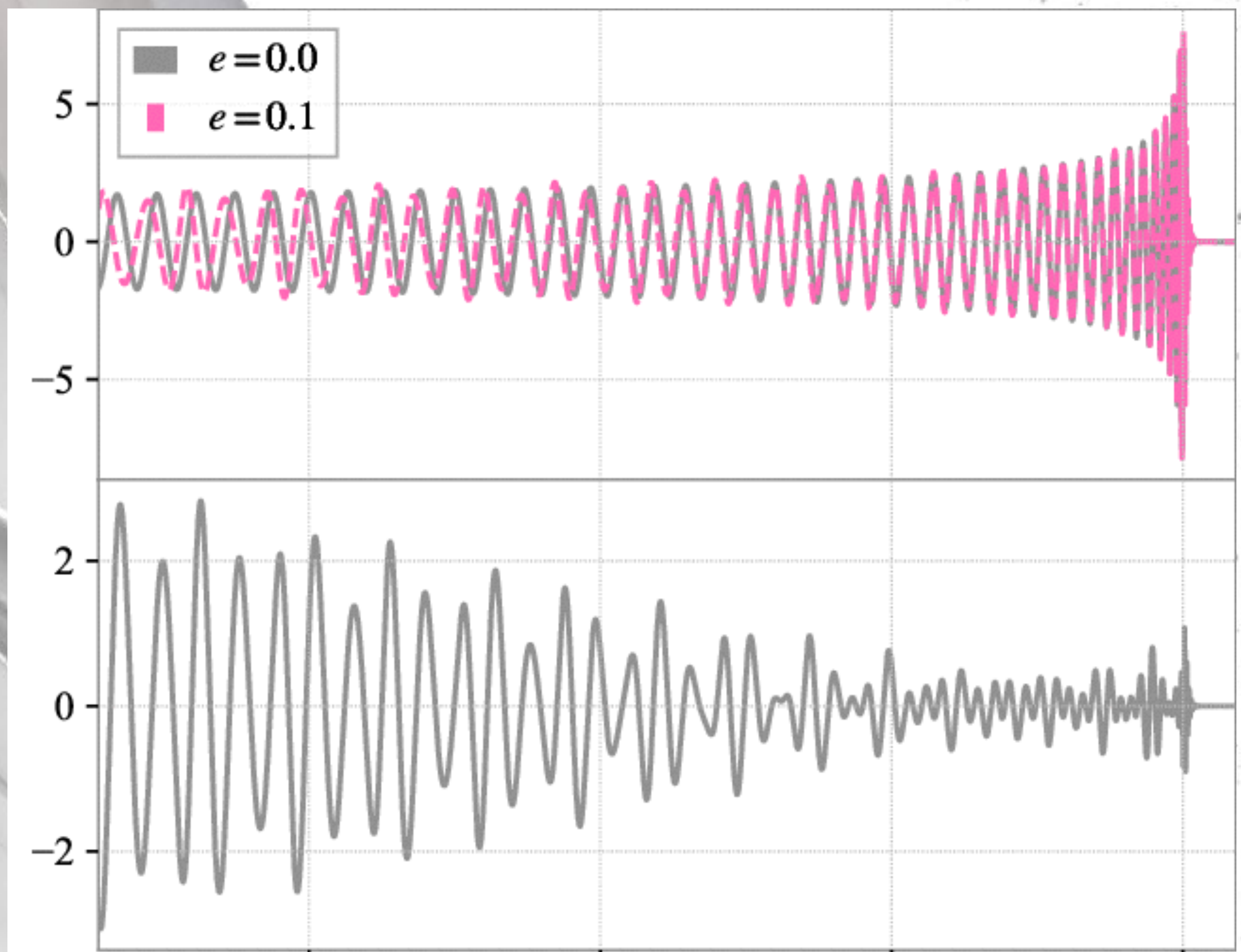


From amplitude and masses one infers distance

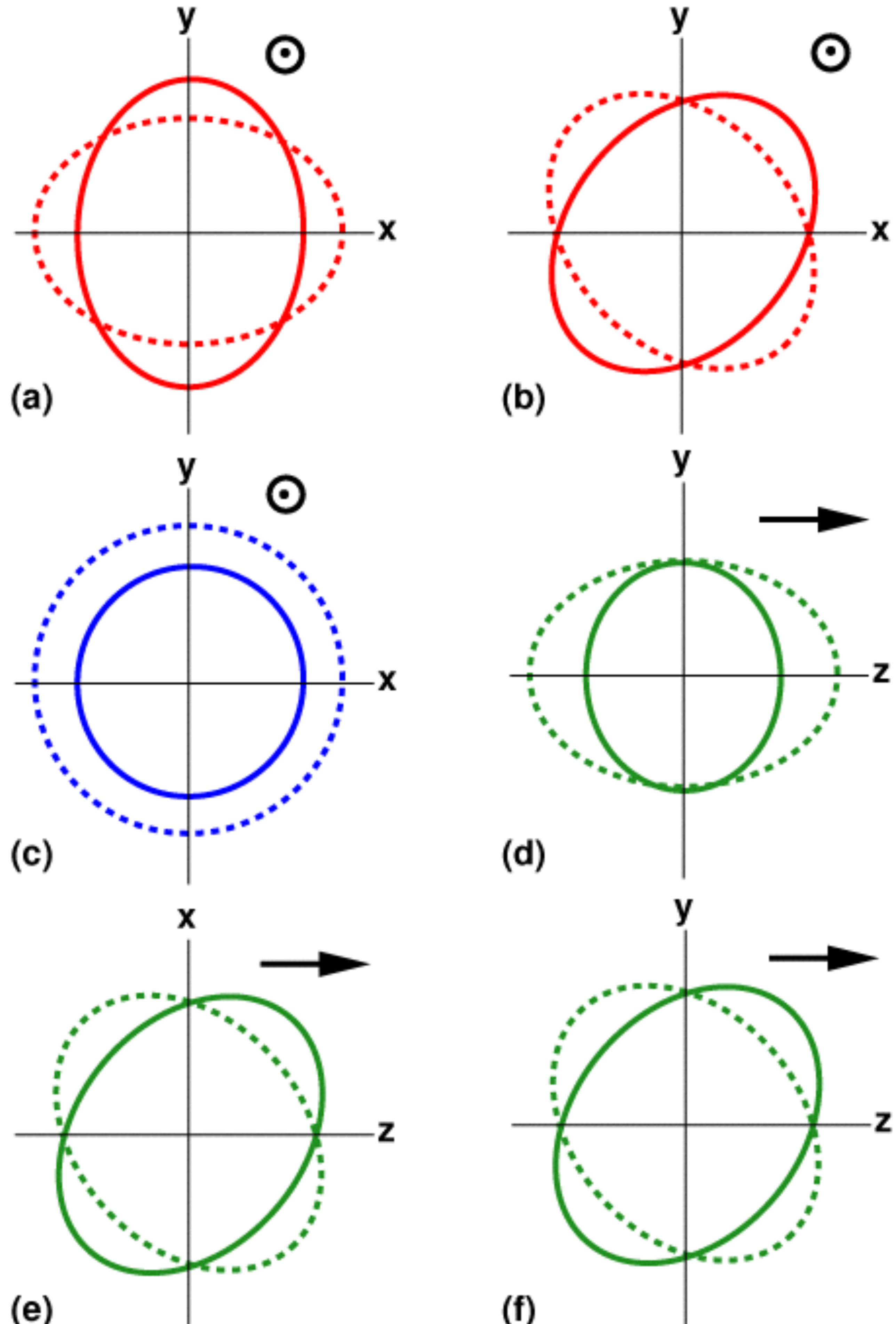
From time of arrival, amplitude and phase at detectors one infers sky location.

