Alternative Theories of Gravity and SKAO constraints

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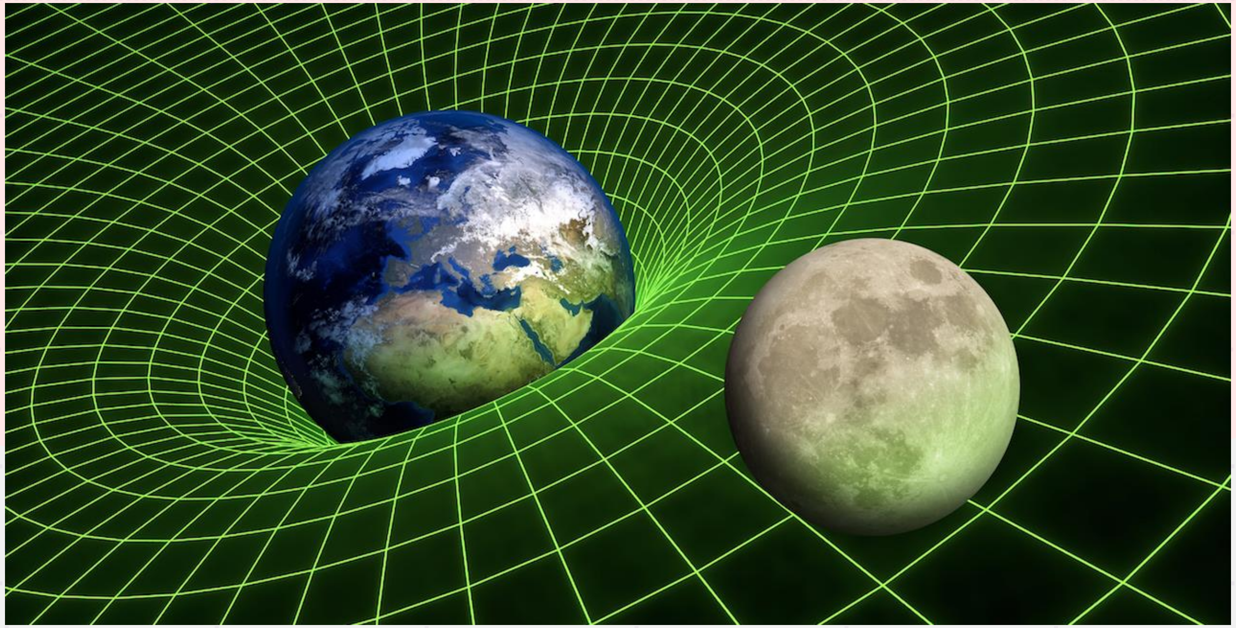
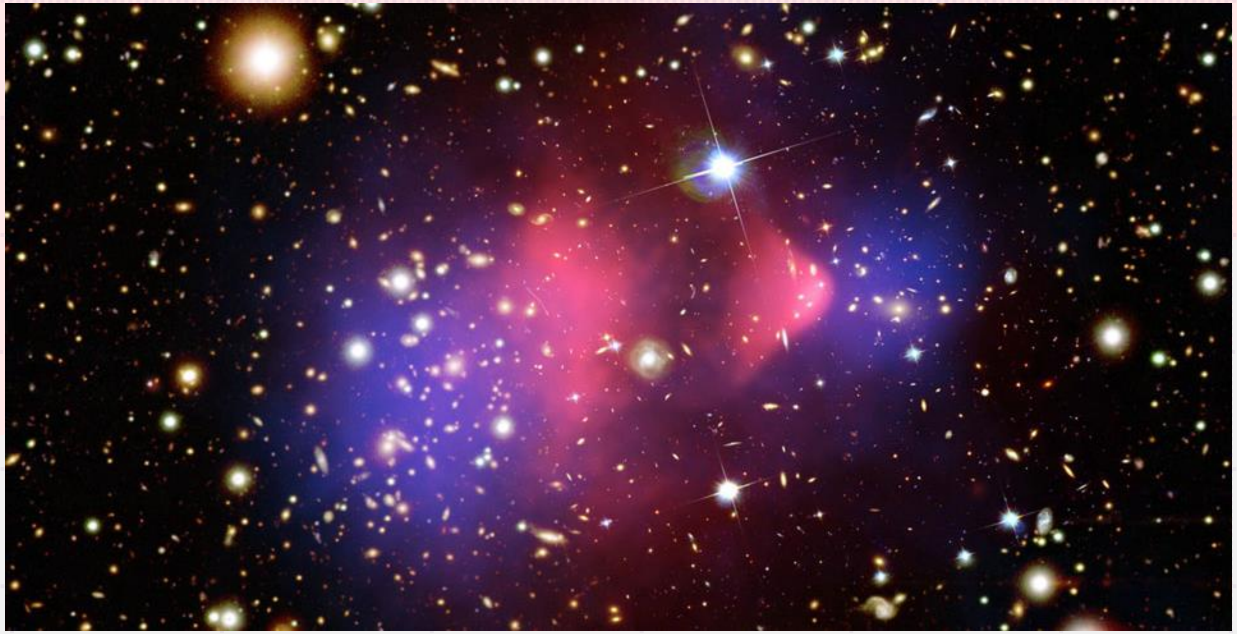
SKA Cosmology SWG meeting 2023, University of Manchester

