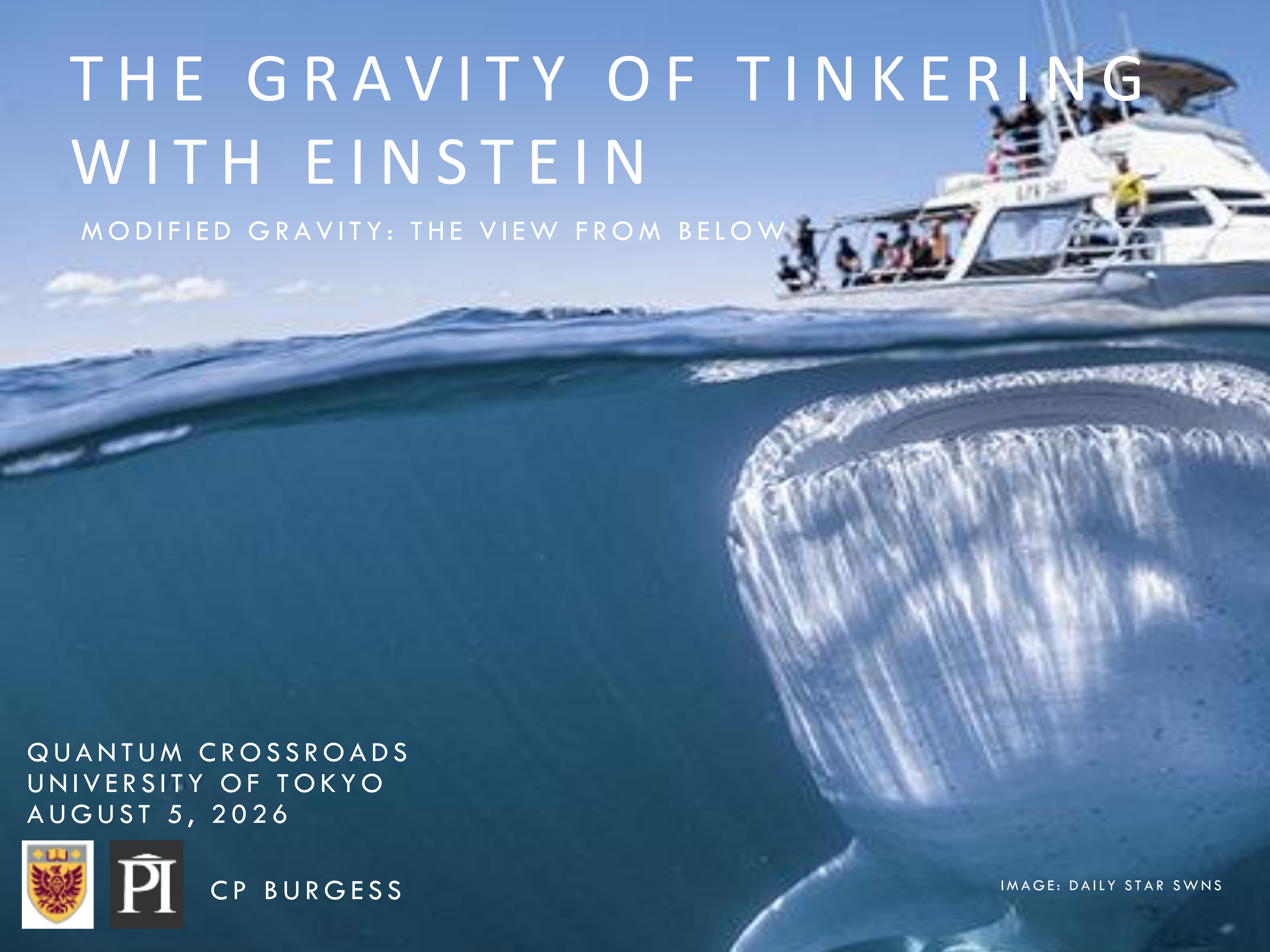


THE GRAVITY OF TINKERING WITH EINSTEIN

MODIFIED GRAVITY: THE VIEW FROM BELOW

QUANTUM CROSSROADS
UNIVERSITY OF TOKYO
AUGUST 5, 2026

CP BURGESS

IMAGE: DAILY STAR SWNS

CONTENTS

- GR IS KING
- GR IS DEAD
- EFFECTIVE METHODS
- LESSONS LEARNED

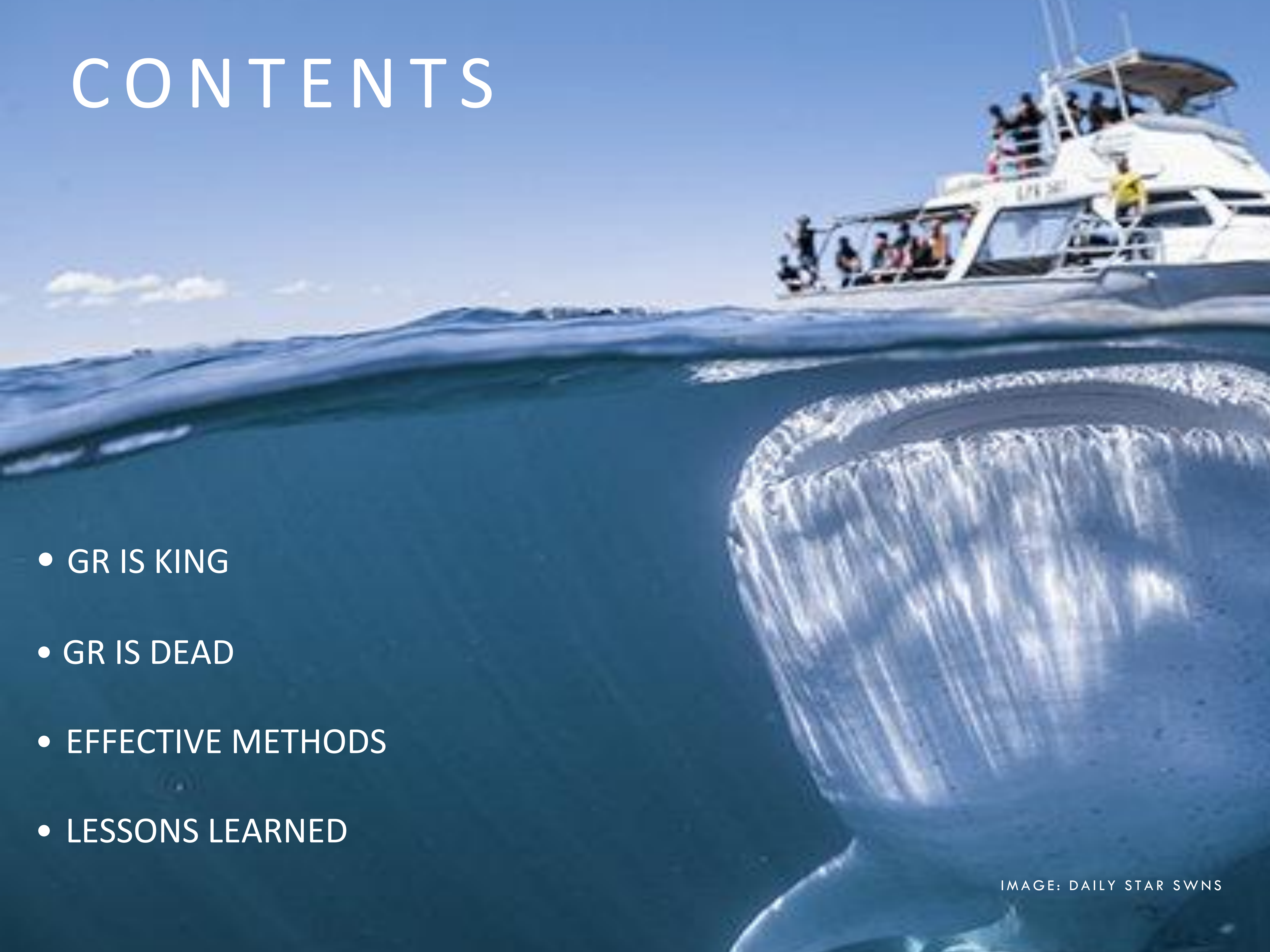


IMAGE: DAILY STAR SWNS


GR IS KING
IMAGE: DAILY STAR SWNS

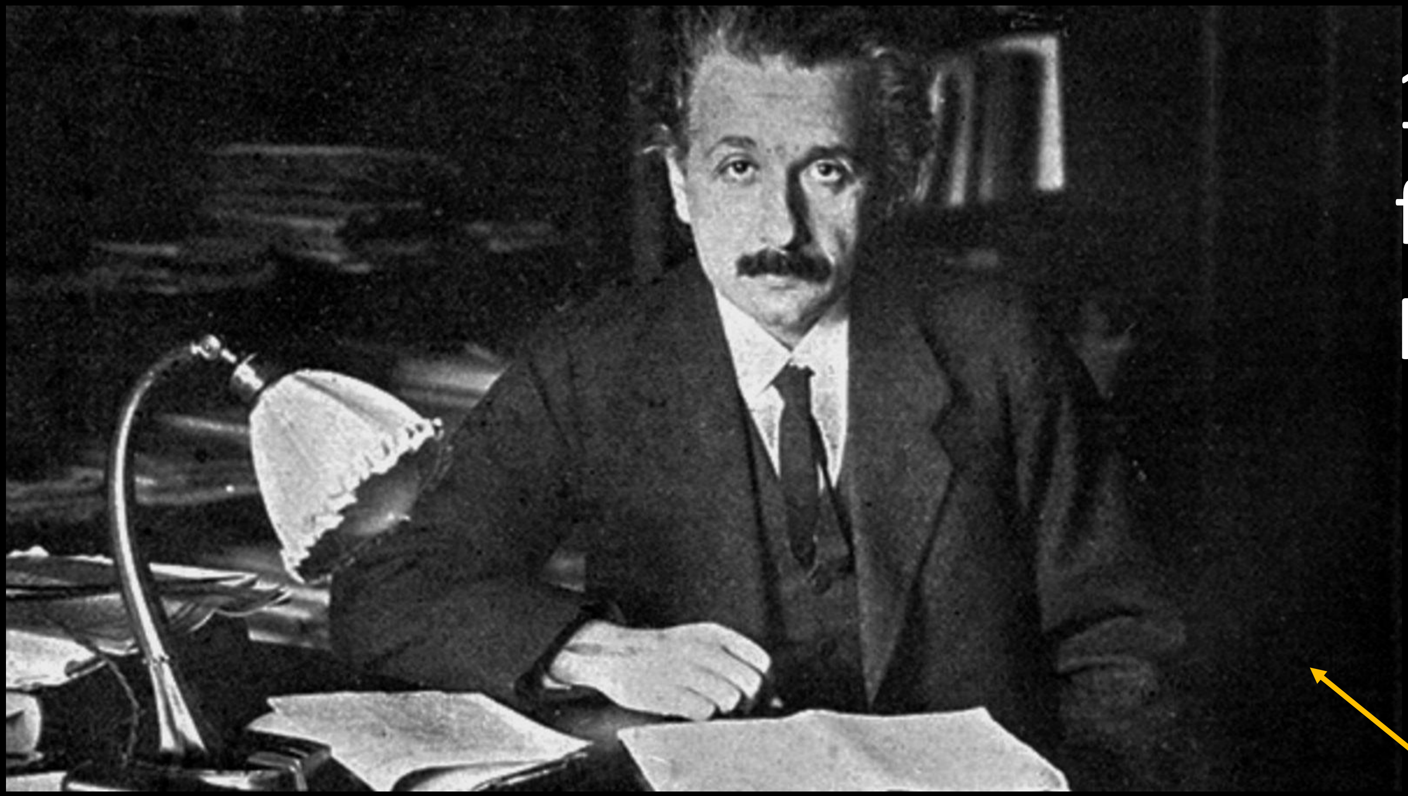
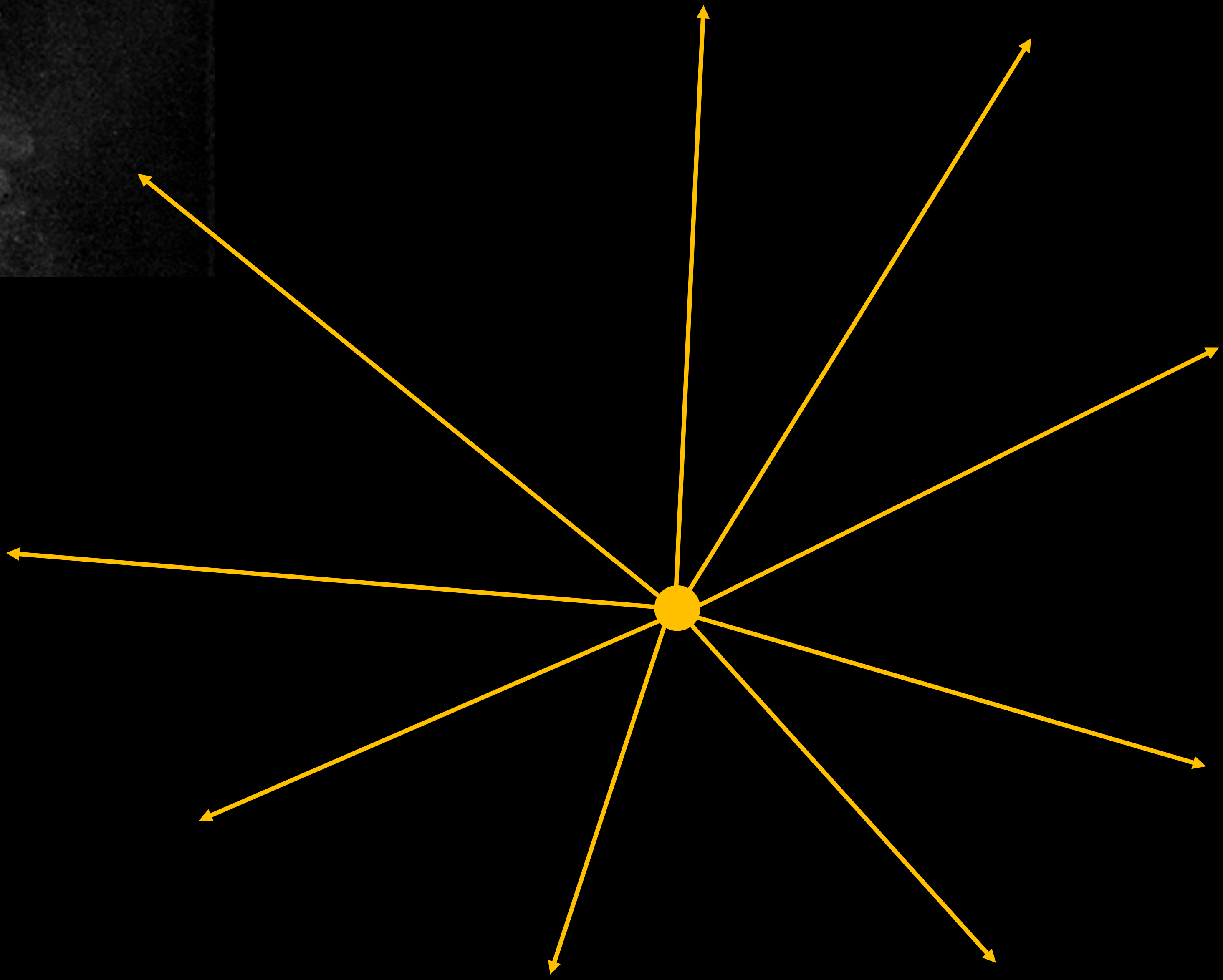


IMAGE: PUBLIC DOMAIN

1905: special Relativity drops forces in favour of fields; Newton's gravity obsolete



