Beyond Dark Matter?

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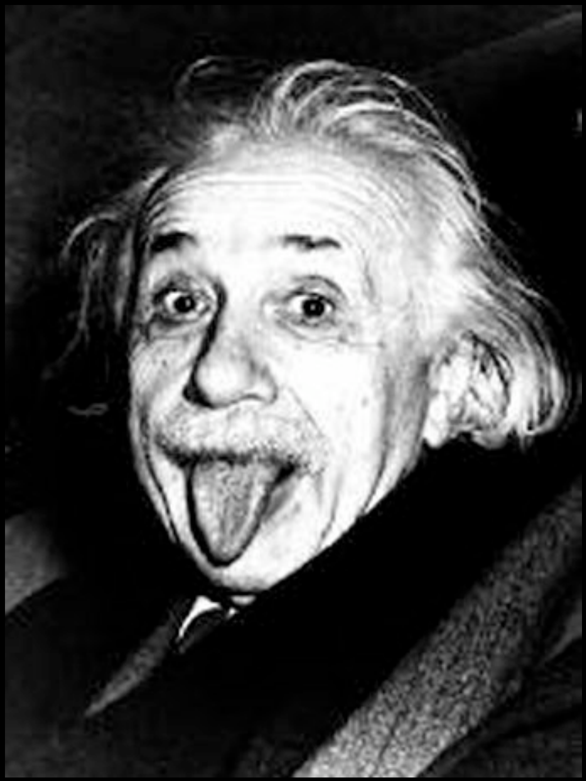
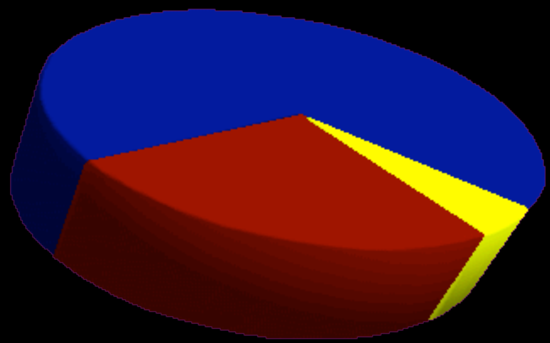


Abstract:

It's not as easy
as you think to
out-Einstein Einstein.

The Standard Cosmology: ingredients

- General Relativity
- Large-scale homogeneity & isotropy
- 5% ordinary matter
- 25% dark matter
- 70% dark energy

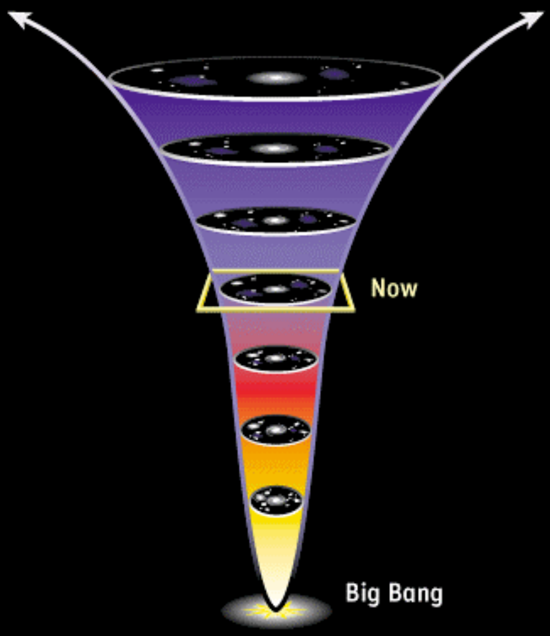


- trace neutrinos and blackbody radiation
- scale-free adiabatic fluctuations ~ 10^{-5}

The dark sector (matter & energy) is the most mysterious part of the standard cosmology

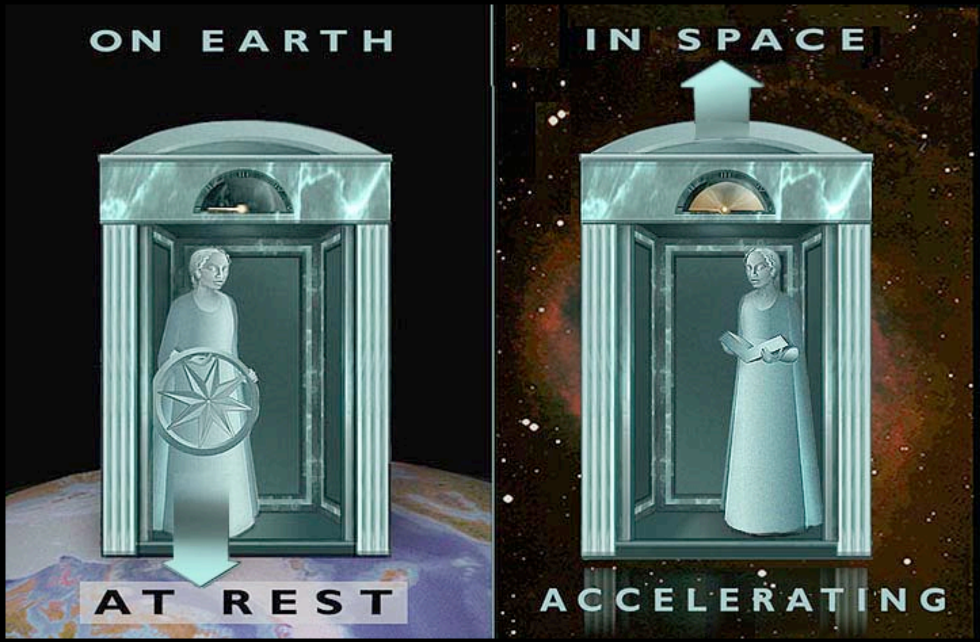
Dark matter: cold, collisionless, 25%

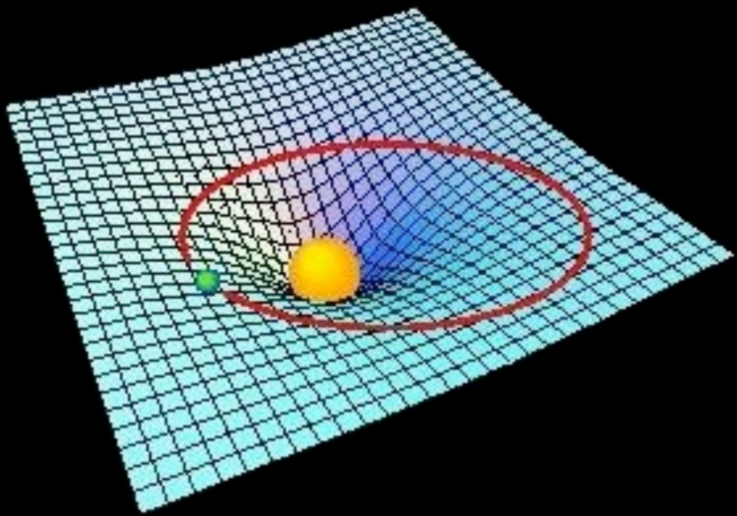
Dark energy: smooth, persistent, 70%



Only detectable via gravity.

