Gravitation theory in multimessenger astronomy I, II

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The International Conference:

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I: Comparison of geometrical and field approaches to the gravity physics

- Gravity Physics in relativistic astrophysics
- Gravity Theory according to

Einstein's geometrical and Feynman's field description of gravitational interaction

II: Crucial observational tests based on GW and optical observations

- Perspectives for observational/experimental testing geometric and field gravity physics

Part I:

Geometrical and Field approaches to the gravity physics

Modern questions discussed in the literature on Relativistic Astrophysics

Does General Relativity hold in the strong field regime?

Does General Relativity hold on cosmological scales?

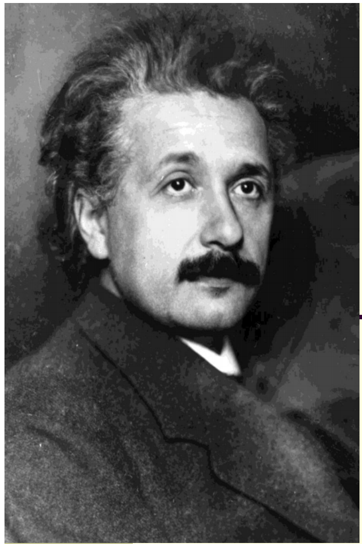
Are there alternative gravity theories which predicts testable crucial experiments/observations?

General Theory of Relativity: Will it survive the next decade?

Search for General Relativity limits

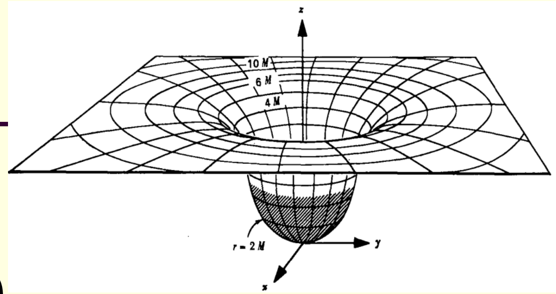
and

Solution of the gravity energy problem



Two ways in gravity theory

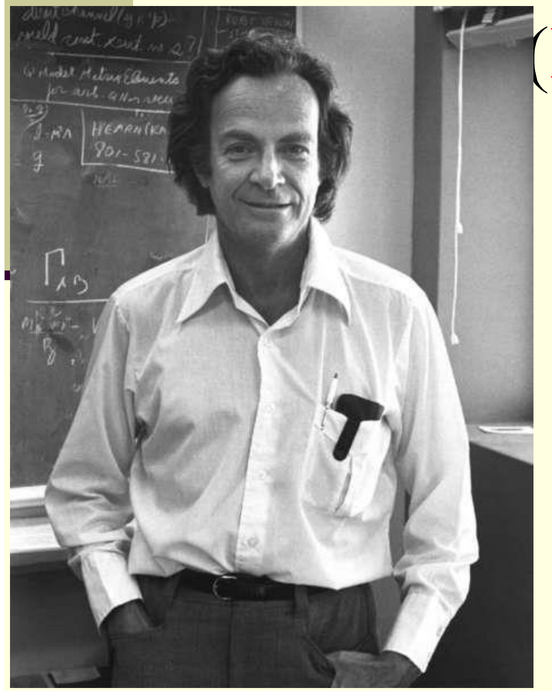
Einstein's Geometrical Gravity



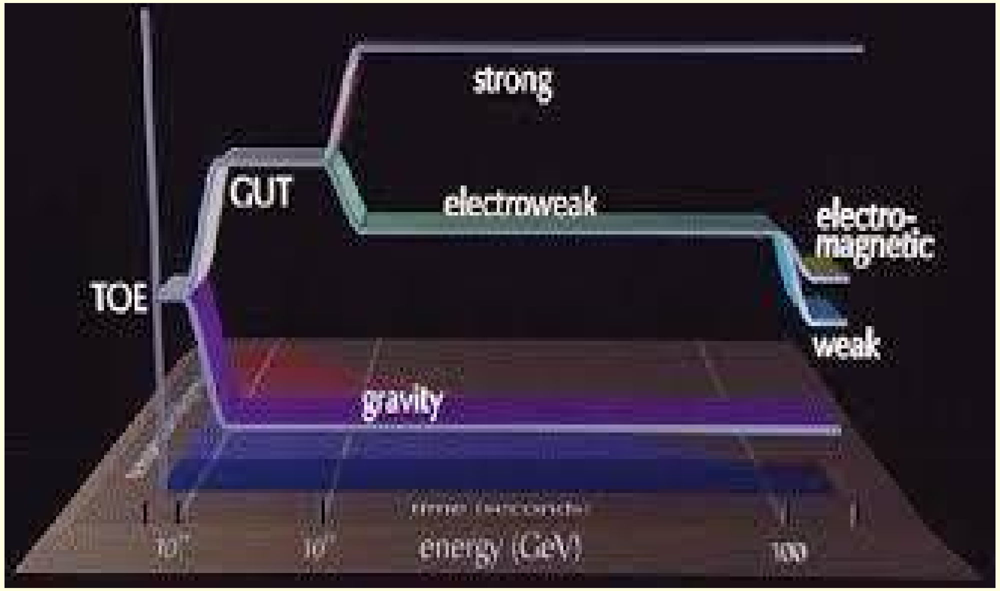
(General Relativity Theory, Geometrodynamics - GRT)

and

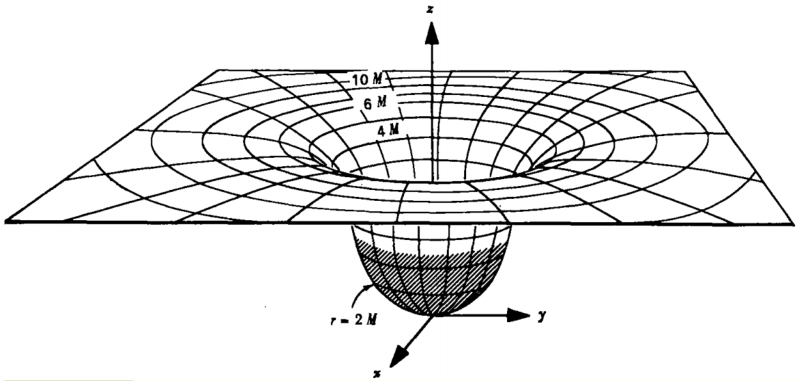
Feynman's Field Gravity Approach

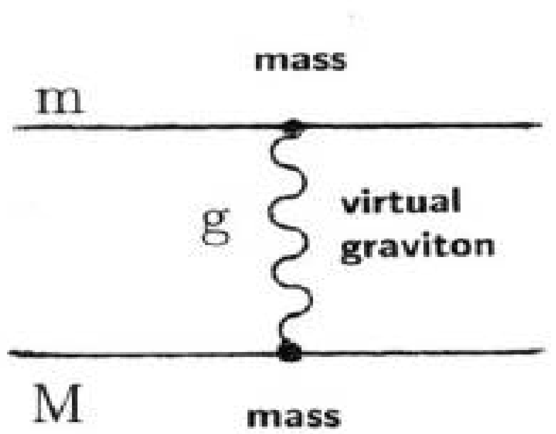


(Field Gravitation Theory, Gravidynamics - FGT)



Metric and nonmetric gravity physics

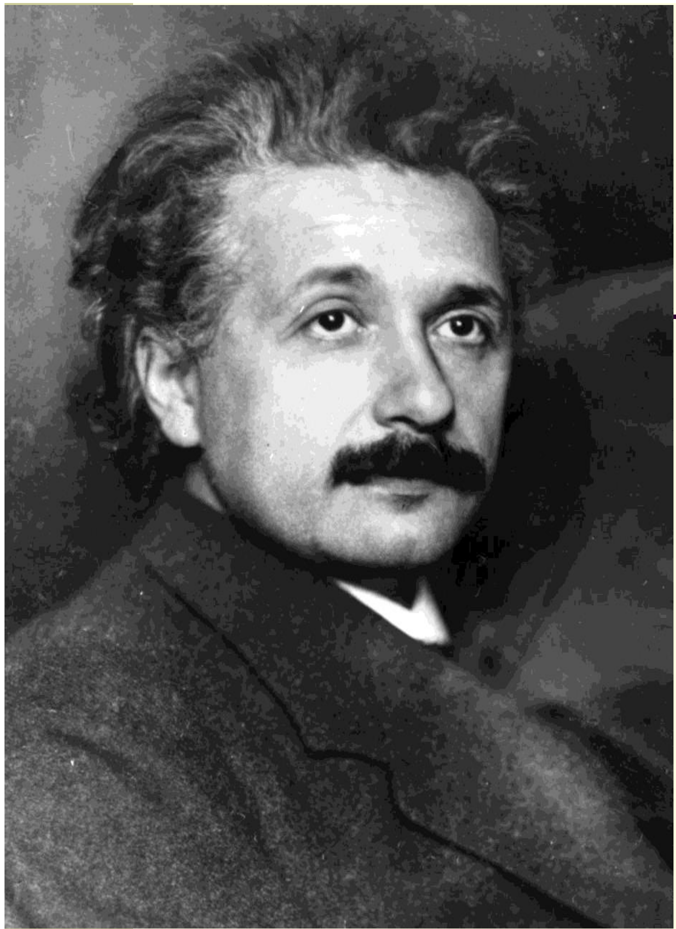




- Einstein's geometrical general relativity theory of curved Riemannian space (GRT and its modifications)
  $g^{ik}(\vec{r},t),\ \mathcal{R}_{iklm}$

- Feynman's relativistic quantum field theory in Minkowski space (FGT)
  $\eta^{ik},\quad \psi^{ik}(\vec{r},t),\quad \vec{F}_g,$

$$T^{00}(t,x) = \varepsilon_g \left(\frac{erg}{cm^3}\right),\quad E_{(g)} = h\nu$$



Albert Einstein
(1879 – 1955)

Nobel Prize in Physics (1921) :

"for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect”

General Relativity Theory (GRT)

Gravity is R-Geometry, g^{ik} is metric

Einstein A., Sitzungsber. K. Preuss. Akad. Wiss. 1, 844 (**1915**) (gravity is not a matter)

Einstein A., Sitzungsber. K. Preuss. Akad. Wiss. 1, 688 (**1916**) ; 154 (**1918**) GW

Gravitational Waves : $g^{ik} \approx \eta^{ik} + h^{ik}$ => $\Box h^{ik} = 0$

Richard Phillips Feynman (1918 – 1988)

Nobel Prize in Physics (1965) :
"for his fundamental work in
quantum electrodynamics "

"Lectures on Gravitation"(1962), CIT

Feynman's Field Gravity approach:

$\eta^{ik}, \quad \psi^{ik}(\vec{r},t), \quad \vec{F}_g, \quad \varepsilon_g\ (erg/cm^3)$

(Gravity is relativistic quantum field in Minkowski space)

"The **geometric interpretation** is **not really necessary or essential to physics"** Gravitational Waves: $\Box\boldsymbol{\psi}^{ik} = \mathbf{0}$

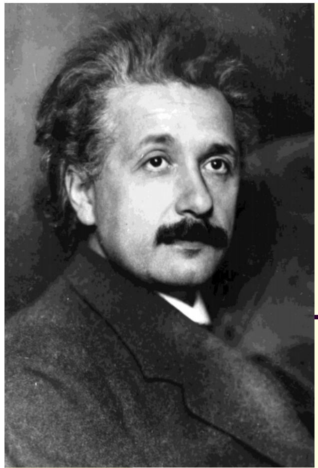
"the situation is exactly **analogous to electrodynamics** - and in the **quantum interpretation**, every radiated **graviton** carries away an amount of **energy ђω**." (A^i - ED, ψ^{ik}- GD)

Field and Geometrical approaches to gravitation

Field Gravitation Theory	General Relativity
$\eta^{ik}, \psi^{ik}(\vec{r},t), \ \vec{F}_g$	$g^{ik}(\vec{r},t), \mathcal{R}_{iklm}$
$\mathbf{Trace}(\boldsymbol{\psi}^{ik}) = \boldsymbol{\eta}_{ik}\boldsymbol{\psi}^{ik}(\vec{\boldsymbol{r}},\boldsymbol{t}) =$ $= \boldsymbol{\psi}(\vec{\boldsymbol{r}},\boldsymbol{t})$ – **fuction of spacetime**	$\mathbf{Trace}(\boldsymbol{g}^{ik}) = \boldsymbol{g}_{ik}\,\boldsymbol{g}^{ik} =$ $= \mathbf{4}$ - **costant**
$f^{ik} = \eta^{ik} + \psi^{ik}$	$g^{ik} \approx \eta^{ik} + h^{ik}$
$f_{ik} = \eta_{ik} + \psi_{ik}$	$g_{ik} \approx \eta_{ik} - h_{ik}$
$\boldsymbol{f}^{i}{}_{k}(\vec{\boldsymbol{r}},\boldsymbol{t}) = \boldsymbol{\eta}^{i}{}_{k} + \boldsymbol{\psi}^{i}{}_{k}(\vec{\boldsymbol{r}},\boldsymbol{t})$	$\boldsymbol{g}^{i}{}_{k} = \boldsymbol{\delta}^{i}{}_{k} = \boldsymbol{const}$
non-metric Spin 2 ⊕ Spin 0	"modifications of GR and other **metric theories**"
"New Relativistic Astrophysics"	
RCO (**noBH**), EMT, GW(T+S)	BH, **no EMT**, GW(T),
Positive Localizable Gravity Energy, Cosmological models with Evolution in Static Space	no Localization of Gravity Energy, Cosmological models with Expanding Space

General Relativity Theory:

basic principles, main equations and predictions



GRT basic principles

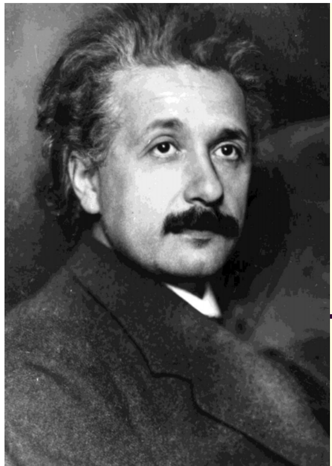
- The **Equivalence Principle:** free falling frames equivalent inertial reference frames , $m_{inert} = m_{grav}$(WEP), …
- The **Geometrization Principle:** gravitational potentials are described by the metric tensor $g^{ik}(\vec{r}, t)$ of the Riemannian space-time

$$A^i{}_k = g^{il} A_{lk} \quad , \qquad A^{ik} = g^{il} g^{km} A_{lm}$$

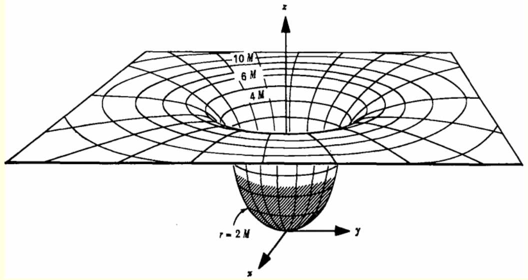
and rigorous equalities for the metric:

$$\mathrm{Tr}(g^{ik}) = g_{ik}\, g^{ik} = 4 \,, \qquad g^i{}_k = \delta^i{}_k$$

- Geometrical extension of the **Stationary Action Principle** $\delta S = \delta(S_m + S_g) = 0$ for δg^{ik}



