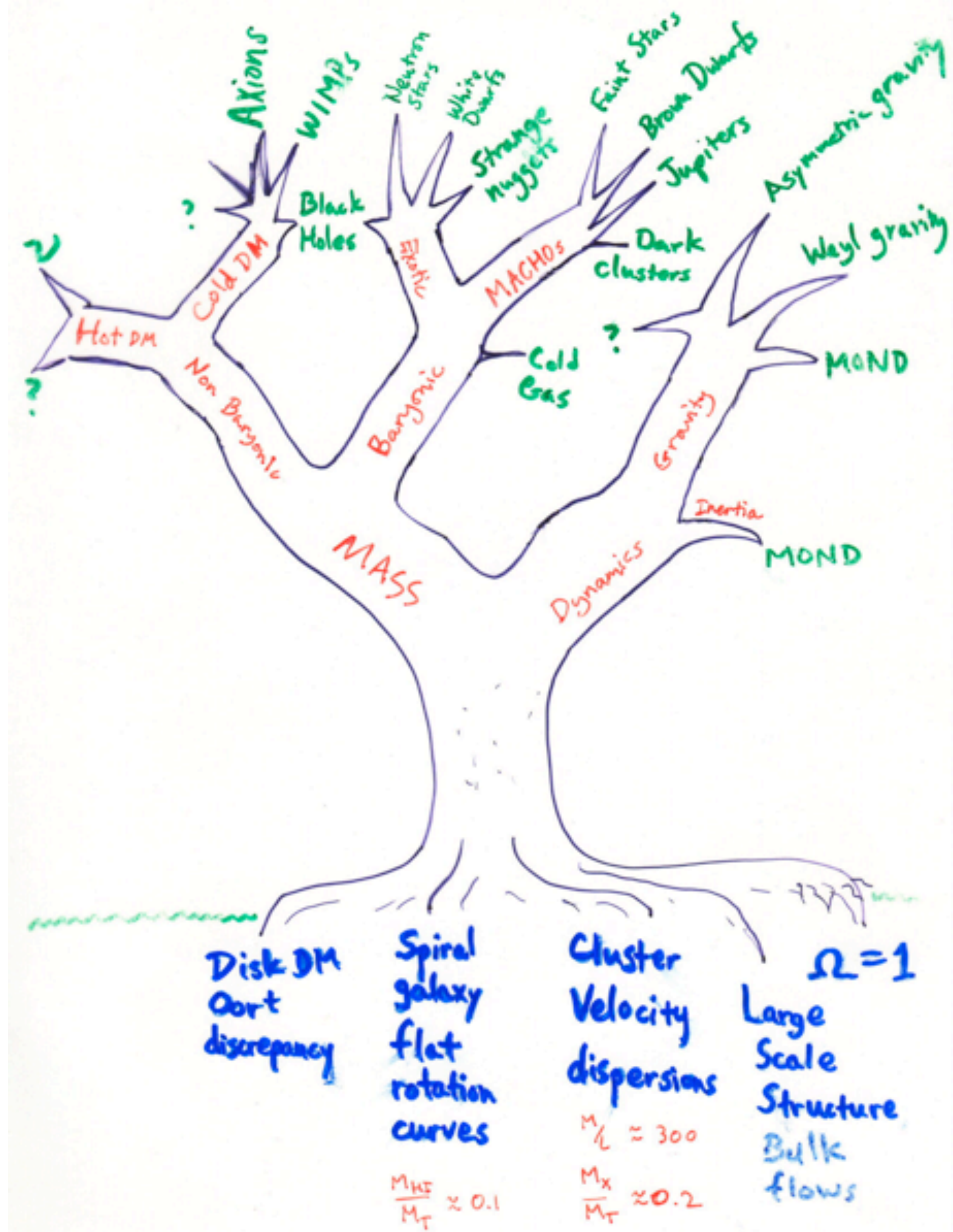
Today:

