GRavitational Fields
On the Scale
Of Clusters of Galaxies

Antonaldo Diaferio

- Università degli Studi di Torino – Dipartimento di Fisica
- Istituto Nazionale di Fisica Nucleare - Sezione di Torino

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The CAUSTIC Group

Conventional And Unconventional Studies & Tools In Cosmology

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Whenever a theory appears to you as the only possible one, take this as a sign that you have neither understood the theory nor the problem which it was intended to solve.

Popper (1972)
What generates the gravitational fields in clusters?

And can we pin it down?

- **Prologue:** Is there a standard gravity?
- The “subtleties” of cluster counting and their mass function
- Snapshots of cluster formation: accretion rates and patchy distributions
- **Epilogue:** Do modified gravity models lag behind observations?
Theories of gravity

Metric theories
GR and virtually all popular modified theories – e.g., $f(R)$, scalar tensor, etc.

Non-Metric theories
Do not meet EEP
(with the exception of the Cartan theory)

**Einstein Equivalence Principle (EEP)**

\[
\text{EEP} = \text{Weak Equivalence Principle} +
\]

*The outcome of any local non-gravitational experiment in a freely falling laboratory is independent of the velocity of the laboratory and its location in spacetime*

(e.g., Will, C. 1989; Ni, W.-T., 2016)
They can be recast as GR + Additional fields that couple to matter
(e.g., Magnano 1995; Calmet and Kuntz 2017)

In general, with a Legendre transformation we can generally move from Jordan frame \( \mathcal{L} = f(R, \phi) \) to Einstein Frame \( \mathcal{L} = R + f(\phi) \)
(e.g., Magnano 1995)

Additional fields
scalar, tensor, and/or spinor fields

DM
CDM, WDM, SfDM, ...

Additional fields or DM?
The observed phenomenology will choose the proper combination of DM/Additional fields

Model degeneracy:
Would different combinations of fields/DM be distinguishable when they fully reproduce the observed phenomenology?
(Calmet and Kuntz 2017)
Metric theories

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ACDM is a modified theory of gravity...

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Would different combinations of fields/DM be distinguishable
when they fully reproduce the observed phenomenology?
(Calmet and Kuntz 2017)
The case of GW170817

The Shapiro time delay:

*a massive object causes a spacetime dilation and increases the path length of a passing-by signal*

Facing observations

Theories where EM waves and GW follow different geodesics

(Boran et al. 2018)

[e.g., TeVeS (Bekenstein 2004)
STVG or MOG (Moffat 2006)]

Theories where GW speed $\sim c$

disfavored compared to $\Lambda$CDM

(Lombriser and Lima 2017)

[e.g. Horndeski’s theory (1974)
(the most general 4-dim. scalar-tensor
with 2nd order field equations)

and Beyond Horndeski (Gleyzes et al. 2015)]

The excluded region in the $\alpha_B$-$\alpha_H$ plane:

GW speed = c implies $\alpha_T=0$

Sakstein and Jain (2017)
Additional field vs. exotic DM: the case of MOND and Superfluid Dark Matter (SfDM)

Berezhiani and Khoury (2015)

Berezhiani et al. (2017)

Hodson et al. (2017)
What if gravity is not a fundamental force – the case of Emergent Gravity

(somewhat controversial on formal grounds - e.g., quantum coherence or energy-momentum conservation)

However...

depends on a number of assumptions

dynamically symmetric mass distribution

sufficiently isolated

The validity of (7.40) depends on a number of assumptions and holds only when certain conditions are being satisfied. These conditions include that one is dealing with a centralized, spherically symmetric mass distribution, which has been in dynamical equilibrium during its evolution. Dynamical situations as those that occur in the Bullet cluster are not described by these same equations. The system should also be sufficiently isolated so that it does not experience significant effects of nearby mass distributions. Finally, in the previous subsection we actually derived an inequality, which means that to get to equation (7.40) we have made an assumption about the largest principle strain $\varepsilon$. While this assumption is presumably true in quite general circumstances, in particular sufficiently near the main mass distribution where the apparent dark matter first becomes noticeable. But as one gets further out, or when other mass distributions come into play, we are left only with an inequality.
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As far as the laws of mathematics refer to reality,
they are not certain,

and as far as they are certain,
they do not refer to reality.

Einstein (1921)
Potential observables

Well defined

- Mass function
- Mass function evolution
- 2-point correlation function

More complicated

- Connection of clusters to the surrounding structure
- Accretion rate of galaxies/”mass”
- Patchiness of galaxies/”mass” distribution in the cluster AND in its outer regions
Mass functions of galaxy clusters: a theoretical example

DM halos

DM subhalos

Baldi and Villaescusa-Navarro (2018)
The case of MOND with sterile neutrinos

Angus et al. (2013)

Angus and Diaferio (2011)

Reiprich and Böhringer (2002)
Rines et al. (2008)

Angus et al. (2013)
Estimate of the mass function requires:

- Cluster identification
- Estimate of the cluster mass

It might not be that simple...
The identification of clusters:
dense spectroscopic redshift surveys
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Unfortunately, redshift surveys are expensive...

