Novel Tests of Gravity Using Astrophysics

Jeremy Sakstein
University of Pennsylvania

Department of Physics & Astronomy
University of Mississippi
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Some Thoughts on Gravitational Physics

Jeremy Sakstein
University of Pennsylvania

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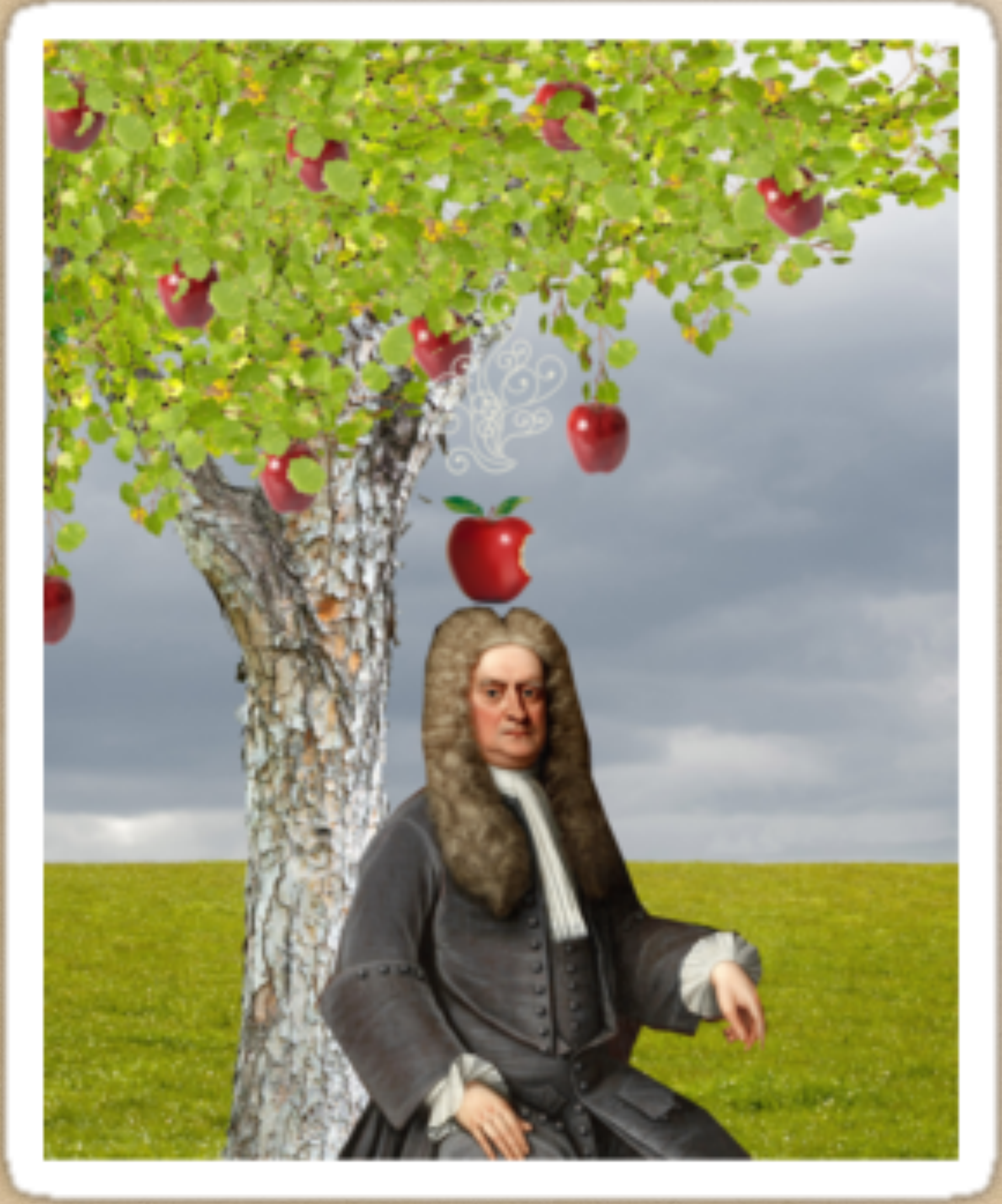
Outline

- What is gravity? Why should we test it?
- Dark energy and cosmic acceleration
- Moden 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?

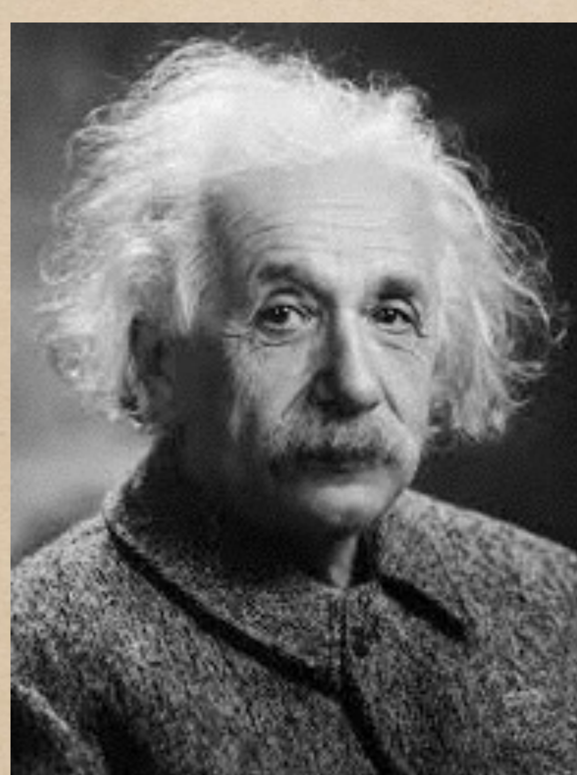


Newton:

Attractive force between massive bodies

$$F = \frac{GMm}{r^2}$$

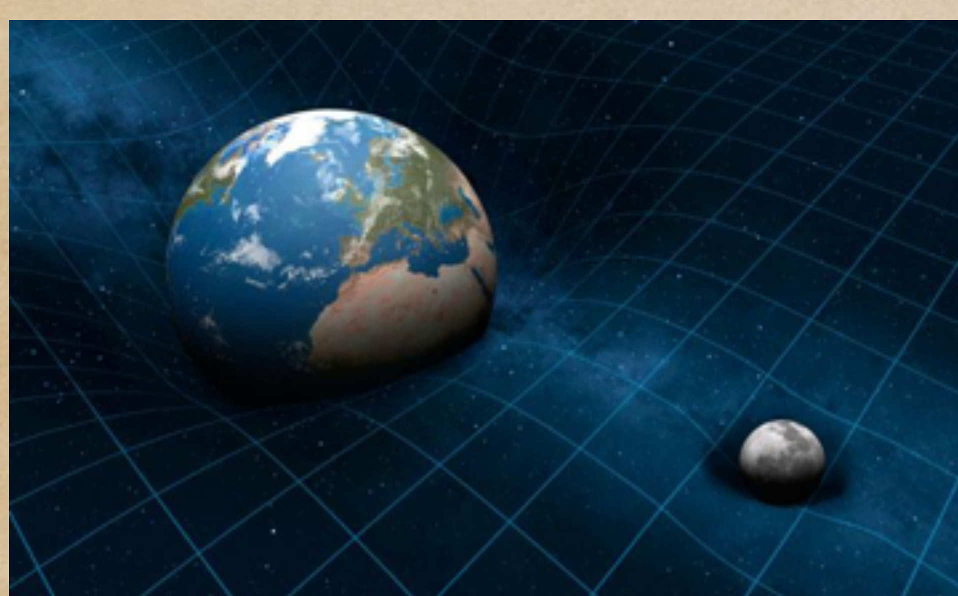
What is gravity?



Einstein: Curvature of space-time

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

Geometry   Matter



Spacetime tells matter
how to move;
matter tells spacetime
how to curve. — John Wheeler

What do we know about gravity?