GRT main equations



$$ds^2 = g_{ik} dx^i dx^k$$

$g^{ik}(\vec{r}, t)$; $\mathcal{R}_{iklm}$; $\boldsymbol{g_{ik}\, g^{ik} = 4}$; δg^{ik}, $\delta S = 0$

$$S = S_{(\mathrm{m})} + S_{(\mathrm{g})} = \frac{1}{c}\int \left(\Lambda_{(\mathrm{m})} + \Lambda_{(\mathrm{g})}\right)\sqrt{-g}\, d\Omega$$

$$\Re^{ik} - \frac{1}{2} g^{ik}\, \Re = \frac{8\pi G}{c^4}\, T^{ik}_{(m)} \qquad T^{ik}_{(\mathrm{m})\,;\,i} = 0 \qquad \frac{du^i}{ds} = -\Gamma^i_{kl} u^k u^l$$

$$\frac{\partial}{\partial x^k}(\sqrt{-g})(T^{ik}_{(\mathrm{m})} + t^{ik}_{(\mathrm{g})}) = 0$$

${T_{(m)}}^{ik} = {T_{(p)}}^{ik} + {T_{(vac)}}^{ik}$ which includes matter and vacuum (*dark energy*) ${T_{(v)}}^{ik} = g^{ik}\Lambda$ but **does not includes the gravity field EMT : gravity field is not a matter in GR (no $\boldsymbol{T_{(g)}}^{ik}$),**

$\boldsymbol{t^{ik}{}_{(g)}(t, x)}$ is the **Energy-Momentum Pseudo-Tensor** of the gravity field

The energy problem in GRT: $t^{ik}{}_{(g)}(t,x)$ is Pseudo-Tensor

L.D.Landau & E.M.Lifshitz "The Classical Theory of Fields", Oxford (1971)

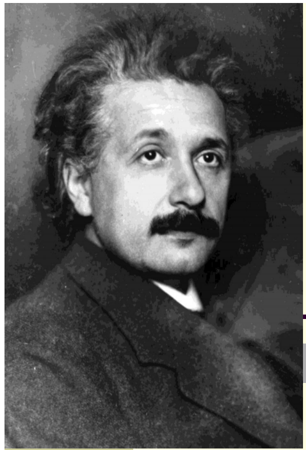
$$T^{00}{}_{(em)}(r) = +\frac{(\nabla\varphi)^2}{8\pi}$$

Misner, C., Thorne, K., Wheeler, J. "Gravitation", Freeman, San Francisco (1973)

$$t^{00}{}_{(gE)}(r) = +\frac{(\nabla\varphi)^2}{8\pi G}$$

$$t^{00}{}_{(gLL)}(r) = -\frac{7(\nabla\varphi)^2}{8\pi G}$$

- "It has no meaning to speak of a definite localization of the energy $t^{ik}{}_{(g)}(t,x)$ of the gravitational field in space" (§101, p.307)
- (§20.4,p.467) "..gravitational energy... is not localizable. The equivalence principle forbids", and (§35.7, p.955): "the stress-energy carried by gravitational waves cannot be localized inside a wavelength".

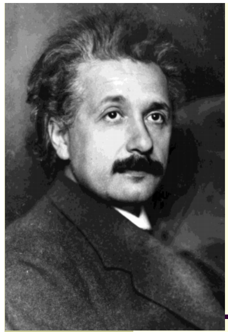


GRT predictions in the weak field approximation

- *Universality of free fall for any bodies,*
- *The deflection of light by massive bodies,*
- *The gravitational frequency-shift,*
- *The time delay of light signals,*
- *The perihelion shift of planets,*
- *The Lense-Thirring effect,*
- *The geodetic precession of a gyroscope,*

+ *Phenomena based on Pseudo-Tensor calculations:*

- *The emission of quadrupole gravitational waves,*
- *The detection of the gravitational waves .*



GRT open questions

- Existence and localization of GW energy (according to MTW 1973 (§20.4, p.467): *"...gravitational energy... is not localizable. The equivalence principle forbids"*

$$g^{ik} \approx \eta^{ik} + h^{ik} \quad => \quad \Box h^{ik} = 0 \quad <=> \quad \boldsymbol{t^{ik}}_{(\boldsymbol{g})}(\boldsymbol{t}, \boldsymbol{x}) = ?$$

- Existence of Black Holes event horizon and singularity

$$r_{Sch} = 2GM/c^2 \qquad => \qquad \boldsymbol{t^{ik}}_{(\boldsymbol{g})}(\boldsymbol{t}, \boldsymbol{x}) = ?$$

$$ds^2 = (1 - \frac{r_{\rm Sch}}{r})c^2 dt^2 - \frac{dr^2}{1 - \frac{r_{\rm Sch}}{r}} - r^2(\sin^2\theta\, d\phi^2 + d\theta^2)$$

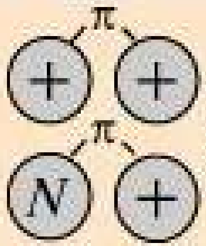
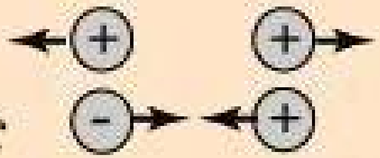
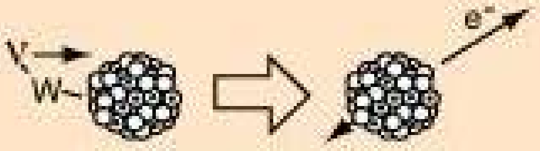
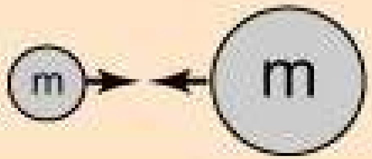
- Existence of continuous space creation with vacuum in Friedmann's cosmological model $r(t) = S(t) \cdot \chi$,

$$ds^2 = c^2 dt^2 - S^2(t) d\chi^2 - S^2(t) I_k^2(\chi)(d\theta^2 + sin^2\theta d\phi^2) \quad \boldsymbol{t^{ik}}_{(\boldsymbol{g})}(\boldsymbol{t}, \boldsymbol{x}) = ?$$

Relativistic Quantum Field Gravitation Theory:

basic principles, main equations and predictions

Fundamental Forces

Force		Strength	Range (m)	Particle
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	 neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

History of the Field Gravitation Theory

Poincare(1905), Fierz & Pauli(1939), Birkhoff(1944), Moshinsky(1950), Thirring (1961), Kalman (1961)…

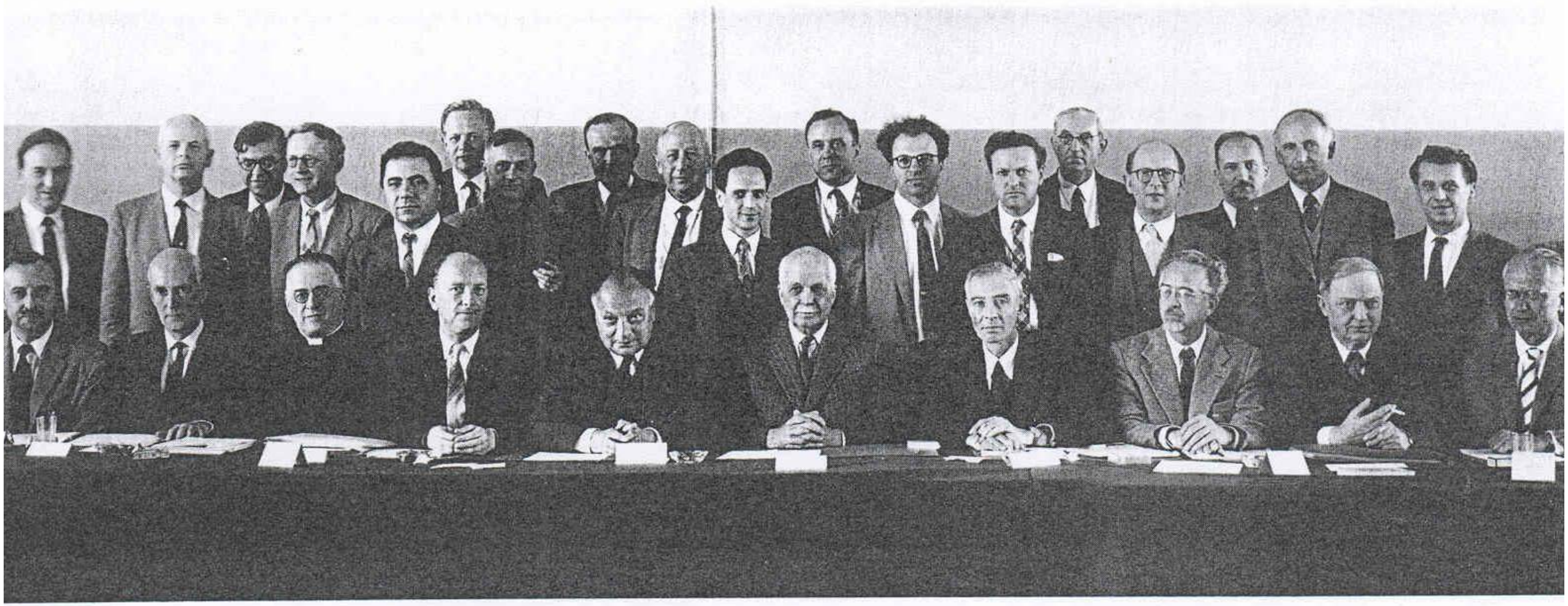
Minkowski space η^{ik} : $A^{i}(\vec{r},t)$- ED, $\psi^{ik}(\vec{r},t)$ - GD

Richard Feynman (1962,1971,1995), *Lectures on Gravitation,* Caltech (Spin 2 gravitons)

V. V. Sokolov, Yu. V. Baryshev(1980),
Field-theoretical approach to gravitation: Energy Momentum Tensor of the field, Gravitation and Relativity Theory, Kazan State University, vyp.17, 34 (1980):

$$\mathrm{Tr}\,\psi^{ik} = \eta_{ik}\psi^{ik} = \psi(\vec{r},t)$$ → Spin 2 + Spin 0

Founders of Relativistic Astrophysics
1958 Solvay conference

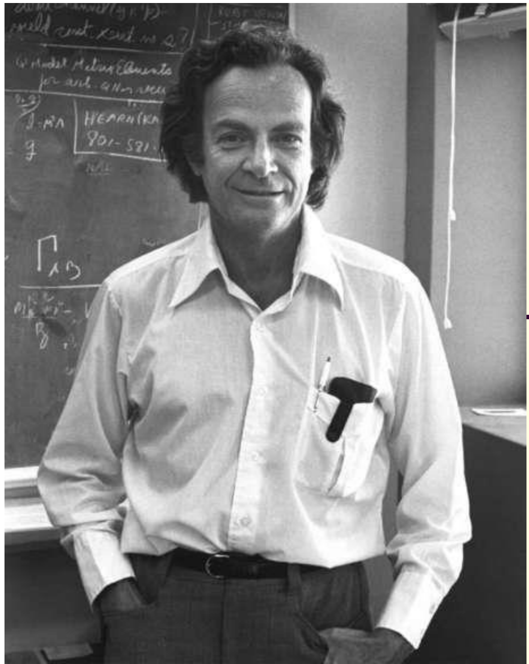


F. HOYLE H. C. van de HULST A. R. SANDAGE J. A. WHEELER H. ZANSTRA L. LEDOUX

S. KLEIN W. W. MORGAN B. V. KUKARKIN M. FIERZ W. BAADE H. BONDI T. GOLD L . ROSENFELD A. C. B. LOVELL J. GÉHÉNIAU

V. A. AMBARZUMIAN E. SCHATZMAN

I. McCREA J. H. OORT G. LEMAÎTRE C. J. GORTER W. PAULI W. L. BRAGG J. R. OPPENHEIMER C. MØLLER H. SHAPLEY O. HECKMA



Feynman Lectures on Gravitation

(1962-1963 course at Caltech)

Lecture 1

1.1 A Field Approach to Gravitation

1.3 Quantum Effects in Gravitation

Lecture 3

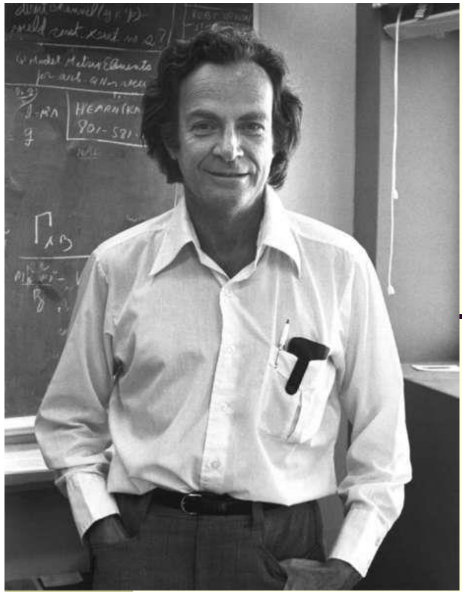
3.1 The Spin of the Graviton

3.5 The Lagrangian for the Gravitational Field

Lecture 16

16.4 Radiation of Gravitons

16.5 The Sources of Classical Gravitational Waves



from Feynman's book :

- "The geometric interpretation is not really necessary or essential to physics." (p.113) (A^i - ED, ψ^{ik}- GD)
- "the situation is exactly analogous to electrodynamics - and in the quantum interpretation, every radiated graviton carries away an amount of energy ђω." (p.220)

From letter to his wife: **"Remind me not to come to any more gravity conferences!"** (Warsaw 1962)

Physical basis for theory of gravitational interaction

Field approach

- The **inertial** reference frames
- The **flat Minkowski** space

η^{ik} – conservation laws

- The concept of potential

$\psi^{ik}(\vec{r},t),\ \psi(\vec{r},t) = \eta_{ik}\psi^{ik}$

scalar part, **force, gravitons**

- The Energy-Momentum

Tensor of the gravity field $T_{(g)}{}^{ik}$

- The **universality** of gravitational interaction
  $\Lambda_{(int)} = \psi_{ik}T^{ik},\quad m_0$

Geometry

- The **non-inertial** reference frames
- The **curved Riemannian** space-time $g_{ik}\, g^{ik} = 4$
- The metric tensor $g^{ik}(\vec{r},t)$, the curvature tensor $\mathcal{R}_{iklm}$
- The EM **Pseudo-Tensor** of the gravity field $t_{(g)}{}^{ik}$
- The Equivalence Principle

  $m_{inert} = m_{grav}$

  free falling frames

Relativistic Compact Objects, GW, Cosmological models

Comparison of FG and GR: field equations

Field Gravity

$\eta^{ik},\ \psi^{ik}(\vec{r},t),\ \psi(\vec{r},t), T_{(g)}{}^{ik}$

$\Lambda_{(int)} = \psi_{ik}T^{ik}$

$$S = S_{(g)} + S_{(int)} + S_{(m)}$$

$$-\psi^{ik,l}{}_{l} + \psi^{il,k}{}_{l} + \psi^{kl,i}{}_{l} - \psi^{,ik} - \eta^{ik}\psi^{lm}{}_{,lm} + \eta^{ik}\psi^{,l}{}_{l} = \frac{8\pi G}{c^2}T^{ik}$$

$$\psi^{ik} \Rightarrow \psi^{ik} + \lambda^{i,k} + \lambda^{k,i} \qquad \psi^{ik}{}_{,k} = \frac{1}{2}\psi^{,i}$$

$$\left(\triangle - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\psi^{ik} = \frac{8\pi G}{c^2}\left[T^{ik} - \frac{1}{2}\eta^{ik}T\right]$$

$$\left(T^{ik}_{(p/m)} + T^{ik}_{(int)} + T^{ik}_{(g)}\right)_{,i} = 0$$

gravity EM Tensor $T_{(g)}{}^{ik}$

General Relativity

$g^{ik},\quad g_{ik}\, g^{ik} = 4,\quad \mathcal{R}_{iklm},$

$$S = S_{(m)} + S_{(g)}$$

$$\Re^{ik} - \frac{1}{2}g^{ik}\Re = \frac{8\pi G}{c^4}T^{ik}_{(m)}$$

$$T^{ik}_{(m)\ ;\ i} = 0$$

$$\frac{\partial}{\partial x^k}(-g)(T^{ik}_{(m)} + t^{ik}_{(g)}) = 0$$

gravity EM Pseudo-Tensor $t_{(g)}{}^{ik}$

Field equations for spin 2 and spin 0 parts

Field Gravity

For spin 2 and spin 0 parts we can rewrite the field equation as

$$\left(\triangle - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi^{ik} = \frac{8\pi G}{c^2}\left[T^{ik} - \frac{1}{4}\eta^{ik}T\right]$$

