Unifying small scale probes with cosmology: astrophysical tests of gravity

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Unifying tests of general relativity workshop
California Institute of Technology
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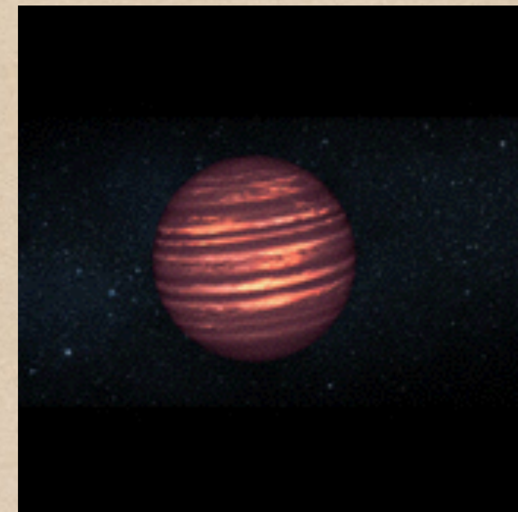
ICG Portsmouth

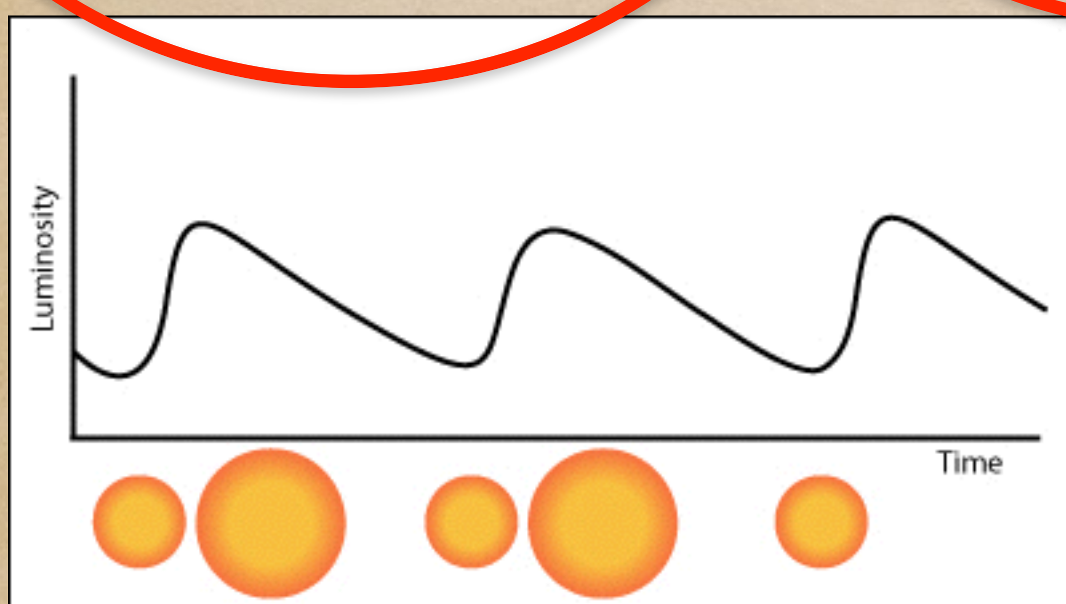
Things we can use to test screening

Neutron stars

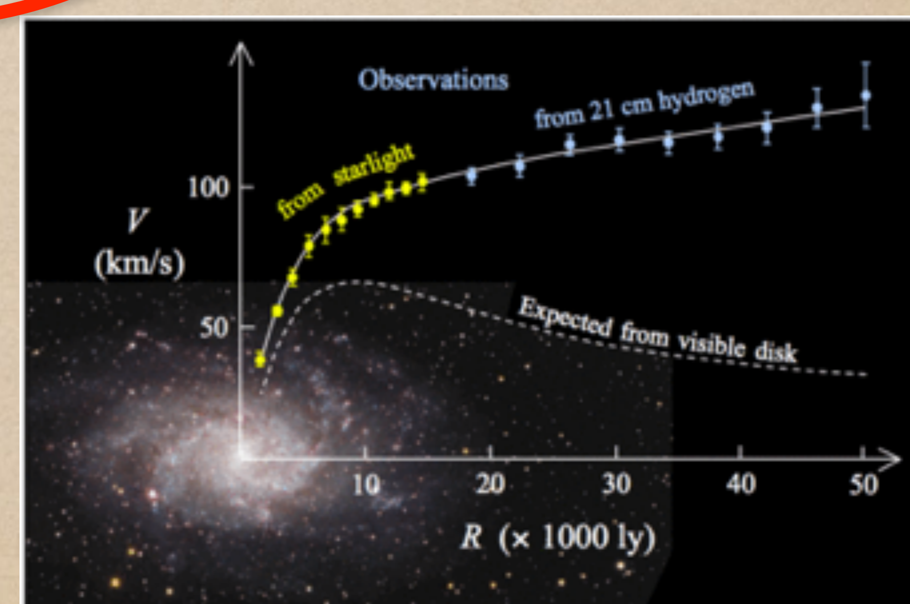


Dwarf stars

Clusters



Cepheid stars



Rotation curves

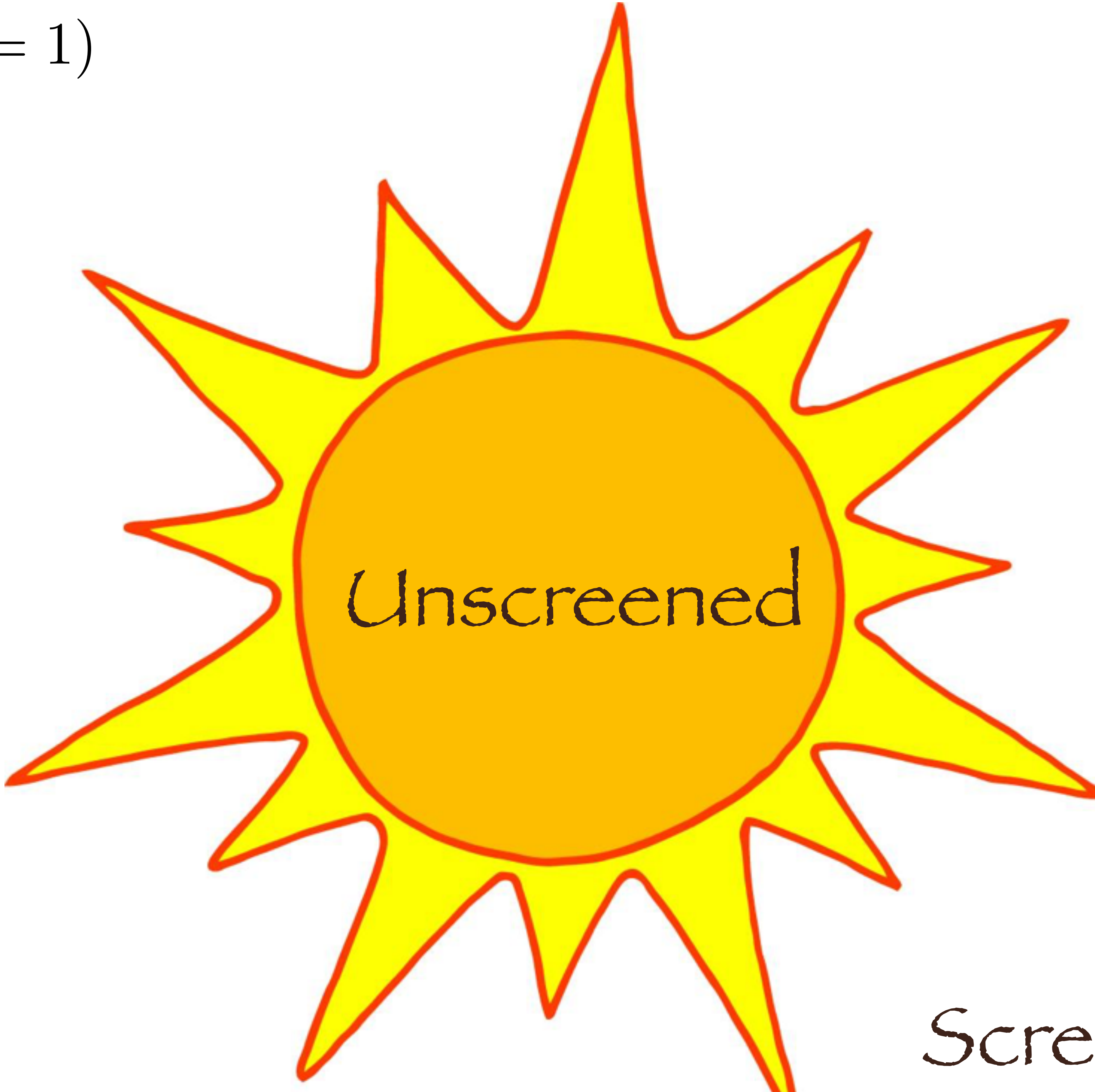
Aim of the talk

"This will be a small meeting with a very tight focus on a single problem -- how to effectively combine GR constraints on small (solar system/pulsar/BH/GW) and large (cosmological) scales."

-Phil Bull

We can do this for beyond Horndeski theories!!!!!

$(\gamma_{\rm PPN} = 1)$



Screened

Vainshtein breaking - Newtonian potential

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

GR

beyond Horndeski

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

No stable stellar configurations Saito et al. 2015

Rule of thumb - works well for stars (not true in strong field regime)

$$\Upsilon_1 < 0$$ — gravity stronger than GR

$$\Upsilon_1 > 0$$ — gravity weaker than GR!

"Effective field theory"

5 functions that control linear cosmology

NR systems probe combinations of three of them:

"beyond Horndeski"

