Galaxies as probes of fundamental physics

Focus has been on large scales and ‘summary’ statistics → power spectra, correlation functions, etc.

Planck

SDSS

Hubble Deep Field
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In large scale structure, galaxies are mere building blocks → "dots".

Different perspective: use individual galaxies as laboratories and look at how their structure depends on environment

Search for fifth forces in galaxies
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See Baker et al, 1908.03480
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Meerkat (Radio) view of centre of our galaxy
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Gravitational screening:

\[ \Phi_s = \frac{\alpha M}{r} e^{-\frac{r}{M}} \]

Depend on environment/mass...

Look at galaxies and constituents in different environments.

E.g., in voids versus clusters

- at stars versus gas and dark matter
- at black holes versus stars.
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Environment: Build a "gravitational map" of the Universe

- Galaxy catalogue

- Fill in long wavelength modes with BORG (Sims)

- Use abundance matching to associate holes to galaxies (short wavelengths)

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2D slices of the Universe

\[ \Phi/c^2 \]

(gravitational potential)

\[ a \]

(\( a = -\nabla \Phi \))

\[ K \]

(curvature \( \sim \Delta^2 \Phi \))
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What do we look for?
Galactic offsets

\[ \text{Gas Halo} \]
\[ Q_{\text{screemed}} = Q_{\text{ext}} + \frac{\Delta G}{G} M_* \]
\[ Q_{\text{ascreened}} = Q_{\text{ext}} + G \frac{M(S_\chi)}{\Gamma_x^2} \]

So

\[ \frac{M(S_x)}{\Gamma_x^2} = \frac{Q_5 \Delta G}{G^2} \]

if \( |\Phi| < |\Phi_c| \)

\[ \Gamma_x = 0 \]

if \( |\Phi| > |\Phi_c| \)

(screened)

(unscreened)
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Offsets

Screening Scale

Desmond & Ferreira, 2010.05877
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What do we look for? Warps

\[ z(x) = -\alpha_{s_{\frac{1}{2}}} \frac{\Delta G}{G_N^2} \frac{1}{M_{\text{halo}}(\leq x)} \frac{|x|^3}{\nabla x} \]

\[ \omega_1 = \frac{1}{\nabla_x^3} \int_{-\nabla x}^{\nabla x} |x| z(x) \, dx \]
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Desmond & Ferren 2010.05817
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What does it mean?

Example: \( f(R) \) theory is screened.

\[
f_{R_0} = \left. \partial R f \right|_{a=a_0}
\]

Galaxy constraints: \( f_{R_0} \leq 10^{-8} \)

i.e. all objects are screened and so no astrophysical significance!
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Vainshtein Screening test.

Galilean models: invariant \( \phi \rightarrow \phi + d_\mu x^\mu + c \)

Have screening but Black holes are unscreened

So

Star Motion \( \neq \) Black Hole Motion

Offset!
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Vanshstein Screening test.

Fifth force has magnitude

\[ a_s = \frac{\Delta G}{G_N} \frac{G_N Q_M}{r^2} (\frac{\sigma}{\sigma_v})^{3/2} \]

Scalar charge

\[ Q = \int \rho \, d^3x \]

Density

Vanshstein Radius
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Van Sloan

Screening test

Black hole offsets → Data

Today 22/1
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Vanuhtain Screening test

Model for offset distribution ($\Delta \theta$)

\[
\frac{f}{\sqrt{2\pi} \sigma_{\text{obs}}} \exp \left[ -\frac{\Delta \theta^2}{2 \sigma_{\text{obs}}^2} \right] + \frac{(1-f)}{2\nu} \exp \left( -\frac{|\Delta \theta|}{\nu} \right)
\]

Gaussian

Laplace
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\[ \frac{\Delta G}{G} \sim 0.1 \]

\[ \text{log}_{10}(r_v / \text{Mpc}) \]

\[ 1\sigma \text{ constraint on } \Delta G/G_N \]
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Summary
- Galaxies have tremendous potential for constraining fundamental physics
- Very, very messy $\rightarrow$ challenging
- "Messy" Bayesian Forward Modelling (The Future)
- Results $\rightarrow$ Constraint on $f(R)$ is strong for $f_\gamma \sim 10^{-9}$ (the whole Universe is screwed!)
- Constraint on Galilean $\frac{\Delta G}{G} \sim 0.1$