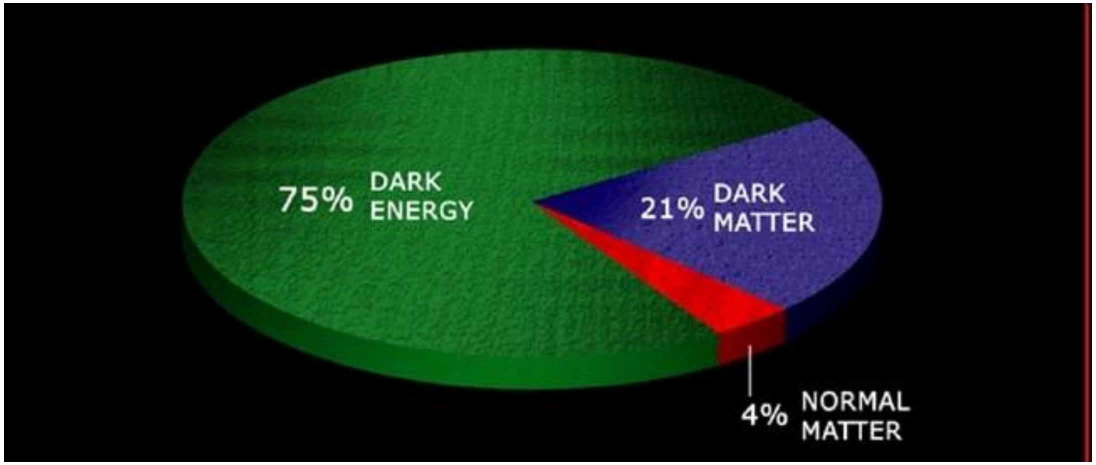
The Dark Sector vs. Modified Gravity



- The Context
- New Physics
- Twist: Stumbling into Age-Old Debate

Standard Model of Particle Physics

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons

- 4 particles which mediate the fundamental forces (photon, 2 W's, Z)
- Two Fermions (Electron and Neutrino)
- Higgs particle: Responsible for Mass

be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac12(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and on a right-handed singlet

$$R \equiv [\tfrac12(1-\gamma_5)]e. \qquad (2)$$

B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi = \binom{\varphi^0}{\varphi^-} \qquad (3)$$

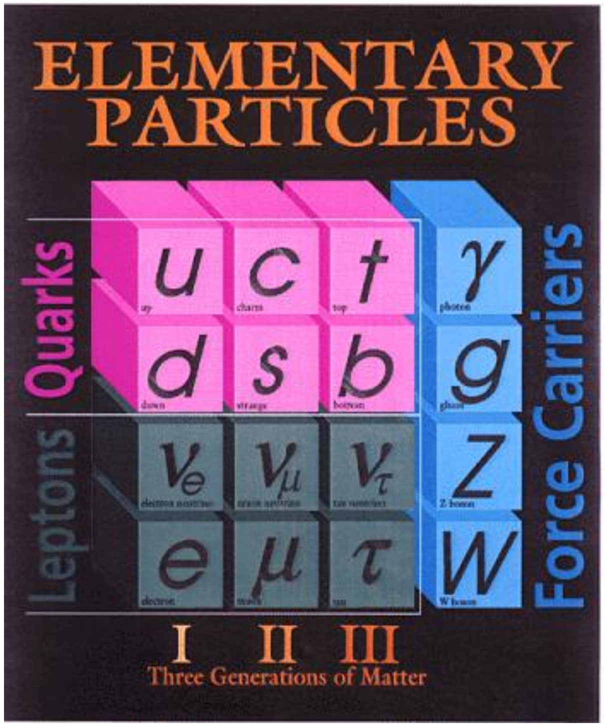
whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathcal{L} = -\tfrac14(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac14(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac12 g'B_\mu)L$$
$$-\tfrac12|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac12 g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \qquad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda \equiv \langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

Three minor extensions (all of which won Nobel Prizes)

- Quarks as well as leptons
- Quantum Chromodynamics: gluons and their interactions
- Three generations: electron, muon, tau (and similarly for quarks)



The Standard Model explains everything ever produced in an accelerator

One page (out of 298)
from the *Particle Data Group* Booklet

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	$\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_0(2330)$	$0^+(0^{++})$
$h_1(1595)$	$0^-(1^{+-})$	• $f_2(2340)$	$0^+(2^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$\rho_5(2350)$	$1^+(5^{--})$
$a_1(1640)$	$1^-(1^{++})$	$a_6(2450)$	$1^-(6^{++})$
$f_2(1640)$	$0^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
$D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)^\pm$	$0(?^?)$
$D_{s1}(2700)^\pm$	$0(1^-)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$1/2(1^+)$
• $B_{s2}^*(5840)^0$	$1/2(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
$\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(3945)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $X(4260)$	$?^?(1^{--})$
$X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\overline{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

NON-$q\overline{q}$ CANDIDATES

NON-$q\overline{q}$ CANDIDATES

Goal: Discover Physics beyond the Standard Model

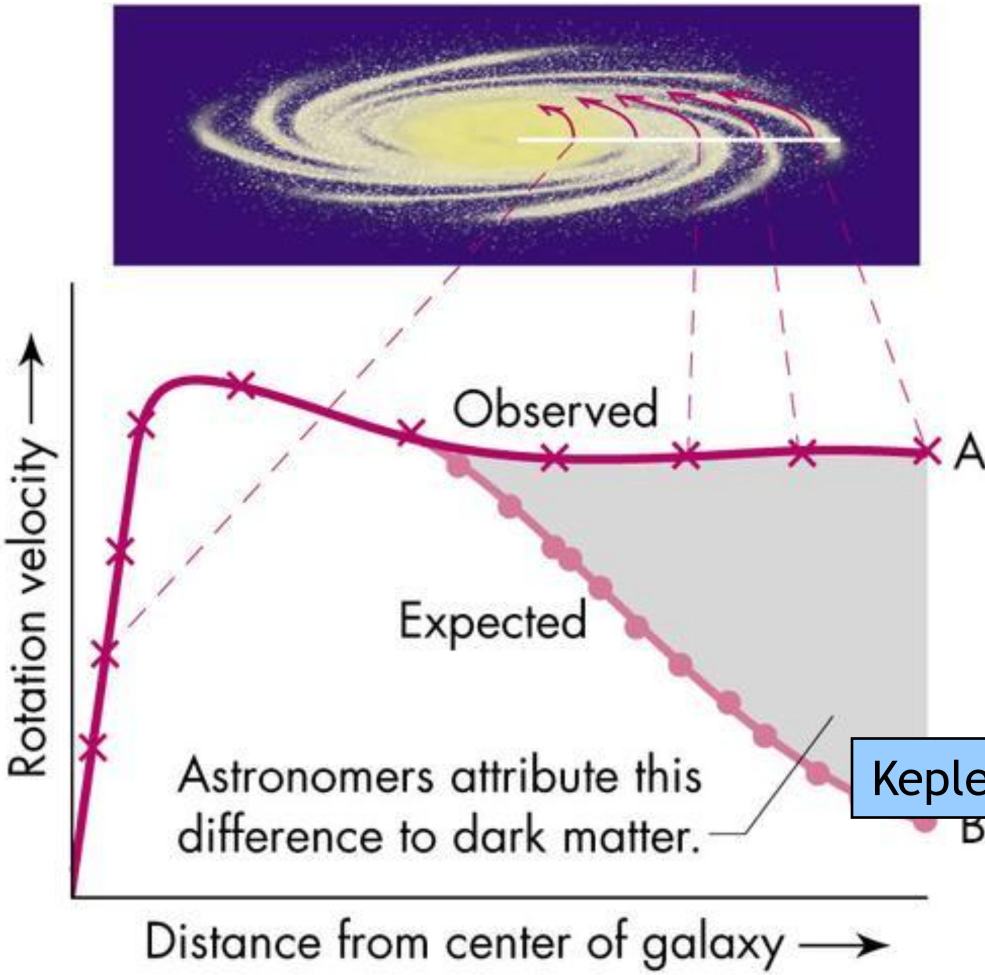
Scott Dodelson,
Fermilab/University of Chicago