CF-UM-UP





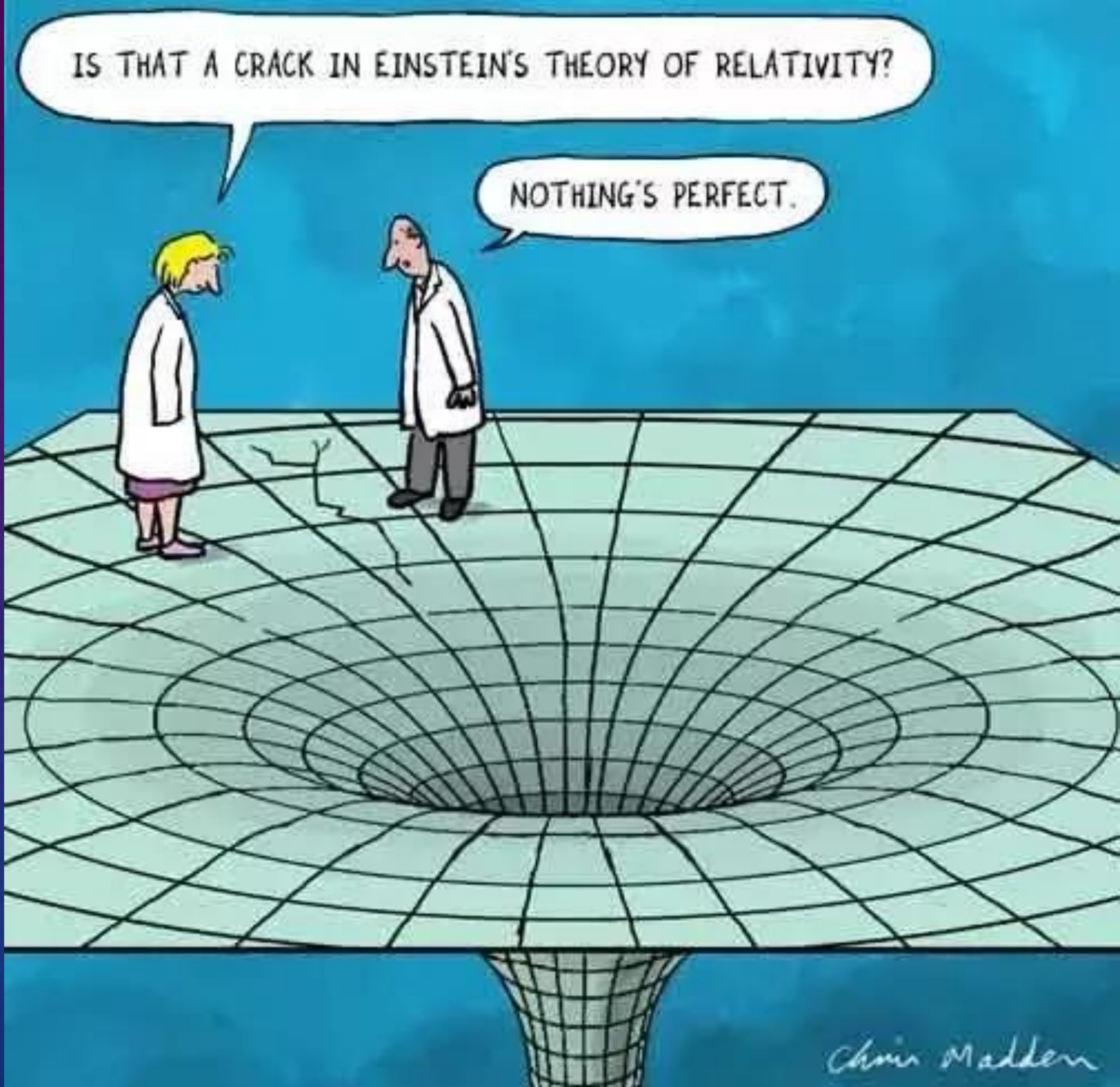
Index

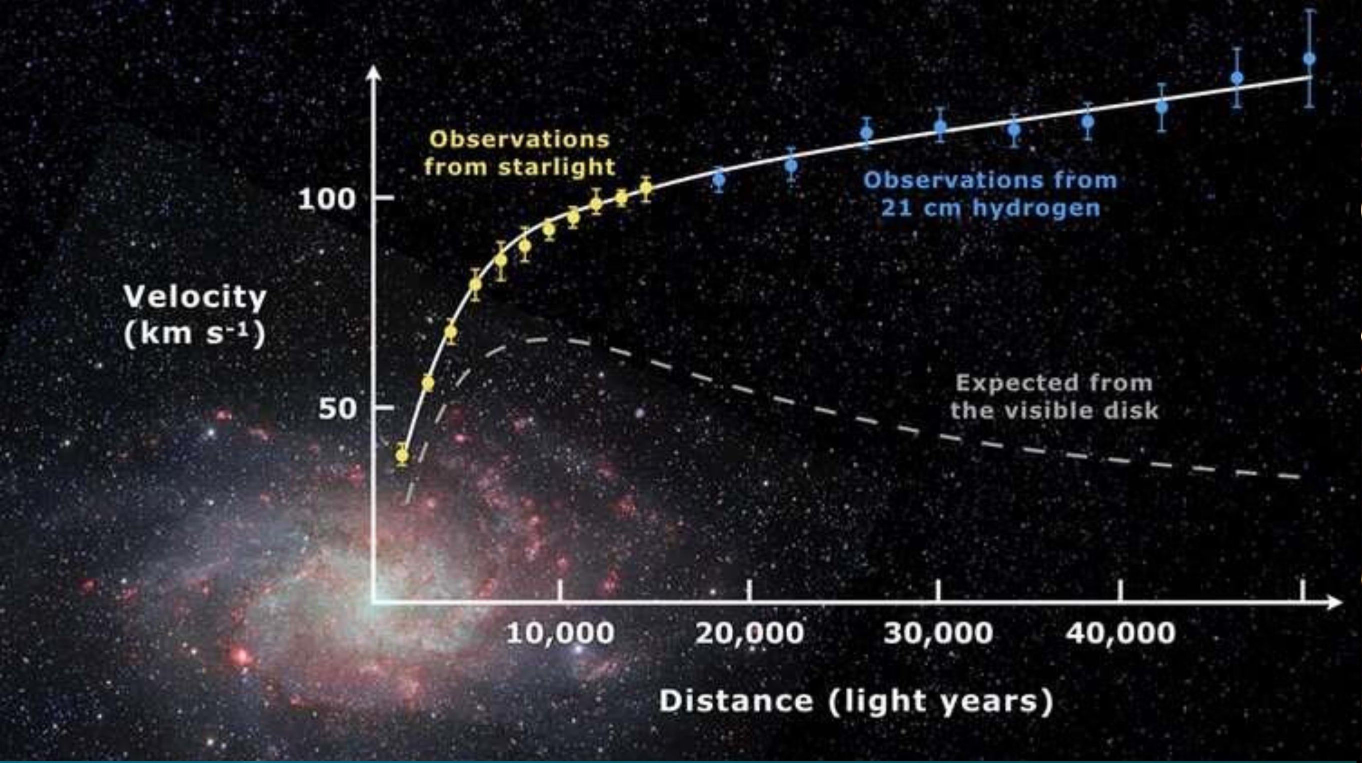
