Title: Testing gravity using astrophysics

Date: Mar 08, 2016 11:00 AM

URL: http://pirsa.org/16030076

Abstract: <p>Alternative theories of gravity are popular alternatives to the LCDM model because they can self-accelerate without a cosmological constant. On smaller scales, consistency with solar system tests of gravity is achieved by utilising screening mechanisms, which act to hide fifth-forces locally. This makes them difficult to distinguish from general relativity. In this talk I will describe recent work using astrophysical objects---stars, galaxies, and clusters---as new and novel probes of alternative gravity theories.</p>

Testing Gravity using Astrophysics

Jeremy Sakstein
Institute of Cosmology and Gravitation, Portsmouth

Perimeter Institute for Theoretical Physics
Ontario, Canada
8th March 2016

Why study alternative gravity theories?

- Dark energy candidates (explain comic acceleration)
- Gravity only tested in solar system and pulsars
- (New class of field theories not previously known)

Dark energy

$$\cdots + G_{\mu\nu} = 8\pi G(T_{\mathrm{m}\ \mu\nu} + T_{\mathrm{DE}\ \mu\nu})$$

Dark energy

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New gravity theory

New matter

Dark energy

$$\cdots + G_{\mu\nu} = 8\pi G(T_{\mathrm{m}\ \mu\nu} + T_{\mathrm{DE}\ \mu\nu})$$

New gravity theory

New matter

- Lots of freedom in general models
- All but the simplest are modified gravity theories

Completeness

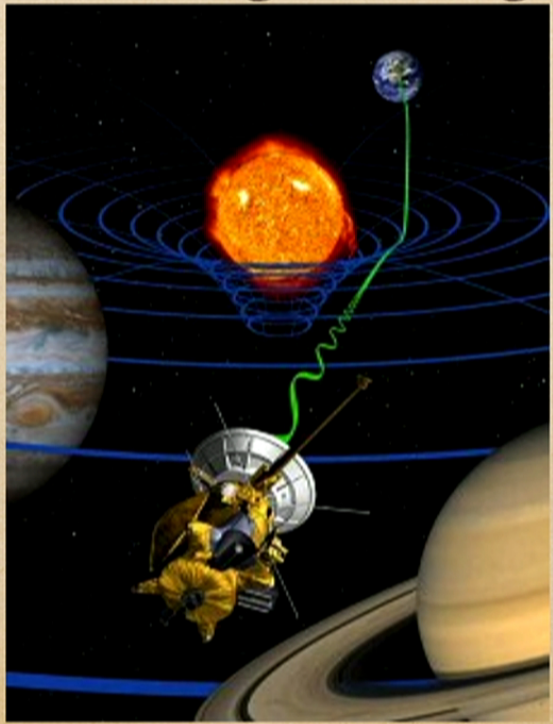
Gravity is only tested to post-Newtonian level:

- Solar system - Newtonian and post-Newtonian
- Binary pulsars - post-Newtonian

Need alternative predictions to test gravity

Local tests

E.g. Cassini measures light bending by the Sun



Local tests

E.g. Cassini measures light bending by the Sun

$$\mathrm{d}s^2 = (-1 + 2\frac{GM}{r})\,\mathrm{d}t^2 + (1 + 2\gamma\frac{GM}{r})\,\mathrm{d}x^2$$

$$|\gamma - 1| < 10^{-5}$$

"How much space is curved by a unit rest mass"

What do local tests mean?

GR:

$$\nabla^2 \Phi_{\rm N} = 4\pi G \rho$$

Field equation

$$F_{\rm N} = -\nabla \Phi_{\rm N}$$

Force law

What do local tests mean?

New scalar graviton:

GR: $\nabla^2 \Phi_{\rm N} = 4\pi G\rho$ $\quad F_{\rm N} = -\nabla\Phi_{\rm N}$

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

$$\phi = 2\alpha\Phi_{\rm N} \Rightarrow \frac{F_5}{F_{\rm N}} = 2\alpha^2$$

Cassini: $\alpha < 10^{-5} \Rightarrow$ 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:

$$\nabla^2 \phi = 8\pi G \alpha \rho$$

What do local tests mean?

New scalar graviton:

GR: $\nabla^2 \Phi_\mathrm{N} = 4\pi G\rho$ $\qquad F_\mathrm{N} = -\nabla\Phi_\mathrm{N}$

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The problem with MG

GR is enough:

$$\nabla^2 \phi = 8\pi G \alpha \rho$$

Change kinetic term

Vainshtein

Kill of source

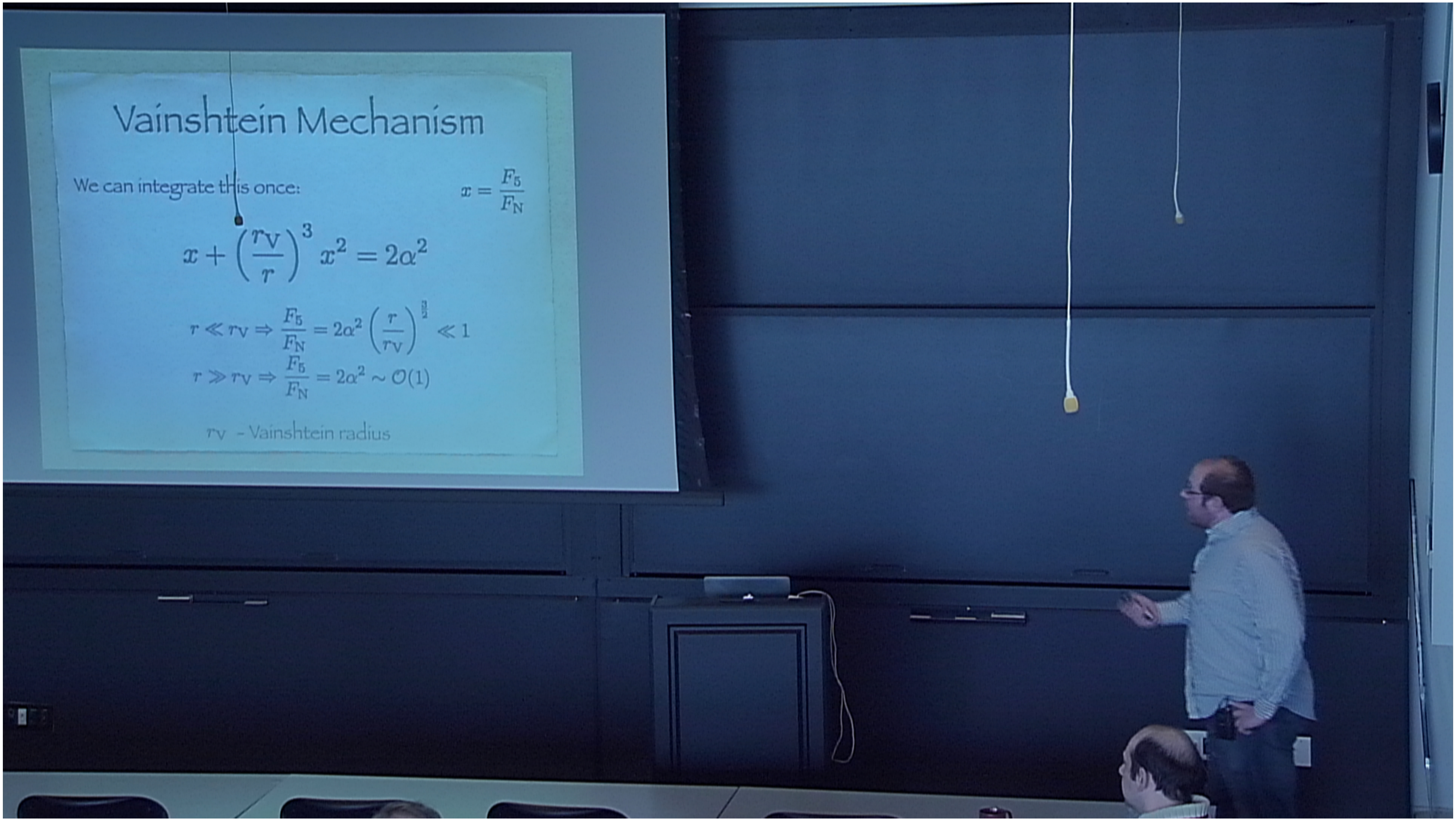
Chameleons

The Vainshtein mechanism

Change kinetic terms — e.g. cubic galileon:

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

Poisson — Non-Poisson — Poisson


Vainshtein Mechanism
We can integrate this once:
$x = \frac{F_5}{F_N}$
$x + \left(\frac{r_V}{r}\right)^3 x^2 = 2\alpha^2$
$r \ll r_V \Rightarrow \frac{F_5}{F_N} = 2\alpha^2 \left(\frac{r}{r_V}\right)^{\frac{3}{2}} \ll 1$