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

speed of tensors

kinetic braiding

Completeness: second parameter

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

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

$$\mathrm{d}s^2 = (1+2\Phi)\,\mathrm{d}t^2 + (1+2\Psi)\,\mathrm{d}x^2$$

Won't talk about this here

Lensing

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 lifetime

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

Vainshtein stars

Gravity stronger

Faster burning rate

Hotter and brighter stars that die faster

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

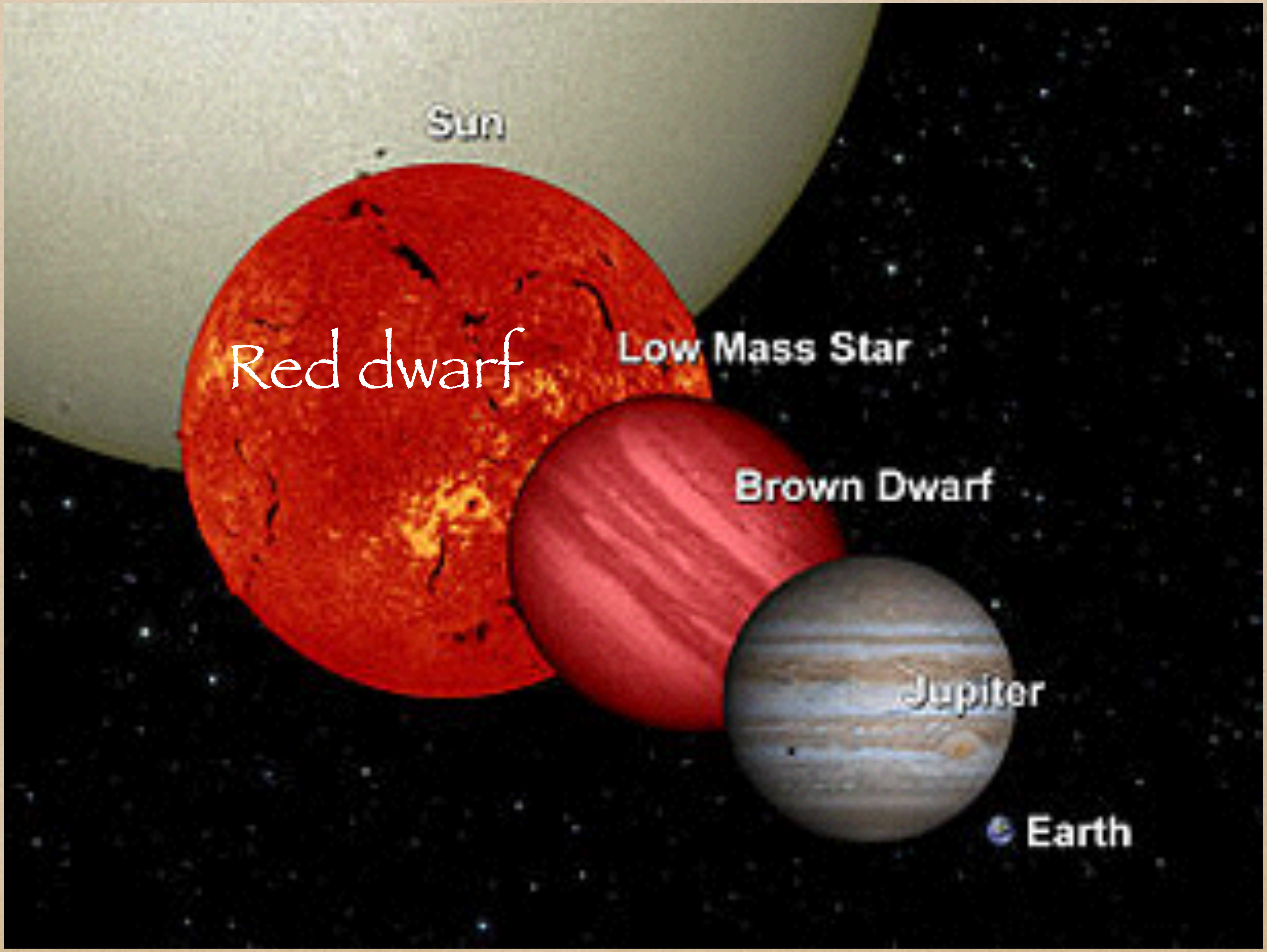
Polytropic stars

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

polytropic index

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

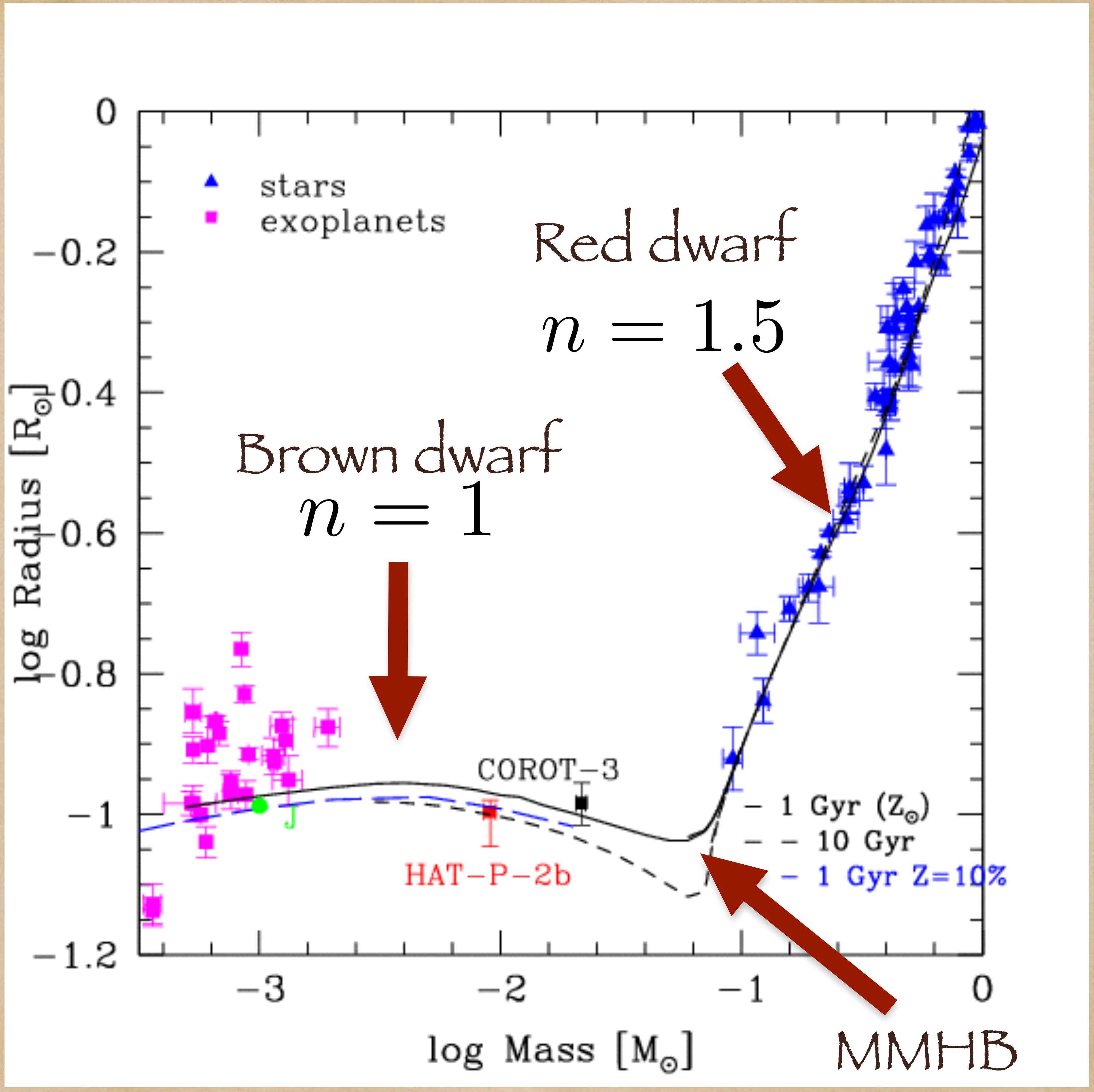
Dwarf stars - a new test of gravity



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 (GAIA, KEPLER)



stars
exoplanets
Red dwarf
$n = 1.5$
Brown dwarf
$n = 1$
COROT−3
HAT−P−2b
J
— 1 Gyr ($Z_\odot$)
– – 10 Gyr
– 1 Gyr Z=10%
MMHB
log Radius [$R_\odot$]
log Mass [$M_\odot$]
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−3
−2
−1
0

