Gravity and geometry: observations versus theories

Peter Ván

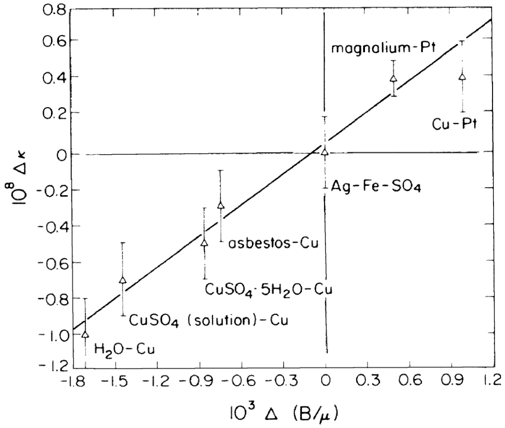
HUN REN Wigner Research Centre for Physics;
BME, Department of Energy Engineering;
Montavid Thermodynamics Research Group

BGL-2024 Budapest

Content

Eötvös-Pekár-Fekete experiment (1904-22)

Fischbach et al. (PRL 1986)



$$\boxed{|F| = \gamma(1 + \Delta\kappa)\frac{mM}{r^2}}$$

B - barion charge, μ - mass,

$\Delta\kappa = 2\frac{a_1 - a_2}{a_1 + a_2}$ - Eötvös parameter

Equivalence principles: weak Einstein, strong Einstein

Einstein Equivalence Principle (EEP):

1. Weak Equivalence Principle (WEP), the Universality of Free Fall (UFF): 'weight' is proportional with 'mass';
2. Local Lorentz Invariance (LLI), for all interactions except gravity;
3. Local Position Invariance (LPI), for all interactions except gravity;

Strong Equivalence Principle (SEP): the same for self-gravitating bodies, that is including gravity

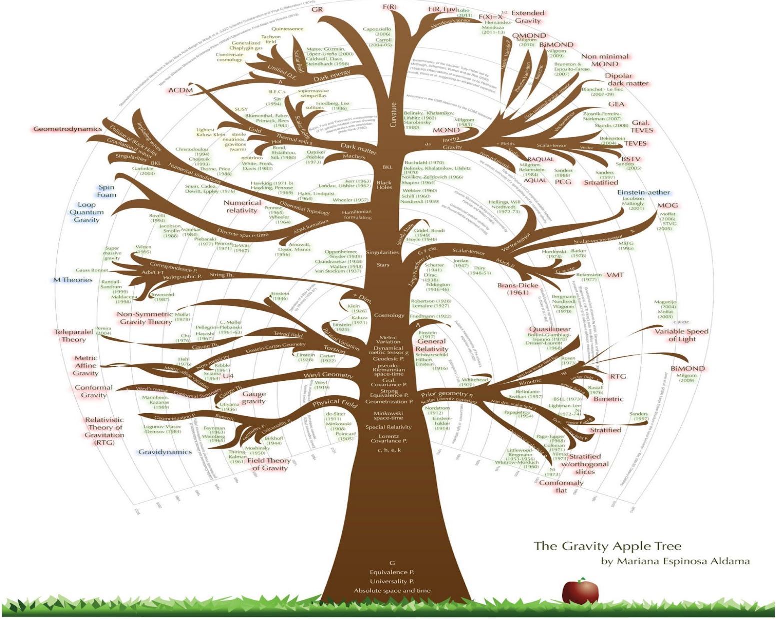
If weak EEP is true, then theory of gravitation can based on curved spacetime. If strong EEP is true, then GR is the only suitable theory.

Will (Living Rev. Relativity, 2014)

EEP is a necessary condition of geometrisation.

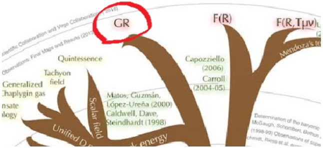
Theories of gravity

Various theories of gravity up to 2015



Theories of gravity

- Pure dinamical: ONLY coupled partial differential equations. Einstein theory.
- Pregeometric: there are absolute parts (Minkowski space, absolute time). Example Newton theory, variable speed of light.



One theory above all?

Theoretical consistency, modelling capability and predictivity.

Conceptual questions

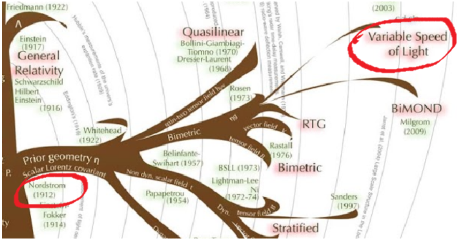
- What is gravity? Mach principle.
- Simplification vs. complexification. Added concepts: inflation, dark matter and dark energy. New epicycles?
- Quantum gravity? Quantum or gravity needs to be modified? Or both?