$\phi^{ik}(\vec{r},t) = \psi_{\{2\}}{}^{ik}$

$$\left(\triangle - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\psi\frac{1}{4}\eta^{ik} = -\frac{8\pi G}{c^2}T\frac{1}{4}\eta^{ik}$$

$\psi(\vec{r},t) = \eta_{ik}\psi^{ik}$

where $\psi_{\{2\}}^{ik} = \phi^{ik}$ and $\eta_{ik}\phi^{ik} = 0.$ For tensor and scalar parts in the case of free field we get ordinary wave equations

Lagrangians : $\Lambda_{\{2\}} = \frac{1}{16\pi G}\phi_{lm,n}\phi^{lm,n}$, and $\Lambda_{\{0\}} = \frac{1}{64\pi G}\psi_{,n}\psi^{,n}$

Corresponding EMT: $T_{\{2\}}^{ik} = \frac{1}{8\pi G}\phi_{lm}{}^{,i}\phi^{lm,k}$, and $T_{\{0\}}^{ik} = \frac{1}{32\pi G}\psi^{,i}\psi^{,k}$

1) $T_{(g)}{}^{ik} = T_{(g)}{}^{ki}$; 2) $T_{(g)}{}^{00} > 0$; 3) $T = \eta_{ik}T_{(g)}{}^{ik} = 0$

Comparison of FGT and GRT: P-N gravitational potentials of SSS body

Field Gravity	General Relativity
Weak field approximation	Weak gravity approximation

$$\left(\triangle - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\psi^{ik} = \frac{8\pi G}{c^2}\left[T^{ik} - \frac{1}{2}\eta^{ik}T\right]$$

$$T^{ik} = T^{ik}_{(p/m)} + T^{ik}_{(int)} + T^{ik}_{(g)}$$

$$(\psi^{ik}) = \mathrm{diag}(\Phi, \varphi_{\mathrm{N}}, \varphi_{\mathrm{N}}, \varphi_{\mathrm{N}})$$

$$\hat{g}_{ik} = \eta_{ik} + \psi_{ik}/c^2$$

$$\hat{g}^{ik} = \eta^{ik} + \psi^{ik}/c^2$$

$$\hat{g}^i_k = \delta^i_k + \psi^k_i/c^2$$

$$\hat{g}_{ik} \cdot \hat{g}^{ik} \approx 4 + 2\psi/c^2$$

$$\varphi_N(r) = -\frac{GM}{r} \quad \text{for} \quad \mathrm{r} > R_0$$

$$g_{ik} = \eta_{ik} + h_{ik} \qquad |h_{ik}| << 1$$

$$\left(\triangle - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h^{ik} = \frac{16\pi G}{c^4}\left[T^{ik}_{(m)} - \frac{1}{2}\eta^{ik}T_{(m)}\right]$$

$$g_{ik} = \eta_{ik} + \frac{2\varphi_N}{c^2}diag(1,1,1,1)$$

$$g^{ik} = \eta^{ik} - \frac{2\varphi_N}{c^2}diag(1,1,1,1)$$

$$g^i_k = \delta^i_k$$

$$g_{ik} \cdot g^{ik} = 4$$

Repulsive force of the scalar part of the gravitational potential in the Field Gravity Theory for SSS body with mass M

Birkhoff's $\psi^{ik}(r) = \varphi_N diag(1,1,1,1), \quad \varphi_N(r) = -GM/r$

can be presented as a sum $\psi^{ik} = \psi^{ik}_{\{2\}} + \psi^{ik}_{\{0\}}$

$$\psi^{ik} = \frac{3}{2}\varphi_N \, \mathrm{diag}(1, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}) - \frac{1}{2}\varphi_N \, \mathrm{diag}(1, -1, -1, -1)$$

then from the equation of motion (Poincare force) we get the expression for Newtonian force $\overrightarrow{F_N} = m_0 d\vec{v}/dt$

$$F_N = F_{\{2\}} + F_{\{0\}} = -\frac{3}{2} m_0 \nabla \varphi_N + \frac{1}{2} m_0 \nabla \varphi_N = -m_0 \nabla \varphi_N$$

Hence the Newton force of gravity is the sum of attraction due to the spin 2 tensor field and repulsion due to the spin 0 scalar field. Thus FGT is, strictly speaking, a scalar-tensor theory. But in contrast to the Brans-Dicke theory that introduces additional scalar field with coupling constant ω, in FGT the scalar field is the trace $\psi = \eta_{ik}\psi^{ik}$ of the tensor potential ψ^{ik} and has the same coupling constant G.

FGT predictions in the weak field approximation

The universality of free fall for non-rotating bodies

The deflection of light by massive bodies

The gravitational frequency-shift

The time delay of light signals

The perihelion shift of planets (17% due to $T_{(g)}{}^{00}$*)*

The Lense-Thirring effect

The geodetic precession of a gyroscope

PLUS

The additional acceleration of rotating bodies (V^2/c^2)

The emission of spin2 and spin 0 gravitational waves,

The localization of the energy of the gravitational waves.

Part II:

Crucial observational tests of gravitation theory

Richard Phillips Feynman (1918 – 1988)

Nobel Prize in Physics (1965) :
for his fundamental work in
quantum electrodynamics

Strategy and Philosophy of science:

«Science is a culture of doubt»

«Knowledge can progress only if people have open minds and test their ideas. So far so good.»

Modern Relativistic Astrophysics

> *Relativistic Compact Objects:* **black hole candidates $3 \div 10^{10}\ M_{sun}$, Energy Sources and Origin of Jets (GRB**, **CCSN** (SN1987A), **AGN, Blazars** (EHT, Fe K_α))

> *Gravitational Radiation:* **binary RCO and massive SN explosions (PSR1913+16, SN1987A, LIGO GW events)**

> *Cosmology:* **cosmological models, Hubble law, large scale structure, fractals, dark matter, deep fields**

Common basis is *relativistic gravity theory*

Modern reviews of alternative gravity theories

Will C., *The Confrontation between General Relativity and Experiment*, Living Rev. Rel., 17, 4 (2014) - **review** of 6 alternative **metric** gravity theories are discussed.

Clifton T. et al., *Modified gravity and cosmology*, Physics Reports, Vol. 513, Iss. 1, p. 1-189 (2012) - **review** of 13 alternative **metric** gravity theories (*1316 references*).

Baryshev Y., *Foundation of Relativistic Astrophysics*, 80pp., arXiv:1702.02020 (2017) – **review** of Feynman's **nonmetric** field approach to gravity physics (*206 references*),

(**main motivation is solution of gravity energy problem**).

Existence of Gravitational Waves which carry positive energy and localization GW by detector

A historical remark on Gravitational Waves prediction

Jules Henri Poincaré (1854–1912)

Poincare H., *Sur la dynamique de l'electron,* Compt. Rend. l'Acad. Sci., 140, p.1504 (**1905**);

Poincare H., *Sur la dynamique de l'electron*, Rend. Circolo matem. di Palermo, 21, p.129 (**1906**).

Gravitation as a fundamental force in relativistic 4d space-time

In 1905, Poincaré first predicted existence of the **gravitational waves** (*"ondes gravifiques"*) from a variable source and **propagating at the speed of light** as being required by the Lorentz transformations:

$$\left(\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\boldsymbol{\Phi} = \Box\boldsymbol{\Phi} = \mathbf{0} \text{ (instead of } \Delta\Phi)$$

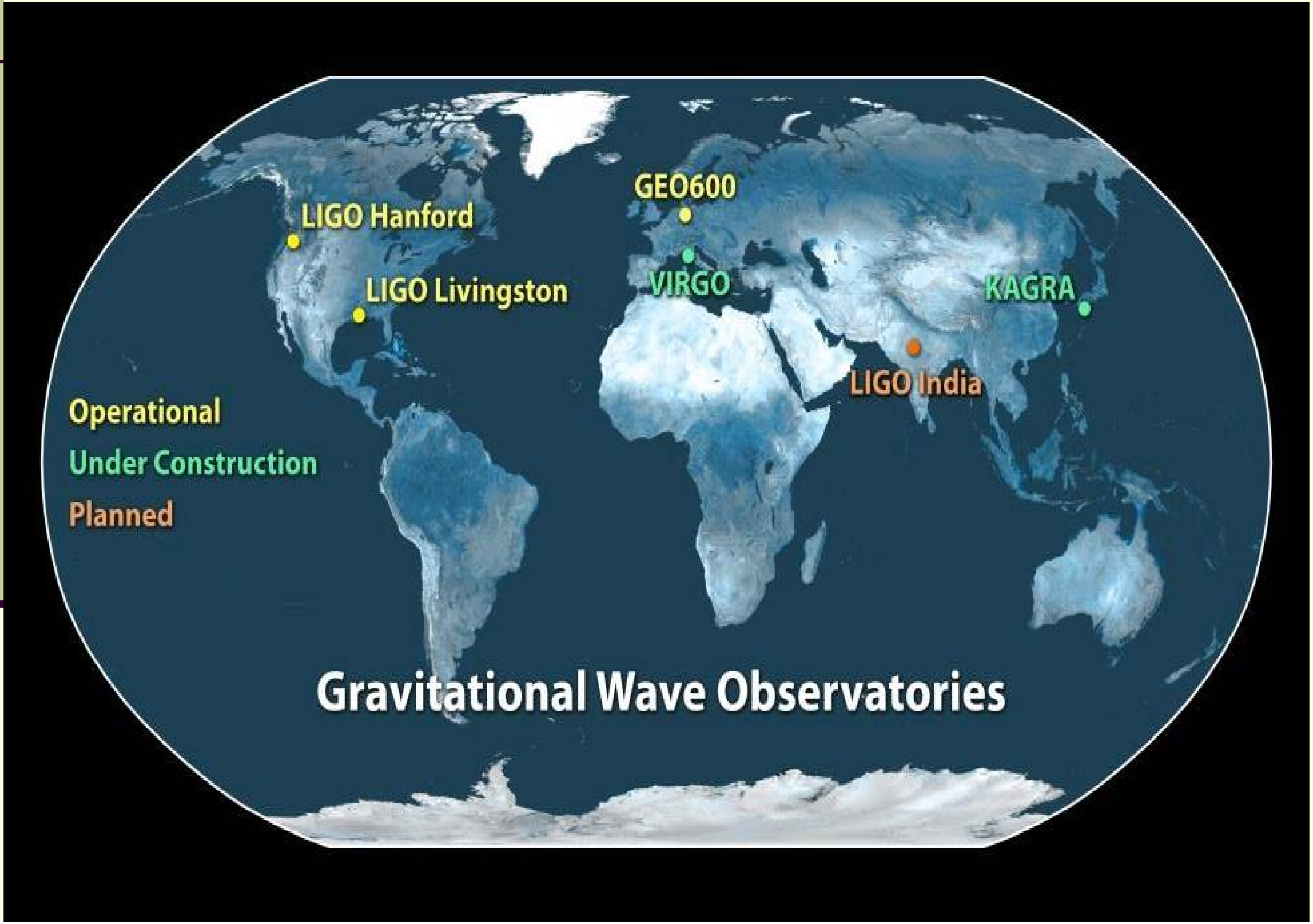
Joseph Hooton Taylor, (born March 29, 1941)

Nobel Prize in Physics (1993)
with Russell Alan Hulse

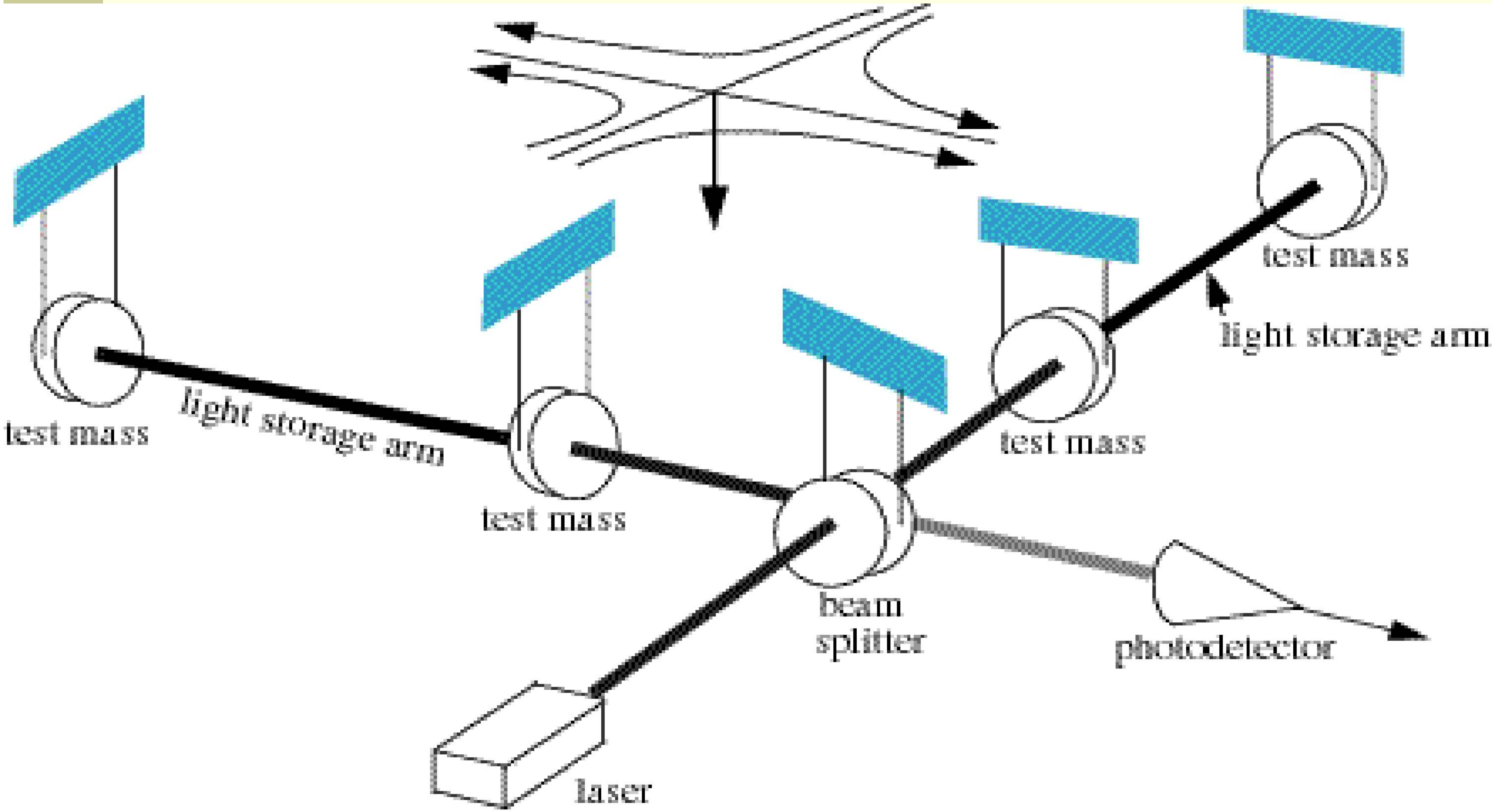
"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

PSR 1913+16 : Decreasing orbital energy via radiation of positive energy of the gravitational waves