Newtonian = non-relativistic: $v^2/c^2 \ll 1$

Reason: most things are Newtonian

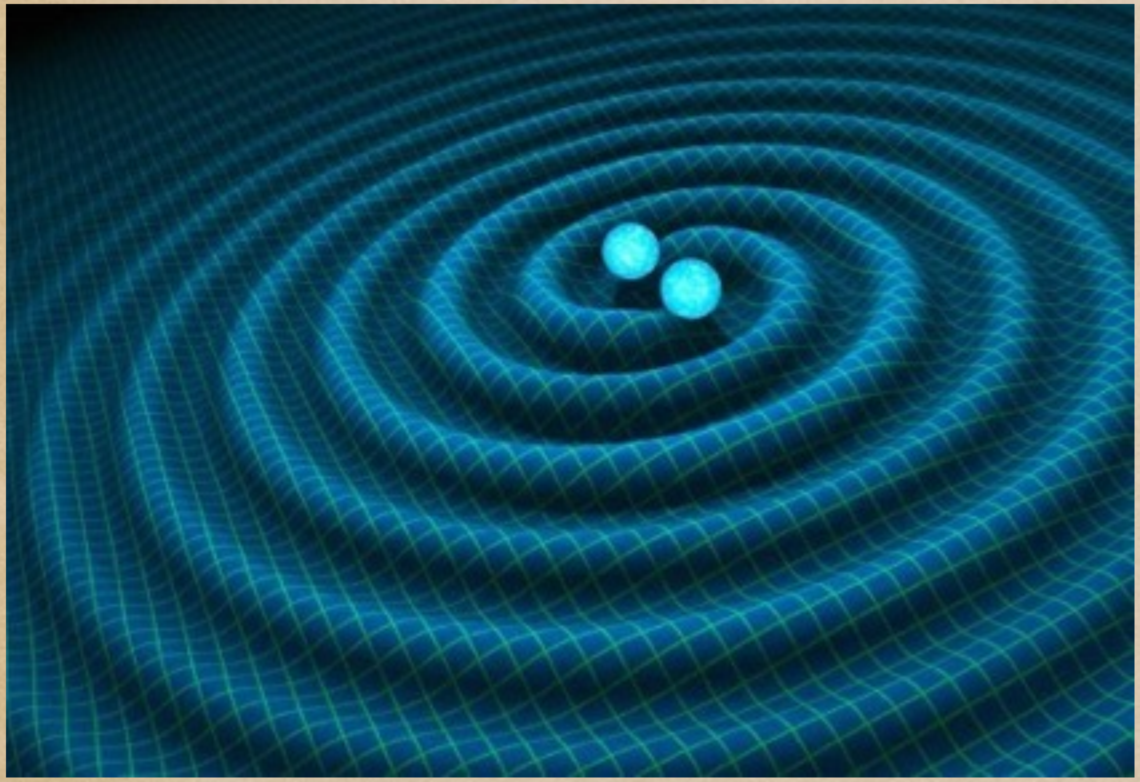
10^{-9}

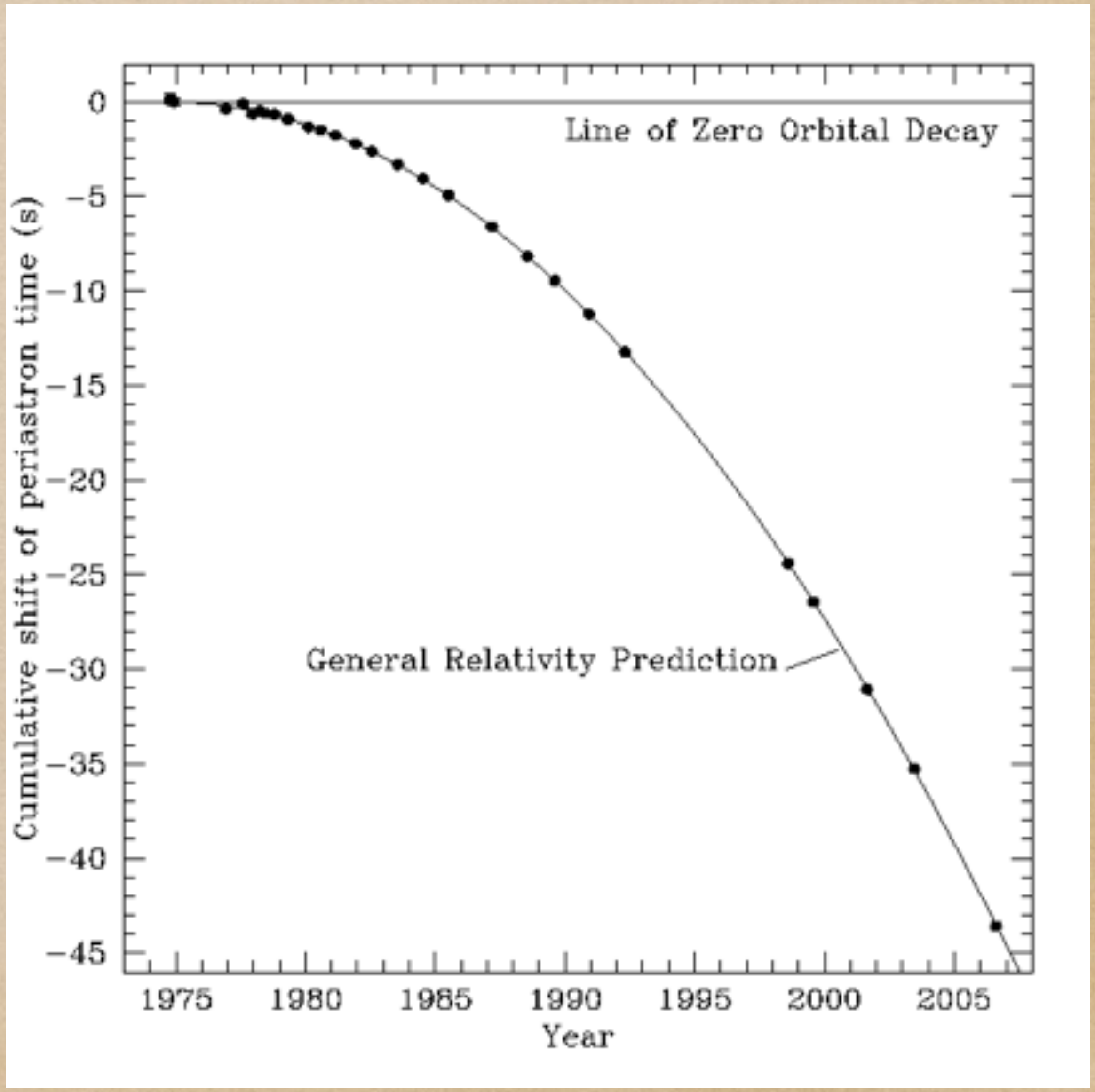
10^{-6}

10^{-6}

Even binary pulsars are non-relativistic

Hulse-Taylor Pulsar

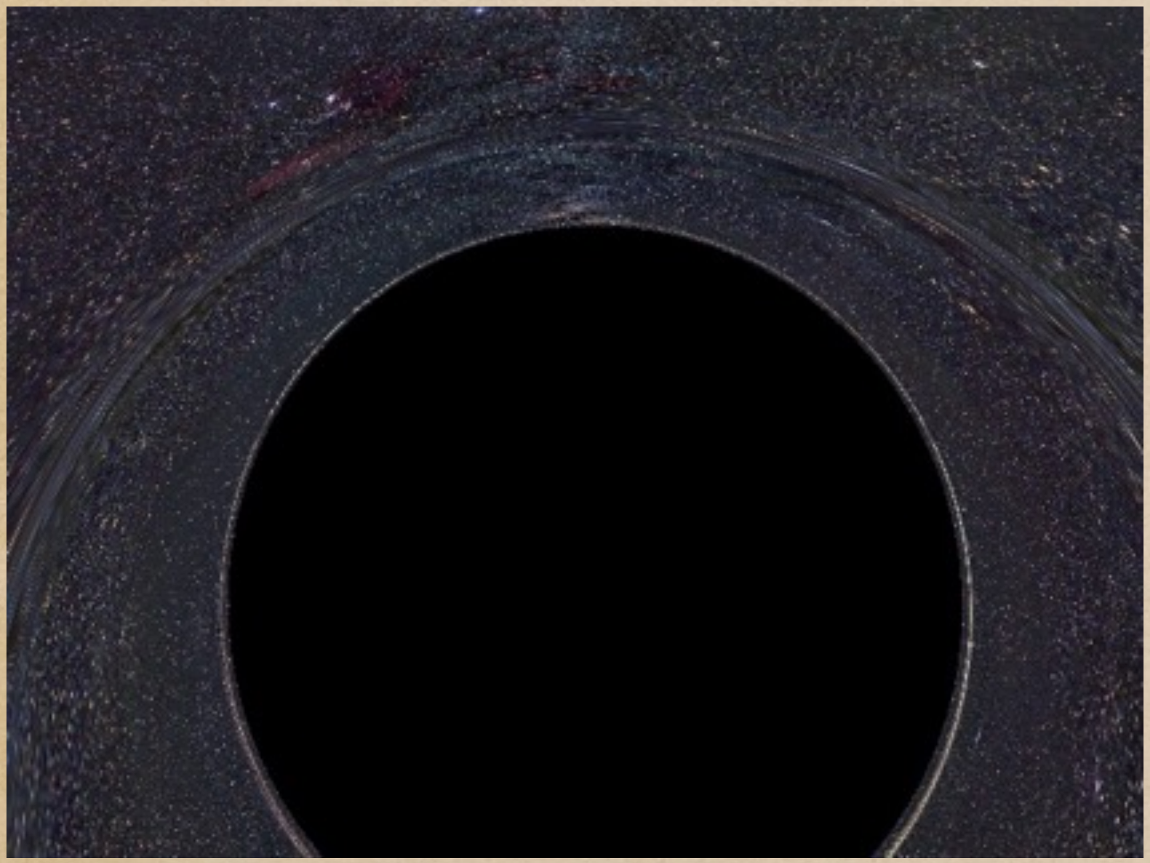


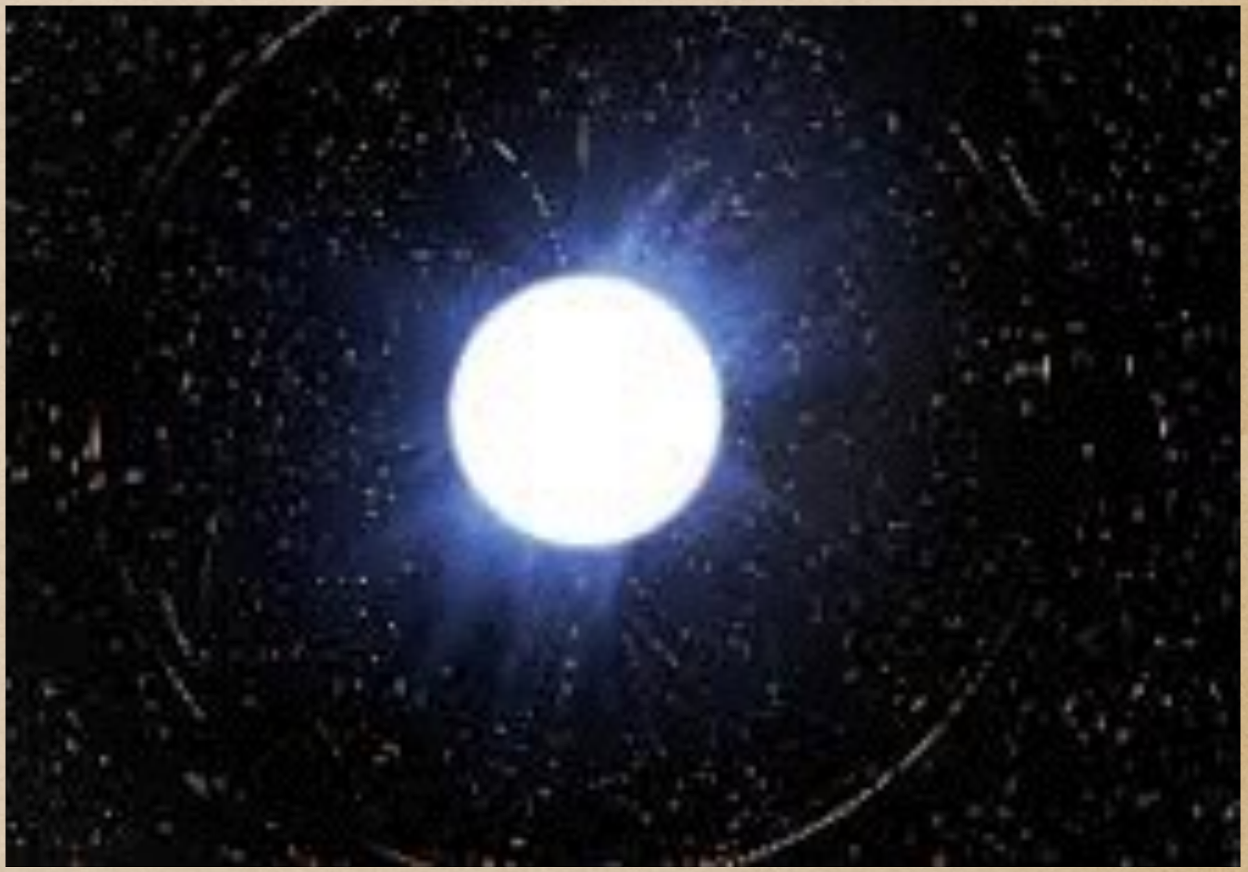


$$v^2/c^2 = 10^{-2}!$$

When is general relativity important?

Strong gravitational fields:



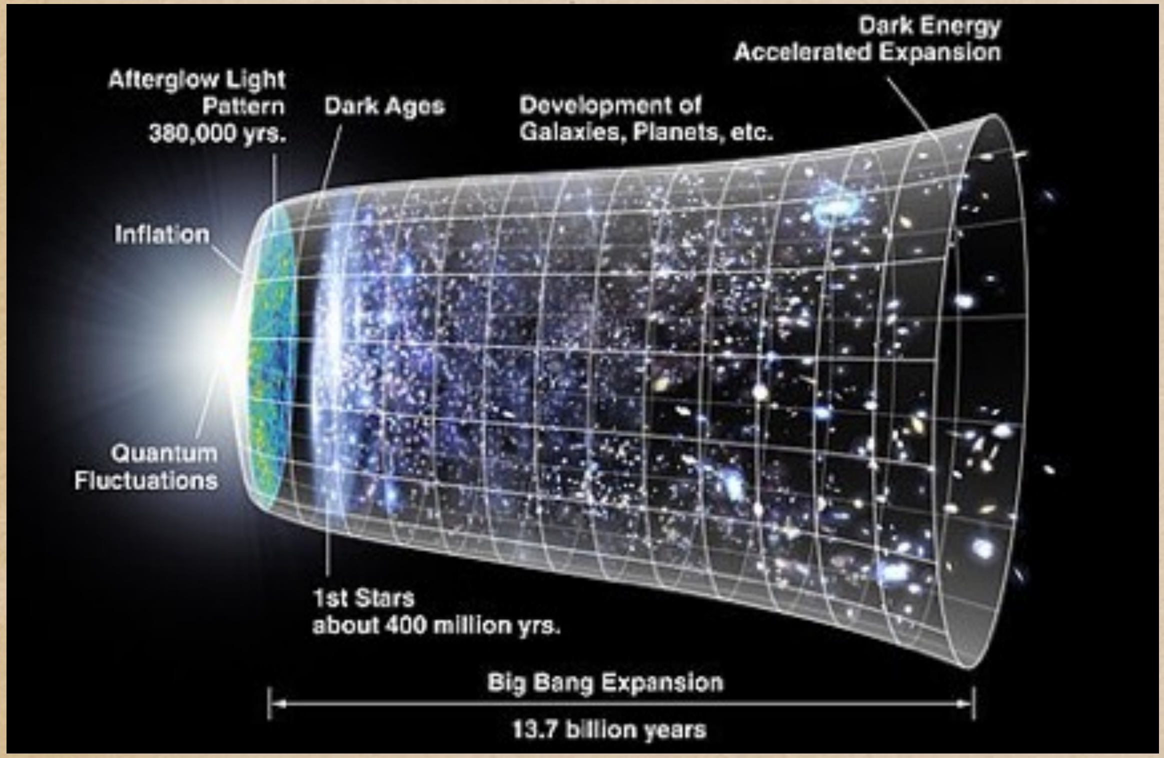


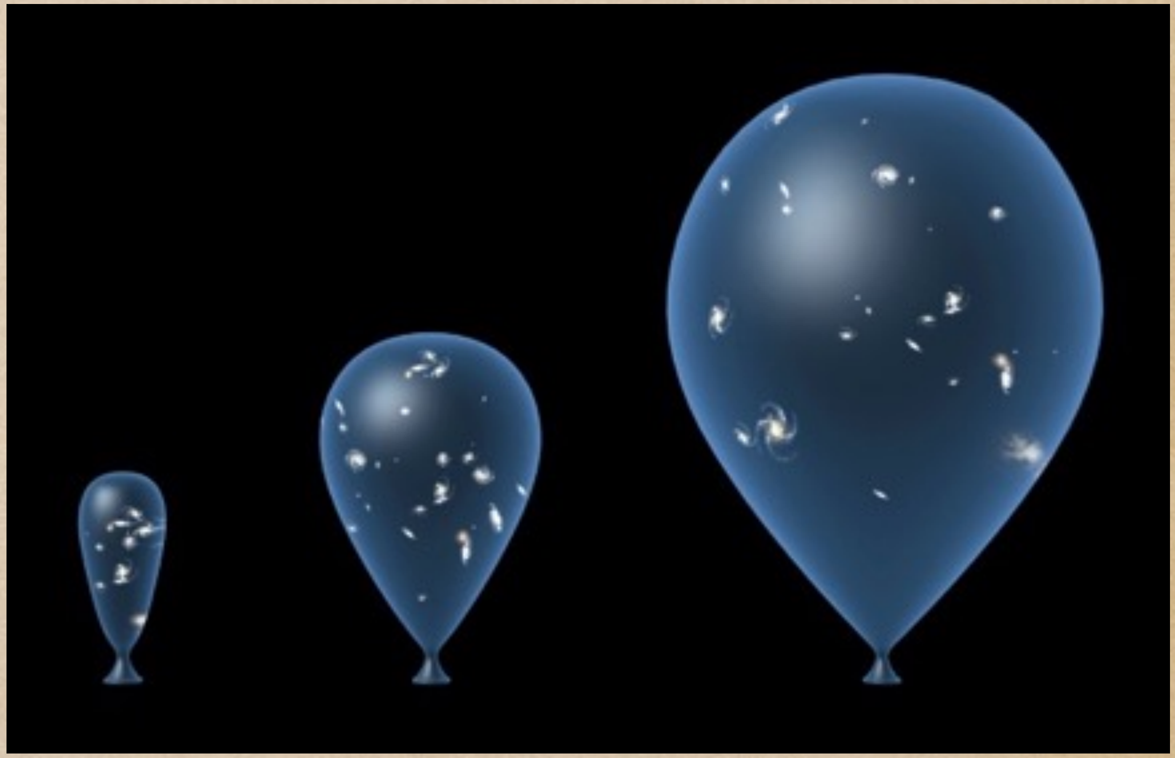
Black holes

Neutron stars

When is general relativity important?