Gravitational Waveform

From modulations of amplitude and phase one infers spins and eccentricity



Gravitational–Wave Polarization

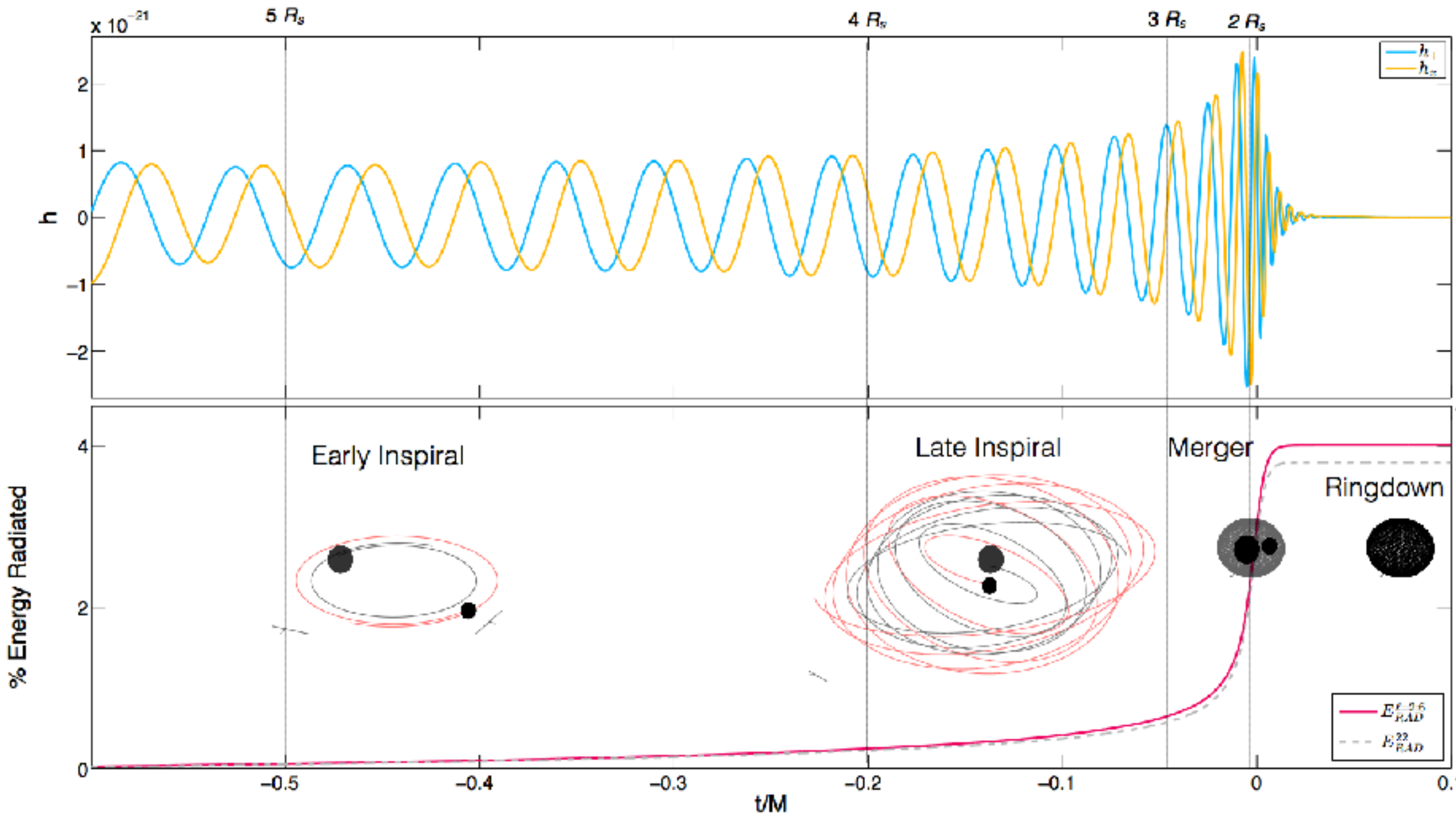


Gravitational Waveform

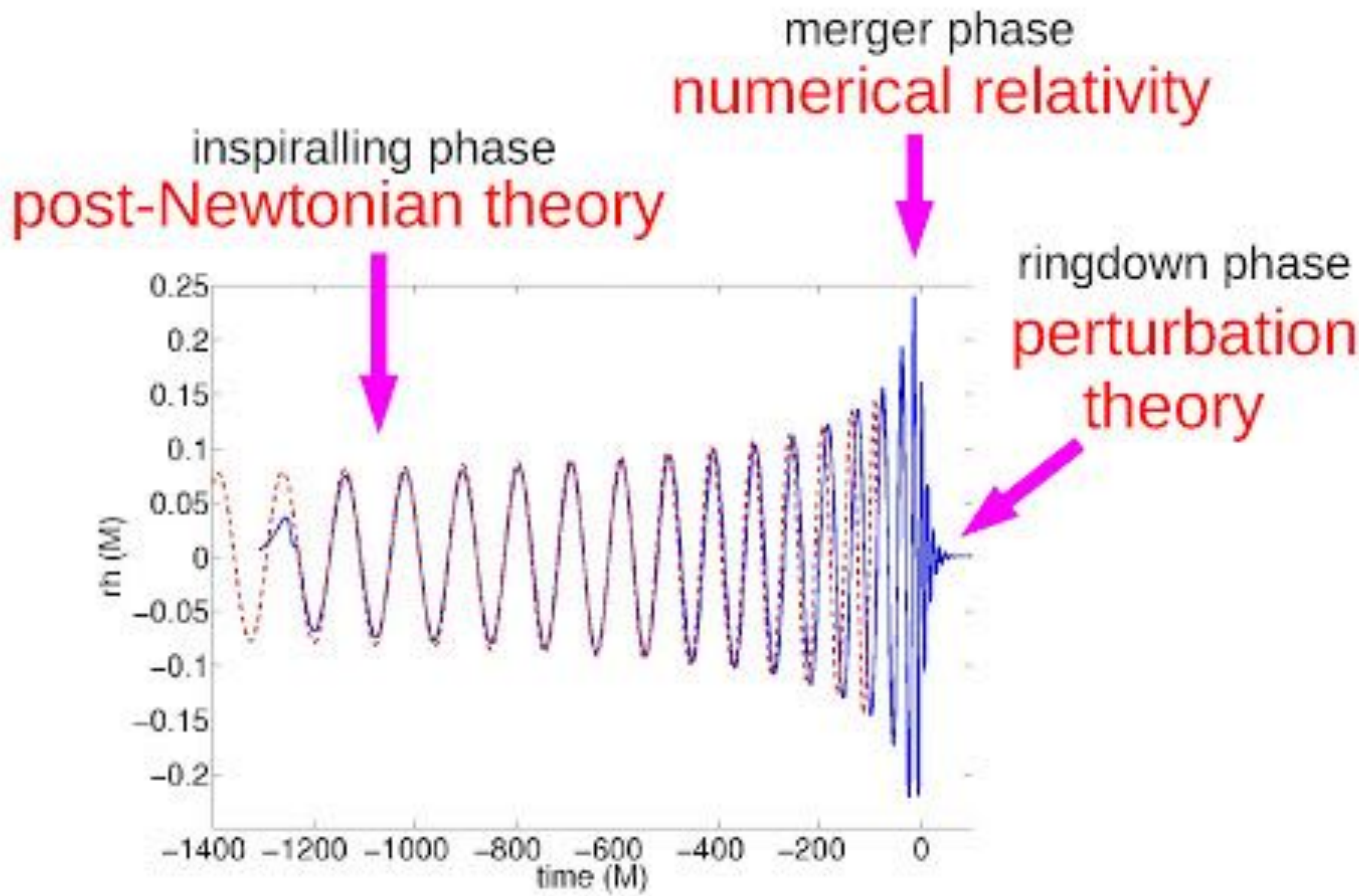
We have to solve Einstein's field equations in order to generate the GW waveform

$$G_{\mu\nu} = \frac{T_{\mu\nu}}{M_{\rm Pl}^2}$$

Gravitational Waveform



Gravitational Waveform



Gravitational Waveform

Linear regime

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon\, h_{\mu\nu}$$

Gravitational Waveform

Linear regime

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon\, h_{\mu\nu}$$

$$S_T^{(2)} = \sum_{\lambda} \int d^4x a^3 M_{\rm Pl}^2 \left\{ \dot{h}_\lambda^2 - \frac{c_T^2}{a^2} (\partial h_\lambda)^2 \right\}$$