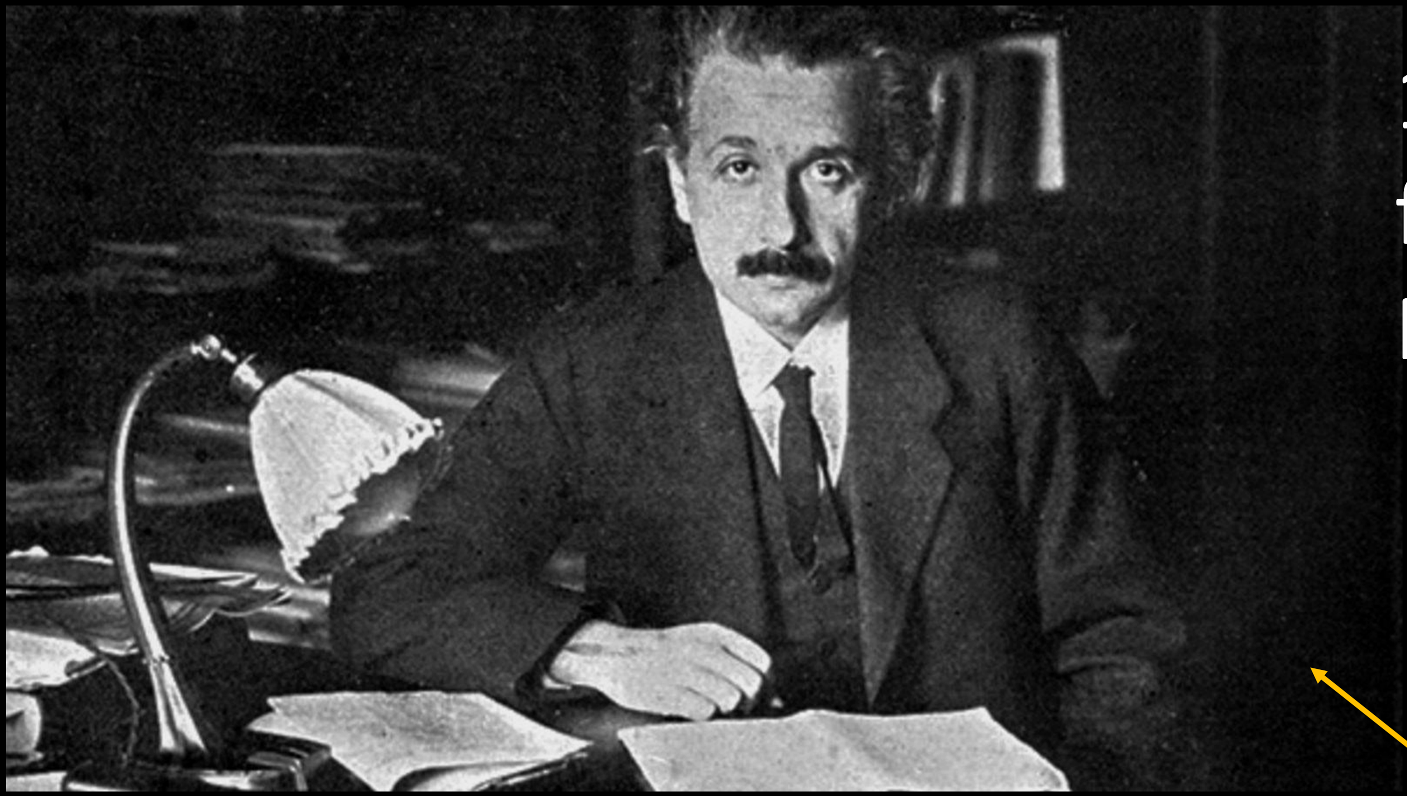


IMAGE: PUBLIC DOMAIN

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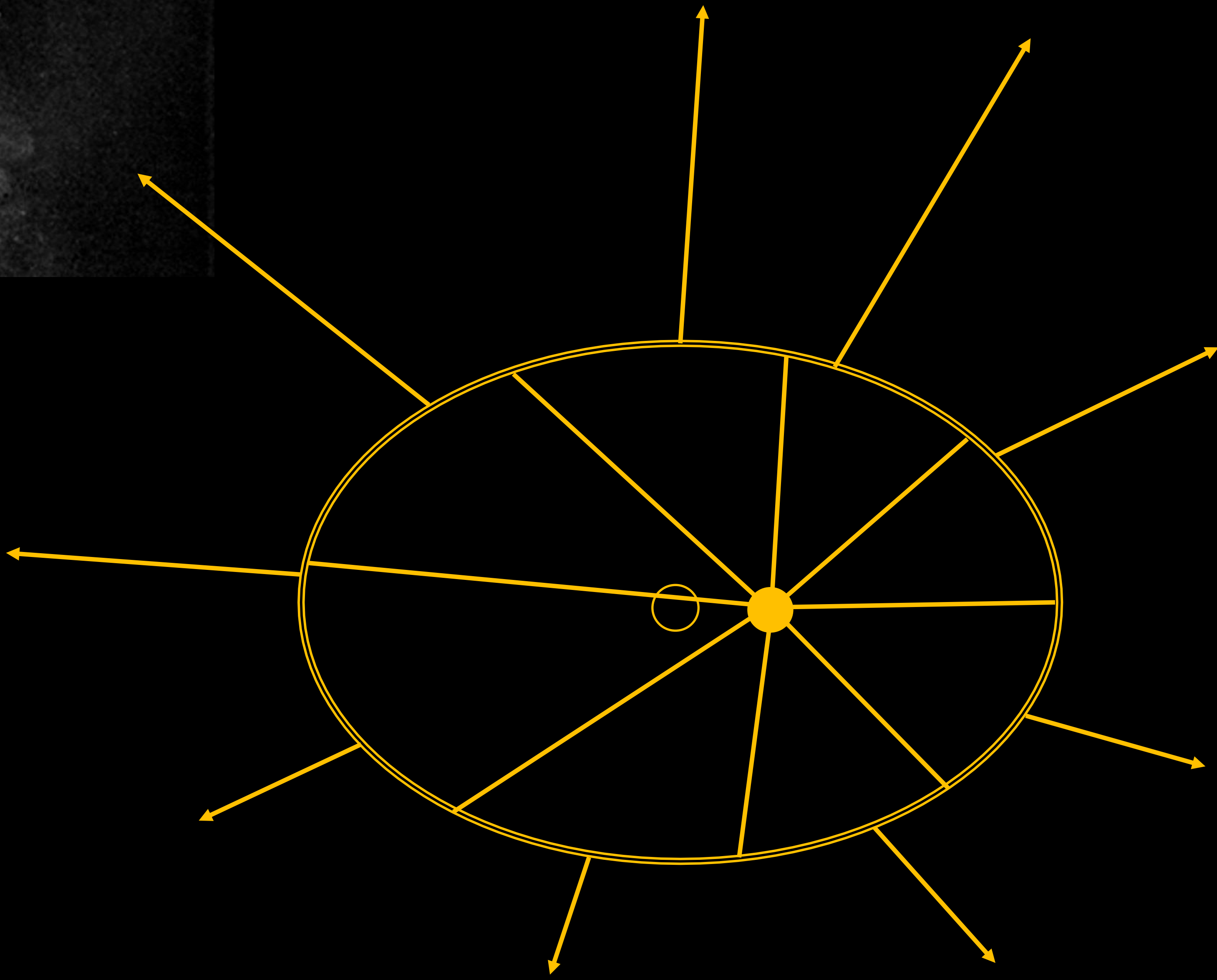


GR IS KING

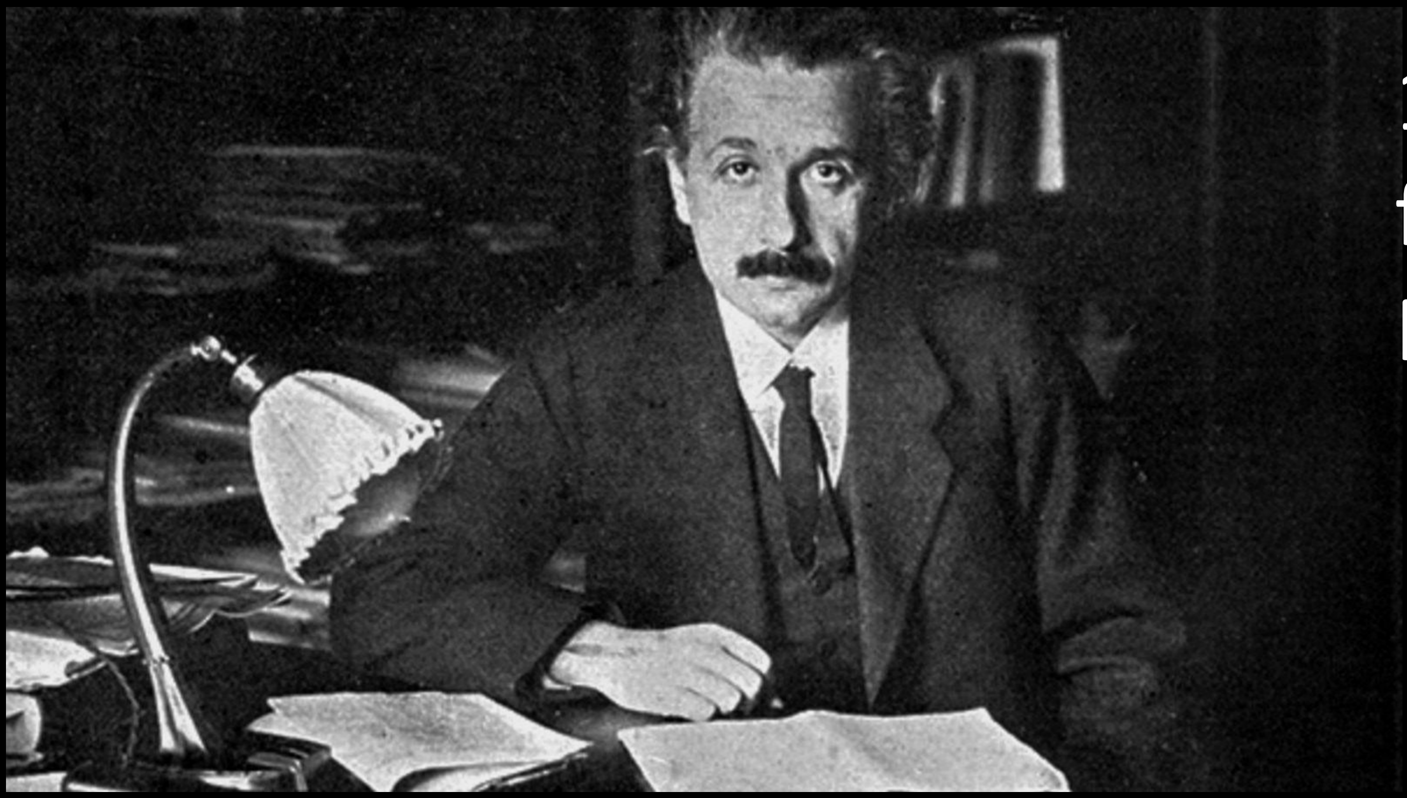
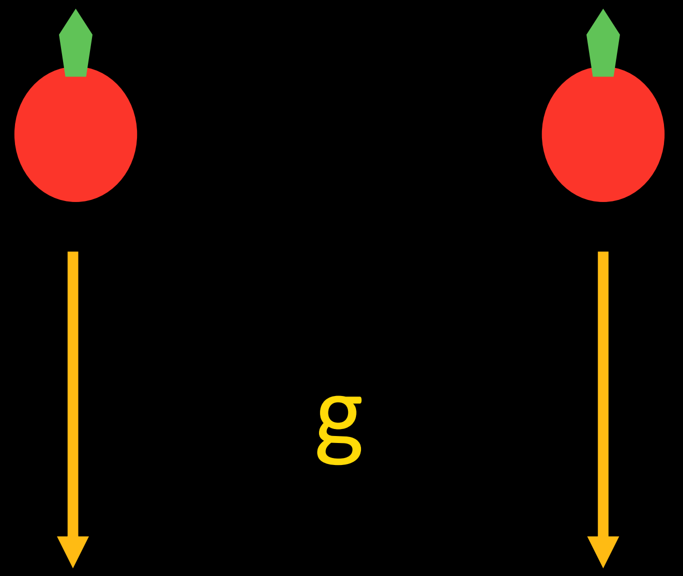


IMAGE: PUBLIC DOMAIN

1905: special Relativity drops forces in favour of fields; Newton's gravity obsolete

What is the field?

Principle of equivalence provides a hint:



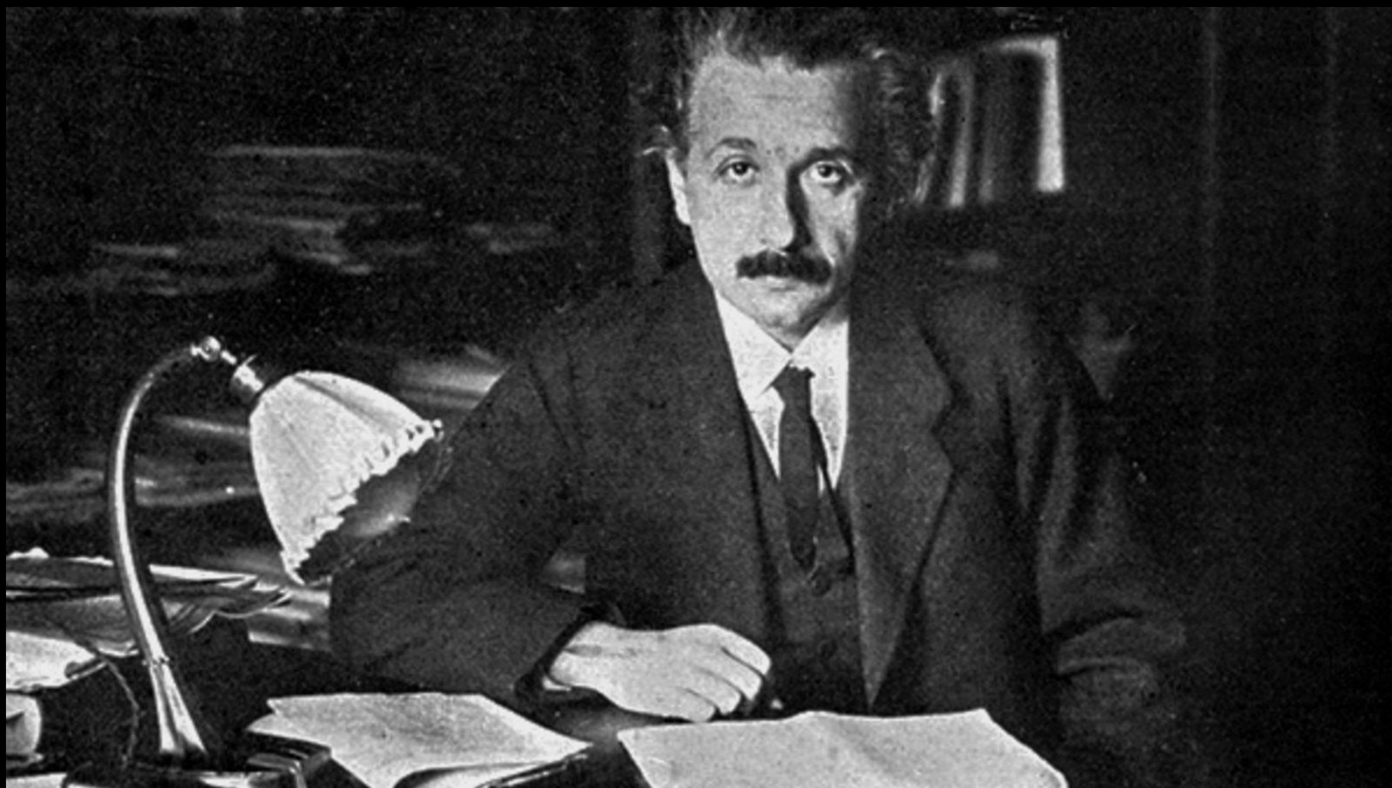


IMAGE: PUBLIC DOMAIN

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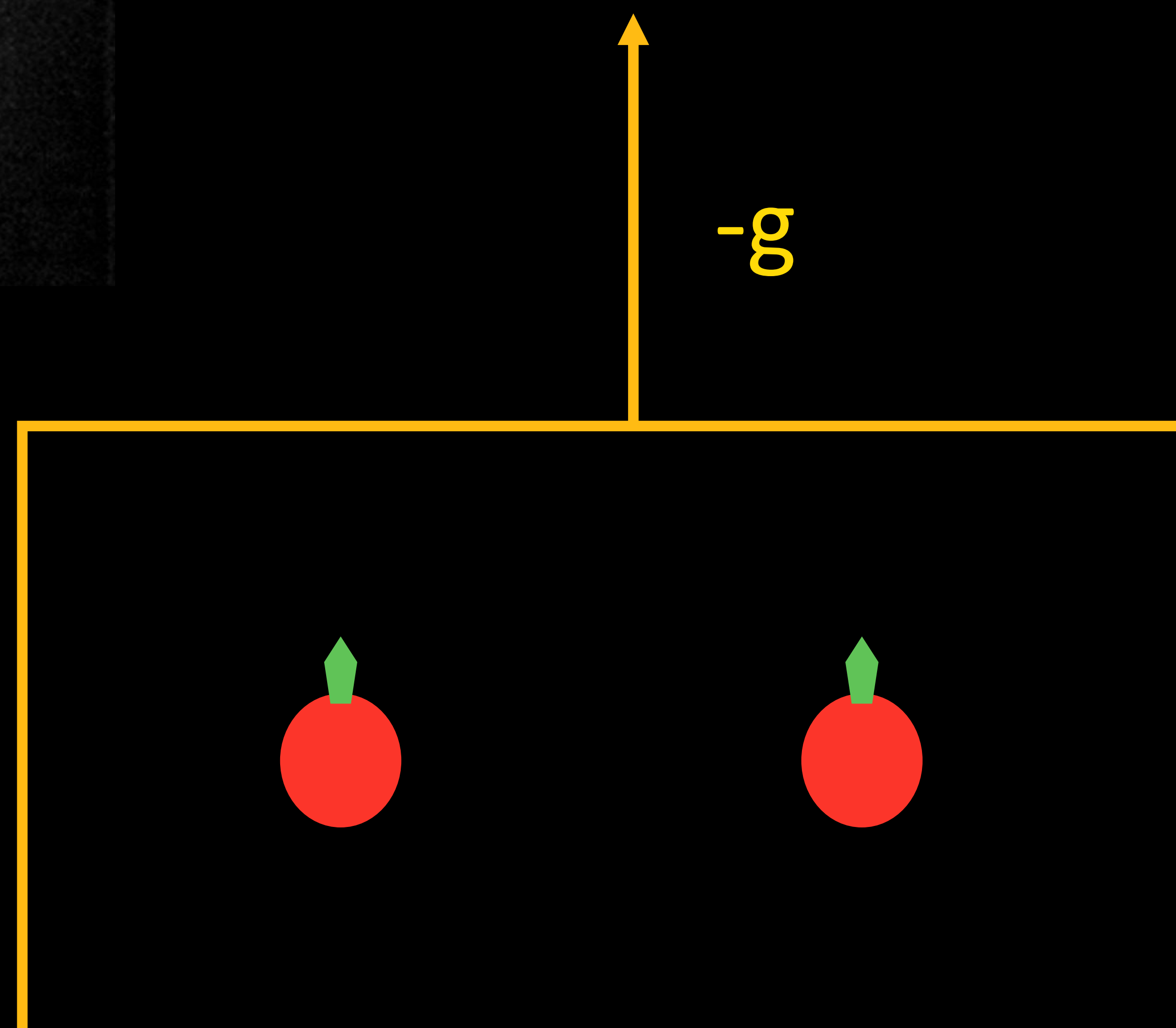