Large distances:





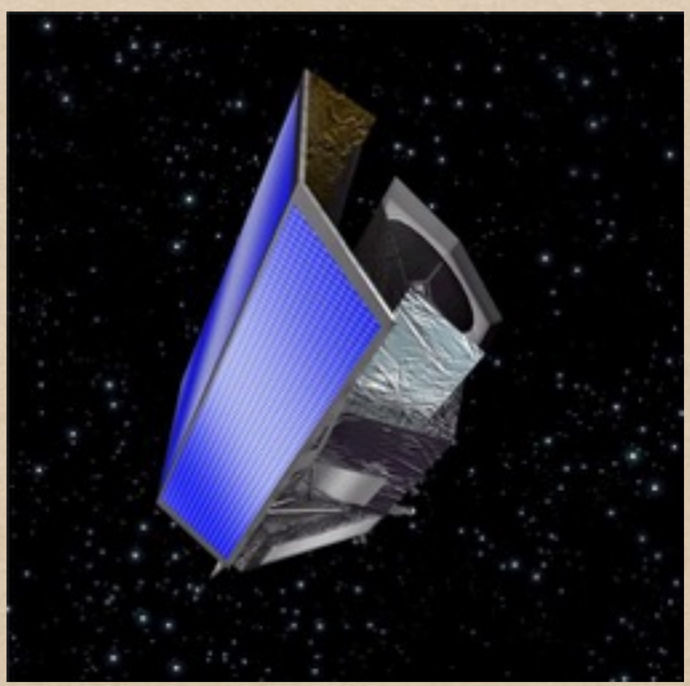
Cosmology

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

Cosmology:

DES

(spectroscipic)



EUCLID

(lensing)

SKA

(21 cm)

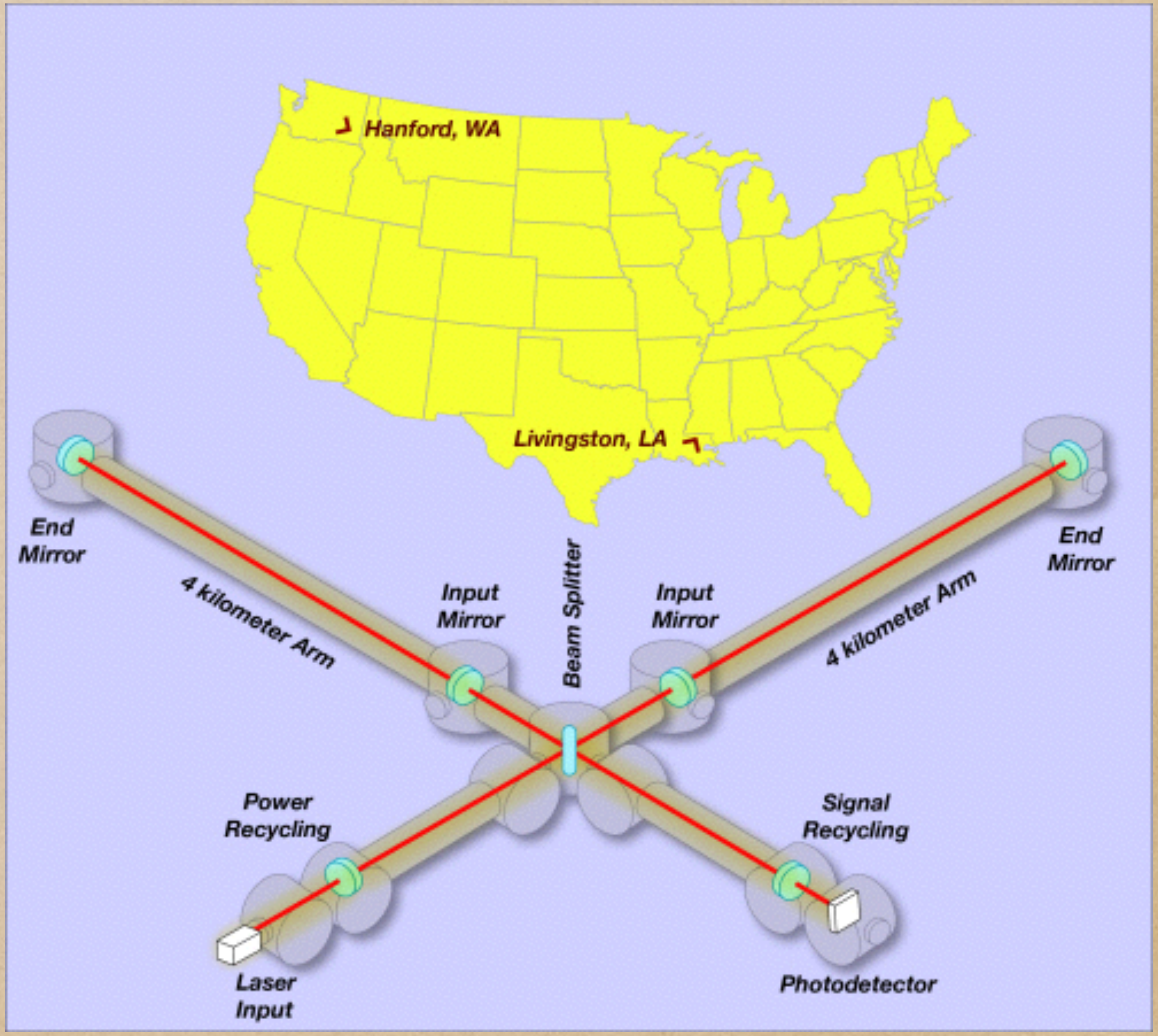
We will test both of these in the next decade and beyond

Strong fields:

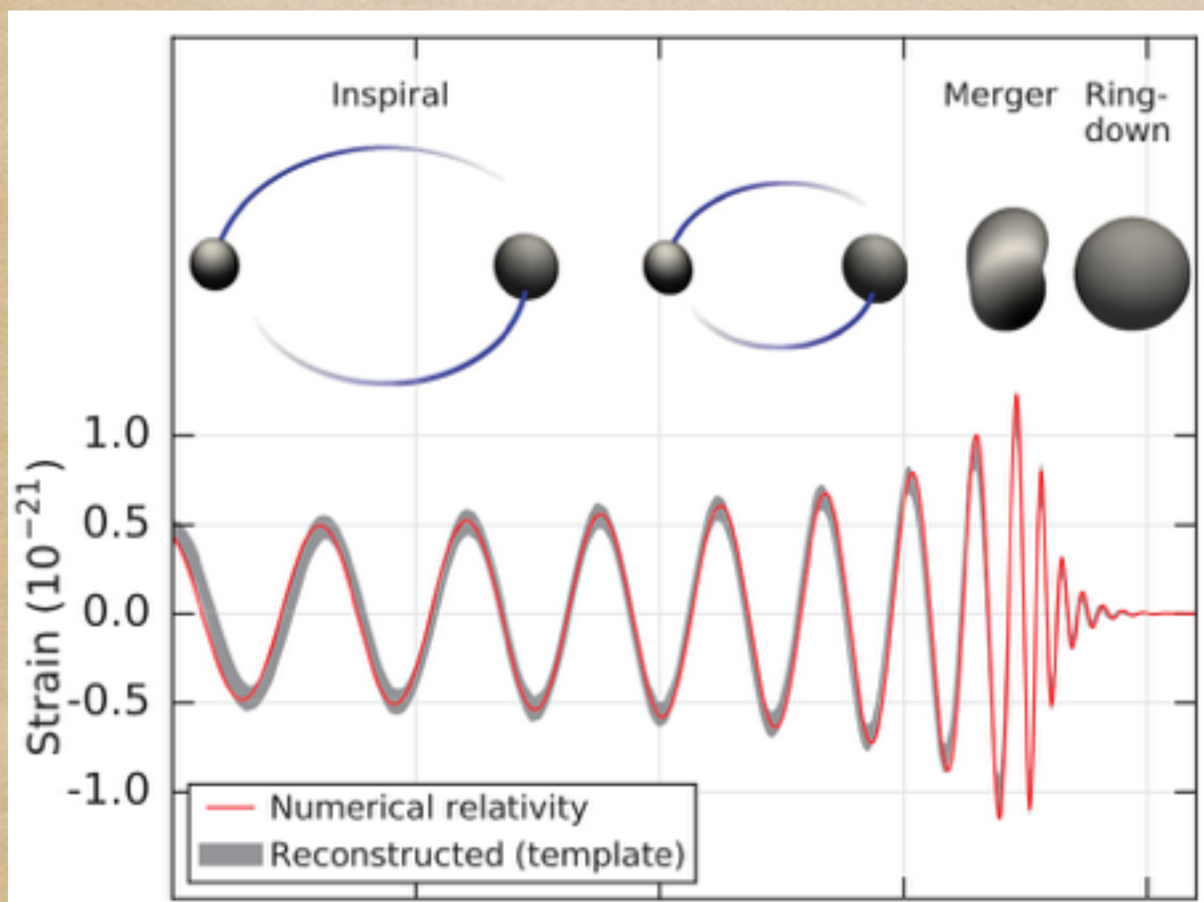
Gravitational waves from

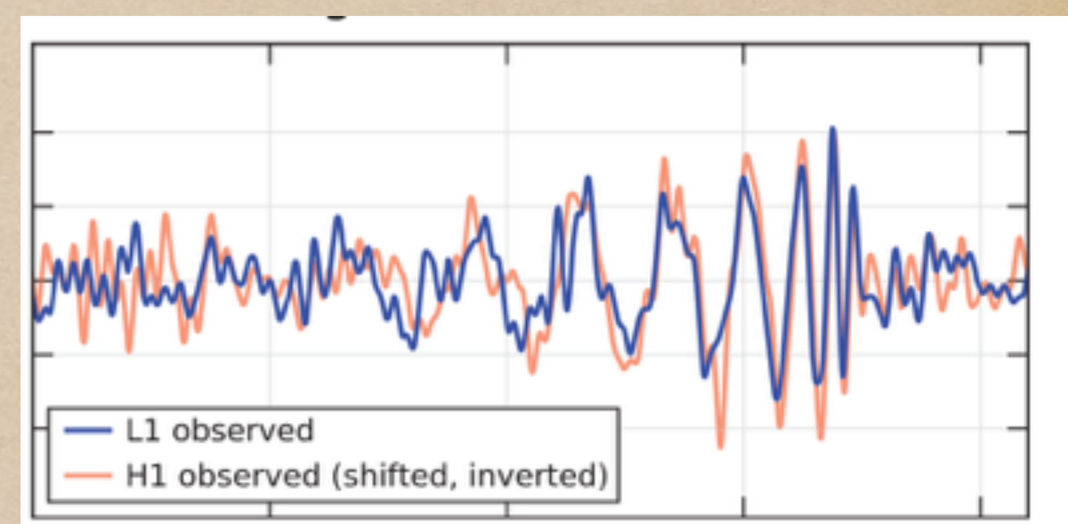
- Black hole mergers
- Neutron star mergers

LIGO



Gravitational waves were discovered last year!

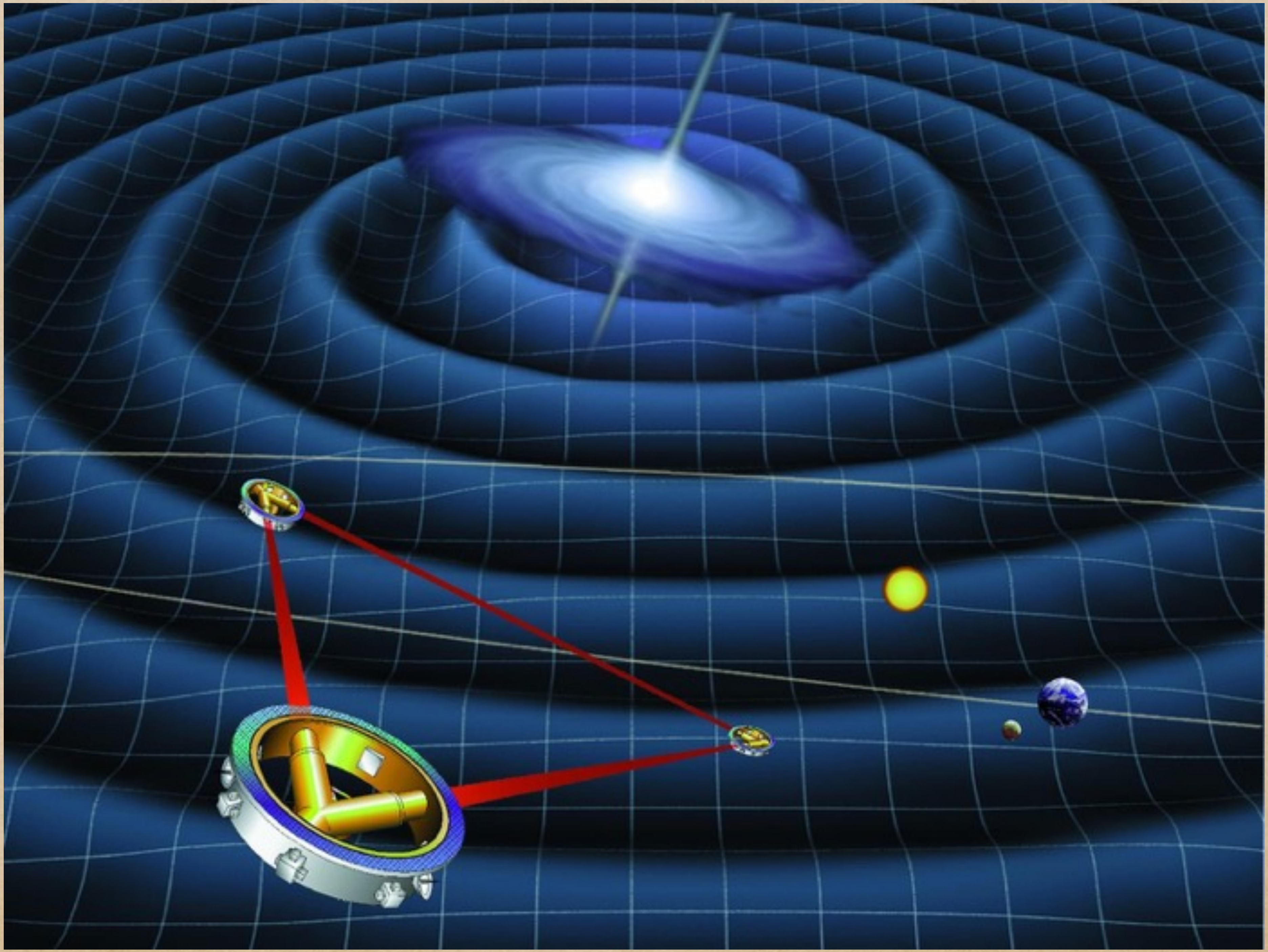




In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves.