Astrophysical observations provide evidence for new physics

- Depth of Potential Wells in the Cosmos
- Brightness of Supernovae
- Pattern of anisotropies in the Cosmic Microwave Background
- Observed Flux of Neutrinos

Physics Beyond the Standard Model I

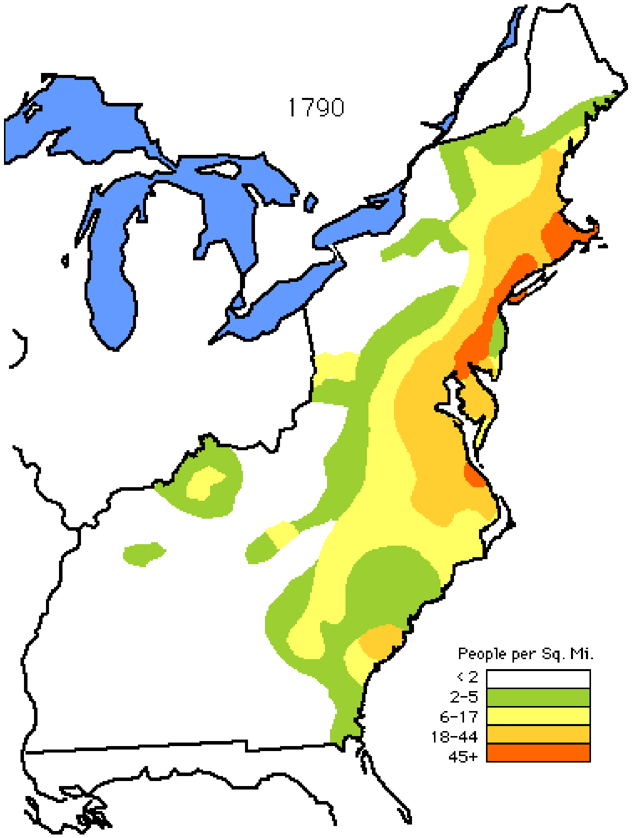
The Standard Model cannot explain the gravitational potentials observed in the cosmos



Kepler: $v=[GM/R]^{1/2}$

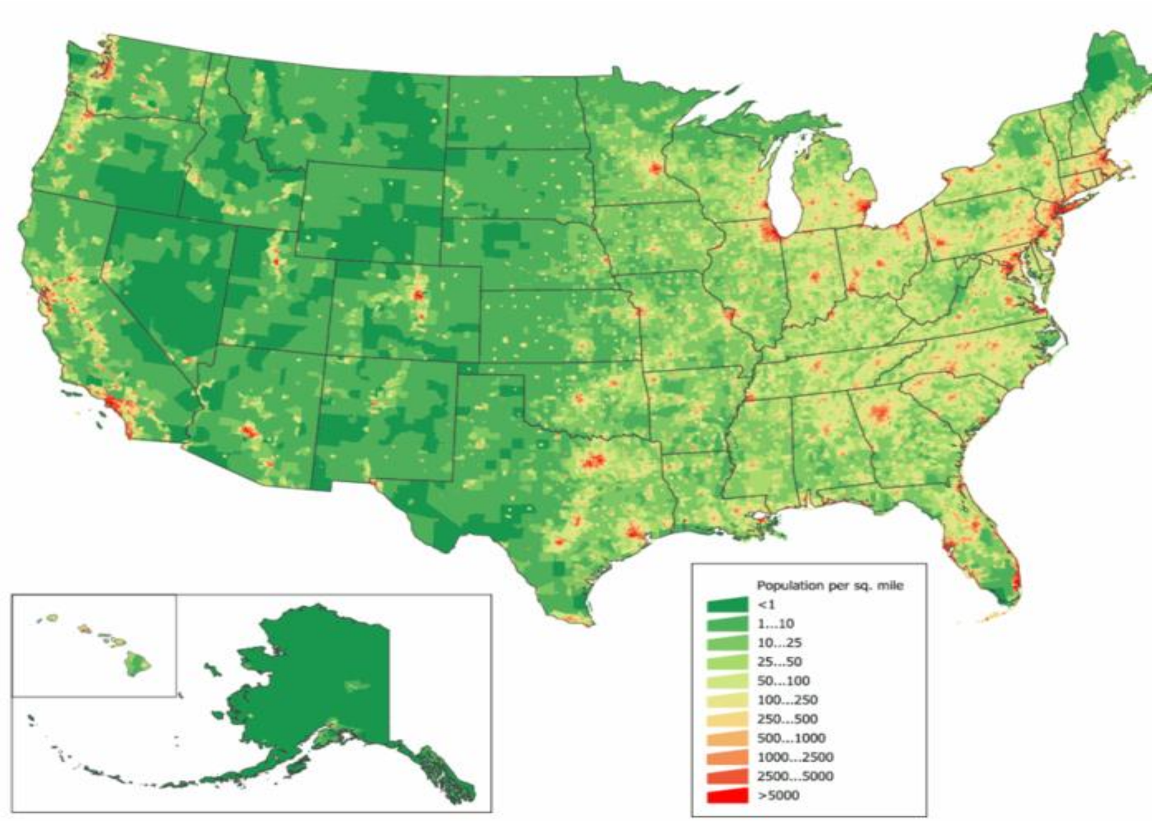
Consider the United States in 1790

- Over-densities of order 50
- Concentrated in East
- Vast Voids with low density



Consider the United States Today

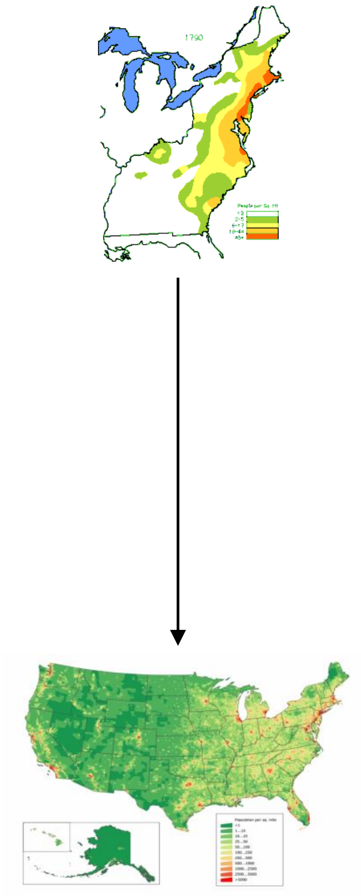
- Over-densities of order 10,000
- Concentration in coasts
- Traces of *primordial* density (Boston-Washington; East > West)
- Vast Voids



Scott Dodelson,
Fermilab/University of Chicago

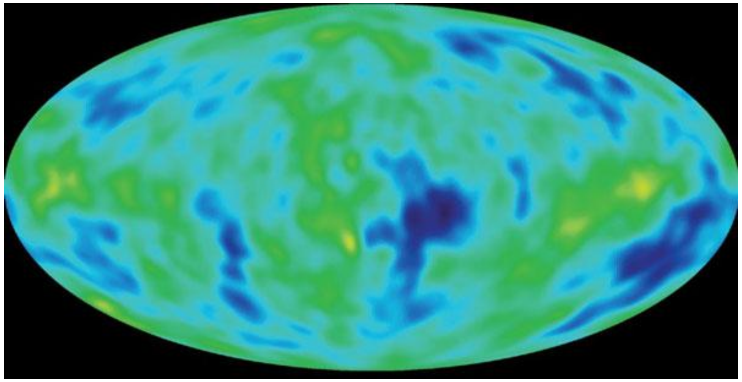
The story of this evolution is the story of the United States

When we understand the evolution from one map to another, we can understand
- the sociological, economic, and political ***forces*** acting on the US
- the people, or the ***constituents****, of the US*



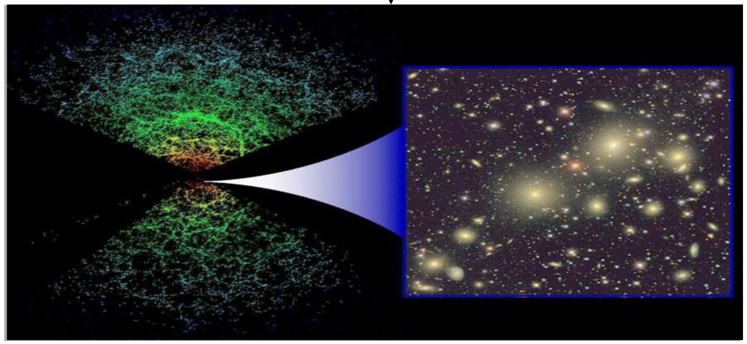
The Universe Would Be Too Smooth Without Dark Matter

At *t=400,000* years (*z=1000*), the photon/baryon distribution was smooth to one part in 10,000.