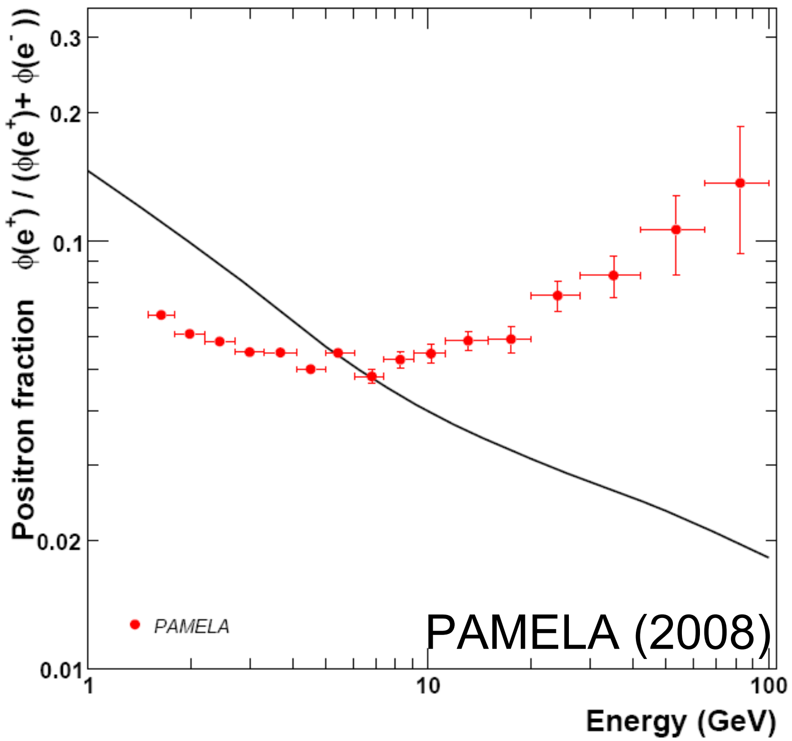
- Jakub
- WIMPs
- MOND

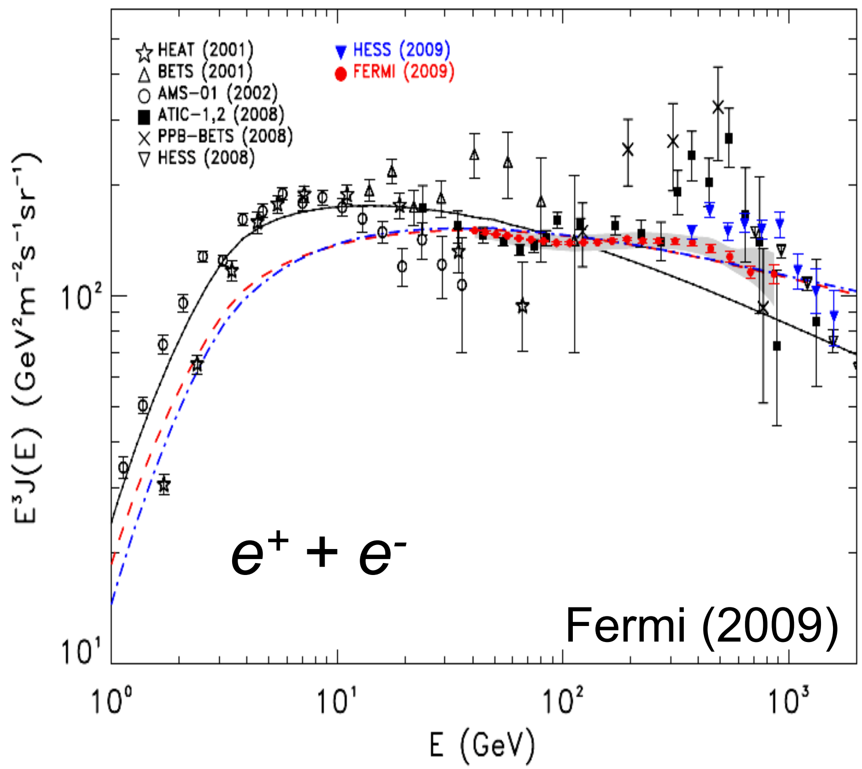
4/19: **Review**
HW due

4/21: **Exam**



INDIRECT DETECTION





Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

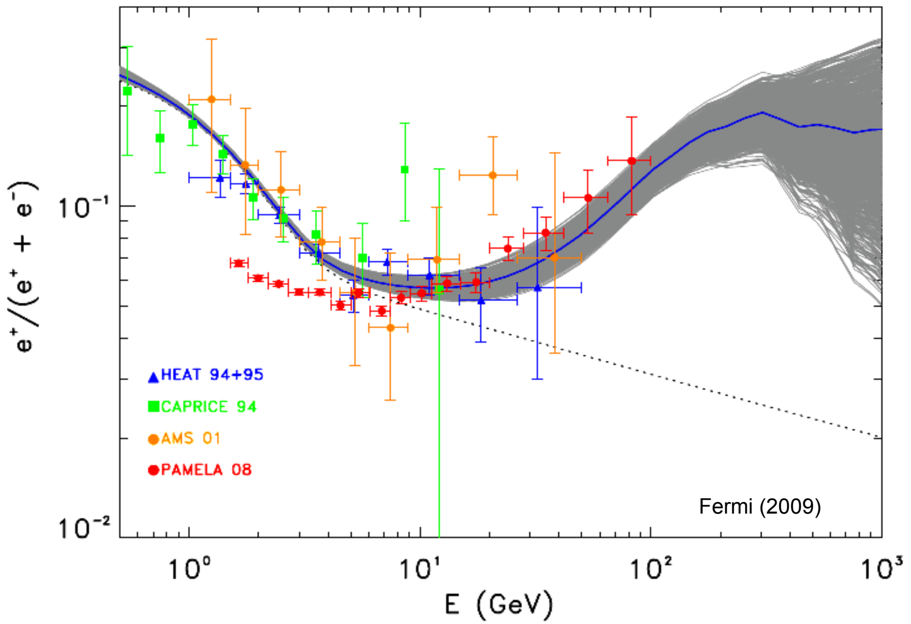
One must exclude astrophysical sources before claiming a detection of dark matter.

From review by Feng et al. linked off course review literature page.

ARE THESE DARK MATTER?

- Pulsars can explain PAMELA

Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008)
Profumo (2008) ; Fermi (2009)



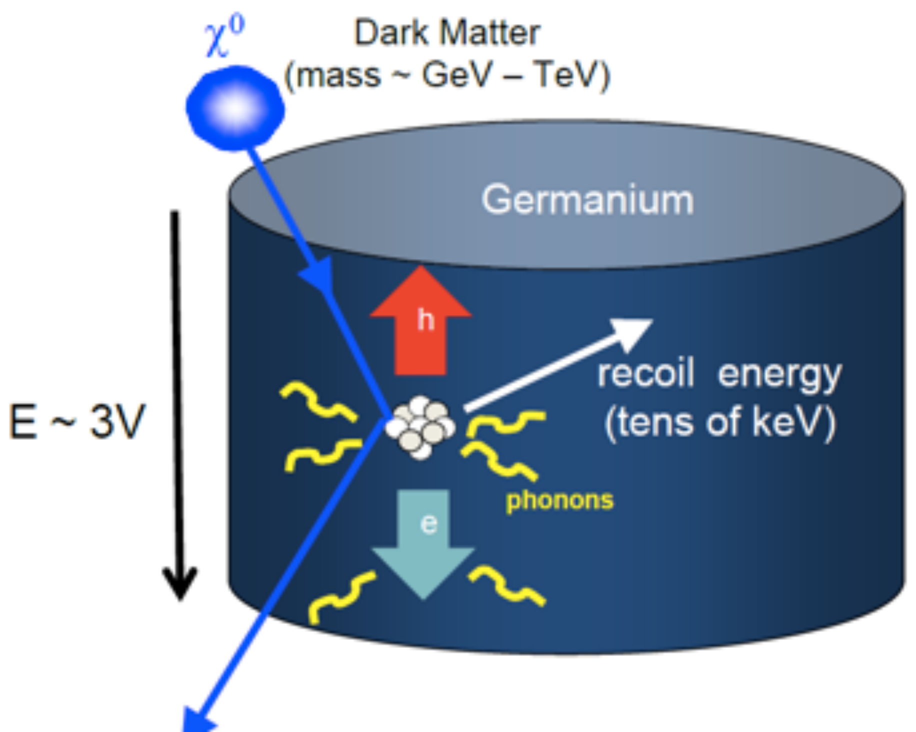
- For dark matter, there is both good and bad news
- Good: the WIMP miracle motivates excesses at ~100 GeV – TeV
- Bad: the WIMP miracle also tells us that the annihilation cross section should be a factor of 100-1000 too small to explain these excesses. Need enhancement from
  - astrophysics (very unlikely)
  - particle physics

From review by Feng et al. linked off course review literature page.

Experimental results to date (early 2016): nada

Direct detection: Many, *many* experiments
CDMS, LUX, XENON, DAMA, etc., etc.

Basic idea: WIMP passing through detector interacts via weak force; scatters off nucleus. Detect deposited energy of recoil. (analogous to neutrino detection).