Can we test gravity with this? See later!

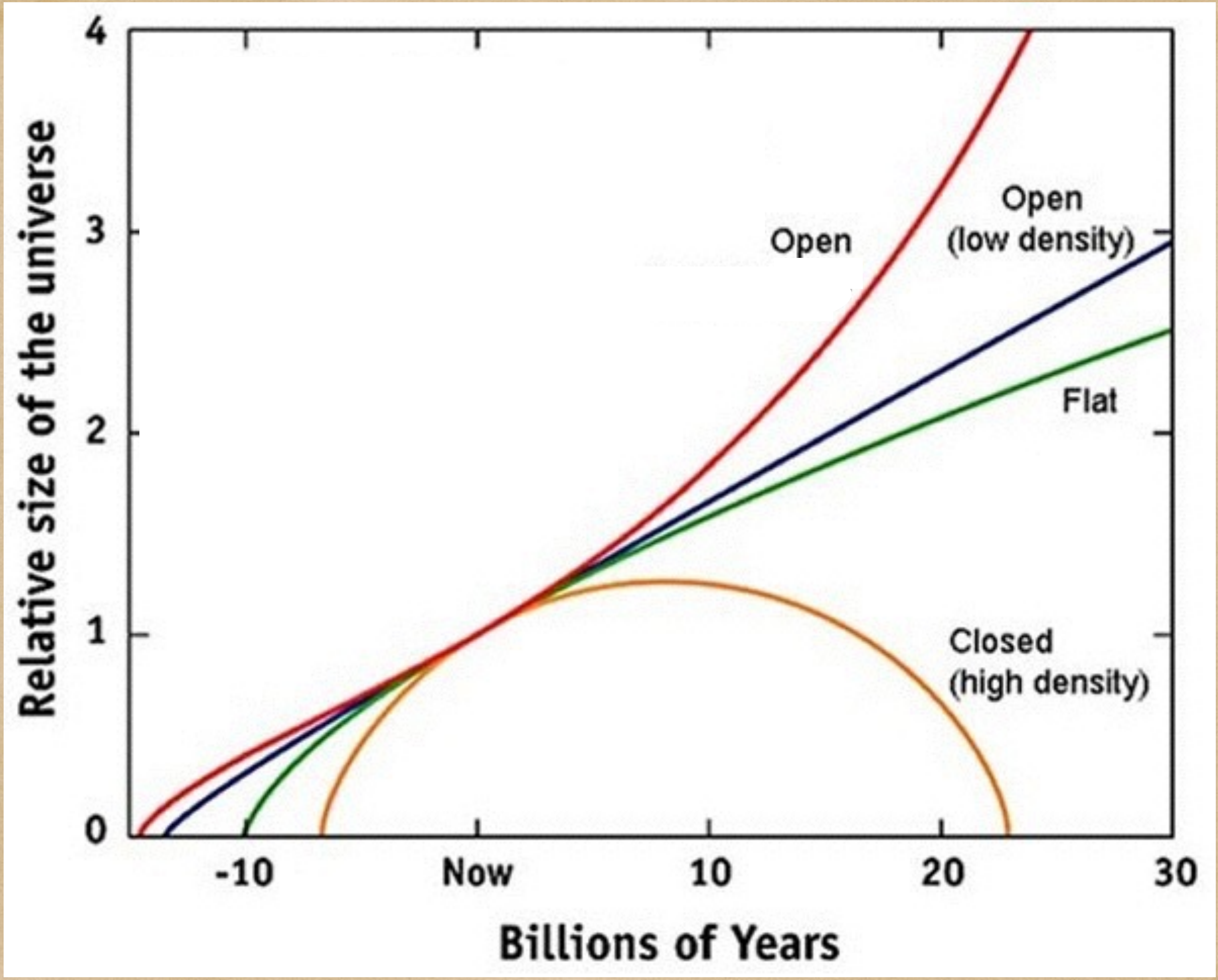
eLISA: Planned



Why do I study modified gravity?

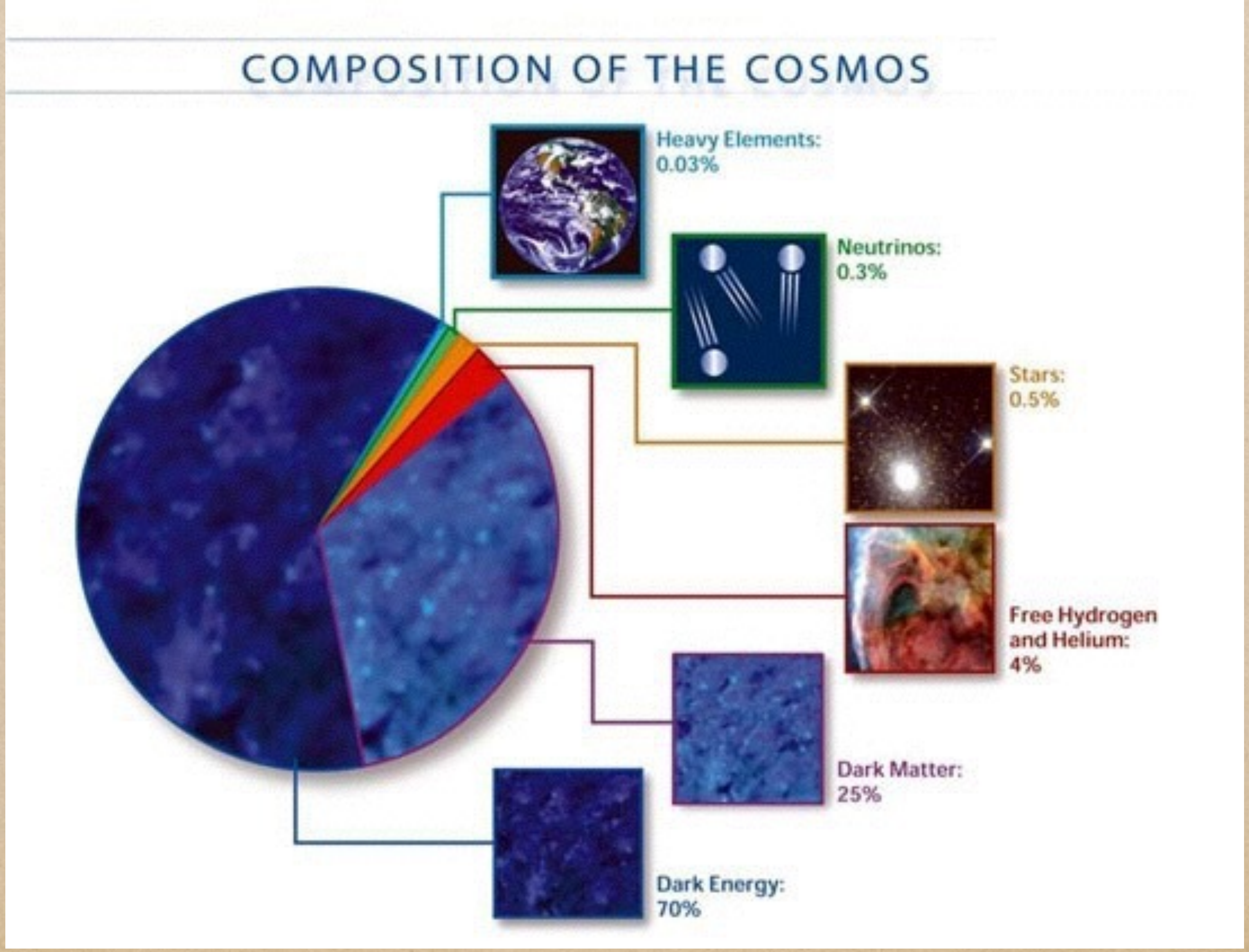
Dark energy: (Dark = we have no idea)

- The expansion of the Universe is accelerating
- Gravity is attractive so it should be slowing down
- We call the accelerating mechanism dark energy



Relative size of the universe
4
3
2
1
0
Open
Open
(low density)
Flat
Closed
(high density)
-10
Now
10
20
30
Billions of Years

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

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

Attractive

repulsive

wins at large distances

General relativity:

Gives exponential acceleration

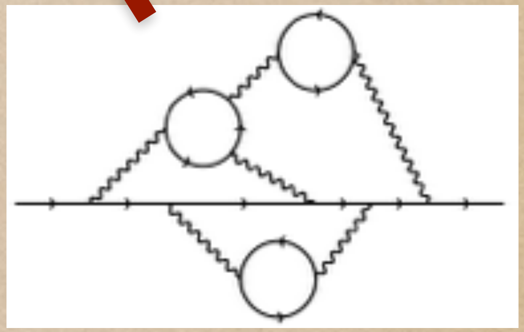
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The cosmological constant is unnatural

Quantum effects change the value:

$$\Lambda = \Lambda_{\mathrm{bare}} + \Lambda_{\mathrm{quantum}}$$

Set by hand



Have to tune to 120 decimal places:

$$\Lambda_{\mathrm{bare}} = -\Lambda_{\mathrm{quantum}} + 10^{-120}$$

Theorists don't like this

Alternative is to add new stuff

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

New gravity theory

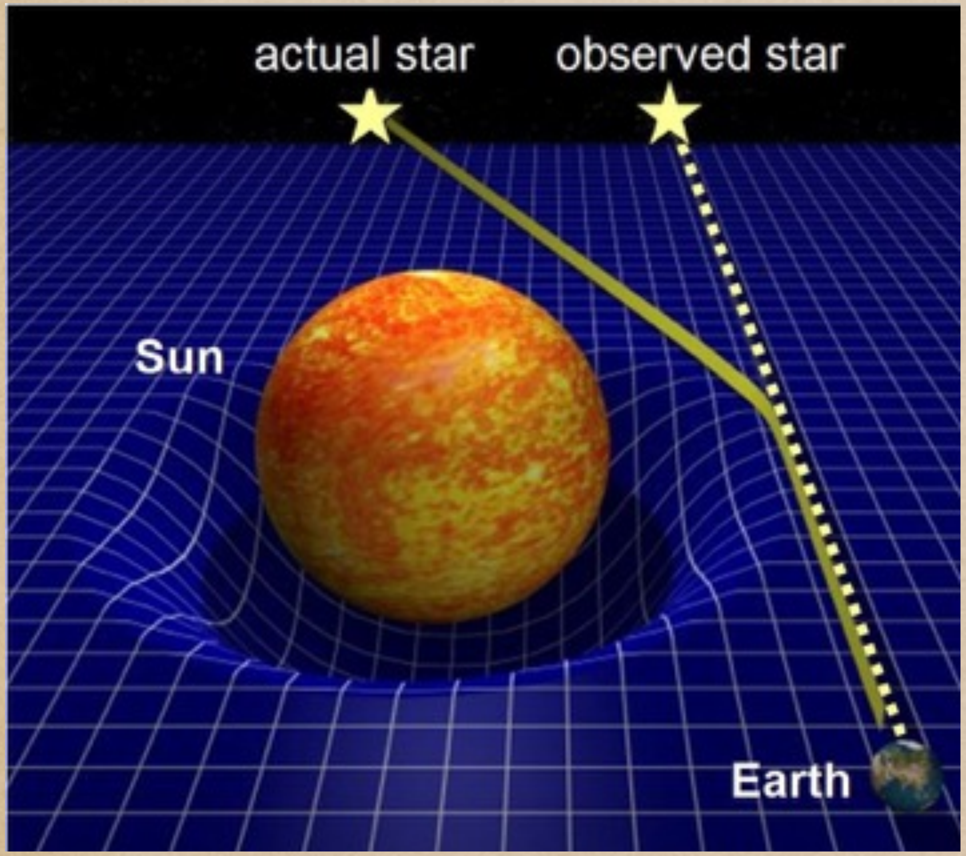
New matter

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

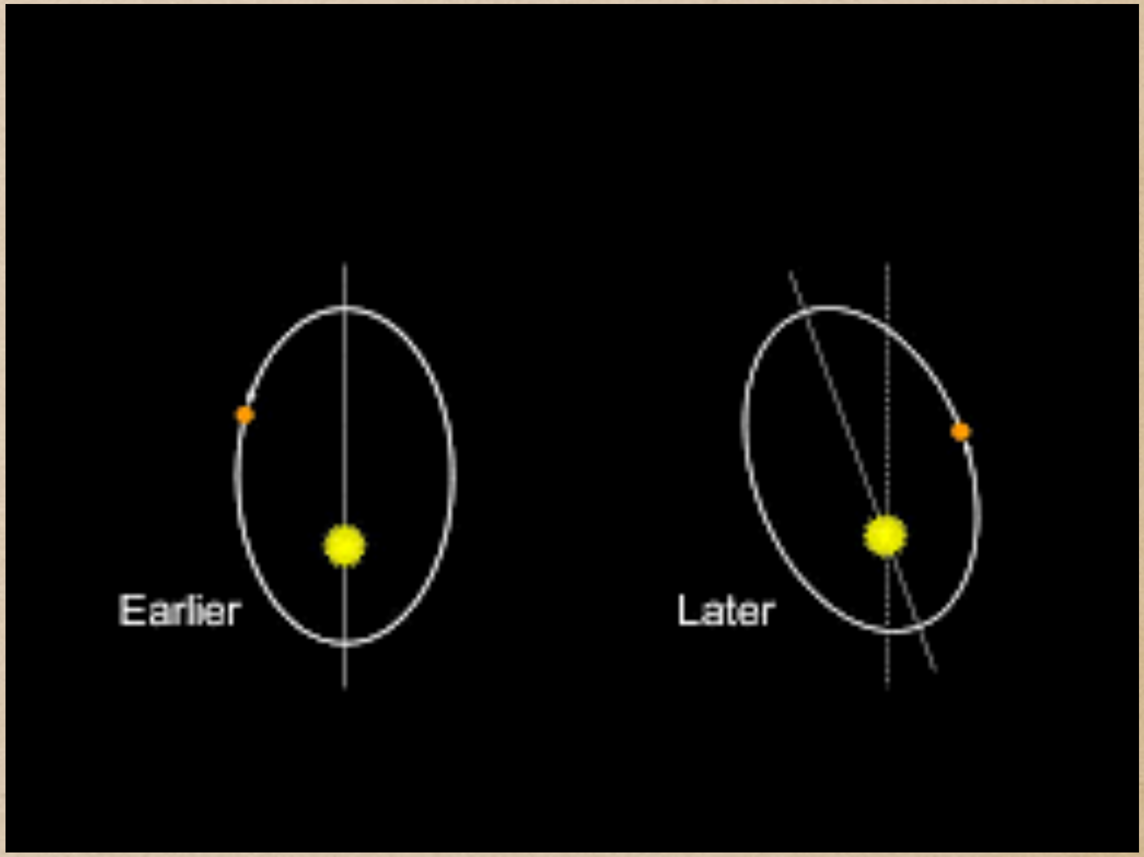
*Still need to explain why $\Lambda = 0$

What does changing gravity do?

