Revisiting the Solar System and Beyond

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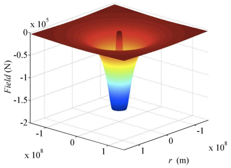
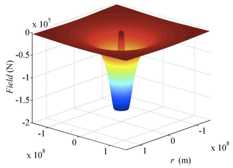


POLYTECHNIQUE MONTRÉAL

Motivation

- A long term quest for a unified description of physical systems in terms of the basic principles of Quantum Mechanics and General Relativity.

- A search for coherent explanations to some open problems encountered in the solar system when these are analyzed with General Relativity or its linear Newtonian approximation.



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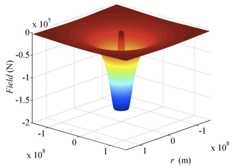
Problems waiting for explanations

1. Fly-by anomalies
2. Residual Pioneer’s delay
3. Secular increase of the astronomical unit
4. Secular increase of the Moon orbit excentricity
5. Sun oblateness
6. …



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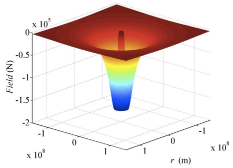
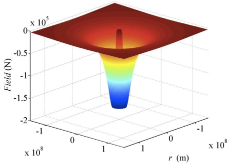


Topics

- **Probabilistic general relativity**
- **Emerging gravity**
- **New symmetric space-time geometry**
- **Predictions**



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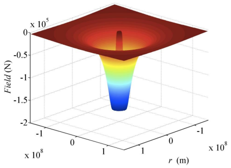
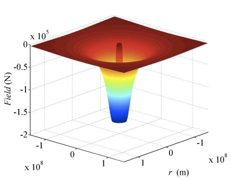


Einstein Gravitation Equation

$$G = KT$$

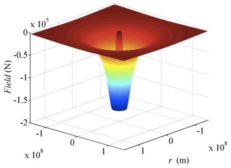


Einstein Gravitation Equation

$$G = KT$$

« Spacetime tells matter how to move; matter tells spacetime how to curve ».

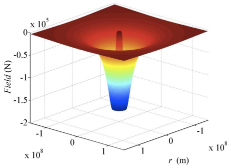
Wheeler, J.A., Ford, K.W., *Geons, Black Holes, and Quantum Foam: A Life in Physics*. W. W. Norton & Company, 2000.



Interdependence principle

Spacetime curvature (S) and matter-energy density (E) are two inextricable information spaces defining the physically observable probabilistic universe (U); they must be mutually exploited to describe any subset U_i of this universe. The probability of observing a subset (U_i) is:

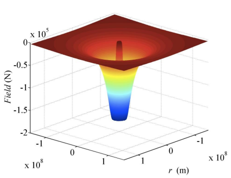
$$P(U_i) = P(S_i, E_i) < 1$$



In terms of Bayes'law…

JOINT PROBABILITIES

$$\mathrm{P}(U_i) = \mathrm{P}(S_i, E_i) = \mathrm{P}(S_i / E_i)\mathrm{P}(E_i) = \mathrm{P}(\mathrm{E}_i / \mathrm{S}_i) P(S_i)$$



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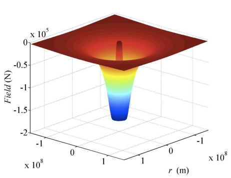
$$f(S_i / E_i) = \frac{f(S_i)}{f(E_i)} \times f(E_i \ / \ S_i)$$



In terms of Bayes'law…

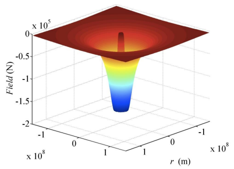
JOINT PROBABILITIES

$$P(U_i) = P(S_i, E_i) = P(S_i / E_i) P(E_i) = P(E_i / S_i) P(S_i)$$

$$f(S_i / E_i) = \frac{f(S_i)}{f(E_i)} \times f(E_i / S_i)$$

For a weak field low speed symmetric static system:

$$G_{00} = K \; T_{00}$$



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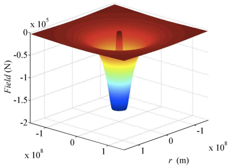
A first question

$$f(E_i \,/\, S_i)\,?$$



A first question

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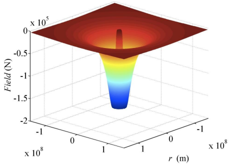
$$G_{00} = K\;T_{00} \times f(E_i / S_i)$$



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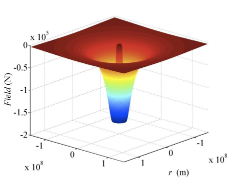
A simple stochastic model

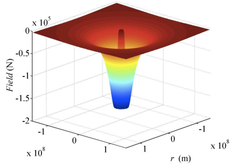
Assuming that in a far remote and isolated part of the Universe, a star is slowly building up from the gradual agglomeration of chunks of matter-energy.

Whatever the physical processes involved, these chunks of matter-energy can be considered as random variables described by their own density functions and, from a probabilistic point of view, the whole process is equivalent to adding random variables, i.e. making the convolution of their corresponding probability density functions.



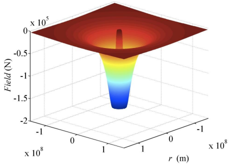
A Gaussian Convergence

- These densities are real, normalized, non-negative functions with a finite third moment and a scaled dispersion.
- The central limit theorem predicts that in a Euclidean flat spacetime, when the number of random chunks is very large (N→∞), the ideal form of the global probability density will be a Gaussian multivariate.



Emergence of the probability density

$$f(\bar{r}) = \frac{1}{4\pi^2\sigma^4}\exp\left(-\frac{\bar{r}^2}{2\sigma^2}\right) \Rightarrow \text{External 4D Flat Space}$$



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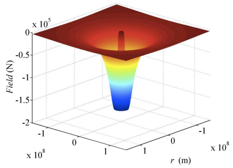
$\sigma \Rightarrow$ emergent parameter

$\sigma \Rightarrow$ intrinsic proper length of the system

$\sigma \Rightarrow$ a range parameter, an anchor point



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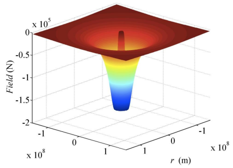
$f(\hat{r}) \Rightarrow$ Internal curved space?