RUSTY GENERAL RELATIVITY?

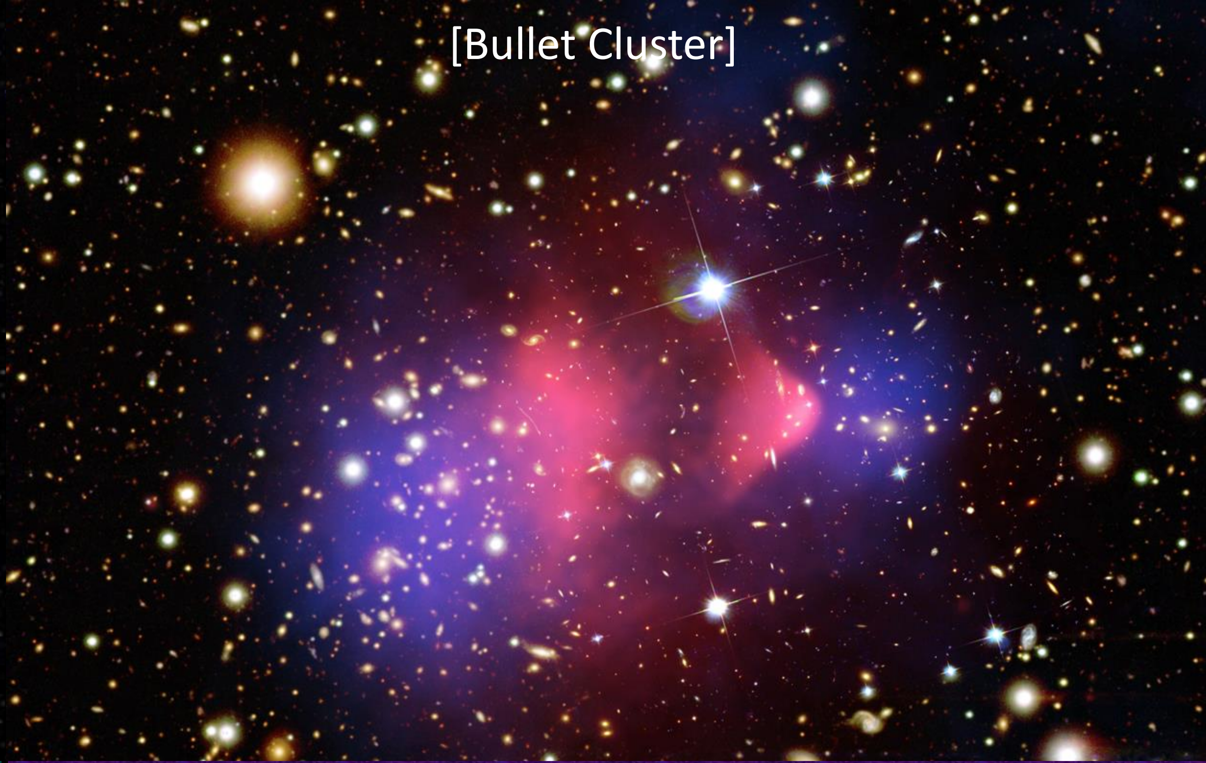
BEYOND GR?