COBE

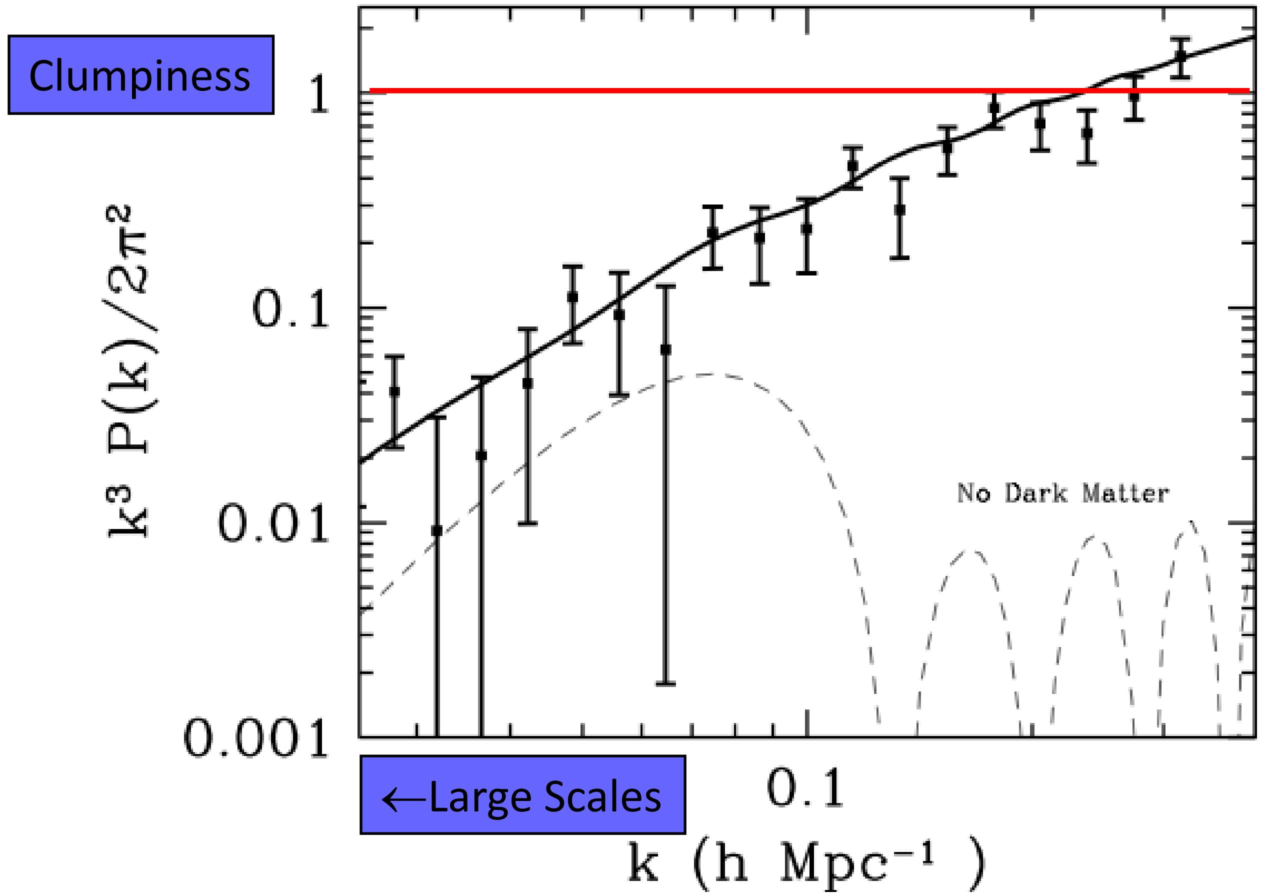
General Relativity predicts that perturbations have grown since then by a factor of 1000



Sloan Digital Sky Survey (SDSS)

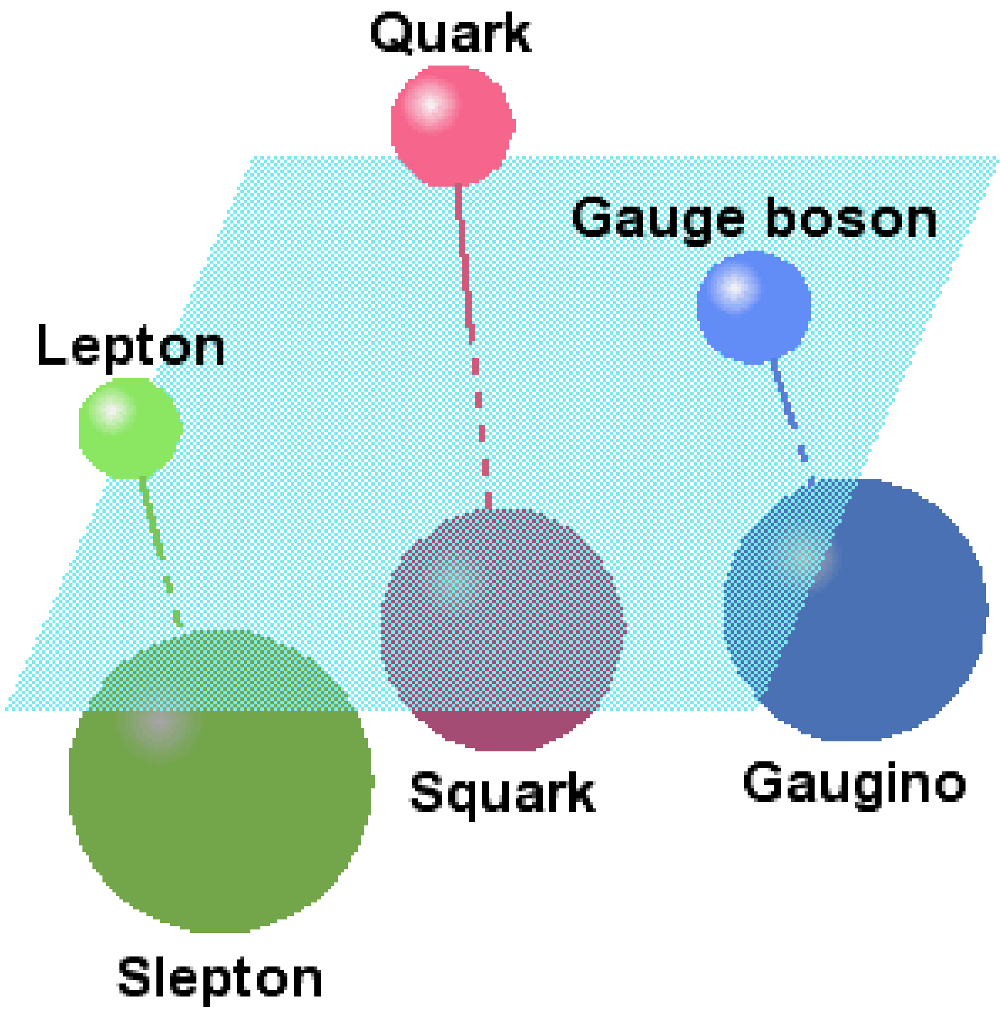
Dark Matter Solves Cosmic Structure Problem

Dark matter was much clumpier than baryons were at the time of the picture of cosmic microwave background (CMB). Enough time for structure to grow!