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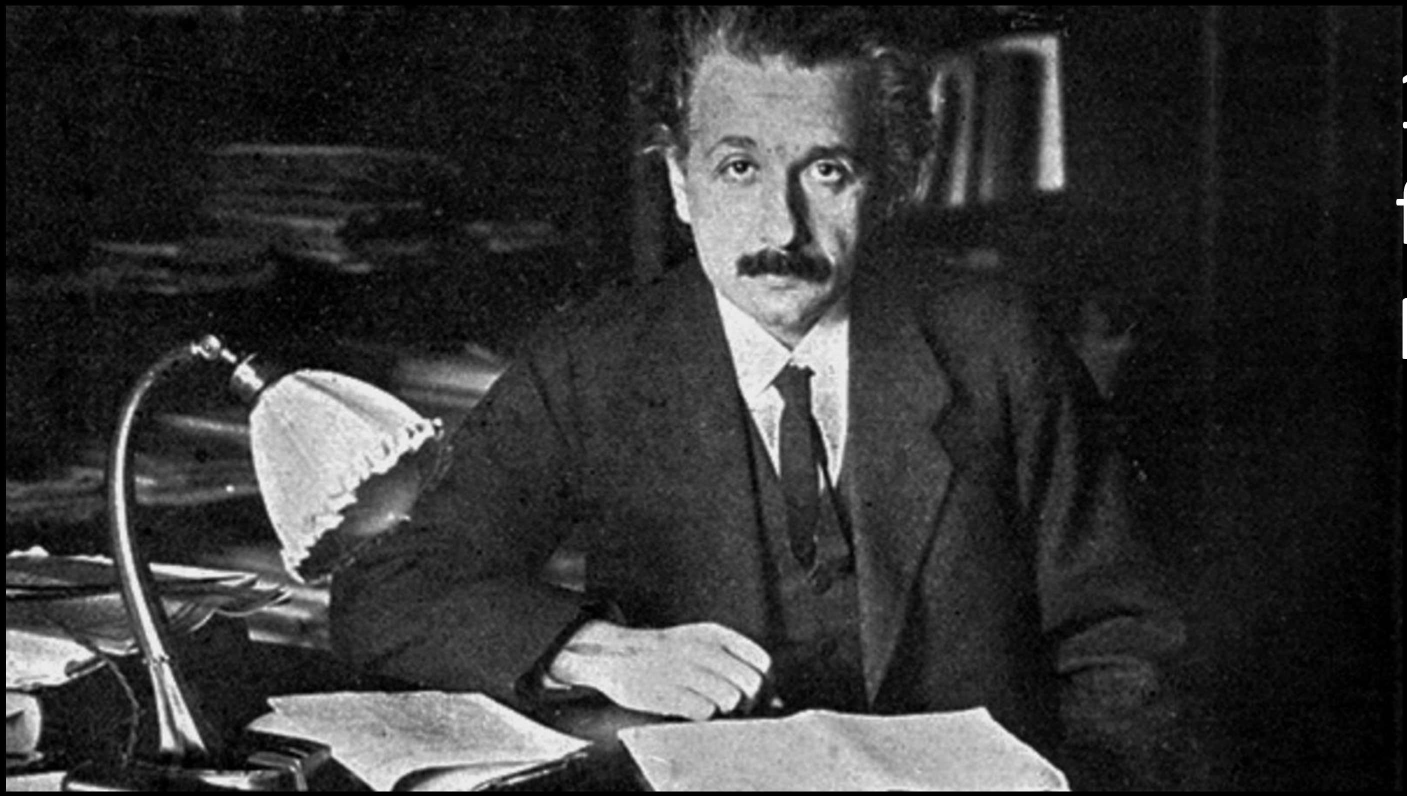

1905: special Relativity drops forces in favour of fields; Newton's gravity obsolete

IMAGE: PUBLIC DOMAIN

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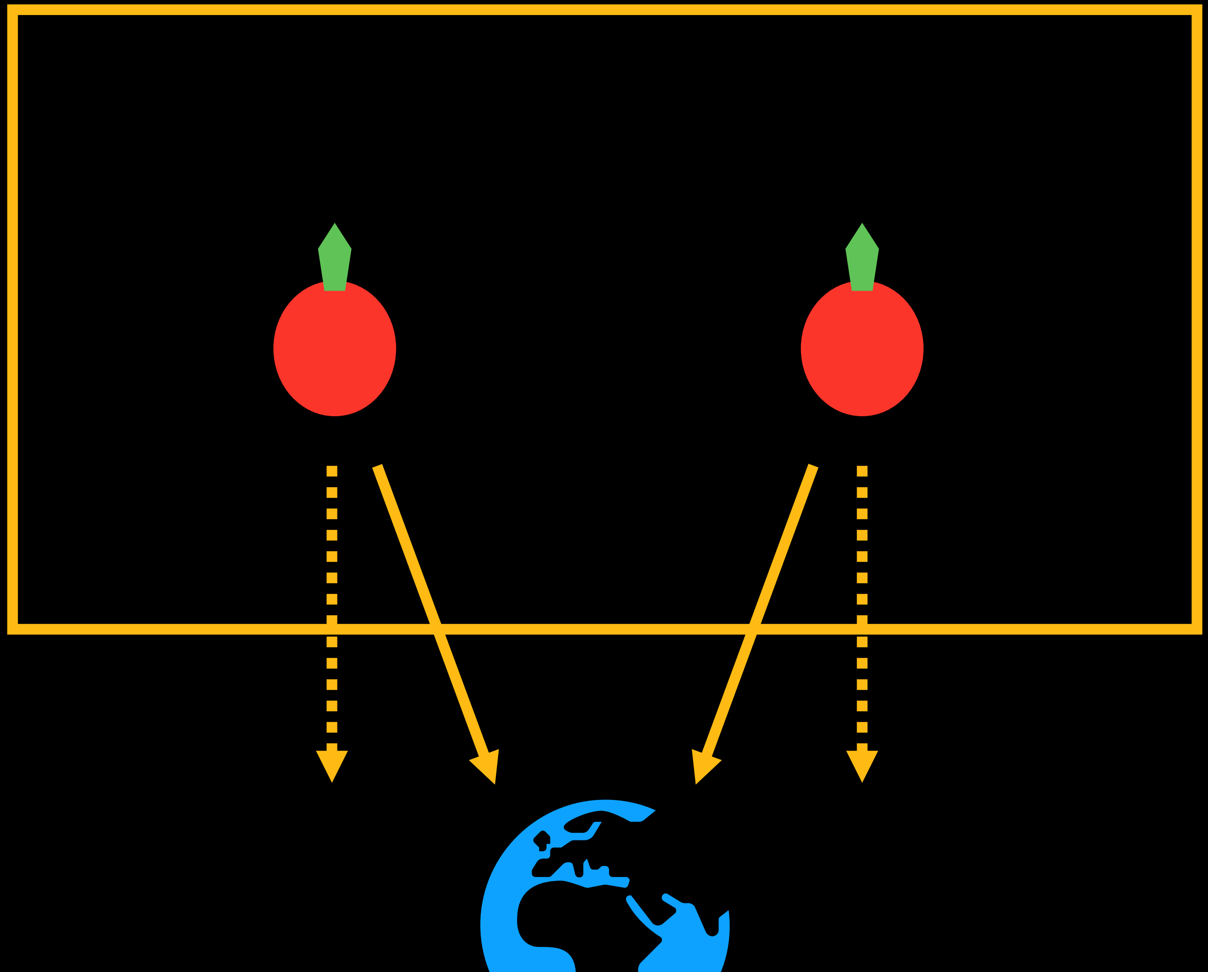

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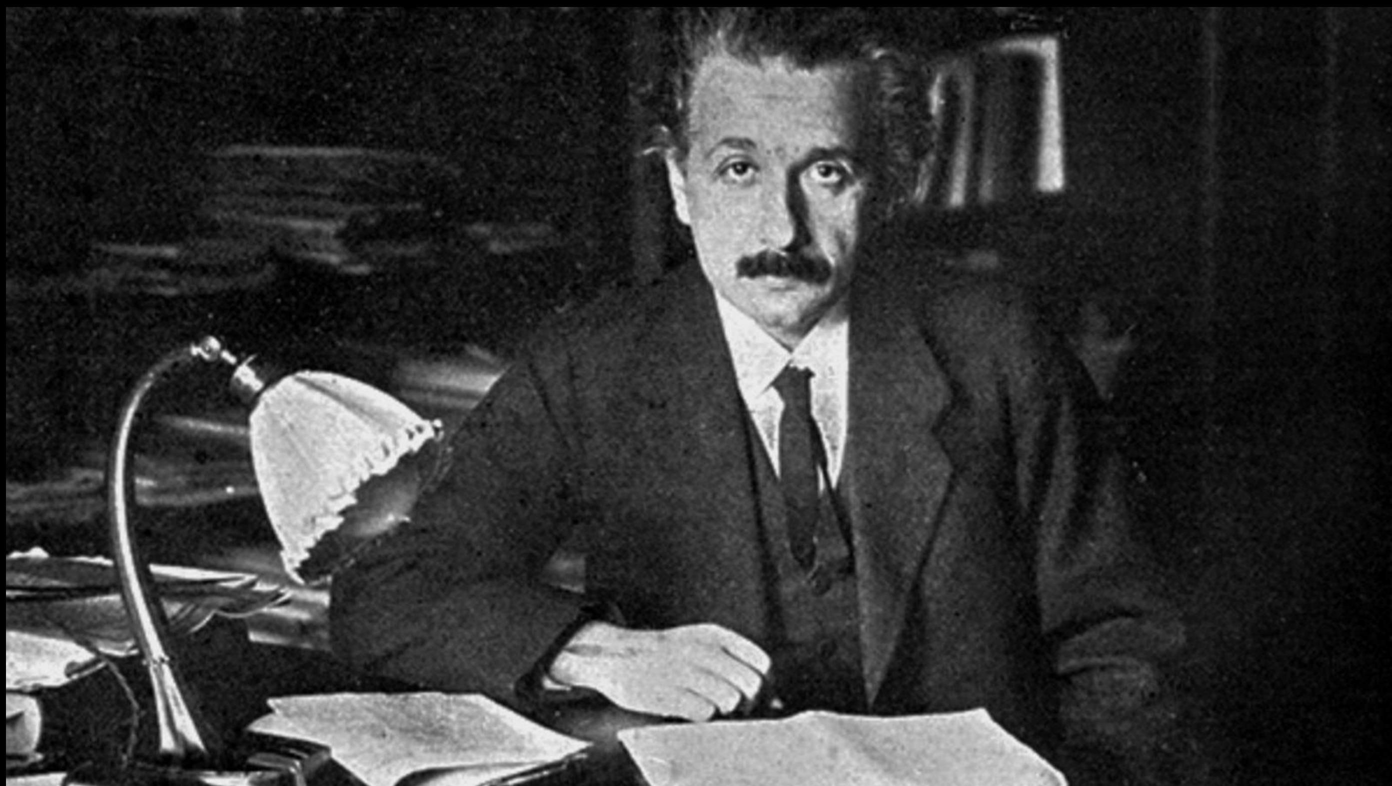


IMAGE: PUBLIC DOMAIN

1905: special Relativity drops forces in favour of fields; Newton’s gravity obsolete

1916: gravitational field is spacetime curvature

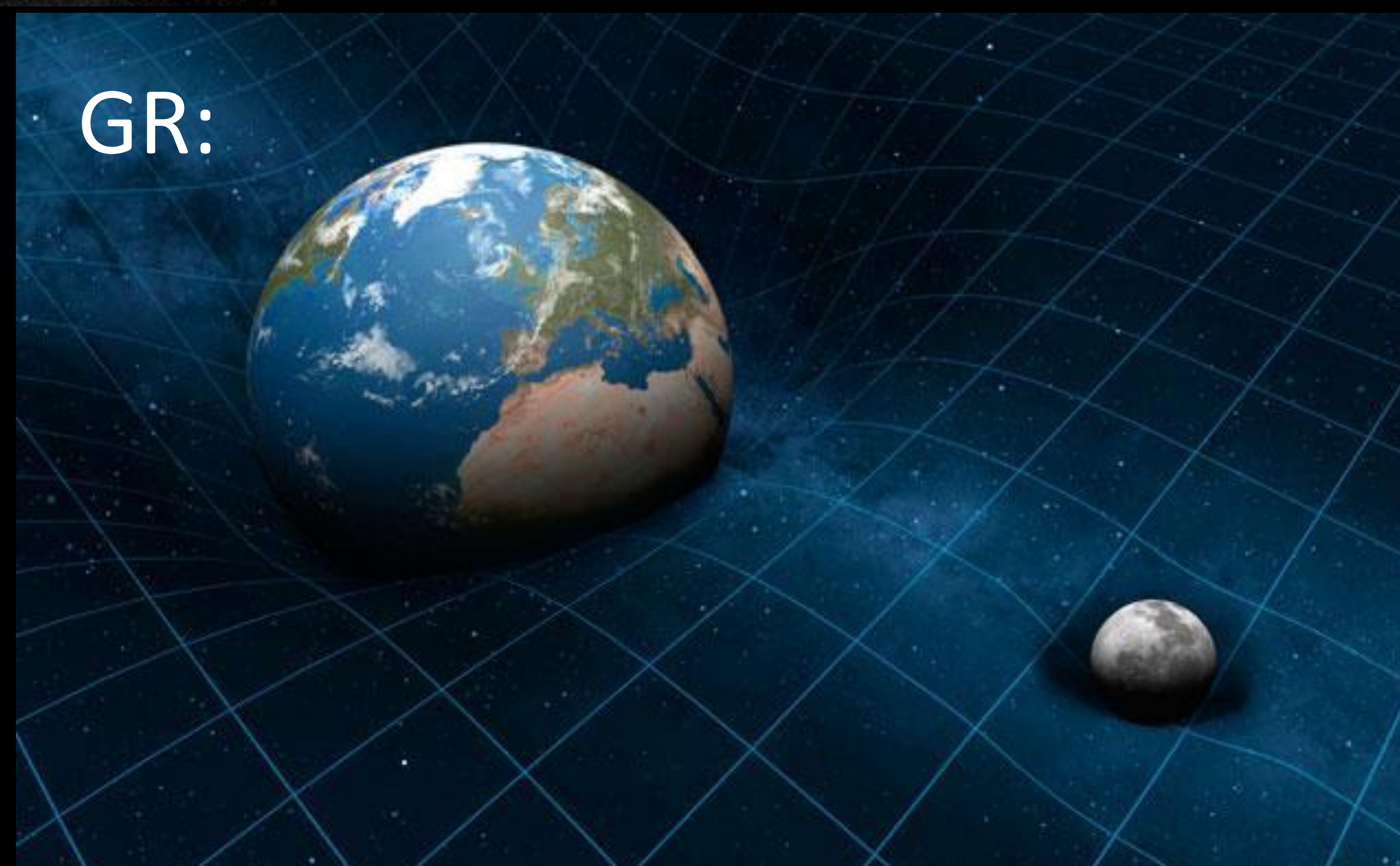
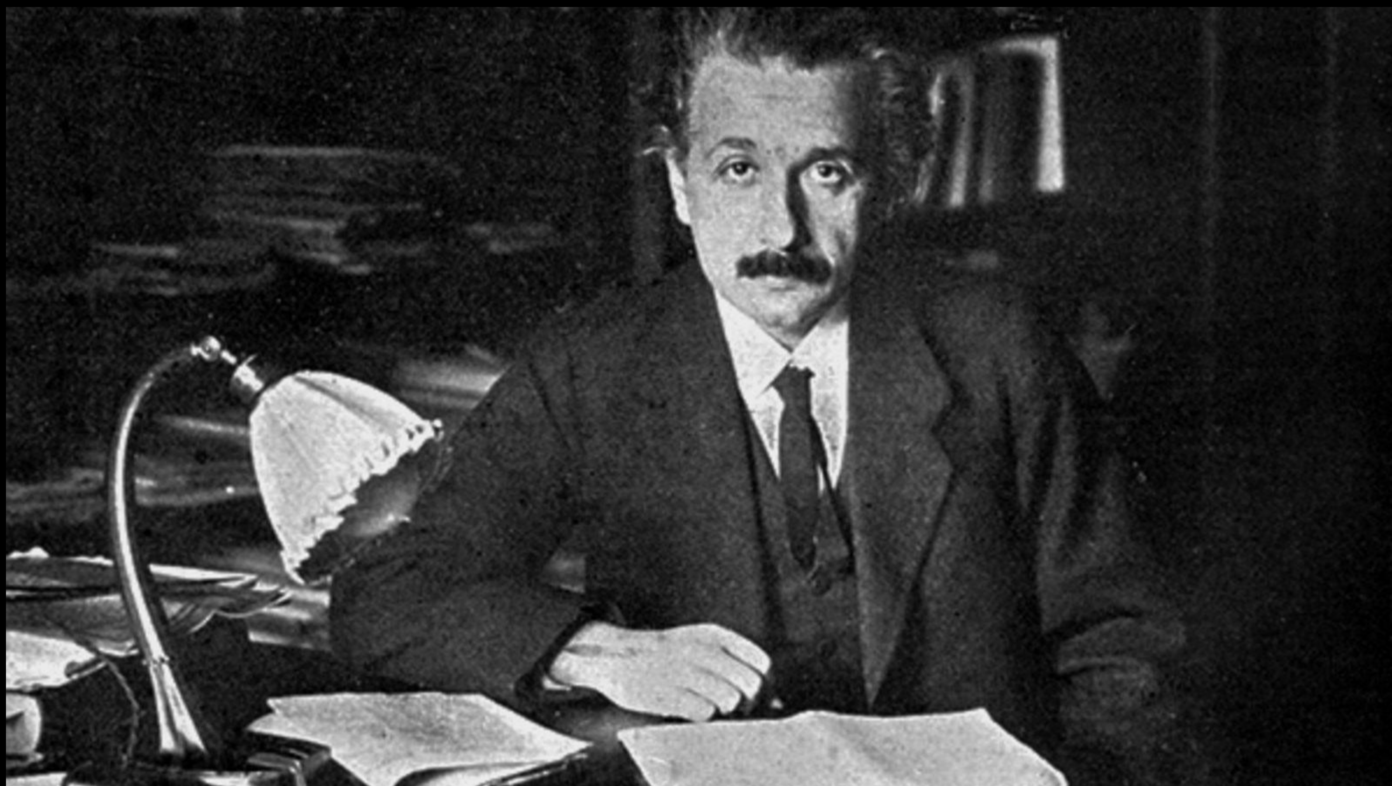


