Novel Tests of Gravity Using Astrophysics

Jeremy Sakstein
University of Pennsylvania

Department of Physics & Astronomy
University of Mississippi
1st November 2016
Some Thoughts on Gravitational Physics

Jeremy Sakstein
University of Pennsylvania

Department of Physics & Astronomy
University of Mississippi

1st November 2016
Outline

• What is gravity? Why should we test it?
• Dark energy and cosmic acceleration
• Modern gravity theories: screening mechanisms
• Stellar structure in MG
• Dwarf stars
• Neutron stars
Why test gravity?

- We’re scientists — that’s what we do!

- Unexplained phenomena — dark energy, dark matter

- Quantum gravity — big problem for gravity

- We can — next decade will be data driven

- Need other theories to give differing predictions
What is gravity?

Newton:

Attractive force between massive bodies

\[ F = \frac{G M m}{r^2} \]
What is gravity?

Einstein: Curvature of space-time

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

Spacetime tells matter how to move; matter tells spacetime how to curve. — John Wheeler
What do we know about gravity?

Newtonian = non-relativistic: $\frac{v^2}{c^2} \ll 1$

Reason: most things are Newtonian

$10^{-9}$  $10^{-6}$  $10^{-6}$
Even binary pulsars are non-relativistic

\[ v^2 / c^2 = 10^{-2}! \]
When is general relativity important?

Strong gravitational fields:

- Black holes
- Neutron stars
When is general relativity important?

Large distances:

Cosmology
We will test both of these in the next decade and beyond.

Cosmology:

- DES (spectroscopic)
- EUCLID (lensing)
- SKA (21 cm)
We will test both of these in the next decade and beyond

**Strong fields:**
Gravitational waves from

- Black hole mergers
- Neutron star mergers

**LIGO**
Gravitational waves were discovered last year!

In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves.

Can we test gravity with this? **See later!**
eLISA: Planned
Why do I study modified gravity?

Dark energy: (Dark = we have no idea)

- The expansion of the Universe is accelerating
- Gravity is attractive so it should be slowing down
- We call the accelerating mechanism dark energy
We don’t just need a little, we need a lot
What is dark energy?

“If your life doesn’t make sense, buy some Dark Energy and balance your equations. We won’t promise that the rest of the world will make any more sense, but at least you’ll have beer.”
Simplest explanation: cosmological constant

\[ F = -\frac{GM}{r^2} + \frac{\Lambda}{3} r^2 \]

General relativity:

\[ G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

Attractive
repulsive
wins at large distances

Gives exponential acceleration
The cosmological constant is unnatural

Quantum effects change the value:

\[ \Lambda = \Lambda_{\text{bare}} + \Lambda_{\text{quantum}} \]

Set by hand

Have to tune to 120 decimal places:

\[ \Lambda_{\text{bare}} = -\Lambda_{\text{quantum}} + 10^{-120} \]

Theorists don’t like this
Alternative is to add new stuff

\[ H_{\mu\nu} + G_{\mu\nu} = \frac{8\pi G}{c^4} \left( T_{\mu\nu}^{\text{matter}} + T_{\mu\nu}^{\text{dark energy}} \right) \]

New gravity theory
New matter

Look for modified gravity theories that can accelerate without a cosmological constant

*Still need to explain why \( \Lambda = 0 \)
What does changing gravity do?

Screws up the solar system:

- Light bending
- Precession of Mercury
What do local tests mean?

GR:

\[ \nabla^2 \Phi_N = 4\pi G \rho \quad \text{Field equation} \]

\[ F_N = -\nabla \Phi_N \quad \text{Force law} \]
What do local tests mean?

New force field $\phi$:

**GR:** $\nabla^2 \Phi_N = 4\pi G \rho \quad F_N = -\nabla \Phi_N$

**MG:** $\nabla^2 \phi = 8\pi \alpha G \rho \quad F_5 = -\alpha \nabla \phi$

$\phi = 2\alpha \Phi_N \Rightarrow \frac{F_5}{F_N} = 2\alpha^2$

Light Bending: $\alpha < 10^{-5} \Rightarrow$ Theory is GR on all scales
Screening mechanisms to the rescue

Non-linear effects decouple cosmological scales from the solar system

solar system  astrophysics  cosmology

screened  partially screened  unscreened
The problem with MG

GR is enough:

\[ \nabla^2 \phi = 8\pi G \alpha \rho \]

- Change kinetic term
  - Vainshtein
- Kill of source
  - Chameleons
The Vainshtein mechanism

Change kinetic terms — e.g. cubic galileon:

\[ \nabla^2 \phi + \frac{1}{\Lambda^3 r^2} \frac{d}{dr} \left( r \phi' \right)^2 = 8\alpha \pi G \rho \]

Poisson | Non-Poisson | Poisson
Vainshtein mechanism

We can integrate this once:

\[ x + \left( \frac{r_V}{r} \right)^3 x^2 = 2\alpha^2 \]

\[ x = \frac{F_5}{F_N} \]

\[ r \ll r_V \Rightarrow \frac{F_5}{F_N} = 2\alpha^2 \left( \frac{r}{r_V} \right)^{\frac{3}{2}} \ll 1 \]

\[ r \gg r_V \Rightarrow \frac{F_5}{F_N} = 2\alpha^2 \sim O(1) \]

\[ r_V \text{ - Vainshtein radius} \]
Vainshtein screening

\[
\frac{F_5}{F_N} = 2\alpha^2
\]