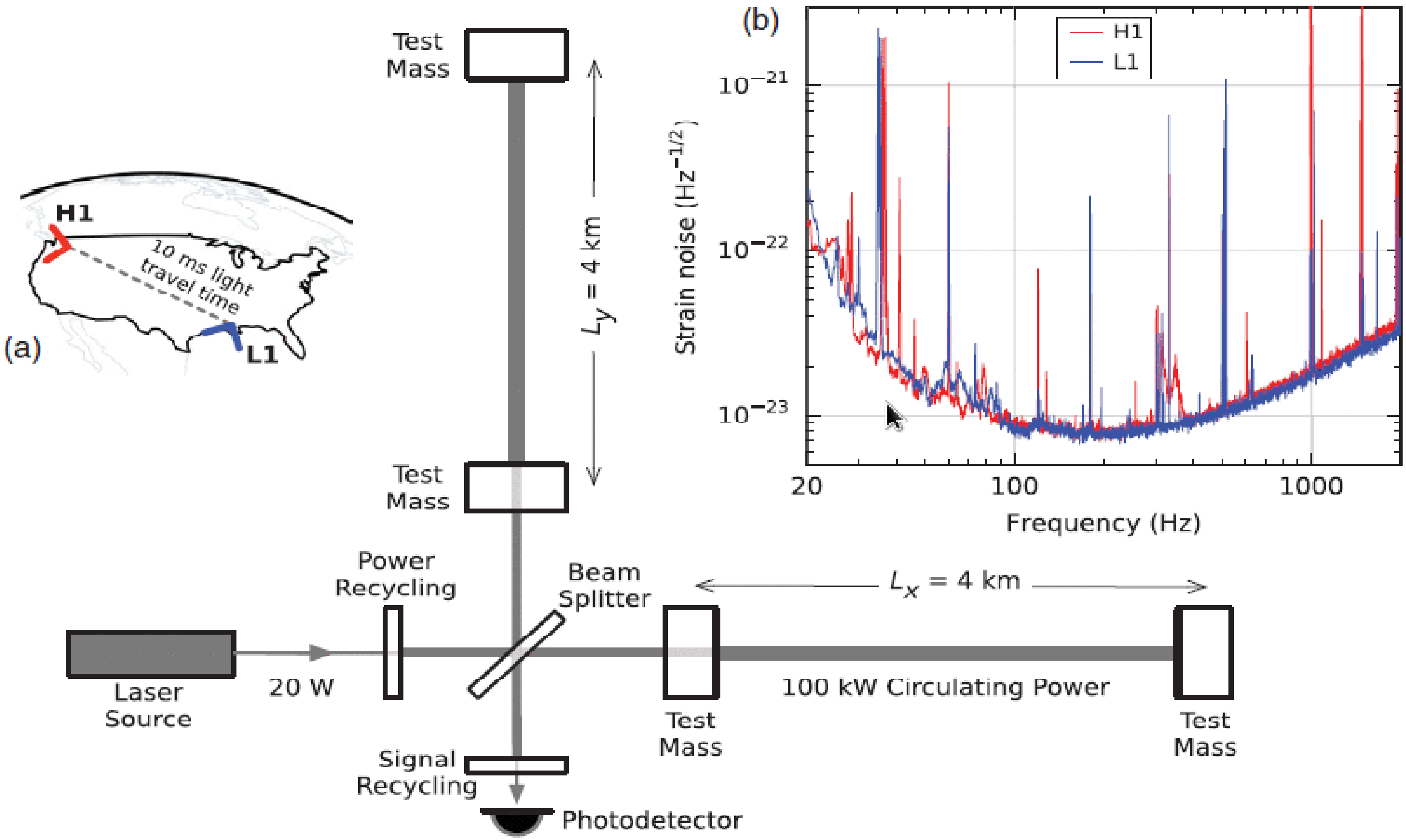
Gravitational Waves detection

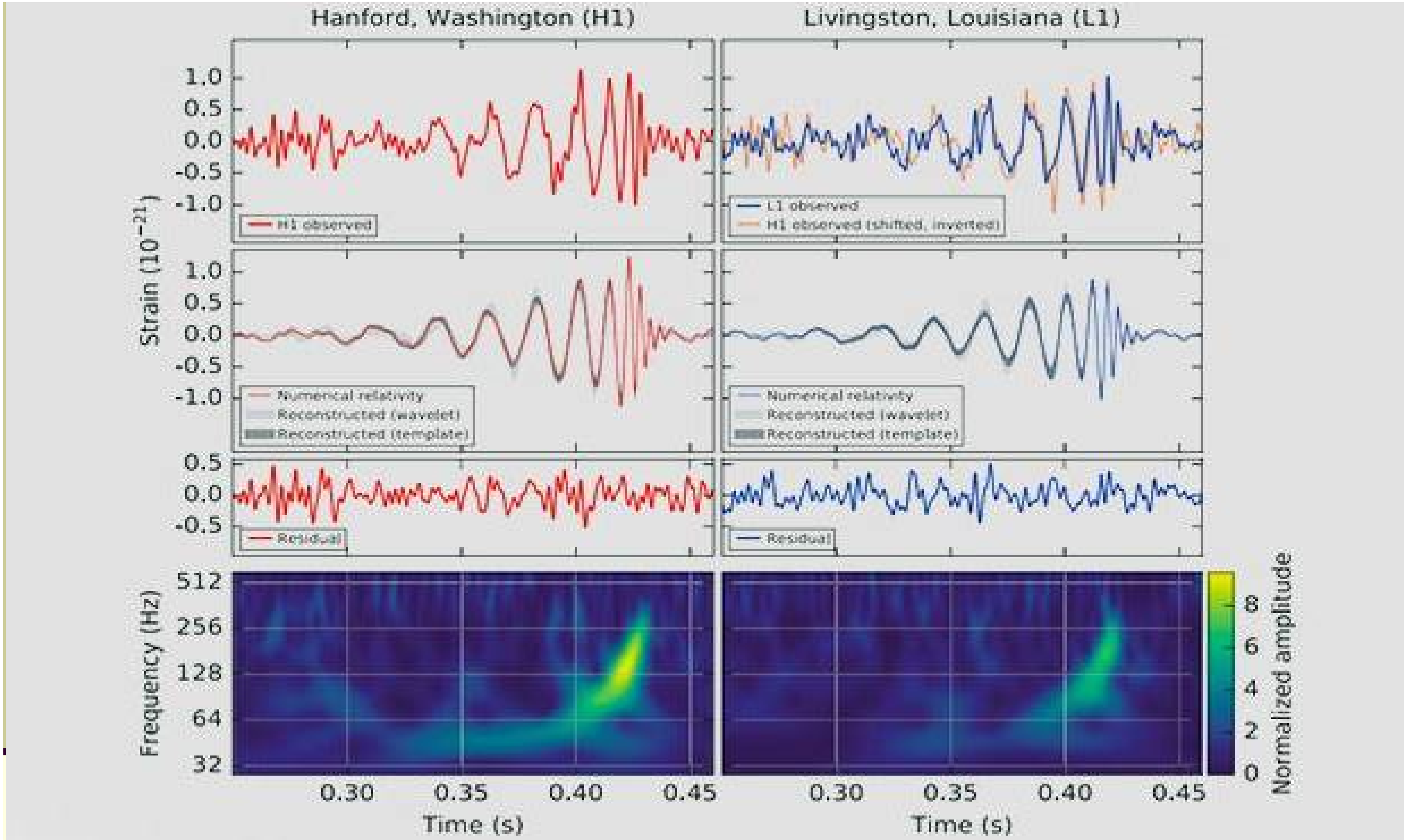


Laser Interferometer Gravitational-Wave Observatory (LIGO)


test mass
light storage arm
test mass
test mass
light storage arm
test mass
beam splitter
photodetector
laser

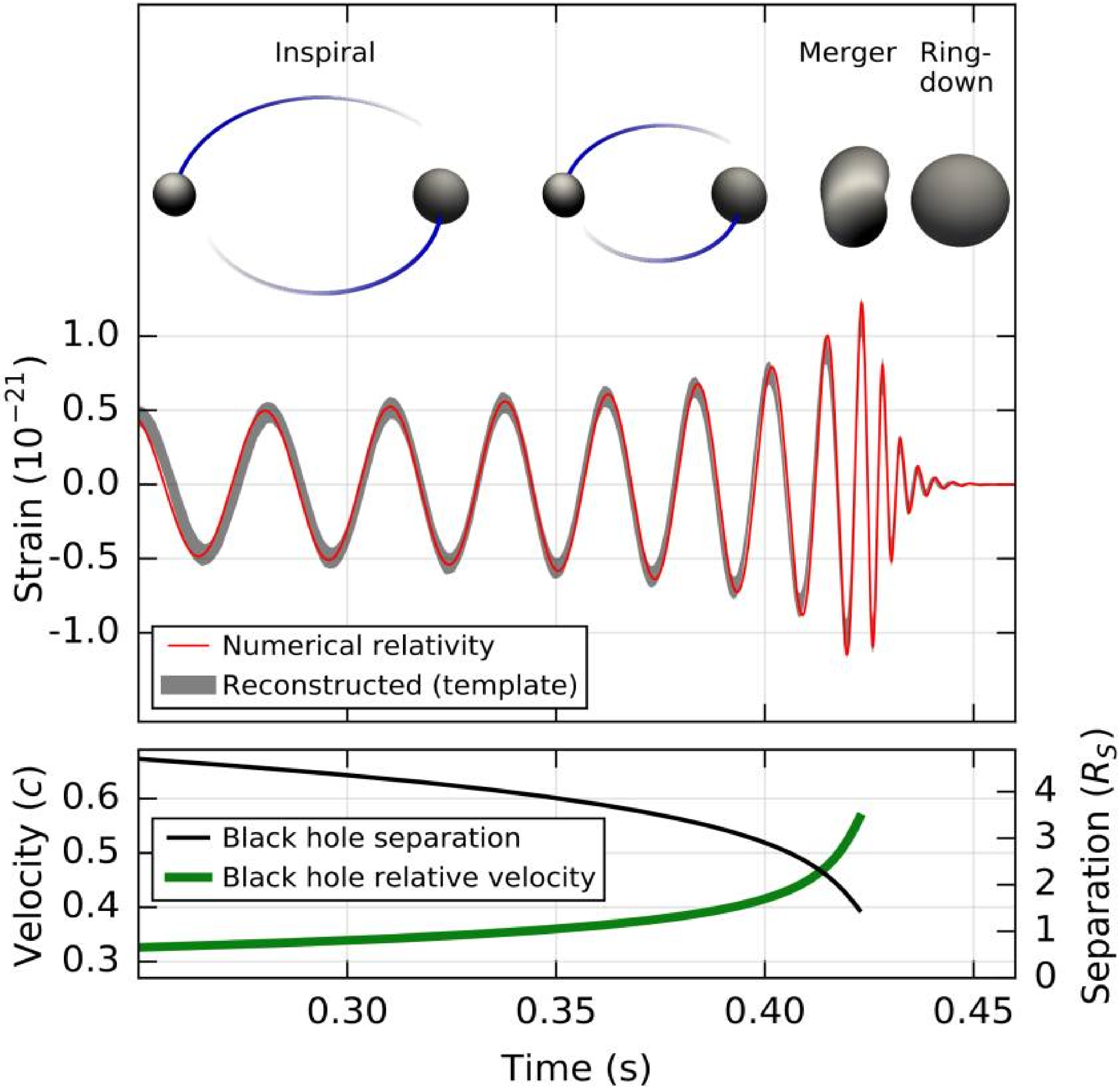
Abbott B. et al., Phys.Rev.Lett., 116, 061102 (2016)
(~ 1013 authors) GW 150914 $\Delta\tau(L1, H1) = 7ms$





$$h = \frac{\Delta l}{l} = 10^{-21}, \qquad \Delta l = 4\,km \times h = 4 \times 10^{-16}\ \text{cm}$$

$$M_1 = 36\,M_\odot, \quad M_2 = 29\,M_\odot, \quad 410\,Mpc, \quad M_{1\cup 2} = 62\,M_\odot$$



GRT: BH
FGT: RCO

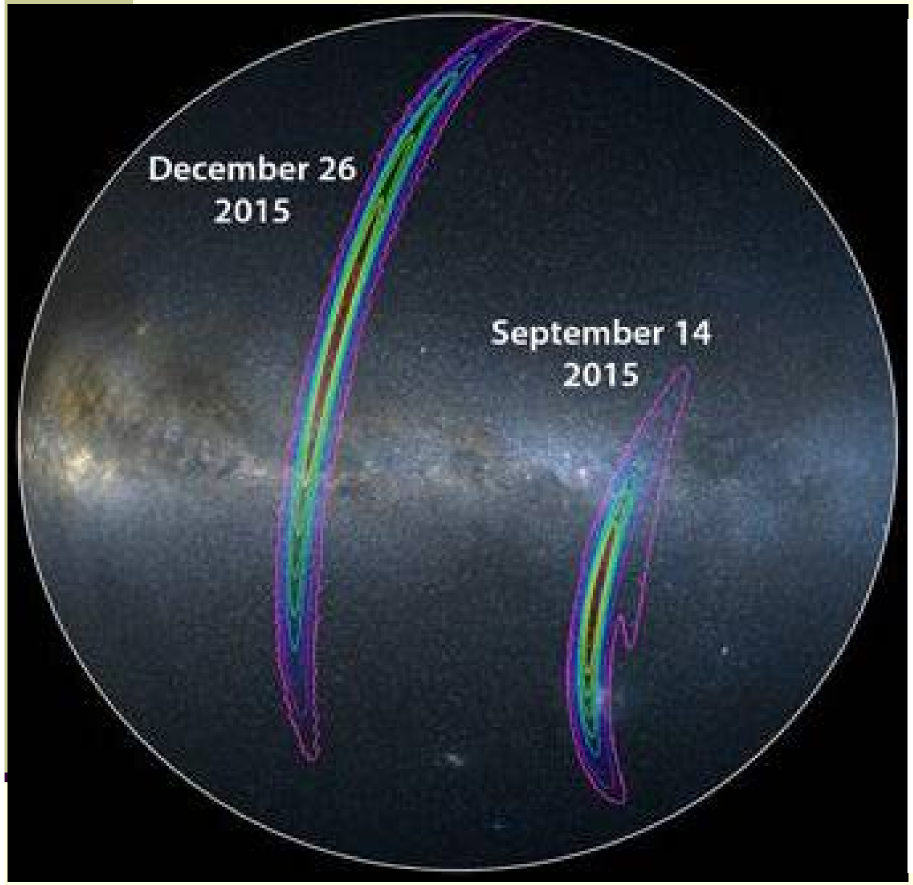
Binding
Energy ?