IMAGE: BBC UNIVERSE

GR IS KING



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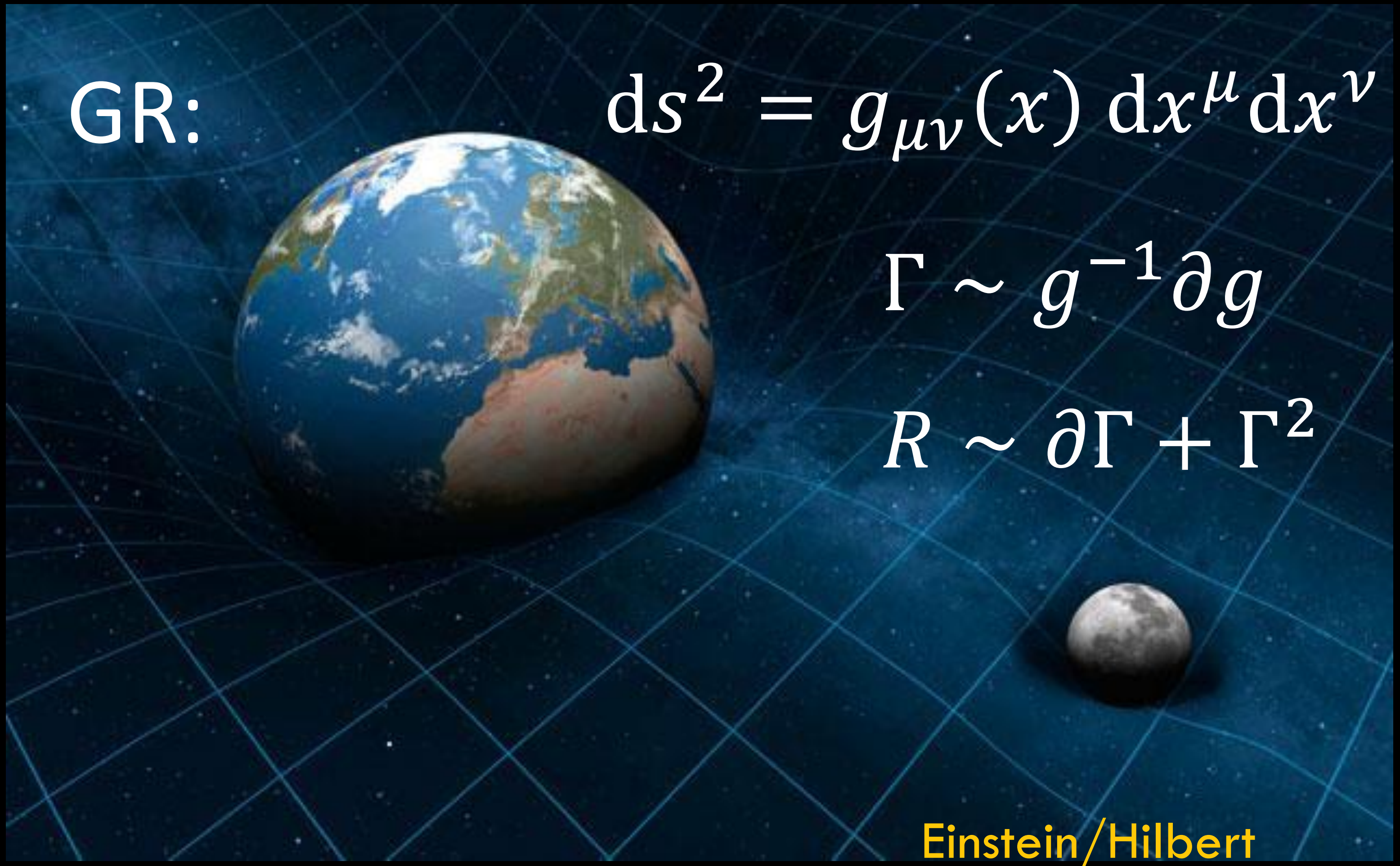

IMAGE: BBC UNIVERSE

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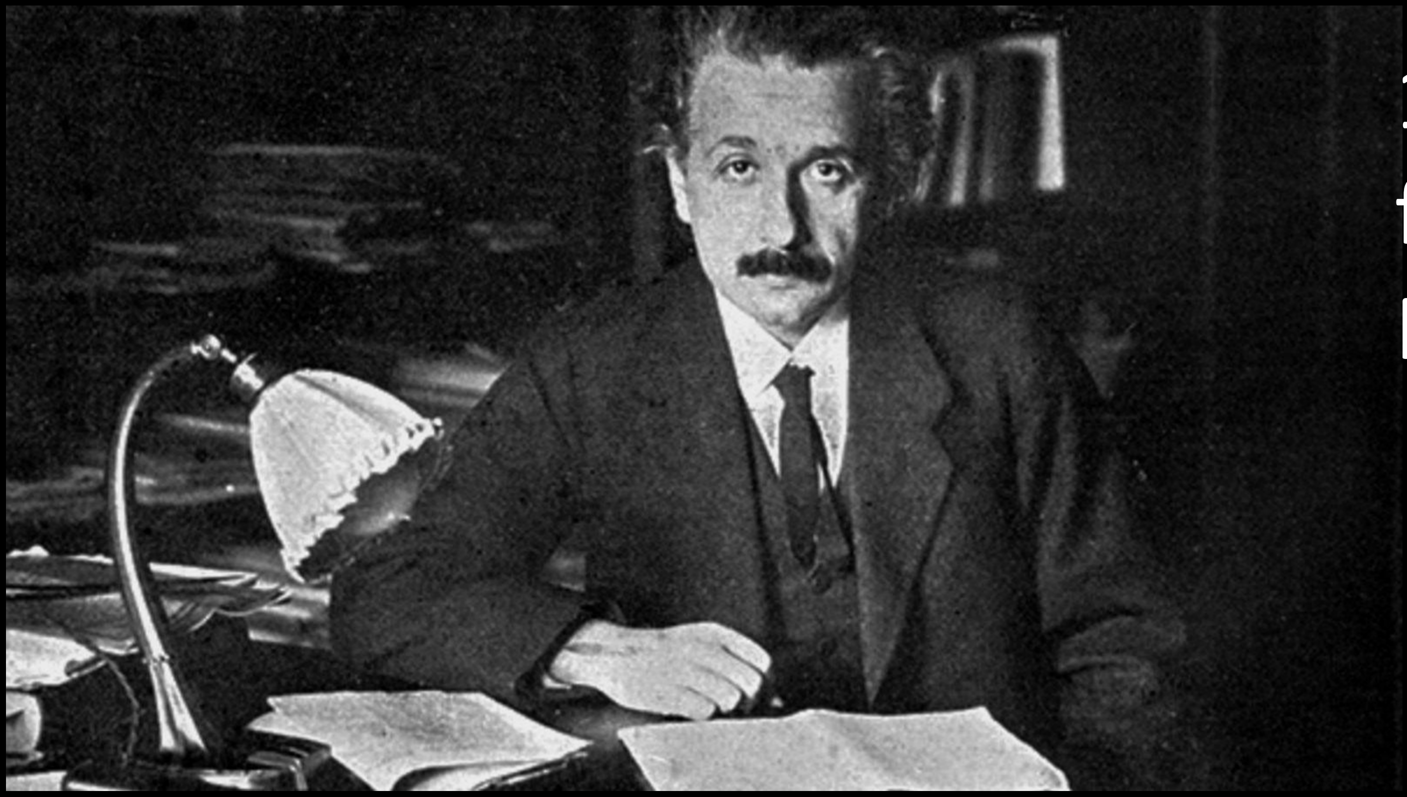


IMAGE: PUBLIC DOMAIN

1905: special Relativity drops forces in favour of fields; Newton's gravity obsolete

1916: gravitational field is spacetime curvature

$$8\pi G = \frac{c^3 \ell_p^2}{\hbar} = \frac{\hbar c}{M_p^2}$$

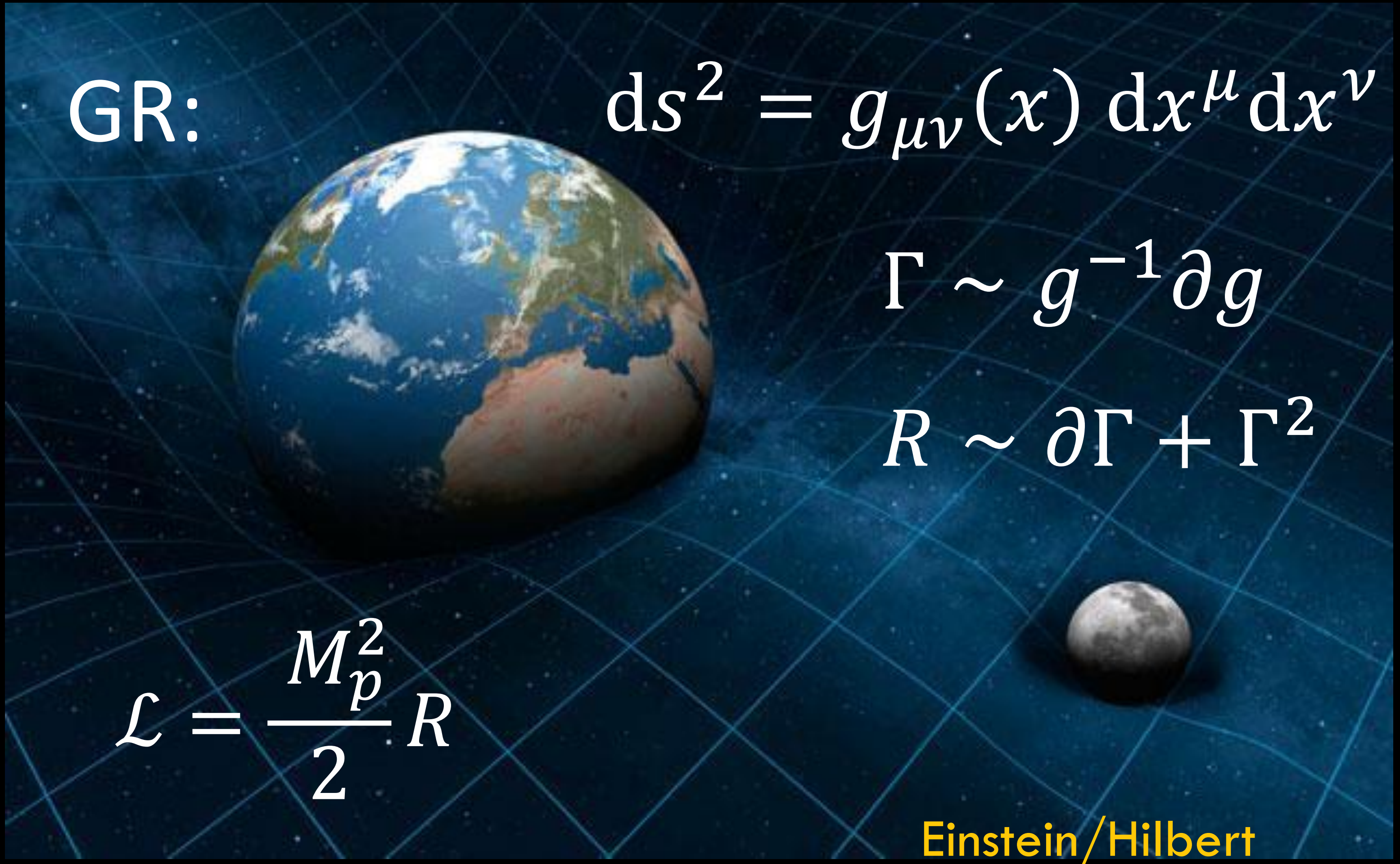
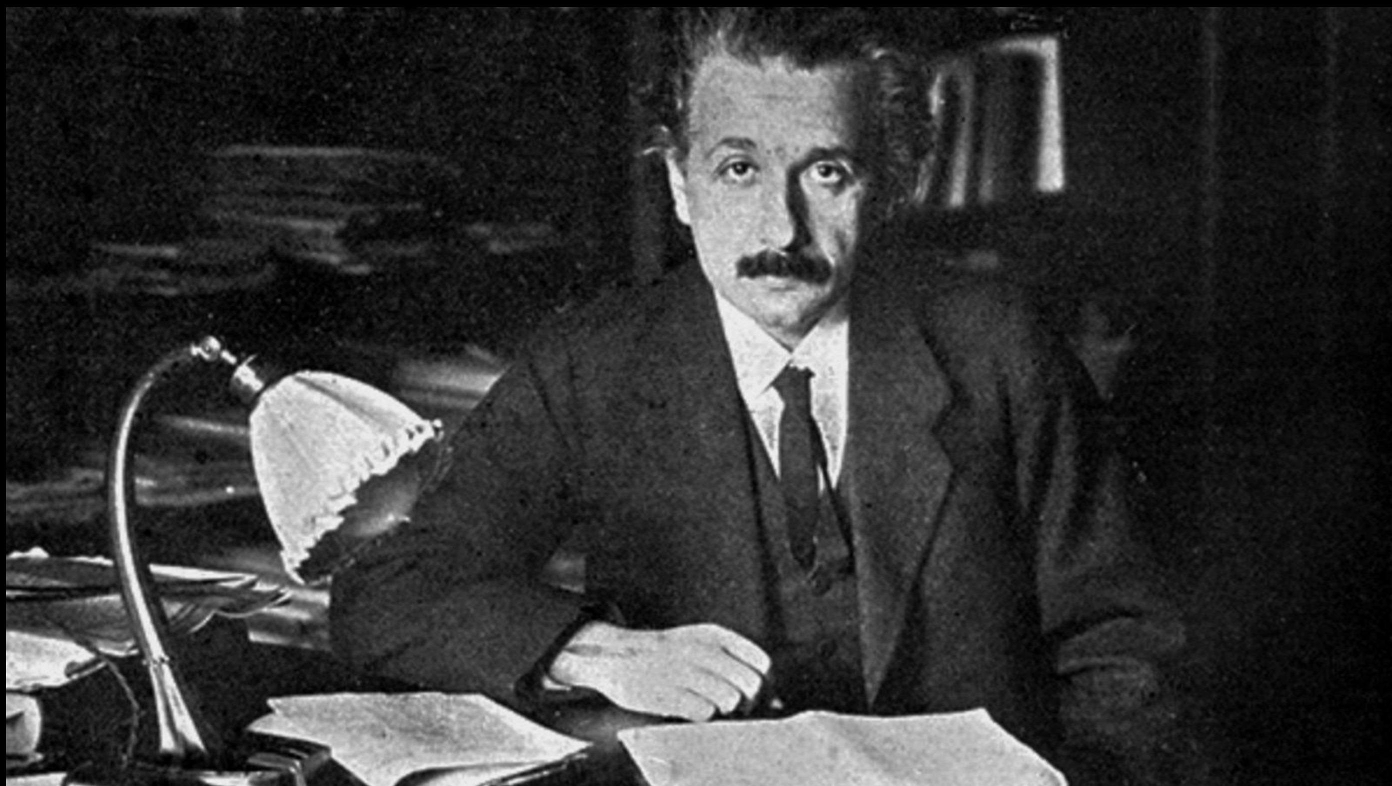


IMAGE: BBC UNIVERSE

GR IS KING



1905: special Relativity drops forces in favour of fields; Newton's gravity obsolete

IMAGE: PUBLIC DOMAIN

$$S = \int \mathrm{d}^4x \sqrt{-\det g}\, \mathcal{L}$$

classical eqs: $\dfrac{\delta S}{\delta g_{\mu\nu}} = 0$

quantum system:

$$\langle \mathcal{O}(g) \rangle = \int \mathcal{D} g_{\mu\nu} \mathcal{O}(g) \exp[iS/\hbar]$$