<u>General relativity</u>:
gravity is the
curvature of spacetime

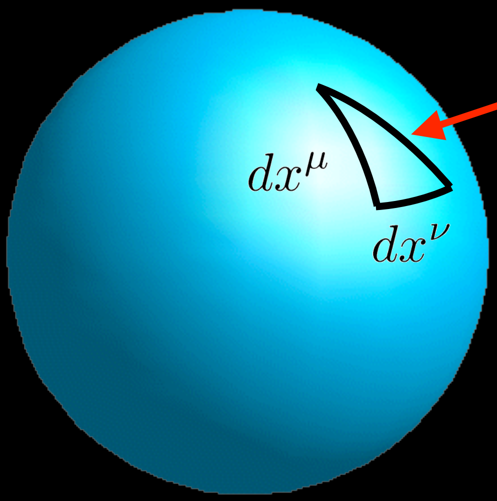




Coordinates on spacetime:

$$x^\mu = (x^0, x^1, x^2, x^3) = (t, x, y, z)$$

Infinitesimal distances are encoded in the line element:



$$ds^2 = \sum_{\mu\nu} g_{\mu\nu} dx^\mu dx^\nu$$

The geometry is described by the metric tensor $g_{\mu\nu}$, and the curvature is described by the Einstein tensor $G_{\mu\nu}$, constructed from derivatives of $g_{\mu\nu}$.

The curvature scalar $R[g_{\mu\nu}]$ is the most basic scalar quantity characterizing the curvature of spacetime at each point. The simplest action possible is thus

$$S = \frac{1}{16\pi G}\int R\, d^4x + S_{(\mathrm{matter})}$$

Varying with respect to $g_{\mu\nu}$ gives Einstein's equation:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}^{(\mathrm{matter})}$$

$G_{\mu\nu}$ is the Einstein tensor, characterizing curvature, and $T_{\mu\nu}$ is the energy-momentum tensor of matter.

Should we look beyond GR?

We <u>infer</u> the existence of dark matter and dark energy. Could it be a problem with general relativity? (Sure.)

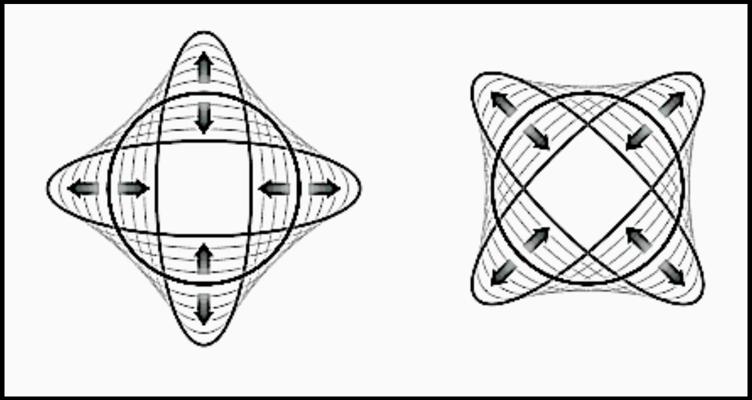
Field theories (like GR) are characterized by :

- ✓ Degrees of Freedom (vibrational modes) -- number, spin.
- ✓ Propagation (massive/Yukawa, massless/Coulomb, etc).
- ✓ Interactions (coupling to other fields & themselves).

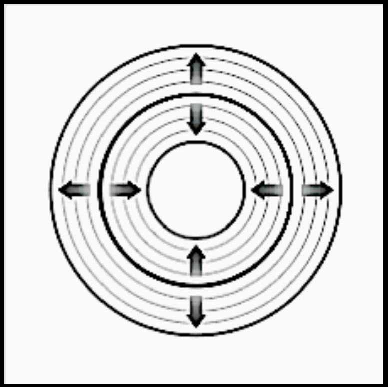
Inventing a new theory means specifying these things.

For example, in GR we have the graviton, which is:

- ✓ spin-2
- ✓ massless
- ✓ coupled to $T_{\mu\nu}$



A scalar (spin-0) graviton would look like this:



Scalar-Tensor Gravity

Introduce a scalar field $\phi\,(x)$ that determines the strength of gravity. Einstein's equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}^{(\mathrm{matter})}$$

is replaced by

$$G_{\mu\nu} = f(\phi)\left[T_{\mu\nu}^{(\mathrm{m})} + T_{\mu\nu}^{(\phi)}\right]$$