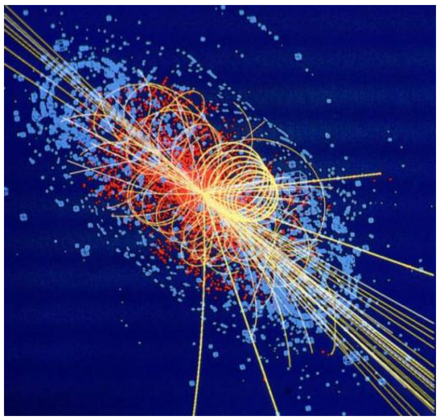


Dark Matter is **not** one of the particles in the Standard Model

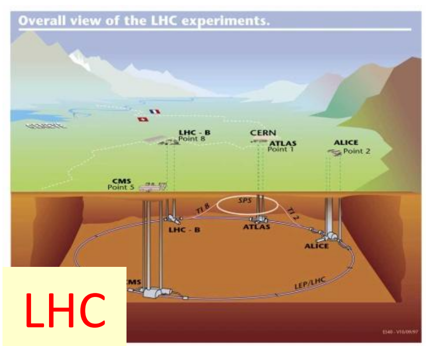
Supersymmetry is an extension of the SM, which predicts heavy partners. One of these satisfies all necessary criteria to be dark matter (massive, neutral, stable, weakly interacting)