Which one is better?

One theory above all?

Theoretical consistency, modelling capability and predictivity.

New sprouts and dead branches.



Every theory is a modell: observations and experiments

- Weak fields – Solar system,
- Strong fields – compact stars, black holes, cosmology
- New observations: inflation, dark matter and dark energy are not enough.
- Equivalence principles: gravitational parameter or constant? E.g. Brans-Dicke

Violation of equivalence principle?

- Extended theories of gravity: Einstein theory is inside. Horndeski, Brans-Dicke, f(R), ...
- Alternative theories of gravity: Einstein theory is outside. Some versions of Teleparallel Gravity (torsion instead/and curvature) (see A. Golovnev yesterday), TeVeS (a version of MOND)

$$m_P = m_I + \eta_N E_g$$

The mass of selfgravitating bodies is corrected: Nordtvedt effect.

m_P passive gravitating mass, m_I inercial gravitating mass.

E_g gravitating self-energy, η_N coupling constant.

Post-newtonian parameters, spherical symmetric masses:

$$\eta_N = 4\beta - \gamma - 3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2.$$

γ, β, curvature and superpositioned nonlinearities; ξ preferred position; $\alpha_{1,2,3}$ preferred-frame; $\zeta_{1,..,4}$ momentum conservation.

Gravitational waves: strong limitations.

Thermodynamics and gravitation

Common property: universality.

Black hole relation

- Entropy is the area of the event horizon: $S = 4\pi E^2, \qquad E = R/2.$
- No-hair theorem versus statistical physics
- What is gravity? "Hypotheses non fingo" = calculate and shut up. (written by Newton in the appendix ("General Scholium") to the second edition of Principia (1713).

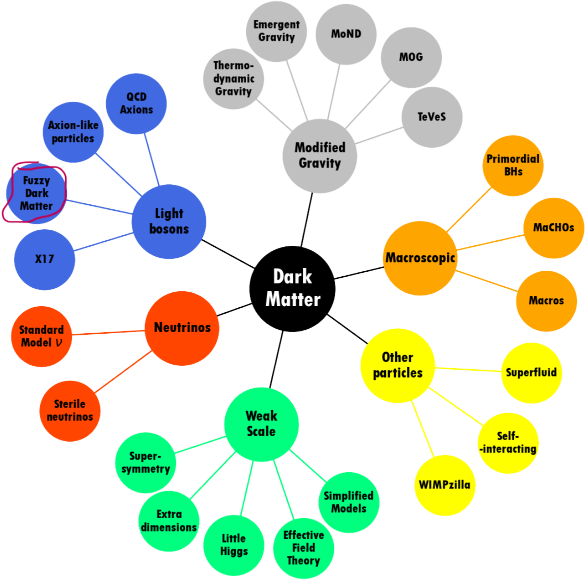
Spacetime thermodynamics

- Einstein equation: equilibrium EOS in the thermodynamics of spacetime.
  📖 Jacobson (PRL, 1995)
- The holographic property is fundamental. 📖 Verlinde (JHEP, 2012)
- Extended gravity: perturbative deviation from thermodynamic equilibrium. Low energy relaxation.

Thermodynamics must be fluid compatible. Dark matter is a test ground.

Dark Matter Test

What is dark matter?



MOND and its variations

MOND = Modified Newtonian Dynamics

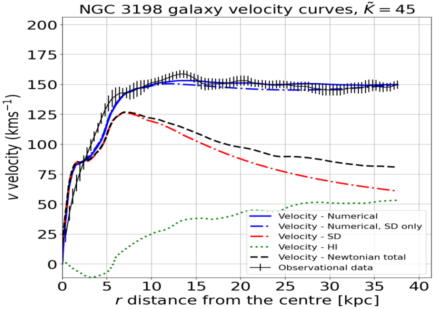
Dynamic version: acceleration dependent inertia.

$$F = m\left(\frac{a}{a_0}\right)a, \qquad m(x) = \begin{cases} 1 & ; \quad x \geq 1 \\ \frac{x}{1+x} & ; \quad \text{otherwise.} \end{cases}$$