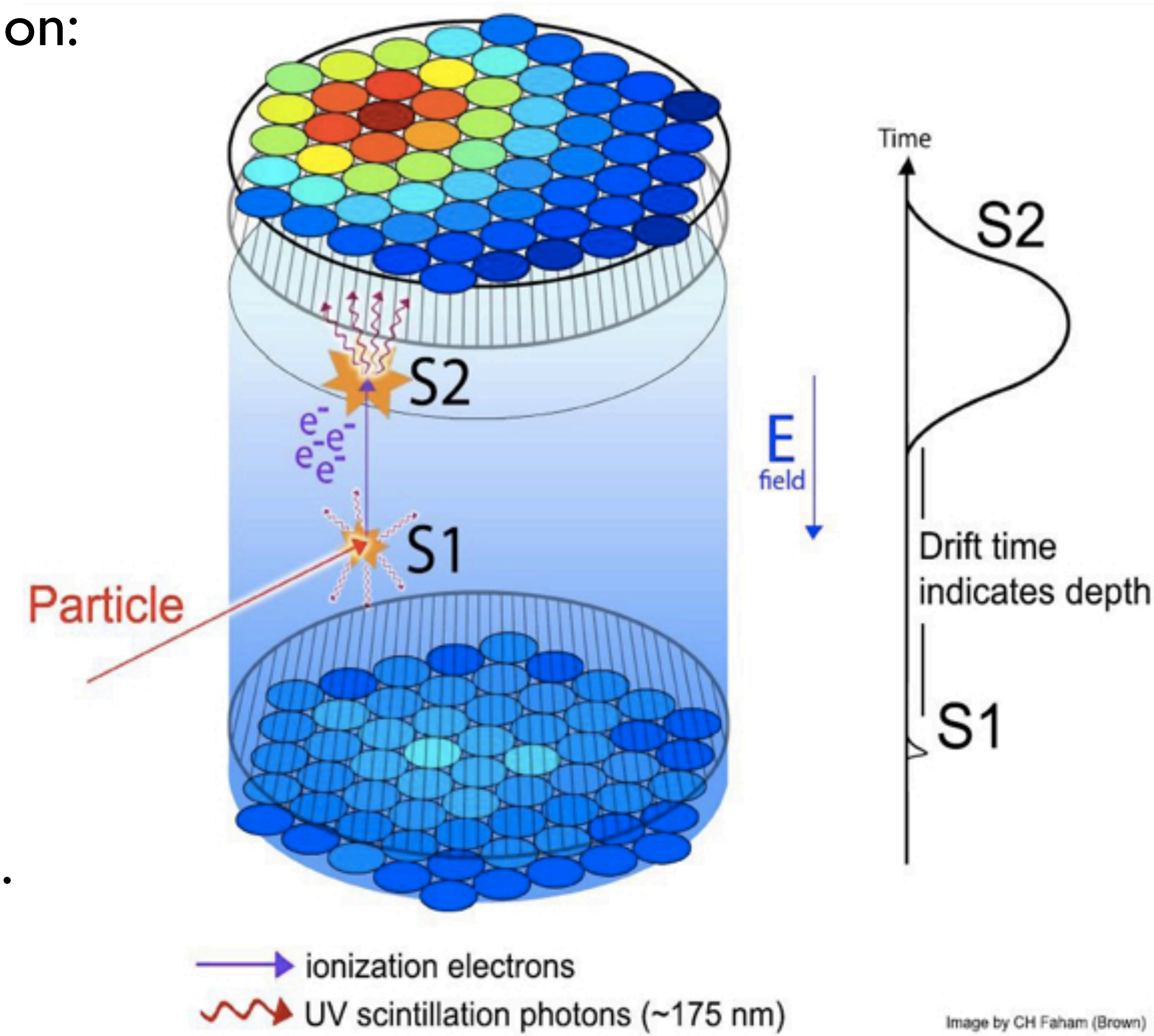


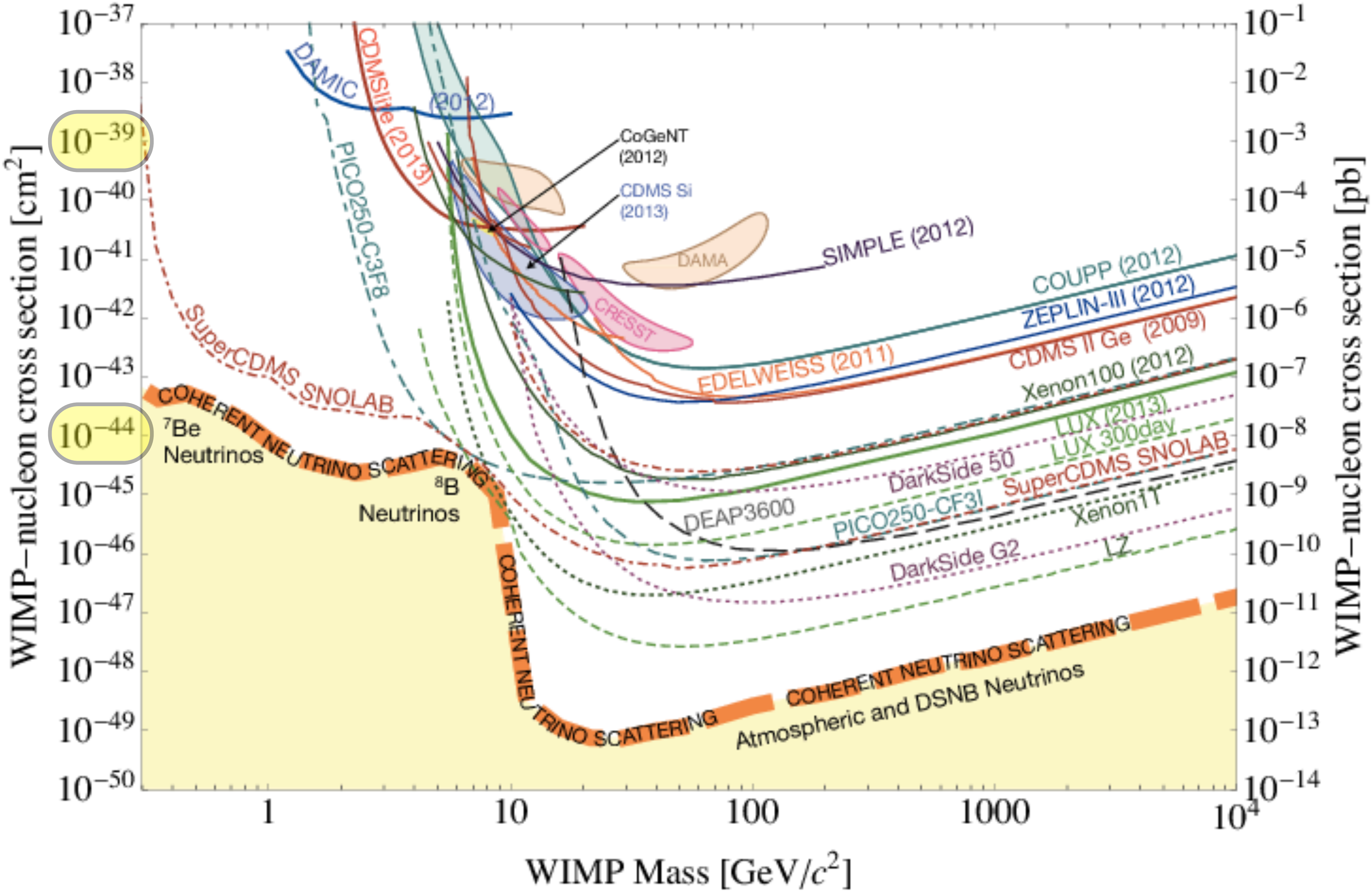
Experimental results to date (early 2016): nada

Direct detection:

Must protect experiments from cosmic rays, natural radioactivity, self-radioactivity, etc., etc.

Bury them deep in mines.





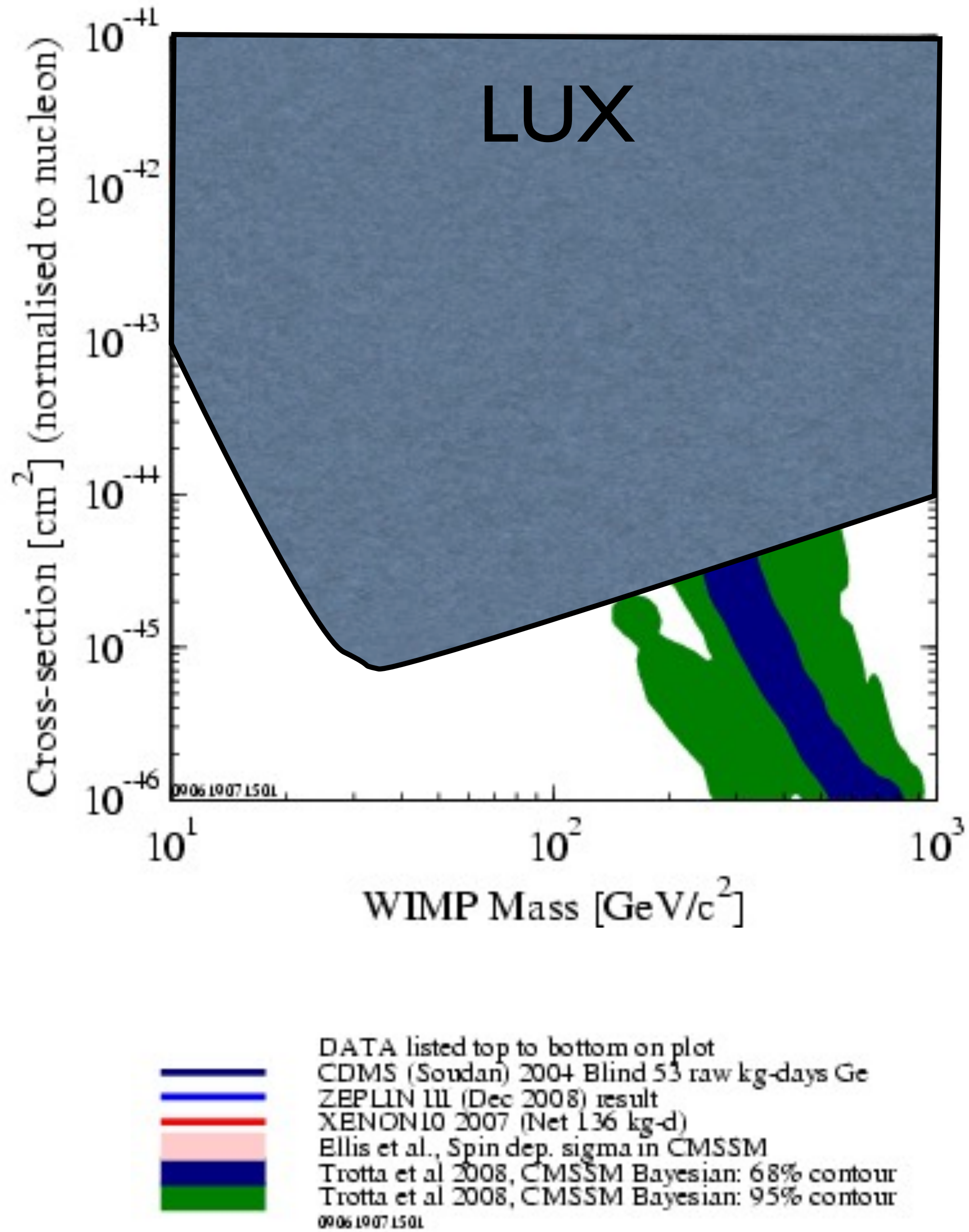
cross section (10^{-39} then 10^{-44} "natural")

WIMP mass (~100 GeV natural)

Many ongoing experimental searches for
Cold Dark Matter

Paging
Cold Dark Matter

Paging
Cold Dark Matter ... hello?