Screws up the solar system:



Light bending



Precession of Mercury

What do local tests mean?

GR:

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

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

Field equation

Force law

What do local tests mean?

New force field ϕ :

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

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

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

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:

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

Poisson

Non-Poisson

Poisson

Vainshtein mechanism

We can integrate this once:

$$x = \frac{F_5}{F_\mathrm{N}}$$

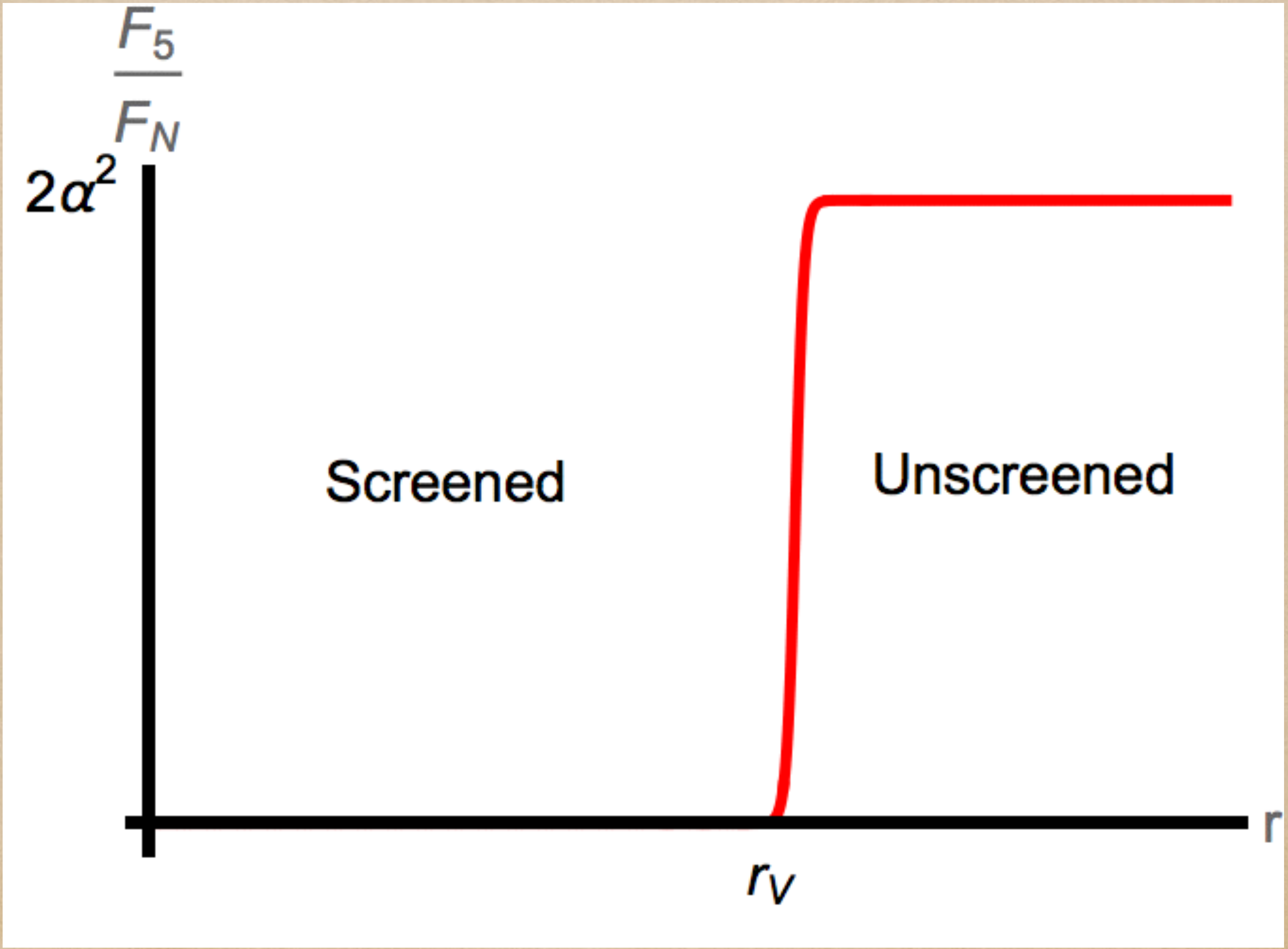
$$x + \left(\frac{r_\mathrm{V}}{r}\right)^3 x^2 = 2\alpha^2$$

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

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

r_V - Vainshtein radius

Vainshtein screening



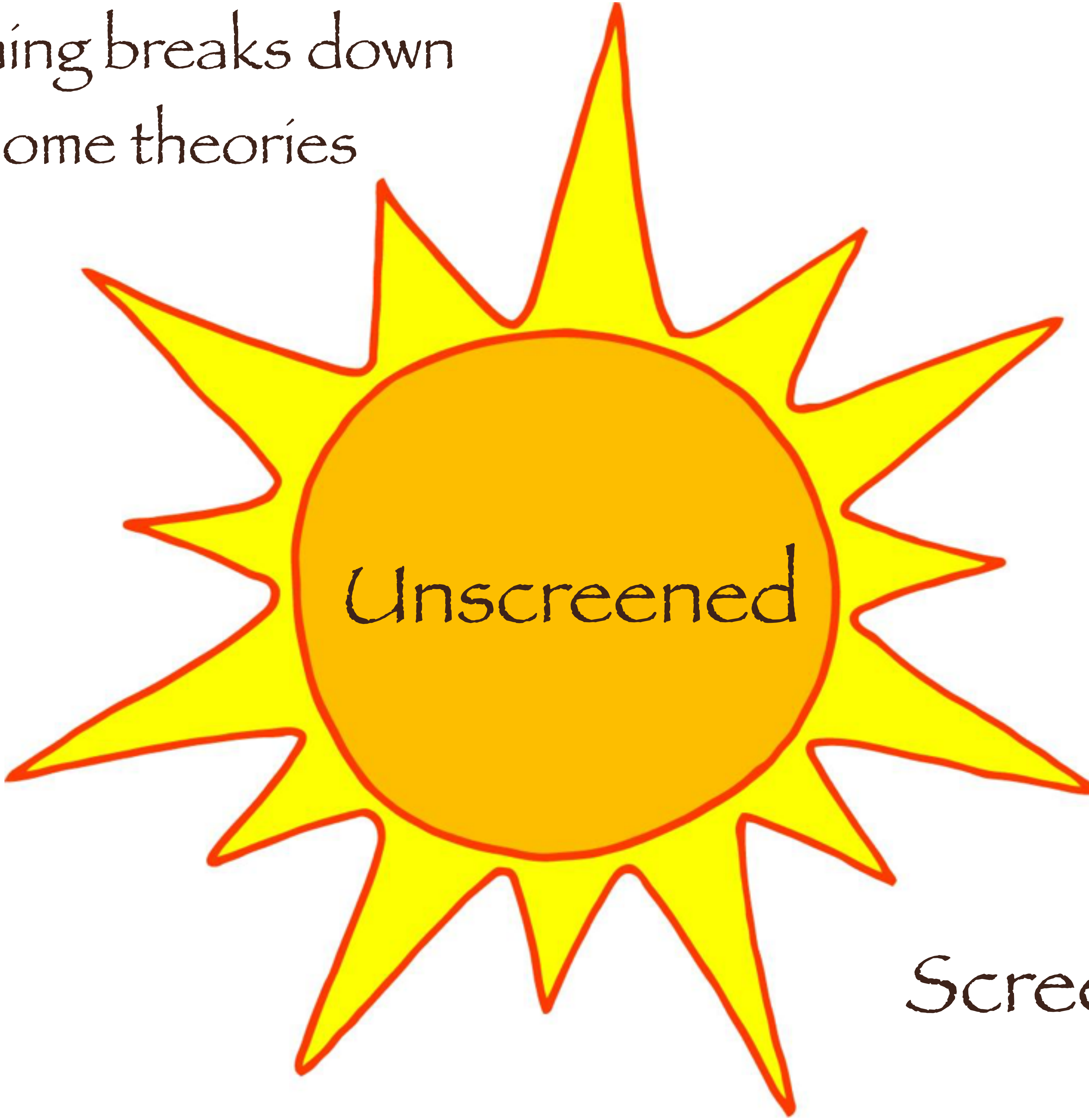
Vainshtein screening

$$r_{\rm V}^{\odot} \geq 10^2 \ {\rm pc}$$

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



Screened

Vainshtein breaking

GR:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{GM(r)}{r}$$

Vainshtein:

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

Υ controls cosmology of the theory

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

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

$$\Upsilon > 0$$ — 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):

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

Hydrodynamics

Newtonian gravity

Vainshtein:

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

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 live longer

Tools of the trade: polytropic stars

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

polytropic index

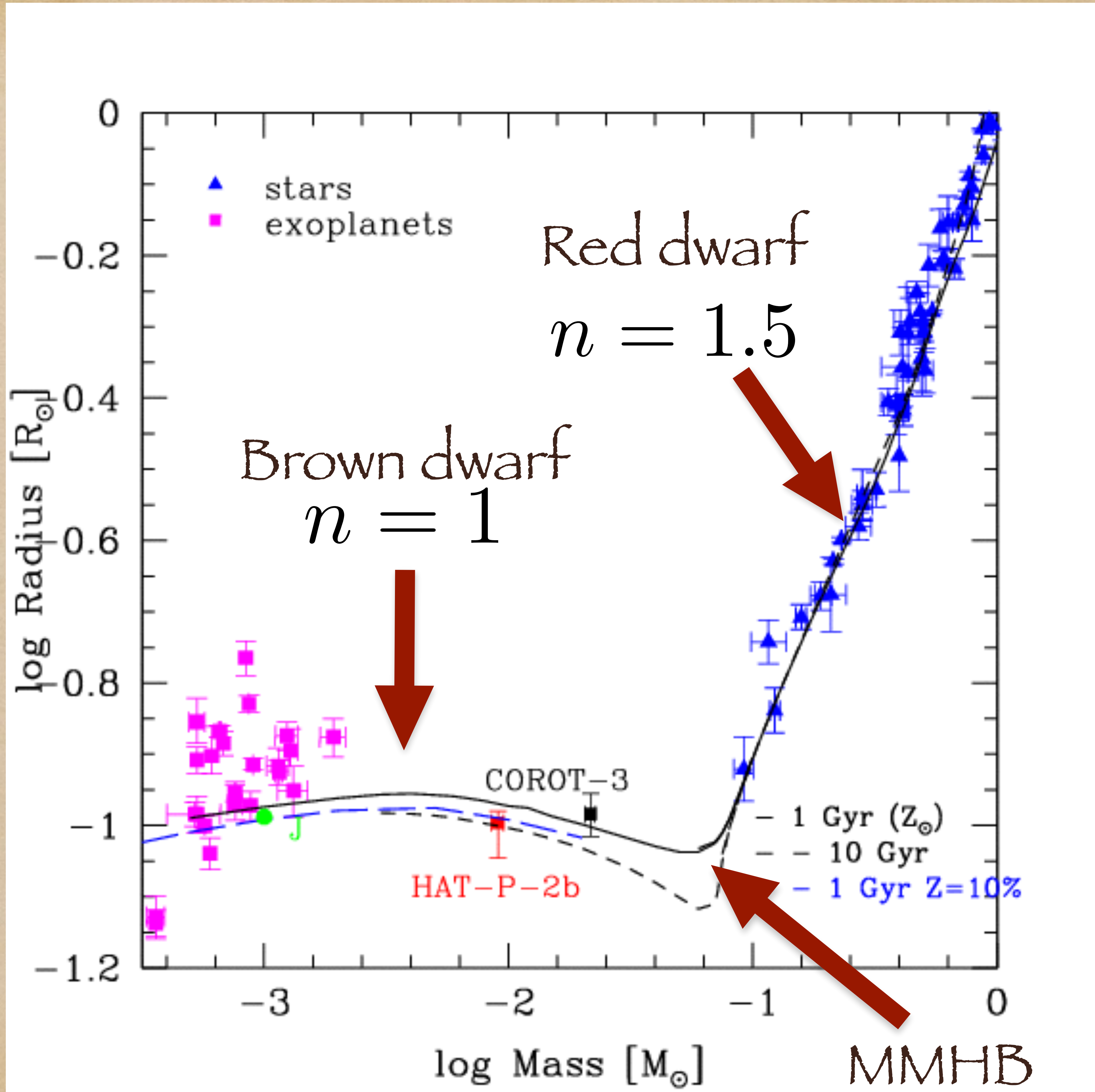
- n = 3 - main sequence, white dwarfs
- n = 1.5 - convective stars, high mass brown dwarfs
- n = 1 - low mass brown dwarfs