$r \gg r_V \Rightarrow \frac{F_5}{F_N} = 2\alpha^2 \sim \mathcal{O}(1)$
r_V - Vainshtein radius

Vainshtein Mechanism

We can integrate this once: $x = \frac{F_5}{F_{\mathrm{N}}}$

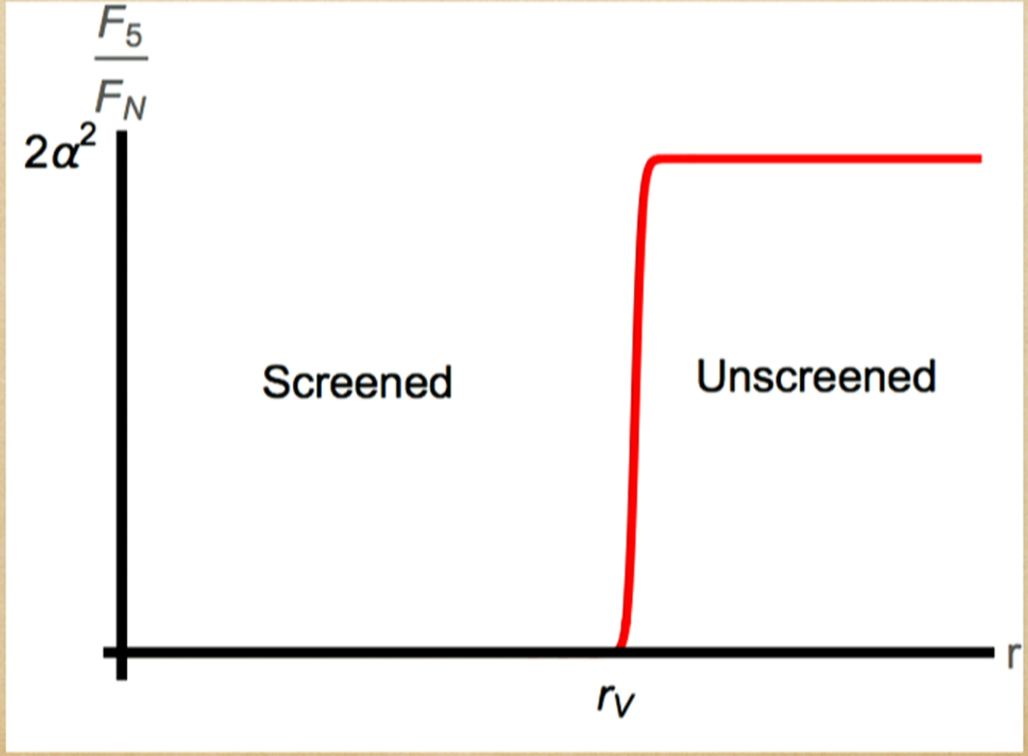
$$x + \left(\frac{r_{\mathrm{V}}}{r}\right)^3 x^2 = 2\alpha^2$$

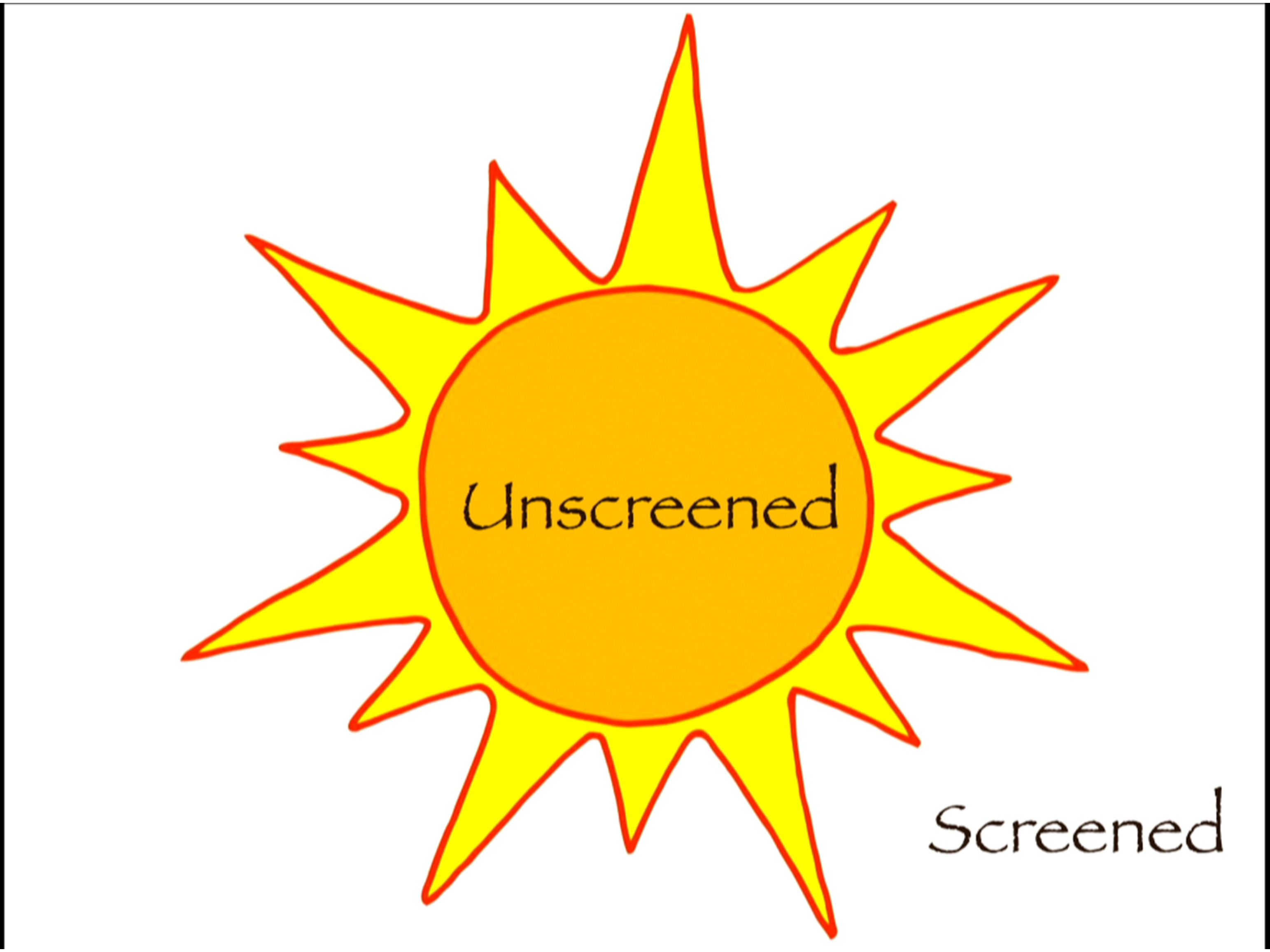
$$r \ll r_{\mathrm{V}} \Rightarrow \frac{F_5}{F_{\mathrm{N}}} = 2\alpha^2 \left(\frac{r}{r_{\mathrm{V}}}\right)^{\frac{3}{2}} \ll 1$$