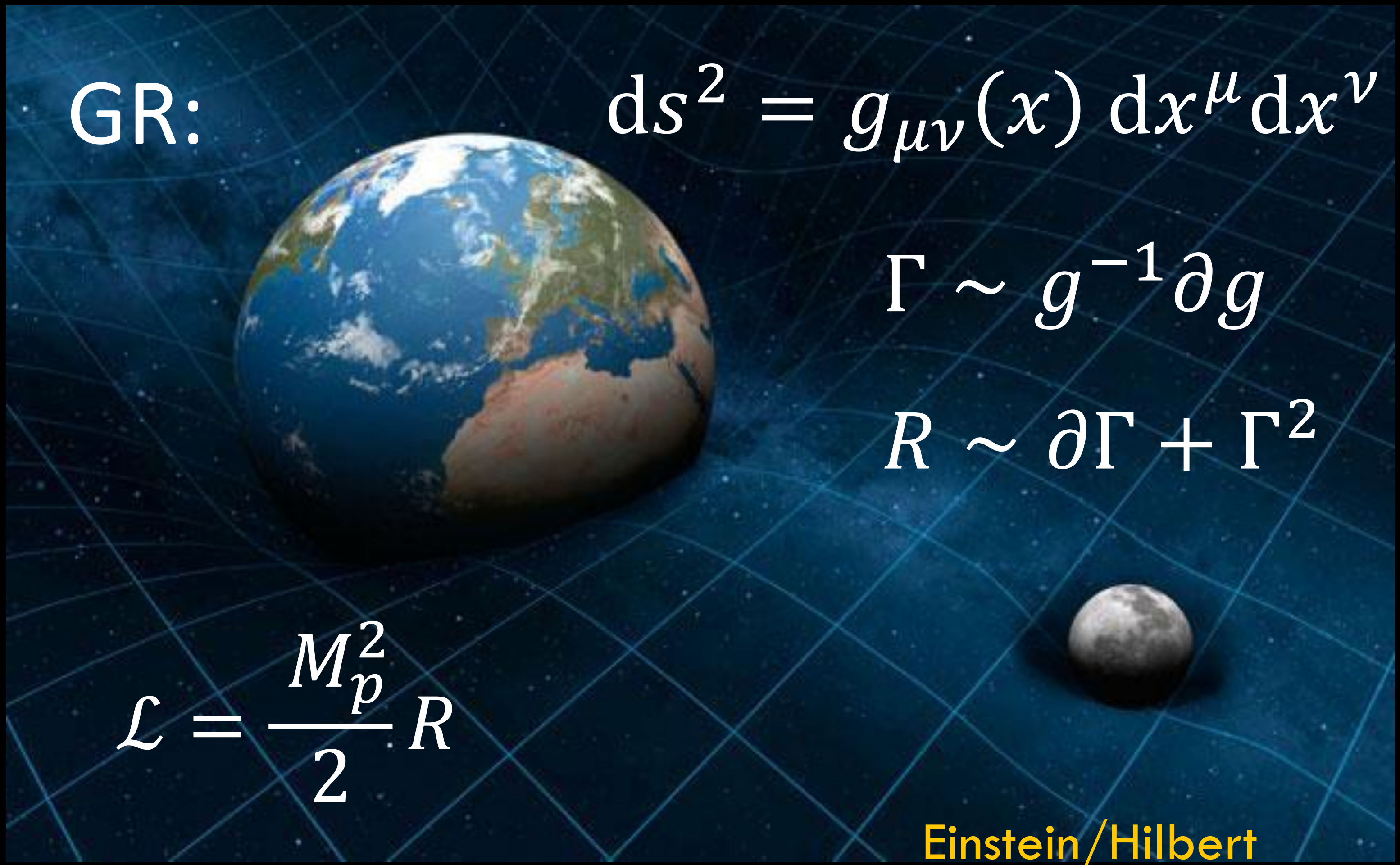
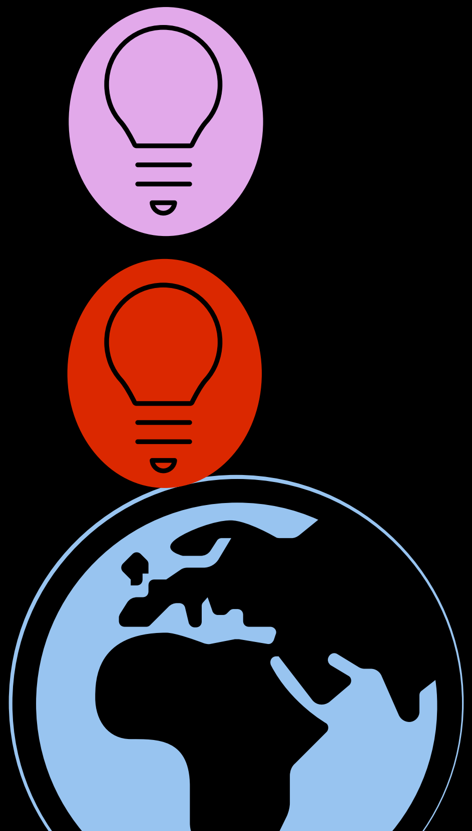
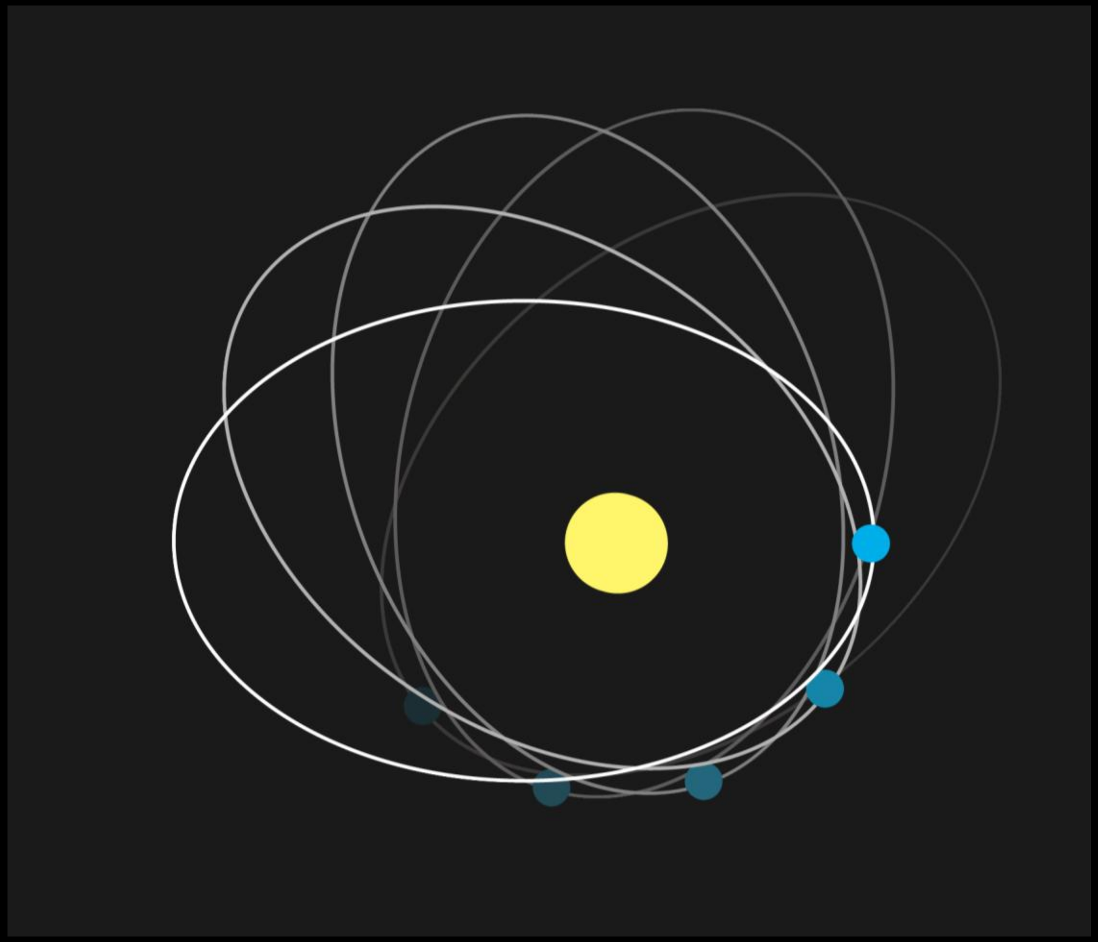


IMAGE: BBC UNIVERSE

CLASSICAL TESTS OF GR

- Anomalous orbital precession of Mercury
- Bending of light by the Sun
- Gravitational redshift



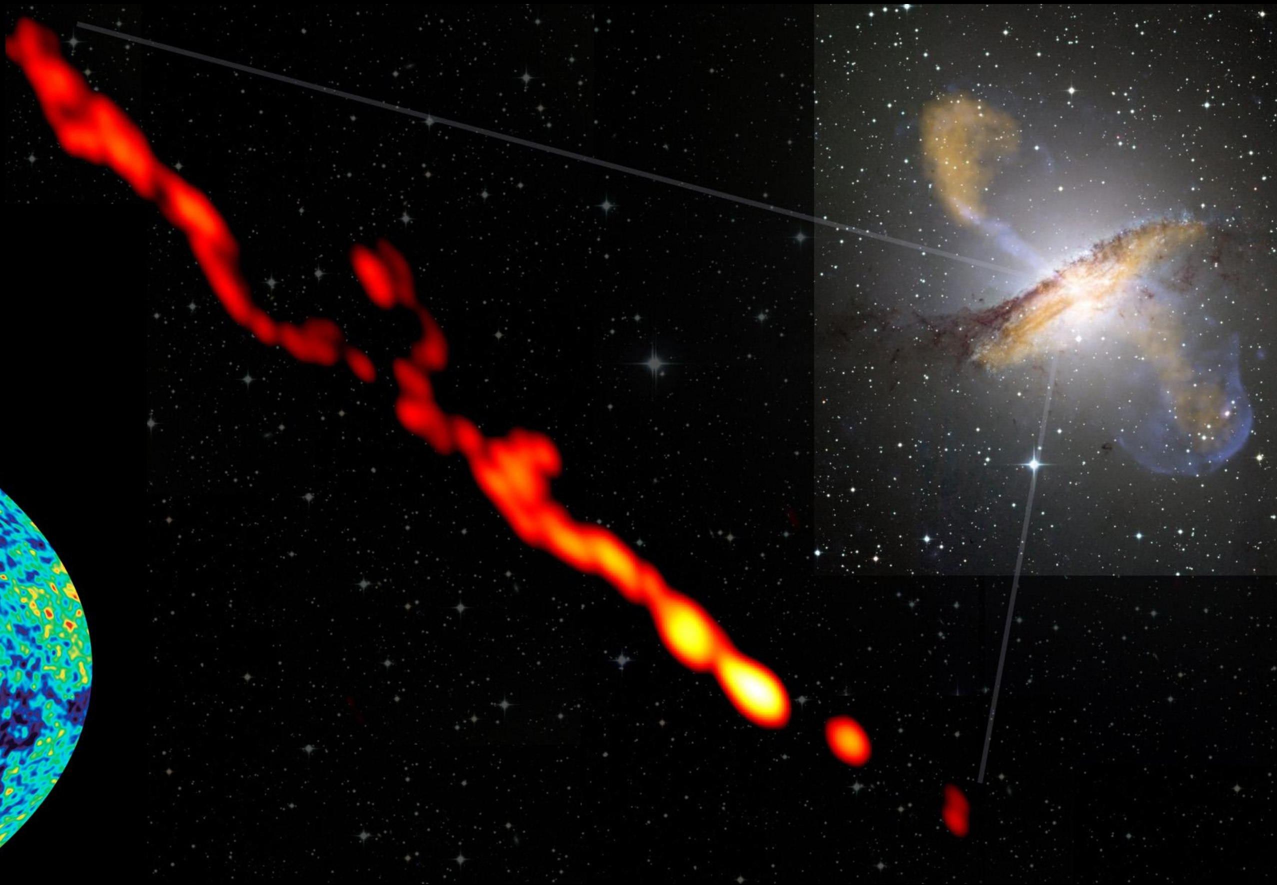


IMAGES: NASA PUBLIC DOMAIN

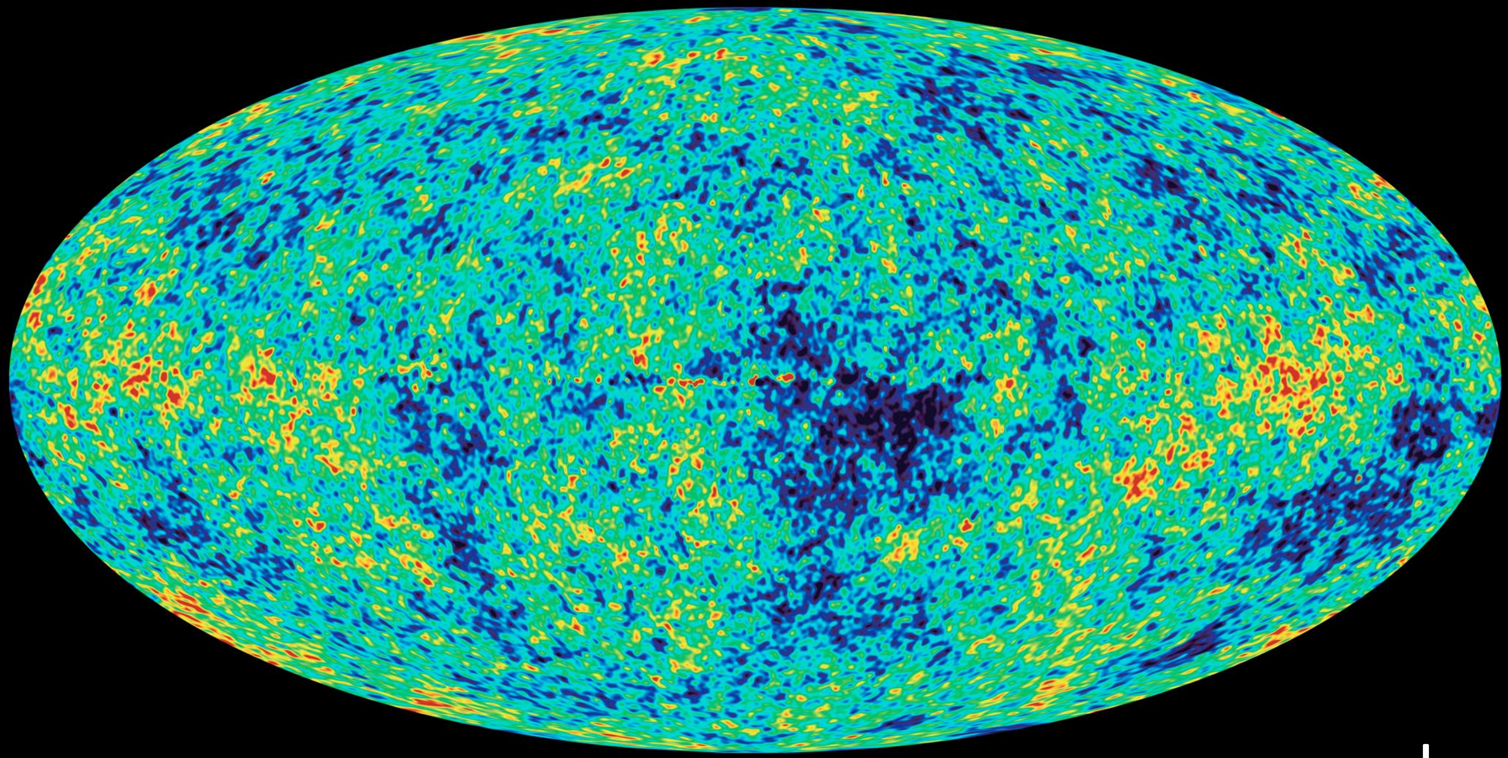
MODERN TESTS OF GR

- Gravitational Lensing
- Relativistic Astrophysics

neutron stars/pulsars



black holes/active galaxies



cosmology

IMAGES: WMAP NASA

MODERN TESTS OF GR

- Gravitational Lensing
- Relativistic Astrophysics
- Spacecraft Tests (eg Cassini)

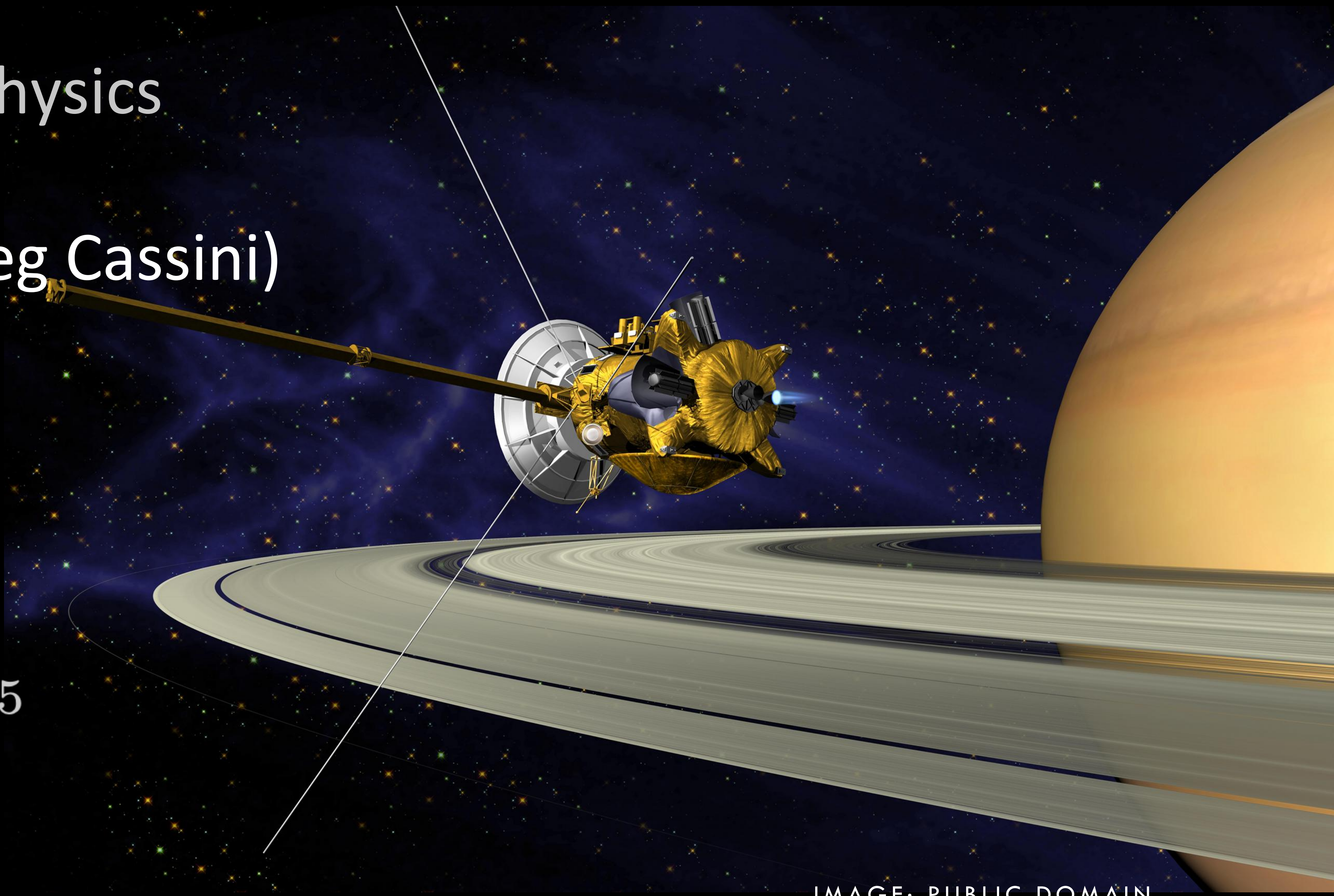


IMAGE: PUBLIC DOMAIN

$$\gamma - 1 < 2.3 \times 10^{-5}$$

$$\beta - 1 < 8 \times 10^{-4}$$

MODERN TESTS OF GR

- Gravitational Lensing
- Relativistic Astrophysics
- Spacecraft Tests (eg Cassi
- Binary Pulsars