Experimental results to date (early 2016): nada

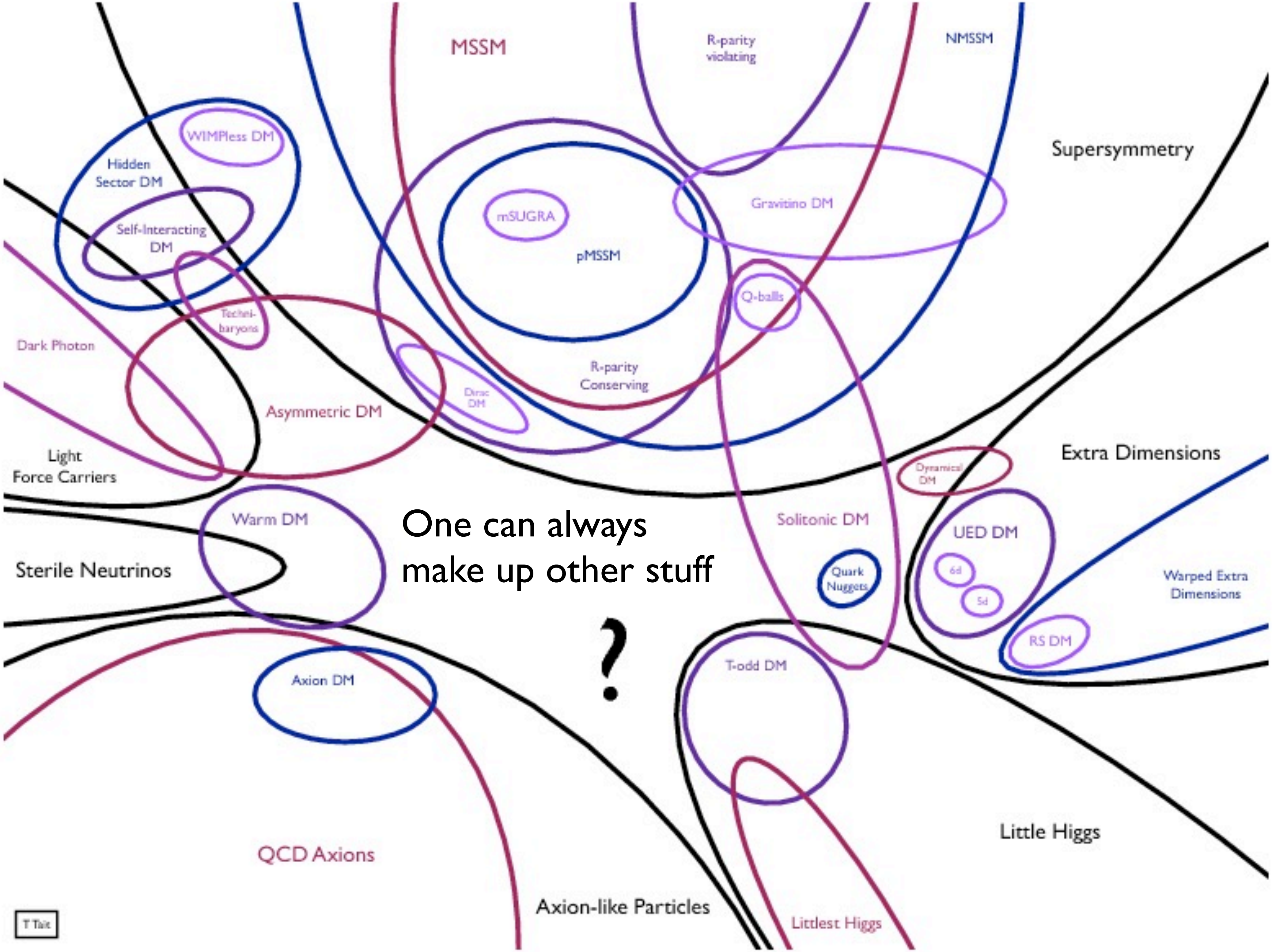
LHC: the LHC sees no indication of dark matter
or even supersymmetry

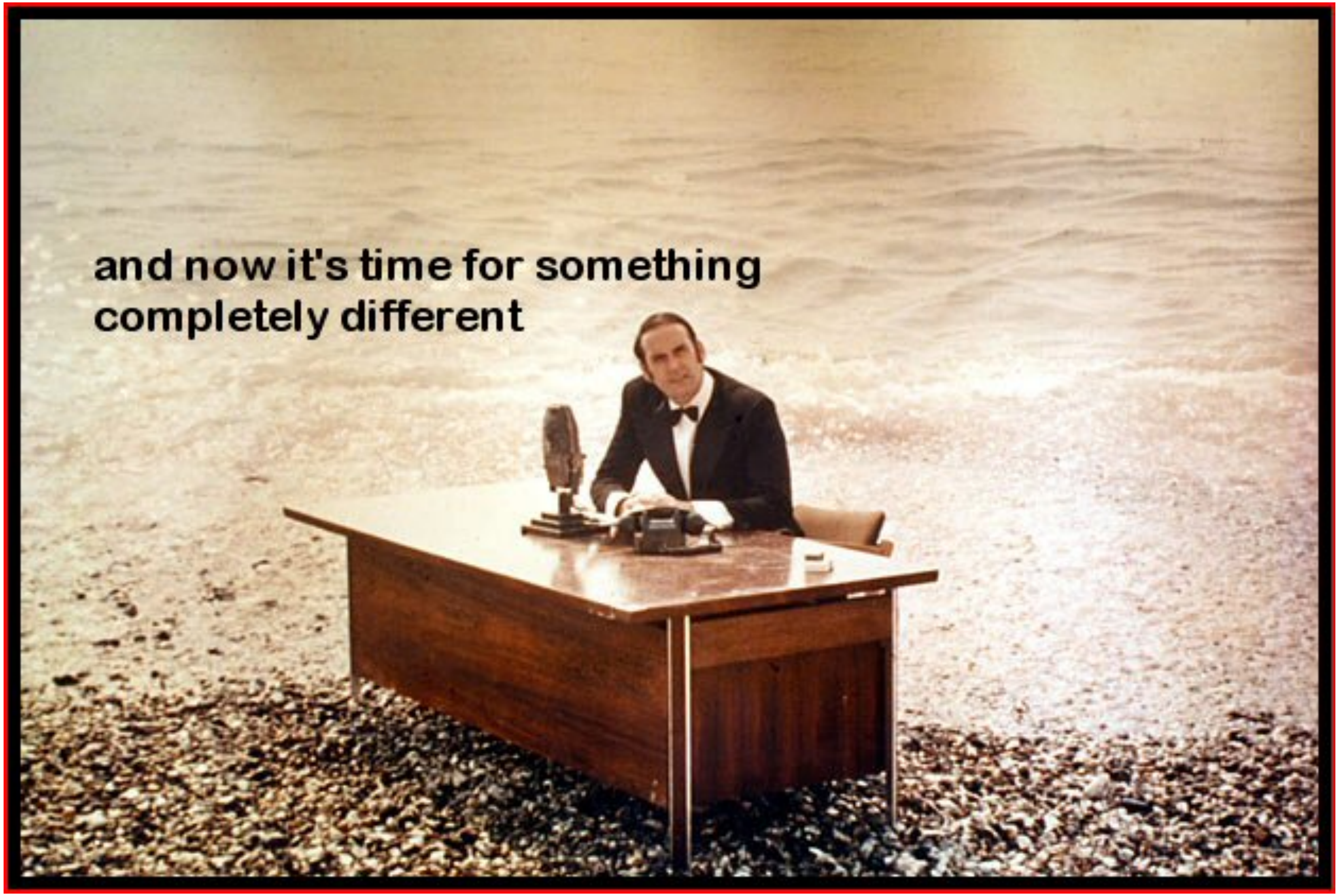
Direct Detection: Nothing so far

Inirect Detection: Various claims

- gamma ray excess near Galactic Center
- cosmic ray excess
- unidentified X-ray lines