$$r \gg r_{\mathrm{V}} \Rightarrow \frac{F_5}{F_{\mathrm{N}}} = 2\alpha^2 \sim \mathcal{O}(1)$$

r_{V} - Vainshtein radius

Vainshtein screening




Unscreened
Screened

Vainshtein breaking

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{GM(r)}{r^2} + \frac{\Upsilon_1 G}{4}\frac{\mathrm{d}^2 M(r)}{\mathrm{d}r^2}$$

Stars and satellites behave differently

$$-\frac{2}{3} < \Upsilon_1 < \infty$$

No stable stellar configurations Saito et al. 2015

Vainshtein breaking

$$\frac{\mathrm{d}\Psi}{\mathrm{d}r} = \frac{GM(r)}{r^2} - \frac{5\Upsilon_2 G}{4r}\frac{\mathrm{d}M(r)}{\mathrm{d}r}$$

Light bends differently

$$-\infty < \Upsilon_2 < \infty$$

Effective field theory

5 functions that control linear cosmology

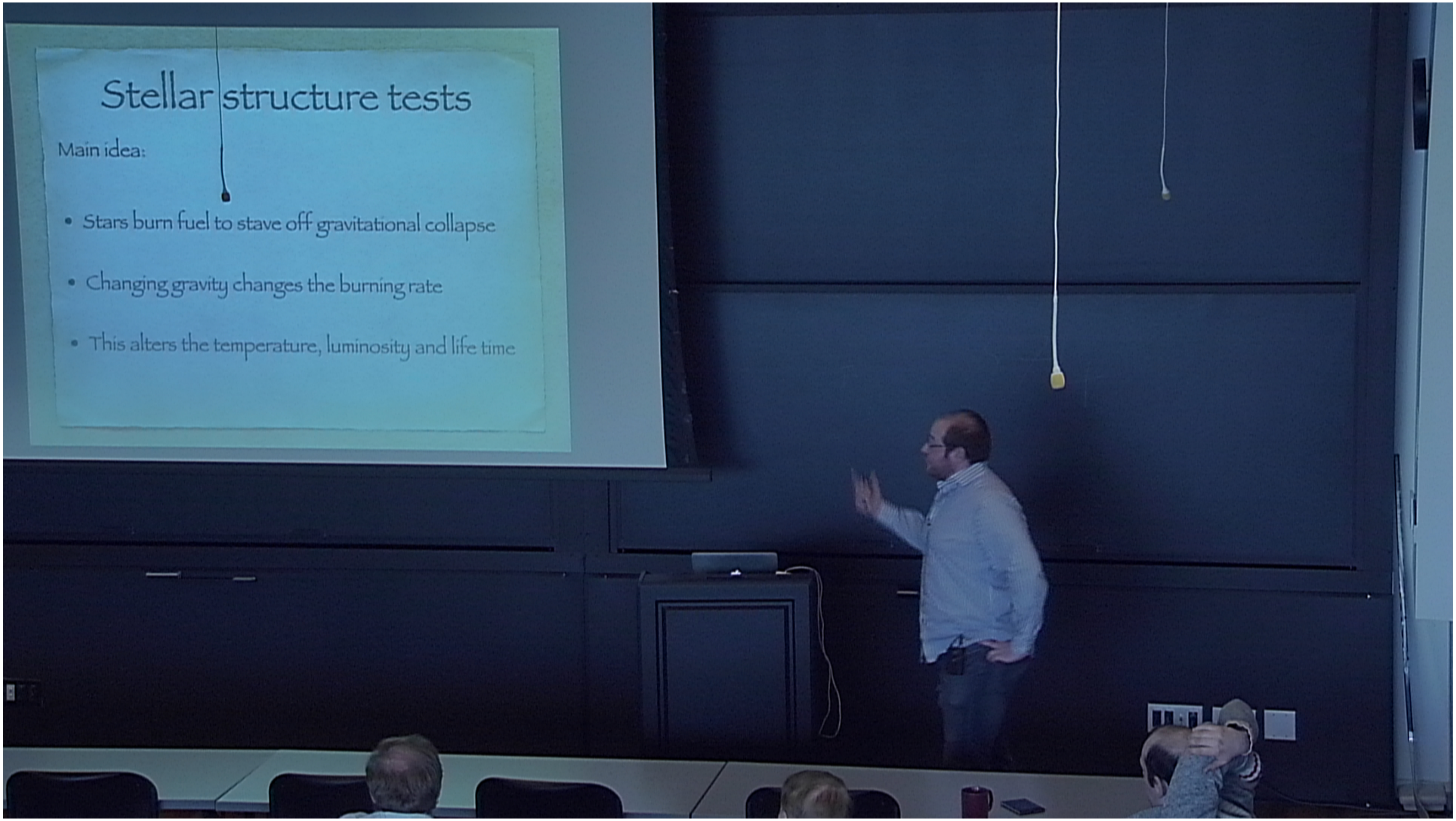
NR probes combinations of three of them:

$$\Upsilon_1 = \frac{4\alpha_H^2}{c_T^2(1+\alpha_B) - \alpha_H - 1}$$

$$\Upsilon_2 = \frac{4\alpha_H(\alpha_H - \alpha_B)}{5(c_T^2(1+\alpha_B) - \alpha_H - 1)}$$

This talk: astrophysical probes

- Stellar structure
- Galactic rotation curves
- Galaxy Clusters
- Dwarf stars


Stellar structure tests
Main idea:
Stars burn fuel to stave off gravitational collapse
Changing gravity changes the burning rate
This alters the temperature, luminosity and life time

