11–12:15 ← not much time!

Beyond GR

1811–1877

~~① gravity at long distances~~

~~② gravity at short distances~~ 100 μm ≲ d ≲ …

~~Motivation~~ Intro: GR { tested, theoretically compelling

① gravity at long distances

   ⓐ galaxy rotation curves ⇒ "dark matter" [plot]

   ⓑ acceleration of universe ⇒ "dark energy" ($p<0$) [plot]

   ⓒ or: modify gravity? 1846: uranus → Neptune; mercury → "Vulcan" false detection until 1915 (Leverrier…)

② Problem: difficult to modify gravity at long distances while keeping virtues of GR

- compatible w/ special relativity
- ~~positive~~ no disasterous instability
- experiment
  - → Newtonian limit (equiv principle)
  - → Post-Newtonian tests

] no detail here

} already rules out most

③ First attempt at modification: Brans – Dicke

GR + scalar field

$$\mathcal{L}_{scalar} = \frac{1}{2}\partial^\mu \varphi \partial_\mu \varphi \qquad \mathcal{L}_{matt}(g_{\mu\nu} \to A^2(\varphi) g_{\mu\nu})$$

$$\ln A = \alpha_0 \frac{(\varphi-\varphi_0)}{\sqrt{8\pi G}} + \frac{1}{2}\beta_0 \frac{(\varphi-\varphi_0)^2}{8\pi G} + \cdots$$

Ordinary scalar couples to matter in a particular way
looks not very well motivated — and it isn't from modern perspective
Historically, motivated tests of GR (equivalence principle, etc.)

~~[plot]~~ Cassini: measured ~~do~~ Doppler shift of radio waves between Cassini satellite and earth passing near sun

$\alpha_0 \lesssim 10^{-3}$

~~[illegible]~~ ⇒ very weak coupling ~~to matter~~ ~ "bending of light by sun"

~~→ MOND?~~

---

④ Modern attempts (long distance mod)

Inspired by ~~[illegible]~~ superconductivity

	supercond	gravity
long range force	E&M	gravity
symmetry	~~gauge invariance~~ ~~phase~~ gauge invariance	~~coordinate invariance~~ local Lorenz invariance

~~[illegible]~~

~~broken~~ break symmetry ⇒ modification of long range forces

Also gravity + extra modes, but now motivates many Lorentz effects

- preferred frames ...
- new long-range forces, e.g.

[plot] spin dependent $\frac{1}{r^2}$ force

(5) above driven by theory:
How can we modify gravity

Do not solve problems at long distance.

Ask: how would we like to modify gravity?

Dark matter or mod grav?
MOND

(6) ~~MOND~~

Totally phenomenological, motivated by galaxy rot curve

Newton: $r > R_{gal} \Rightarrow$

~~MOND~~: $a = \frac{v^2}{r} = \frac{F_{grav}}{m} \sim \frac{1}{r^2}$

$\Rightarrow v \sim r^{-1/2}$

MOND: $F_{grav} \sim \frac{1}{r}$ when $a_N < a_0$ = new const

~~Problem: not a theory! (How to test in lab?)~~

~~Evidence for DM from lensing of galaxies~~
~~Bekenstein: "AQUAL" theory has many adjustable params ...~~

Also: other evidence for DM

- lensing of galaxies ← especially hard for MOND
- structure formation

MOND: not a theory. (hard to test in lab)
Bekenstein: keeps trying to make relativistic theory of MOND, but requires many arbitrary params.