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



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

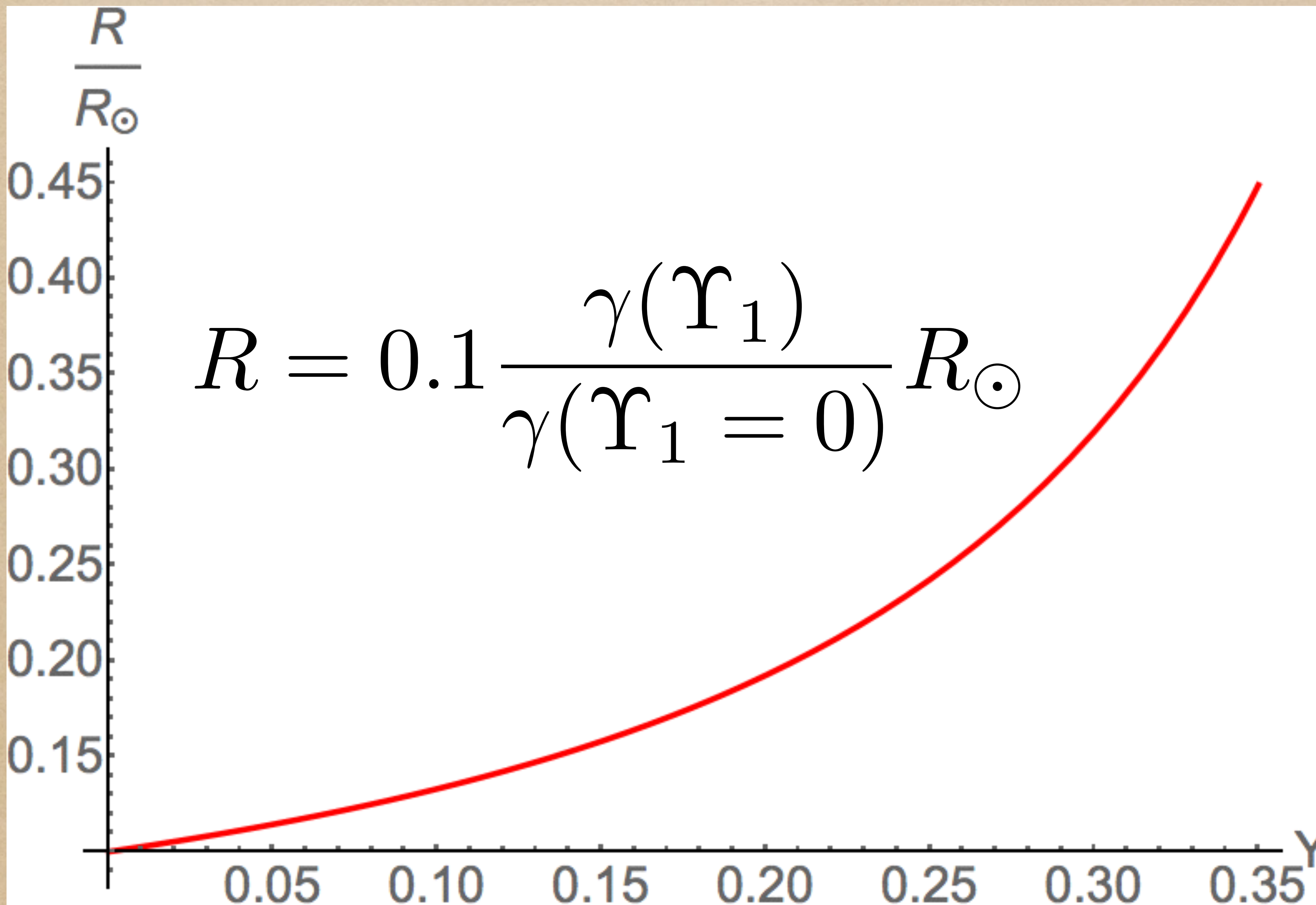
Coulomb pressure $\Rightarrow \; n = 1 \qquad (P = K\rho^2)$

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

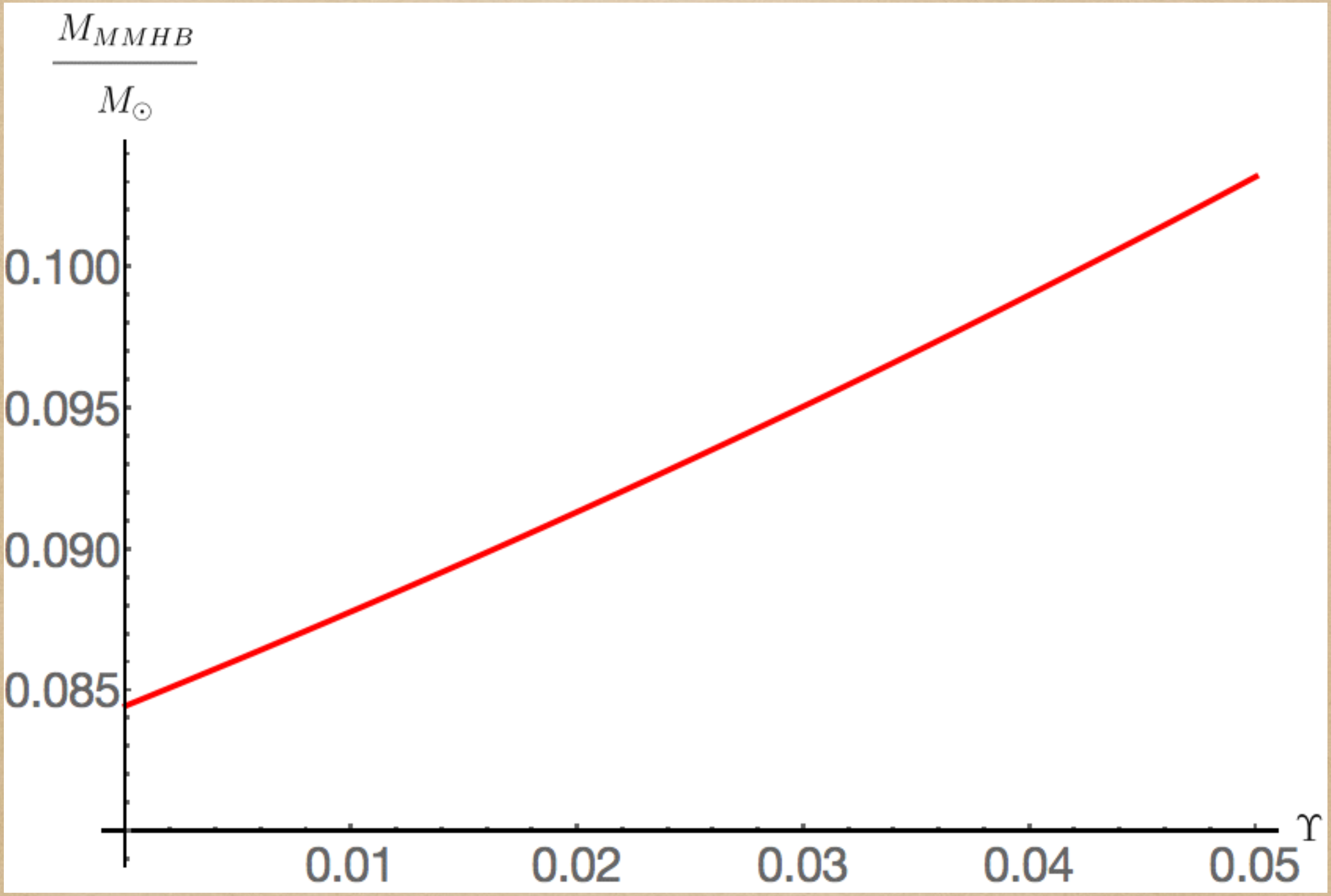
$L_{\mathrm{HB}} = L_{\mathrm{eff}}$:

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

Proton burning

$n = 1.5$ + theory of gravity

JS '15, PRL


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

New constraint

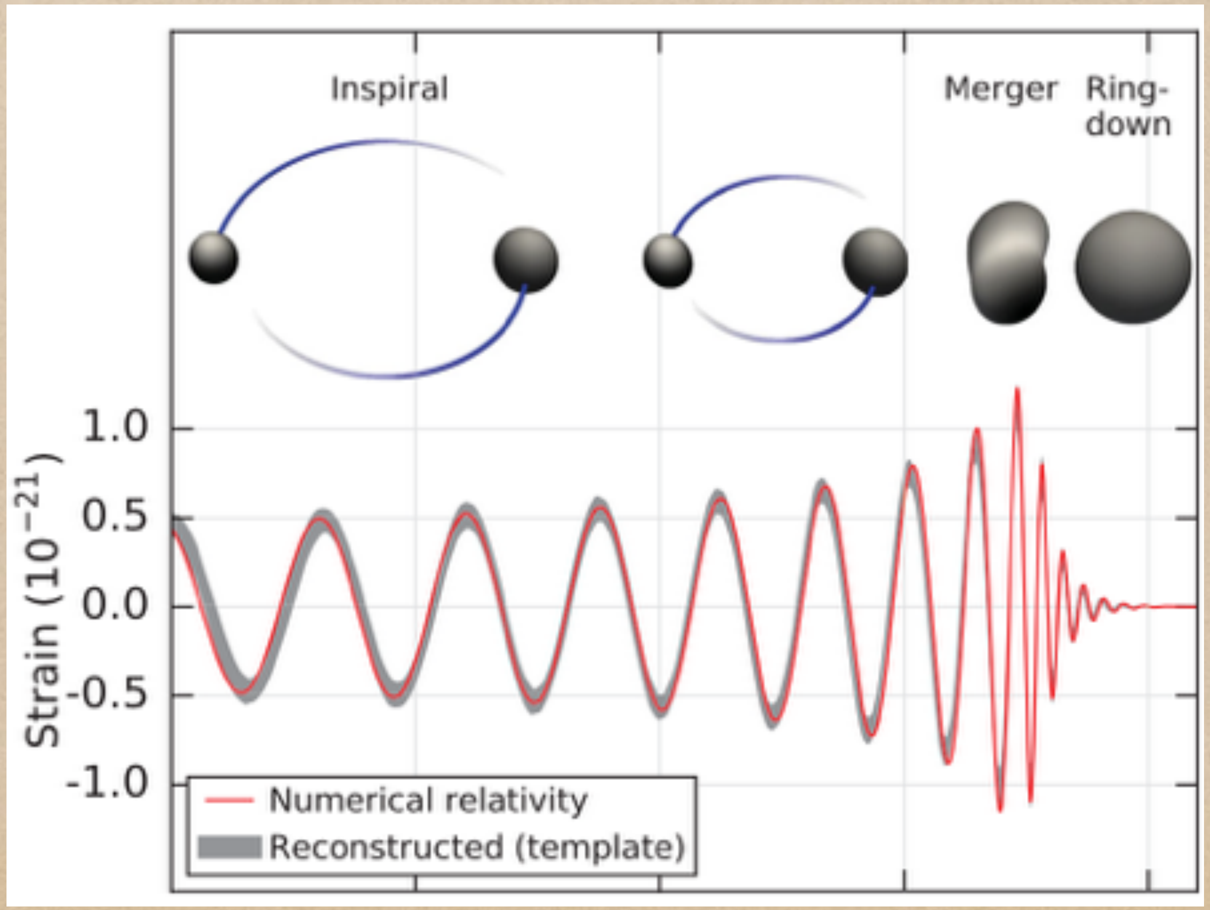
Lowest mass star is Gl 886 C

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

$$\Rightarrow \Upsilon < 0.027$$

Strong field tests of gravity

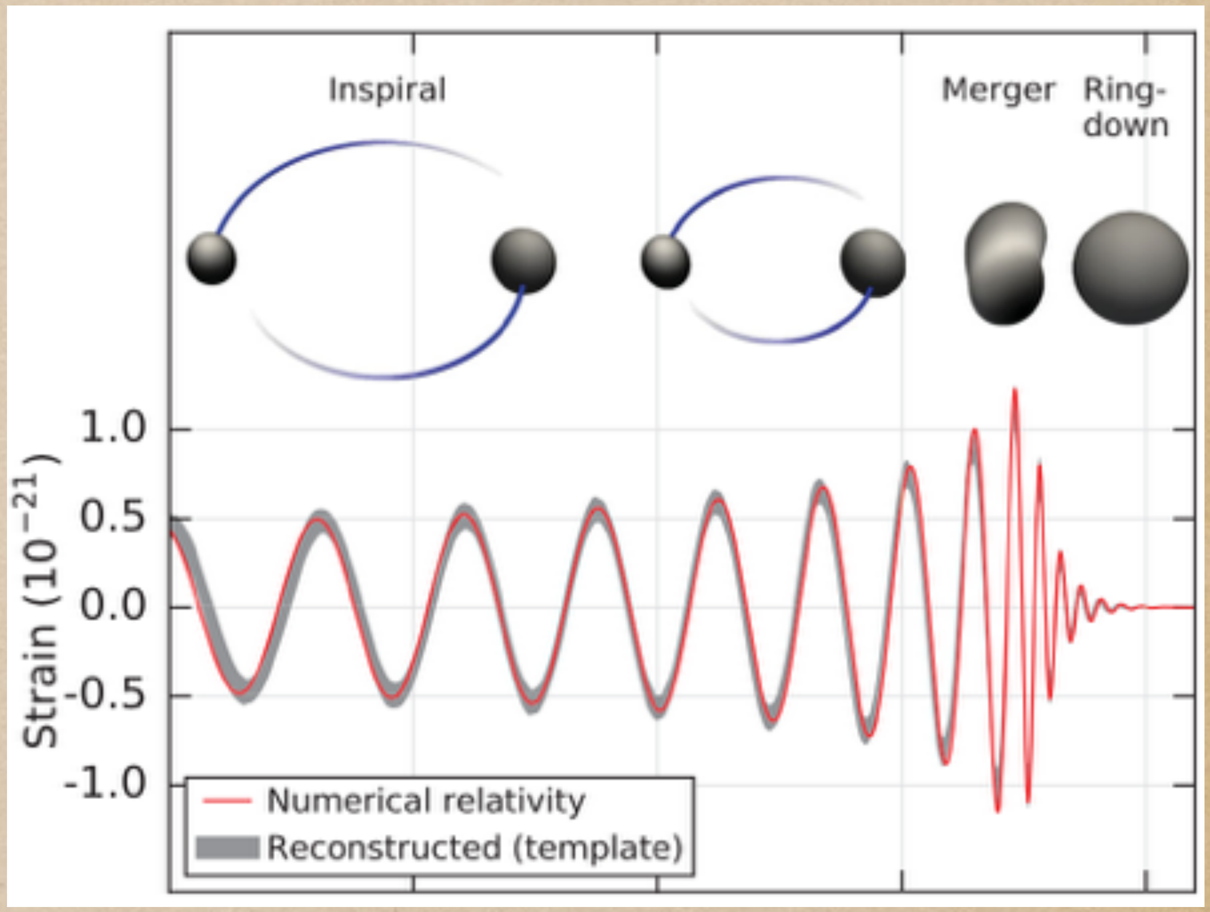
Q: Can GWs from BHs test GR?