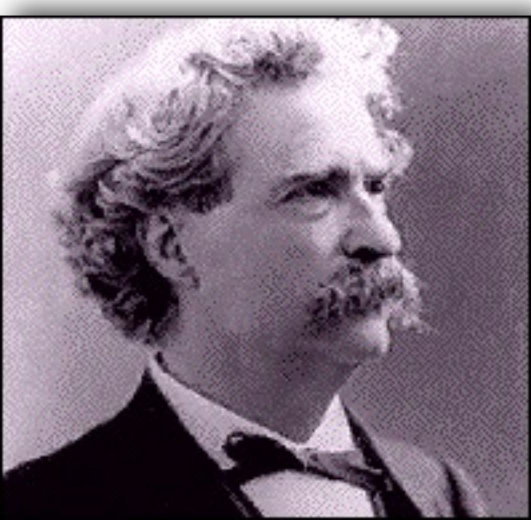
As yet: *nothing credible*.


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
One can always make up other stuff
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait


and now it's time for something
completely different

What gets us into trouble is not what we don't know.

It's what we know for sure that just aint so.



\- Mark Twain

A few things we know for sure...

$$\nabla^2\Phi = 4\pi G\rho$$
$$F = ma$$

which basically means

$$mV^2/R = GMm/R^2$$

i.e,

$$V^2 = GM/R$$

ergo...

The universe is filled with non-baryonic cold dark matter.

TF Relation

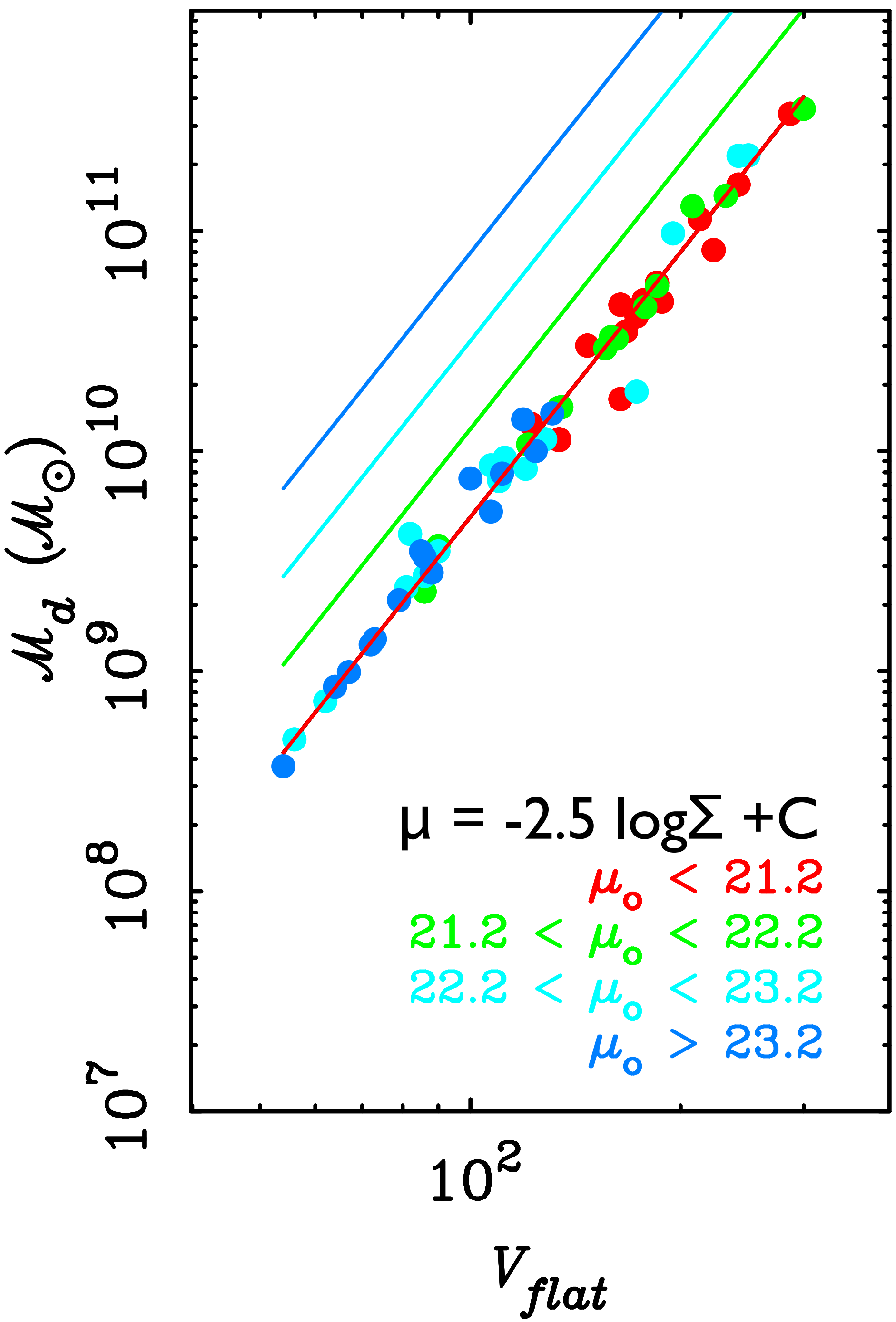
<u>Newton says</u>

$V^2 = GM/R$.