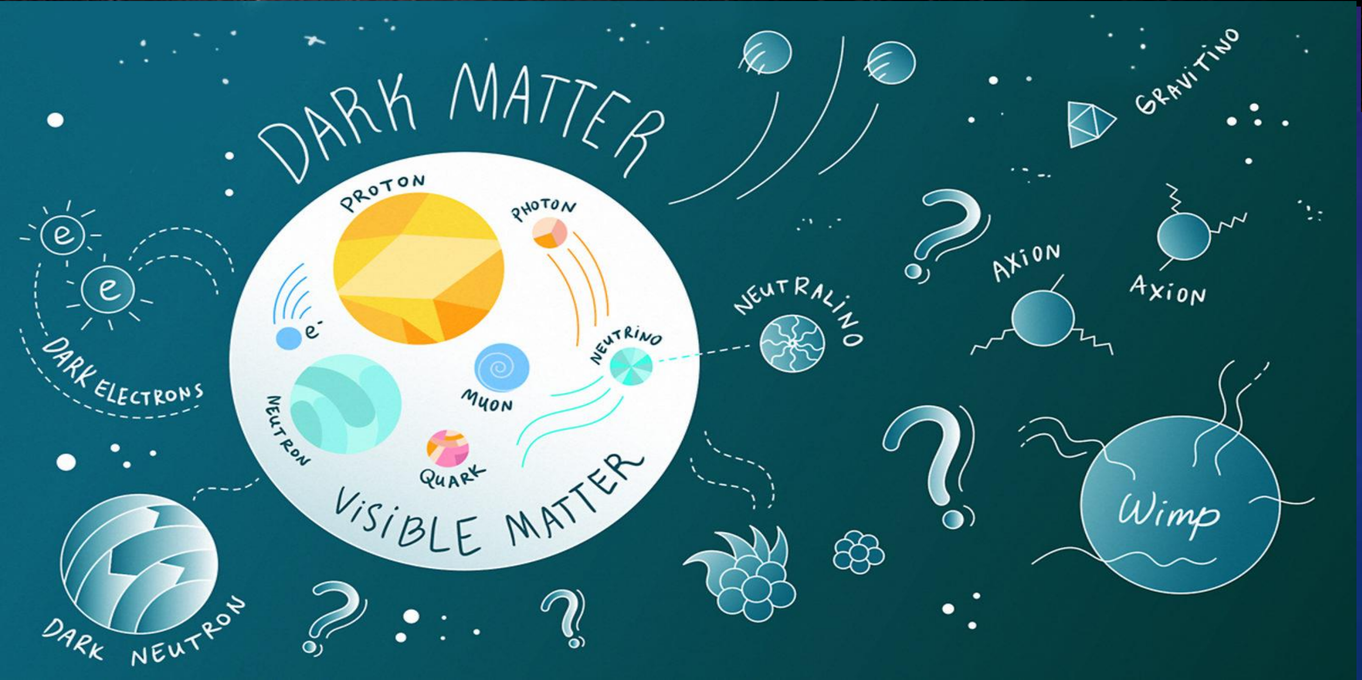
- Despite its successes:
  - Solar System tests;
  - Black Hole shadow;
  - Gravitational Waves;
  - GPS…

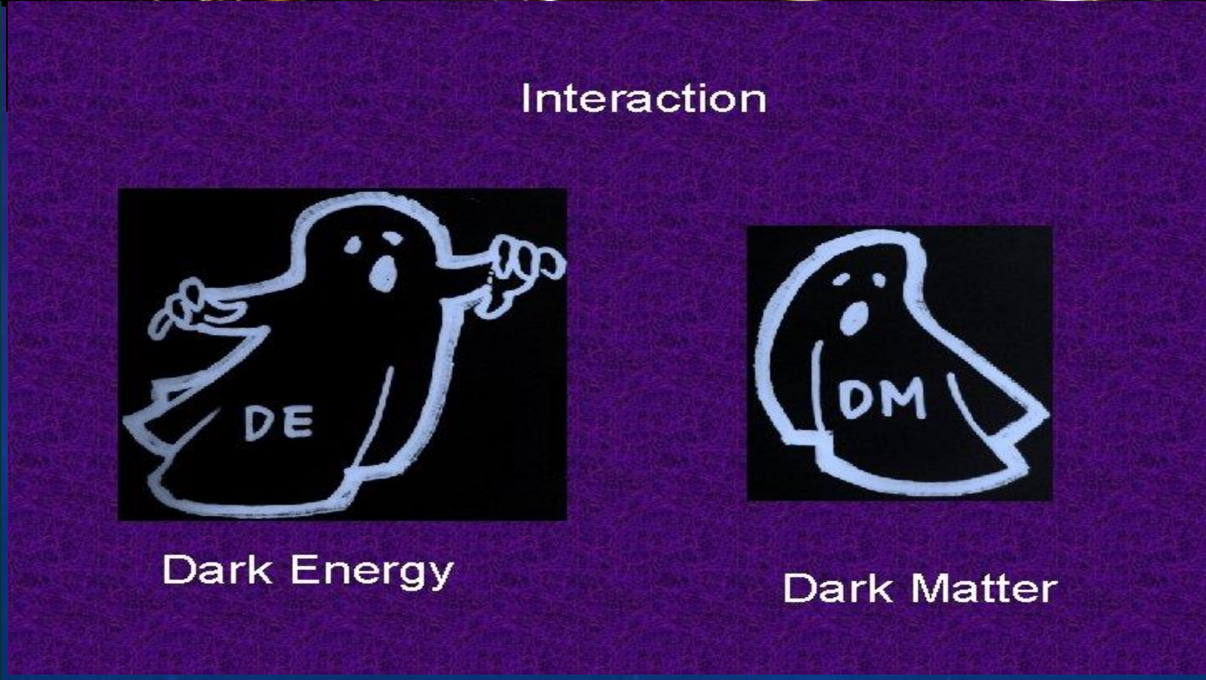
- Several Conundrums:
  - Lack of a consistent quantum version;
  - Singularities;
  - Dark Matter and Dark Energy;
  - Cosmological Constant, …

