# Stellar Structure and Galactic probes of Modified Gravity

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Itzykson 17 Heart of Darkness

# "... and a lot of Astrophysics is messy." Mark Wyman

- Evading Solar System Bounds : Screening Mechanisms
- "Real" Astrophysical Probes : spectra/structure of galaxies, stars, HI regions.
- Stellar structure and modified Gravity
- Simulating stellar evolution in the presence of modified gravity

### New Exotic Matter or New Gravity?

General Relativity is very strongly constrained on solar system scales.

Large Scales (GR Broken?)

CMB, Large Scale Structure, Supernova Type Ia

 $v_s$ 

Solar System Scales (GR OK)

Mercury Precession, Torsion Tests, lensing by sun, Spacecraft trajectories lunar ranging etc.

Our Ingredients : gravity + 1 scalar d.o.f.

### "Screening" Mechanisms Loophole : change gravity at large scales, but keep gravity "the same" at small scales

*Screening*: suppress the effects of the extra scalar degree of freedom 'locally', while allowing it to change GR globally.





Hubble expansion (not GR)

### "Screening" Mechanisms

Our Ingredients : gravity + 1 scalar d.o.f.

### Three known mechanisms :

Khoury + Weltman (2004)

Pietroni (2004), Hinterbichler + Khoury (2010)

Relies on changing gravity as a function of *local ambient potential* e.g. *<sup>f</sup>*(*R*) Brax et al (2010)

mmetrons

Vainshstein Mechanism Vainshstein (1972)

Chameleons

operate via non-trivial scalar self-couplings (e.g. massive gravity)

Any viable theory of modified gravity must have some form of screening mechanism

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Screened and Unscreened Objects  $\mathsf{F}$  such states  $\mathsf{F}$ How is this achieved?  $\Box \phi \propto \mathsf{v} \cup \rho(\varphi) \mathsf{v} \varphi$ Homogenous ambient  $\rho_b$  = no gradients = no 5th force If the perturbing body is large the perturbing body inside the field inside the field inside the field inside the objective the 5th force is proportional to gradient of  $\phi$  $\mathbf{F}_{\phi} \propto \sqrt{G} \beta(\phi) \vec{\nabla} \phi \qquad \qquad \beta(\phi) = \frac{d \ln A(\phi)}{d \phi}$  $G\beta(\phi)\nabla$  $\bar{\nabla}$  $\phi$ 

> $D$ Perturbation around ambient generates *gradients*

The Big Perturbation from ambient density is said to be seen the body in the body is said to be seen the body in the body is said to be seen the  $\sim$ density "Thin Shell Screening"

**If Small Perturbation from ambient** density body. The field will vary through the entire body. "Fully Unscreened"





perturbation.

### **Partially Screened Objects** exterior of the star star. Partially Screened Objects



### Parameterizing Modified Gravity

Two Parameters : χ*<sup>b</sup> ,* α*<sup>b</sup>*

Is it unscreened? If it is, how strong is the fifth force?



Halo Cluster, Schmidt (2009)

### Who screens What?



For MG to act, should be not self-screened or screened by other objects.

motion: for the same reasons articulated above, weak

and <del>Denver represent the gravitation</del> and potential potentials of an object the gravitation of an object to an

## Some Assumptions/Fine Print

- Quasi-static Limit : *d*<sup>φ</sup> *dt*  $\approx 0$
- Scalar field contributes little energy density
- Conformal/Coupling factor  $A^2(\phi) \approx 1$

# A ton of Astrophysical Data!!

- Large Galaxy Surveys (SDSS/LSST) : galaxy *spectra*, metallicities, morphology
- Internal structure of galaxies : orbits of HI gas clouds, globular clusters, satellites
- Stellar census of globular clusters, nearby dwarfs (ANGST), Cepheids/RR Lyrae, red giants stars  $\mathbf{y}$ data ntc  $\overline{\mathbf{r}}$



SDSS Spectroscopic Survey HST Cepheids Survey



**The ANGST Galaxy Sample**



### Messy, but also a lot of information

- Complex interaction between different processes at many different energy scales
- Some *standard* physical processes not well understood (e.g. supernova feedback, effects of galactic B field, galaxy-galaxy interaction etc.)
- MG => O(1) effects! Problem are : *degeneracies*  between modified gravity signatures and "regular observables".
- We want to figure out what are the signatures and how to break the degeneracies.