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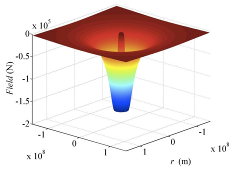

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Curved vs flat space representations

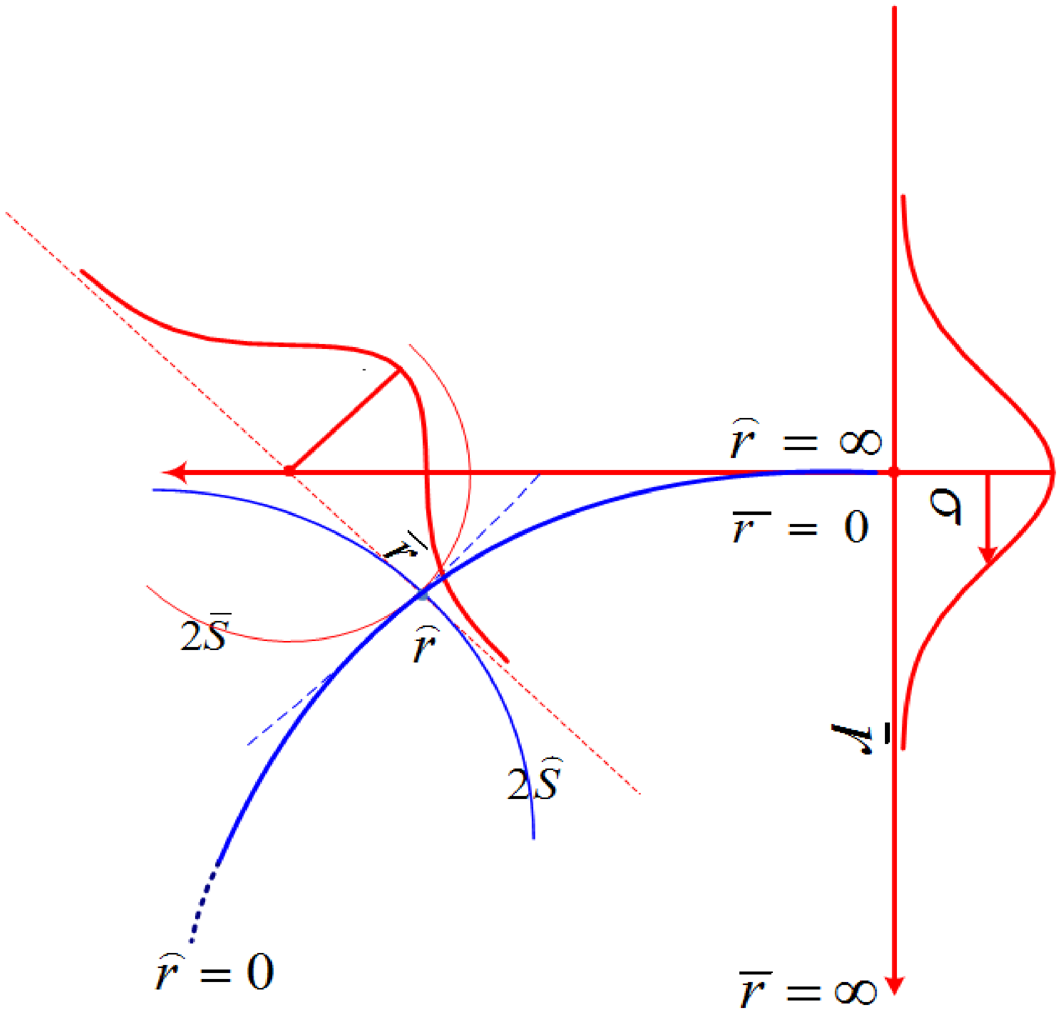
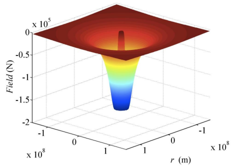


Figure 1



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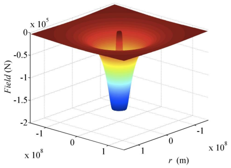
Curved vs flat space representations

$$\begin{bmatrix} \bar{r} = 0 \text{ at } \widehat{r} = \infty \\ \bar{r} = \infty \text{ at } \widehat{r} = 0 \end{bmatrix} \Rightarrow \bar{r} = \frac{s}{\widehat{r}}$$



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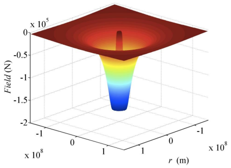
$$\bar{r} = \sigma = \overset{\frown}{r} \Rightarrow s = \sigma^2$$



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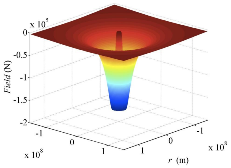
$$\frac{\overline{r}}{\sigma} = \frac{\sigma}{\overset{\frown}{r}}$$



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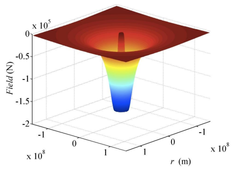
Invariance of the proper length

$$\text{Mapping} \Rightarrow \frac{\bar{r}^{2}}{\sigma^{2}} = \frac{\sigma^{2}}{\overset{\frown}{r}^{2}}$$

$$f(\overset{\frown}{r}) = \frac{1}{4\pi^{2}\sigma^{2}\overset{\frown}{r}^{2}} \exp\left(-\frac{\sigma^{2}}{2\overset{\frown}{r}^{2}}\right) \Rightarrow \text{Internal Curved Space}$$