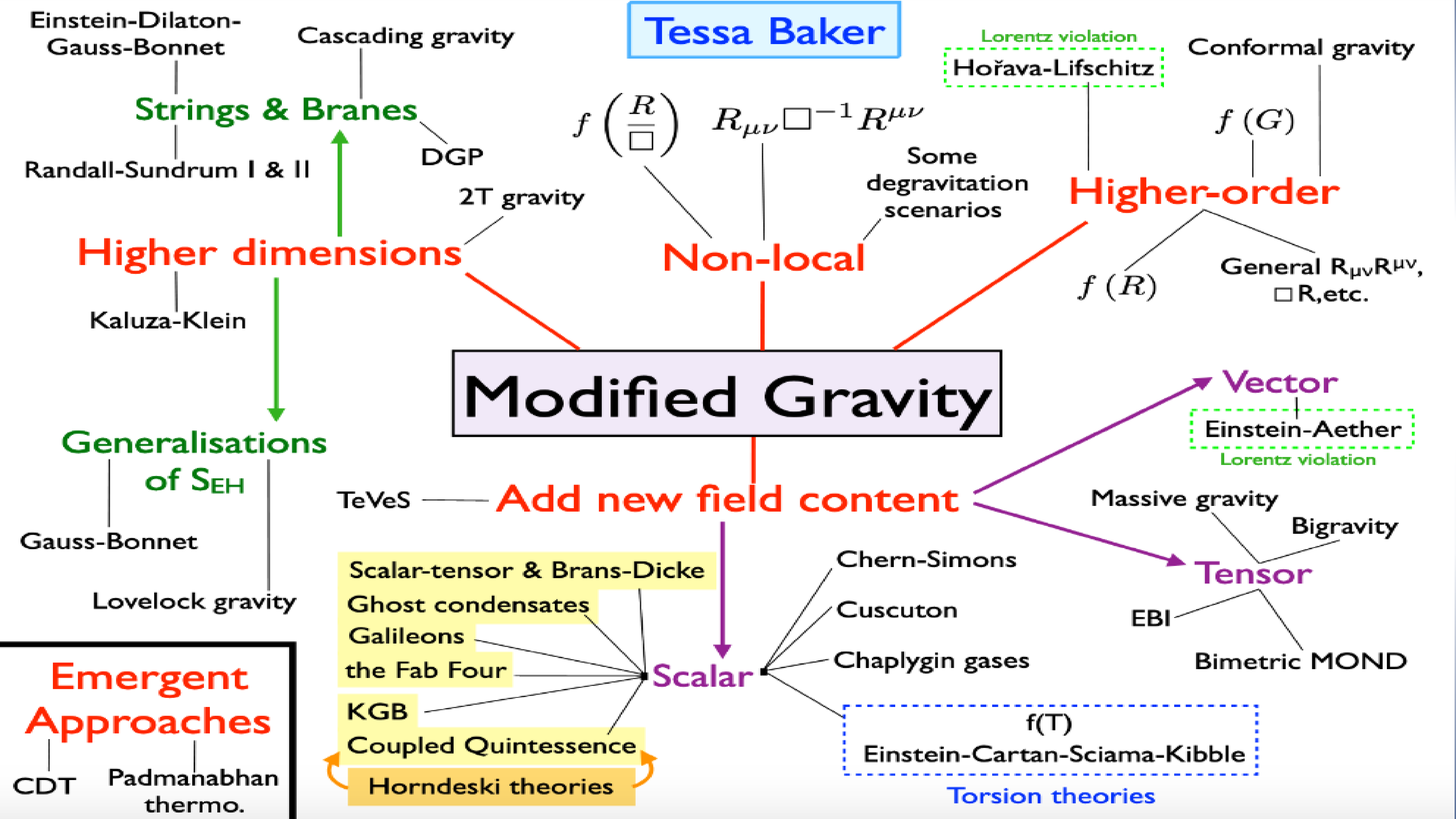



Observations from starlight
Observations from 21 cm hydrogen
Velocity (km s-1)
100
50
Expected from the visible disk
10,000
20,000
30,000
40,000
Distance (light years)


[Bullet Cluster]


DARK MATTER
PROTON
PHOTON
e-
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
e
e
DARK ELECTRONS
DARK NEUTRON
GRAVITINO
NEUTRALINO
AXION
AXION
Wimp


Interaction
DE
DM
Dark Energy
Dark Matter


Tessa Baker
Modified Gravity
Higher dimensions
Strings & Branes
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Randall-Sundrum I & II
DGP
2T gravity
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
Non-local
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Higher-order
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Add new field content
TeVeS
Vector
Einstein-Aether
Lorentz violation
Tensor
Massive gravity
Bigravity
EBI
Bimetric MOND
Scalar
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Emergent Approaches
CDT
Padmanabhan thermo.

SKAO MISSION

- Carilli, Rawlings, New Astronomy Reviews 48, 979–984 (2004)
- Bull, Ferreira, Patel, Santos, ApJ 803, 21 (2015)
- Raccanelli, et. al. PoS (AASKA14) 031 (2014)
- Bertolami, Gomes in Portuguese SKA White book

- Evolution of galaxies and cosmology;
- Strong gravity through pulsars and black holes;
- Origin and evolution of cosmic magnetism;
- Cosmic history of the Universe at dark ages and reionisation epochs;
- Putative cradle of life...