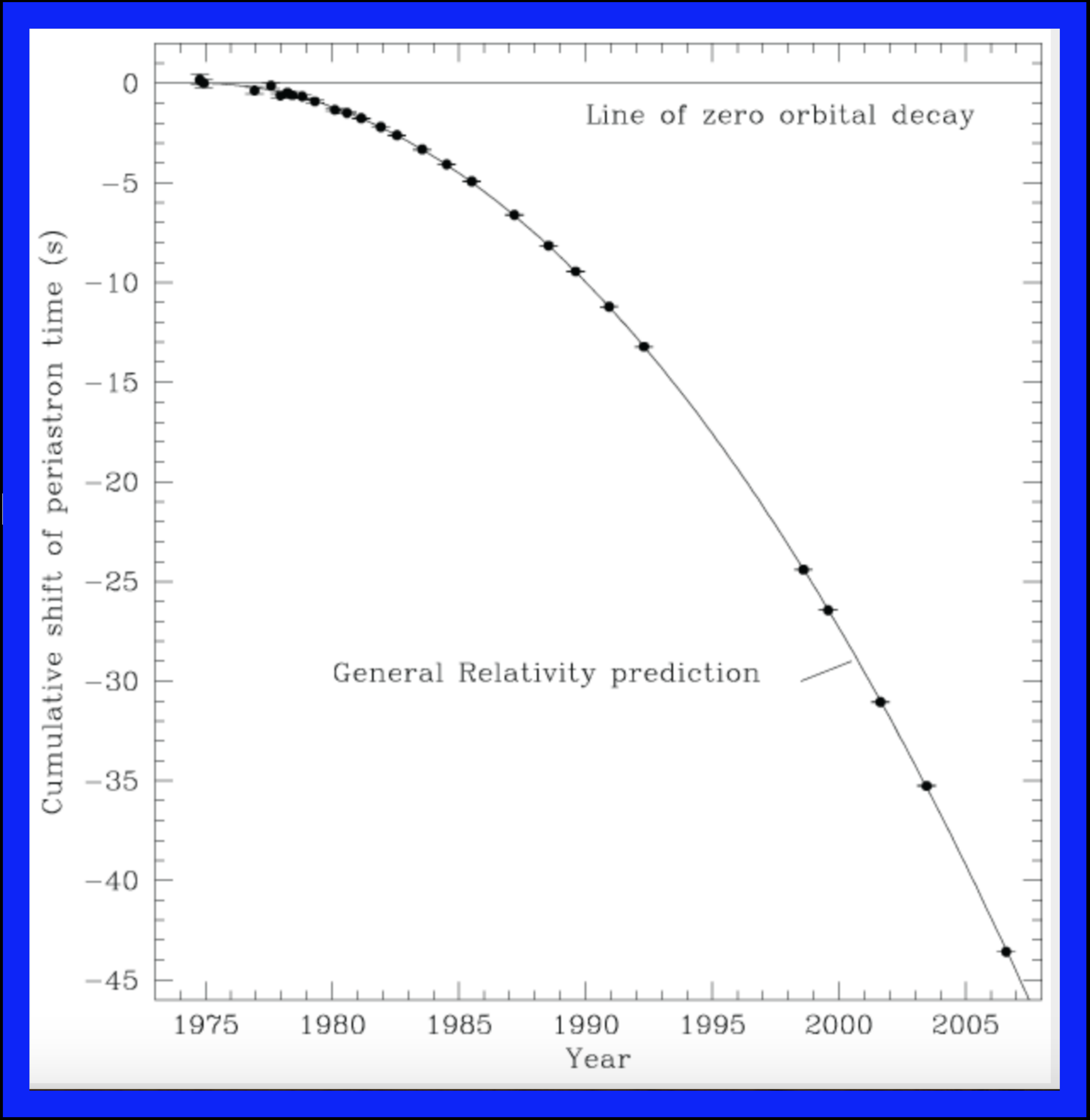


IMAGE: ARXIV: 1011.0718

MODERN TESTS OF GR

- Gravitational Lensing
- Relativistic Astrophysi
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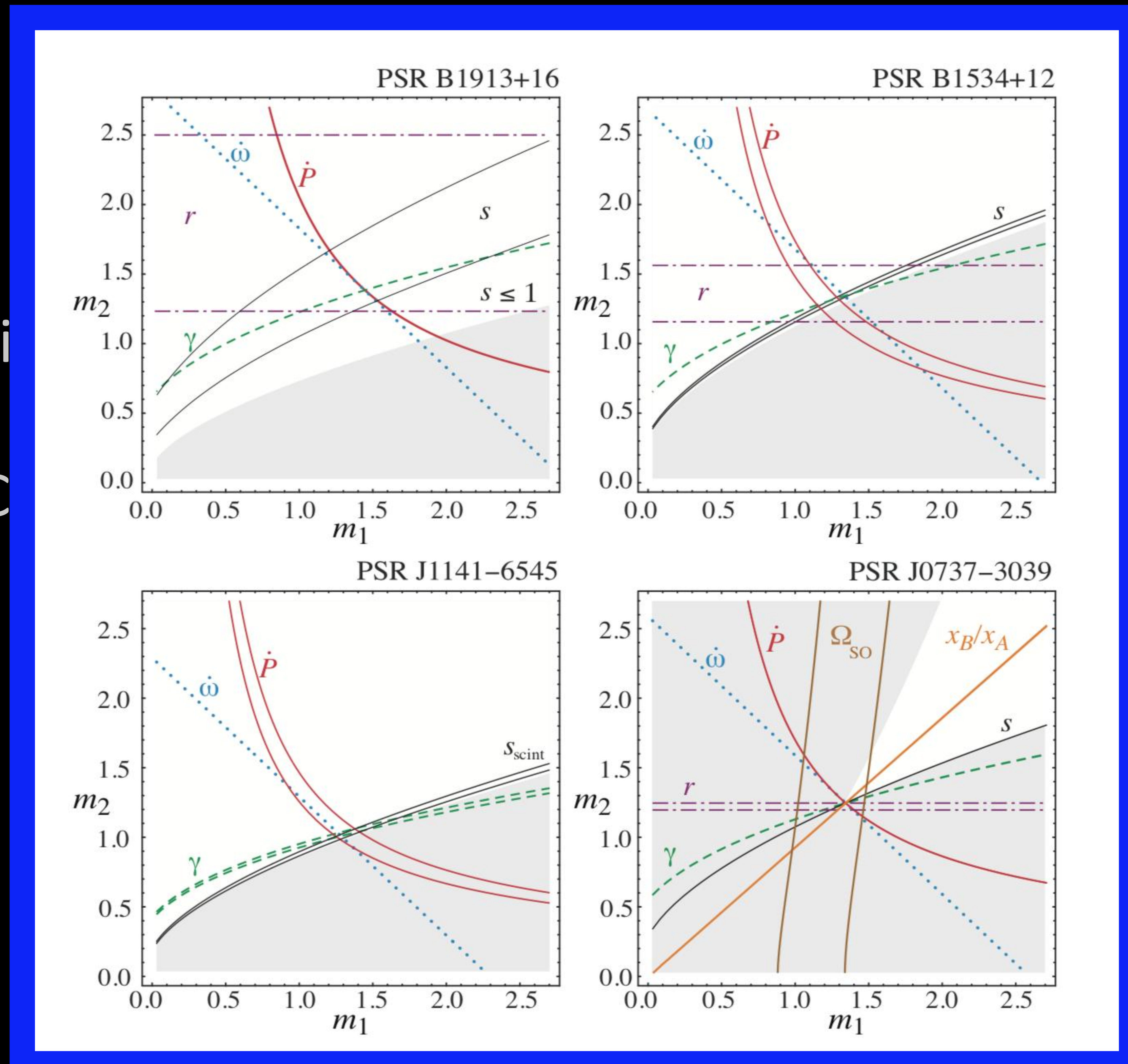
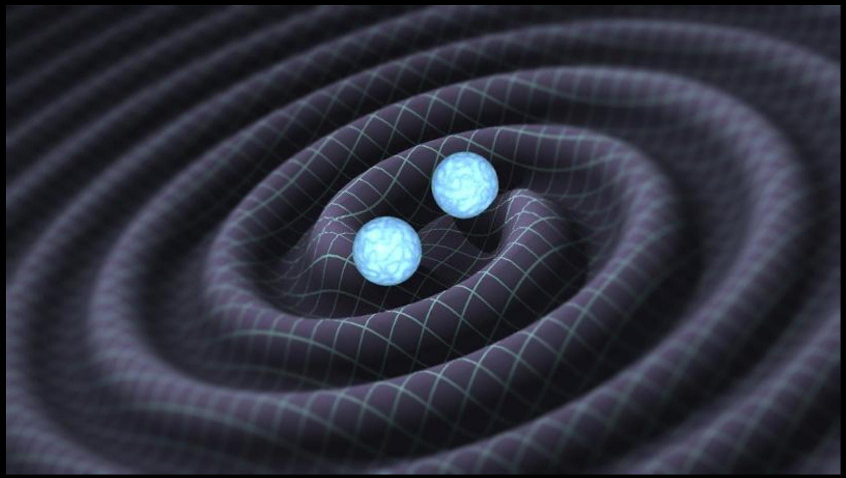
- Binary Pulsars

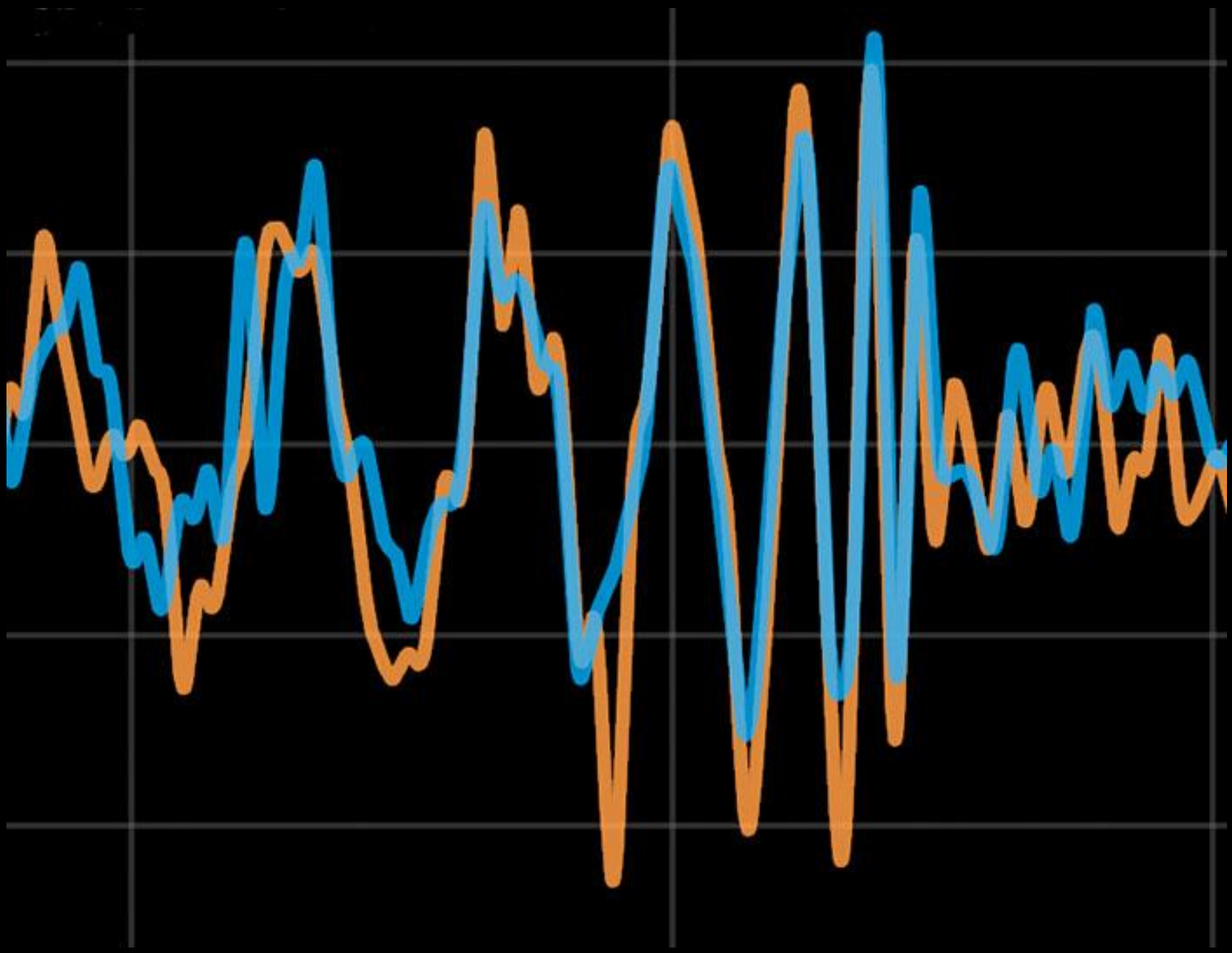


IMAGES: NASA PDG

MODERN TESTS OF GR



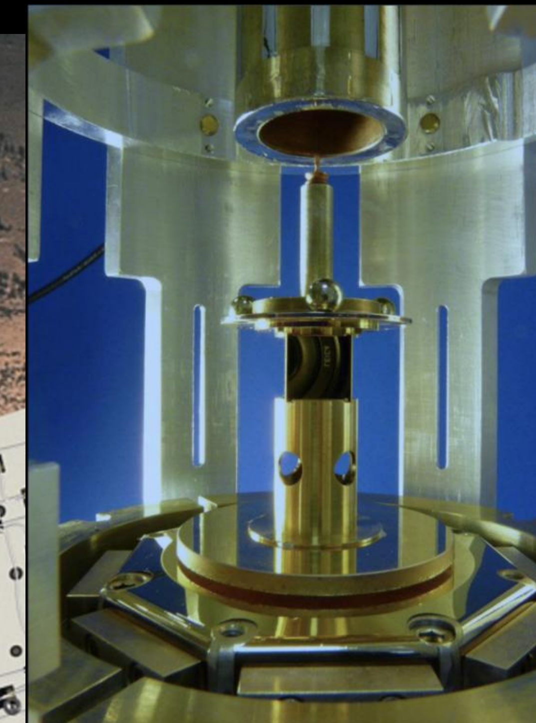
- Gravitational Lensing
- Relativistic Astrophysics
- Spacecraft Tests (eg Cassini)
- Binary Pulsars
- Gravitational Waves