# Next : Modified Gravity Changes Stellar Behavior

Chang + Hui (2010), Davis, Lim, Sakstein, Shaw (2011)

- Modified Gravity makes gravity stronger
- To support itself, stars need higher pressures
- Hence it needs to be hotter and burns fuel at a higher rate
- Stars are then more luminous, but live shorter lives!

### Rest of the Talk will be about Stars!

### The Life of a Star

### Astronomy-in-a-minute



### Sun lifetime ~ 10 Gyr

Roughly : Burn H to make He to make C to make N and O as Temperature increase

### The Life of a Star



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# The Life of a Star

- Hertzrung-Russell Diagram (HR diagram)
- Evolutionary tracks (isochrones) depends on mass, composition and its environment. *And gravitational model!*
- Assumption (dangerous) : ambient density remains the same.



## Stellar Structure Equations



Radiative Transfer Energy Generation

## Stellar Structure Equations





$$
P=(\rho,T)
$$

Hydrostatic Equilibrium Mass Conservation Equation of State

$$
\frac{dT}{dr} = -\frac{3}{4ac} \frac{\kappa \rho}{T^3} \frac{L(r)}{4\pi r^2} , \frac{dL(r)}{dr} = 4\pi r^2 \epsilon(r)
$$

Radiative Transfer Energy Generation

### The only component of the system of equations that needs changing is the Hydrostatics Equilibrium Equation

# Lonely Star Model

Am I self-screened?

# Solving the Stellar Structure Equations

- Dimension Analysis
- Analytic solution : Eddington Standard model
- Numerical solution (with MESA)

### 1. Dimension Analysis

See also Fred Adams (2008)

Assuming completely *unscreened* stars :  $G_{eff} \rightarrow (1 + \alpha_b)G$  $P_{gas} \propto \rho T$  ,  $P_{rad} \propto T^4$  ,  $\rho \sim M R^{-3}$ 

Low Mass / Gas Supported Stars

 $L \propto G_{eff}^4 M^3$ 

High Mass / Radiation Supported Stars  $L \propto G_{eff} M$ 

Example :  $f(R)$  theories,  $\alpha_b = 1/3$ 





 $P=(\rho,T)$ 

Hydrostatic Equilibrium Mass Conservation Equation of State

$$
\frac{dT}{dr} = -\frac{3}{4ac} \frac{\kappa \rho}{T^3} \frac{L(r)}{4\pi r^2} \ , \ \frac{dL(r)}{dr} = 4\pi r^2 \epsilon(r)
$$

Radiative Transfer Energy Generation

$$
\frac{dP}{dr} = -F_{\text{total}}(r)\rho ,
$$

$$
\frac{d\pi r}{dr} = 4\pi r^2 \rho
$$

*dm*

$$
P=(\rho,T)
$$

Hydrostatic Equilibrium Mass Conservation

Equation of State

Ultimately, we will consider the general case where 0 *<*

*•* the fifth force is highly suppressed *r*<sup>s</sup> ≈ *R* or gravity

*•* the fifth force is completely unsuppressed: *r*<sup>s</sup> = 0,

αeff(*r*) *<* α0, however let us first build up intuition by

considering simple scaling relations [6] in the two limits

unmodified α<sup>0</sup> = 0: *G*eff ≈ *G* = const and

*G*eff(*r*) = (1 + α0)*G* = const.

$$
\frac{dT}{dr} = -\frac{3}{4ac} \frac{\kappa \rho}{T^3} \frac{L(r)}{4\pi r^2} \ , \ \frac{dL(r)}{dr} = 4\pi r^2 \epsilon(r)
$$

librium the pressure gradient must balance the other ra-**Radiative Transfer** 

d*P*(*r*)

= −

**! de la posta** 

**Energy Generation** 

ρ(*r*)*.* (30)

$$
F(r) = f_{\text{grav}} + f_{\phi} = \frac{\mathrm{d}\Phi_{\text{N}}}{\mathrm{d}r} + \frac{\beta(\phi)}{M_{\text{pl}}} \frac{\mathrm{d}\phi}{\mathrm{d}r}.
$$
\ngravity 5th force