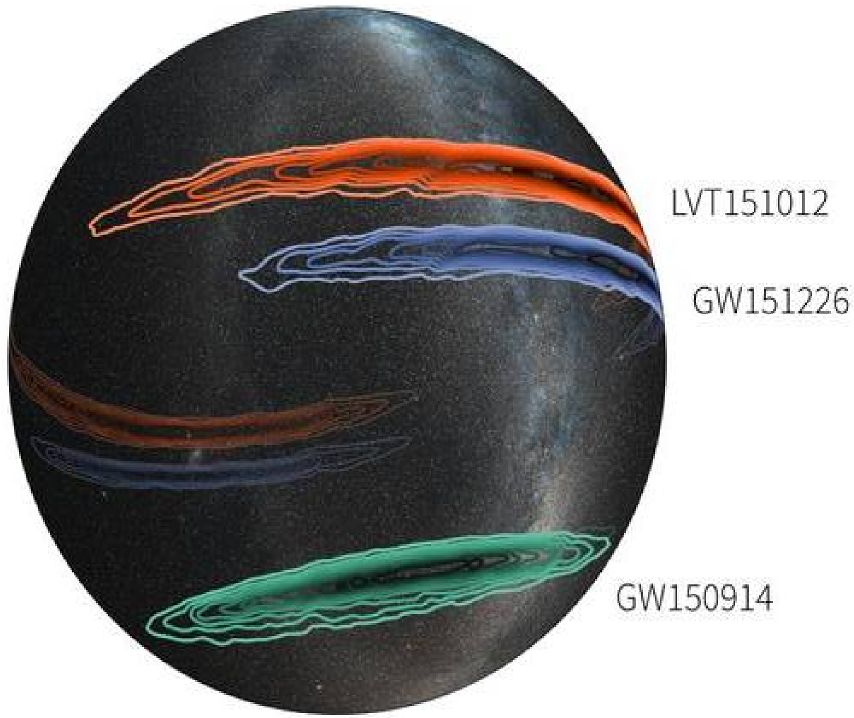
$$E_{rad} = 3M_{\odot}c^2$$

Localization
of the GW
Energy ?

$$\boldsymbol{t^{ik}}_{(g)}(\boldsymbol{t}, \boldsymbol{x}) = ?$$

LIGO: 3 GW events sky positions
GW150914, GW151226 and LVT151012





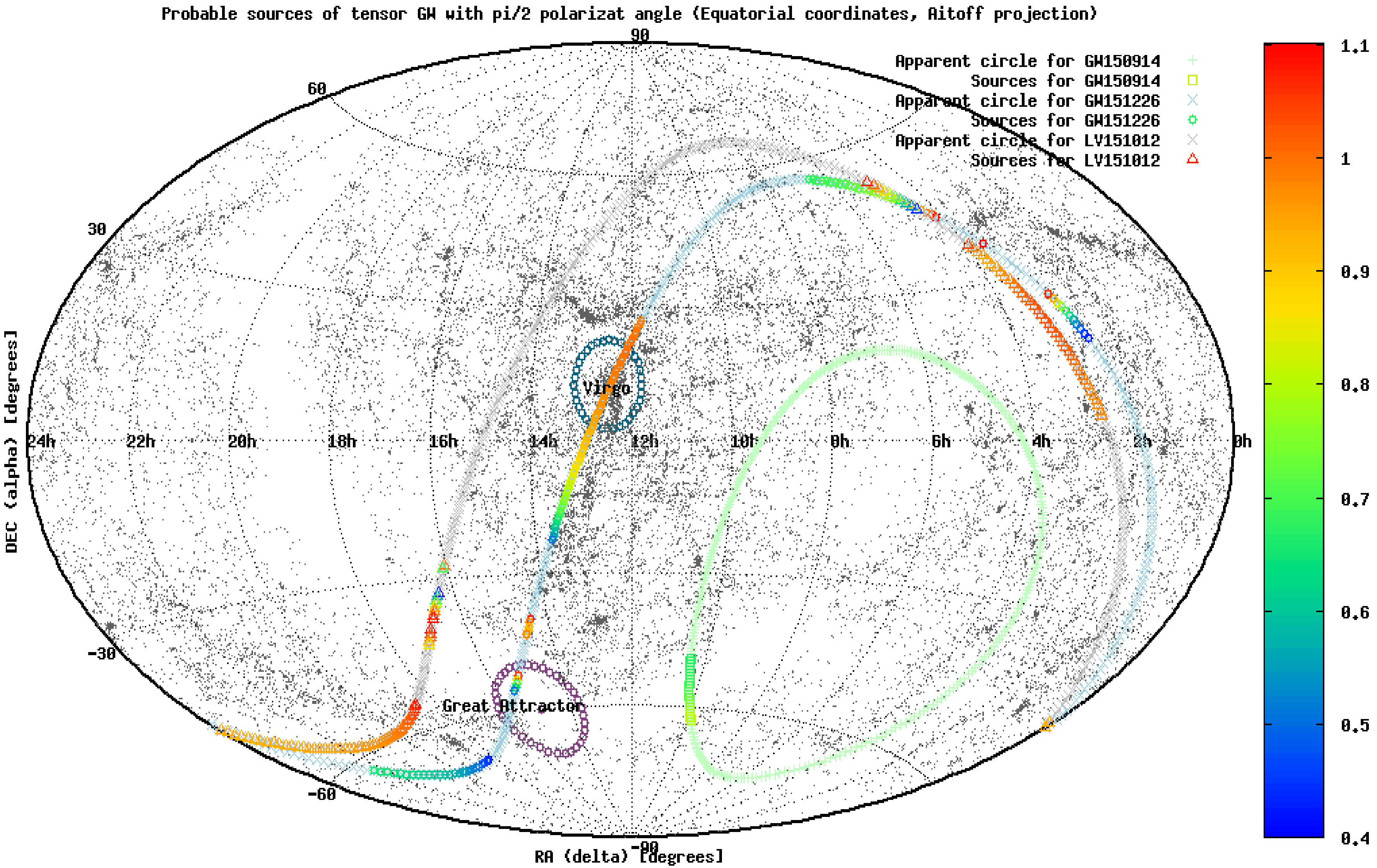
GW150914 : $M_1 = 36\, M_\odot$, $M_2 = 29\, M_\odot$, $420\, Mpc$

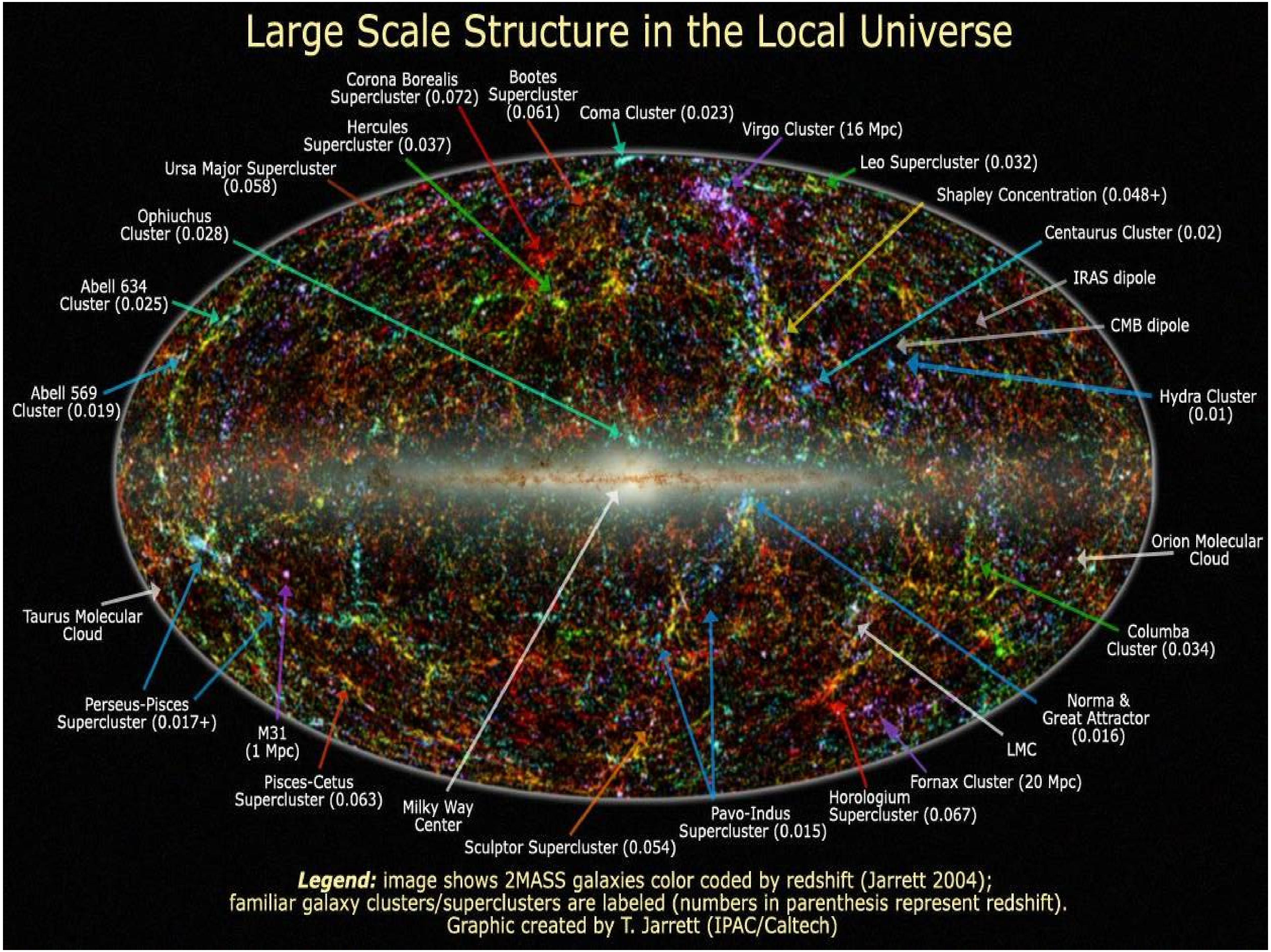
GW151226 : $M_1 = 14\, M_\odot$, $M_2 = 7.5\, M_\odot$, $440\, Mpc$

LVT151012: $M_1 = 23\, M_\odot$, $M_2 = 13\, M_\odot$, $1000\, Mpc$

LIGO: 3 GW events sky positions

GW150914, GW151226, LVT151012 (Fesik et al., arXiv:1702.03440)



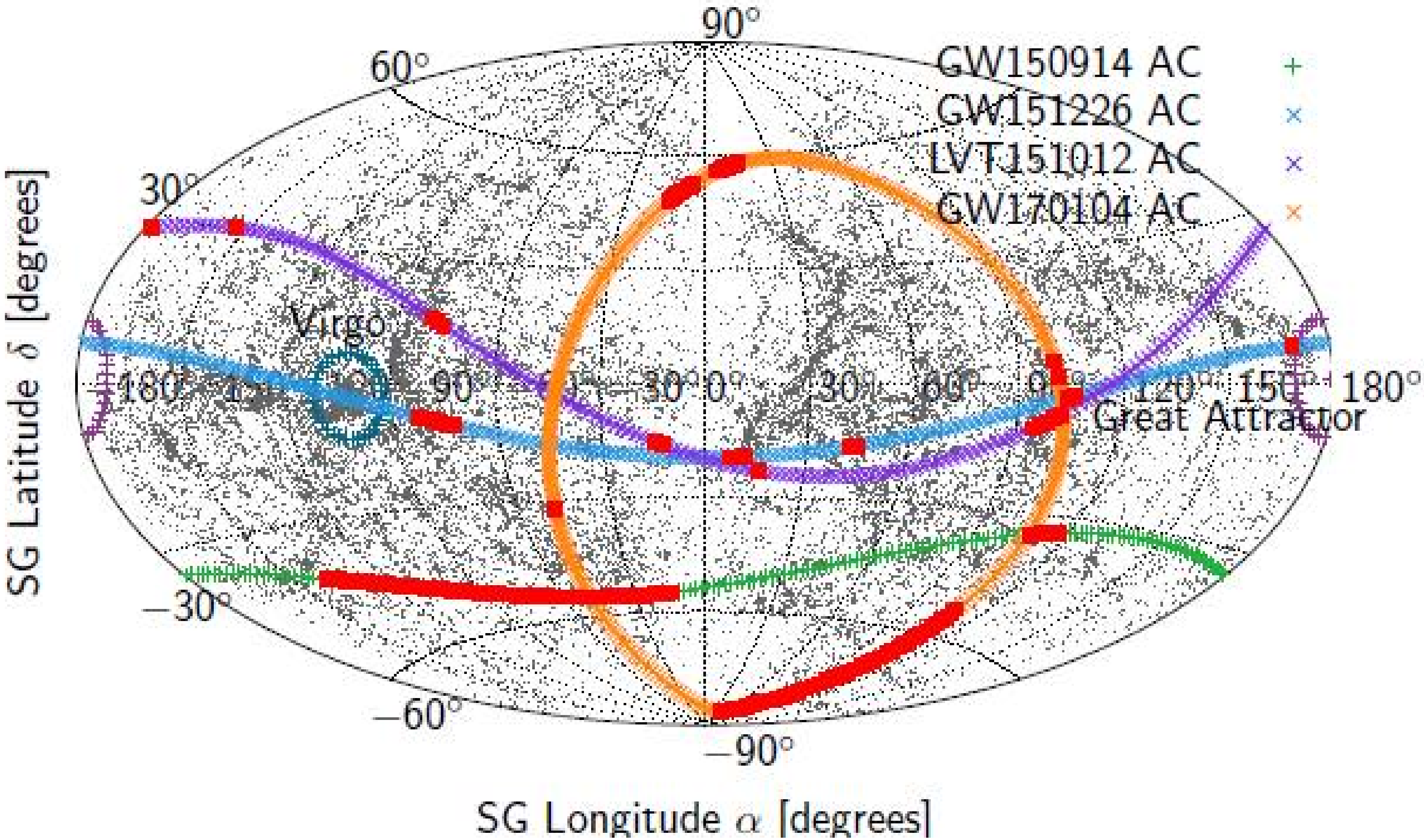


Large Scale Structure in the Local Universe
Corona Borealis Supercluster (0.072)
Bootes Supercluster (0.061)
Coma Cluster (0.023)
Virgo Cluster (16 Mpc)
Hercules Supercluster (0.037)
Leo Supercluster (0.032)
Ursa Major Supercluster (0.058)
Shapley Concentration (0.048+)
Ophiuchus Cluster (0.028)
Centaurus Cluster (0.02)
IRAS dipole
Abell 634 Cluster (0.025)
CMB dipole
Abell 569 Cluster (0.019)
Hydra Cluster (0.01)
Orion Molecular Cloud
Taurus Molecular Cloud
Columba Cluster (0.034)
Perseus-Pisces Supercluster (0.017+)
Norma & Great Attractor (0.016)
M31 (1 Mpc)
LMC
Pisces-Cetus Supercluster (0.063)
Fornax Cluster (20 Mpc)
Milky Way Center
Horologium Supercluster (0.067)
Pavo-Indus Supercluster (0.015)
Sculptor Supercluster (0.054)
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

LIGO: 4 GW events sky positions

GW150914, GW151226, LVT151012, GW170104

(Fesik et al., arXiv:1702.03440)



Existence of Black Holes event horizon and singularity

"The reluctant Father of Black Holes", Sci. Am., June 1996: discussed the paper by Einstein (1939) where he clamed that "Schwarzschild singularity cannot exist in physical reality"

A. Einstein, *On a stationary system with spherical symmetry consisting of many gravitating masses*, Ann. Math., 40, 922 (1939)

Why Black Holes physically impossible:

$V_{ff} < c \rightarrow R > R_{Sch}$

+ New argument:

$E_{fg} < mc^2 \rightarrow R > R_g$

$$T^{00}{}_{(fg)} = \varepsilon_{(fg)} = + \frac{(\nabla \varphi_N)^2}{8\pi G}$$

Albert Einstein and Robert Oppenheimer in Princeton University (1949)

“Stephen Hawking: There are no black holes”

Z. Merali, Nature, 24 January 2014 (arXiv: 1401.5761)

Notion of an 'event horizon', from which nothing can escape, is incompatible with quantum theory.

A full explanation of the process would require a theory that successfully ***merges gravity with the other fundamental forces of nature.***

But that is a goal that has eluded physicists for nearly a century.