The case of redMaPPer clusters in HectoMAP

- HectoMAP galaxies
  - HectoMAP X-ray clusters
  - HectoMAP-red clusters

red-sequence Matched-filter Probabilistic Percolation

\[
g(r) = \frac{g(r)_{\text{true}}}{g(r)_{\text{true}} + \sigma^2}
\]

Rykoff et al. (2014)

~20% of the clusters are missed by the redMaPPer catalog
~23% of the spectroscopic BCG are not the redMaPPer central galaxy

Sohn et al. (2018)
Estimating the mass also is expensive...
The case of scaling relations and the issue of calibration

Nevertheless, even cluster member ID is not trivial...
Hierarchical clustering models: anisotropic and episodic accretion

$\tau_{\text{CDM}}$

$z=0.13-0.27$

$z=0.27-0.43$

$z=0.43-0.62$

Colberg et al. (1999)
The Caustic method: Cluster membership

Example: CL0024

How can we identify the cluster members for the calibration?

Within $R_{200}$
- Completeness = 96%
- Interlopers = 2%

Within $3 \times R_{200}$
- Completeness = 95%
- Interlopers = 8%

Caustic amplitude = Escape velocity

Serra and Diaferio (2013)

Diaferio and Geller (1997)
The case of dynamical mass vs. SZ mass

Motl et al. (2005)

Andreon et al. (2017)
The Caustic method: Mass profile

Example: CL0024

Sky

Redshift diagram

Mass profile

Caustics

Caustic amplitude = Escape velocity

Diaferio and Geller (1997)

\[ GM(< r) = \frac{1}{2} \int_0^r A^2(x) \, dx \]
The Caustic method:
Gravitational potential and mass profiles

Caustic vs. lensing

Caustic vs. X-ray

Geller et al. (2013)

Maughan et al. (2016)
HeCS: The ultimate cluster mass

Infalling matter

present time $z=0$

future $z=-0.99$

in $\Lambda$CDM $M_{\text{fin}} = 1.9 \, M_{200}$

From HeCS $M_{\text{ta}} = 1.99 \pm 0.11 \, M_{200}$

Busha et al. (2005)

Radial distance

Busha et al. (2005)

Rines et al. (2013)
The Caustic method: Measure of the accretion rate

[Graph showing accretion rate profiles and simulations]

De Boni et al. (2016)
Accreting substructures and surrounding groups

Satellite Identification:
- 2D overdensity
- 2D FoF

Fraction of mass in substructures

Accretion time
Smith and Taylor (2008)

Rines et al. (2001)

Lemze et al. (2013)

satellite mass/cluster mass
The Caustic method:
Identifying substructures and surrounding groups

Within $R=6 \, h^{-1} \text{Mpc}$ recovers
60% of the surrounding groups
80% of the cluster substructures

Yu et al. (2018)
Accreting substructures and surrounding groups with optical and X-ray spectroscopy: the case of A85

Yu et al. (2016)
Accreting substructures and surrounding groups with optical, X-ray spectroscopy and lensing: the case of A2142

Liu et al. (2018)
One fact:

- Observations are more detailed than available theories

One piece of advice:

- Do not compare “toy” models with observations

Two questions:

- **What smoking guns** are there that can be realistically compared with observations?
  (e.g. GW speed vs. $c$ worked, but for the formation of structure, it might not be that simple)

- **What tools** do we have that return measures that are (almost) independent of the system complexity?
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We need more data...
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We need more data... We need more accurate modelling...
An example of a theory lagging behind:
The case of gravitational lensing in Conformal Gravity

\[ S_W = -\alpha_g \int d^4x \left(-g\right)^{1/2} C_{\lambda\mu\nu k} C^{\lambda\mu\nu k} \quad g_{\mu\nu}(x) \rightarrow \Phi(x) g_{\mu\nu}(x) \]

Schwarzschild-like
\[ ds^2 = \Phi(r) \left[-A(r) dt^2 + \frac{1}{A(r)} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\phi^2)\right] \]

with point source
\[ A(r) = 1 - \frac{\beta(2 - 3\beta\gamma)}{r} - 3\beta\gamma + \gamma r - kr^2 \]

without point source
\[ A_g(r) = 1 - \frac{\beta(2 - 3\bar{\beta}\bar{\gamma})}{r} - 3\bar{\beta}\bar{\gamma} + \bar{\gamma} r - k\bar{r}^2 \]

\( \gamma > 0 \)
- e.g., Pireaux (2004)
- Cattani et al. (2013)

\( \gamma < 0 \)
- e.g., Edery and Paranjabe (1998)
- Pireaux (2004)

\[ Q = -6\beta \left(4k + \gamma^2 - 6k\beta\gamma\right) + \frac{18\beta^2 \gamma^2}{r} + \frac{18\beta^2 \gamma(2 - 3\beta\gamma)}{r^2} + \frac{6\beta^2(2 - 3\beta\gamma)^2}{r^3} \]

\[ \delta Q = 24k \left(\bar{\beta} - \beta\right) \quad \sim \text{source mass?} \]

Campigotto et al. (2018)
Sometimes, I fear that those who discover nothing are those who only talk when they are sure to be right.

Eco (1985)