- In particular, in Cosmology:
  - constrain the equation of state parameter for dark energy → discriminating between several models of cosmic acceleration;
  - dark matter power spectrum;
  - test modified theories of gravity using weak lensing observations;
  - bounds on the mass and the number of neutrinos families;
  - cosmic magnetism (seeds from inflation? Or dynamo effect?)…

MODIFIED THEORIES OF GRAVITY

- Three model dependent parameters for growth of structures in any gravity theory [Amendola et al. Living Rev. Relativity 16, 6 (2013)]:

Gauge-invariant density contrast

Poisson eqn. $$-2k^2\hat{\Psi} = 8\pi G_N a^2 \rho D \, \tilde{\mu}(a,k)$$

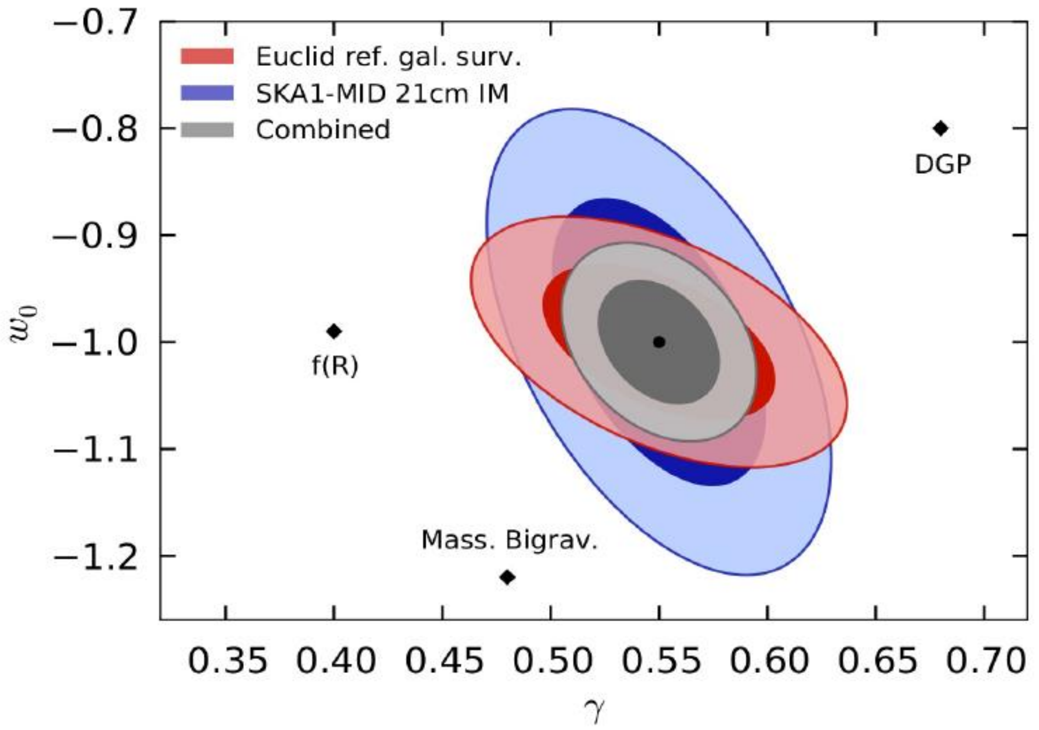
Slip relation $$\hat{\Phi} = \hat{\Psi} \, \tilde{\gamma}(a,k)$$