variable "Newton's constant"   extra energy-momentum from ϕ

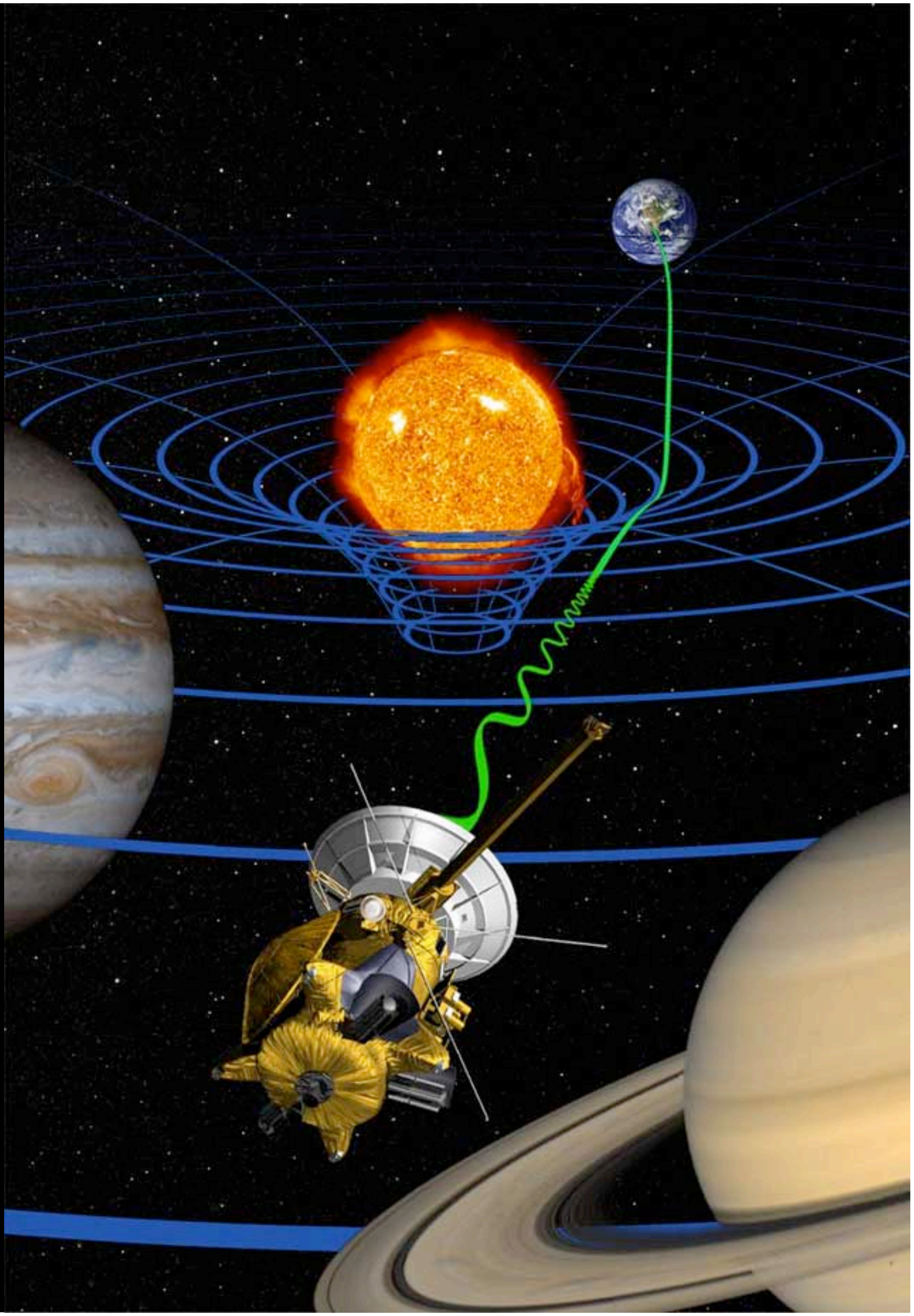
The new field $\phi\,(x)$ is an extra degree of freedom; an independently-propagating scalar particle.
Also: tightly constrained from Solar-System tests of gravity and measurements of constancy of G.

The scalar ϕ is sourced by planets and the Sun, distorting the metric away from Schwarzschild. It can be tested many ways, e.g. from the time delay of signals from the Cassini mission.

Experiments constrain the "Brans-Dicke parameter" ω to be

$$\omega > 40{,}000 \,,$$

where $\omega = \infty$ is GR.

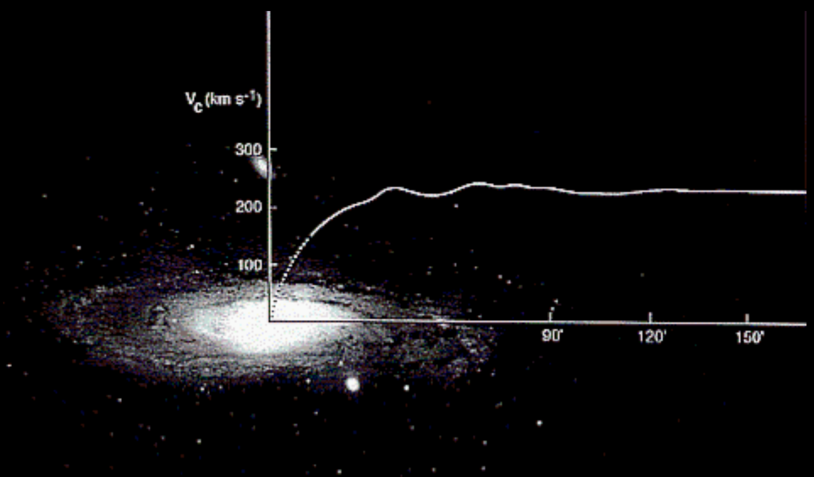


Tests of GR + DM + DE

	GR	DM	DE
Solar system	x		
Binary pulsar	x		
BB nucleosynthesis	x		
Lensing by clusters	x	x	
Power spectrum	x	x	x
CMB (+ H_0)	x	x	x
Supernovae	x		x

Modified Newtonian Dynamics -- MOND

Milgrom (1984) noticed a remarkable fact: dark matter is only needed in galaxies once the acceleration due to gravity dips below $a_0 = 10^{-8}\ \mathrm{cm/s^2} \sim cH_0$.

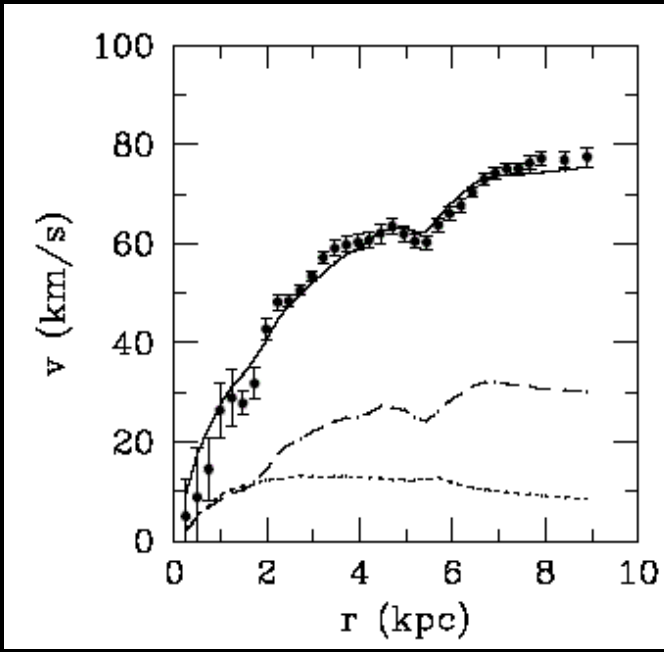


He proposed a phenomenological force law, MOND, in which gravity falls off more slowly when it's weaker:

$$F \propto \begin{cases} 1/r^2, & a > a_0, \\ 1/r, & a < a_0. \end{cases}$$

MOND successes: phenomenology works!

- Fits to rotation curves are generally very good
- Tully-Fisher relation is automatic, unlike CDM
- No problems with cusps etc.