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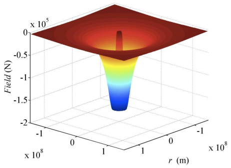
A second question

$$T_{00}\ ?$$



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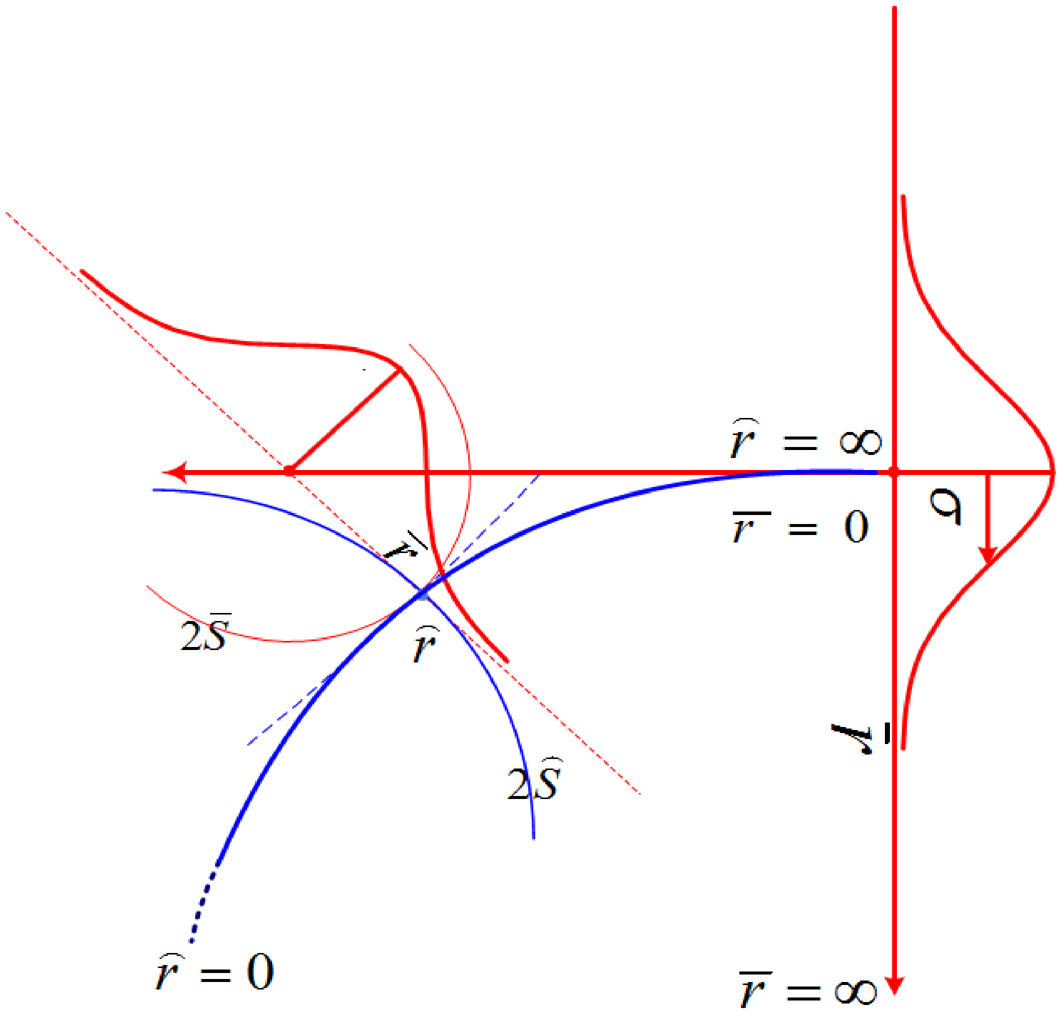

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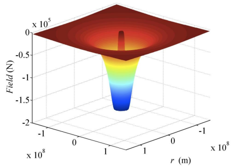

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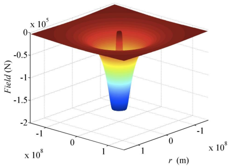
Estimating the momentum- energy tensor

$$T_{00}\big|_{\bar{r}=\sigma} = T_{00}\big|_{\hat{r}=\sigma} = \frac{M_{tot}c^2}{4\pi\sigma^2}$$



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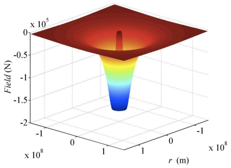
$$T_{00}\Big|_{\bar{r}} = \left(\frac{M_{tot}c^2}{4\pi\sigma^2}\right)\frac{V_{3b.\bar{r}}}{V_{3b.\sigma}} = \left(\frac{M_{tot}c^2}{4\pi\sigma^2}\right)\frac{\frac{4\pi}{3}\bar{r}^3}{\frac{4\pi}{3}\sigma^3} = \frac{M_{tot}c^2}{4\pi\sigma^2}\frac{\bar{r}^3}{\sigma^3}$$



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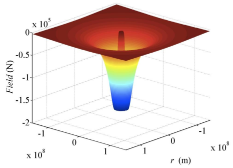
$$T_{00\,\hat{r}} = \frac{M_{tot}c^2}{4\pi\sigma^2}\left(\frac{\sigma}{\hat{r}}\right)^3 = \frac{M_{tot}\sigma c^2}{4\pi\hat{r}^3}$$

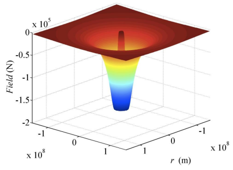


Emergence of Newton's law of gravitation

$$R_{00} \cong \frac{1}{c^2}\nabla^2\Phi = \frac{1}{2}KT_{00}\, f(E_i \,/\, S_i)$$

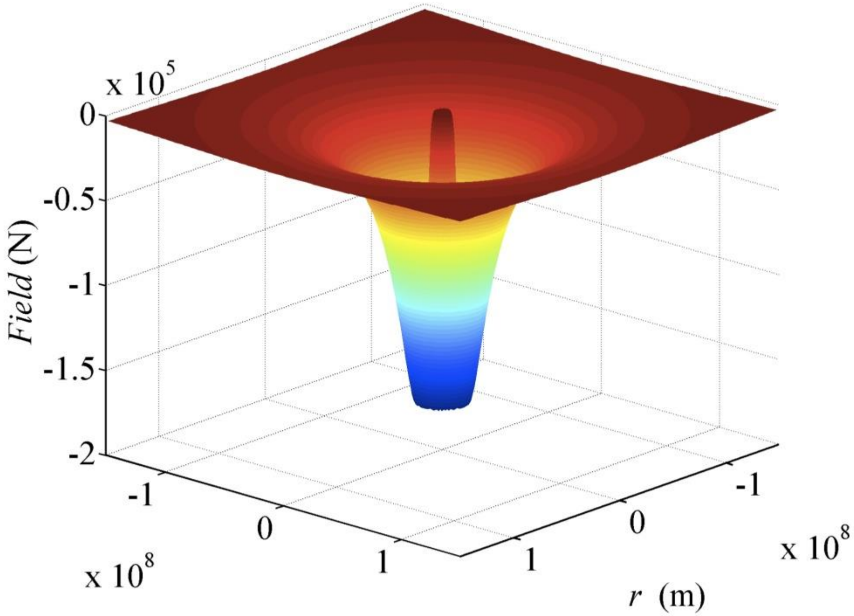
$$\nabla^2\Phi = \frac{2KMc^4\sigma^2}{4\pi\sigma^3 r^5}\exp\left(-\frac{\sigma^2}{2r^2}\right)$$