Equivalently,

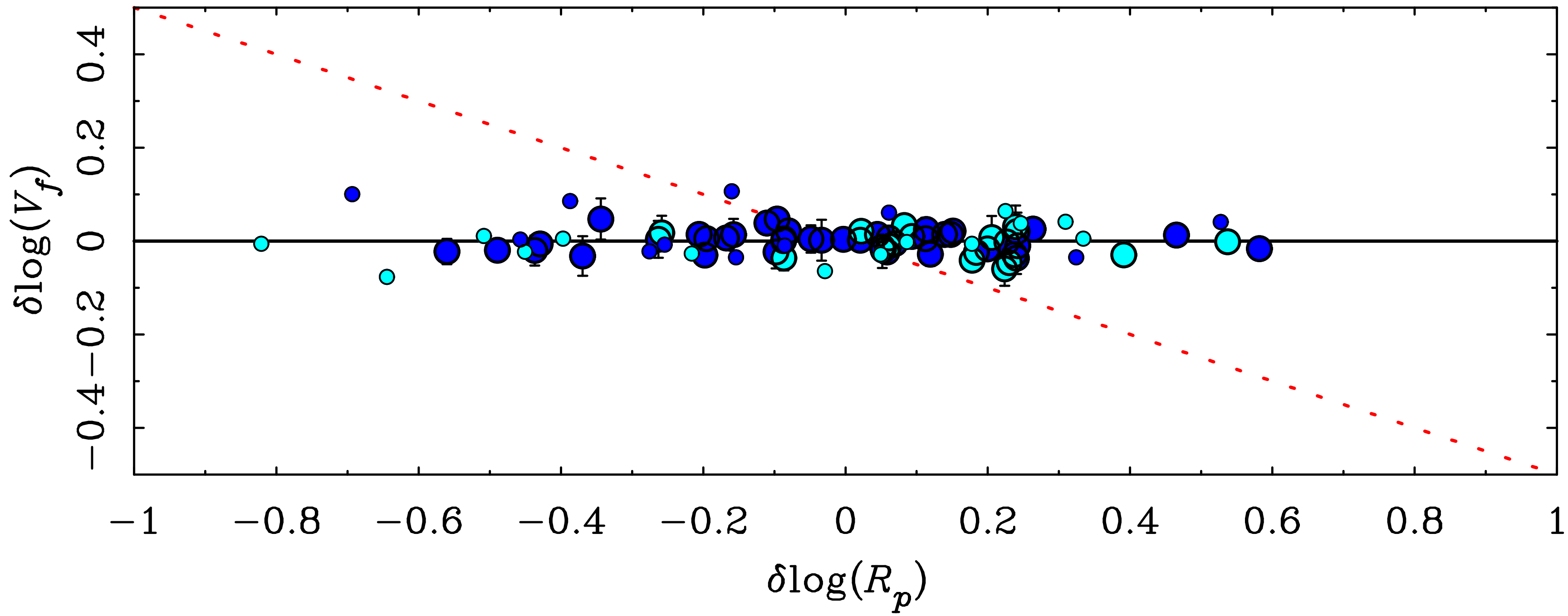
$\Sigma = M/R^2$

$V^4 = G^2 M \Sigma$



<u>Therefore</u>

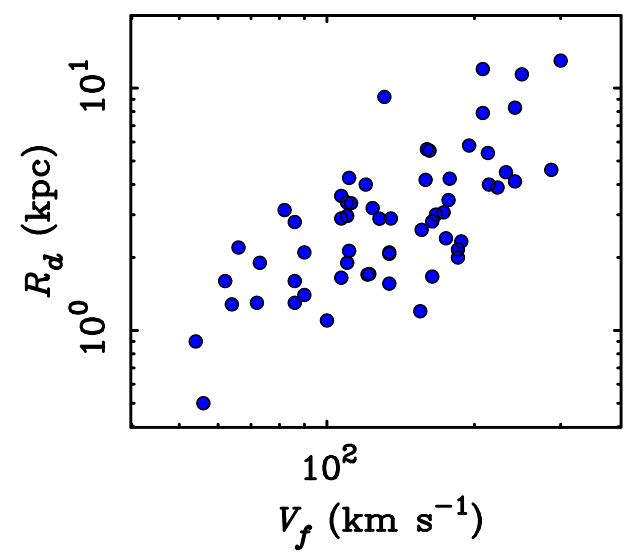
Different Σ *should* mean different TF normalization.



No residuals from TF with size or surface density for disks

$$V^2 = \frac{GM}{R} \quad \rightarrow \frac{\delta \log(V)}{\delta \log(R)} = -\frac{1}{2}$$ expected slope (dotted line)

Note: large range in size at a given mass or velocity



For disk galaxies

Newton says: $$\frac{V^2}{R} = \frac{GM}{R^2} = G(\Sigma_b + \Sigma_{DM})$$

surface density $$\Sigma = \frac{M}{R^2}$$

So we infer that $\Sigma_{DM} \gg \Sigma_b$

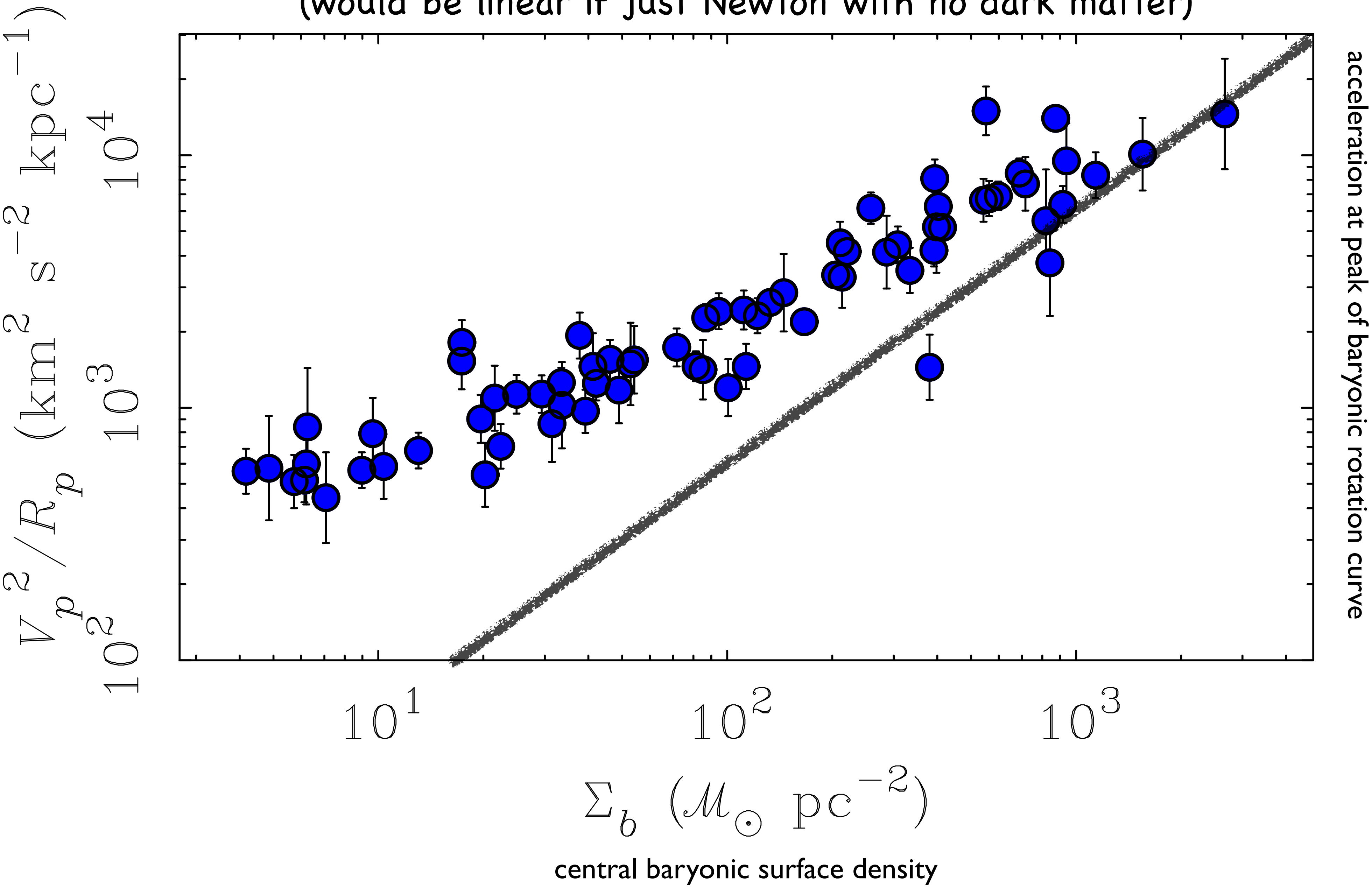
(i.e., that all disks are dark matter dominated) in order to explain the lack of TF residuals with luminous size R_p

But we also infer that the baryons do matter...