Brown dwarfs — the radius plateau

Coulomb pressure $\Rightarrow\ n = 1 \qquad (P = K\rho^2)$

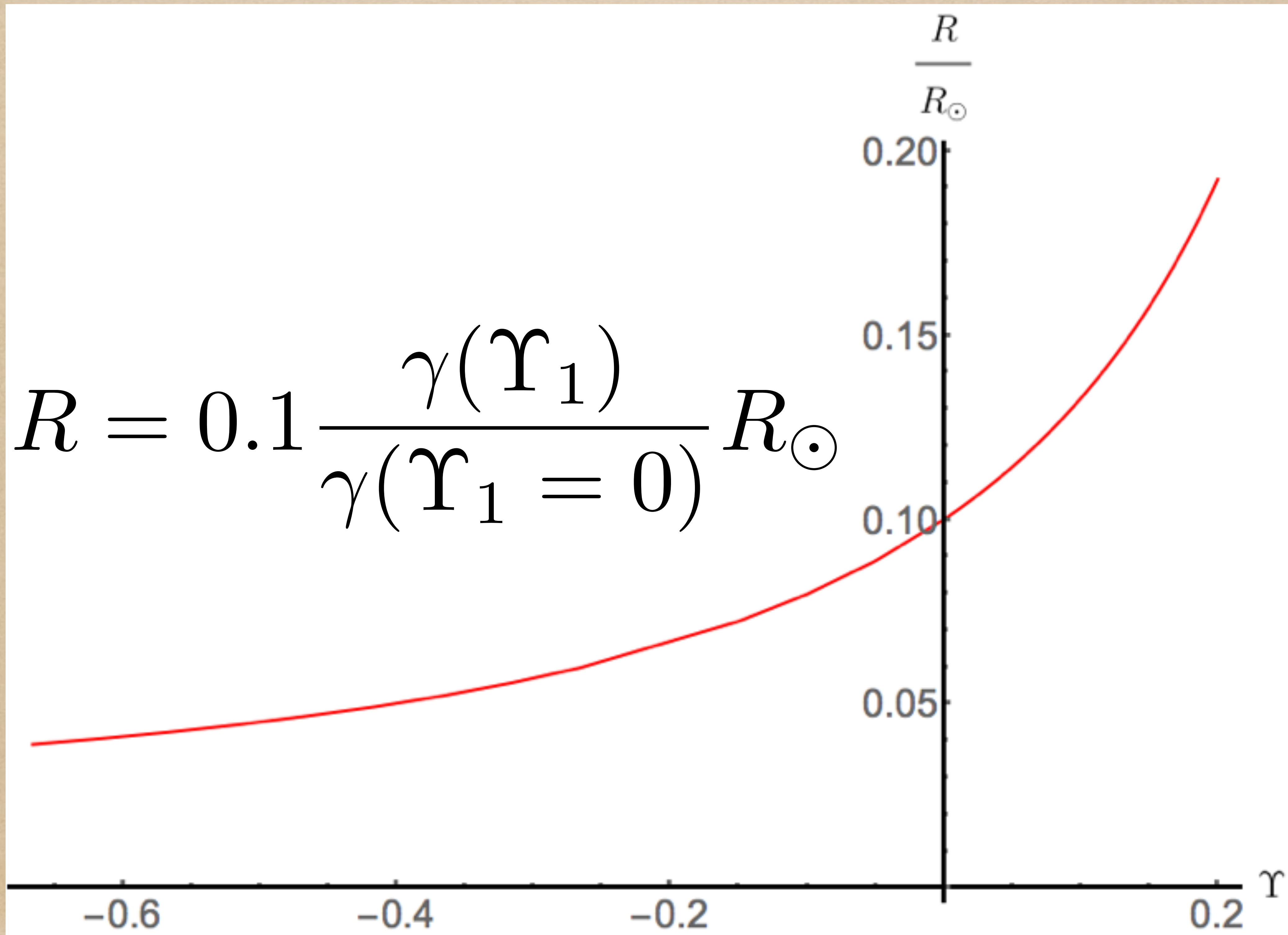
Constant/non-gravitational physics

$$R = \gamma\left(\frac{K}{G}\right)^{\frac{1}{2}}$$

Theory of gravity

Brown dwarfs — the radius plateau

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



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

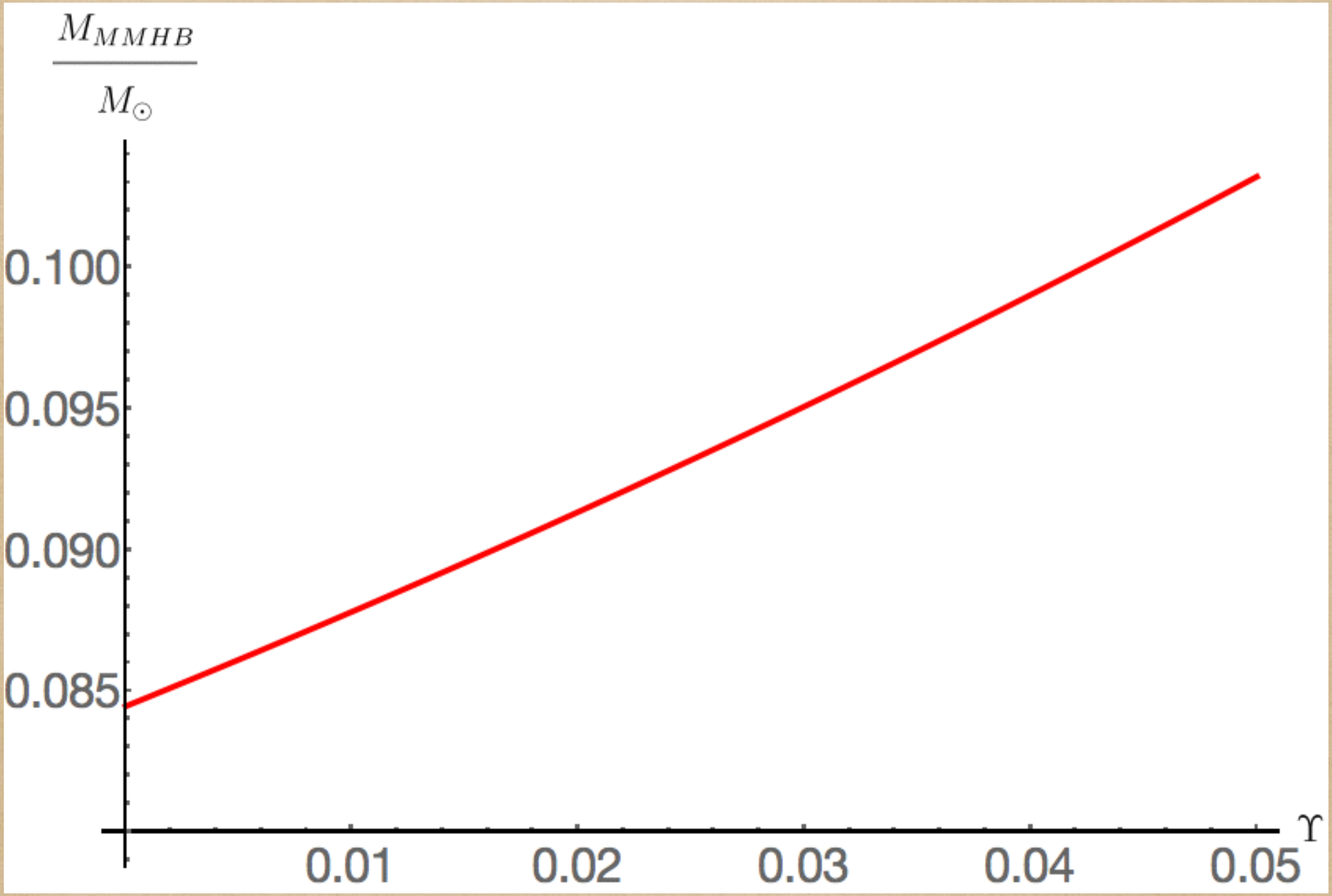
$L_{\rm HB} = L_{\rm eff}$:

$$M_{\rm MMHB} = 0.08 \frac{\delta(\Upsilon_1)}{\delta(\Upsilon_1 = 0)} M_\odot$$