Stellar structure tests

Main idea:

- Stars burn fuel to stave off gravitational collapse
- Changing gravity changes the burning rate
- This alters the temperature, luminosity and life time

Gravity only effects the hydrostatic equilibrium equation

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM(r)\rho(r)}{r^2} - \frac{\Upsilon_1 G\rho(r)}{4}\frac{\mathrm{d}^2M(r)}{\mathrm{d}r^2}$$

Vainshtein stars

Gravity weaker

Slower burning rate

Dimmer and cooler stars that live longer

Polytropic stars

$$P = K\rho^{\frac{n+1}{n}}$$

polytropic index

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

Mass-G-Luminosity relation

$$P_{\rm gas} = \frac{\rho k_{\rm B} T}{\mu m_{\rm H}} \qquad P_{\rm rad} = \frac{1}{3} a T^4$$

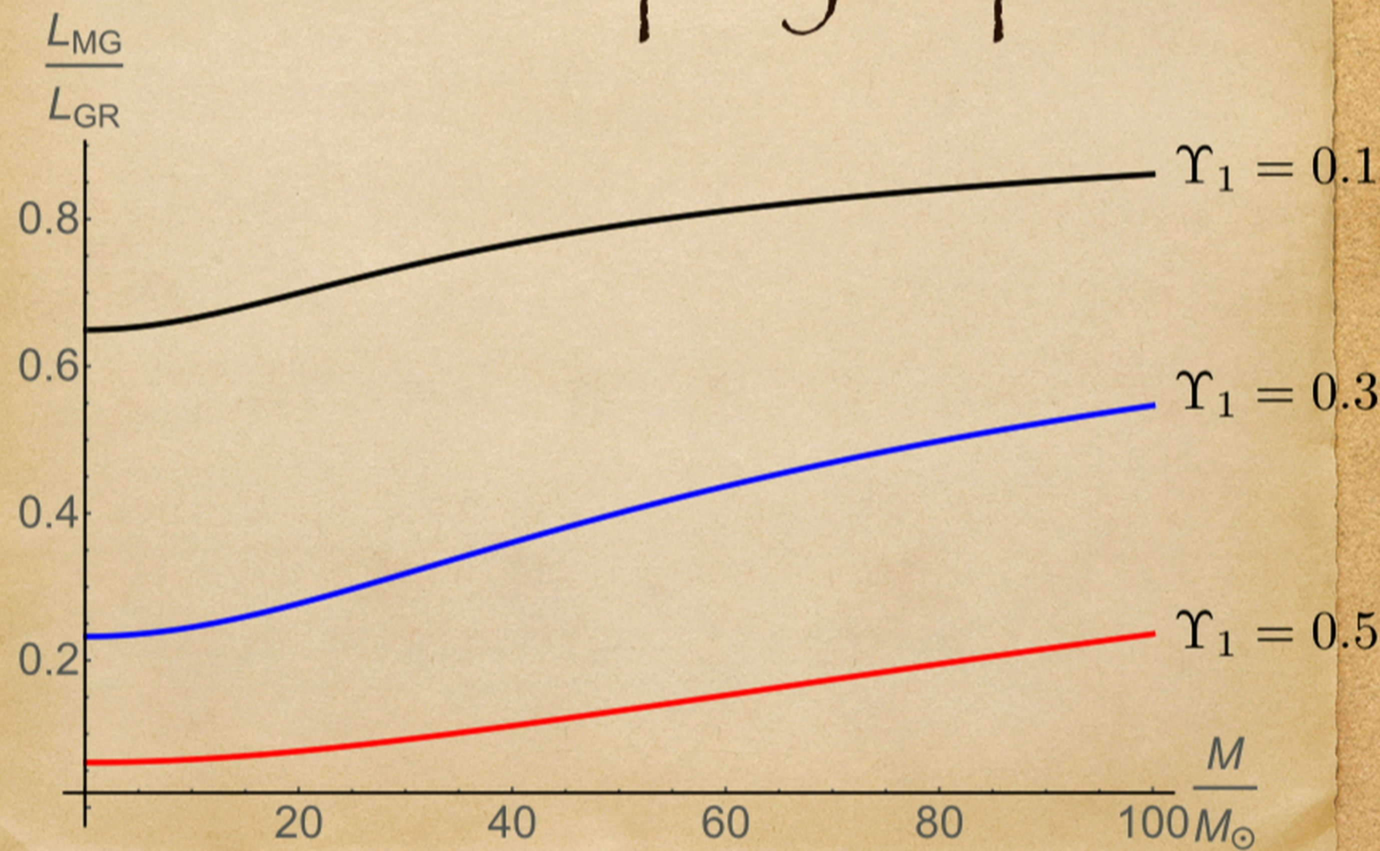
Gas pressure — $L \propto G^4 M^3$

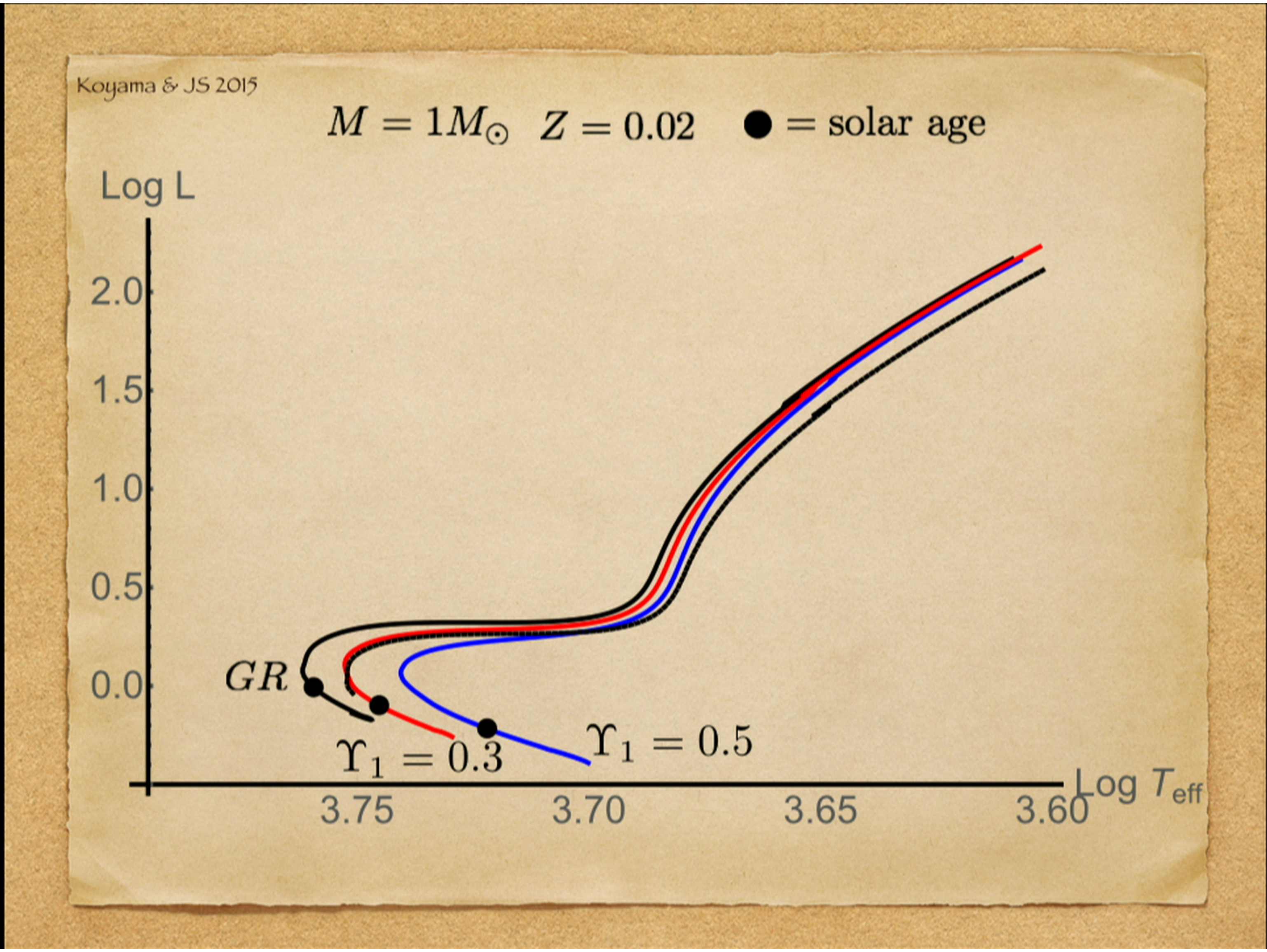
Radiation pressure — $L \propto GM$

High-mass stars are more radiation pressure-supported

Vainshtein polytropes

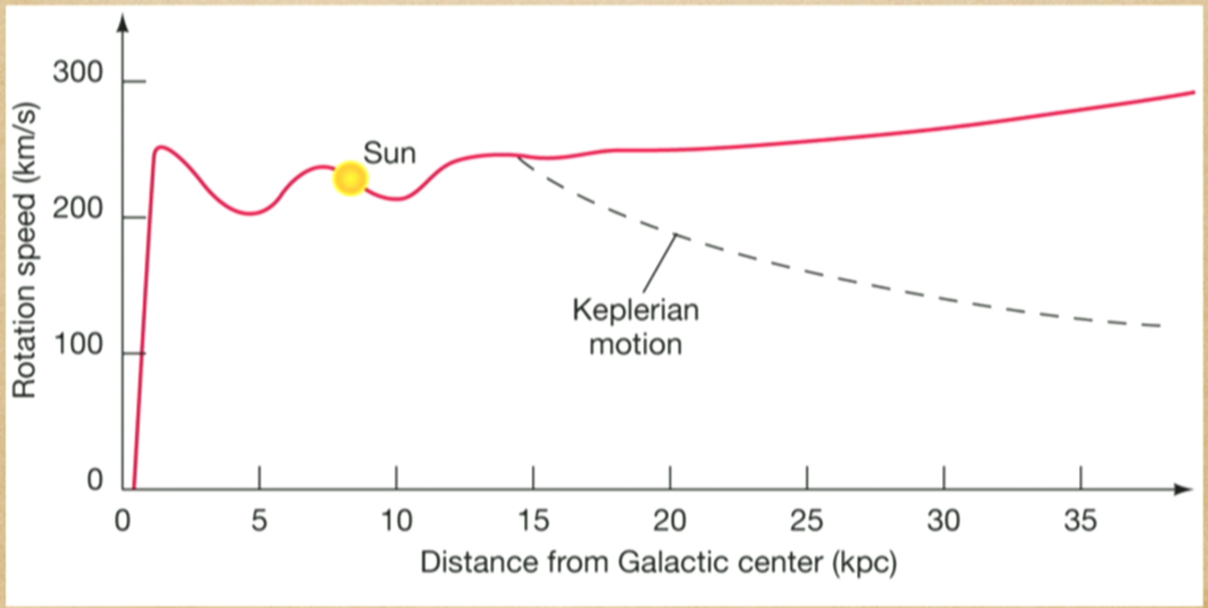
Koyama & JS 2015




Koyama & JS 2015
$M = 1M_\odot$ $Z = 0.02$ ● = solar age
Log L
2.0
1.5
1.0
0.5
0.0
GR
$\Upsilon_1 = 0.3$
$\Upsilon_1 = 0.5$
3.75
3.70
3.65
3.60
Log $T_{\rm eff}$