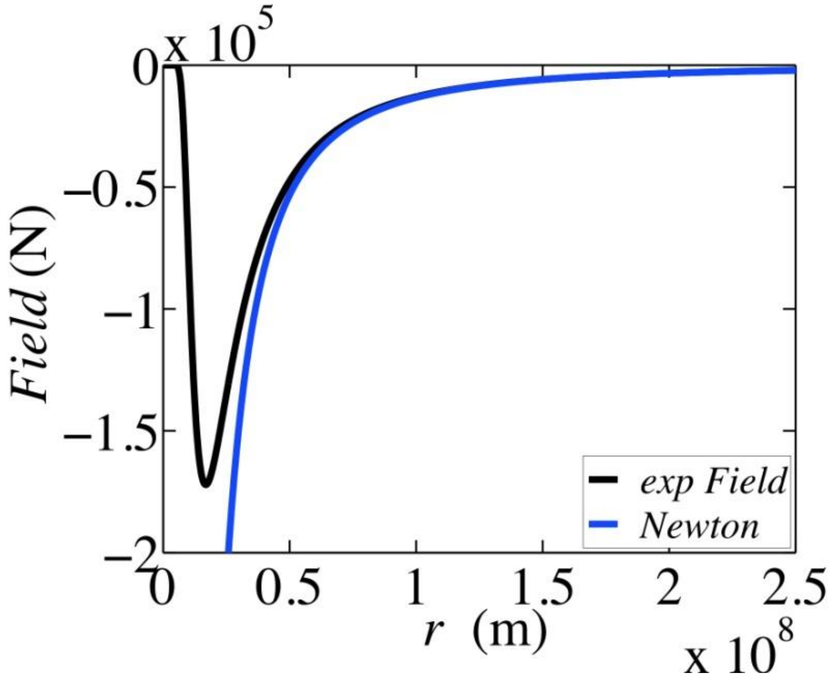
where from now on, the curved hat over the coordinate *r* is omitted.

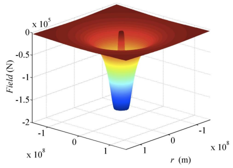


Emergence of a Modified Newton's law of gravitation

$$g(r) = -\left|\vec{\nabla}\Phi\ r\right| = -\frac{GM}{r^2}\exp\left(-\frac{\sigma^2}{2r^2}\right)$$



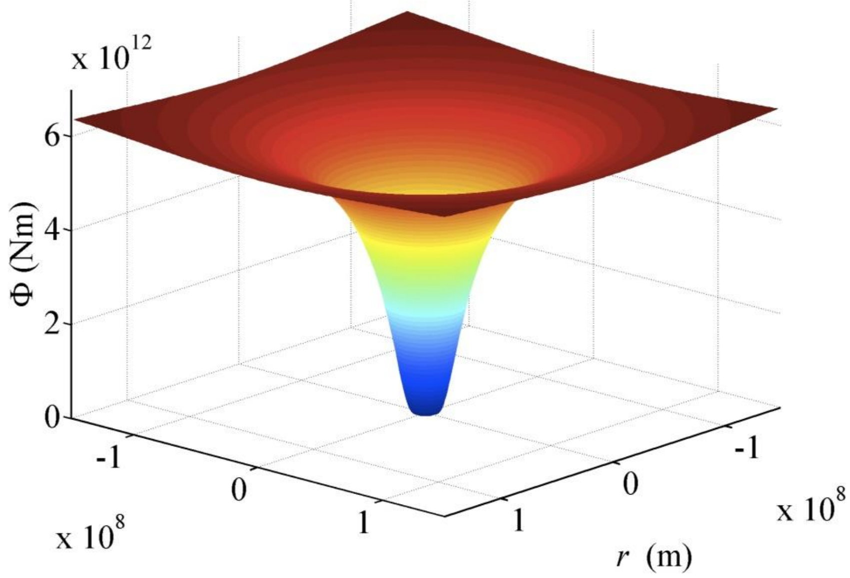


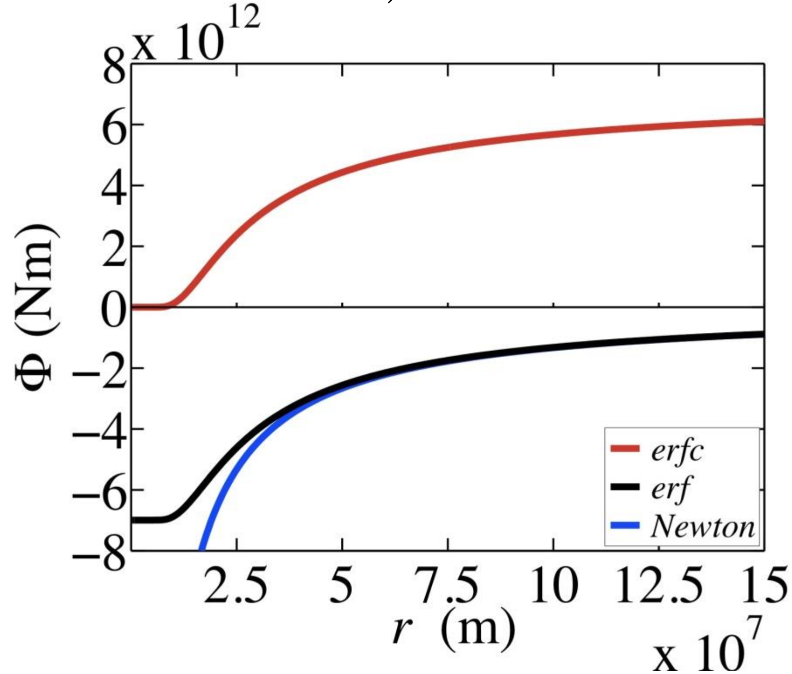


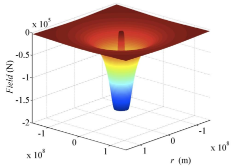
Emergence of Newton's law of gravitation: the potential

$$\Phi_{erfc}(r) = \frac{2KMc^4}{4\pi\sigma^3}\left(\frac{\sqrt{\pi}}{\sqrt{2}\sigma}\right) erfc\left(\frac{\sigma}{\sqrt{2}r}\right) = \varPhi_{erfc}(r)$$

$$\Phi_{erf}(r) = -\frac{2KMc^4}{4\pi\sigma^3}\left(\frac{1}{r} - \frac{1}{6r^3} + \frac{1}{40r^5} - \ldots\right) \cong -\frac{GM}{r}$$