Proton burning

$n = 1.5$ + theory of gravity

JS, PRL 2015



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

New constraint

Lowest mass star is Gl 886 C

$$M = 0.0930 \pm 0.0008 M_\odot$$

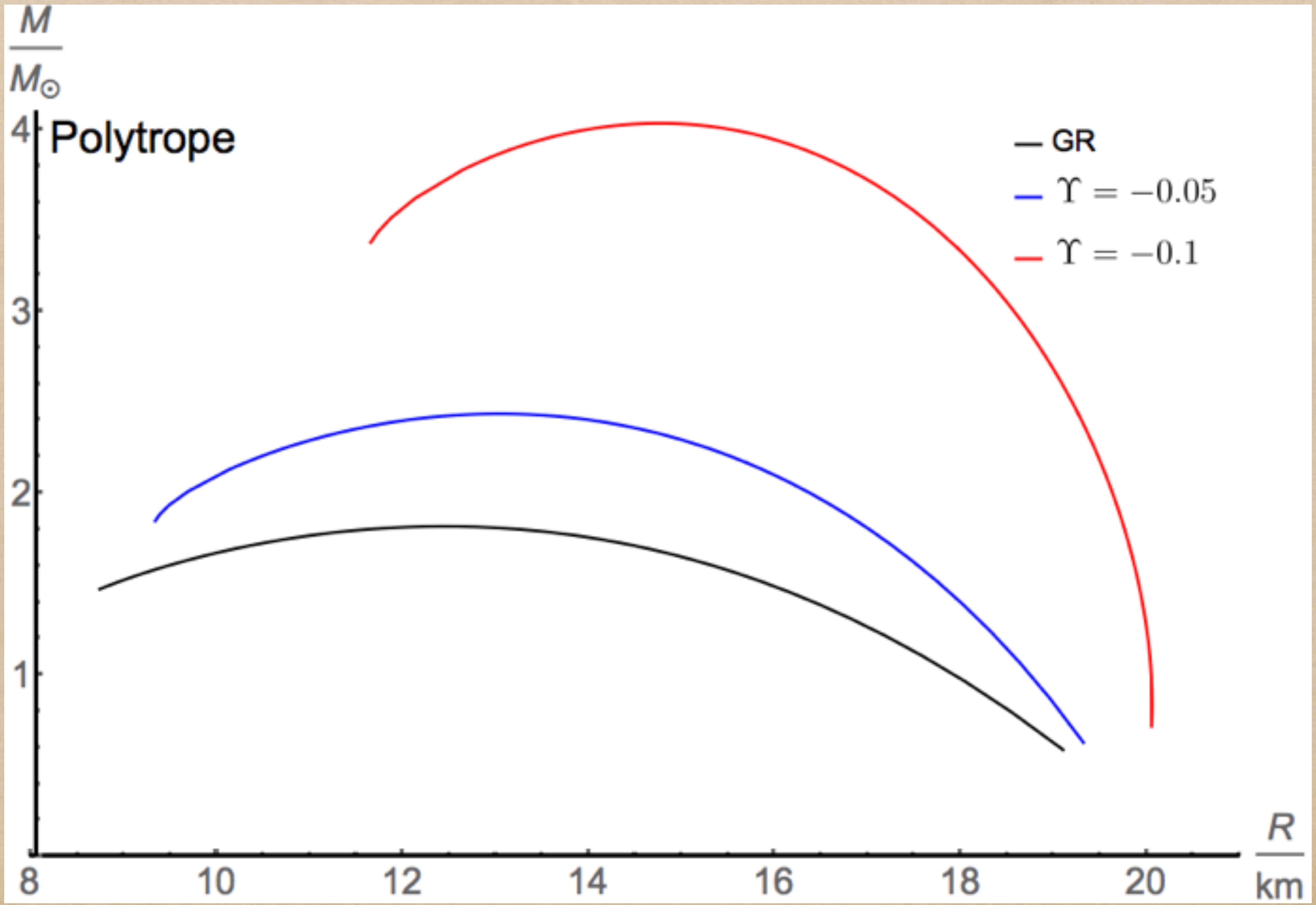
$$\Rightarrow \Upsilon_1 < 0.027$$

Neutron Stars

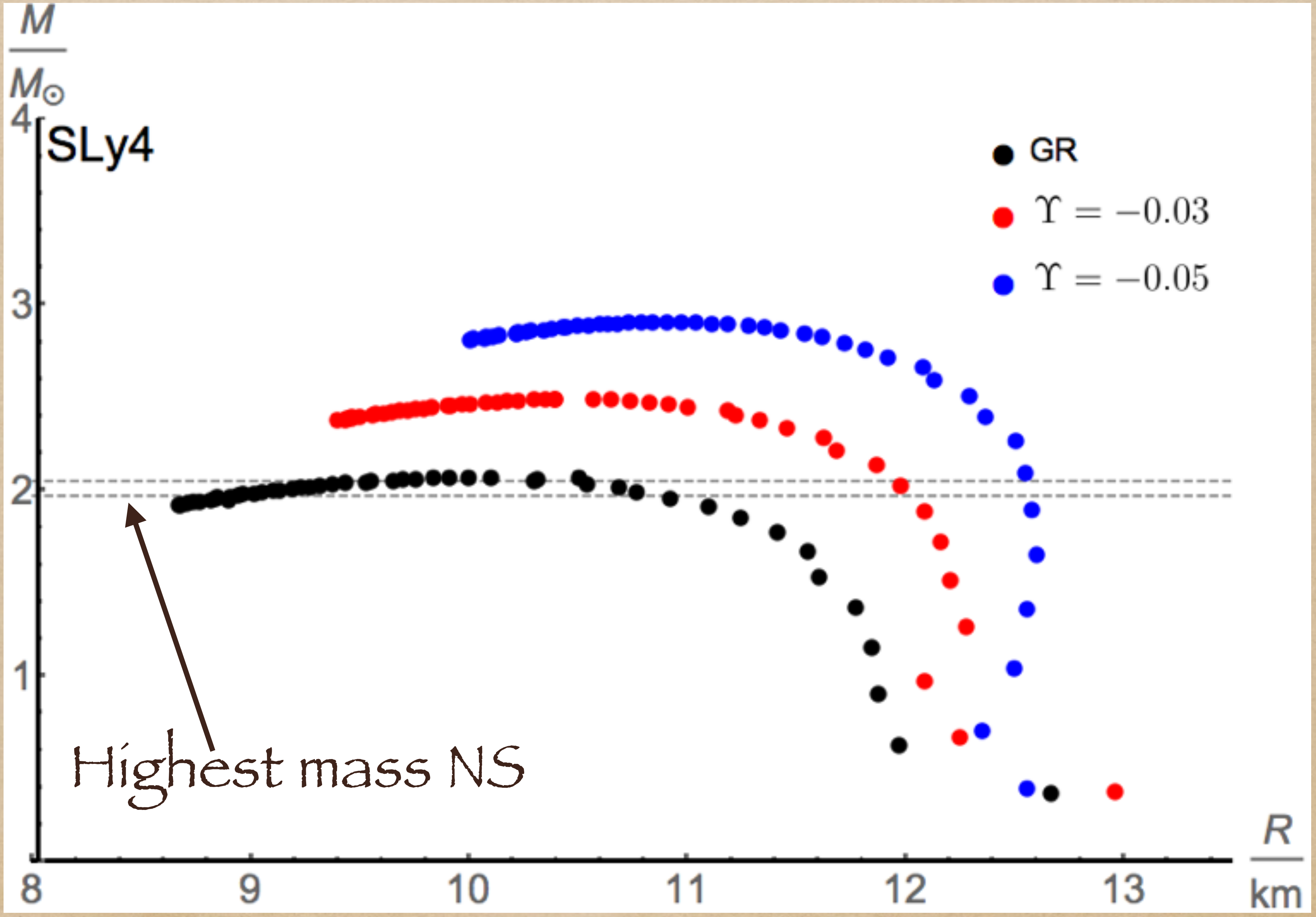
- Answer technical questions (e.g. asymptotics)
- Not great probes of MG (EOS uncertainty)?
- Need to check they exist
- Correct precession of Mercury $(\beta_{\rm PPN} = 1)$