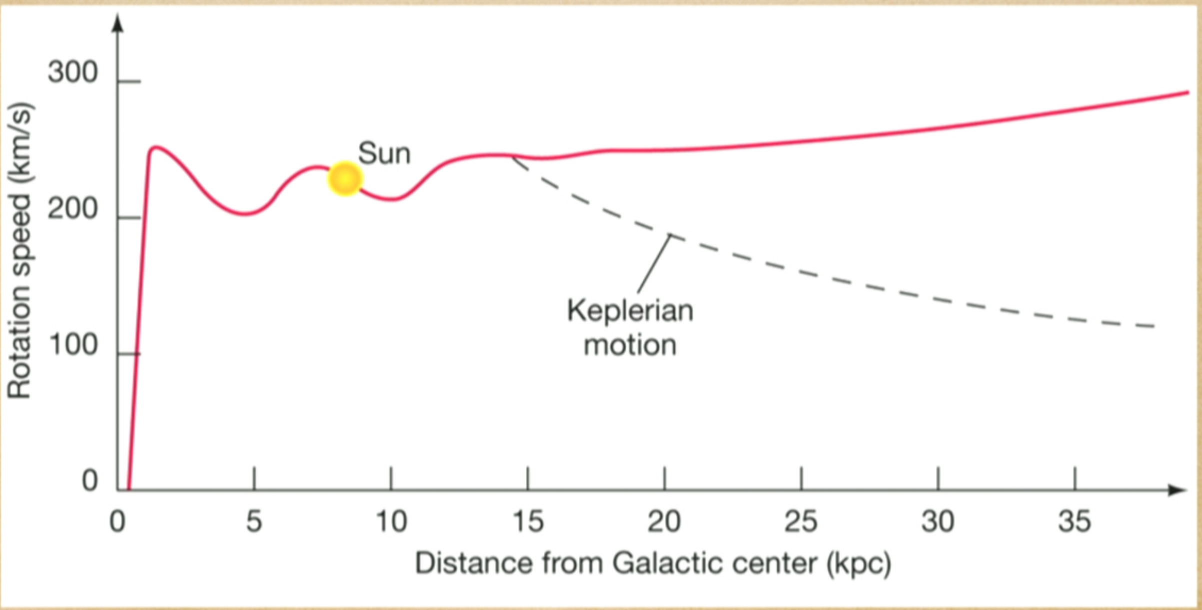
Rotation curves

Circular velocity: $v_{\mathrm{circ}}^2 = \frac{\mathrm{d}\Phi}{\mathrm{d}r}$

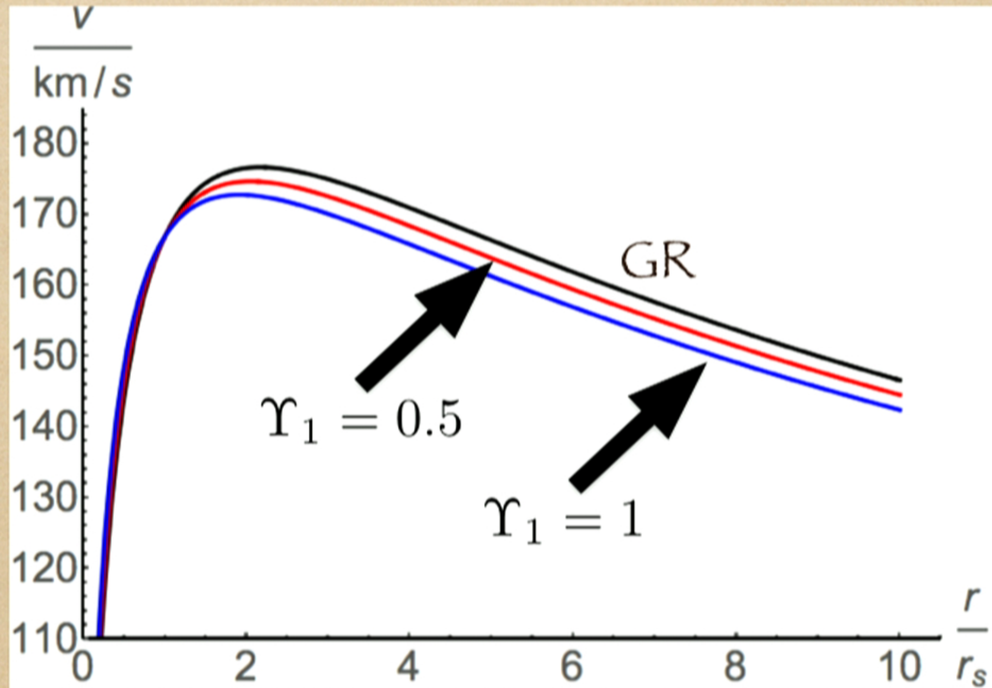


Rotation curves

Circular velocity: $v_{\mathrm{circ}}^2 = \frac{\mathrm{d}\Phi}{\mathrm{d}r}$



Vainshtein rotation curves



Koyama & JS 2015

NFW profile for MW

Galaxy cluster tests

Compare hydrostatic and lensing mass:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM_{\mathrm{hydro}}\rho}{r^2}$$ Probe using X-ray brightness

$$\frac{\mathrm{d}(\Phi + \Psi)}{\mathrm{d}r} = \frac{2GM_{\mathrm{WL}}}{r^2}$$ Probe using lensing

GR: $M_{\mathrm{lens}} = M_{\mathrm{hydro}}$

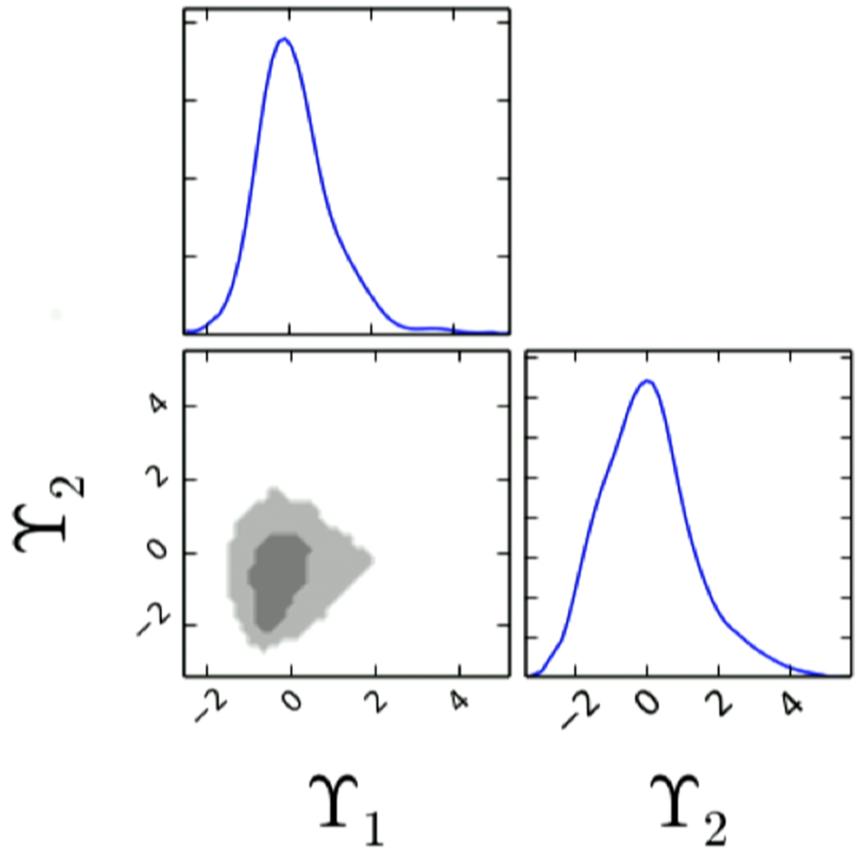
Galaxy cluster tests

GR: $M_{\rm lens} = M_{\rm hydro}$

MG: $M_{\rm lens} = M_{\rm hydro} + \frac{4}{3}\pi r_s^3 \rho_s f(\frac{r}{r_s}, \Upsilon_1, \Upsilon_2)$

Non-agreement probes gravity!