POLYTECHNIQUE MONTRÉAL

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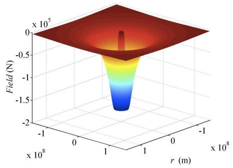

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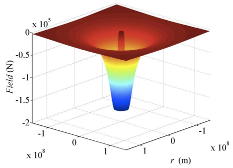
A New Symmetric Metric (Schwarzchild approach)

$$ds^2 = \left[1 + \frac{2\Phi}{c^2}\right] c^2 dt^2 - \left[1 + \frac{2\Phi}{c^2}\right]^{-1} dr^2$$

$$-r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$$

where: $$\Phi = \frac{2K_\sigma}{c^2} erfc\left(\frac{\sigma}{\sqrt{2}r}\right)$$



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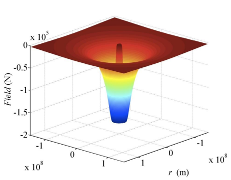
A New Symmetric Metric

$$ds^2 = \left[1 + \frac{2K_\sigma}{c^2} erfc\left(\frac{\sigma}{\sqrt{2}r}\right)\right] c^2 dt^2 - \left[1 + \frac{2K_\sigma}{c^2} erfc\left(\frac{\sigma}{\sqrt{2}r}\right)\right]^{-1} dr^2 - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$$

where: $K_\sigma = \sqrt{\pi} GM \ / \ \sigma\sqrt{2}$



POLYTECHNIQUE MONTRÉAL

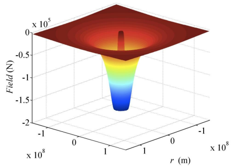
A New Symmetric Metric

No Singularities,
(neither coordinate or intrinsic)

Two types of corrections predicted by the *erfc* potential

$$erfc(x) = 1 - erf(x)$$

$$erf(x)\big|_{x \to \infty} \cong 1/x$$

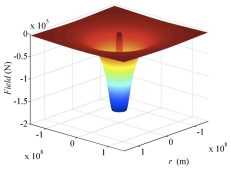


Two Type of Corrections

1- Due to the constant offset associated with the definition of the *erfc* potential

2- Due to the difference between an *erf* potential and the Newton's $1/r$ law.

(of the order of $\frac{\sigma^2}{6r^2}$)



POLYTECHNIQUE MONTRÉAL

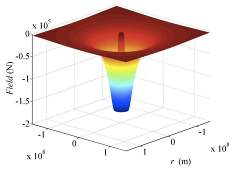
A New Symmetric Metric at $r \to \infty$

$$ds^2 = \left[1 + \frac{2K_\sigma}{c^2}\right] c^2 dt^2$$

$$- \left[1 + \frac{2K_\sigma}{c^2}\right]^{-1} dr^2$$

$$- r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2$$

where: $K_\sigma = \sqrt{\pi} GM \ / \ \sigma\sqrt{2}$

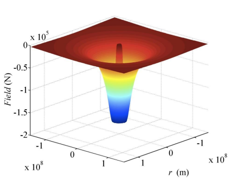


POLYTECHNIQUE MONTRÉAL

Artificially getting rid of the constant offset potential $r \rightarrow \infty$

$$\left[1+\frac{2K_\sigma}{c_{th}^2}\right]c_{th}^2 dt^2 - \left[1+\frac{2K_\sigma}{c_{th}^2}\right]^{-1} dr^2 = c_d^2 dt^2 - dr^2 = 0$$

when $r \rightarrow \infty$



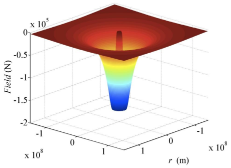
POLYTECHNIQUE MONTRÉAL

Artificially getting rid of the constant offset potential

$$\left[1+\frac{2K_\sigma}{c_{th}^2}\right]c_{th}^2 dt^2-\left[1+\frac{2K_\sigma}{c_{th}^2}\right]^{-1}dr^2=c_d^2dt^2-dr^2=0$$

$$\text{when } r\to\infty$$

$$c_{th}^2-c_d c_{th}+\frac{\sqrt{2\pi GM}}{c_{th}^2\sigma}=0$$



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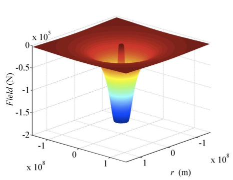
Problems when $r \neq \infty$

$$ds^2 = \left[1 + \frac{2K_\sigma}{c_{th}^2} - \frac{2K_\sigma}{c_{th}^2} erf\left(\frac{\sigma}{\sqrt{2}r}\right)\right] c_{th}^2 dt^2 - \left[1 + \frac{2K_\sigma}{c_{th}^2} - \frac{2K_\sigma}{c_{th}^2} erf\left(\frac{\sigma}{\sqrt{2}r}\right)\right]^{-1} dr^2$$

$$\neq \left[1 - \frac{2K_\sigma}{c_{th}^2} erf\left(\frac{\sigma}{\sqrt{2}r}\right)\right] c_d^2 dt^2 - \left[1 - \frac{2K_\sigma}{c_{th}^2} erf\left(\frac{\sigma}{\sqrt{2}r}\right)\right]^{-1} dr^2$$

The *erf* terms of the time components are weighted differently.

For measurements based on photons, there will be a systematic error resulting from the difference between these two expressions.



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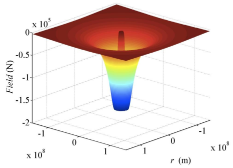
Topics

- **Putting general relativity into a probabilistic context**
- **Emerging gravity**
- **New symmetric space-time geometry**
- **Predictions**



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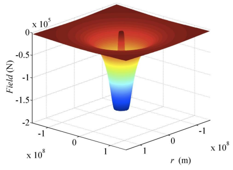
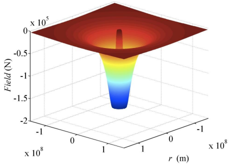
Predictions

The range parameter σ is an empirical factor, a proper length specific to a given star. It should be measured experimentally to study its effect in a particular environment. Nevertheless, we can estimate it to highlight the interest of exploring this venue and make some numerical predictions.