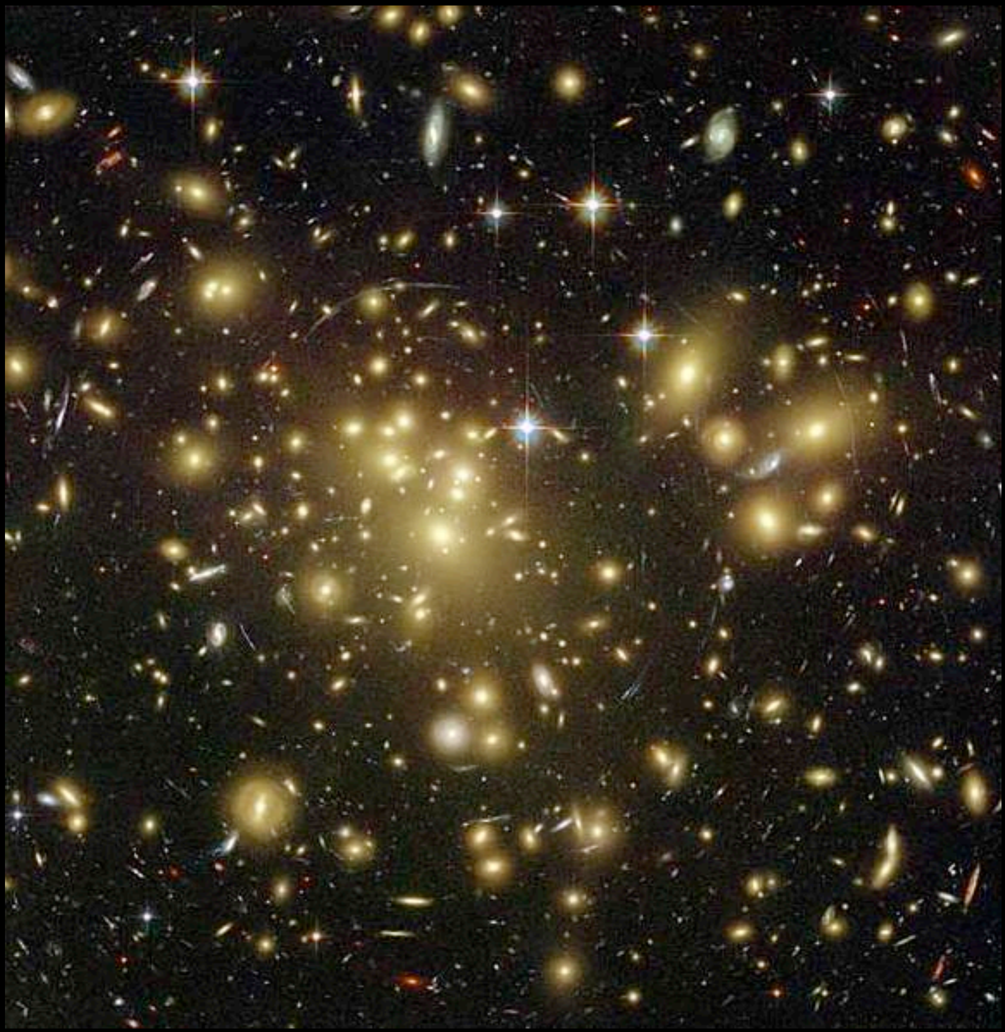


[Sanders & McGaugh 02]

- Even works well for low surface brightness galaxies, where it has no right to (purportedly lots of dark matter, hadn't been measured in 1984).

MOND is apparently "right" for galaxies – but why?

Empirical problems: galaxy clusters



MOND should apply to motions in clusters. But fits are off by factors of 2 to 10.

Only known solution: dark matter!
Neutrinos or light bosons. (Sanders)

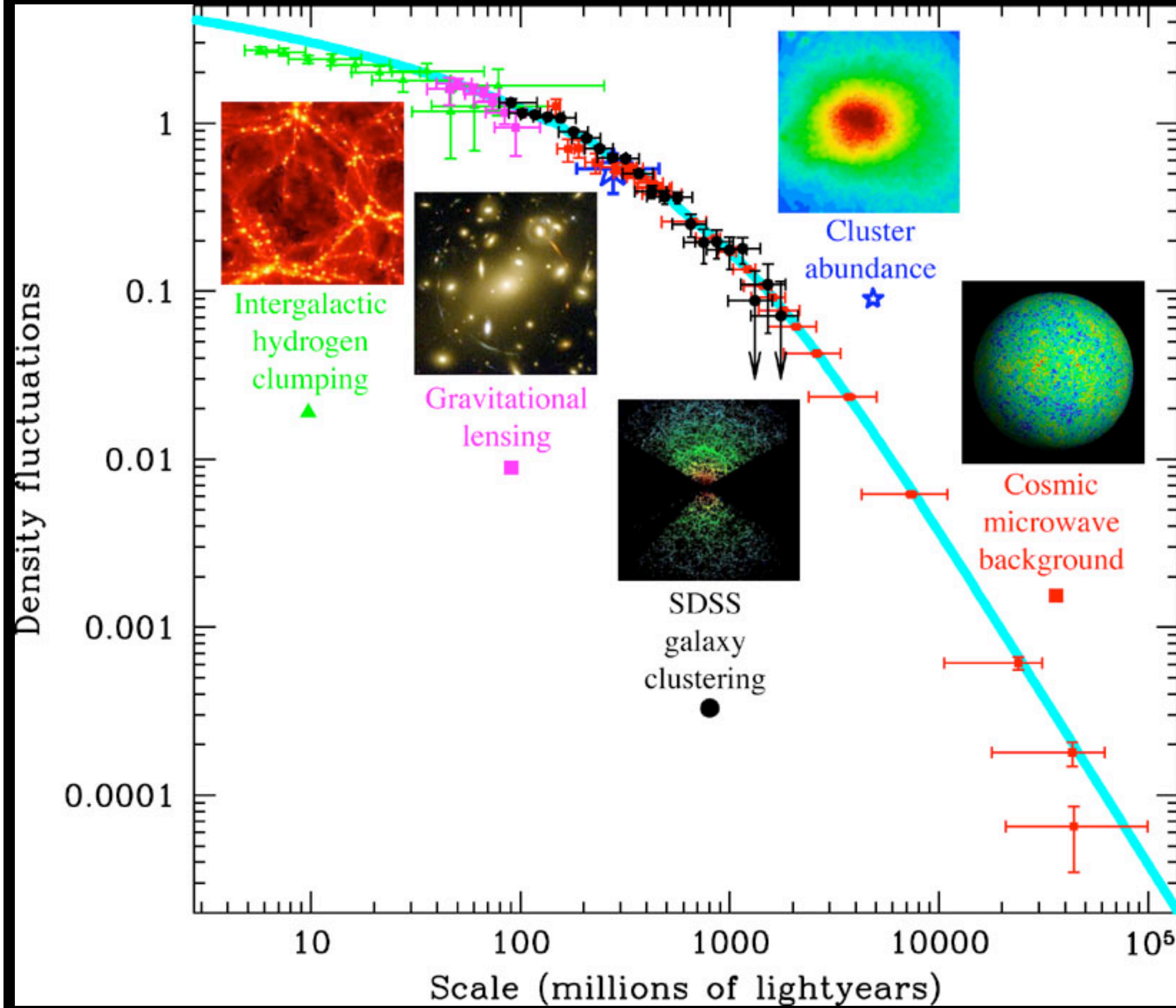
Theoretical problems: a relativistic model?