 $+$   $\frac{1}{2}$ 

ng

### 2. Analytic solution : Eddington Standard Model equation, the presence of modified gravity only changes that particular particular equation and  $n=2$ . And  $n=12$ Let's focus on the HSE equation. For hydrostatic equilibrium the pressure gradient must balance the other radial forces, *F*, i.e. gravitational and  $\overline{P}$ Ultimately, we will consider the general case where 0 *<*  $$  $\Lambda$  is  $\Lambda$  for  $\Lambda$  for  $\Lambda$  the pressure support that the pressure support that the pressure support of  $\Lambda$ must actes and the gravitation of the gravitation of the gravitation of the gravitation of the gravitation force carried by the scalar. To find the gravitational **Foldington Standard** continuity Equation to obtain the solution to obtain the solution to the gravi-Suppose that *<sup>P</sup>* <sup>∝</sup> <sup>ρ</sup>*<sup>p</sup>T<sup>q</sup>* where the constant of proportionality depends only on non-gravitational physics. Under *G* → *G*(1 + α"), we assume that the solutions to  $\Lambda$ odel  $P$  *<u>P(<i>r*)  $P$  *c*<sub>*r*</sub>  $P$  *c*<sub>*r*</sub>  $P$  *c*<sub>*r*</sub></u> must act against both the gravitational force and the  $\alpha$  can be a scalar contraction by the scalar force, we integrate the Poisson Equation E  $\Gamma$  define the  $\Gamma$ tational potential as a function of mass *m*(*r*),  $U$ the stellar structure equations simply sequence as *c<sup>P</sup> P*(*r*), ρ(*r*) → *c*ρρ(*r*), *r* → *crr*, *l*(*r*) → *cLl*(*r*) and ard Model α"; we take κop(*r*) ≈ κes = const. We consider a star of Motivation Screening Mechanisms Stellar Structure Galaxies Summary and Outlook Partially Screened Stars (1) In practice, stars will be partially screened i.e. there is a *screening radius r<sup>s</sup>* that separates the screened interior from the unscreened

$$
F(r) = f_{\text{grav}} + f_{\phi} = \frac{d\Phi_{\text{N}}}{dr} + \frac{\beta(\phi)}{M_{\text{pl}}} \frac{d\phi}{dr}.
$$
  
gravity  $f_{\text{th}} \text{ force}$   
using  $\vec{\nabla}^2 \phi \approx \begin{cases} \beta_0 \rho(r)/M_{\text{pl}} & r_{\text{s}} < r \ll m_0^{-1} \\ 0 & r < r_{\text{s}} \end{cases}$   
 $\frac{\beta(\phi)}{M_{\text{pl}}} \frac{d\phi}{dr} \approx \alpha_0 \left[ \frac{G(m(r) - m(r_{\text{s}}))}{r^2} \right] H(r - r_{\text{s}}).$ 

for the scalar force carried by the scalar carried by the gravitation of the gravitation of the gravitation of

To finally close the system of equations, we find *r*<sup>s</sup> from

to iterate to iterate to find the complete solution. We will do this complete sol

0



B. Scaling Relations

*<sup>T</sup>* . The scaling of the

*.* (38)

portionality depends only on non-gravitational physics.

portionality depends only on non-gravitational physics.

*c*4

3*q*

Using the equation of state and hydrostatic equilibrium

– radiation *P*rad or gas *P*gas. Stars of around solar mass or

less are domoinated by gas pressure *P*gas = *k*Bρ*T /µm*<sup>H</sup>

T = (1 + and so: 0)

*q*

Under *G* → *G*(1 + α"), we assume that the solutions to

the stellar structure equations simply scale as *P*(*r*) →

*c<sup>P</sup> P*(*r*), ρ(*r*) → *c*ρρ(*r*), *r* → *crr*, *l*(*r*) → *cLl*(*r*) and

Using the equation of state and hydrostatic equilibrium

hydrostatic equilibrium and radiative transfer experiments of the contract of the contract of the contract of<br>The contract of the contract o

Stars can be supported by two kinds of pressure terms

$$
4\pi G \int_{r_{\rm s}}^{R} r\rho(r) dr = \chi_0 \equiv \frac{\phi_0}{2\beta_0 M_{\rm pl}}.
$$
  
 
$$
G_{eff} \to \alpha_{eff}(r) = \alpha
$$
  
 Implicit equation for

in the next section for a *polytropic* star, but first we note

screening radius

Poisson Eqn. (13) yields an implicit solution for *r*<sup>s</sup>

It is a straightform the production that the pressure supported that the pressure that the pressure supported t

$$
4\pi G \int_{r_{\rm s}} r\rho(r) dr = \chi_0 \equiv \frac{\varphi_0}{2\beta_0 M_{\rm pl}}.
$$
  