Growth rate $$f(a,k) = \left(\frac{a^2 8\pi G_N \rho}{3H^2}\right)^{\gamma}$$

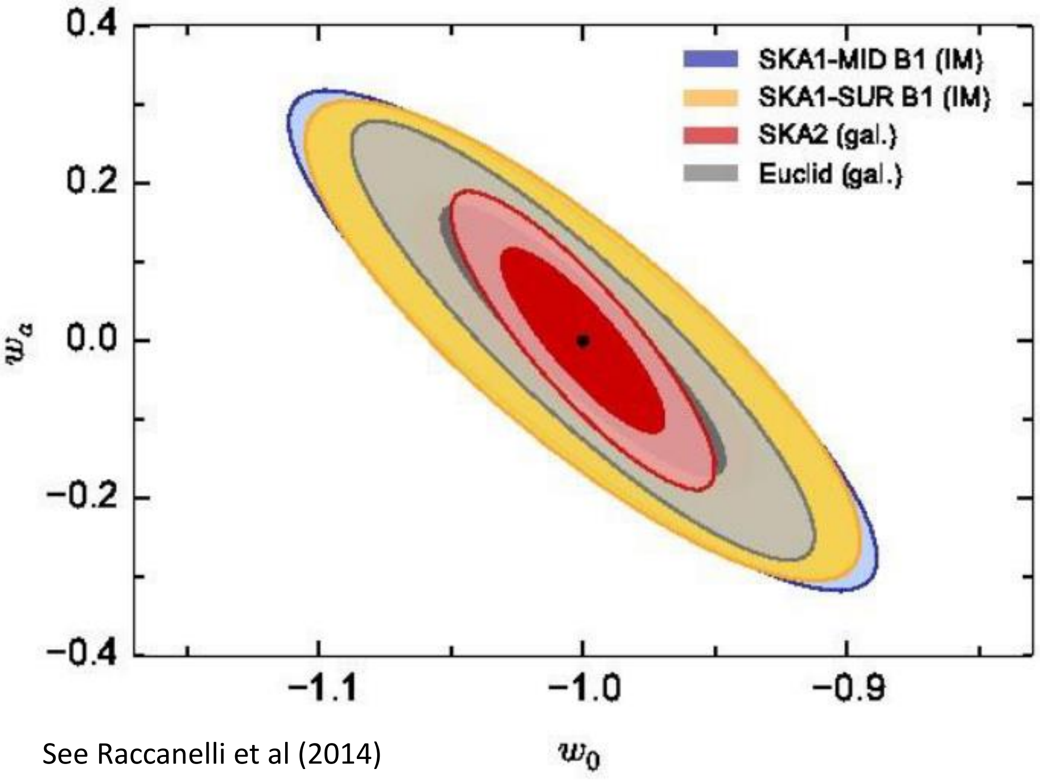
=1 in GR

=0,545 in GR

GROWTH OF STRUCTURES IN MODIFIED GRAVITY



See Bull et al. (arXiv:1405.1452)



See Raccanelli et al (2014)

$w=p/\rho$

$w=w_0+w_a(1-a)$

COSMIC VIRIAL THEOREM (LAYZER-IRVINE OR DMITRIEV-ZELDOVICH EQUATION)

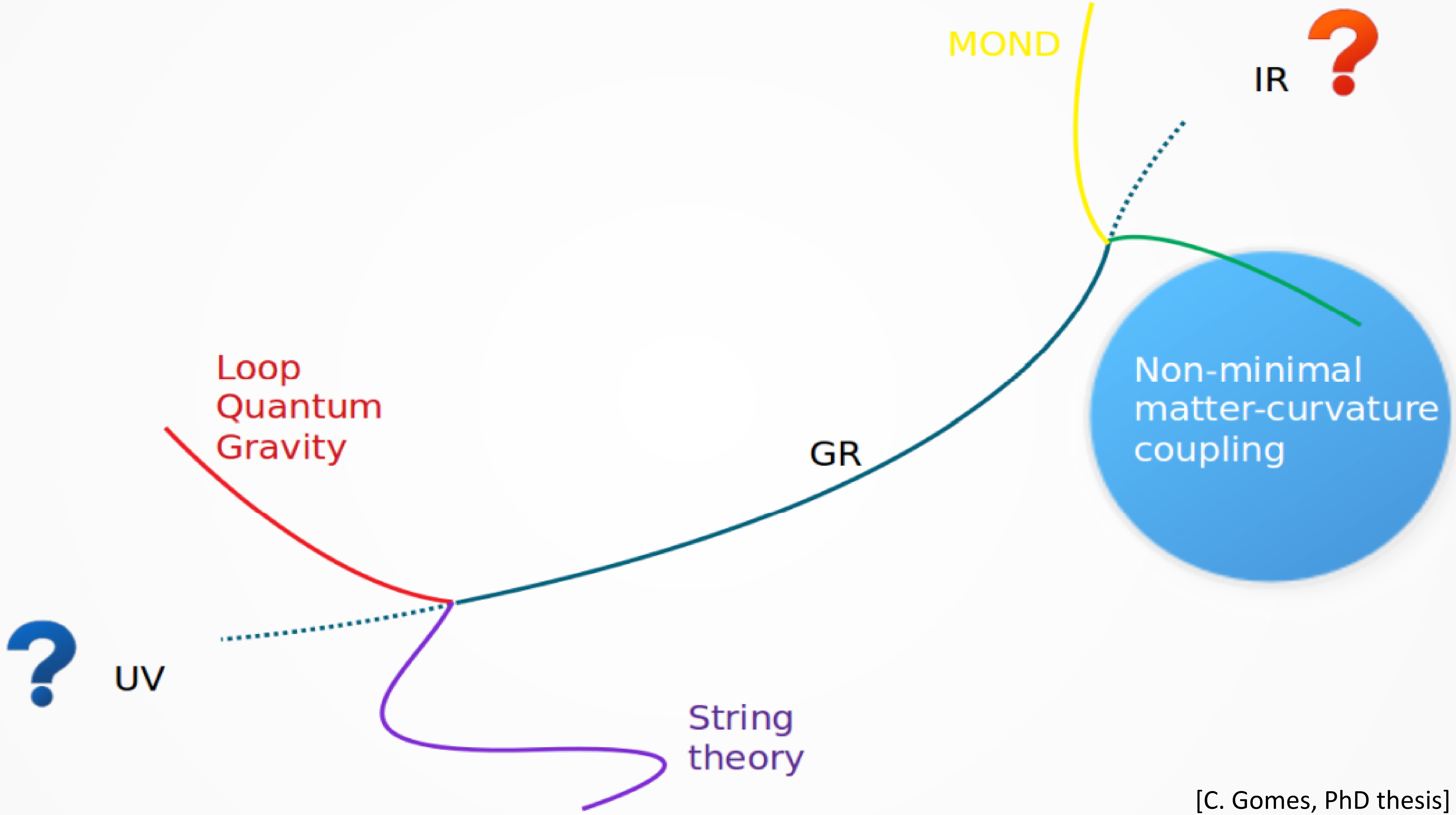
- Clusters rich in radio galaxies:
  - Dark matter – dark energy interaction
  - Modified Gravity

- Bertolami, Pedro, Delliou 2007, 2009, 2012

- Bertolami, Gomes 2014

- Cosmological Solvers?