Gravitational Waveform

Linear regime

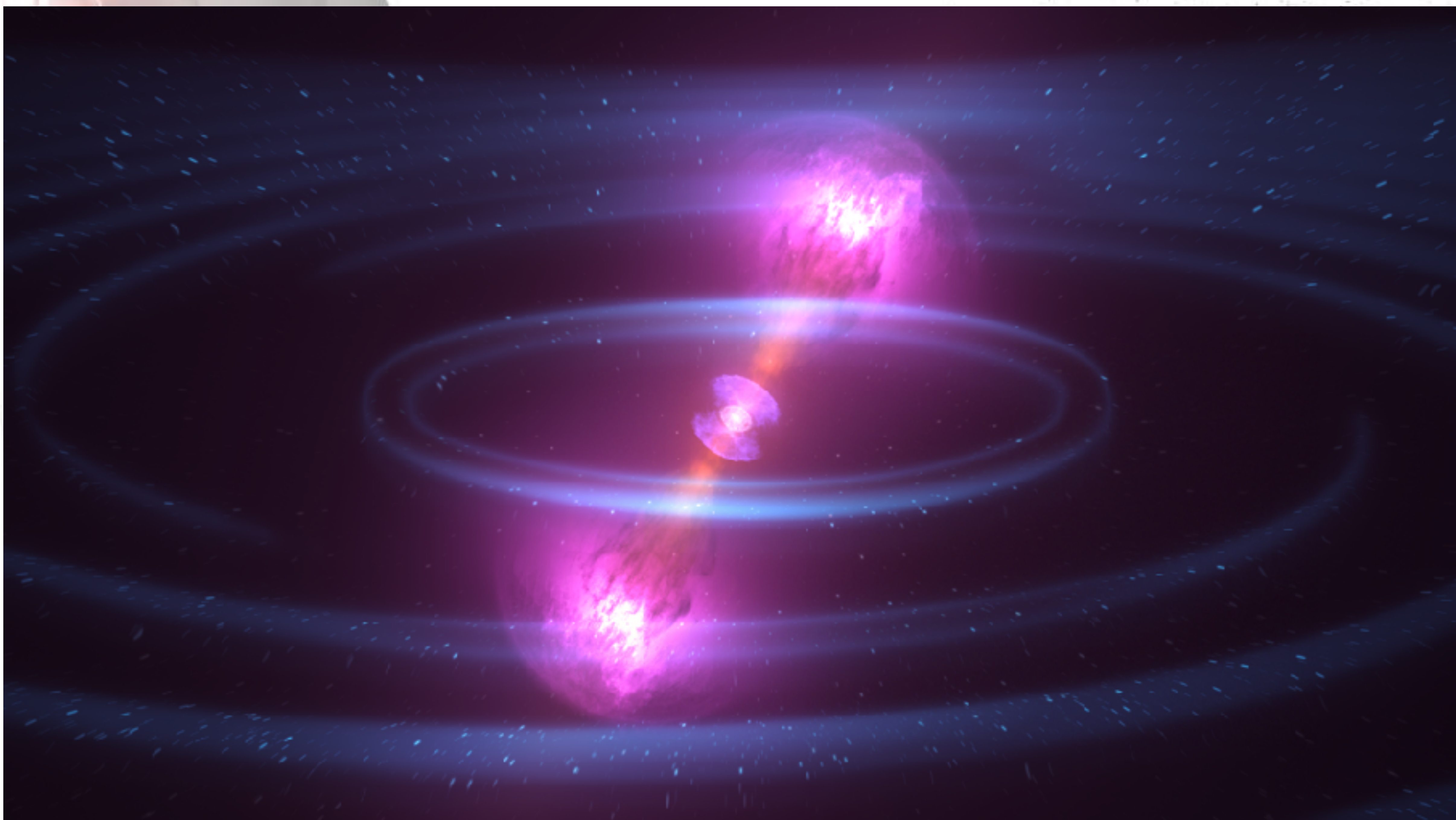
$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon\, h_{\mu\nu}$$

$$S_T^{(2)} = \sum_\lambda \int d^4x a^3 M_{\rm Pl}^2 \left\{ \dot{h}_\lambda^2 - \frac{c_T^2}{a^2}(\partial h_\lambda)^2 \right\}$$