Sakstein, Wilcox, Nichol, Koyama, and Bacon to appear



-2
0
2
4
Υ_2
Υ_1
Υ_2

Cluster tests

$$\Upsilon_1 = -0.11^{+0.93}_{-0.67}$$

$$\Upsilon_2 = -0.22^{+1.22}_{-1.19}$$

Note: This applies at redshift 0.33

Cluster tests

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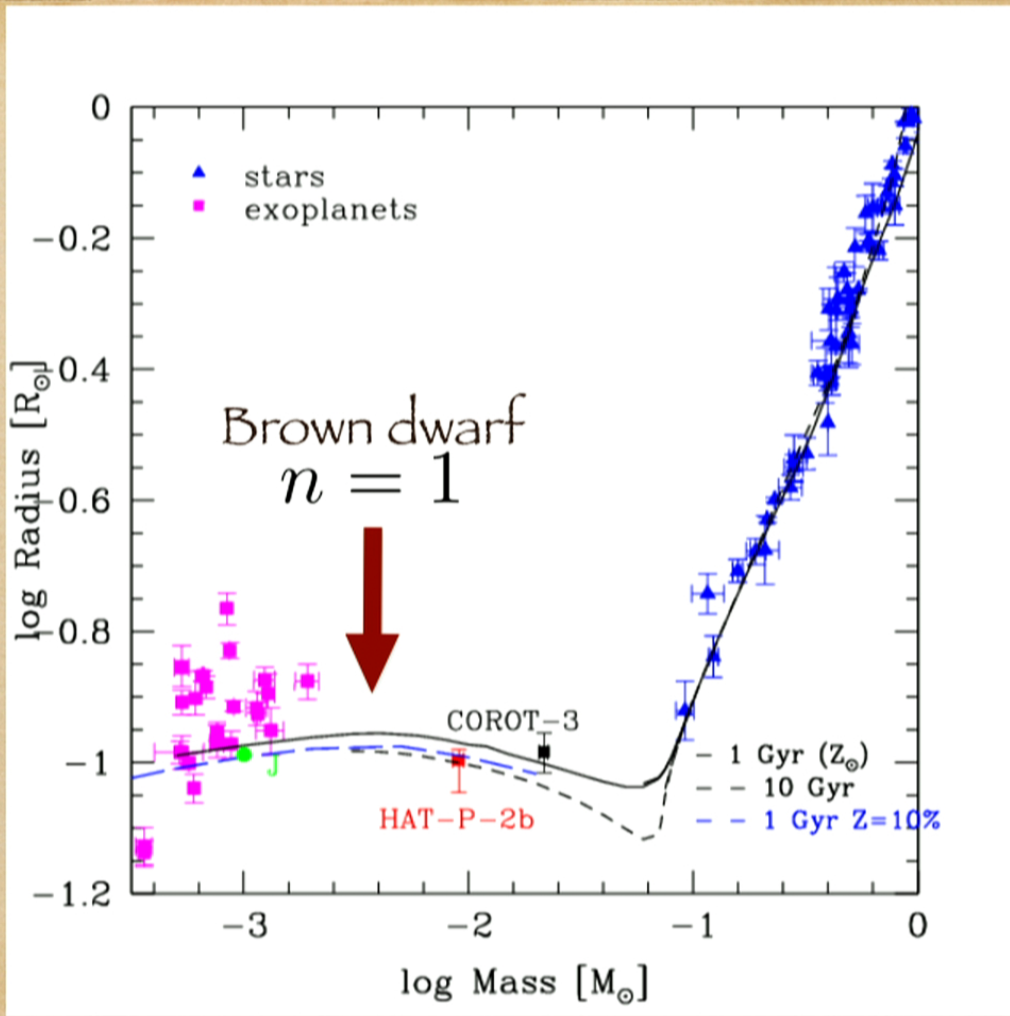
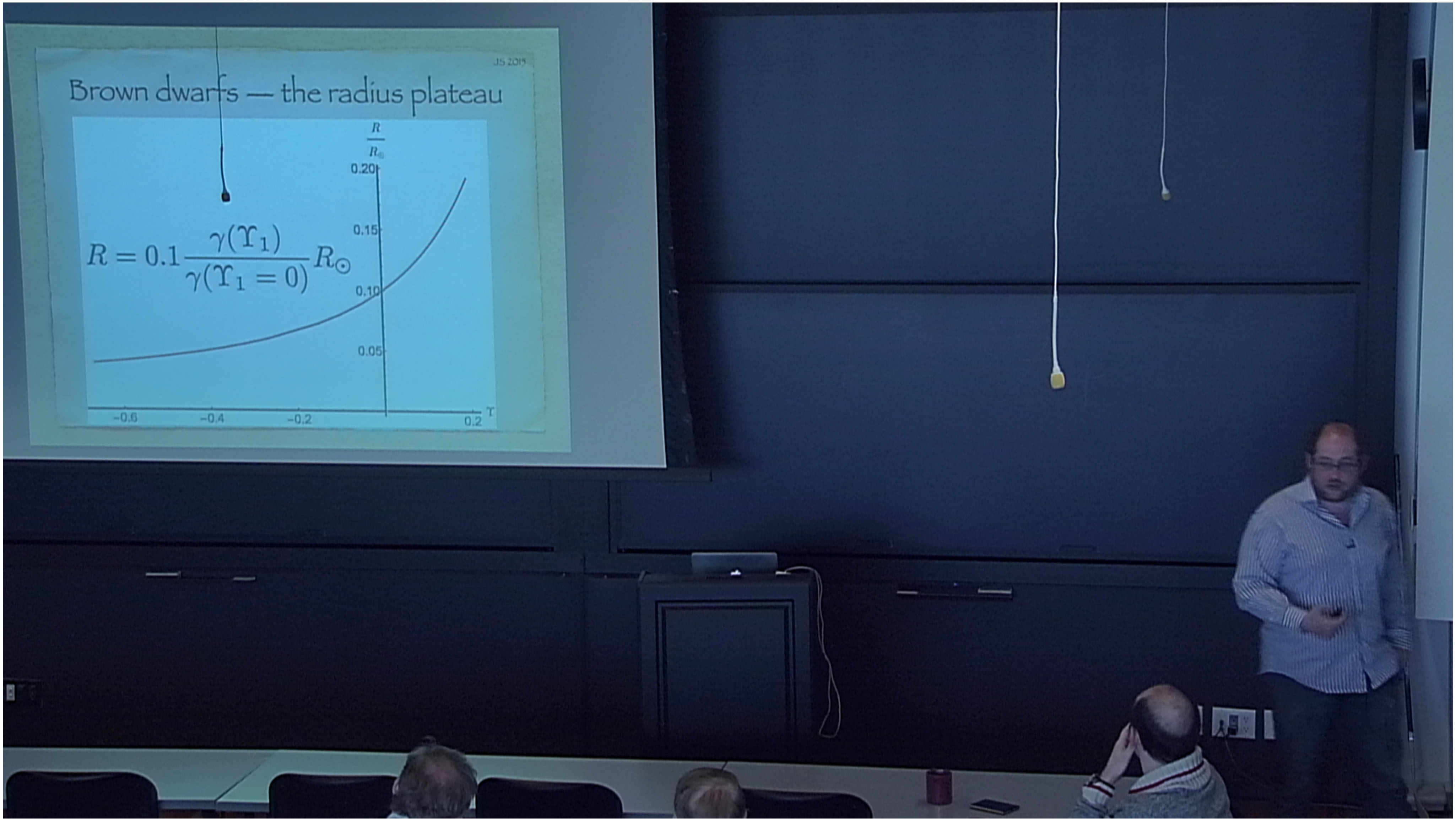
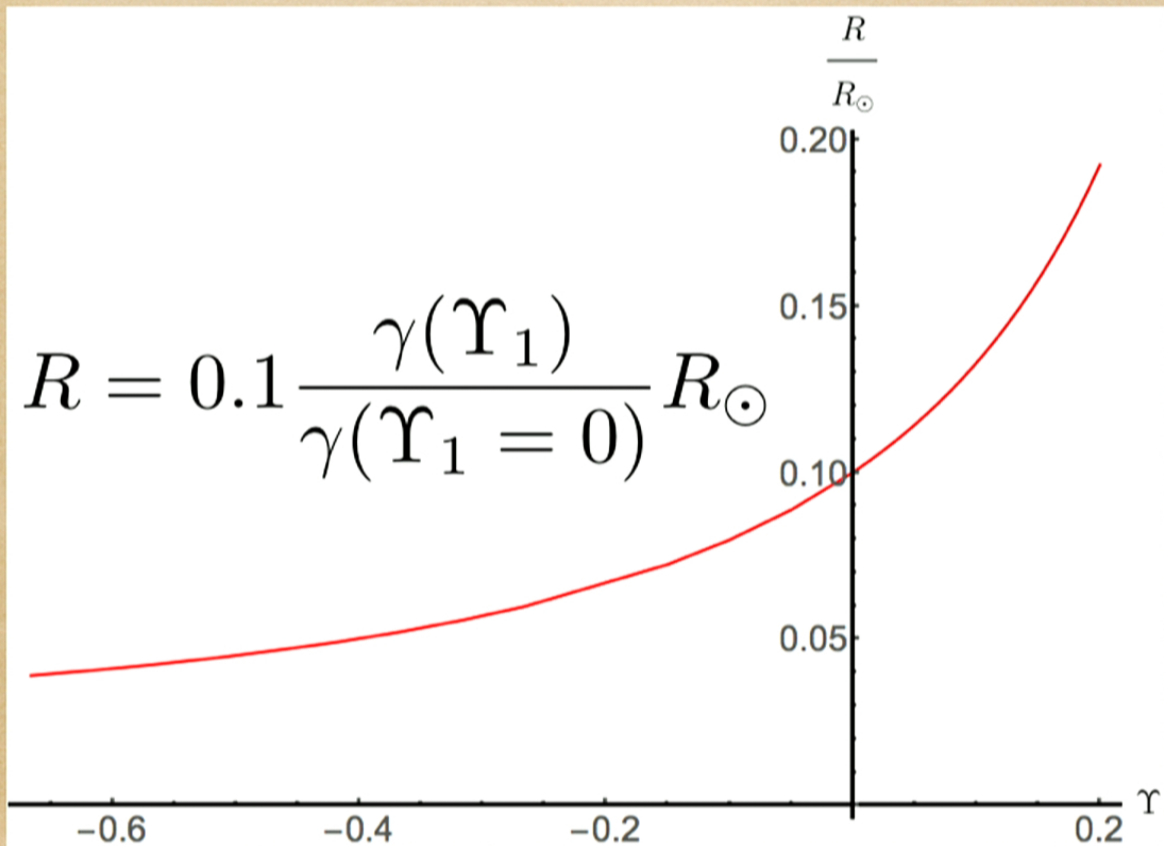