[See Ziad Sakr talk]



[C. Gomes, PhD thesis]

THE NON-MINIMAL MATTER-CURVATURE COUPLING MODEL [BERTOLAMI,BOHMER,HARKO,LOBO, 2007]

$$S = \int \left[\kappa f_1(R) + f_2(R)\mathcal{L}\right]\sqrt{-g}\,d^4x \quad , \tag{4}$$

where $\kappa = M_P^2/2$.

Varying the action relatively to the metric $g_{\mu\nu}$:

$$\begin{aligned} 2\left(\kappa F_1 - F_2\rho\right)\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) =& f_2 T_{\mu\nu} + \kappa\left(f_1 - F_1 R\right)g_{\mu\nu} + \\ & + F_2\rho R g_{\mu\nu} + 2\Delta_{\mu\nu}\left(\kappa F_1 - F_2\rho\right) \end{aligned} \tag{5}$$

where $F_i \equiv df_i/dR$, and $\Delta_{\mu\nu} \equiv \nabla_\mu\nabla_\nu - g_{\mu\nu}\Box$.

One recovers GR by setting $f_1(R) = R$ and $f_2(R) = 1$.

Using the Bianchi identities, one finds the covariant non-conservation of the energy-momentum tensor:

$$\nabla_\mu T^{\mu\nu} = \frac{F_2}{f_2}\left(g^{\mu\nu}\mathcal{L} - T^{\mu\nu}\right)\nabla_\mu R \qquad (6)$$

For a perfect fluid, the extra force due to the NMC can be expressed as:

$$f^\mu = \frac{1}{\rho + p}\left[\frac{F_2}{f_2}(\mathcal{L} - p)\nabla_\nu \mathrm{R} + \nabla_\nu p\right] h^{\mu\nu}, \qquad (7)$$

with $h^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$ being the projection operator, and u^μ is the 4-velocity of the fluid.

MOTIVATIONS

- Effective brane-world and the loop quantum cosmology background expansion histories can be reproduced (with advantages from Palatini formalism over metric one) [G.J. Olmo, D. Rubiero-Garcia, 2015]
- ΛCDM suitably embedded [M. Ortiz-Baños, M. Bouhmadi-López, R. Lazkoz, V. Salzano, 2021]
- Resemblence with effective gravity expanded around Minskowskian spacetime background

THEORETICAL AND OBSERVATIONAL IMPLICATIONS

- Degeneracy-lifting of the Lagrangian choice [O. Bertolami, F. S. N. Lobo, J. Páramos, 2008]
- Mimicking Dark Matter (galaxies, clusters) [O. Bertolami, J. Páramos, 2010; O. Bertolami, P. Frazão, J. Páramos, 2013]
- Cosmological Perturbations [O. Bertolami, P. Frazão, J. Páramos, 2013]
- Modified Layzer-Irvine equation and virial theorem [O. Bertolami, C. Gomes, 2014]
- Inflationary dynamics [C. Gomes, O. Bertolami, J.G. Rosa, 2017]
- Gravitational Waves [O. Bertolami, C. Gomes, F.S.N. Lobo, 2017]
- Boltzmann equation [O. Bertolami, C. Gomes, 2020]
- Jeans instability [C. Gomes, 2020]
- Cassini and extra force constraints [R. March, O. Bertolami, M. Muccino, C. Gomes, S. Dell'Agnello, 2022]
- Quantum and kinetic effects in star formation [C. Gomes, K. Ourabah, 2023]

TULLY-FISHER LAW [BERTOLAMI ET AL 2007]

- Non geodesic motion (extra force):

$$\frac{Du^\alpha}{ds} \equiv \frac{du^\alpha}{ds} + \Gamma^\alpha_{\mu\nu} u^\mu u^\nu = f^\alpha$$

$$f^\alpha = \frac{1}{\epsilon + p}\left[\frac{\lambda F_2}{1 + \lambda f_2}(\mathcal{L}_m + p)\nabla_\nu R + \nabla_\nu p\right] h^{\alpha\nu}$$

- In 3D and in the Newtonian limit:

$$\vec{a} = \vec{a}_N + \vec{f}$$

$$\vec{a}_N \approx \frac{a}{a_E}\vec{a}$$

Similar to MOND

$$a_N = GM/r^2$$

+

$$a \approx \sqrt{a_E a_N}$$

$$a \approx \sqrt{a_E GM/r} = v_{tg}^2/r$$

rotation velocity of the particle under the influence of a central force

[See Federico Lelli and Anastasia Ponomareva talks in the afternoon]

L ~ v^4_∞ where $v_\infty^4 = a_E GM$

OTHER MODELS

- Nonminimally coupled f(Q) gravity [T. Harko, T.S. Koivisto, F.S.N. Lobo, G.J. Olmo, D. Rubiera-Garcia, 2018]

$$L \sim f_1(Q) + f_2(Q) L_M$$

- Nonminimally coupled Weyl gravity [C. Gomes, O. Bertolami, 2019]

$$D_\lambda g_{\mu\nu} = A_\lambda g_{\mu\nu}$$

- f(R,L) theories [T. Harko, F.S.N. Lobo, 2010]

$$S = \int f\left(R, L_m\right) \sqrt{-g}\, d^4x$$

- Hybrid metric-Palatini theories [T. Harko, T.S. Koivisto, F.S.N. Lobo, G.J. Olmo, 2012]

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\left[R + f(\mathcal{R})\right] + S_m$$

- Generalised Hybrid metric-Palatini theories [N. Tamanini, C.G. Boehmer, 2013]

$$S_f = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}\, f(R, \mathcal{R})$$

Thank you for your attention!

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