Screened

Unscreened

\( r \)

\( r_V \)
Vainshtein screening

\[ r_V^\odot \geq 10^2 \text{ pc} \]

Solar system is well within the Vainshtein radius:

- Classical tests (light bending etc.) don’t apply
- Need new and novel ways of testing the theory
- Screening partially broken in some theories
Screening breaks down in some theories.
Vainshtein breaking

\[ \frac{d\Phi}{dr} = \frac{GM(r)}{r} \]

Vainshtein:

\[ \frac{d\Phi}{dr} = \frac{GM}{r^2} + \frac{\Upsilon G}{4} \frac{d^2M(r)}{dr^2} \]

\(\Upsilon\) controls cosmology of the theory
Rule of thumb - works well for stars (not true in strong field regime)

\[ \mathcal{Y} < 0 \quad \text{— gravity stronger than GR} \]

\[ \mathcal{Y} > 0 \quad \text{— gravity weaker than GR!} \]
Stellar structure tests of gravity

Main idea:

- Stars are a balance of gravity and pressure
- Burn fuel to stave off gravitational collapse
- Changing gravity changes the structure
- Changes temperature, luminosity, mass, radius, etc.
Stellar structure

Inward gravity = outward pressure:

GR (non-relativistic):

$$\frac{dP}{dr} = - \frac{GM(r)\rho(r)}{r^2}$$

Hydrodynamics

Vainshtein:

$$\frac{dP}{dr} = - \frac{GM(r)\rho(r)}{r^2} - \frac{\Upsilon G \rho(r)}{4} \frac{d^2 M(r)}{dr^2}$$

Newtonian gravity
Vainshtein stars

Gravity weaker

Slower burning rate

Dimmer and cooler stars that live longer
Vainshtein stars

Gravity stronger

Faster burning rate

Hotter and brighter stars that live longer
Tools of the trade: polytropic stars

\[ P = K \rho \frac{n+1}{n} \]

- \( n = 3 \) - main sequence, white dwarfs
- \( n = 1.5 \) - convective stars, high mass brown dwarfs
- \( n = 1 \) - low mass brown dwarfs

Work well when physics is simple
Dwarf stars - a new test of gravity

Perfect tests:

• Chemically and structurally homogeneous
• Equation of state is well-known
• Polytropic models are good approximations
• Lots of interest in low mass objects
Low mass M-R

Brown dwarf
\( n = 1 \)

Red dwarf
\( n = 1.5 \)
Brown dwarfs — the radius plateau

Coulomb pressure $\Rightarrow n = 1$  \hspace{2cm} (\(P = K \rho^2\))

Constant/non-gravitational physics

Theory of gravity

$$R = \gamma \left(\frac{K}{G}\right)^{\frac{1}{2}}$$
Brown dwarfs — the radius plateau

\[ R = 0.1 \frac{\gamma(\gamma_1)}{\gamma(\gamma_1 = 0)} R_\odot \]
Red dwarfs — MMHB

Hydrogen burning when core is hot and dense enough

Gravity weaker

Core cooler and less dense at fixed mass

Higher MMHB
Red dwarfs — MMHB

Stable burning when production balances loss

\[ L_{\text{HB}} = L_{\text{eff}} : \]

\[ M_{\text{MMHB}} = 0.08 \frac{\delta (Y_1)}{\delta (Y_1 = 0)} M_{\odot} \]

Proton burning

\[ n = 1.5 + \text{theory of gravity} \]
New constraint

Lowest mass star is Gl 886 C

\[ M = 0.0930 \pm 0.0008 M_\odot \]

\[ \Rightarrow \ U < 0.027 \]
Strong field tests of gravity

Q: Can GWs from BHs test GR?
No-hair theorem

Black holes described by:

• Mass M
• Spin a
• Charge Q

Lots of theories look like GR!
Neutron stars

Life Cycle of a Star

\[ e^- + p \rightarrow n \]
Neutron stars

Mass — Sun

Radius — few km

Mass, spin, charge, quadrupole moment,…, hair!

Relativistic: \( \frac{v}{c} \sim 1 \)
Tolman-Oppenheimer-Volkov equation

\[ \frac{dP}{dr} = -\frac{GM\rho}{r^2} \left[ 1 + \frac{P}{\rho c^2} \right] \left[ 1 + \frac{4\pi r^3}{M} \frac{P}{\rho c^2} \right] \left[ 1 - \frac{2GM}{rc^2} \right] \]

Relativistic hydrodynamics

General relativity

Vainshtein: + . . .
Can we test Vainshtein with this?

Larger maximum mass
Devil is in the detail

Most massive NS observed

Larger radii

Babichev, ..., JS ‘16
Equation of state is unknown!
Need EOS-independent tests

Breu, Rezzolla '16

Moment of inertia
We can do this for Vainshtein
Modifications are larger than the scatter.
Summary

- Many unsolved problems with gravity
- Next decade will be data-driven
- Need alternative predictions from alternative theories
- Screening evades solar system tests
- Need new and novel ways to test gravity
- Can test Vainshtein with dwarf and neutron stars
Thank you
(and to my collaborators)

- Kazuya Koyama — ICG, Portsmouth (UK)
- David Langlois — APC, Paris (FR)
- Eugeny Babichev — Orsay, Paris (FR)
- Ryo Saito — Yukawa Institute, Kyoto (JP)