Modified Newtonian Dynamics – we know better.
Old-school MOND depends fundamentally on Newtonian notions, like "acceleration due to gravity."

Without a relativistic formulation, there's a lot we can't do with any confidence:

- Gravitational waves (binary pulsar)
- Gravitational lensing (cluster mass consistency)
- Expansion history (Friedmann equation, BBN)
- Cosmological structure: power spectrum, CMB

Power Spectrum of large-scale structure



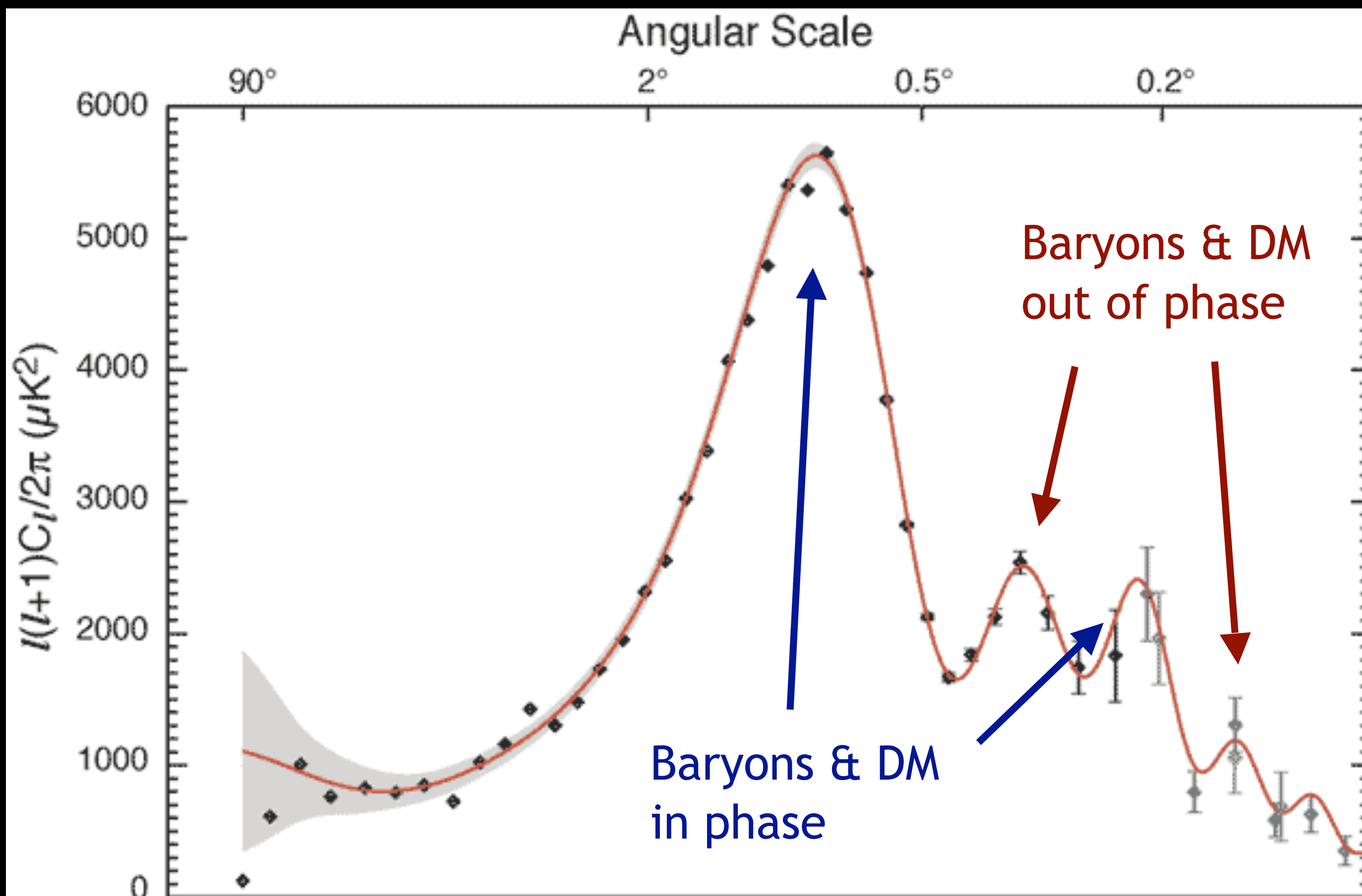
The linear power spectrum fits ΛCDM over four orders of magnitude, and depends crucially on the existence of dark matter. Otherwise, small scales killed by Silk damping.

Can MOND match that (just by coincidence)?

[Tegmark]

CMB temperature anisotropies

ΛCDM obviously fits CMB data very well. More importantly: DM plays a crucial role in determing the relative peak heights (boosts odd-numbered peaks).



[WMAP &c.]

Bekenstein's Relativistic MOND: TeVeS

In 2004 (after much groundwork) Bekenstein proposed a relativistic theory that reduces to MOND in the Newtonian regime. He calls it *TeVeS*, for Tensor-Vector-Scalar; the dynamical fields include a metric tensor $g_{\mu\nu}$, a fixed-length timelike vector U_μ, and a scalar field ϕ. Ordinary matter feels a transformed metric:

[related work by Milgrom, Sanders, Woodard, Moffat, etc.]

$$\tilde{g}_{\mu\nu} = e^{-2\phi} g_{\mu\nu} + 2\sinh(2\phi) U_\mu U_\nu$$

Not only is MOND reproduced, but even gravitational lensing seems to work out well! (Lorentz invariance is spontaneously violated, but okay.)