No-hair theorem

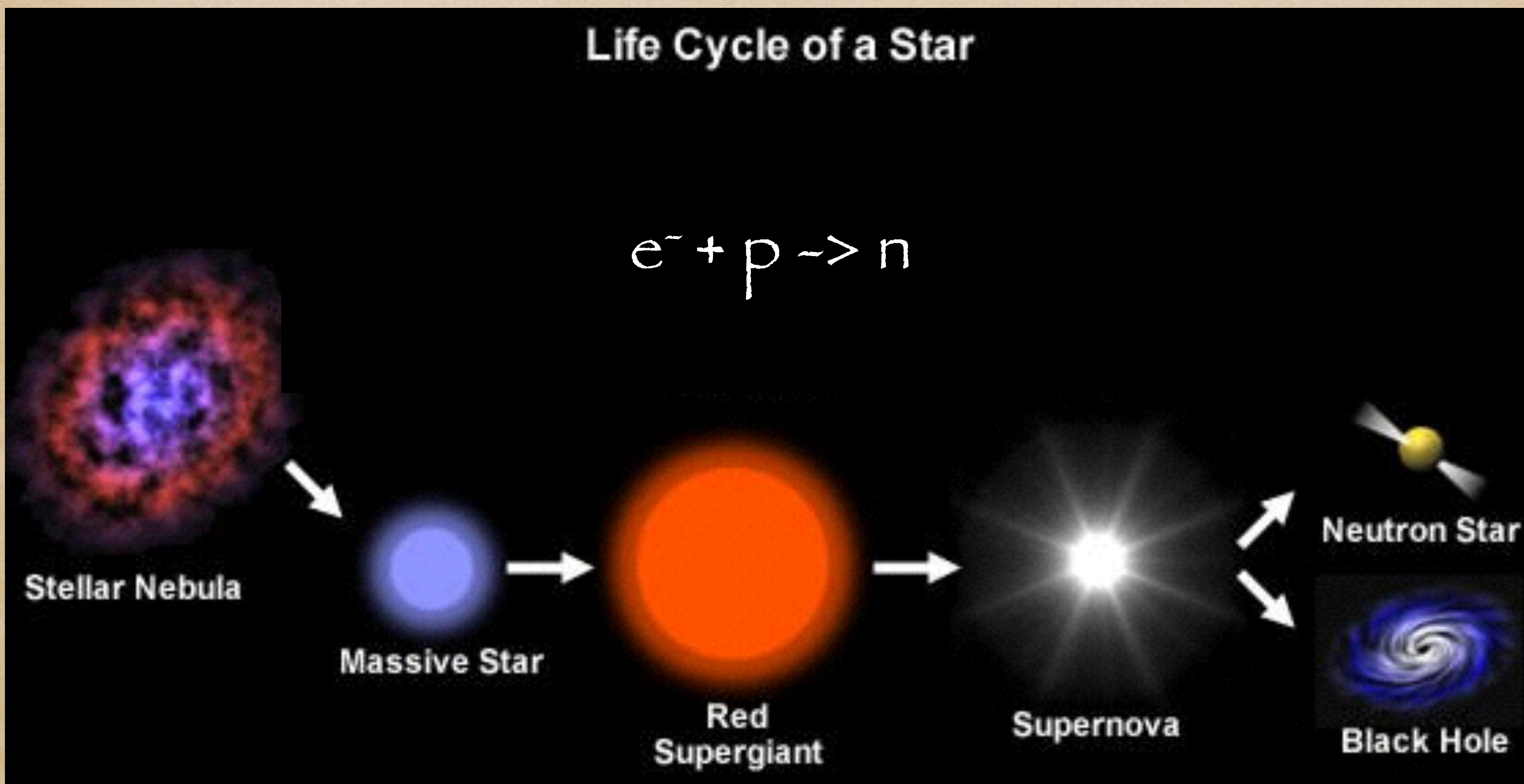
Black holes described by:

- Mass M
- Spin a
- Charge Q



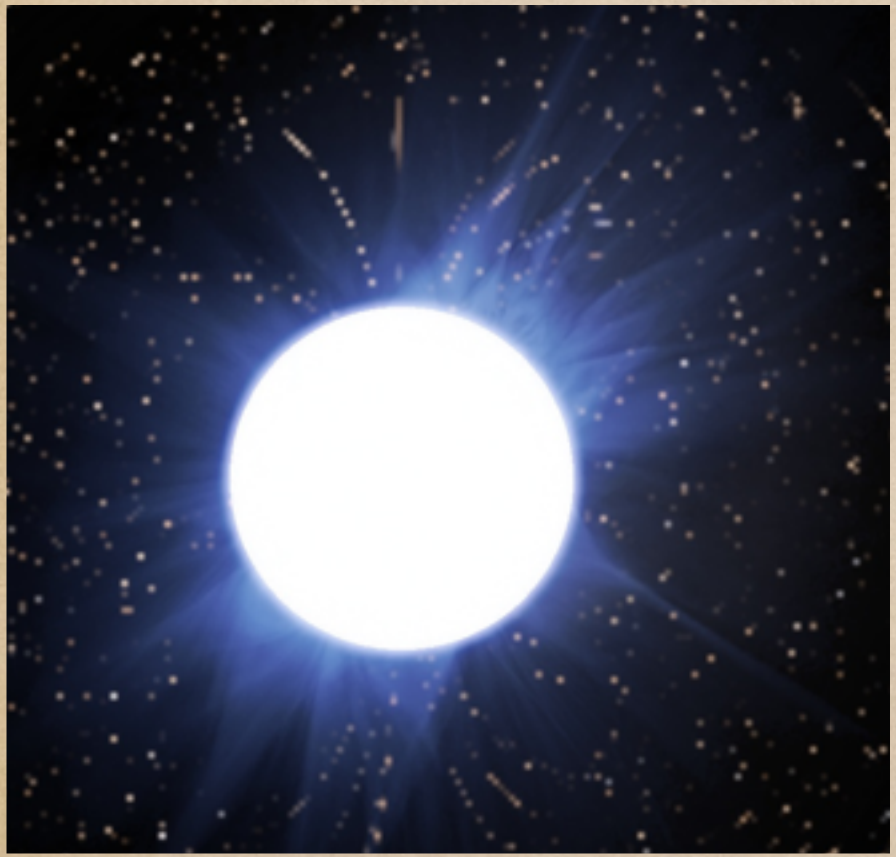
Lots of theories look like GR!

Neutron stars



$$e^- + p \rightarrow n$$

Neutron stars



Mass — Sun

Radius — few km

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

Relativistic: $v/c \sim 1$

Tolman-Oppenheimer-Volkov equation

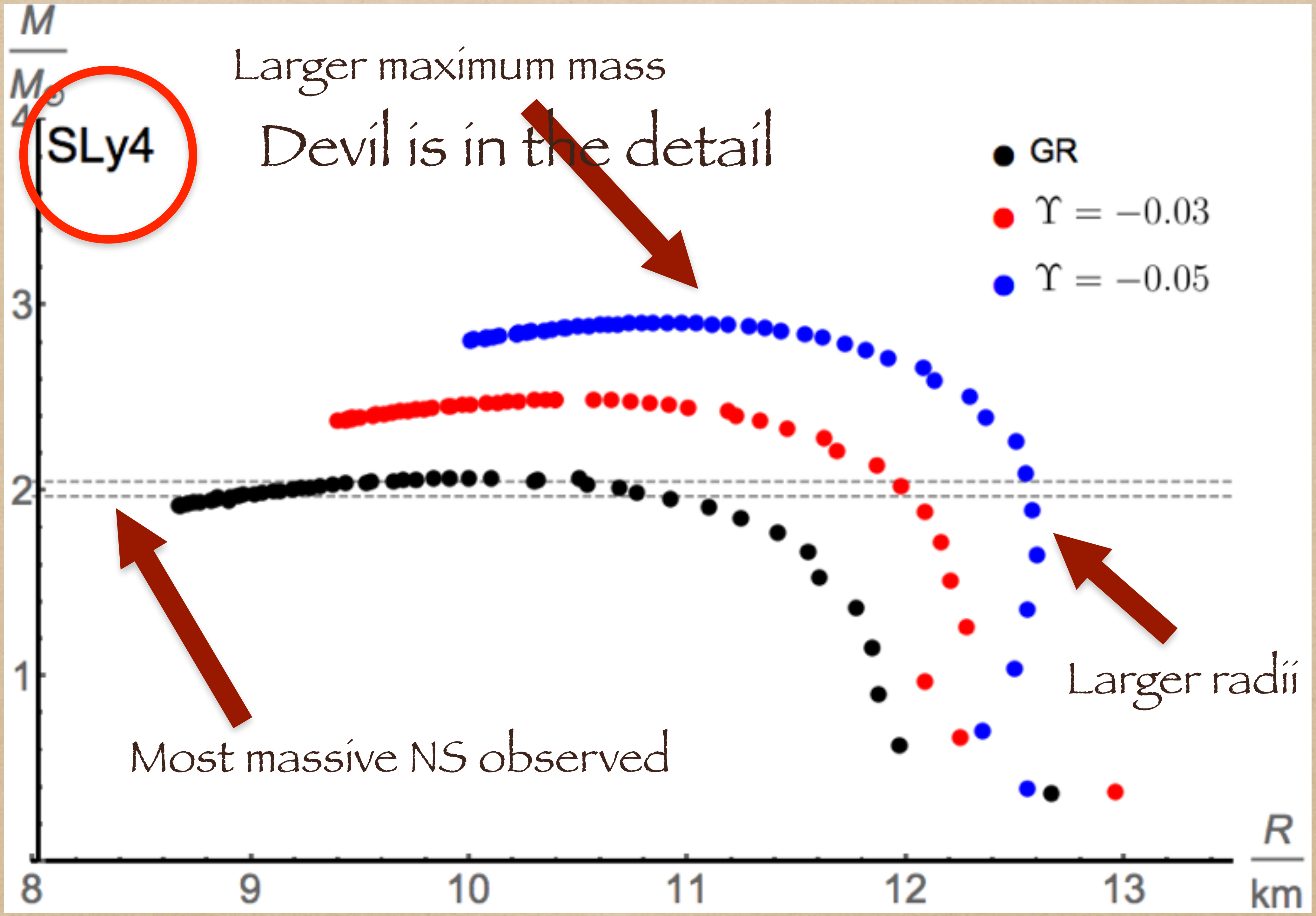
$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM\rho}{r^2}\left[1+\frac{P}{\rho c^2}\right]\left[1+\frac{4\pi r^3}{M}\frac{P}{\rho c^2}\right]\left[1-\frac{2GM}{rc^2}\right]^{-1}$$