However Feynman’s nonmetric field gravitation theory is just such a unification of gravity with other fundamental forces: (A^i - ED, ψ^{ik}- GD)

Hawking Evaporation is Inconsistent with a Classical Event Horizon at r = 2M

B. Chowdhury and L. Krauss

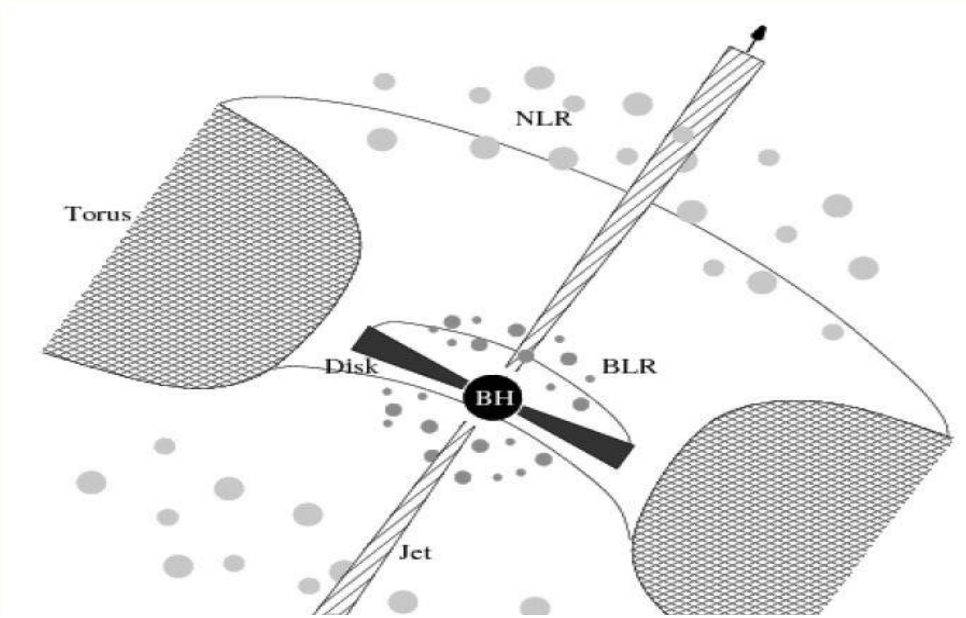
Department of Physics, Arizona State University, Tempe, AZ 85287 (Dated: April 13, 2015) (arXiv: 1409.0187)

In the frame of a distant observer an infall cutoff outside the event horizon of a black hole must be imposed in order for the formation time of a black hole event horizon to not exceed its evaporation time.

$$\tau_{(infall)} = \infty \; > \; \tau_{(evap)} \approx 5 \cdot 10^3 \text{sec} \left(\frac{\text{M}}{10^{10} g}\right)^3$$

Observational testing existence of Black Hole Event Horizon

- S. Doeleman et al., *Imaging an Event Horizon : VLBI EHT* , arXiv: 0906.3899 (VLBI observations)
- King A., et al., *What is on tap? The role of spin in compact objects and relativistic jets*, arXiv: 1305.3230 (K_alpha Fe line profile X-ray observations)



VLBI imaging of Black Holes Candidates

S. Doeleman et al., arXiv: 0906.3899

Imaging an Event Horizon: submm-VLBI of a Super Massive Black Hole

VLBI EHT Event Horizon Telescope:

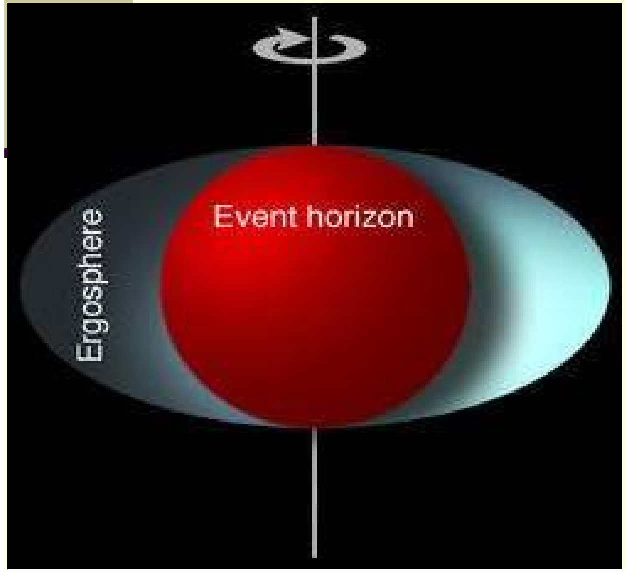
- Does General Relativity hold in the strong field regime?
- Is there an Event Horizon? $R_{hor} = ?$
- Can we estimate Black Hole spin by resolving orbits near the Event Horizon?

Kerr BH : $R_{hor} = R_g\left(1 + \sqrt{1 - a^2}\right),$

$a = J/J_{max} \qquad J_{max} = McR_g$

$R_{hor} = R_g = \frac{GM}{c^2} \;(a = 1)$;

$R_{hor} = R_{Sch} = \frac{2GM}{c^2} \;(a = 0)$



How do Black Holes accrete matter and create powerful jets?

The Event Horizon Telescope (EHT) is finally ready to take a picture of SgrA*

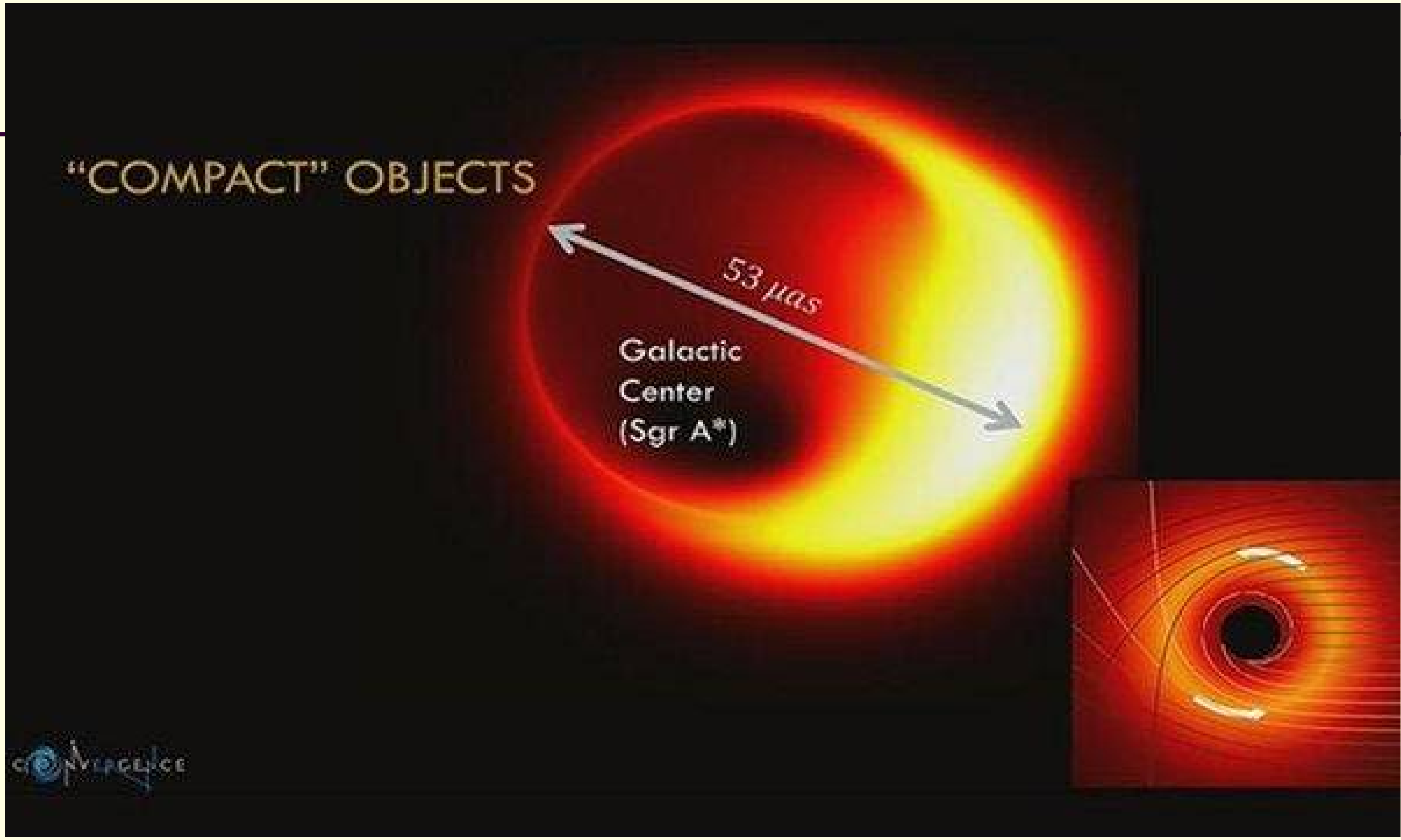
From April 5th to 14th (2017)

with linear resolution $l \sim R_{Sch} = \frac{2GM}{c^2}$

$\lambda \sim 0.6\ mm$

1. South Pole Telescope **2.** Atacama Large Millimeter/submillimeter Array and Atacama Pathfinder Experiment (Chile) **3.** Large Millimeter Telescope (Mexico) **4.** Submillimeter Telescope (Arizona) **5.** James Clerk Maxwell Telescope and Submillimeter Array (Hawaii) **6.** IRAM 30-meter (Spain)

Expected SgrA* image in GRT



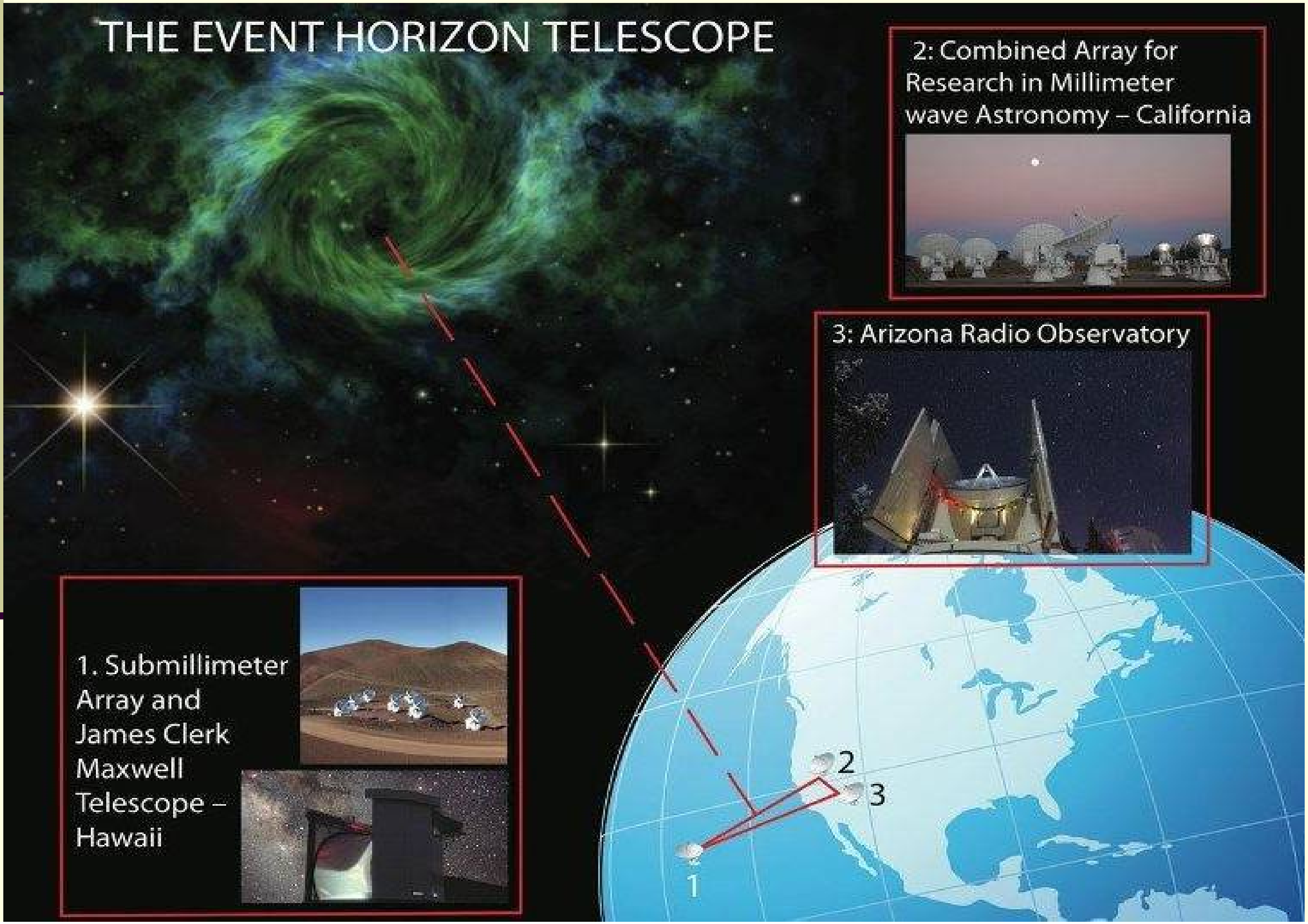
$M_{RCO} = 4.3 \cdot 10^6 M_\odot, \qquad D = 8.3\ kpc$

$R_{Sch} = 1.3\ \cdot 10^{12} cm \qquad \theta_{R_{Sch}} = 10.2\ \mu as$

$\theta_{ring} = 5.2\theta_{R_{Sch}} = 53\ \mu as$ (light ring diameter)

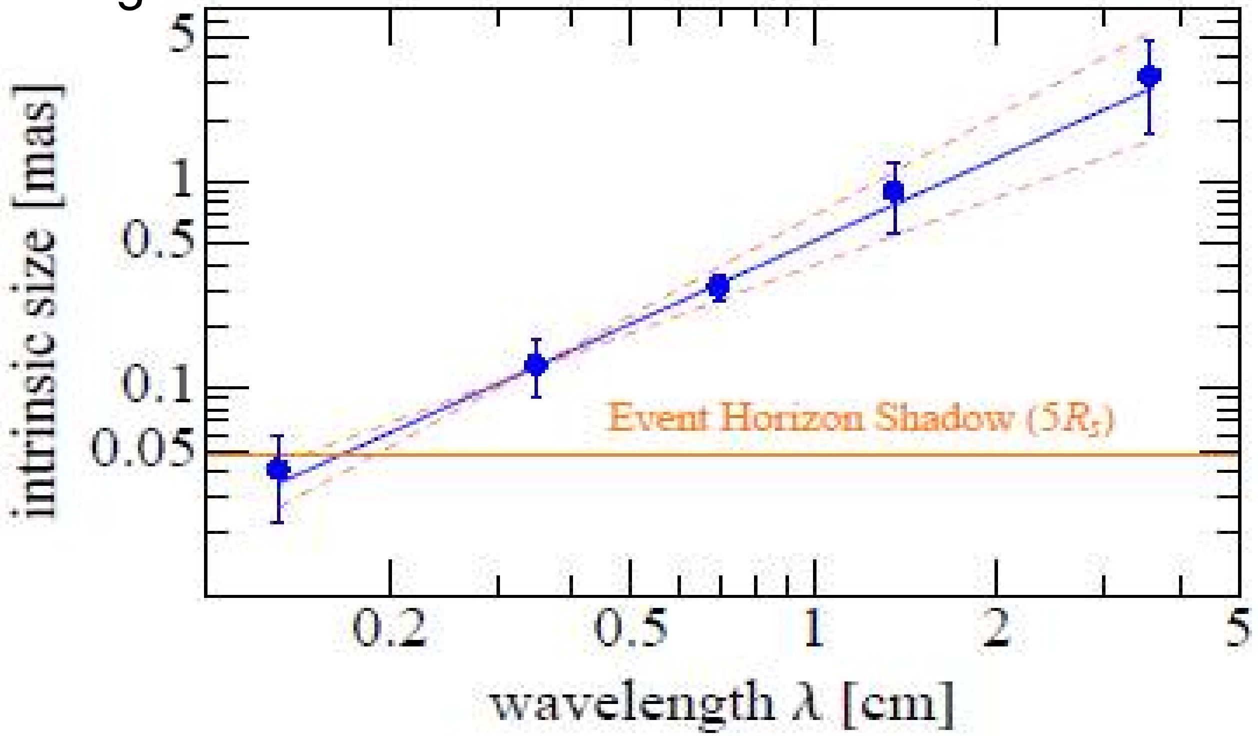
The EHT first results at 1.35 mm

Doeleman, S. S., et al. 2008, Nature, 455, 78



Falcke H., Markoff S., Towards the event horizon – the supermassive black hole in the Galactic Center, Class. Quant. Grav., 30, iss. 24, id. 244003 (2013)

Sgr A* VLBI EHT λ=1.35 мм



Existence of BH horizon?