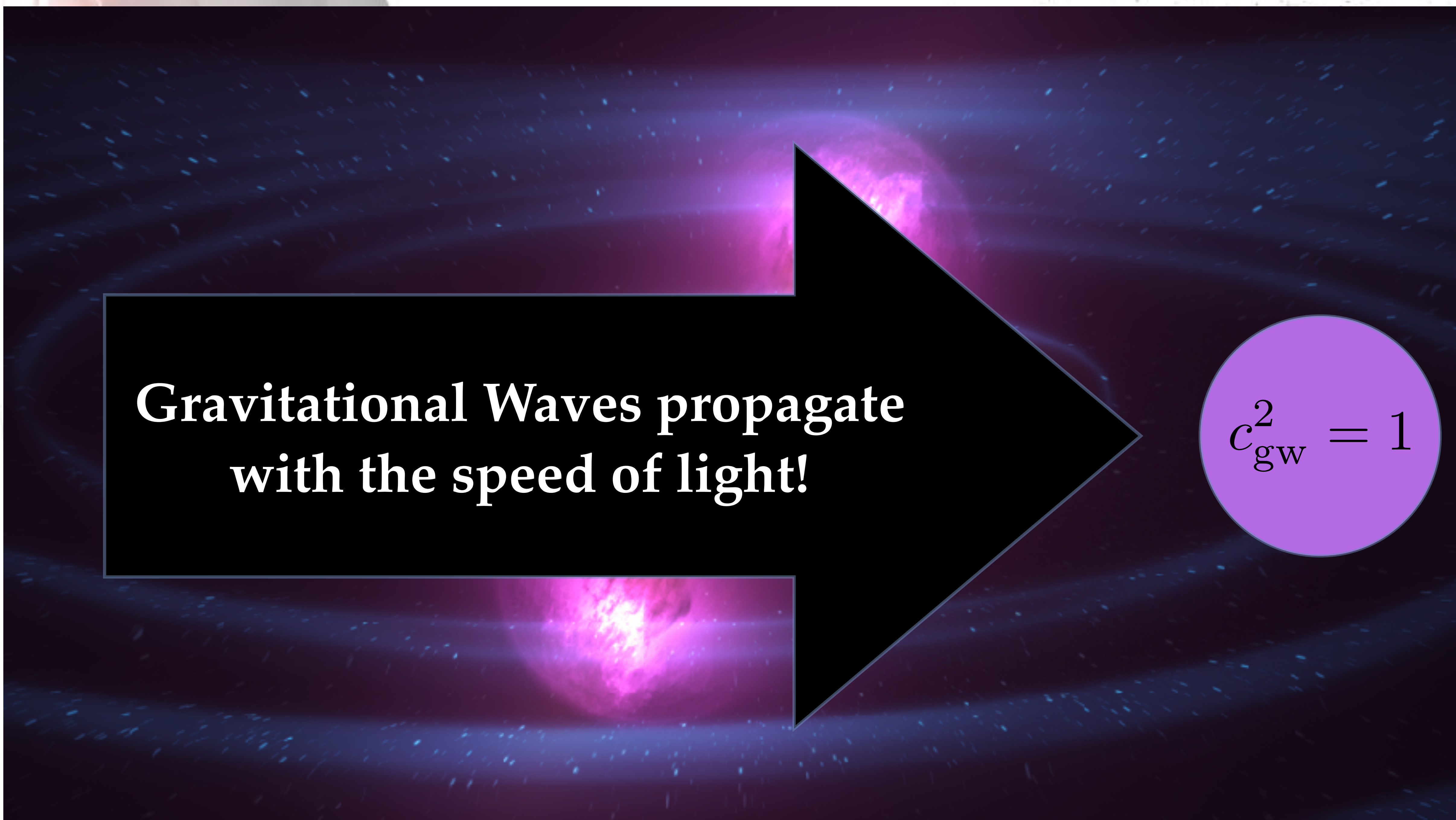
GW strain

$$h_{\rm GW}(f) = A_{\rm GW}(f) e^{i\psi_{\rm GW}(f)}$$

Multi-messenger: GWs & EM



Multi-messenger: GWs & EM



Gravitational Waveform

Linear regime

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon\, h_{\mu\nu}$$

$$S_T^{(2)} = \sum_\lambda \int d^4x a^3 M_{\rm Pl}^2 \left\{ \dot{h}_\lambda^2 - \frac{c_T^2}{a^2} (\partial h_\lambda)^2 \right\}$$

$c \pm 10^{-15}$

Scalar Field (Horndeski)

π

Luminal GWs propagation

Scalar Field (Horndeski)

π

Luminal GWs propagation

$$\mathcal{L}_2 = K(\pi, X)$$

$$\mathcal{L}_3 = G_3(\pi, X)[\Pi]$$

$$\mathcal{L}_4 = G_4(\pi, X)R + \cancel{G_{4,X}([\Pi]^2 - [\Pi^2])}$$

$$\mathcal{L}_5 = \cancel{G_5(\pi, X)G_{\mu\nu}\Pi^{\mu\nu} - \frac{G_{5,X}}{6}([\Pi]^3 - 3[\Pi][\Pi^2] + 2[\Pi^2])}$$

$$c_{\mathrm{gw}}^2 = 1$$

P. Creminelli, F. Vernizzi, PRL119 (2017) 251302

J. M. Ezquiaga, M. Zumalacarregui, PRL119 (2017) 251304

A_μ

Vector Field (Generalized Proca)

Luminal GWs propagation

$$\mathcal{L}_2 = G_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$

$$\mathcal{L}_3 = G_3(Y)\nabla_\mu A^\mu$$

$$\mathcal{L}_4 = G_4(Y)R + \cancel{G_{4,Y}\left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]}$$

$$\mathcal{L}_5 = \cancel{G_5(Y)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,Y}\Big[(\nabla \cdot A)^3} \\ \cancel{+ 2\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma - 3(\nabla \cdot A)\nabla_\rho A_\sigma \nabla^\sigma A^\rho\Big]} \\ - \tilde{G}_5(Y)\tilde{F}^{\alpha\mu}\tilde{F}^{\beta}{}_{\mu}\nabla_\alpha A_\beta$$

$$\mathcal{L}_6 = G_6(Y)L^{\mu\nu\alpha\beta}\nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{G_{6,Y}}{2}\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu \nabla_\beta A_\nu$$