Once upon a time...

An observer living on a planet *P* orbiting a star *S* of mass M_S and radius r_S has defined a reference length unit l_{ref} and used a fraction *y* of this length to define a reference volume $(yl_{ref})^3$. He has poured in this volume a quantity *x* of a substance s_1, to establish a macroscopic unit of mass u_m. He then has defined a local volumetric mass reference density ρ_{ref} using the selected quantity *x* of the arbitrary reference substance s_1.



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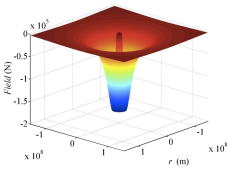
Heuristics

Working with 3-ball density ρ_{3b} instead of the 2-sphere projections ρ_{2s} used previously in his model, he proposes the following heuristic to estimate the proper length of his star:

$$\sigma_S = \frac{\rho_{2s}}{\rho_{3b}}\left[\frac{\rho_{ref}}{\rho_S}\right]\left[\frac{u_m}{m_{s1}}\right] = \frac{\left(\dfrac{M_S}{4\pi r_S^2}\right)}{\left(\dfrac{3M_S}{4\pi r_S^3}\right)}\left[\frac{\rho_{ref}}{\rho_S}\right]\left[\frac{u_m}{m_{s1}}\right] = \frac{r_S\,\rho_{ref}\,u_m}{3\rho_S\, m_{s1}}$$



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An Observer in the Solar System

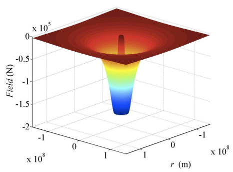
$$\sigma_{Sun} = 9.1508(20) \times 10^{6} \text{ m}$$

$$c_{th1} = c_{th} = 299671152(27) \text{ m/s}$$

$$c_{th2} = 121306(27) \text{ m/s}$$

$$c_{d} = c_{th1} + c_{th2} = 299792458 \text{ m/s}$$

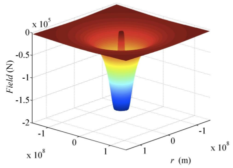
$$\Rightarrow c_{th2} = \Delta c = c_{d} - c_{th1}$$



Classical general relativity tests

a)-Mercury Precession

$$\Delta\phi_{precession} \cong \frac{6\pi G M_{Sun}}{c_{th}^2\, a\left(1-\frac{e^2 c_d^2}{c_{th}^2}\right)} = 43.13''/\,\mathrm{cy}$$



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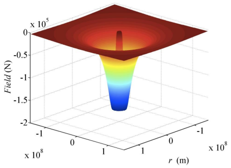
2-Classical general relativity tests

b)-Light Bending

$$\Delta\phi_{bending} \cong \frac{4GM_{Sun}}{c_d\, c_{th}\, b} = \Delta\phi_{Einstein}\, \frac{c_d}{c_{th}}$$



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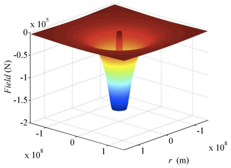
2-Classical general relativity tests

c)-Radar Echoes

$$\Delta t \cong \frac{4GM_{Sun}}{c_d^2 c_{th}}\left[\ln\frac{r_E r_V}{r_0^2}+1\right]$$

$$r_0 \cong r_{0Einstein}\left[\frac{c_d^3}{c_{th}^3}\right]^{1/2}$$



An Observer Leaving on Earth

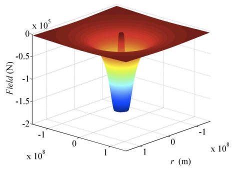
$$\sigma_{Earth} = 2.1298(2) \times 10^4 \text{ m}$$

$$c_{th1} = c_{th} = 299792232(.02) \text{ m/s}$$

$$c_{th2} = 156(.02) \text{ m/s}$$

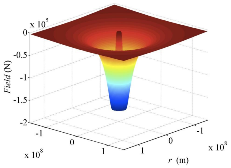
$$c_d = c_{th1} + c_{th2} = 299792458 \text{ m/s}$$

$$\Rightarrow c_{th2} = \Delta c = c_d - c_{th_1}$$



Back to the Two Types of Errors

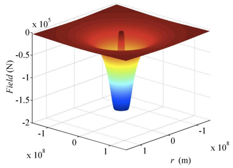
Revisiting some open problems…



1-Flyby Anomalies

Flyby anomalies are unexpected small increases in the osculating hyperbolic excess velocity of some spacecraft during Earth flybys . Indeed, Doppler and ranging data analysis have pointed out that, in the geocentric range-rate, encompasses anomalous changes of the order of 1 to 10 mm/s :

$$V_\infty = \sqrt{v^2(r,\theta) - \frac{2GM_E}{r}}$$



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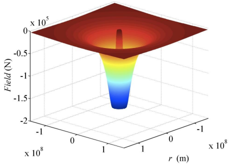
, this leads to

1-Flyby Anomalies

$$V_\infty = \sqrt{v^2(r,\theta) - \frac{2GM_E}{r}\left(1 - \frac{\sigma_E^2}{6r^2}\right)}$$



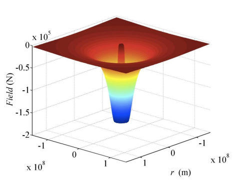
, this leads to

1-Flyby Anomalies

$$V_\infty = \sqrt{v^2(r,\theta) - \frac{2GM_E}{r}\left(1 - \frac{\sigma_E^2}{6r^2}\right)}$$

For a satellite flying slightly above the Earth radius at about the escape velocity $v_{esc} = 11.2\,\mathrm{km/s}$:

$$\Delta V_\infty \cong \frac{\sigma_E^2}{12\pi r_E^2} v_{esc}$$



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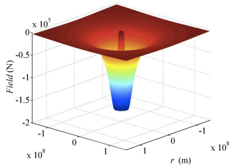
1-Flyby Anomalies

$$V_{\infty} = \sqrt{v^2(r,\theta) - \frac{2GM_E}{r}\left(1 - \frac{\sigma_E^2}{6r^2}\right)}$$

For a satellite flying slightly above the Earth radius at about the escape velocity $v_{esc} = 11.2\text{km/s}$:

$$\Delta V_{\infty} \cong \frac{\sigma_E^2}{12\pi r_E^2} v_{esc} = 10.6\text{mm/s}$$

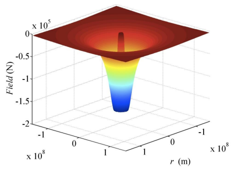


2-Residual Pioneer delays

It has been known for many years that the Pioneer space crafts were behind their predicted position. When the satellites were at about 80 astronomical units (1.196×10^{13} m) from the Sun, it was estimated that they were about 400 000 kilometres behind their expected position [1]. Using complex simulations models, about 80% of this delay has been recently explained as resulting from some potential thermal recoil force effects effects [2].