Relativistic hydrodynamics

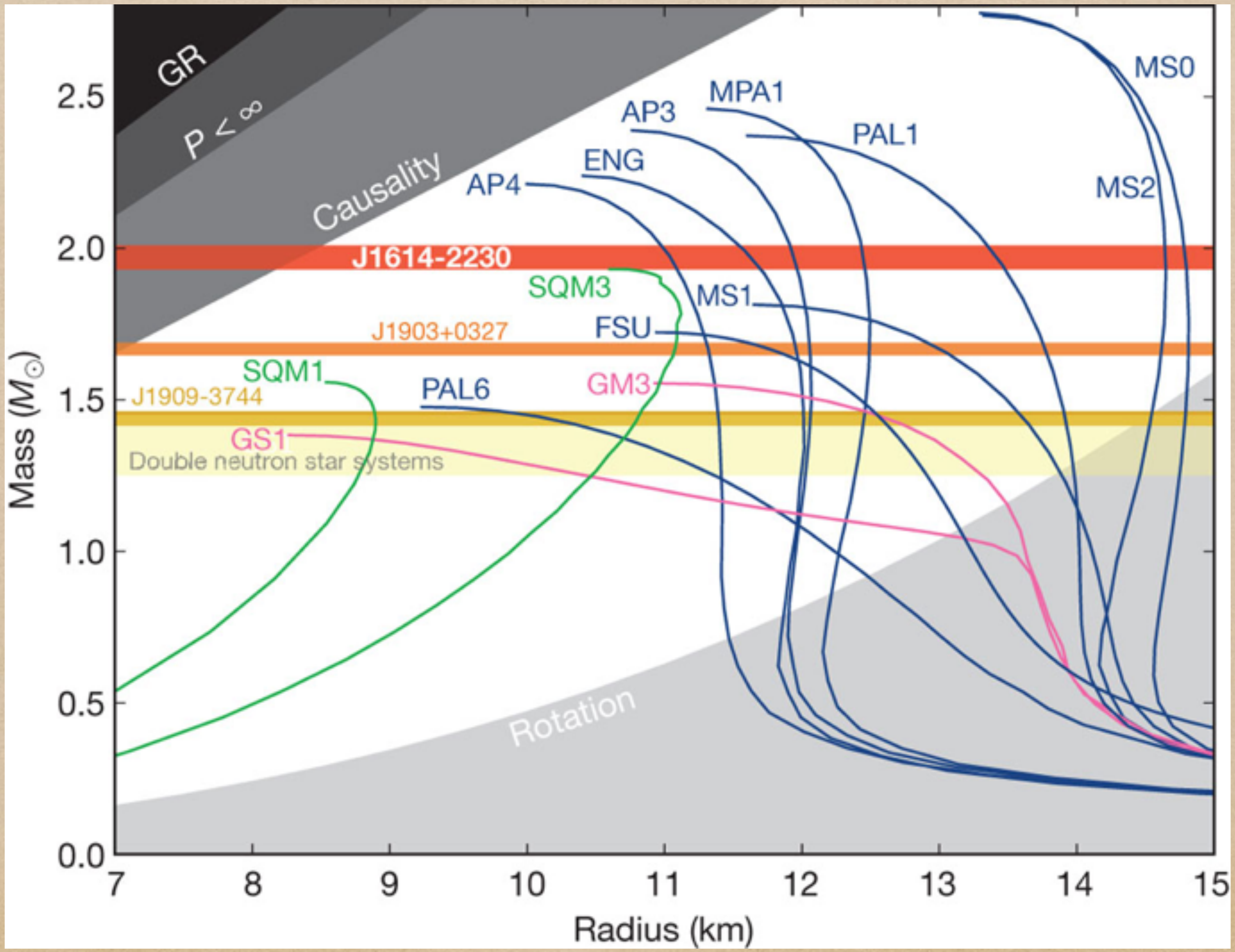
General relativity

Vainshtein: $+\cdots$

Can we test Vainshtein with this?

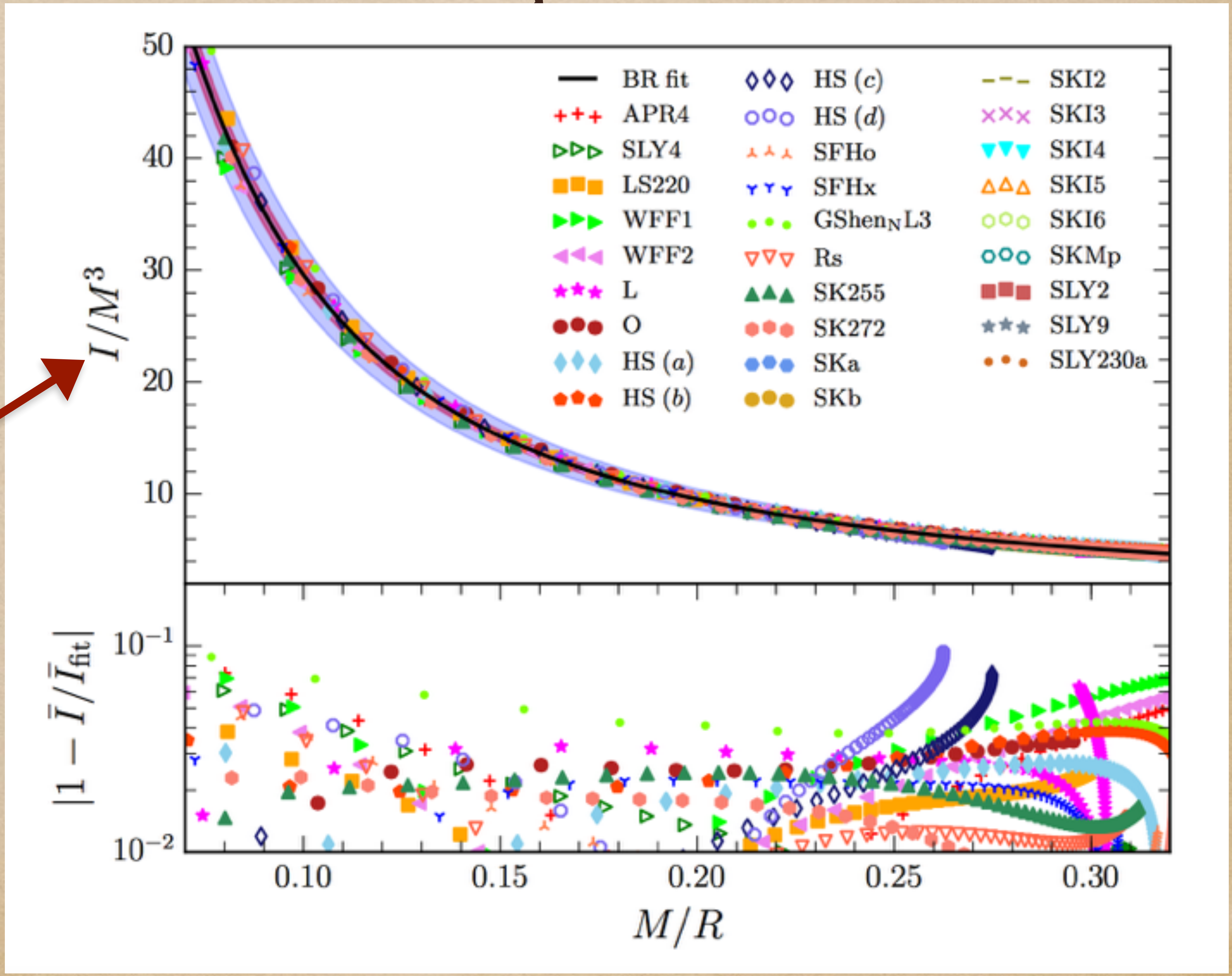


Equation of state is unknown!



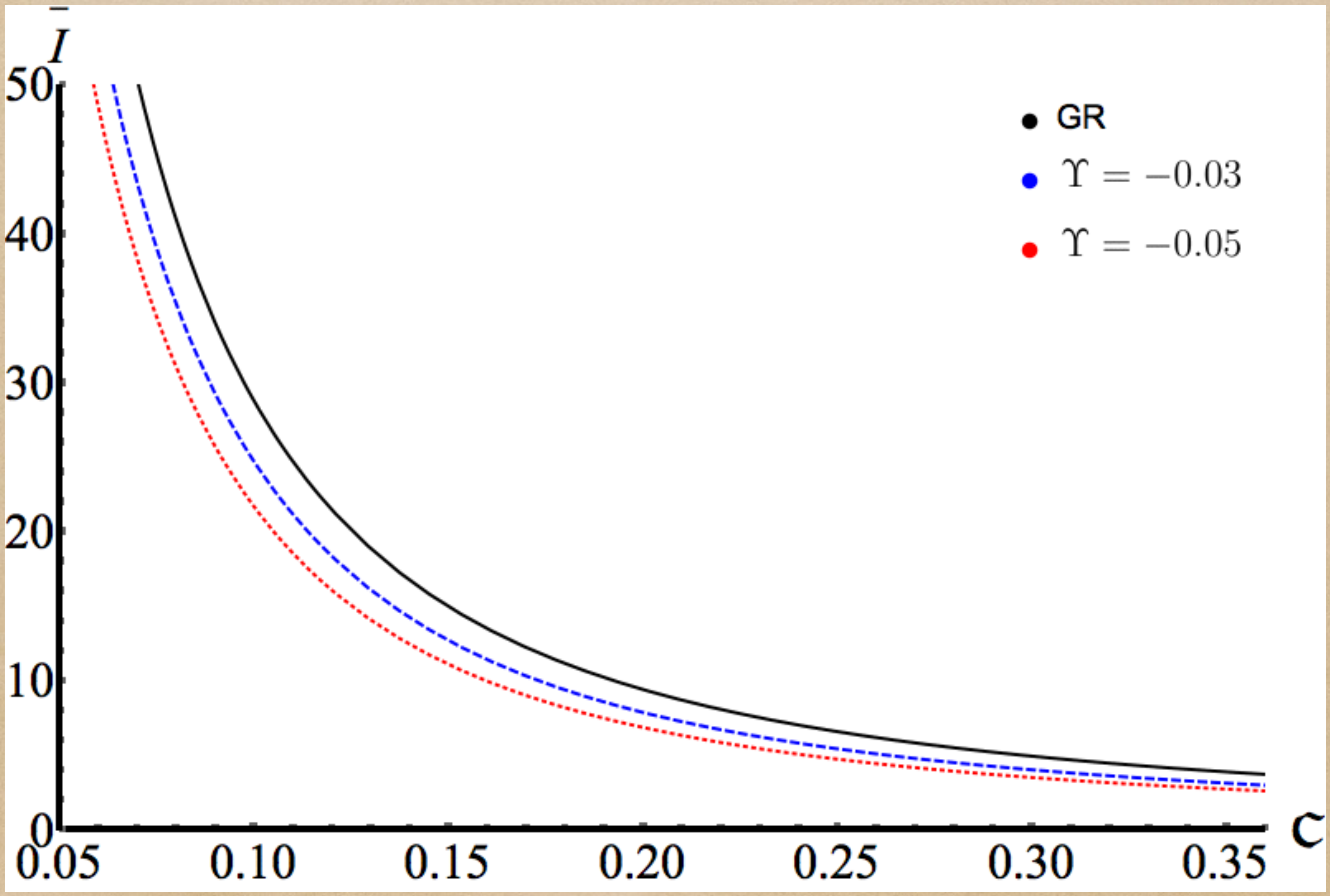
Breu, Rezzolla '16

Need EOS-independent tests

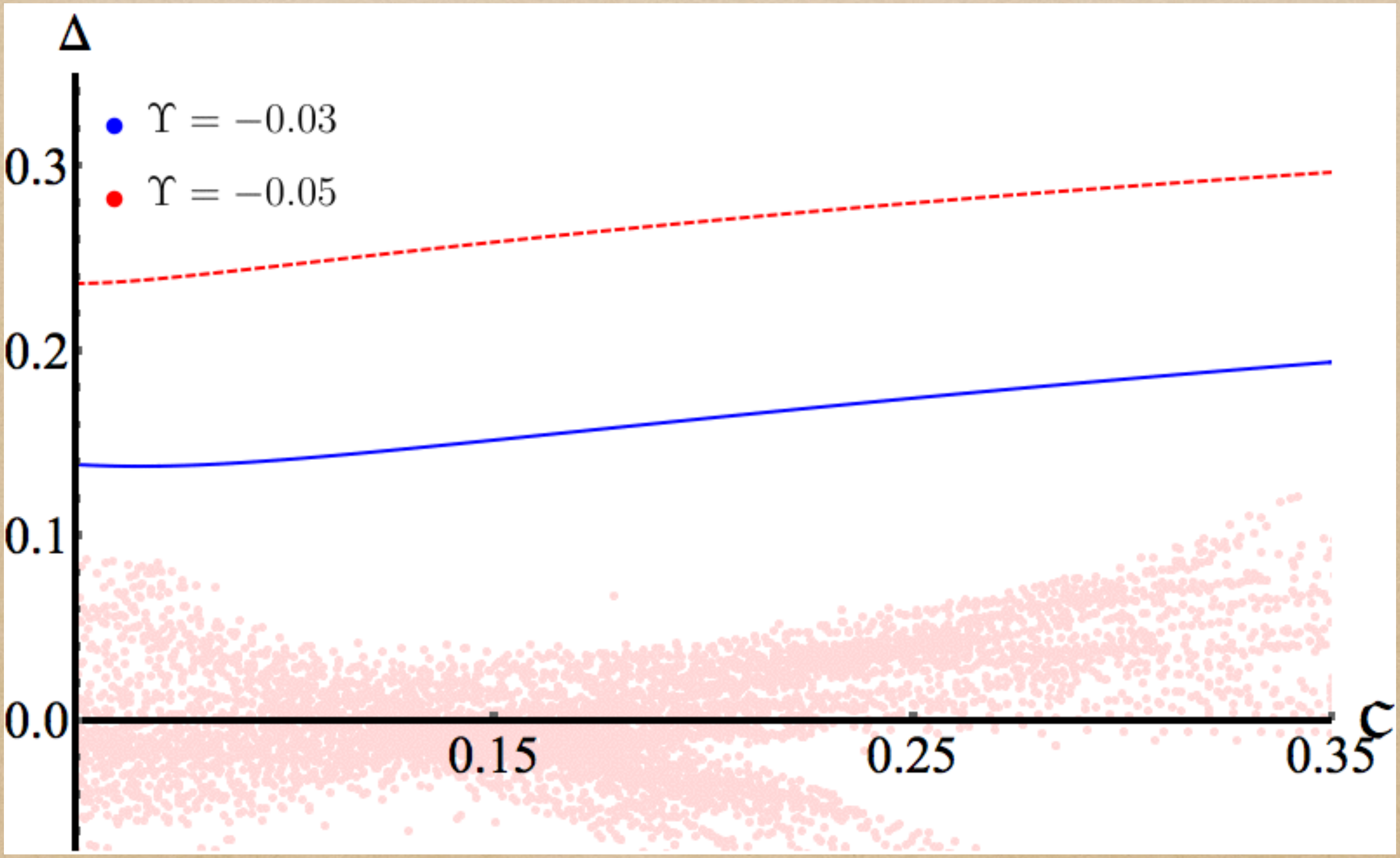


Moment of inertia

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)

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- Ryo Saito — Yukawa Institute, Kyoto (JP)