stars
exoplanets
Brown dwarf
$n = 1$
COROT−3
HAT−P−2b
J
1 Gyr ($Z_\odot$)
10 Gyr
1 Gyr Z=10%
log Radius [$R_\odot$]
log Mass [$M_\odot$]
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−3
−2
−1
0


JS 2015
Brown dwarfs — the radius plateau
$R = 0.1 \frac{\gamma(\Upsilon_1)}{\gamma(\Upsilon_1 = 0)} R_\odot$
$\frac{R}{R_\odot}$
0.20
0.15
0.10
0.05
−0.6
−0.4
−0.2
0.2
Υ

Brown dwarfs — the radius plateau



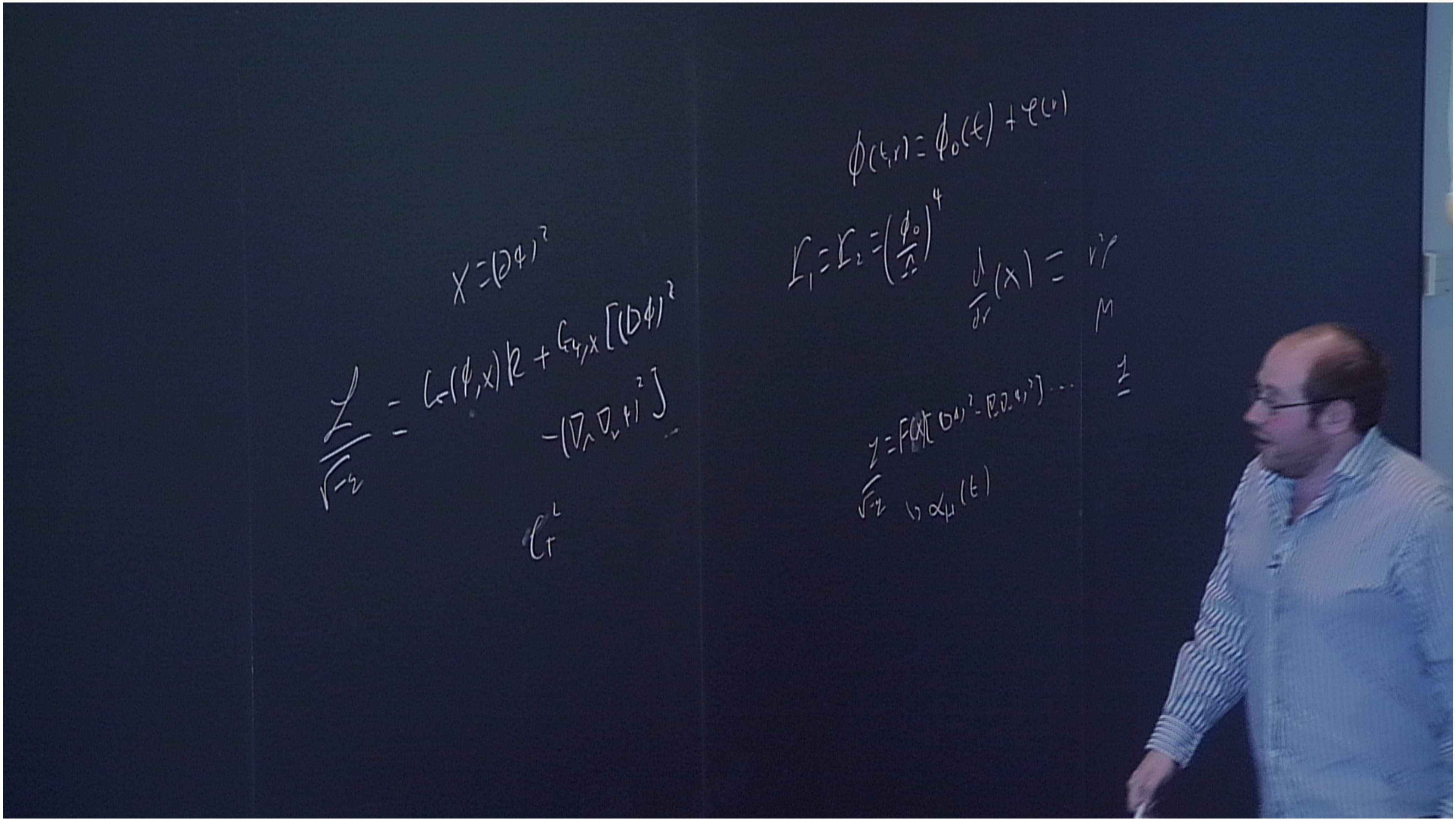
$$R = 0.1\frac{\gamma(\Upsilon_1)}{\gamma(\Upsilon_1 = 0)}R_\odot$$

$\frac{M_{MMHB}}{M_{\odot}}$
0.100
0.095
0.090
0.085
0.01
0.02
0.03
0.04
0.05
Υ

Summary

Modified gravity is worth exploring:

- Dark energy, self-acceleration
- Needed to test GR
- Can satisfy SS tests using screening mechanisms


X = (∂φ)²