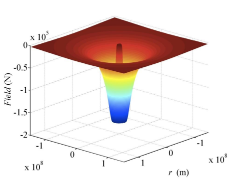
[1] Turyshev, S.G., Toth, V.T., Ellis, J. and Markwardt, C.B., *Support for Temporal Varying Behavior of the Pioneer Anomaly from the Extended Pioneer 10 and 11 Doppler Data Sets*. Phys. Rev. Lett. **107**, 081103 (2011).

[2] Anderson, J.D., Lau, E.L., Krisher, T.P., Dicus, D.A., Rosenbaum D.C. and Teplitz, V.L., *Improved Bounds on Nonluminous Matter in Solar Orbit*. Astrophys. J. **448**, 885 (1995).



2-Residual Pioneer delays

$$\Delta t = \int dt \cong \int \frac{\sqrt[4]{2}\sqrt{\pi}\, r^{1/2} dr}{\left[c_d^2 - c_{th}^2\right]^{1/2} 2\sigma^{1/2}} = \frac{\sqrt[4]{2}\sqrt{\pi}\, r^{3/2}}{\left[c_d^2 - c_{th}^2\right]^{1/2} 3\sigma^{1/2}}$$



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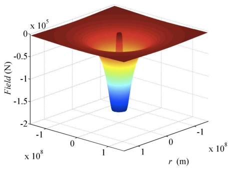
This model predicts a delay of about 70,000 km. In other words, 17.5% of the residual mismatch could be explained by the effect of σ_{Sun}



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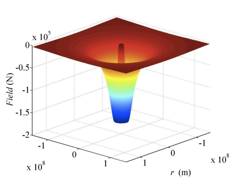
In the early days of these investigations…

- Some authors [1] have advocated that Pioneers’delay could be the result of a uniform inward acceleration acting on the spacecrafts.
- Moreover, a connection between this acceleration and the Hubble constant was also pointed out, suggesting a possible local manifestation of the cosmological expansion.

v.g.[1]Rosales, J.L., The Pioneer’s accelaration anomaly and the Hubble’s constant, arXiv:gr-qc/0212019v2.

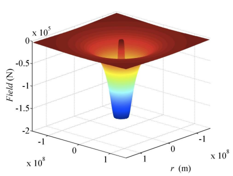


3-Space time expansion

If an observer expresses , the difference between the defined and the theoretical value of the speed of light, as an apparent redshift:

$$\Delta c = \frac{\lambda_{th} - \lambda_d}{\lambda_d} c_d = \frac{\Delta\lambda}{\lambda_d} c_d$$

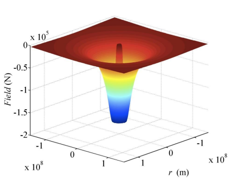
and then measures time in million years (My) and the distance of an external galaxy in megaparsec (Mpc)…



3-Space time expansion

He will find:

$$V_{Gal} = \frac{2\Delta\lambda D_{Gal(\mathrm{Mpc})}}{3.26\lambda_d\left(3.26\mathrm{My}\right)} = \frac{2\Delta c D_{Gal(\mathrm{Mpc})}}{3.26\left(\mathrm{Mpc}\right)} = H_o D_{Gal(\mathrm{Mpc})}$$



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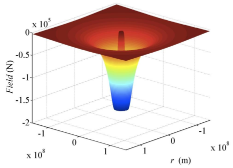
where:

$$H_0 = \frac{2\Delta c}{3.26\left(\mathrm{Mpc}\right)}$$



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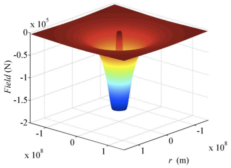
where:

$$H_0 = \frac{2\Delta c_{Sun}}{3.26\left(\mathrm{Mpc}\right)} \Rightarrow H_0 = 74.42(.02)\left(\mathrm{km/s}\right)/\,\mathrm{Mpc}$$



Consistent with Doppler shift measurements
but higher than Planck CMB measurements

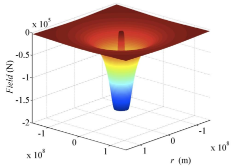
POLYTECHNIQUE MONTRÉAL

4-Secular increase of the Astronomical Unit

Among the anomalies recently detected in the solar system, the secular increase of the astronomical unit has attracted the attention of several researchers [1,2] and still remains an open problem. The astronomical unit (AU), which is defined as 149597870700 meters has been reported to increase of about $7 \pm 2\text{cm-yr}^{-1}$

[1]Iorio, L., An Empirical Explanation of the Anomalous Increases in the Astronomical Unit and the Lunar Eccentricity, The Astronomical Journal, 142:68 , (2011)

[2]Acedo, L., Anomalous post-newtonian terms and the secular increase of the astronomical unit, arXiv:1401.4056v1, (2014)



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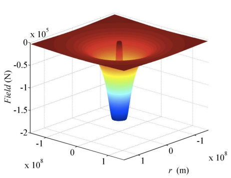
4-Secular increase of the Astronomical Unit

Repeating the approach used to define the Hubble's constant,

$$\frac{da}{dt} = \frac{3.26\Delta c \times 100 \times 1yr \times a}{Mpc} \text{cm-yr}^{-1}$$

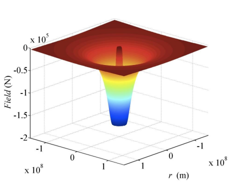
with Earth data (σ_{Earth}) :



4-Secular increase of the Astronomical Unit

Repeating the approach used to define the Hubble's constant, with Earth data (σ_{Earth})

$$\left.\frac{da}{dt}\right|_{a=1AU} = \frac{3.26\Delta c_{Earth} \times 100 \times 1yr \times a}{Mpc} \,\text{cm-yr}^{-1}$$



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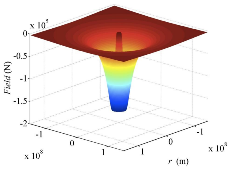
Repeating the approach used to define the Hubble's constant, with Earth data (σ_{Earth})

$$\left.\frac{da}{dt}\right|_{a=1AU} = \frac{3.26\Delta c_{Earth} \times 100 \times 1yr \times a}{Mpc} \text{cm-yr}^{-1}$$

$$\dot{a}_{Earth} \cong 7.8\text{cm-yr}^{-1}$$



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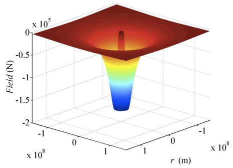
Concluding Remarks

- Incorporating the probability of presence of matter-energy density (a quantum mechanical concept) into Einstein’s equation leads to predicting the emergence of a gravitational field (quasi Newtonian).