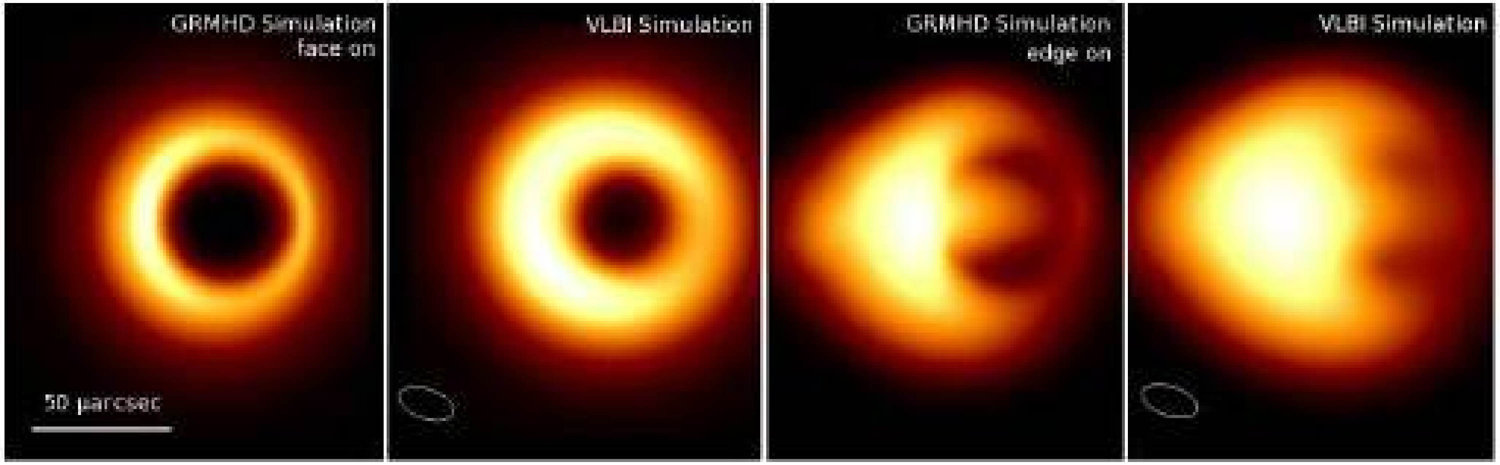
Intrinsic sizes of black hole candidates as crucial observational tests for gravitation theories

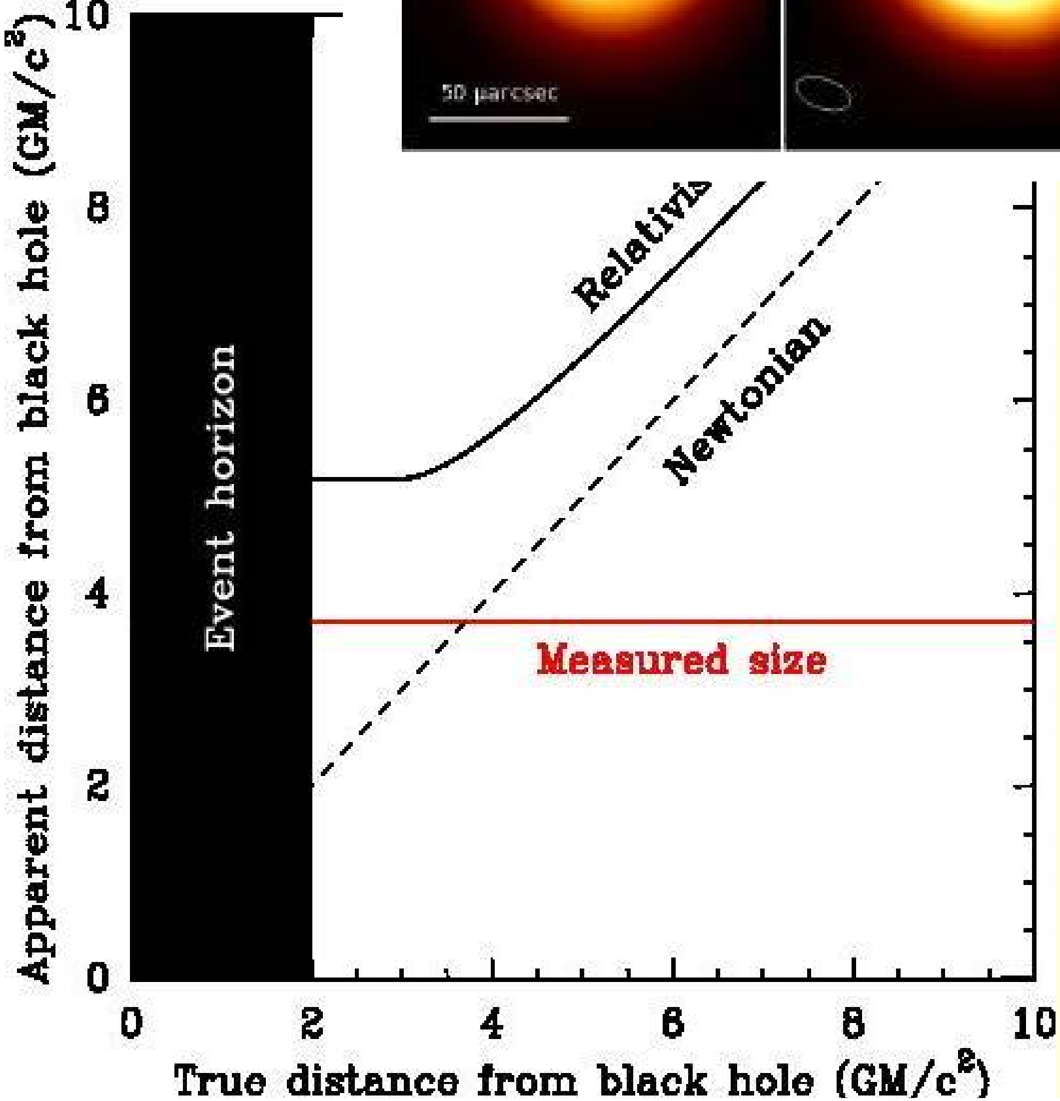
Universal light ring around BH:

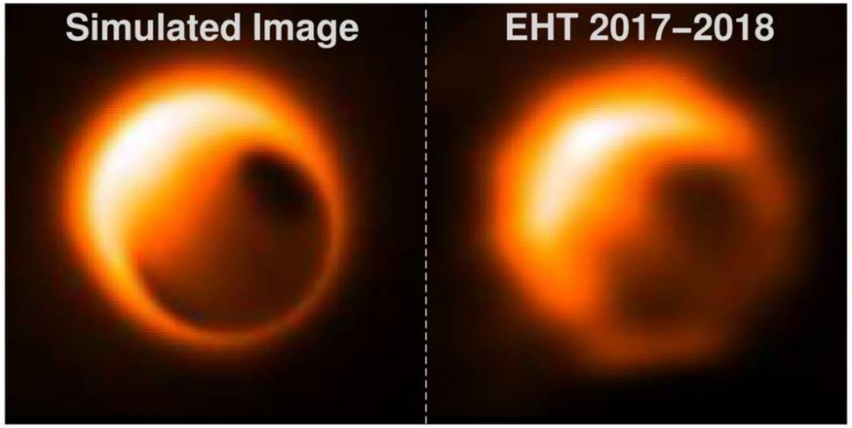
$D_{ring} = 5.2 R_{Sch}$

Observed size SgrA* : $\theta_{obs} \approx 37 \mu as \quad (4\, R_{Sch})$

(Doeleman, S. S., et al. 2008, Nature, 455, 78)



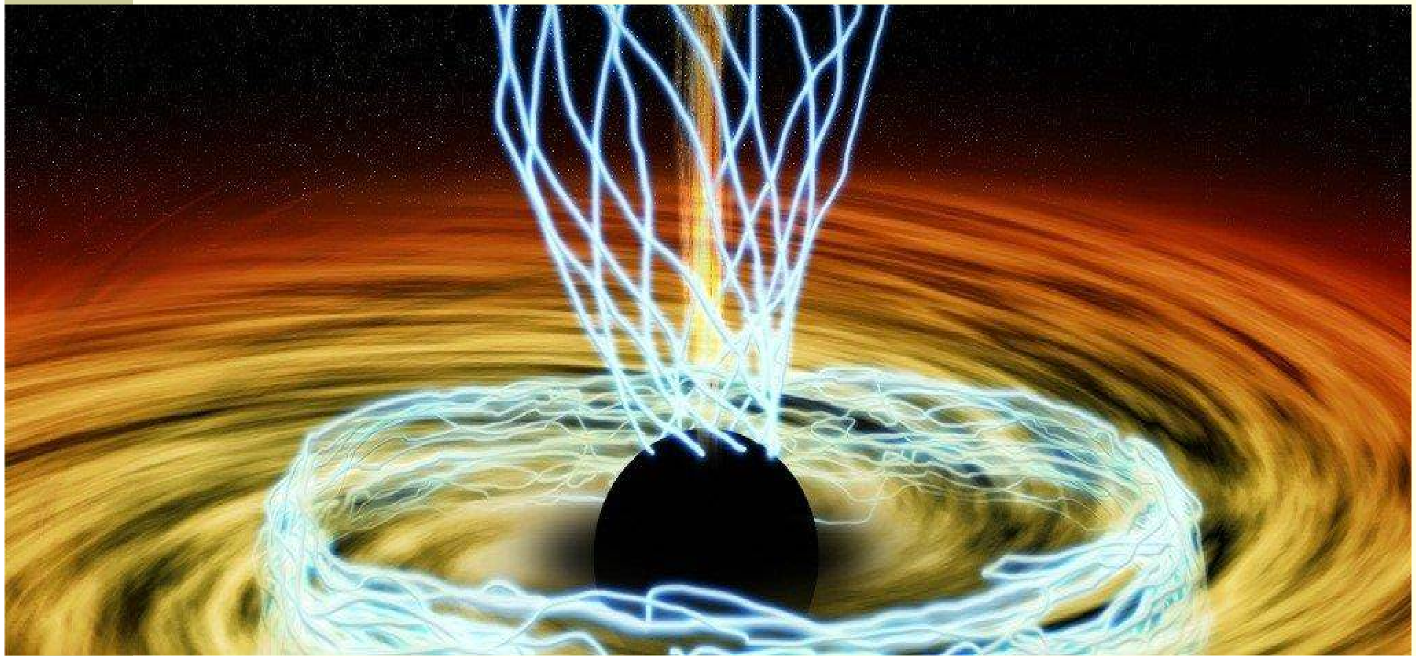




$$r \sim R_g = \frac{GM}{c^2} = R_{Sch}/2$$

Universal light ring around BH: $53\ \mu as$?

Michael D. Johnson et al. (EHT), Science 04 Dec 2015: Vol. 350, Issue 6265, pp. 1242-1245



"Resolved magnetic-field structure and variability near the event horizon of Sagittarius A* "

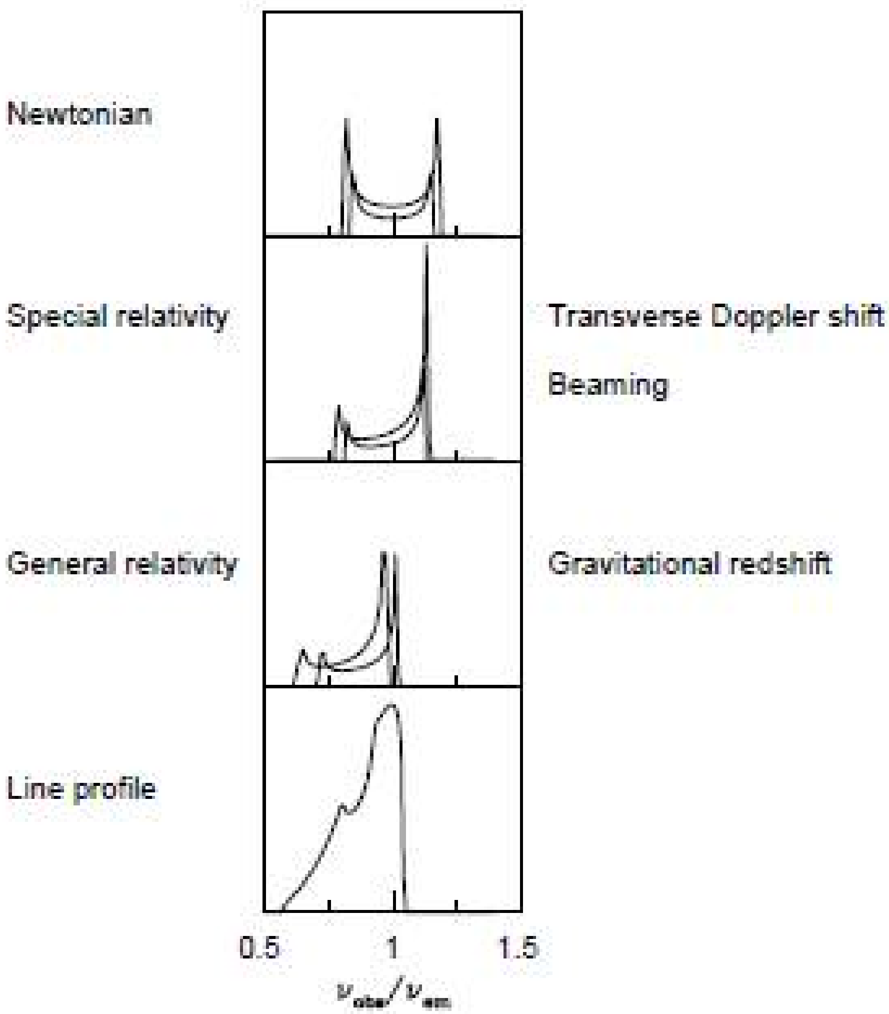
$$r \sim R_g = GM/c^2 = R_{Sch}/2$$

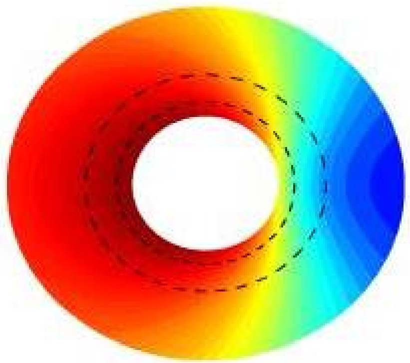
GRT : Kerr Black Hole

FGT : Relativistic Compact Object (RCO)