\n
$$
G_{eff} \to G(1 + \alpha_{eff}(r))
$$
  
\n
$$
\alpha_{eff}(r) = \alpha_b \left(1 - \frac{m(r_s)}{m(r)}\right) H(r - r_s)
$$
  
\nscreening radius

*q*

*p*−4*/*3 <sup>ρ</sup> *c*

gives *c*

d*r*



*dr*  $=$   $\frac{3}{4a}$ 4*ac T*<sup>3</sup>  $\frac{2(r)}{4\pi r^2}$  ,  $\frac{d\mu(r)}{dr} = 4\pi r^2 \epsilon(r)$ 

Radiative Transfer Energy Generation







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## Semi-Analytic Prescription

Modified Lane-Emden Equations

$$
\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta(\xi)}{d\xi}\right) = -[1+\alpha_b\Theta(\xi-\xi_s)]\theta^3(\xi)
$$

$$
\xi \equiv r (P_c / \pi G \rho_c)^{-1/2}
$$

$$
P = P_c \theta^4(\xi) , \ \rho = \rho_c \theta^3(\xi) , \ T = T_c \theta(\xi)
$$

Upshot : Luminosity as a function of stellar mass  $M$  and  $Xb$ (Totally screened star is an n=3 polytrope.)

$$
L = \frac{4\pi c (1-b(\alpha_{eff}))[1+\alpha_{eff}(R)]GM}{\kappa}
$$

### Zeroth-order effect : Stellar Luminosity  $\mathcal{L}$  $f(R)$  theories,  $\alpha_b = 1/3$



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## Live Fast, Die Young

 $\tau_{MS} = 10 \left( \frac{M}{M} \right)$ *M*<sup>⊙</sup> " ! *<sup>L</sup>*<sup>⊙</sup> *L*(*M*) " Main Sequence Lifetime  $\tau_{MS} = 10 \left( \frac{1}{M} \right) \left( \frac{20}{I(M)} \right)$  Gyr

3 times increase in luminosity = 3 times shorter in life!

Stars make metals : MG galaxies more metal rich?

## What about the Sun?

- The Sun must be screened, or almost screened.  $Self\text{-}screening$  bounds  $\chi_b \sim 10^{-6}$
- Not self-screened, but screened by Milky Way bounds  $\chi_b \sim 10^{-6}$
- But perhaps the Local Group dominates? I.e. the Sun is screened by a much deeper potential well?
- Most conservative constraints  $\chi_b \sim 10^{-4}$  from galaxy cluster statistics. (Schmidt 2009)



# 3. Building Realistic Stars/ Galaxies (Numerical)

- To test all this stuff, we need more precise predictions.
- Construct stars/isochrones using stellar simulator (modified MESA code). (w/ Bill Paxton)
- Construct galaxies with galaxy synthesis code (GALEV).

# Modified MESA code

• MESA is a 1-D stellar evolution code with complete convective, nuclear energy generation, opacity modeling.



Bill Paxton (KITP)

toward surface



Fig. 9.— Schematic of some cell and face variables for MESA star. Calculate  $G_{eff}$  and  $r_s$  using previous step  $\rho(r)$ 

### Evolution of screened and unscreened stars



Black : Unmodified

Red Blue Green : Modified

FIG. 2: The Hertsprung-Russell diagram for stars of one solar mass with initial metallicity *Z* = 0*.*02. The black line shows Compare Eddington Standard model prediction  $\Lambda T$  and  $\Lambda T$  radius and age at the point where the central hydrogen mass fraction  $\Lambda T$  $t_1$  and 10−5 is shown for  $N$  and  $n$ in the Main Sequence  $\Delta T_{eff} \sim \mathcal{O}(100) \text{ K}$ 

we assume that all stars with the all stars with the star

This will form the basis of any observation of any observation of any observation of the basis of any observation of the basis of any observation of the basis of the basi searching for the theories using stellar effects. The stellar effects using stellar effects.

## $\chi_b = 10^{-6}$  ruled out?

- 65% Solar Mass *Main sequence* star unscreened, O(100) Kelvins temperature boost
- Degenerate with metallicities
- Degenerate with stellar lifetime
- Degenerate with stellar mass.
- Lonely star model breaks -- screening from environment?