$$c_{\mathrm{gw}}^2 = 1$$

A_μ

Vector Field (Generalized Proca)

Luminal GWs propagation

$$\mathcal{L}_2 = G_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$

$$\mathcal{L}_3 = G_3(Y)\nabla_\mu A^\mu$$

$$\mathcal{L}_4 = G_4(Y)R + \cancel{G_{4,Y}\left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]}$$

$$\mathcal{L}_5 = \cancel{G_5(Y)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,Y}\Big[(\nabla\cdot A)^3}$$
$$\cancel{+ 2\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma - 3(\nabla\cdot A)\nabla_\rho A_\sigma \nabla^\sigma A^\rho}\Big]$$
$$- \tilde{G}_5(Y)\tilde{F}^{\alpha\mu}\tilde{F}^{\beta}{}_{\mu}\nabla_\alpha A_\beta$$

$$\mathcal{L}_6 = G_6(Y)L^{\mu\nu\alpha\beta}\nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{G_{6,Y}}{2}\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu \nabla_\beta A_\nu$$

$$c_{\rm gw}^2 = 1$$

A_μ

Vector Field (Generalized Proca)

No effects on GWs, but on scalar perturbations!

$$\mathcal{L}_2 = G_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$
$$\mathcal{L}_3 = G_3(Y)\nabla_\mu A^\mu$$
$$\mathcal{L}_4 = G_4(Y)R + \cancel{G_{4,Y}\left[(\nabla_\mu A^\mu)^2 - \nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]}$$
$$\mathcal{L}_5 = \cancel{G_5(Y)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,Y}\Big[(\nabla\cdot A)^3}$$
$$\cancel{+2\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma - 3(\nabla\cdot A)\nabla_\rho A_\sigma \nabla^\sigma A^\rho\Big]}$$
$$-\tilde{G}_5(Y)\tilde{F}^{\alpha\mu}\tilde{F}^{\beta}{}_{\mu}\nabla_\alpha A_\beta$$
$$\mathcal{L}_6 = G_6(Y)L^{\mu\nu\alpha\beta}\nabla_\mu A_\nu \nabla_\alpha A_\beta + \frac{G_{6,Y}}{2}\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\nabla_\alpha A_\mu \nabla_\beta A_\nu$$