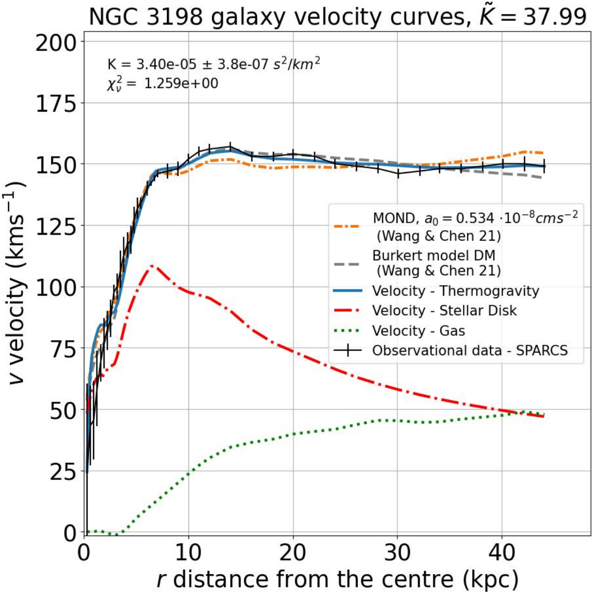
Gravity version: modified gravity. AQUAL (Milgrom-Bekenstein (1984)), TeVeS. Merged with Einstein theory.

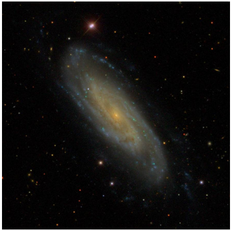
Predictions

- Tully-Fisher relation
- Velocity curves:
  $$\frac{ma^2}{a_0} = \frac{mG}{R^2} \to a = \frac{\sqrt{a_0 G}}{R}$$



Thermogravity, MOND and dark matter





NGC 3198	
M_{DM+BM}	M_{aa}
180	227.5

Unit: $10^9 M_\odot$

TG: nonlinear extension

Stacionary, nonlinear field equation. CANNOT be derived by variational principles!

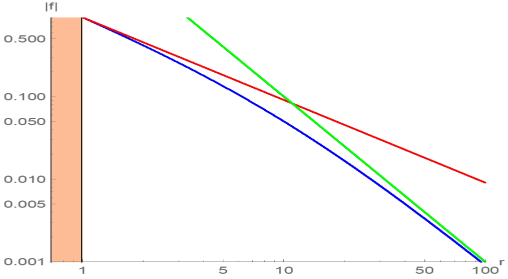
$$\boxed{0 = \Delta\varphi - 4\pi G\rho - K\nabla\varphi\cdot\nabla\varphi.}$$

Vacuum solutions ($\rho = 0$):

$$\varphi(\boldsymbol{r}) = \frac{1}{K}\ln(r)$$

Force field, point mass source, spherical symmetry. Apparent and real masses:

$$f(r) = -\frac{GM_{aa}}{r(r+r_1)}$$



📖 VP-Abe, Abe-VP (2022)

Summary and discussion

More detailed observations: theoretical bubbles and 'epicycles'. One theory above all?
Theoretical consistency: compatibility with General Relativity.

Observations and experiments

- Weak field effects: Solar system tests. Dark Matter (velocity curves, ...), equivalence principle (TG is OK, MOND?). Further weak field modifications:
$$0 = \Delta\varphi - 4\pi G(\rho - A\Delta\rho) - K\nabla\varphi\cdot\nabla\varphi.$$
- Strong field effects. Compact stars, ...
- Cosmology: Dark Energy.

Predictions

- What is gravity? Lack of answers - restricted predictions.
- What is important? Ockham weights. Theory versus observations. MOND survives, with reason.
- Unification? Universality. Quantum gravity. E.g. quantum fluids (Fuzzy DM!)

Our research

Nonequilibrium thermodynamics: universality. 📖Topical issue of PTRSA, 2022.

Weak field

- Eötvös balance. Seismology.
  📖 Tóth Gy. et al. (PoS, 2019), 📖 Tóth Gy. (EPJ Plus, 2020), 📖 Völgyesi et al. (arXiv, 2022)
- Einstein Telescope Group
- Modified Newtonian gravity. Dark Matter.
  📖VP-Abe (Physica A, 2022) 📖Abe-VP (Symmetry, 2022) 📖Pszota-VP (arXiv: 2306.01825)
- Unification based on universality. Nonequilibrium thermodynamics, quantum mechanics and gravity. Fluid physics based approach.
  📖 VP (PoF, 2023; PTRSA, 2023) 📖 Szücs-VP (manuscript)

Geometry?

Thank you for your attention!

Special thanks: Máté Pszota, Mátyás Szücs.
Coworkers: S. Abe, T.S. Biró, G. Barnaföldi, E. Fenyvesi, E. Imre, B. Kiss, P. Kovács, R. Kovács, P. Lévai, T. Pálinkás, Gy. Szondy, Gy. Tóth, L. Völgyesi.