3 Law: Gravitational force correlates with baryonic surface density

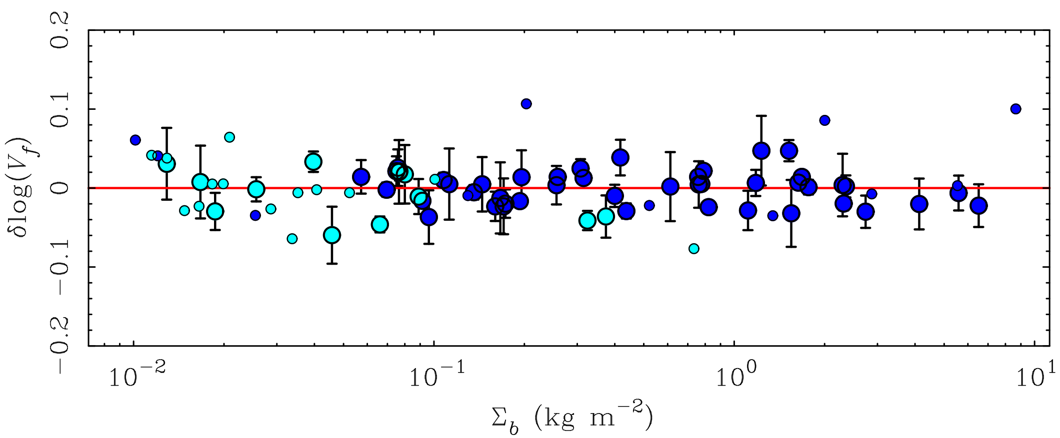
$$a \sim \Sigma_b^{1/2}$$

(would be linear if just Newton with no dark matter)



But wait - before we decided $\Sigma_b \ll \Sigma_{DM}$

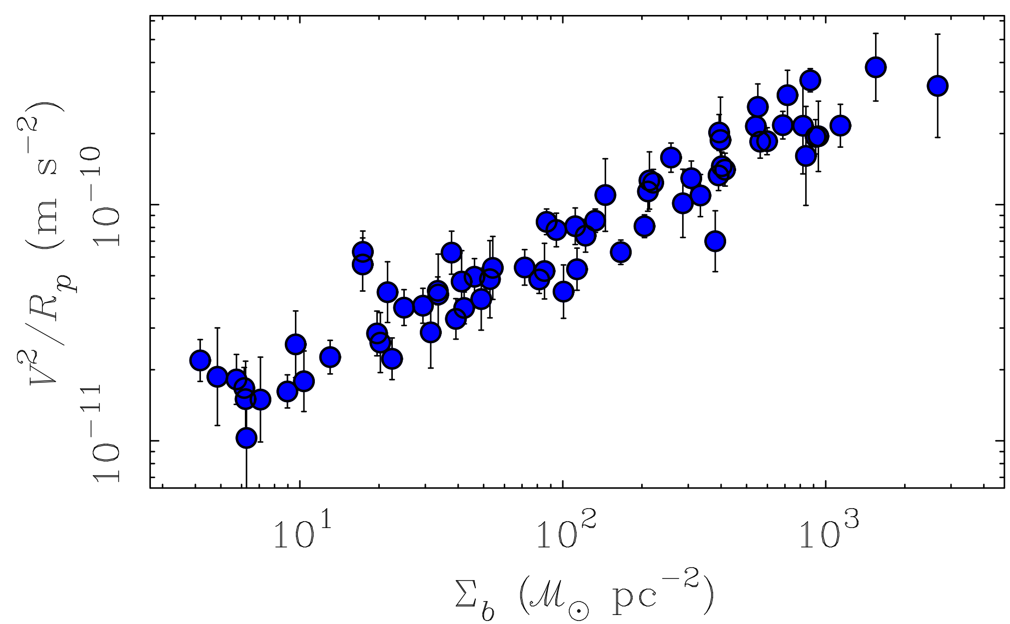
Now Σ_b is observed to correlate with gravitational force. Is this a contradiction?

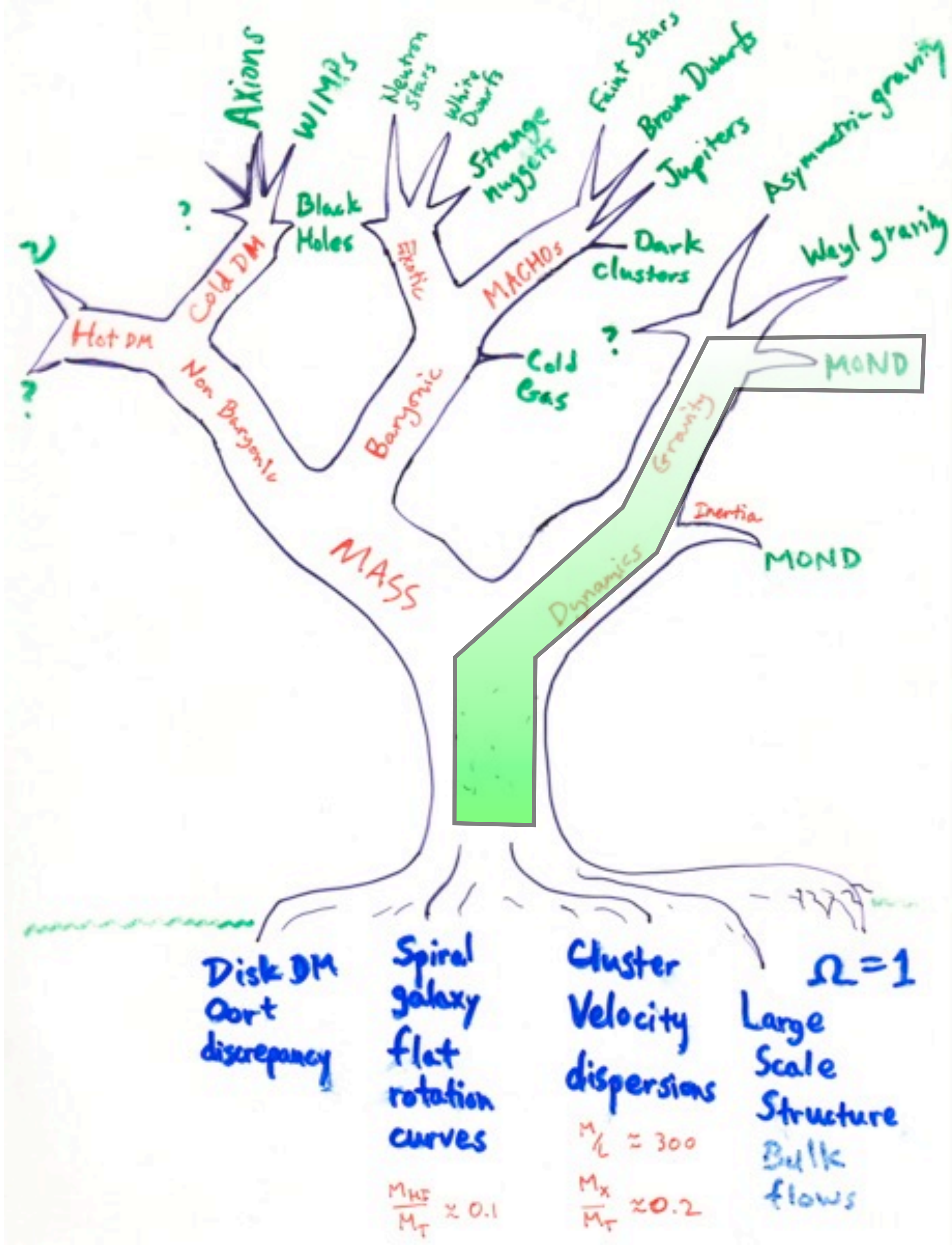


Lack of TF residuals says baryon distribution does not matter.

Correlation of dynamical force with observed surface density says the baryon distribution does matter.