$$c_{\rm gw}^2 = 1$$

Probing cosmological fields with GWs oscillations

Probing cosmological fields with GWs oscillations

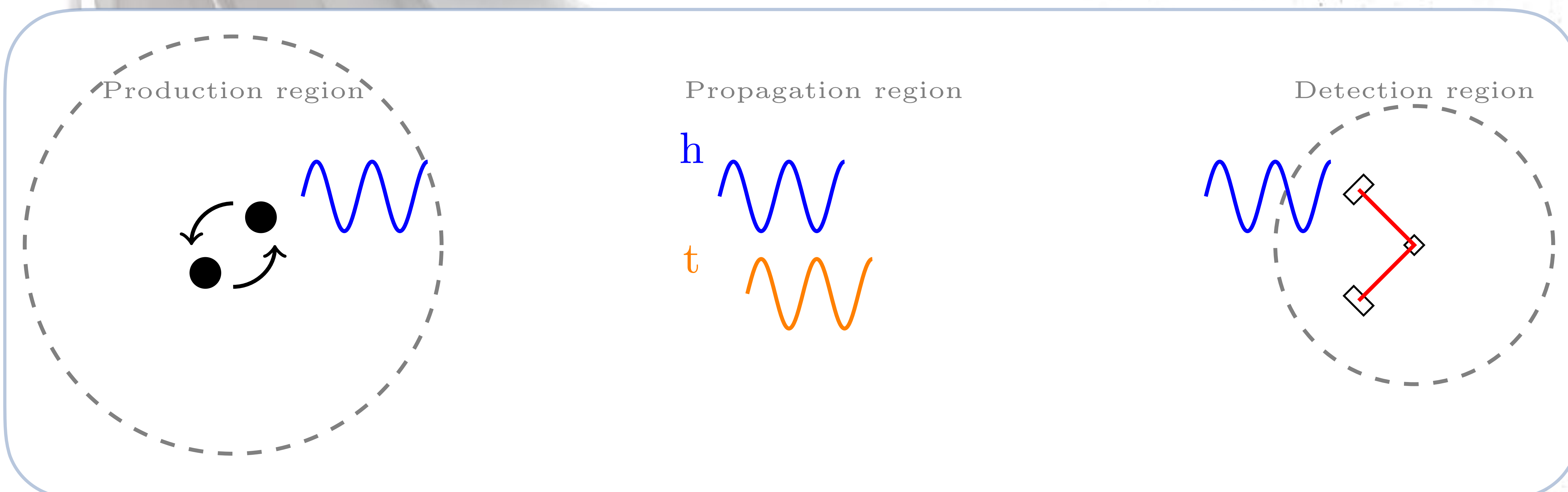
GR + **YM**

$g_{\mu\nu}$ A^a_μ

Probing cosmological fields with GWs oscillations

GR + **YM**

$g_{\mu\nu}$ A_μ^a

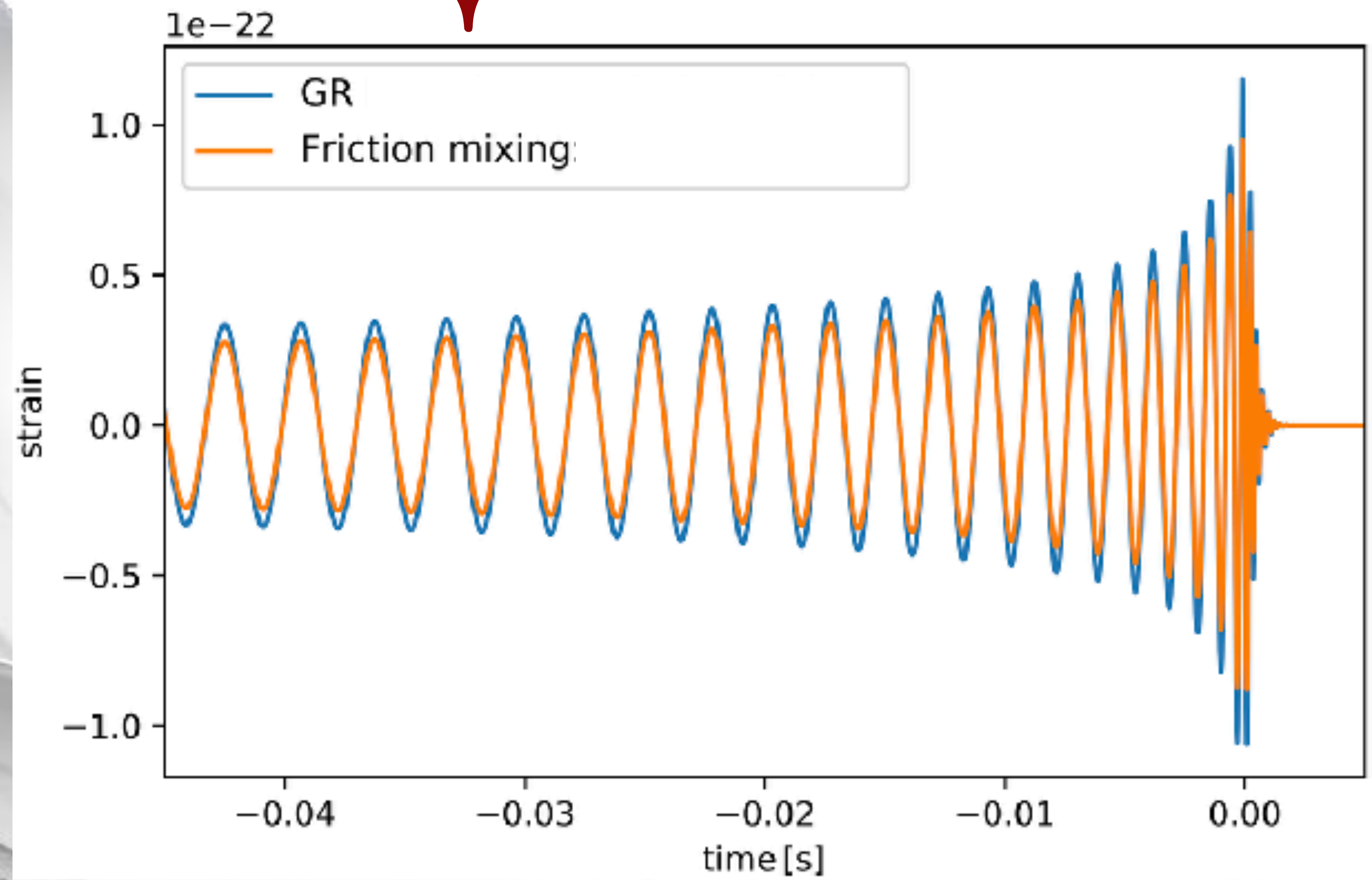


Probing cosmological fields with GWs oscillations

GR + **YM**

$g_{\mu\nu}$ A^a_μ

$$\left[\frac{\mathrm{d}^2}{\mathrm{d}\eta^2} + \begin{pmatrix} 0 & -2\alpha \\ 2\alpha & 4\Delta\nu \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}\eta} + \begin{pmatrix} c_h^2 & 0 \\ 0 & c_t^2 \end{pmatrix} k^2 \right] \begin{pmatrix} h \\ t \end{pmatrix} = 0$$