② CC problem
Very fund qualitative problem

$$V \mapsto V + \text{const}$$

Einstein GR: $T_{\mu\nu} \mapsto T_{\mu\nu} + \underbrace{\text{const} \cdot g_{\mu\nu}}_{p = -\rho}$

QM: $E_{vac} = \sum_{\text{modes}} \frac{1}{2}\hbar\omega = \infty ?$

Good news: understand how it can be finite: SUSY! (cancellation between bosons & fermions)

Bad news: SUSY broken at energy scales $\gtrsim$ 100 GeV ~~10^{11} eV~~ $(\hbar = c = 1)$ GeV $\simeq m_p c^2$

current particle searches ~~$\sim 10^{8} \times \rho_{Nuclear}$~~

minimum cancellation

$\Rightarrow V_{th} \gtrsim$ ~~$(10^{11}\,eV)^4$~~ $(10^2\,GeV)^4 \simeq 10^8 \rho_{Nuclear}$

~~What would be eff~~

~~$\Rightarrow$ spacetime~~ $\Rightarrow$ universe expands at rate

$H_{th}^2 \sim G_N V_0$

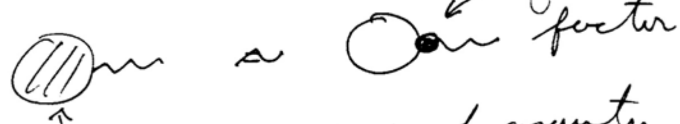
$\Rightarrow H_{th}^{-1} \sim$ cm $\sim 10^{-8}$ s

size of horizon; Hubble time

$\exists$ of lecture $\Rightarrow$ big trouble!

$$\frac{H_{obs}}{H_{th}} \sim 10^{28} \Rightarrow \frac{V_{obs}}{V_{th}} \sim 10^{56}$$

(8) Andrum: modify gravity so that vacuum energy does not gravitate

$"V_{vac}" \sim$  form factor $\sim \Lambda^4$

$\left(\sum_{modes} \frac{1}{2}\hbar\omega\right)^4 \sim \Lambda^4$

vacuum as source of gravity

$\Lambda^4 \lesssim V_{obs}$ $V_{obs} \sim G_N H_{obs}$

$\Rightarrow \Lambda \lesssim \left(\frac{H_{obs}^2}{G_N} \right)^{1/4} \sim 10^{-2}\,eV$

Expect modification of Newton force at distance

$r \sim \frac{1}{\Lambda} \sim 10^{2}\,eV \sim 10^{-3}\,cm$

[Note $\Lambda \downarrow \Rightarrow r \uparrow \Rightarrow$ no wiggle room!]

Expect that gravity becomes <u>weaker</u> at a micron ....

Note: no model (grav hard to modify) but ~~[illegible]~~ idea is sufficiently intriguing to keep in mind (and Sundrum is working on an "existence proof"!)

(9) Large extra dim

Motivated by particle physics

$M_W \sim 100$ GeV $M_P \sim \frac{1}{\sqrt{G_N}} \sim 10^{19}$ GeV

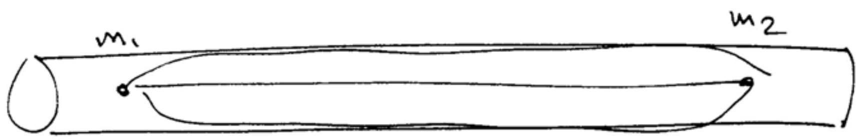
Why different?

Usual framework: Mp represents scale of new physics (quantum gravity, strings...)

ADD: 100 GeV is <u>most fund</u> scale
largest scale

Then: how to ~~exp~~ explain weakness of gravity?

$r \gg R$: $d = 3$



$\simeq$ 

$F_{grav} \sim \frac{1}{M_4^2} \frac{m_1 m_2}{r^2}$ $\qquad G_N \sim \frac{1}{M_4^2}$

Match at $r \sim R$: $\quad D = 4 + n$

$$\frac{1}{M_*^{2+n}} \frac{1}{R^{2+n}} \sim \frac{1}{M_4^2 R^2}$$

$$\boxed{M_4^2 \sim M_*^{2+n} R^n}$$

$M_* \sim 10^8$ GeV $\quad M_* \sim 1000$ GeV

[illegible]

$n = 1$: $R \sim 10^{13}$ cm $\sim \frac{1}{10}$ AU

$n = 2$: $R \sim$ mm $\leftarrow$ test this

$n = 3$: $R \sim 10^{-7}$ cm ~ 10 Å

$\vdots$

Gravity gets stronger at mm.

Specific model $\Rightarrow$ can really constrain it.

[plot]