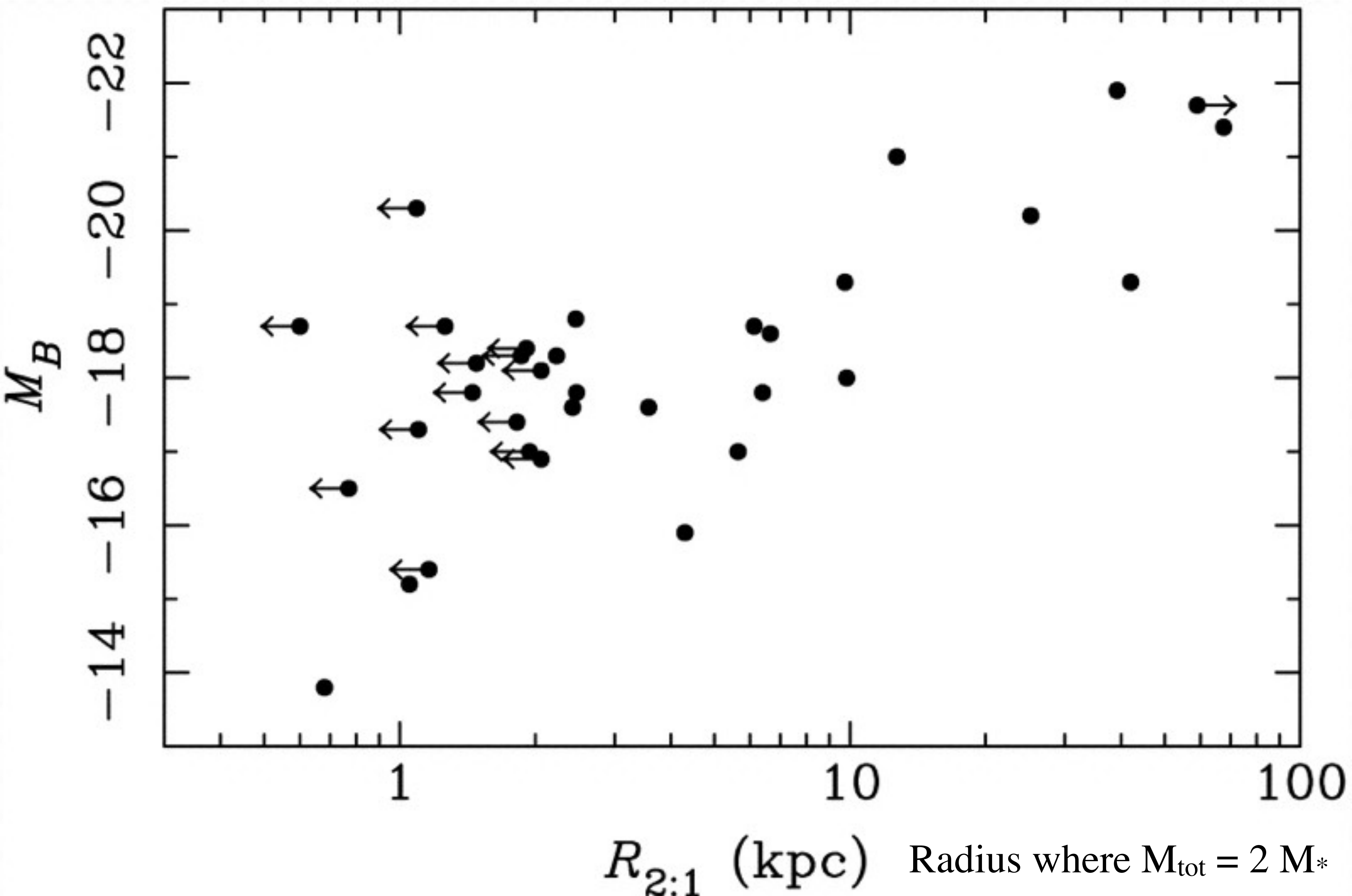
$$\frac{V^2}{R} = G\left(\Sigma_b + \Sigma_{DM}\right)$$





or maybe we've been using the wrong equation

Not any theory will due - length scale based modifications can be immediately excluded as the discrepancy does not appear at a particular length scale.



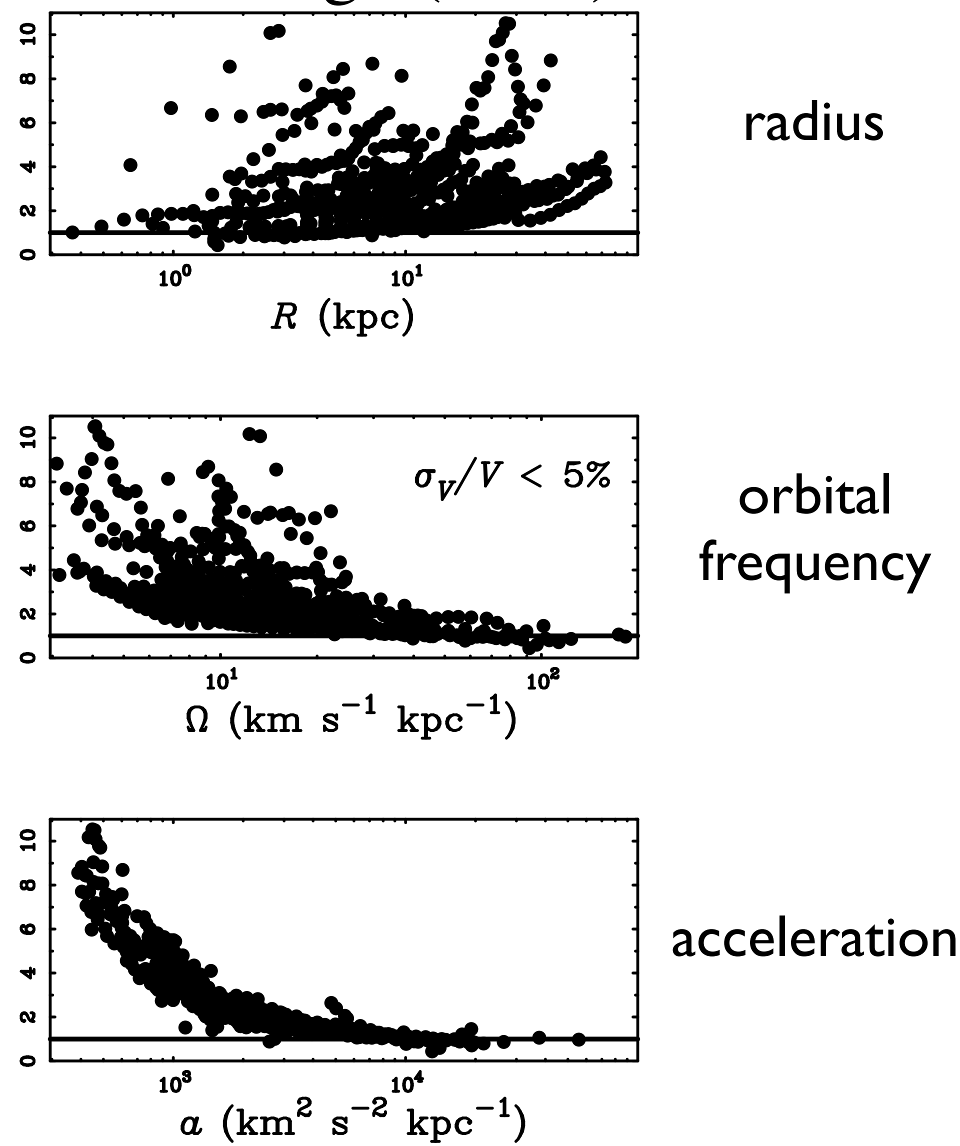
Radius where $M_{tot} = 2\ M_*$

Not just any force law...

No unique size scale in the data. Can generically exclude any modification of gravity where a change in the force law appears at a specific length scale.

There is a characteristic acceleration scale in the data

McGaugh (2004)



60 galaxies

> 600 points

(errors < 5%)

MOND

Modified Newtonian Dynamics (Milgrom 1983)

Instead of invoking dark matter, modify gravity (or inertia). Milgrom suggested a modification at a particular acceleration scale a_0

Newtonian regime

$a = g_N$ for $a \gg a_0$

MOND regime

$a = \sqrt{g_N a_0}$ for $a \ll a_0$

MOND regime invariant under transformations $(t, \mathbf{x}) \to \lambda(t, \mathbf{x})$

Regimes smoothly joined by $$\mu\left(\frac{a}{a_0}\right) a = g_N$$

$\mu(x) \to 1$ for $x \gg 1$ $\quad$ $\mu(x) \to x$ for $x \ll 1$ $\quad$ $x = \dfrac{a}{a_0}$

Modified Poisson equation

$$\nabla\left[\mu\left(\frac{\nabla\Phi}{a_0}\right)\nabla\Phi\right] = 4\pi G\rho$$

Derived from aquadratic Lagrangian of Bekenstein & Milgrom (1984) to satisfy energy conservation.