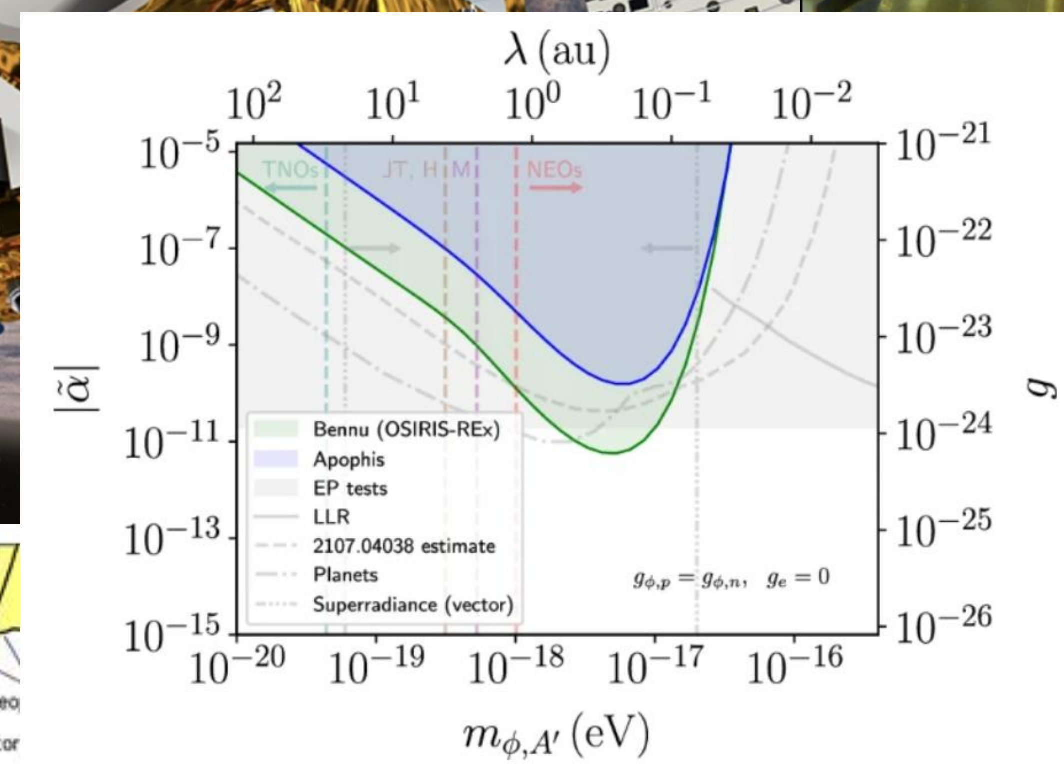


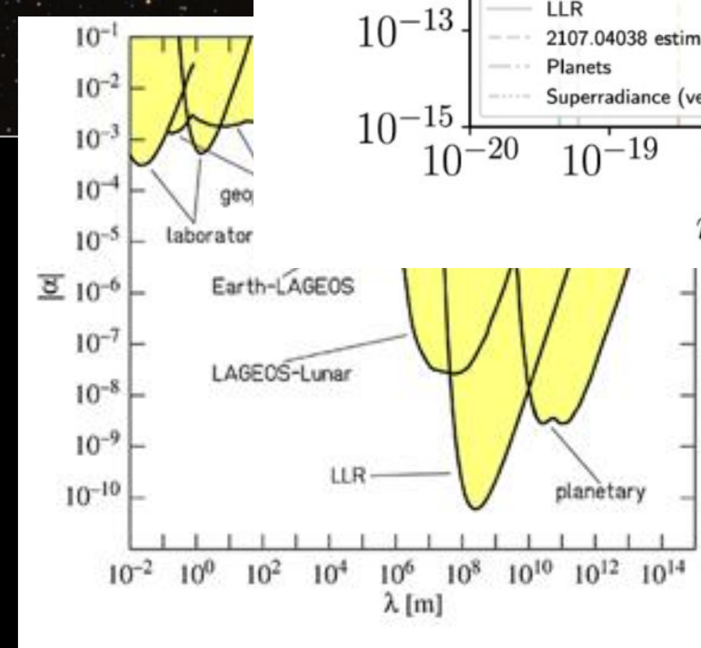
IMAGES: LIGO

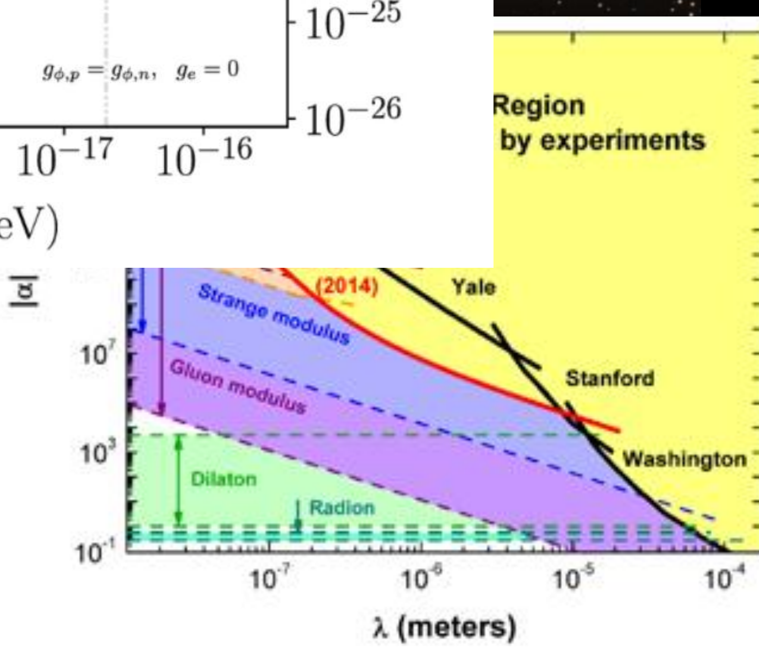
MODERN TESTS OF GR

- Gravitational Lensing
- Relativistic Astrophysics
- Spacecraft Tests (eg Cassini)
- Binary Pulsars
- Gravitational Waves
- Terrestrial Tests









TSAI ET AL (2024)

IMAGES: EOTWASH, MICROSCOPE, NAUTILUS

GR IS DEAD

IMAGE: DAILY STAR SWNS

REASONS TO DROP GR?

- Consistency with Quantum Mechanics

$$\Delta x < \ell_c \Rightarrow \Delta p > \frac{\hbar}{\ell_c} \Rightarrow \rho > \frac{\hbar c}{\ell_c^4} \Rightarrow \frac{1}{\ell_c^2} \sim \frac{G\rho}{c^4} > \frac{\hbar G}{\ell_c^4 c^3}$$

$$\Rightarrow \ell_c^2 > \ell_p^2 = \frac{\hbar G}{c^3}$$

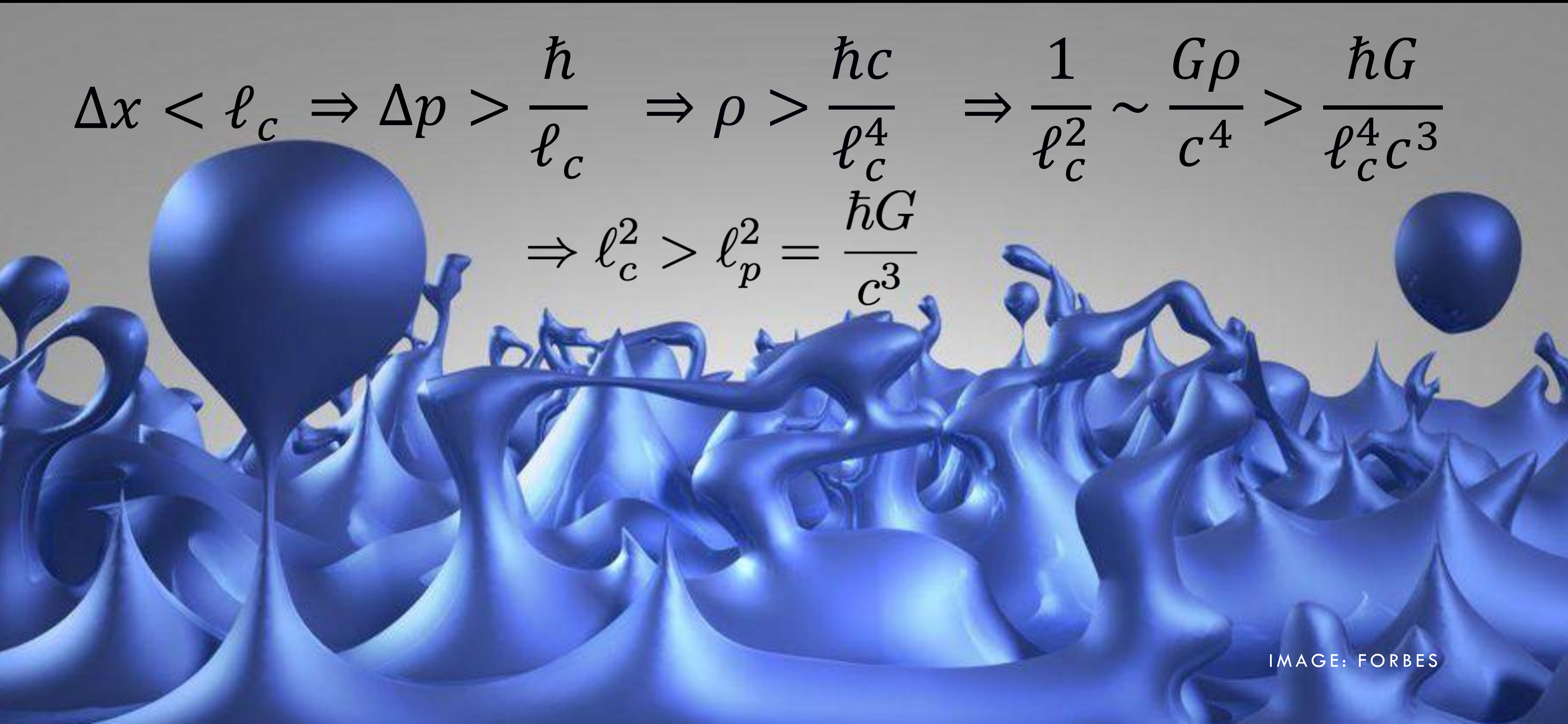


IMAGE: FORBES

REASONS TO DROP GR?

- Consistency with Quantum Mechanics: nonrenormalizable

e.g. for graviton-graviton scattering about a static background in GR:

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{h_{\mu\nu}}{M_p}$$

$$L = (\partial h)^2 + \frac{1}{M_p} h(\partial h)^2 + \frac{1}{{M_p}^2} h^2(\partial h)^2 + ..$$

gives

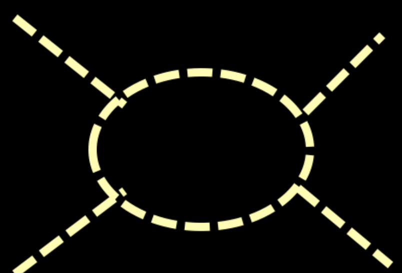
$$A_{no\ loops} \cong \frac{Q^2}{{M_p}^2} = 8\pi i G \frac{s^3}{tu}$$

DeWitt

REASONS TO DROP GR?

- Consistency with Quantum Mechanics: nonrenormalizable

Loop integrals diverge, and higher-order loops diverge more and more (because the coupling has dimensions of negative powers of mass)



$$A_{1loop} = \frac{Q^2}{{M_p}^4}\int \frac{d^4p}{(2\pi)^4}\frac{p^6}{(p^2+Q^2)^4}$$

$$+\frac{Q^4}{M_p^4}\int \frac{d^4p}{(2\pi)^4}\frac{p^4}{(p^2+Q^2)^4} + \cdots$$

But: cannot absorb divergent Q^4 terms into Newton’s constant

REASONS TO DROP GR?

- Consistency with Quantum Mechanics
- Dark Matter

many lines of evidence point to there being five times as much clustering matter as there are baryons (galaxy rotation; galaxy cluster masses; CMB vs LSS timing; BAO; CMB; BBN; ..)

REASONS TO DROP GR?

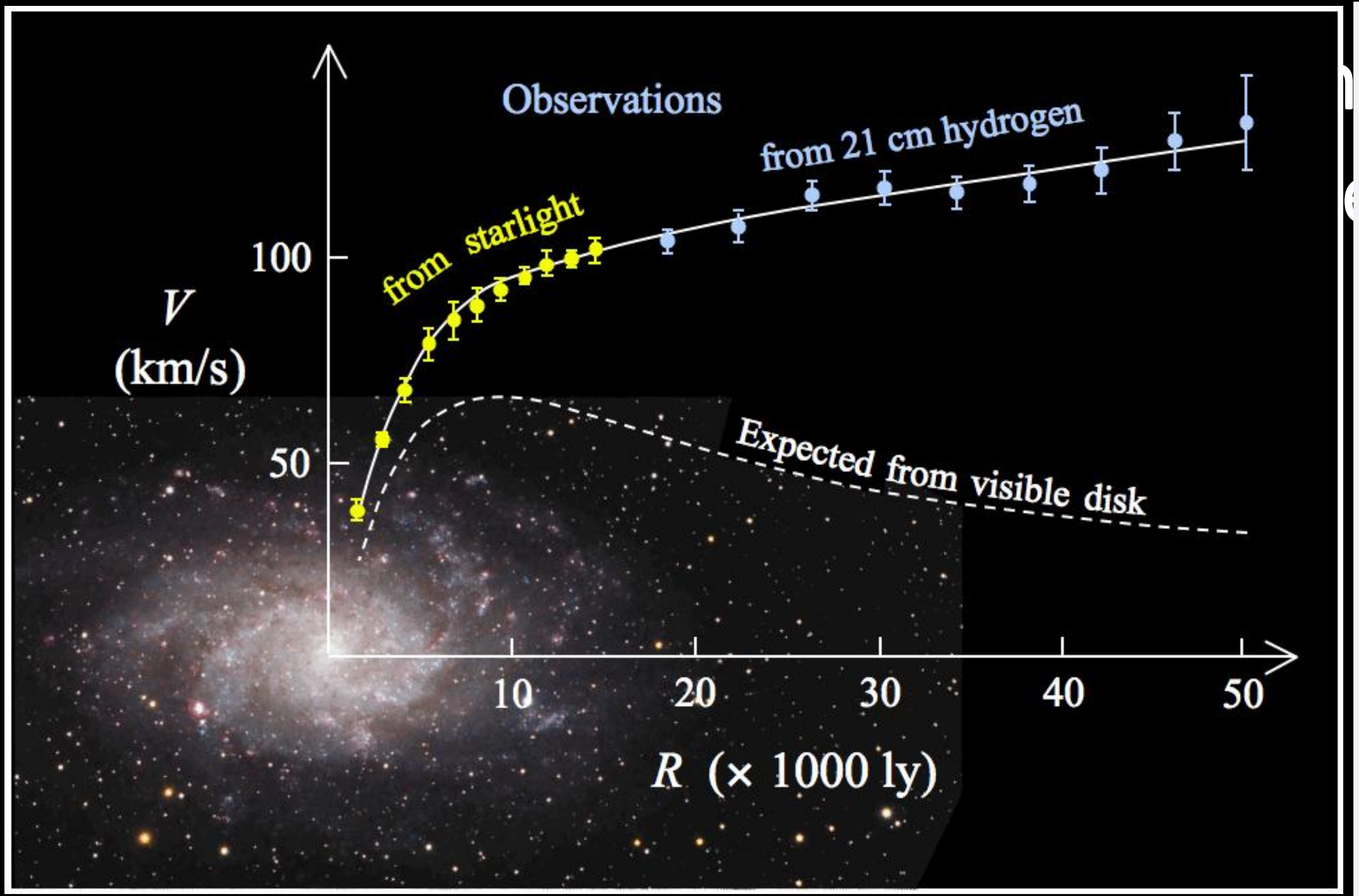
- Consistency with Quantum Mechanics
- Dark Matter

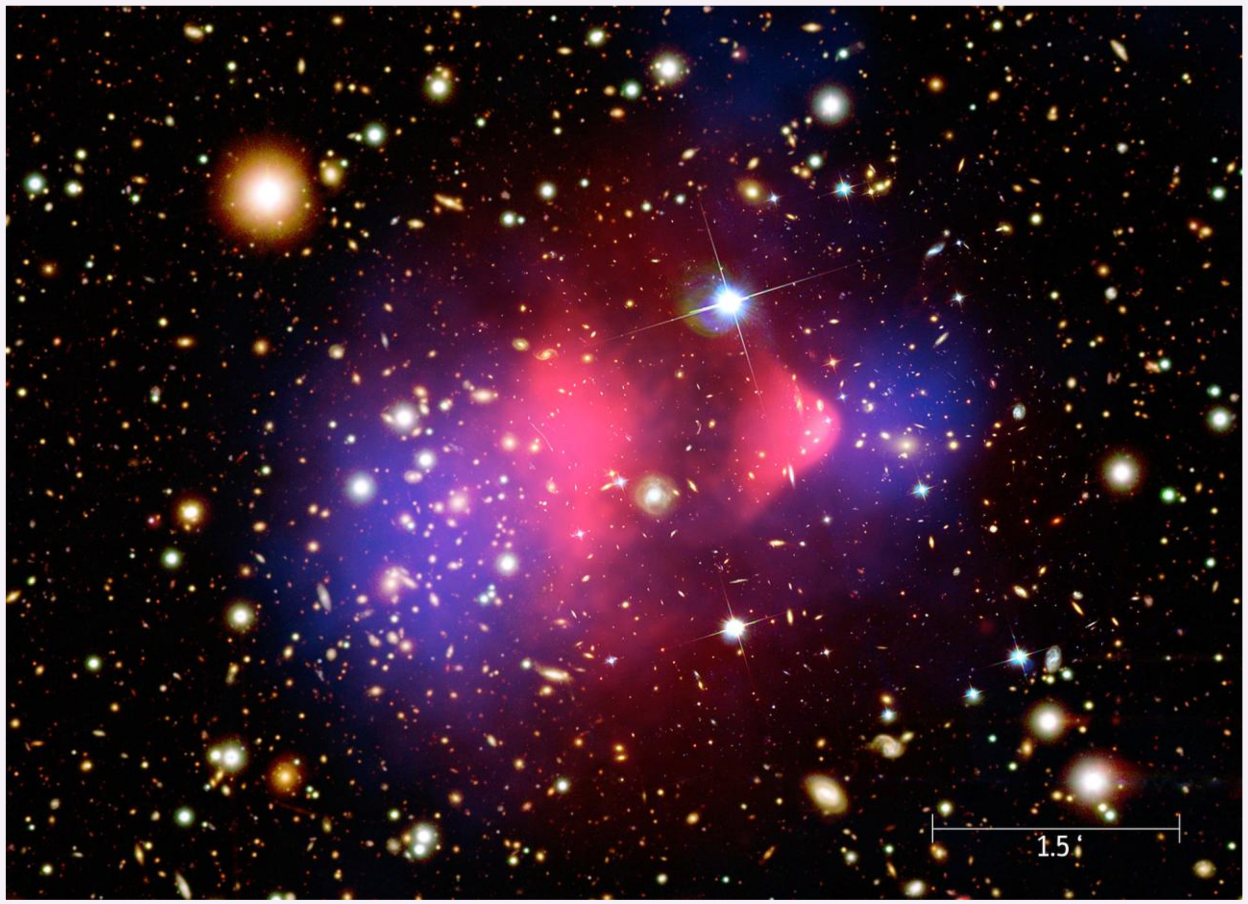
Structure formation

CMB properties

Baryon Acoustic Oscillations

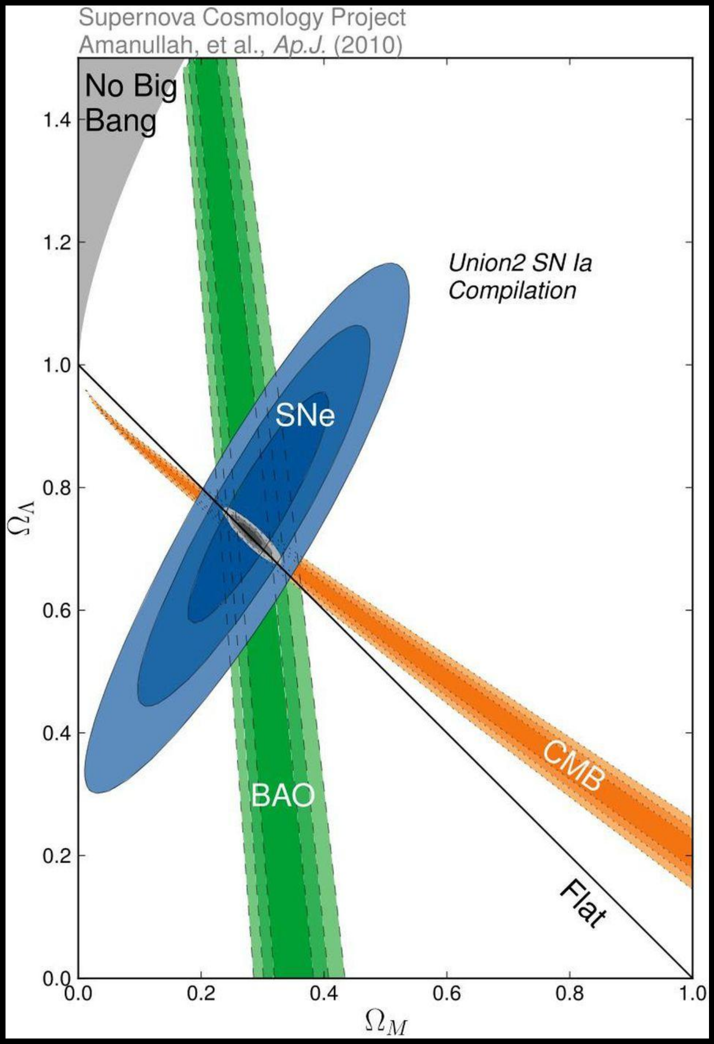
Nucleosynthesis





REASONS TO DROP GR?