Scalar field and hydrodynamics

$s(e - \varphi - \frac{\nabla\varphi\cdot\nabla\varphi}{8\pi G\rho}, \rho)$. Specific Gibbs relation:

$$du = Tds + \frac{p}{\rho^2}d\rho = de - d\left(\varphi + \frac{\nabla\varphi\cdot\nabla\varphi}{8\pi G\rho}\right).$$

The potential energy, φ, the field energy and internal energy are separated.

Balances of mass, momentum, internal energy + field equation:

$$\dot{\rho} + \rho\nabla\cdot\boldsymbol{v} = 0,$$
$$\rho\dot{\boldsymbol{v}} + \nabla\cdot\boldsymbol{P} = \boldsymbol{0},$$
$$\rho\dot{e} + \nabla\cdot\boldsymbol{q} = -\boldsymbol{P} : \nabla\boldsymbol{v},$$
$$\dot{\varphi} = f.$$

Constraints of the entropy inequality:

$$\boxed{\rho\dot{s} + \nabla\cdot\boldsymbol{J} = \Sigma \geq 0}$$

Constitutive state variables: $(e, \nabla e, \rho, \nabla\rho, (\boldsymbol{v}), \nabla\boldsymbol{v}, \varphi, \nabla\varphi, \nabla^2\varphi)$

$\rightarrow$ thermodynamic state variabless: $(e, \rho, \varphi, \nabla\varphi)$

$$\rho\dot{s} + \nabla\cdot\boldsymbol{J} =$$

$$\left(\boldsymbol{q} + \frac{\dot{\varphi}}{4\pi G}\nabla\varphi\right)\cdot\nabla\left(\frac{1}{T}\right)$$

$$+\boxed{\frac{f}{4\pi G T}\left(\Delta\varphi - 4\pi G\rho\right)}$$

$$-\left[\boldsymbol{P} - p\boldsymbol{I} - \frac{1}{4\pi G}\left(\nabla\varphi\nabla\varphi - \frac{1}{2}\nabla\varphi\cdot\nabla\varphi\boldsymbol{I}\right)\right] : \frac{\nabla\boldsymbol{v}}{T} \geq 0$$

- Perfect self-gravitating (isothermal) fluids are holographic:

$$\nabla\cdot\left(p\boldsymbol{I} + \frac{1}{4\pi G}\left(\nabla\varphi\nabla\varphi - \frac{1}{2}\nabla\varphi\cdot\nabla\varphi\boldsymbol{I}\right)\right) = \rho\nabla(\mu+\varphi)$$

Brans-Dicke theory

Einstein equation ($c = 1$):

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

(Einstein–)Hilbert action:

$$S = \int \mathcal{L}\sqrt{-g}\, d^4x, \qquad \mathcal{L} = \frac{R}{16\pi G} + \mathcal{L}^{(m)}, \qquad T^{(m)}_{\mu\nu} = \frac{\delta \mathcal{L}^{(m)}}{\delta g^{\mu\nu}}$$

Brans–Dicke theory:

$$\mathcal{L}^{BD} = \frac{1}{16\pi G}\left[\varphi R - \frac{\omega}{\varphi}\nabla^{\mu}\varphi\nabla_{\mu}\varphi\right] + \mathcal{L}^{(m)}$$

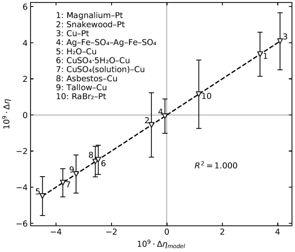
where ω is the BD parameter. $G_{eff} = \frac{G}{\varphi}$ effective gravitational parameter.

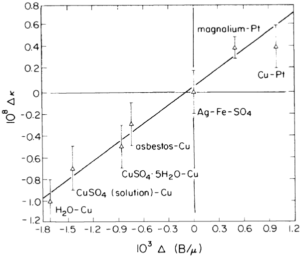
- Mach principle: effect of boundaries.

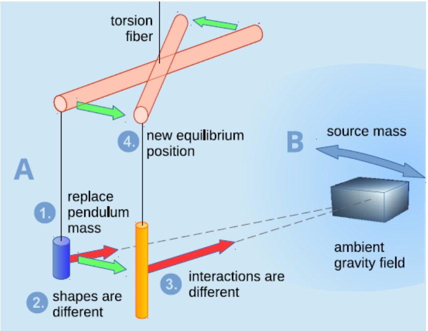
- Conformal transformation: decoupling. Jordan and Einstein frames (see F. Lobo yesterday). Which one is the "physical"?

Biró-VP (Foundations of Physics, 2015)

Shape-force? (2017)







Gyula Tóth (EPJ Plus, 2020)