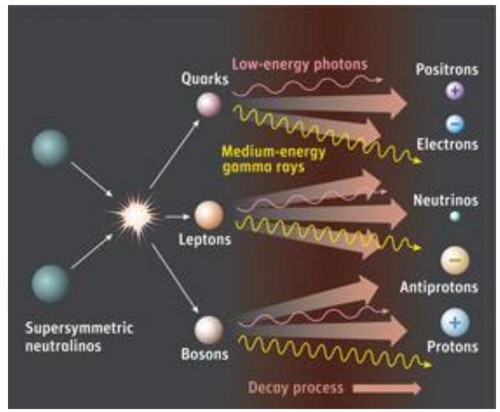


Three-Prong Search for Dark Matter

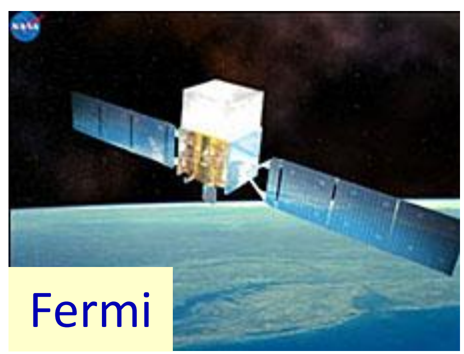


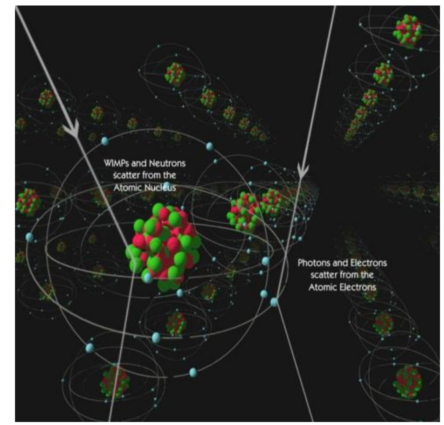
Accelerators





Indirect Detection

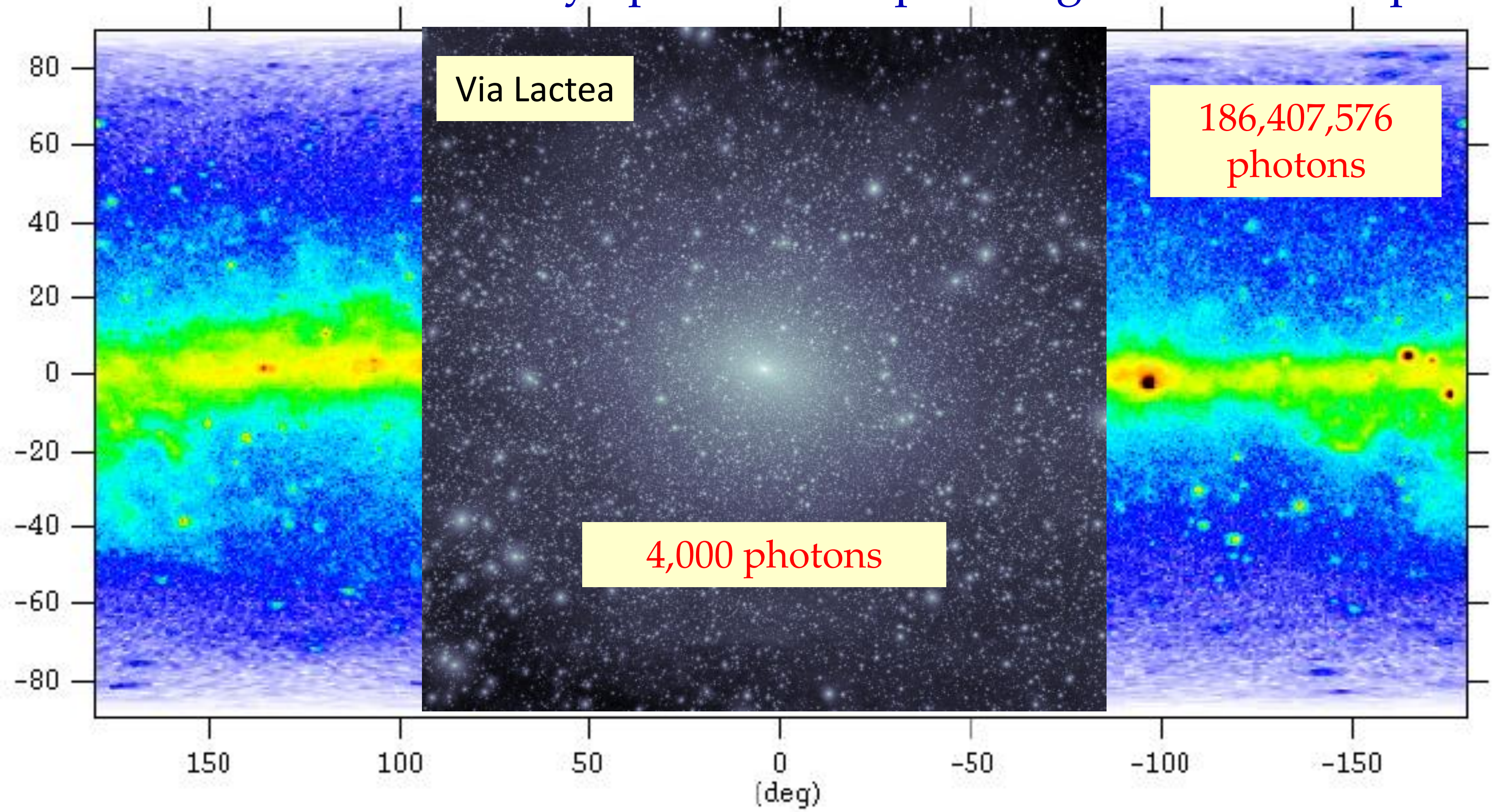




Direct Detection

Indirect Detection: The Challenge

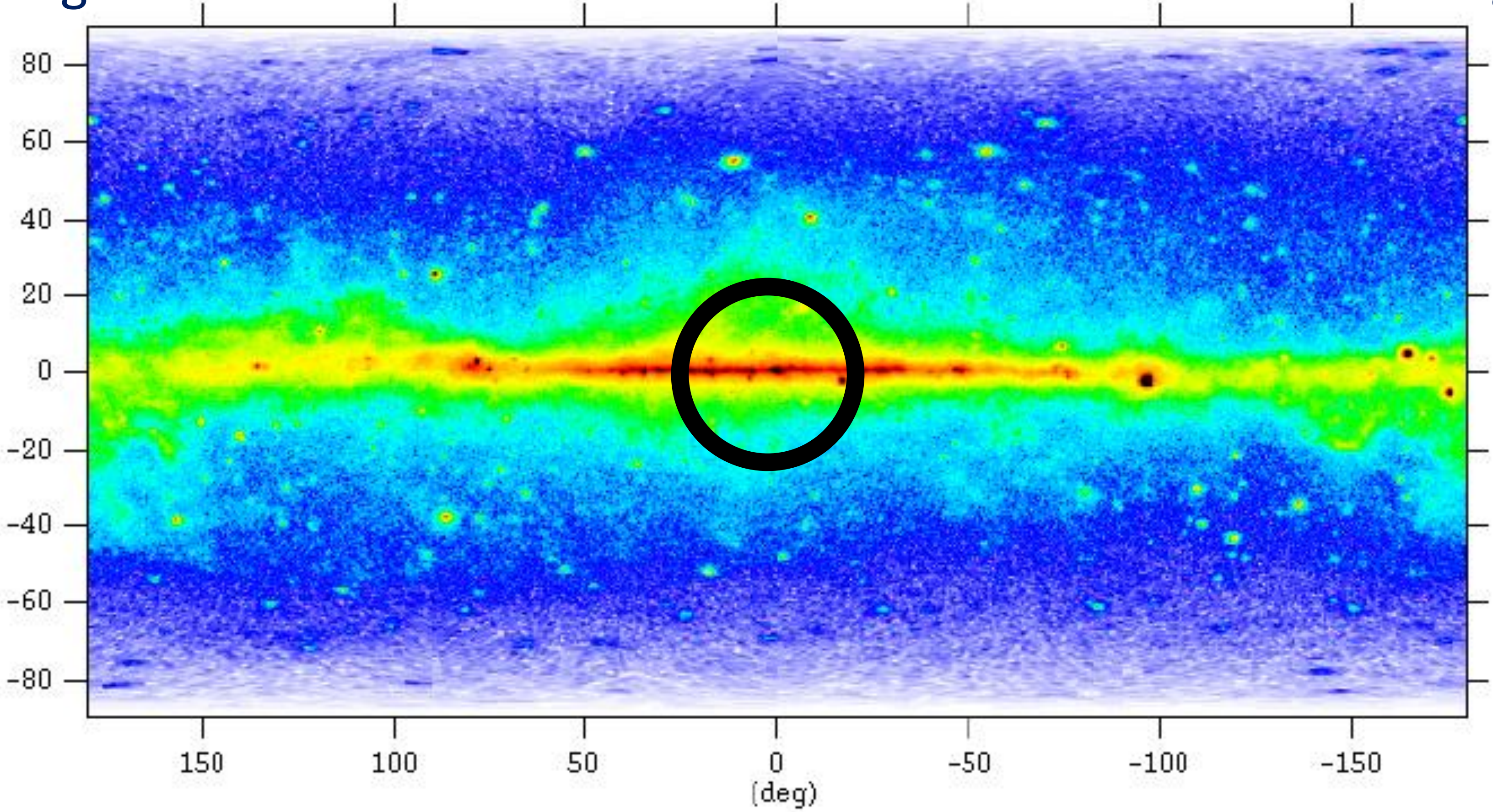
Fermi Gamma-ray Space Telescope : Large Area Telescope



Scott Dodelson,
Fermilab/University of Chicago

Ring Analysis

Signal from Dark Matter should be the same all around the ring

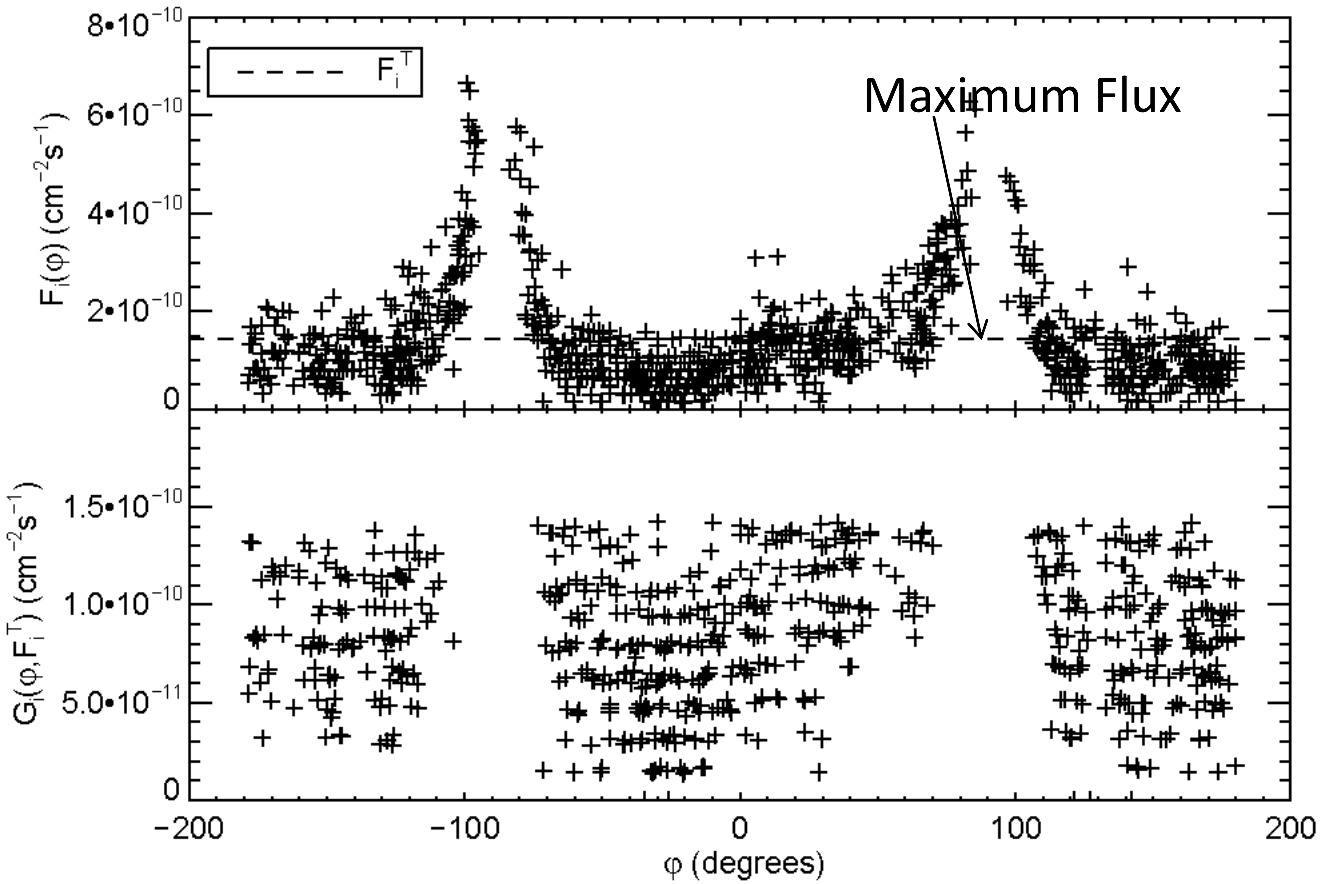


Ring Analysis

Find the maximum flux consistent with an *independent and identically distributed* signal