X-ray spectroscopy of Fe K_alfa line

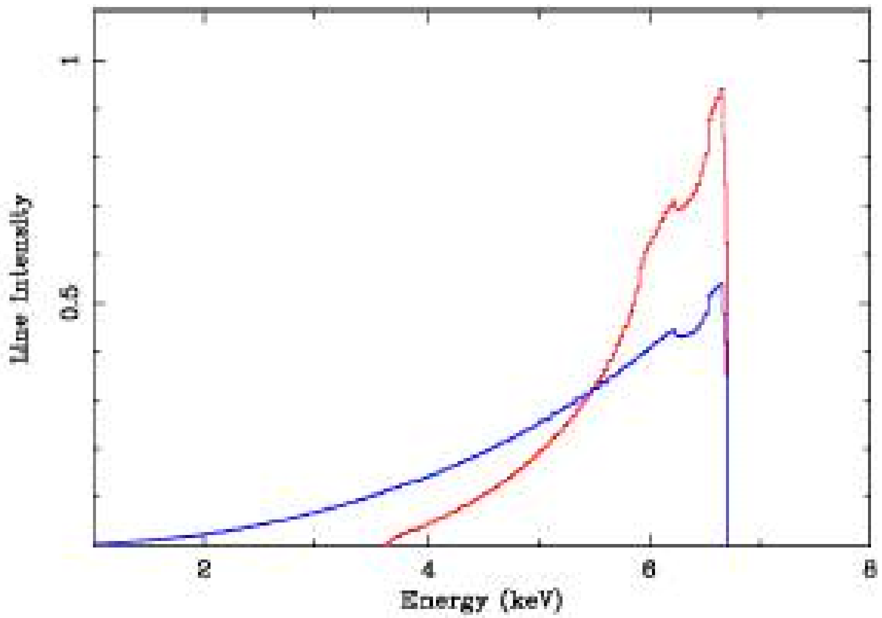
A.C. Fabian, Probing General Relativity with Accreting Black Holes, arXiv:1211.2146 (2012)



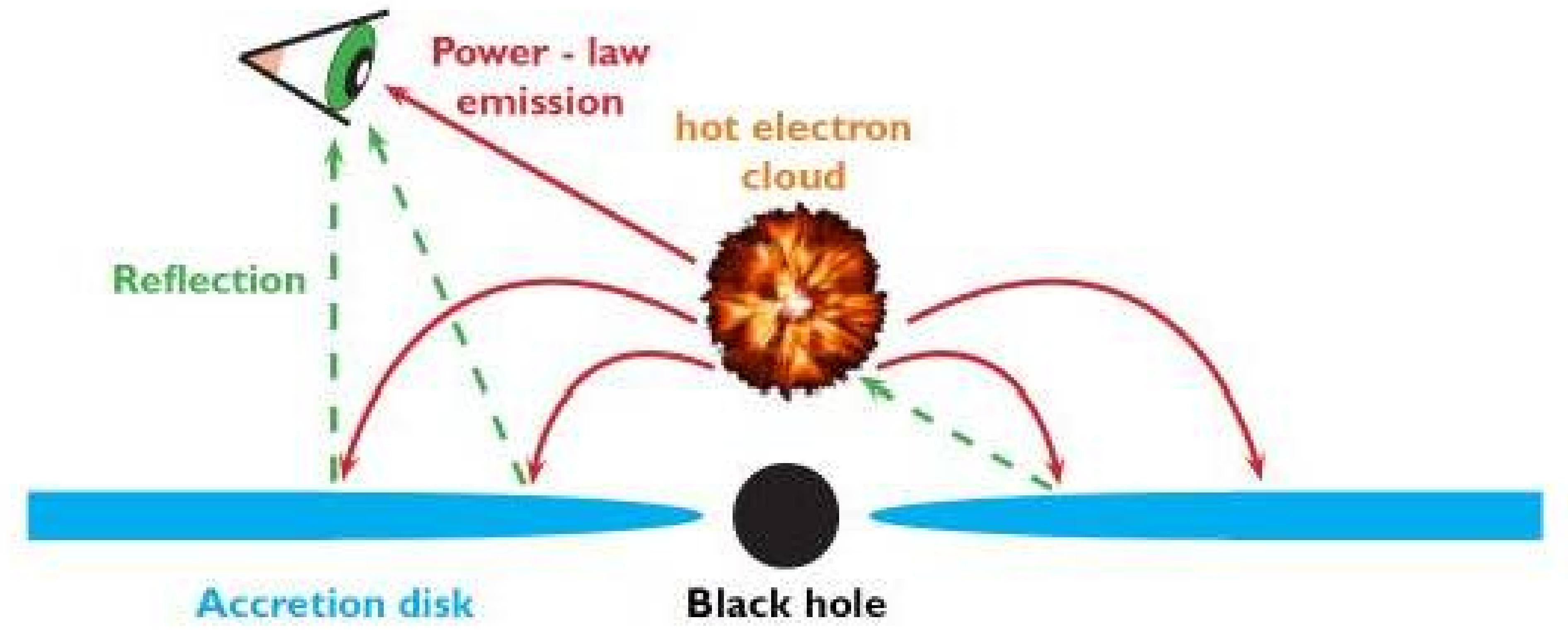


$r_{in} = 3R_{Sch}$

$r_{in} = 0.6R_{Sch}$



Fe K_alfa X-ray spectral observations of Seyfert-1 galaxies: model of BH/RCO jets and accretion disc



$r \sim R_g = GM/c^2 = R_{Sch}/2$ (MCG-6-30-15 $r_{in} = 0.615 R_{Sch}$)

GRT : Kerr Black Hole (Mrk 335 $r_{in} = 0.62 R_{Sch}$)

FGT : Relativistic Compact Object (RCO)

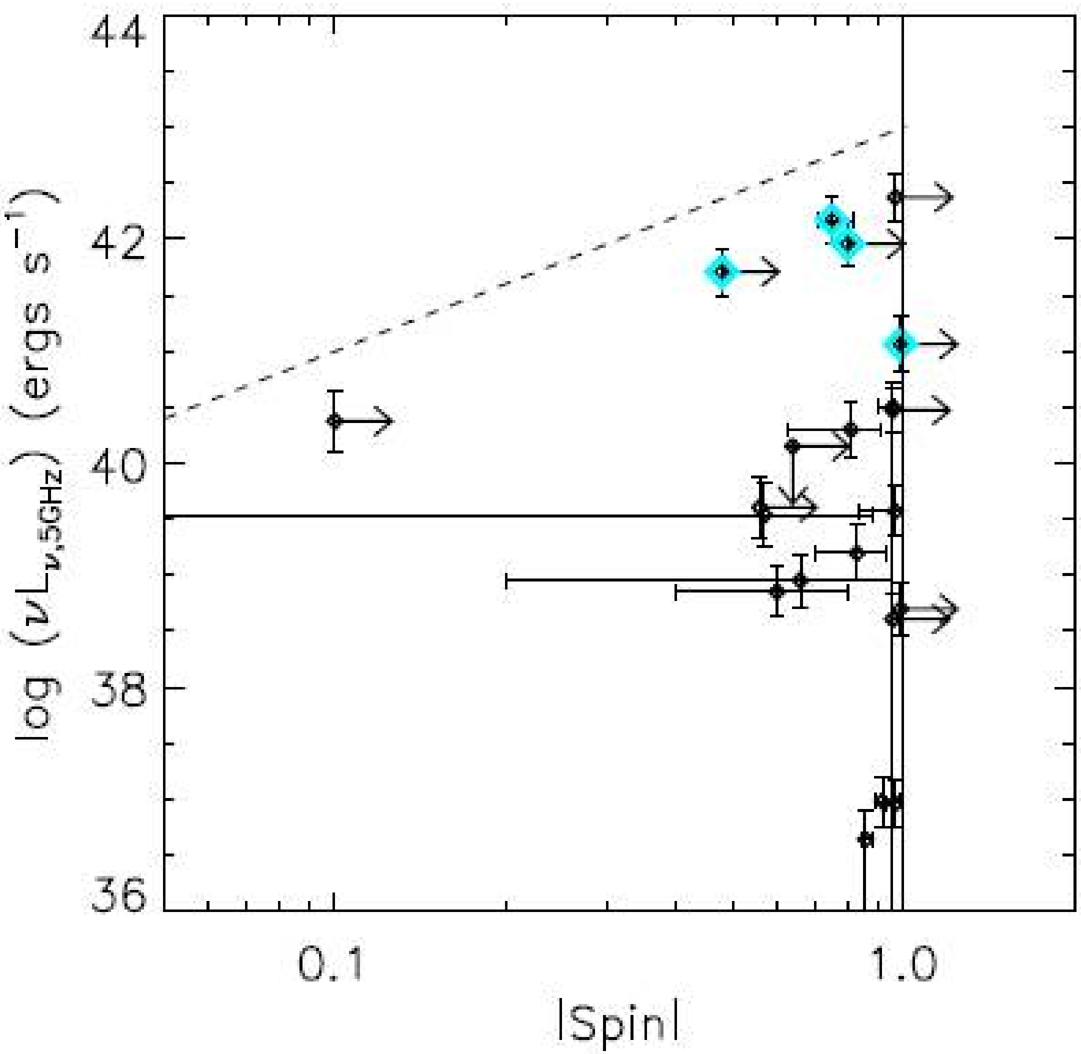
Driving extreme variability: The evolving corona and evidence for jet launching in Markarian 335

D.Wilkins, L.Gallo, MNRAS,449,129 (2015)

During all epochs, we find that the maximum measured redshift in the wing of the relativistically broadened iron K_alfa emission line is statistically consistent with the accretion disc extending as far in as the innermost stable circular orbit of a maximally rotating black hole at

$r_{in} = 1.235\, R_g$ supporting findings that the black hole spin, $a > 0.9$.
There is no evidence for truncation of the accretion disc between the high and low flux epochs.

King A., et al., What is on tap? The role of spin in compact objects and relativistic jets, Ap.J., 771, 84 (2013)



37 Seyfert-1

K_alfa Fe line

Disc intrinsic size

$$r_{in} \sim R_g = GM/c^2$$

Kerr BH model:

$$|Spin| = a = \frac{J}{J_{max}}$$

$$R_{hor} = R_g(1 + \sqrt{1 - a^2}\ )$$

For a = 1:

$$R_{hor} = R_g = GM/c^2$$

For a = 0:

$$R_{hor} = 2R_g = R_{Sch} = 2GM/c^2$$

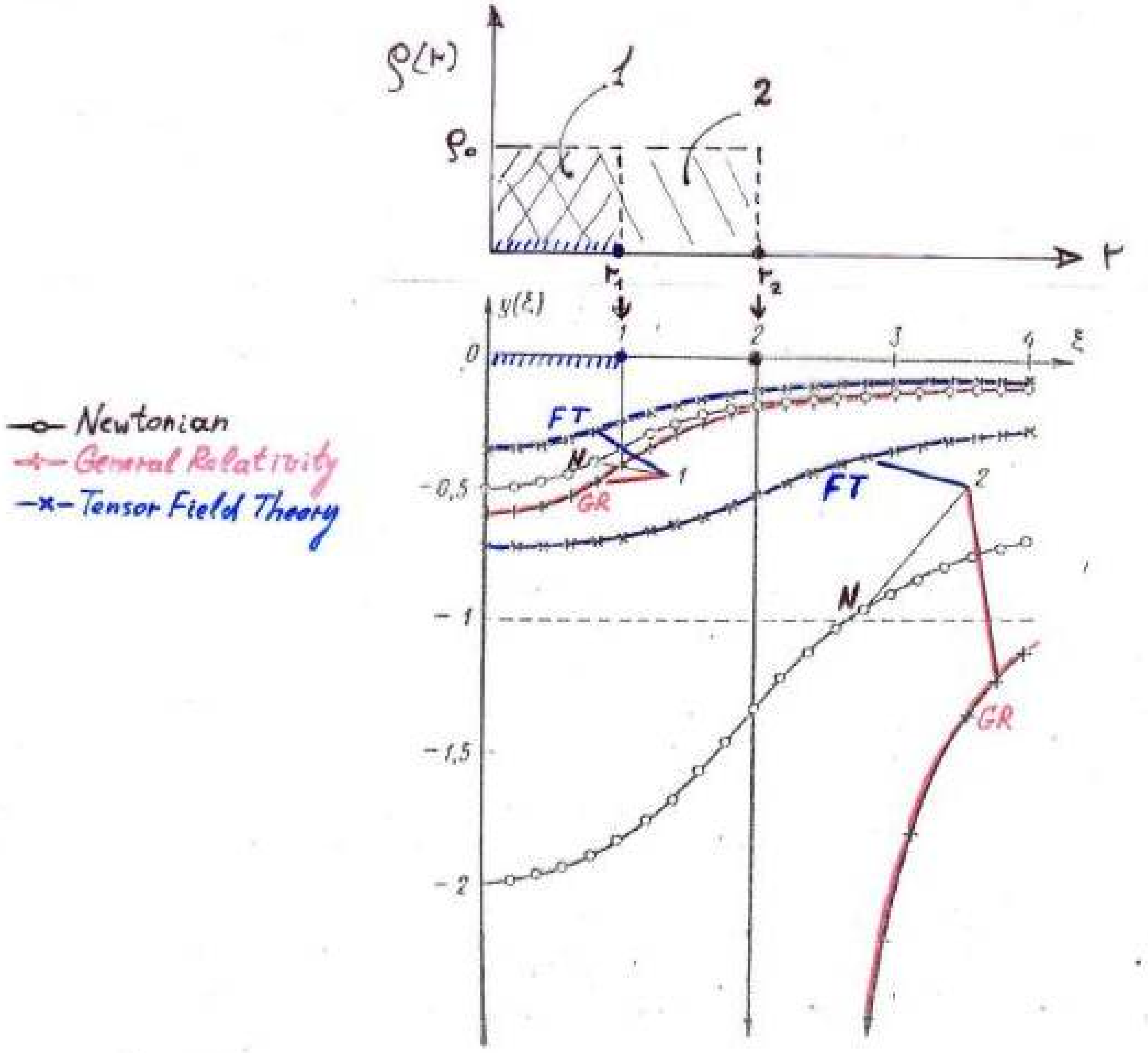
Modern view on the Central Energy Source in AGN

Jet begins very close to gravitational radius

$$r \sim R_g < R_{Sch}$$

BH or RCO ?

GRT-Newton-FGT:
Relativistic Compact Objects



Strongly Binded Objects

Comparison of FG and GR: hydrostatic equilibrium

Field Gravity | **General Relativity**

Field Gravity

$$\frac{dp}{dr} = -\frac{G(\varrho_0 + \delta\varrho)\, M_r^*}{r^2}$$

$$\delta\varrho = \frac{e+p}{c^2} + 2\varrho_0 \frac{\Phi}{c^2}$$

$\Phi = \psi^{00}, \;\; M_0^r = \int_0^r 4\pi r^2 \rho_0 dr$

$$M_r^* = \int_0^r 4\pi r'^2 (\varrho_0 + \frac{e+3p}{c^2} + 2\frac{\varrho_0 \Phi}{c^2}$$
$$+ 2\frac{(d\Phi/dr)^2}{8\pi G c^2})dr'$$

so $\frac{dp}{dr} = const$ for $r = r_g$

General Relativity

TOV equation

$$\frac{dp}{dr} = -\frac{G(\rho + p/c^2)(M + 4\pi p r^3/c^2)}{r^2(1 - r_{\mathrm{Sch}}/r)}$$

for $r \to r_{Sch}$

$$\frac{dp}{dr} \to \infty$$

Crucial tests for comparison FGT and GRT predictions

- *The universality of free fall for rotating bodies (additional acceleration of rotating bodies (V^2/c^2))*
- *The scalar-tensor nature of the symmetric tensor potentials* $\psi^{ik}(\vec{r},t)$, $\psi(\vec{r},t) = \eta_{ik}\psi^{ik}$ *(repulsion by the trace part of the symmetric tensor)*
- *The structure, masses and sizes of RCO (Quark stars, SMRCO having* $\boldsymbol{r \sim R_g = GM/c^2 = R_{Sch}/2}$)
- *The emission and detection of spin2 and spin 0 gravitational waves (EMT of GW :* $T_{\{2\}}{}^{00}$ *and* $T_{\{0\}}{}^{00}$)

Thank for attention