L.H & J.Beltran, J. Ezquiaga, arXiv:1912.06104

GW luminosity distance

GW luminosity distance

$$d_{\mathrm{L}}^{\mathrm{GW}} = \frac{M_c^{5/3} f^{2/3}}{|h_{+,\times}|} F_{+,\times}$$

GW luminosity distance

$$d_{\mathrm{L}}^{\mathrm{GW}} = \frac{M_c^{5/3} f^{2/3}}{|h_{+,\times}|} F_{+,\times}$$

In standard $\Lambda\mathrm{CDM}$ **model**

$$d_{\mathrm{L}}^{\mathrm{GW}} = d_{\mathrm{L}}^{\mathrm{EM}} = (1+z)\int_0^z \frac{c}{H(z)} dz$$

GW luminosity distance

$$d_{\mathrm{L}}^{\mathrm{GW}} = \frac{M_c^{5/3} f^{2/3}}{|h_{+,\times}|} F_{+,\times}$$

In standard $\Lambda\mathrm{CDM}$ **model**

$$d_{\mathrm{L}}^{\mathrm{GW}} = d_{\mathrm{L}}^{\mathrm{EM}} = (1+z)\int_0^z \frac{c}{H(z)} dz$$

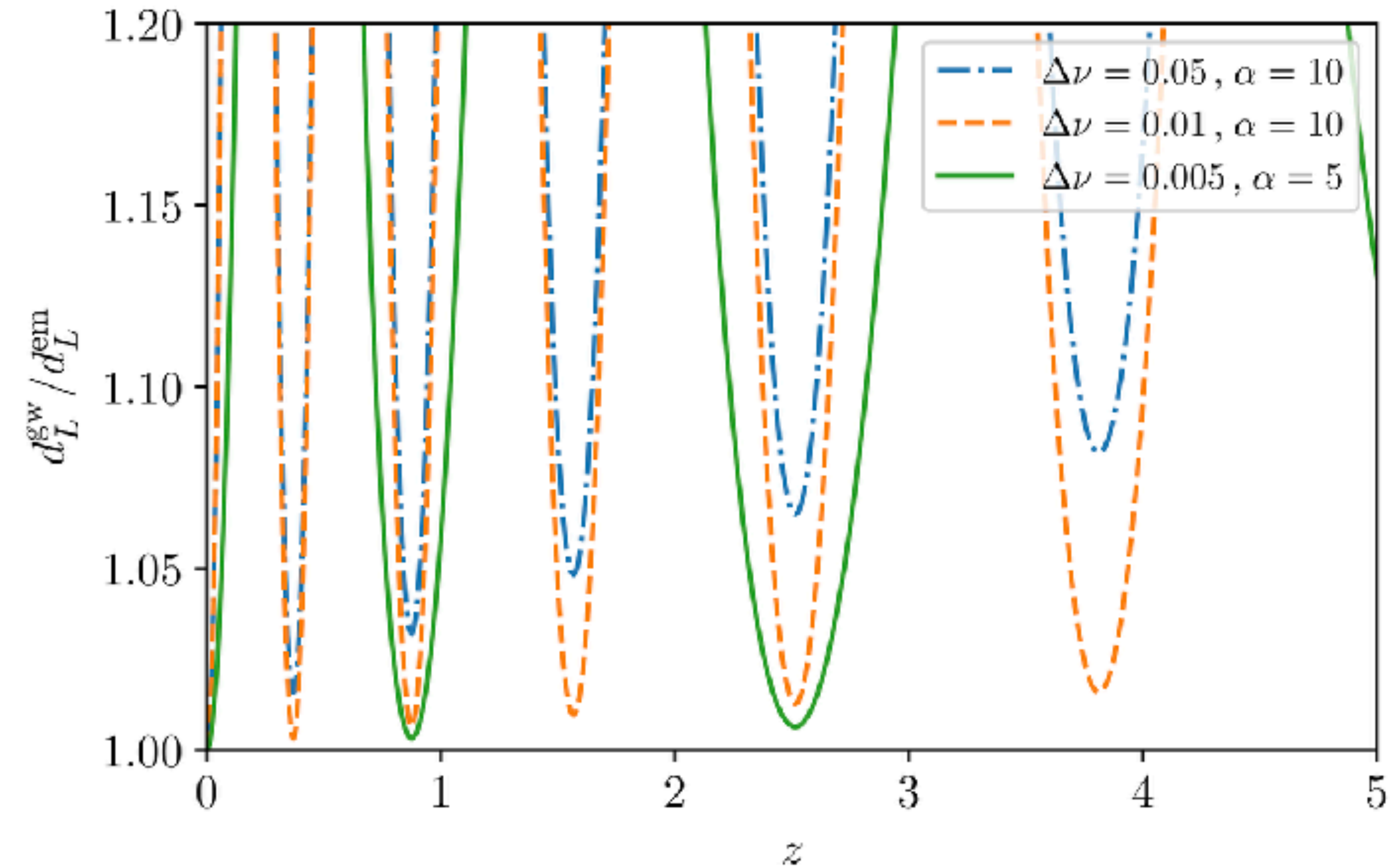
GWs as standard sirens!