The gravitational action for TeVeS is an Einstein term for the metric, plus actions for U_μ, ϕ, and a non-dynamical field η (Lagrange multiplier):

$$S = \frac{1}{16\pi G} \int d^4x \, (R + \mathcal{L}_U + \mathcal{L}_\phi)$$

where

$$\mathcal{L}_U = -\frac{1}{2} K F^{\mu\nu} F_{\mu\nu} + \lambda (g^{\mu\nu} U_\mu U_\nu + 1)$$

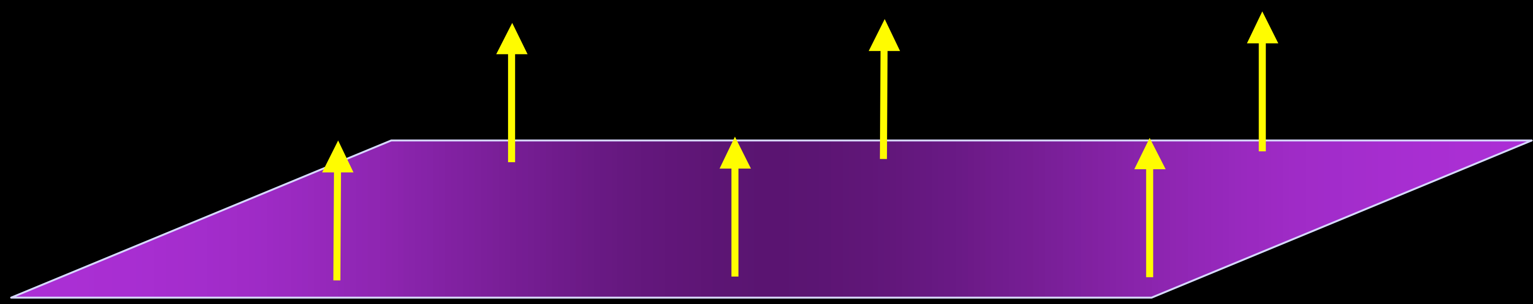
$$\mathcal{L}_\phi = -\mu_0 \eta (g^{\mu\nu} - U^\mu U^\nu) \partial_\mu \phi \partial_\nu \phi - V(\eta)$$

$$V(\eta) = \frac{3\mu_0}{128\pi l_B^2} \left[\eta (4 + 2\eta - 4\eta^2 + \eta^3) + 2 \ln^2 (\eta - 1) \right]$$

Not something you'd stumble upon by accident.

Lorentz-violating vector fields
(the secret to “absolute accelerations”)

In particle physics we are used to scalar fields getting a vacuum expectation value (e.g. the Higgs field).

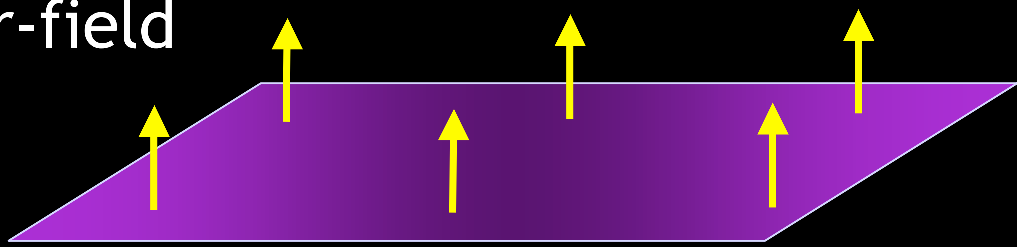


If a vector field U^μ has a nonzero expectation value, it violates Lorentz invariance. (Which is okay, but subject to interesting experimental constraints.)
What about gravitational effects? (In a simple model.)

[Carroll, Field & Jackiw 1990; Kostelecky et al.; Jacobson & Mattingly]

Einstein's equation: $G_{\mu\nu} = 8\pi G T^{(\mathrm{matter})}_{\mu\nu} + 8\pi G T^{(\mathrm{vector})}_{\mu\nu}$

Cosmologically, the vector-field energy-momentum tensor is always proportional to the Einstein tensor, decreasing the effective value of Newton's constant:



$$8\pi G T^{(\mathrm{vector})}_{\mu\nu} = -\alpha G_{\mu\nu} \rightarrow G_{\mu\nu} = \frac{8\pi G}{(1+\alpha)} T^{(\mathrm{matter})}_{\mu\nu}$$

A similar thing happens in the Solar System, except that Newton's constant is increased. This leads to a mismatch between the local and cosmological values of G, "slowing the universe down" compared to expectations.

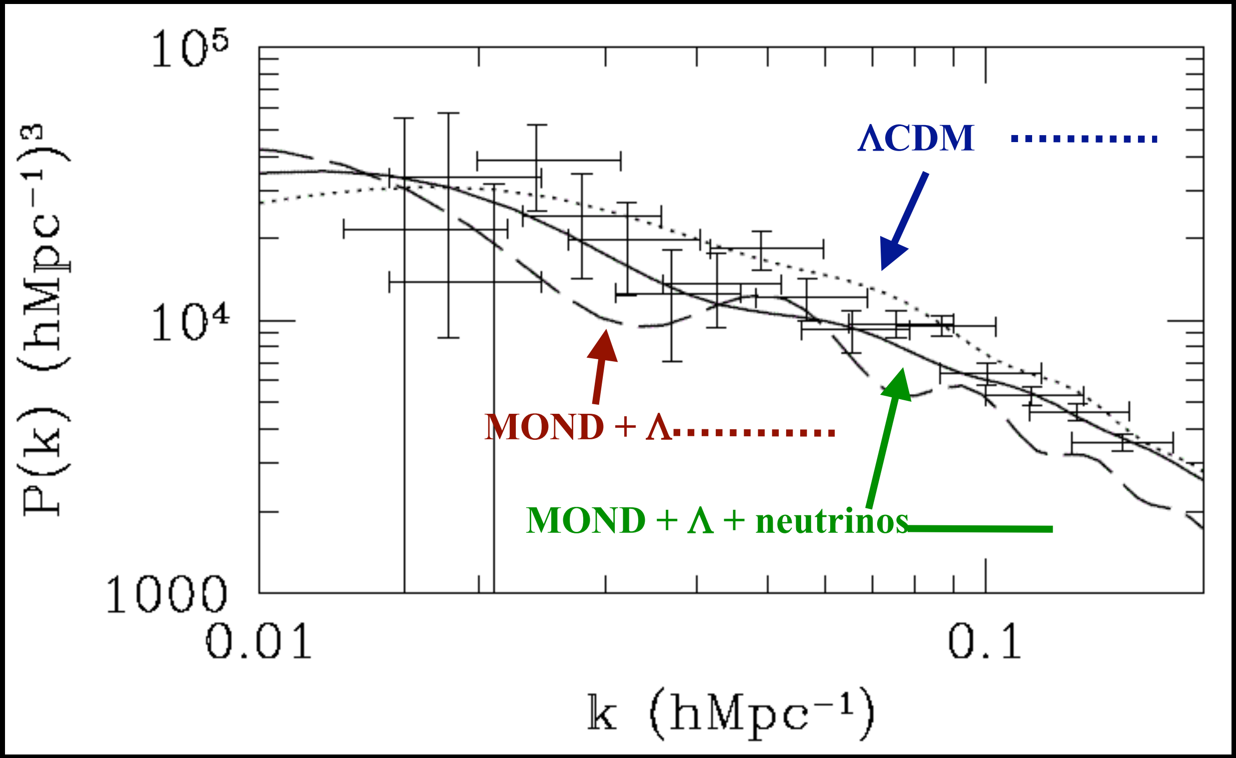
[Carroll & Lim 2004]

With TeVeS, we can do MONDian cosmology!