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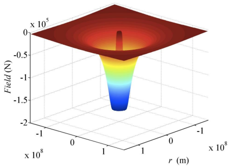
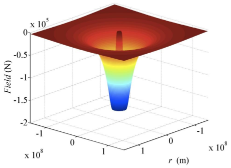
Concluding Remarks

- Incorporating the probability of presence of matter-energy density (a quantum mechanical concept) into Einstein’s equation leads to predicting the emergence of a gravitational field (quasi Newtonian).
- Incorporation the resulting *erfc* potential provides a new metric that could explain some currently observed anomalies and revisit some open questions in the solar system and beyond.



In Other Words…

- These anomalies and open questions would result from the existence of a Sun proper length σ_{Sun} , that we neglect when we are working with the defined value of the speed of light.
- These anomalies and open questions provide methods to experimentally measure σ_{Sun} , although our previous heuristics seems to give a realistic estimate.



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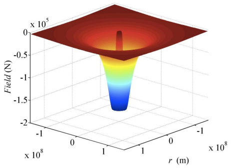
To investigate further…

A brief survey of the whole methodology regarding emerging patterns:

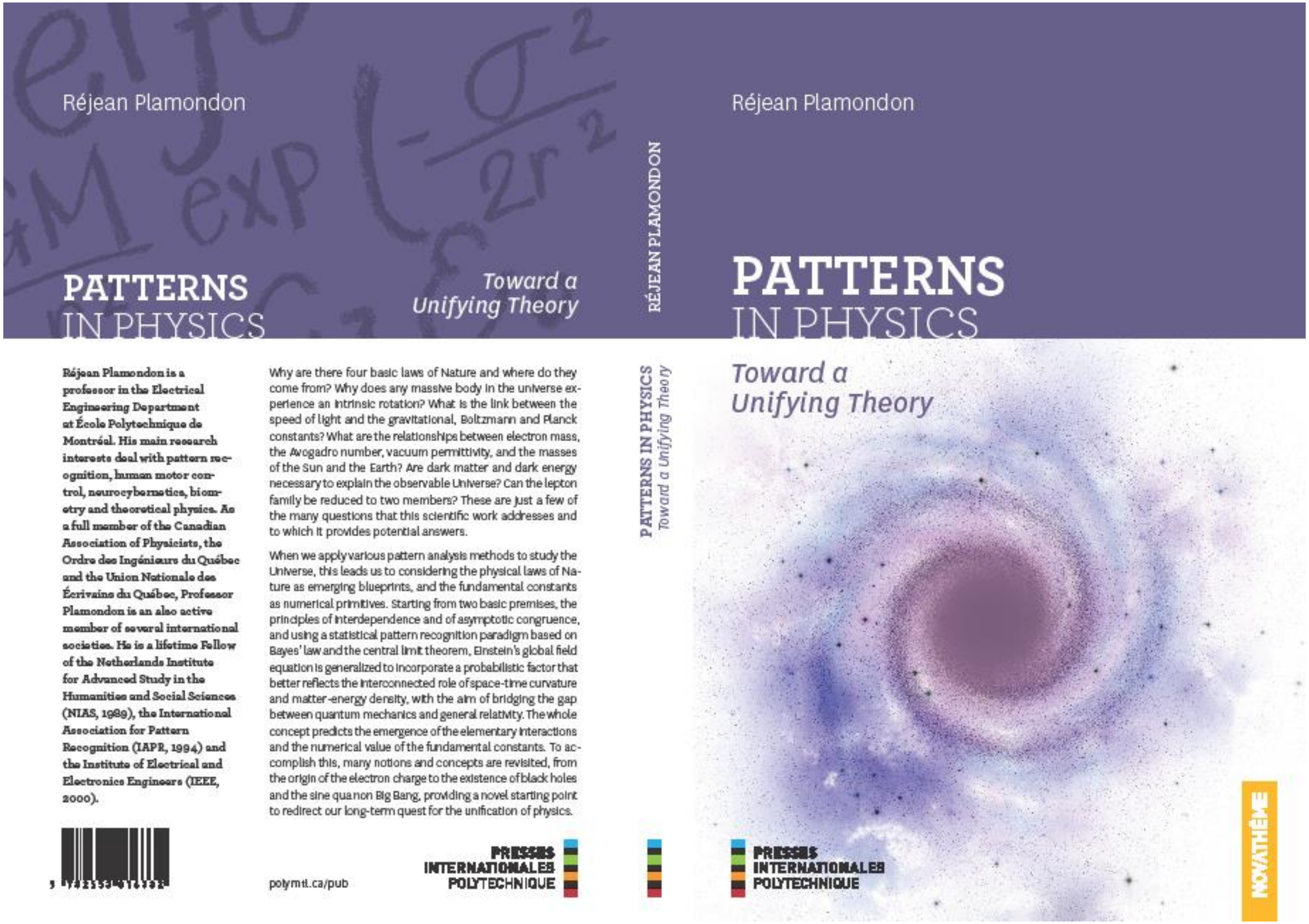
Pattern Recognition, 47, (2014), pp: 929–944.

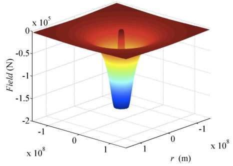
A short summary regarding the new metrics:

Proc. 13th Marcel Grossmann meeting on General Relativity, World Scientific, (2015), pp:1301-1303.



To go deeper…





POLYTECHNIQUE MONTRÉAL

Revisiting the Solar System and Beyond

Réjean Plamondon

Département de Génie Électrique

École Polytechnique de Montréal

Questions?