Zeroth Order prediction : unscreened Galaxies are brighter Total luminosity is the sum of all stars' output  $L_{gal} =$  $\int 100M_{\odot}$  $0.08M_\odot$  $dM$   $f_0(M,\tau_{age})L_{star}(M;\chi_a)\Psi(M)$ 

**Initial Mass Function IMF**  $\Psi(M) = \frac{dN}{dM} \propto M^{-2.35}$ Number of stars *born* in mass range dM (Salpeter IMF)

Fraction of stars that have gone off main sequence

 $f_0(M, \tau_{age}) = \begin{cases} 1 & \tau_{age} < \tau_{MS} \\ \tau_{MS} / \tau & (M) \end{cases}$  $\tau_{MS}/\tau_{age}(M)$   $\tau_{age} > \tau_{MS}(M)$ 

Note  $\tau_{MS} \propto L_{star}^{-1}$  so high mass (more luminous) stars scale out of the integral.

### Luminosity Enhancement (1) Galaxy Luminosity



Most *additional* contribution comes from low mass stars : redder? But they are hotter : bluer?

# Galaxy Clusters and Void Galaxies

- Galaxy Clusters are sitting in deep potential well  $\chi_b \sim 10^{-6}$  : galaxies and stars inside must be screened
- Milky Way Class galaxies  $\chi_b \sim 10^{-6}$  possibly screening out all the stars inside.
- Dwarf Galaxies residing in intercluster voids only feel their own grav potential :  $\chi_b \sim 10^{-8}$

Void Dwarf Galaxies should look very different from Cluster Dwarf Galaxies

### Observational tests?

w/Davis, Sakstein, Banerji

- Void Dwarf galaxies are *more luminous*
- Void Dwarf galaxies are roughly *redder*
- Hertzsprung-Russell diagram different
- Shorter life-cycles : higher metalicities (look older?)
- Look for deviations in populations of dwarfs in SDSS color-color diagrams.

# Dwarf Populations in Voids

### SDSS Local Volume galaxies



## Dwarf Populations in Voids





### Other tests

 $\tau_{free} \propto (G_{eff} \rho)^{-1/2}$ arXiv:1204.6044 Jain,Vikram, Sakstein, • Stellar Pulsations (Cepheids) and distance indicators



· Angular momentum of Galactic Halos : MG halos have higher specific AM. dispersion monitudition state in relation between the two samples.  $\bigcap_{i=1}^n$  is the shaded regions show the shaded regions show the shaded regions show the shaded regions show the upper limits at the upper  $6.7919$  confident level in the two states in the two states for the gravity parameters as discussed in the text. The effects of discreteness are due to the small samples are due  $\alpha$  and  $\alpha$  axis is extended to  $\alpha$  axis is extended to  $\alpha$  $\mathsf{f}(\mathsf{c}\mathsf{A}\mathsf{N})$  model parameter  $\mathsf{f}(\mathsf{c}\mathsf{A})$  model parameter  $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf{f}(\mathsf{c}\mathsf{A})$   $\mathsf$ **u** 

Fig. 3.— The *P* − *L* relation for the galaxies in our sample. In the left panel, we show all the

arXiv:1204.6608 Lee,Zhao,Li,Koyama

We have shown that current data is consistent with GR and is inconsistent with GR and is incomplete with chameleon theories over a parameter range that is more than two orders of magnitude below previous astrophysical tests. Figures 4 and 5 show our upper limits for the two parameters: the coupling α*<sup>c</sup>* and the background field value χ*c*. For chameleon theories with α*<sup>c</sup>* = 1*/*3 (all *f*(*R*) models) the upper limit on <sup>χ</sup>*<sup>c</sup>* is about 5 <sup>×</sup> <sup>10</sup>−<sup>7</sup> at 95% confidence. We show results for values of <sup>α</sup>*<sup>c</sup>* in the range

Fig. 5.— Upper limits on the two parameters of chameleon theories: the coupling parameter α*<sup>c</sup>*

# Understanding degeneracies

- Mass vs Modified Gravity
- Metallicities vs Modified Gravity
- Environmental evolution (void galaxies vs cluster galaxies) vs Modified Gravity
- Galactic Mass vs Modified Gravity
- Many others etc....

## Summary

- MG = O(1) Effects! Stellar structure are modified.
- *Main sequence* stars are affected!
- MG stars are more luminous, more blue, smaller, and live shorter lifetimes.
- Individual stars are hard (no statistics), but galactic effects may be observable.

## Thanks!

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