Skordis, Mota, Ferreira & Boehm 2005: Friedmann equation, large-scale structure, CMB anisotropies. Results for expansion history of the universe:

- Friedmann equation ($H^2 = 8\pi G\rho/3$) is basically unaltered, save for a (small) time-dependence for G.
- Energy density ρ_U for the vector is negligible.
- Scalar energy ρ_ϕ shows "tracking" behavior: since it must be small during BBN, will be small today.
- So: expansion basically normal; we need a big Λ.

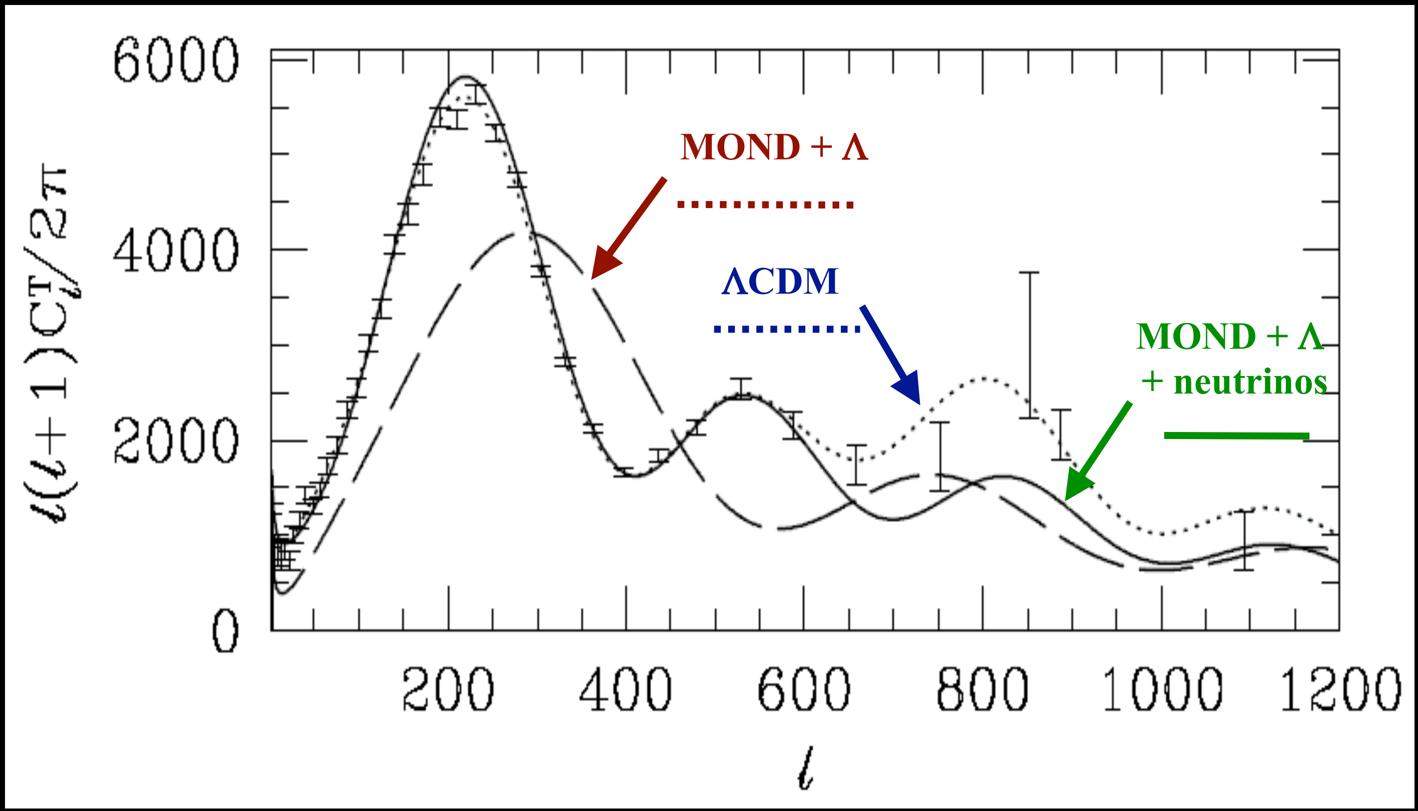
Interestingly: small-scale power spectrum looks okay!



[Skordis et al.;
data from SDSS]

Why isn't small-scale power wiped out by Silk damping? Because scalar field ϕ “freezes,” preserving initial small-scale perturbations against damping.