Flux in a given ring as a function of azimuthal angle

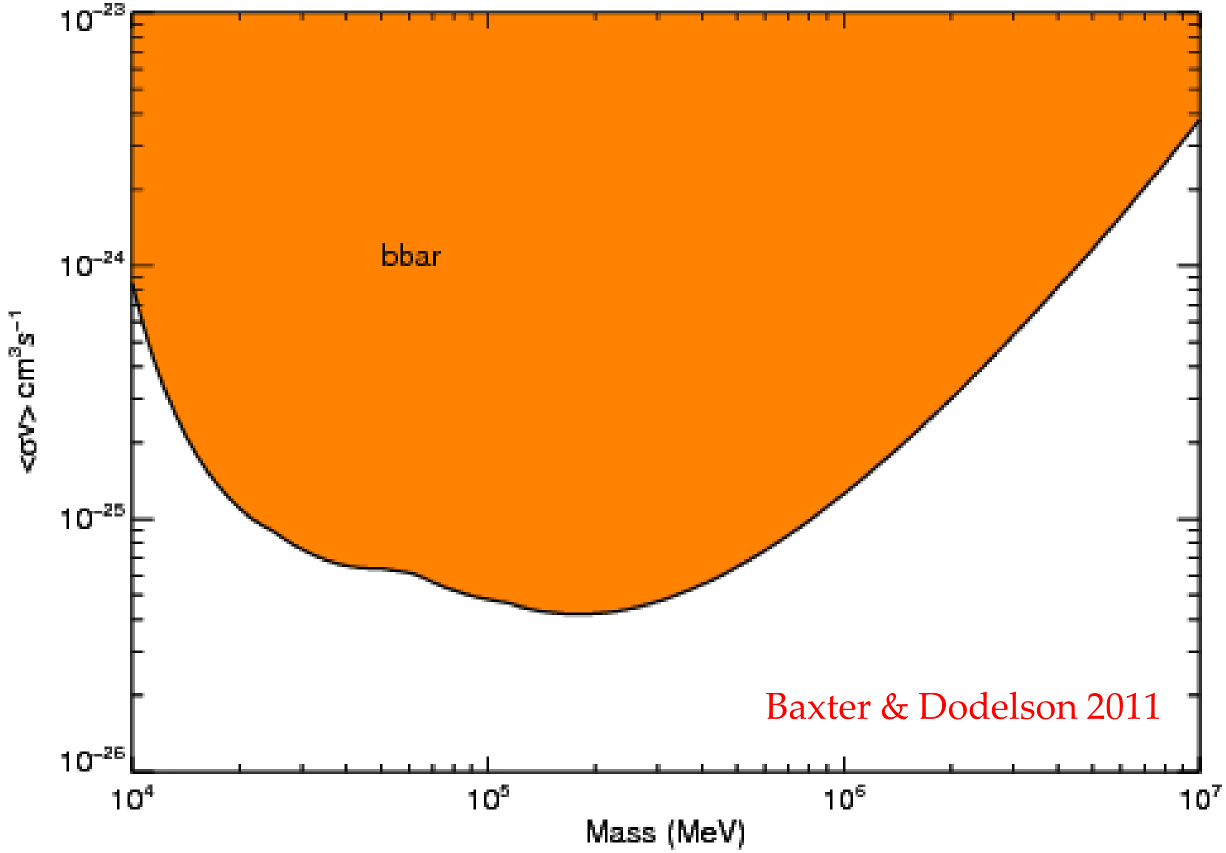
Truncated flux



Baxter & Dodelson 2011

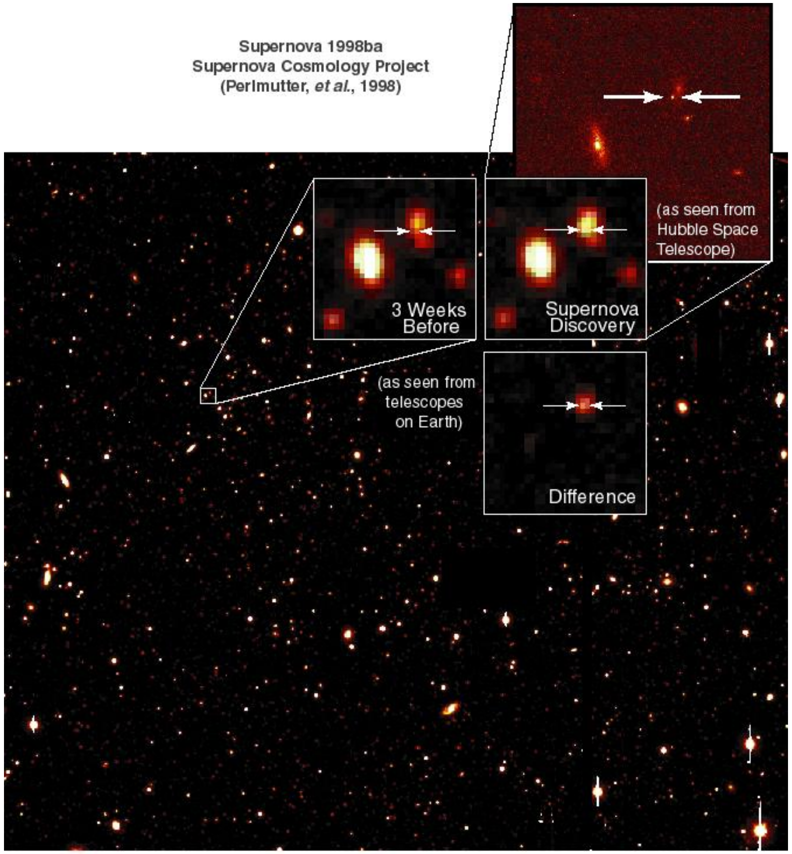
Ring Analysis

This upper limit on the flux corresponds to an upper limit on properties of the DM particle



Physics Beyond the Standard Model II

The Standard Model cannot explain the observed brightness of distant Supernovae

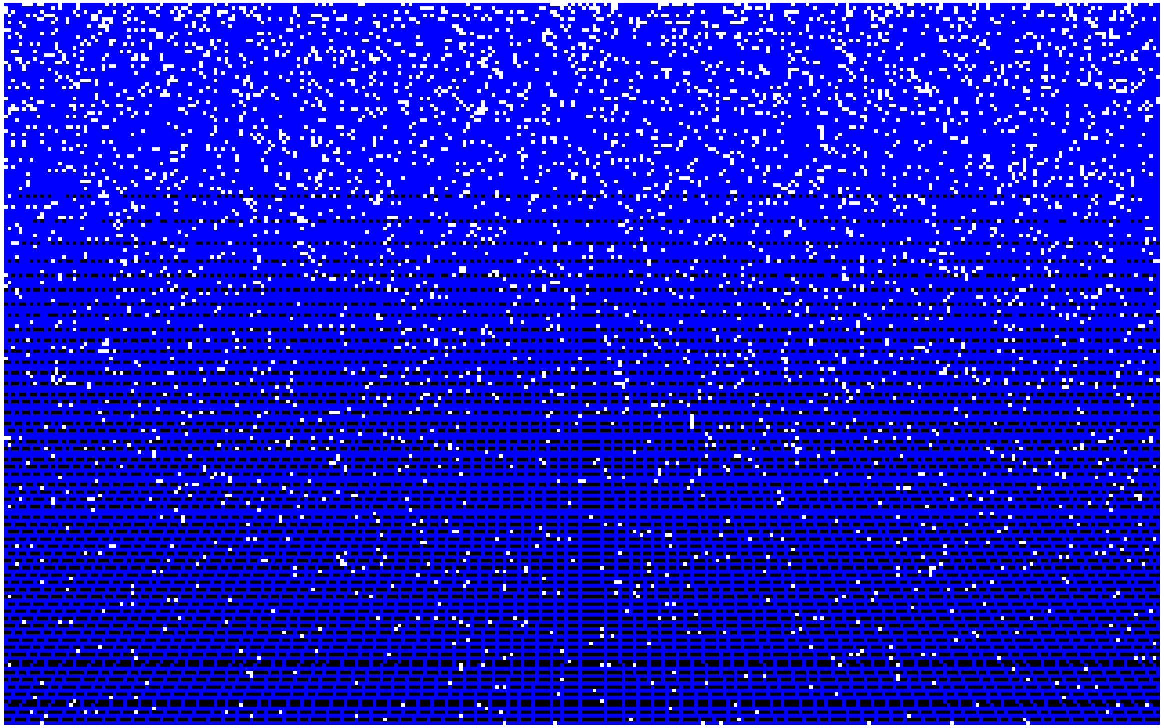


Brightness can be used to infer distance

Scott Dodelson,
Fermilab/University of Chicago

Distances in cosmology

Physical distances proportional to scale factor *a*, which increases with time



Einstein's Equations seem to require *$d^2a/dt^2<0$ (Deceleration)*

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right)$$

Can measure this because distance traveled by light depends on the expansion history:

$$d(z) = c\int_{1/(1+z)}^{1} \frac{da}{a\dot{a}} = c\int_0^z \frac{dz'}{H(z')}$$

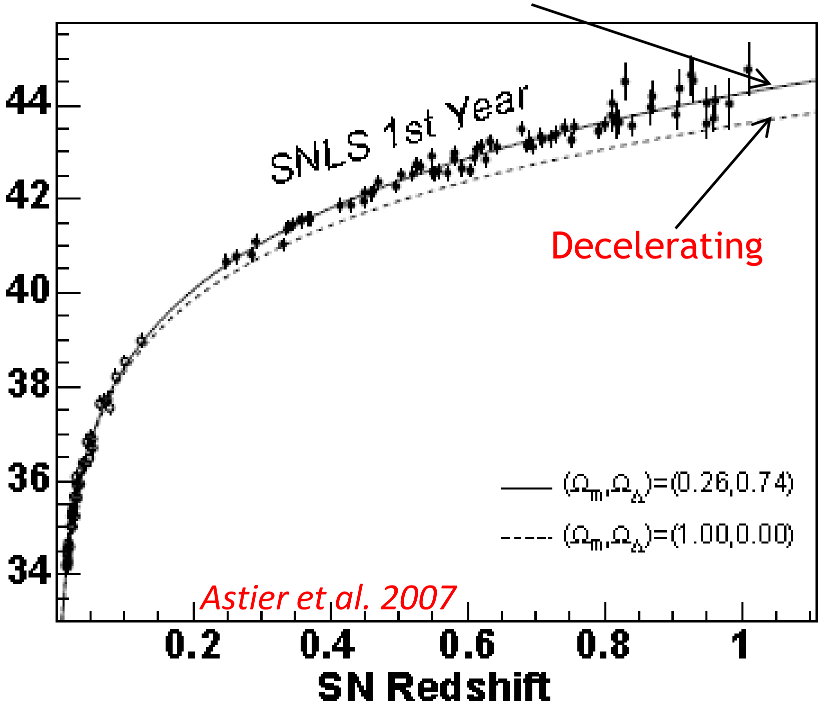
Redshift *$1+z=1/a$*

Since light travels *coordinate* distance *$c\,dt/a$*

Hubble expansion rate dln(a)/dt

The Universe is Accelerating

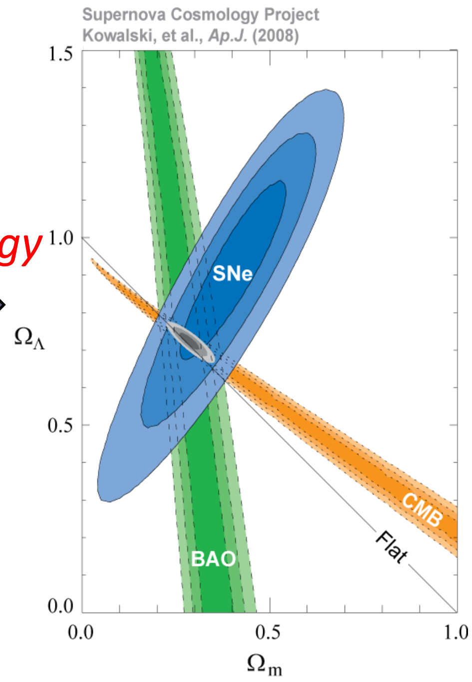
Accelerating



Deceleratinging

←Brighter

Requires *Dark Energy*



Scott Dodelson,
Fermilab/University of Chicago

Strange substance (Dark Energy) required to produce acceleration

Dark Energy has *negative* pressure
→ density remains roughly constant as universe expands
($H^2 = 8\pi G\rho/3$)

$$\rho(a) = \rho_0 \exp\left\{ 3\int_a^1 \frac{da'}{a'} \left[1 + w(a')\right] \right\}$$

Energy density today

Equation of state: $w = P/\rho$

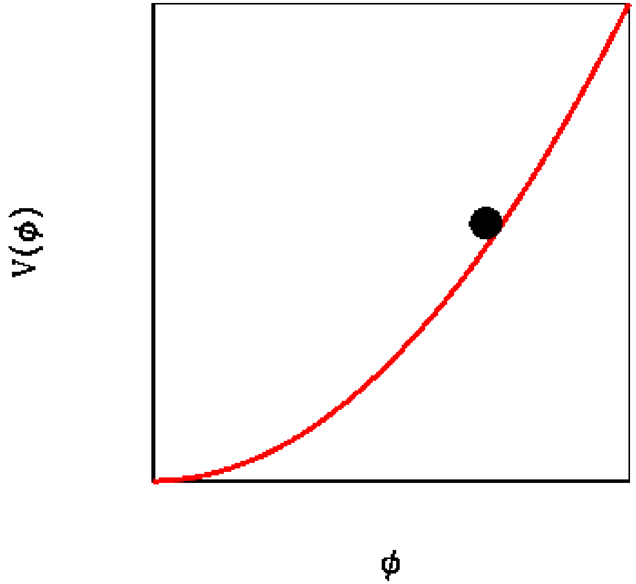
One possibility: Cosmological Constant

$$T_{\mu\nu} = g_{\mu\nu}\frac{\Lambda}{8\pi G}$$

- Energy associated with empty space
- Pressure is equal and opposite the energy density (*w=-1)*
- Expect non-zero contribution to the vacuum energy due to quantum fluctuations
- Amplitude is too large (by 120 orders of magnitude!)

Another possibility: Scalar Field

- Require roughly constant energy density
- Potential energy larger than kinetic energy
- Friction term due to expansion dominates, so $(V'')^{1/2}=m<10^{-33}$ *eV* (Hubble rate today)



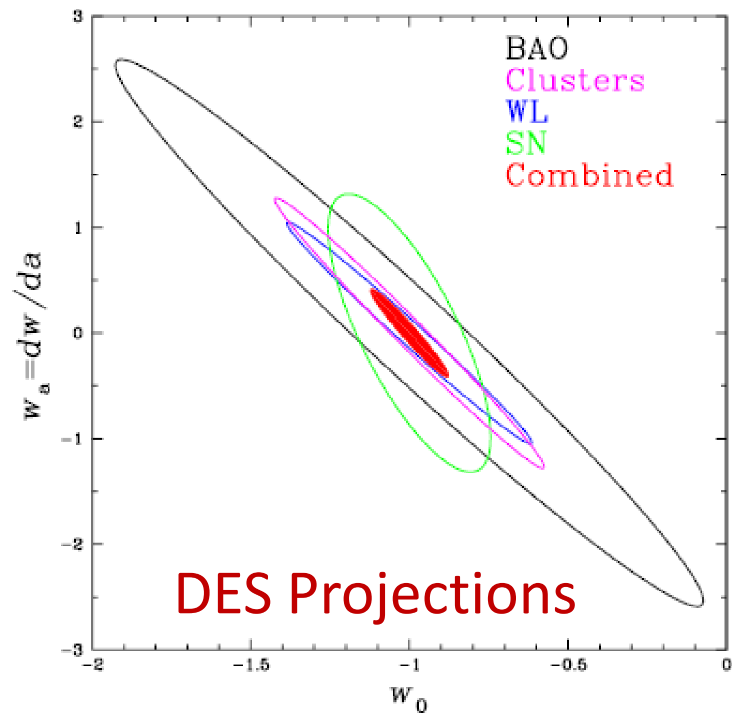
$$\ddot{\phi}+3H\dot{\phi}+\frac{dV}{d\phi}=0$$