Babichev, Koyama, Langlois, Saito & JS 2016

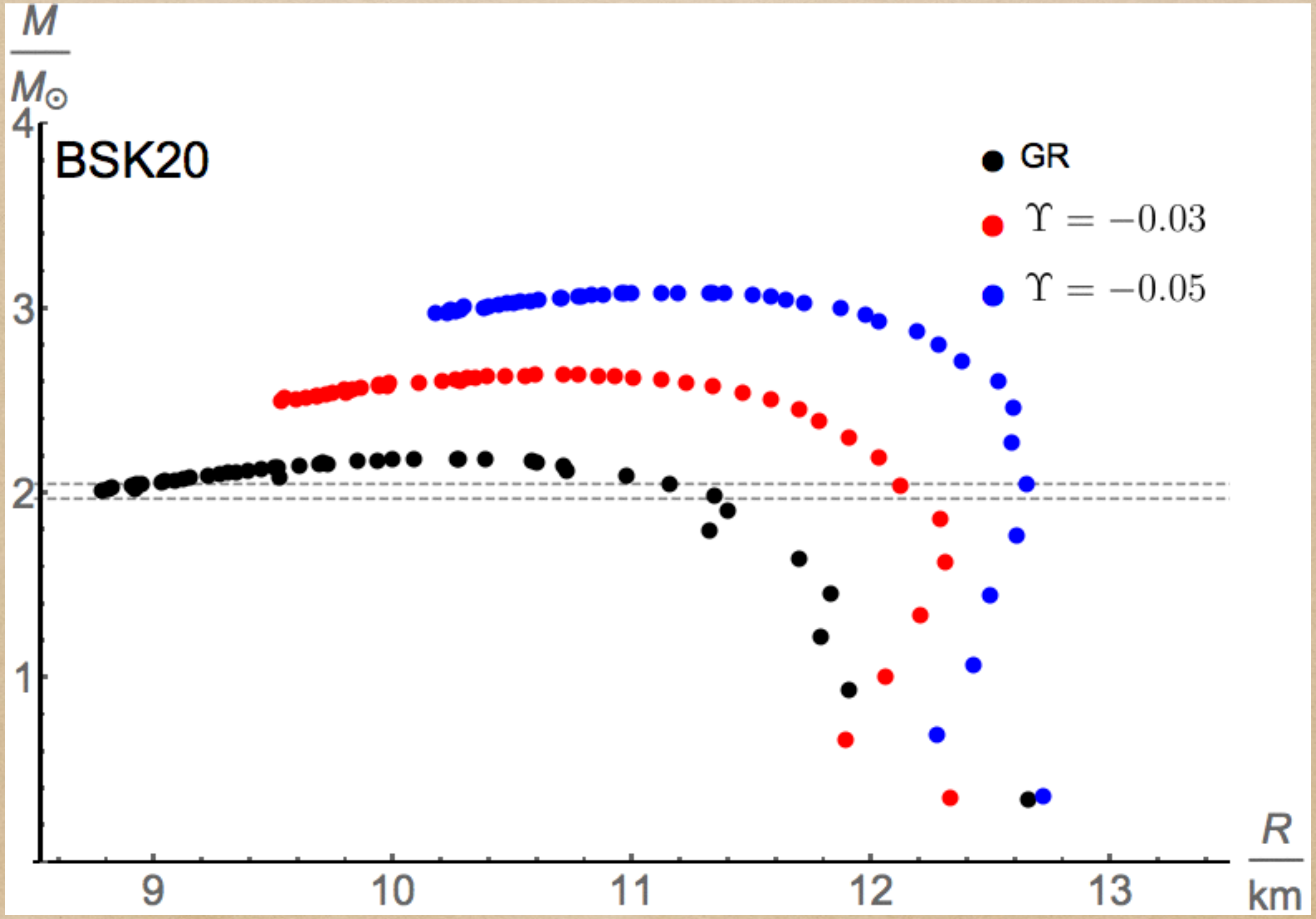
Polytropic model: $P = K\rho^2$



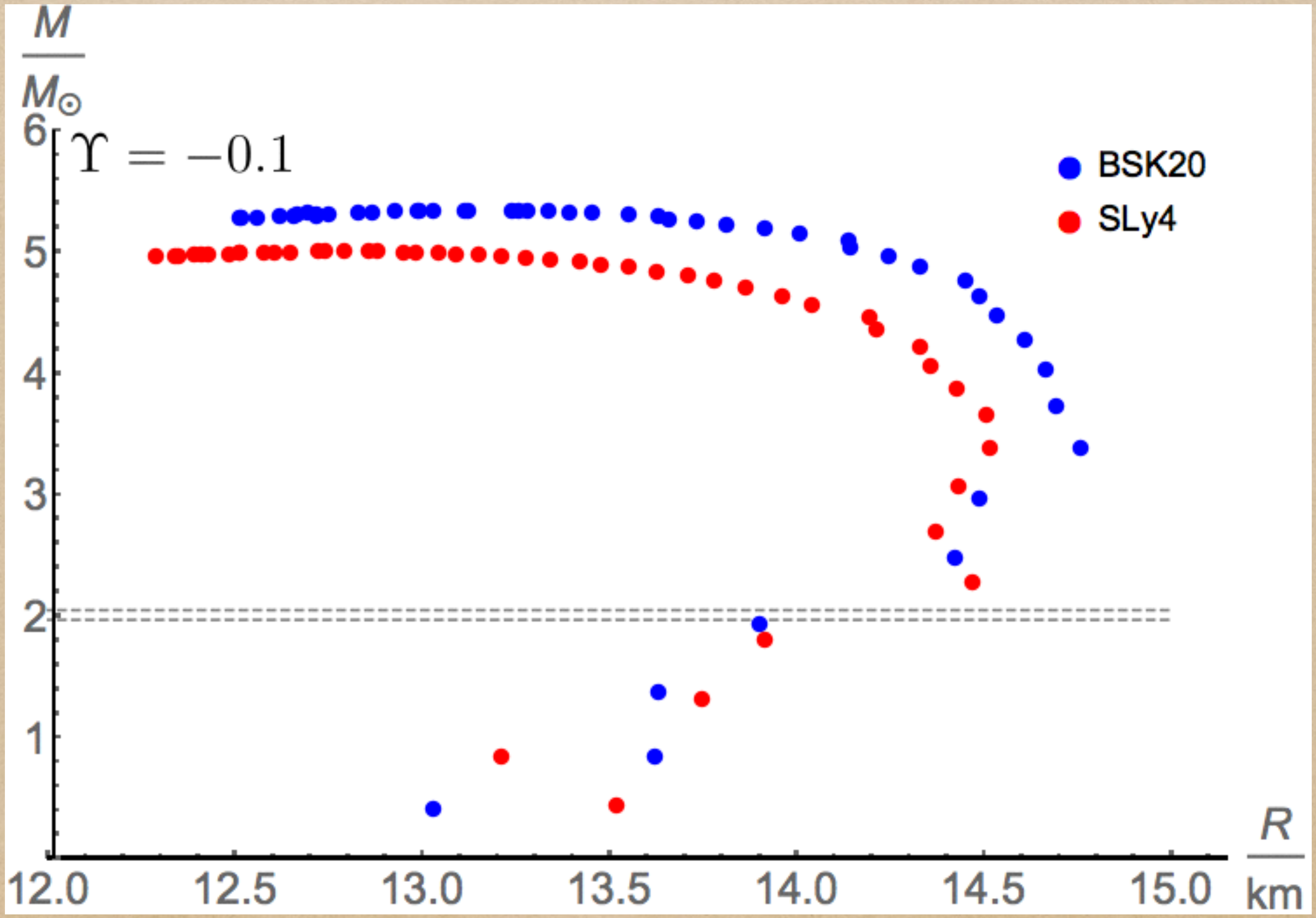
Realistic EOS (SLy4)



Realistic EOS (BSK20)



Extreme parameters



Summary - testing beyond Horndeski using stars

- Beyond Horndeski unscreened inside objects
- Parameter Υ connects directly to Cosmology (EFT)
- Radius of brown dwarfs is a new potential probe
- MMHB constrains $\Upsilon < 0.027$
- NS can probe $\Upsilon < 0$

Thank you!
(and to my collaborators)

Collaborators	Papers
Kazuya Koyama (ICG)	1606.06627
David Langlois (APC)	1511.01685
Eugeny Babichev (LPT)	1510.05964
Ryo Saito (APC & Kyoto)	1502.06872