- Consistency with Quantum Mechanics
- Dark Matter
- Dark Energy



several lines of evidence point to ~70% of the universe consisting of matter that causes the universal expansion to accelerate rather than decelerate

REASONS TO DROP GR?

- Consistency with Quantum Mechanics
- Dark Matter
- Dark Energy

} more efficient to modify gravity than postulate two new kinds of things?

REASONS TO DROP GR?

- Consistency with Quantum Mechanics
- Dark Matter
- Dark Energy
- Conceptual Puzzles

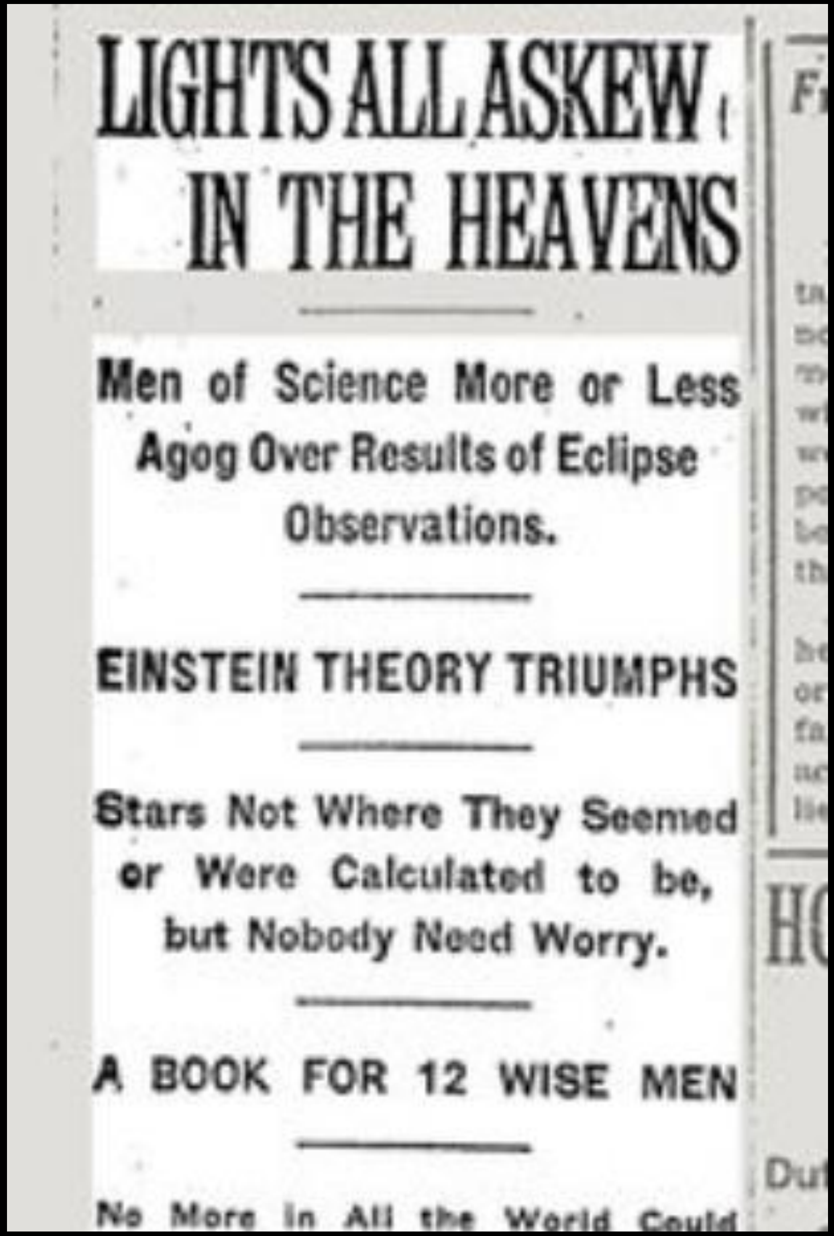
black hole entropy and information loss? singularity resolution? tunnelling of geometries? IR issues…

IMAGE: PETER ADSHEAD

REASONS TO DROP GR?

- Consistency with Quantum Mechanics
- Dark Matter
- Dark Energy
- Conceptual Puzzles
- Fame & Glory

tomorrow's Einstein or Hawking?



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could

PROPOSALS TO REPLACE GR

- f(R) theories
- DGP, massive gravity theories
- Lorentz breaking theories, MOND…
- scalar tensor vector theories (possibly in extra dims)
- string theory
- spacetime foam, loop QG, causal sets,…

IMAGE: MUSIC REWIND

IMAGE: DAILY STAR SWNS

WHY DOES CLASSICAL GR WORK?

- If quantum contributions to gravity cannot be quantified, why is it meaningful to compare GR with experiment?

Quantum field theory is a precision science:

e.g. QED:

$$a_\mu = 1159652188.4(4.3)\ 10^{-12}\ \text{(exp)}$$

$$a_\mu = 1159652140(27.1)\ 10^{-12}\ \text{(th)}$$

QED's renormalizability is an important part of its calculability, and so also underpins the theory error

WHY DOES CLASSICAL GR WORK?

- If quantum contributions to gravity cannot be quantified, why is it meaningful to compare GR with experiment?

General Relativity is also a precision science:

e.g. solar system tests, binary pulsar, ...

$$dP/dt = -2.408(10)\,10^{-12} \quad \text{(exp)}$$

$$dP/dt = -2.40243(5)\,10^{-12} \quad \text{(th)}$$

EFFECTIVE FIELD THEORY

- Quantum corrections are controlled once it is recognized GR is low-energy limit of something more fundamental:

Divergences can be absorbed if GR is regarded as the first term in a low-energy derivative expansion

$$\frac{\mathcal{L}}{\sqrt{-g}} = v^4 + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$

Quantum corrections can be quantified, and turn out to be controlled by powers of Q/M_p and Q/m

EFFECTIVE FIELD THEORY

- Non-GR terms likely arise as high-energy states are integrated out, such as in string theory.

How to interpret the non-GR terms in the action?

$$\frac{\mathcal{L}}{\sqrt{-g}} = \boxed{m^4 + \frac{m^2}{2} R} + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$

If multiple particles are integrated out then:

the *largest* mass wins in the numerator (eg coeff of *R*)

EFFECTIVE FIELD THEORY

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How to interpret the non-GR terms in the action?

$$\frac{\mathcal{L}}{\sqrt{-g}} = m^4 + \frac{m^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \boxed{\frac{c_3}{m^2} R^3} + \cdots$$

If multiple particles are integrated out then:

the *largest* mass wins in the numerator (eg coeff of *R*)

smallest mass wins in the denominator (eg coeff of R^3).

EFFECTIVE FIELD THEORY

- Low energies make this predictive. For example: using

$$\frac{\mathcal{L}}{\sqrt{-g}} = v^4 + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$

compute amplitude for scattering E gravitons at L loops using V_{ik} vertices involving i fields and k derivatives:

GR-QC/0311082
0902.4465
1708.07443

$$\mathcal{B}_E(Q) \simeq M_p \left(\frac{Q^2}{M_p}\right)^{E-1} \boxed{\left(\frac{Q}{4\pi M_p}\right)^{2L}} \times \prod_{d_n \geq 4} \left[\left(\frac{Q}{M_p}\right)^2 \left(\frac{Q}{m}\right)^{d_n - 4}\right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{Q^2 M_p^2}\right)^{V_n}$$

*Semiclassical (loop) expansion *is* the low-energy expansion!*

EFFECTIVE FIELD THEORY

- Low energies make this predictive. For example: using

$$\frac{\mathcal{L}}{\sqrt{-g}} = v^4 + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$

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Higher derivative interactions ($d_n > 2$) are more suppressed at low energies

EFFECTIVE FIELD THEORY

- Low energies make this predictive. For example: using

$$\frac{\mathcal{L}}{\sqrt{-g}} = v^4 + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$

compute amplitude for scattering E gravitons at L loops using V_{ik} vertices involving i fields and k derivatives:

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0902.4465
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$$\mathcal{B}_E(Q) \simeq M_p \left(\frac{Q^2}{M_p}\right)^{E-1} \left(\frac{Q}{4\pi M_p}\right)^{2L}$$

$$\times \prod_{d_n \geq 4} \left[\left(\frac{Q}{M_p}\right)^2 \left(\frac{Q}{m}\right)^{d_n - 4} \right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{Q^2 M_p^2}\right)^{V_n}$$

Zero derivative interactions ($d_n < 2$) are *enhanced* at low energies

EFFECTIVE FIELD THEORY

- Low energies make this predictive. For example: using

$$\frac{\mathcal{L}}{\sqrt{-g}} = v^4 + \frac{M_p^2}{2}\,R + c_1\,R^2 + c_2\,R_{\mu\nu}R^{\mu\nu} + \frac{c_3}{m^2}\,R^3 + \cdots$$

compute amplitude for scattering E gravitons at L loops using V_{ik} vertices involving i fields and k derivatives:

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$$\mathcal{B}_E(Q) \simeq M_p \left(\frac{Q^2}{M_p}\right)^{E-1} \left(\frac{Q}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{Q}{M_p}\right)^2 \left(\frac{Q}{m}\right)^{d_n-4}\right]^{V_n} \prod_{d_n=0} \left(\frac{v^4}{Q^2 M_p^2}\right)^{V_n}$$

No penalty for $d_n = 2$ interactions (GR nonlinearities cannot be ignored)

EFFECTIVE FIELD THEORY

View of GR as effective quantum theory has other benefits

Can understand GR as the most general possible interactions allowed by special relativity and quantum mechanics for a massless spin-2 particle at low energies. WEINBERG 1979

WEINBERG

Maxwell's equations are similarly inevitable at low energies given massless spin-one particle.

Standard Model is most general low-energy interactions allowed given particle content.

IMAGE: PUBLIC DOMAIN

IMAGE: DAILY STAR SWNS

REASONS TO DROP GR?

- Consistency with Quantum Mechanics

Short distance problem

- Dark Matter
- Dark Energy
- Conceptual Puzzles
  - Black hole entropy; information loss; cosmological initial conditions; singularity resolution;

Long distance problem

- Fame and Glory

personal problem

PROPOSALS TO REPLACE GR

- f(R) theories
- DGP, massive gravity theories

Long distances

- Lorentz breaking theories...
- scalar tensor vector theories

Bit of both

- string theory
- spacetime foam, loop QG, causal sets,...

Short distances

MODIFYING GRAVITY

- Sensible examples of short distance modifications to GR now exist (eg string theory), but low-energy expansion makes them hard to test at low energies

IMAGE: QUORA

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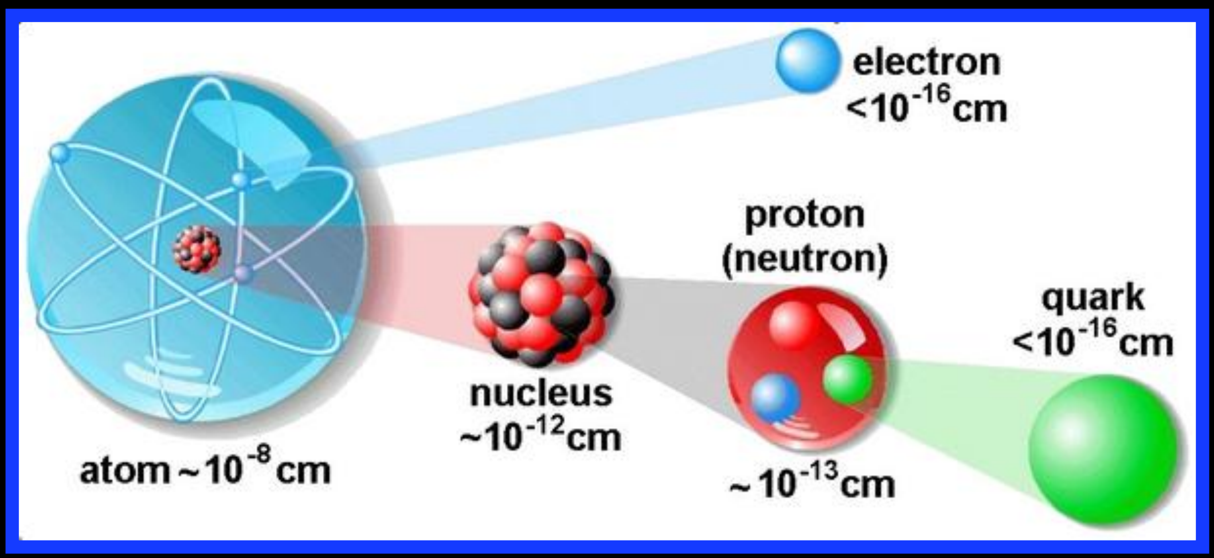

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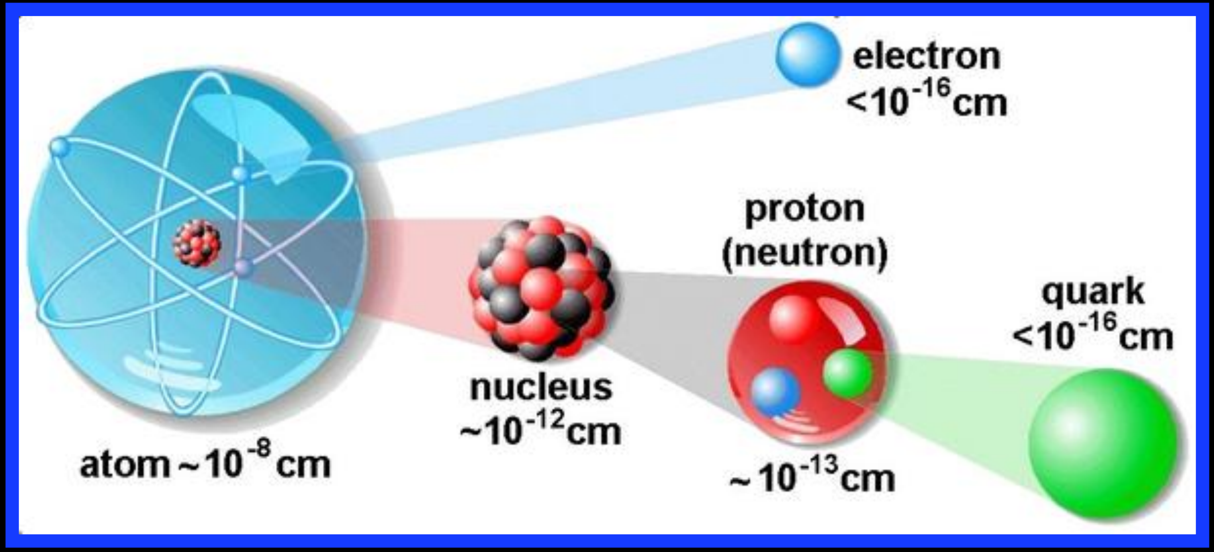

Decoupling of small-distance physics is two-edged sword: it explains why IR is robust, but makes specific UV modifications hard to test

- Can anything useful be said at low energies given the ruthless efficiency of decoupling?

IMAGE: QUORA

USEFUL LOW ENERGY INFORMATION

- Many proposals for modified gravity make no sense as a low-energy theory, and for these the question is: what justifies the (usually classical) approximations used?

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  eg MOND does well for galaxies, not so well for clusters, cosmology

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- Power counting suggests concrete kinds of theories to seek

LOW-ENERGY SUGGESTIONS

- Recall that low-energy scalar-tensor theories of the form

$$\frac{\mathcal{L}}{\sqrt{-g}} = v^4 U(\phi) + \frac{M_p^2}{2} R + f^2 G_{ab}(\phi) \partial_\mu \phi^a \partial^\mu \phi^b + c_1 R^2 + \cdots$$

contribute to observables at low energy Q by an amount:

$$\mathcal{B}_E(Q) \simeq M_p \left(\frac{Q^2}{M_p} \right)^{E-1} \left(\frac{Q}{4\pi M_p} \right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{Q}{M_p} \right)^2 \left(\frac{Q}{m} \right)^{d_n - 4} \right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{Q^2 M_p^2} \right)^{V_n}$$

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BUT notice there is NO PENALTY for two-derivative interactions

REVIEW: 2509.00688

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2410.11099
2512.13544

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- Axio-dilaton theories provide an interesting 2-scalar benchmark, well motivated by UV physics and provide novel new approaches to the Dark Sector

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{f^2}{2}\left[\frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right]$$

2310.02092
2408.10820
2505.05450
2603.20008

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IMAGE: THE MATRIX

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IMAGE: THE MATRIX

Gravity has much to learn from and teach other areas of physics

(eg open systems, duality, late-time failure of ptbn theory)


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