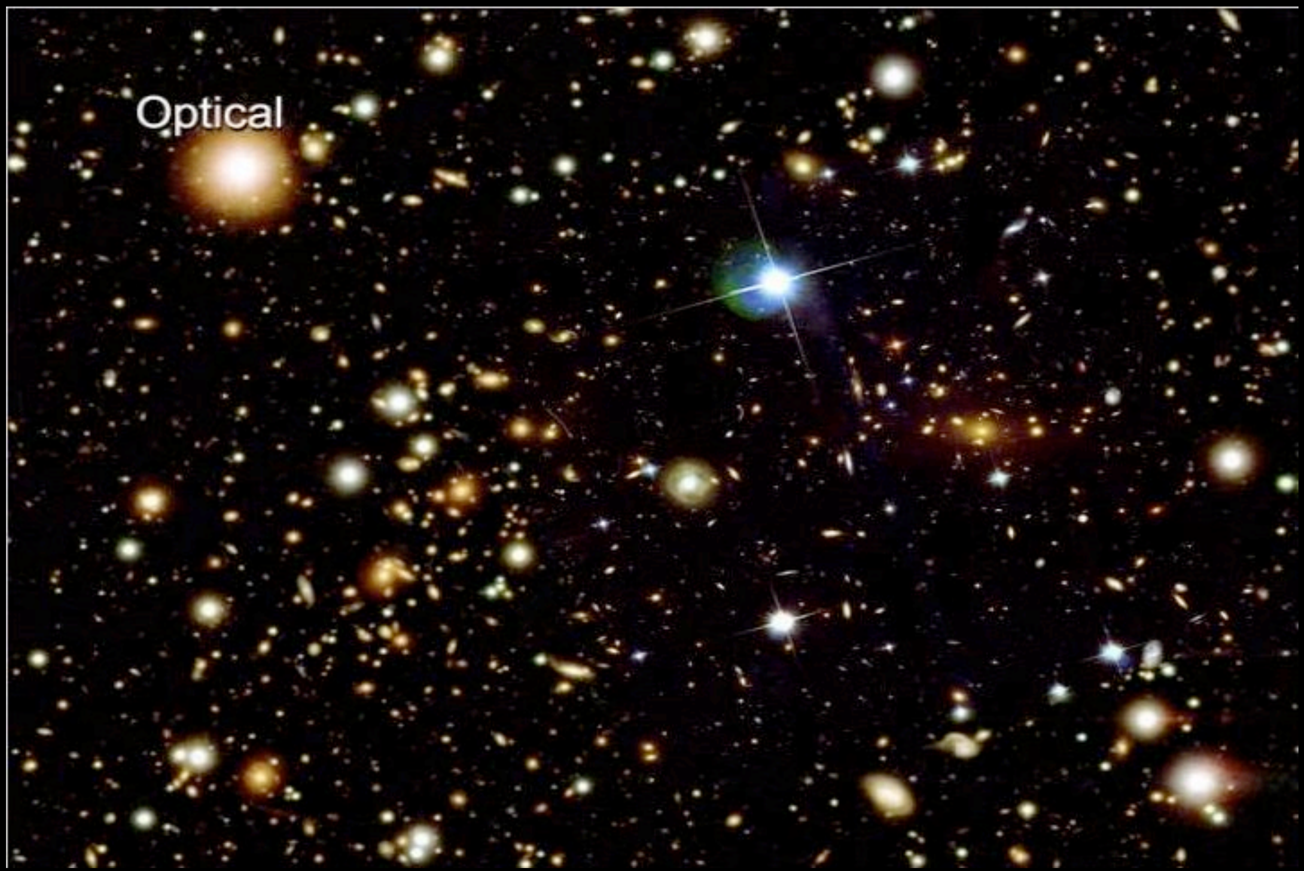
Crucial test: CMB anisotropy spectrum



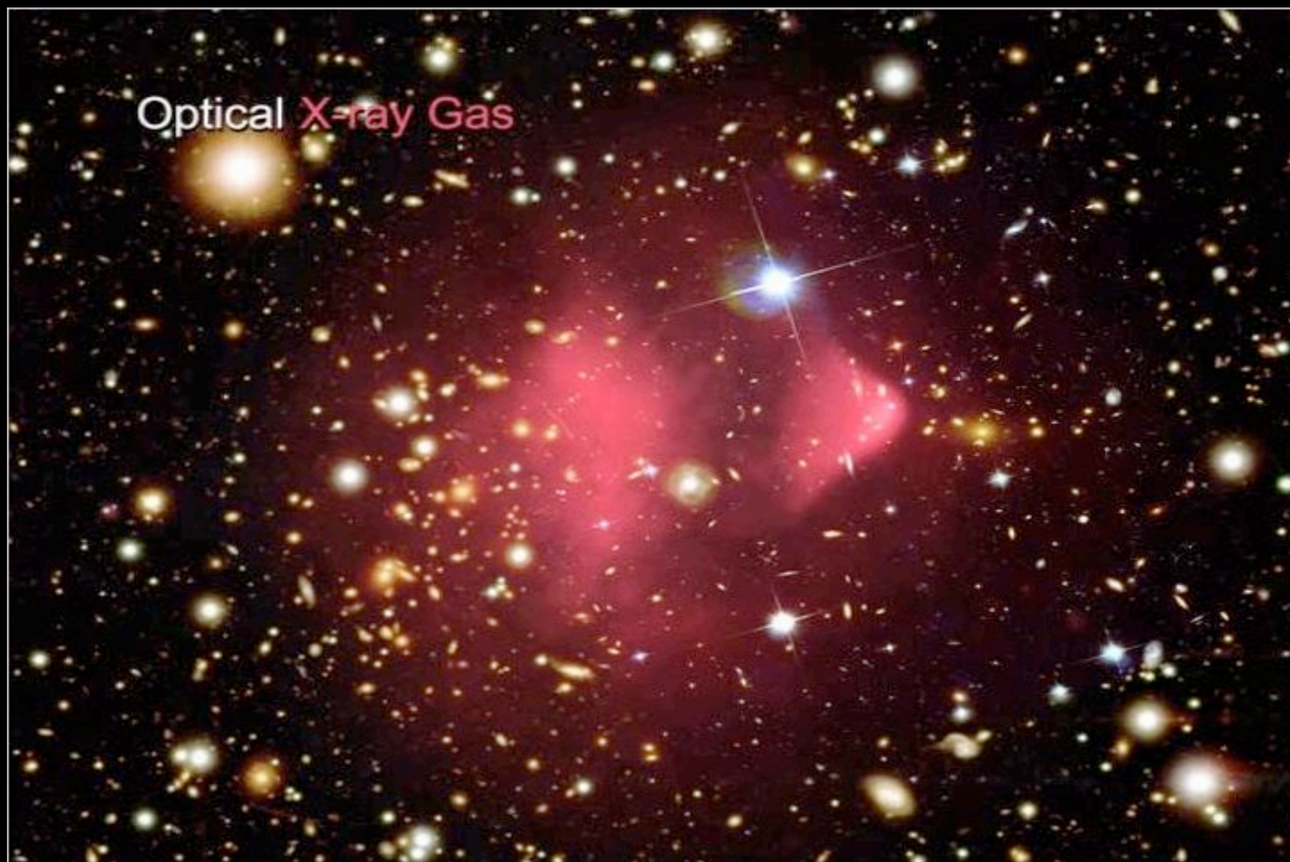
[Skordis et al.; data from WMAP, CBI, etc.]

Without any dark matter: hopeless. But with Ω_ν = 0.17, MOND does pretty well. The third peak will tell us whether there is dark matter or not.

Bullet Cluster



Bullet Cluster



Bullet Cluster

Bullet Cluster

Lessons of the Bullet Cluster

- There is gravity pointing in a direction where there is no ordinary matter to source it!
- This can't be explained (plausibly) by modifying gravity; there must be dark matter.
- BBN and CMB put an upper limit on the amount of baryonic matter; the DM must be non-baryonic. (We already knew this for MOND.)
- Claims to explain the Bullet Cluster in modified-gravity models are cheating; it's really DM.
- Which is not to say that gravity isn't <u>also</u> modified.

Outlook

- The success of MOND as a phenomenological description of galaxies warrants an explanation
- Failure to fit clusters (and CMB) without dark matter is a blow to the modified-gravity idea
- Bekenstein's relativistic version of MOND allows us to study cosmology, at least in this one model
- MOND cosmology does better than we might have expected, but 3rd peak is a problem
- Bullet cluster proves dark matter, of some sort, really exists