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_{\mathrm{DE}}(z)}$$

GW luminosity distance

GR + YM

$g_{\mu\nu}$ A^a_μ

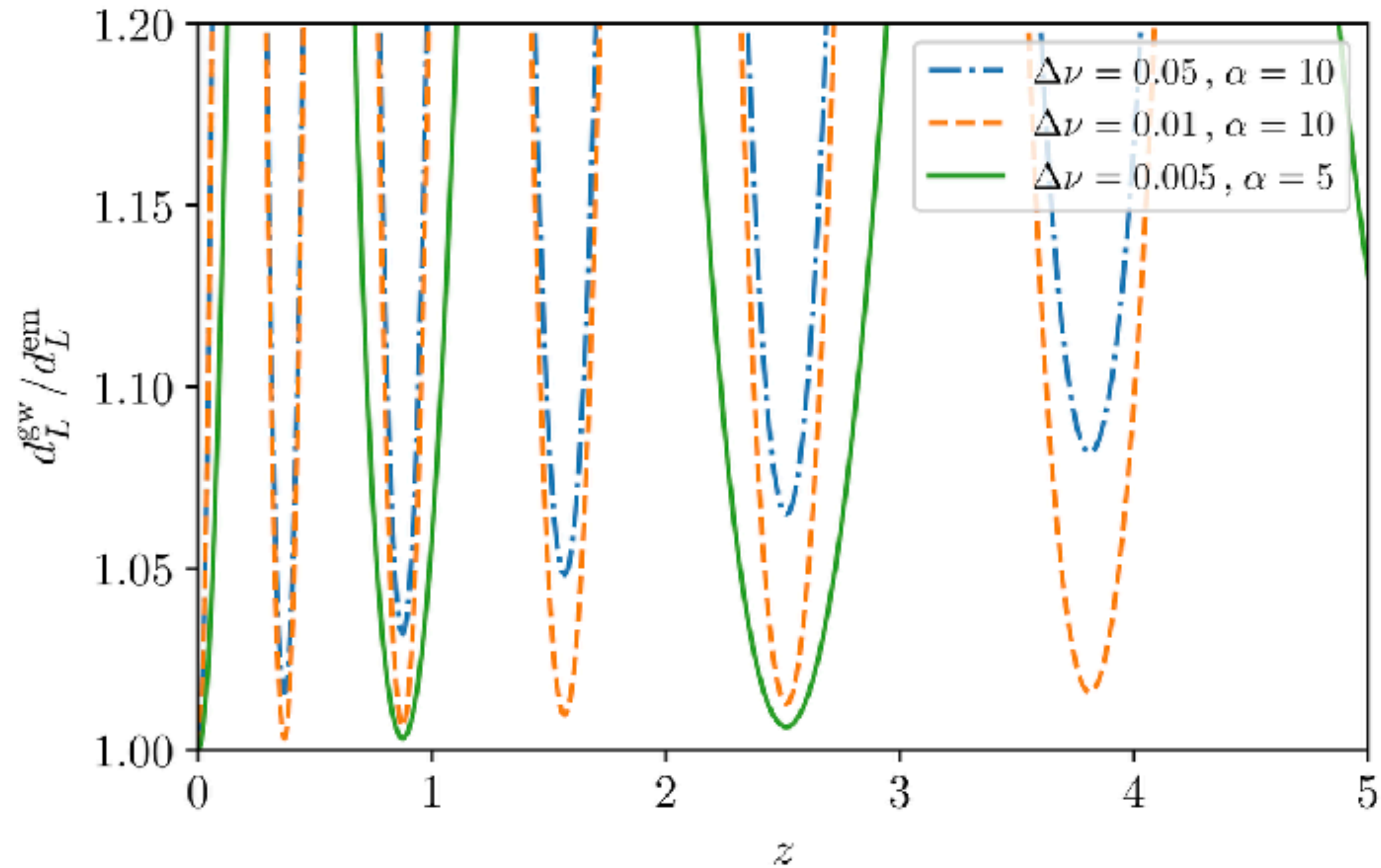


L.H & J.Beltran, J. Ezquiaga, arXiv:1912.06104

GW luminosity distance

GR + YM

$g_{\mu\nu}$ $\quad$ A^a_μ



L.H & J.Beltran, J. Ezquiaga,
arXiv:1912.06104

arXiv:1807.01725

A systematic approach to generalisations of General Relativity and their cosmological implications

Lavinia Heisenberg

Institute for Theoretical Studies, ETH Zurich, Clausiusstrasse 47, 8092 Zurich, Switzerland.

Abstract

A century ago, Einstein formulated his elegant and elaborate theory of General Relativity, which has so far withstood a multitude of empirical tests with remarkable success. Notwithstanding the triumphs of Einstein's theory, the tenacious challenges of modern cosmology and of particle physics have motivated the exploration of further generalised theories of spacetime. Even though Einstein's interpretation of gravity in terms of the curvature of spacetime is commonly adopted, the assignment of geometrical concepts to gravity is ambiguous because General Relativity allows three entirely different, but equivalent approaches of which Einstein's interpretation is only one. From a field-theoretical perspective, however, the construction of a consistent theory for a Lorentz-invariant massless spin-2 particle uniquely leads to General Relativity. Keeping Lorentz invariance then implies that any modification of General Relativity will inevitably introduce additional propagating degrees of freedom into the gravity sector. Adopting this perspective, we will review the recent progress in constructing consistent field theories of gravity based on additional scalar, vector and tensor fields. Within this conceptual framework, we will discuss theories with Galileons, with Lagrange densities as constructed by Horndeski and beyond, extended to DHOST interactions, or containing generalized Proca fields and extensions thereof, or several Proca fields, as well as bigravity theories and scalar-vector-tensor theories. We will review the motivation of their inception, different formulations, and essential results obtained within these classes of theories together with their empirical viability.

Keywords: Modified Gravity, Massive Gravity, Scalar-Tensor theories, Generalized Proca, Multi-Proca, Scalar-Vector-Tensor theories, Cosmology