Scott Dodelson,
Fermilab/University of Chicago

Measure Equation of State of Dark Energy

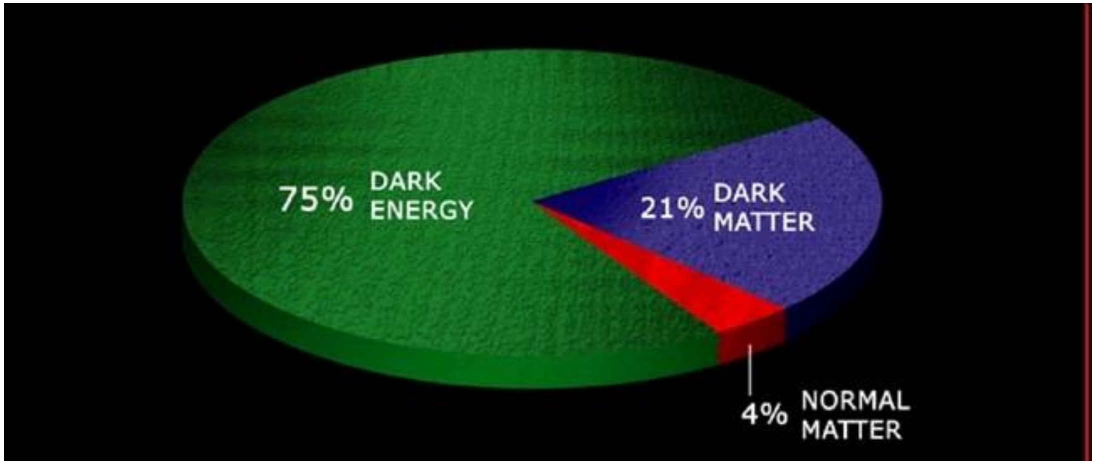
HSC+PFS @ Subaru

DARK ENERGY
Survey



Summary: Studying the Dark Sector

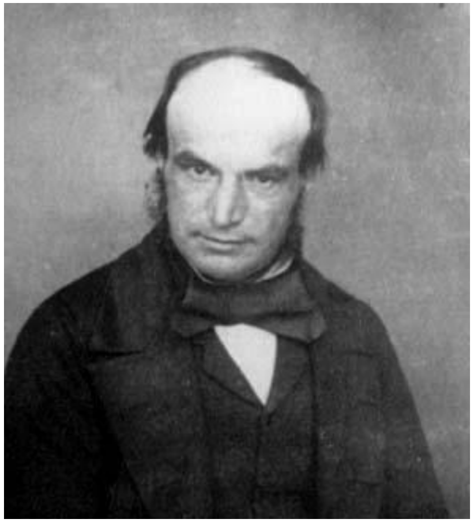
- Find Dark Matter via Accelerators, Direct Detection, Indirect Detection
- Measure the Equation of State of Dark Energy to determine the Nature of Dark Energy



Scott Dodelson,
Fermilab/University of Chicago

Remember how Neptune was discovered

"Formed a design in the beginning of this week, of investigating, as soon as possible after taking my degree, the irregularities of the motion of Uranus, which are yet unaccounted for; in order to find out whether they may be attributed to the action of an undiscovered planet beyond it; and if possible thence to determine the elements of its orbit, etc.. approximately, which would probably lead to its discovery."



John Adams

Undergraduate Notebook, July 1841

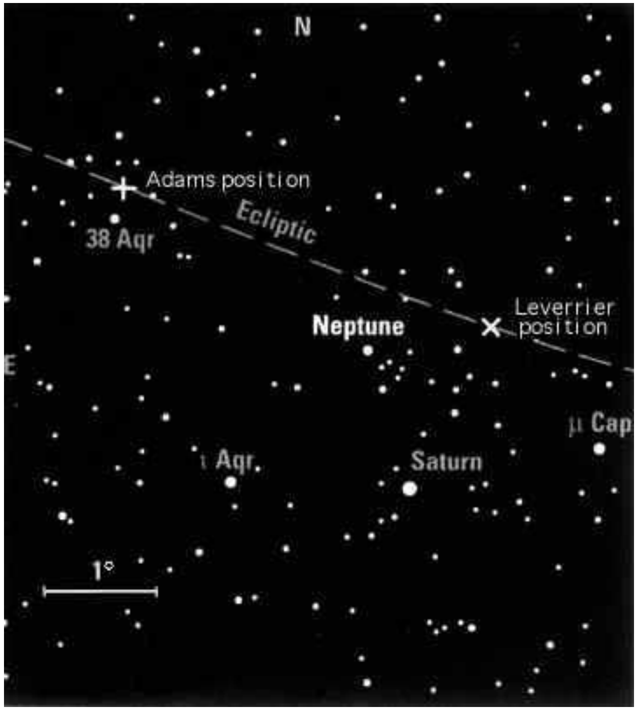
Not everyone believed a new planet was responsible

Adams informed Airy of his plans, but Airy did not grant observing time. He believed deviation from $1/r^2$ force responsible for irregularities

Astronomer Royal, George Airy

By June 1846, both Adams and French astronomer LeVerrier had calculated positions

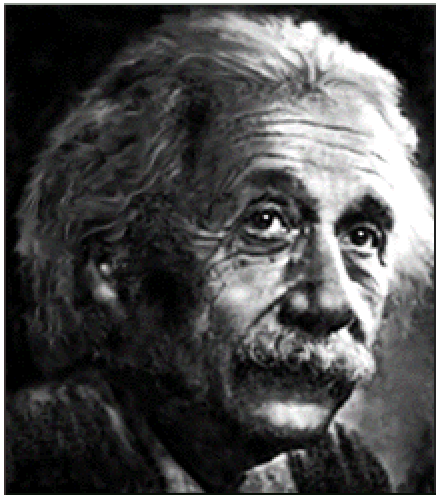
Competition is a good thing: Airy instructed Cambridge Observatory to begin a search in July, 1846, and Neptune was discovered shortly thereafter.



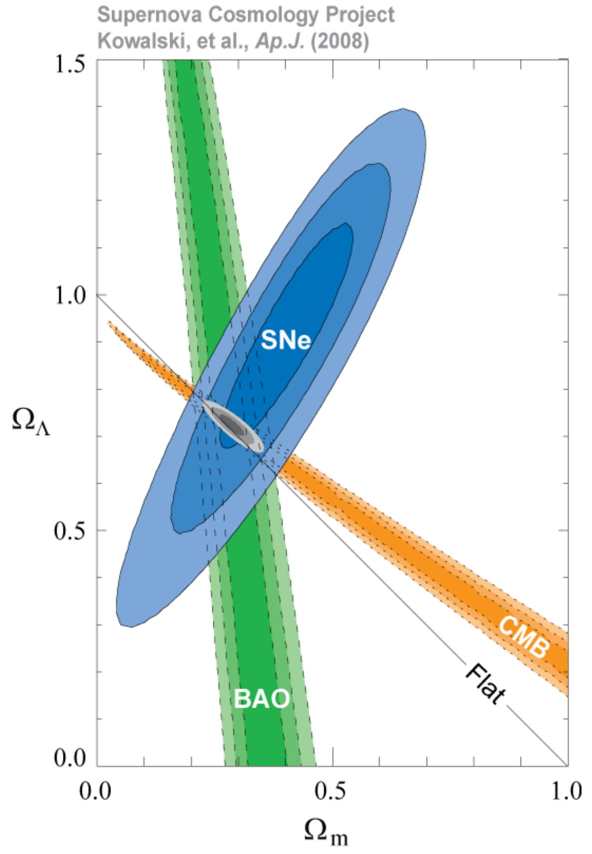
Anomalous precession of Mercury's perihelion went the other way

LeVerrier assumed it was due to a small planet near the Sun and searched (in vain) for such a planet (Vulcan).

We now know that this anomaly is due to a whole new theory of gravity.



Is Dark Energy necessary to explain acceleration?



f(R) Models for Acceleration

Modify the Einstein-Hilbert Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R + f(R)\right] + \int d^4x\sqrt{-g}\,L_m$$

For the cosmological metric, the acceleration equation generalizes to:

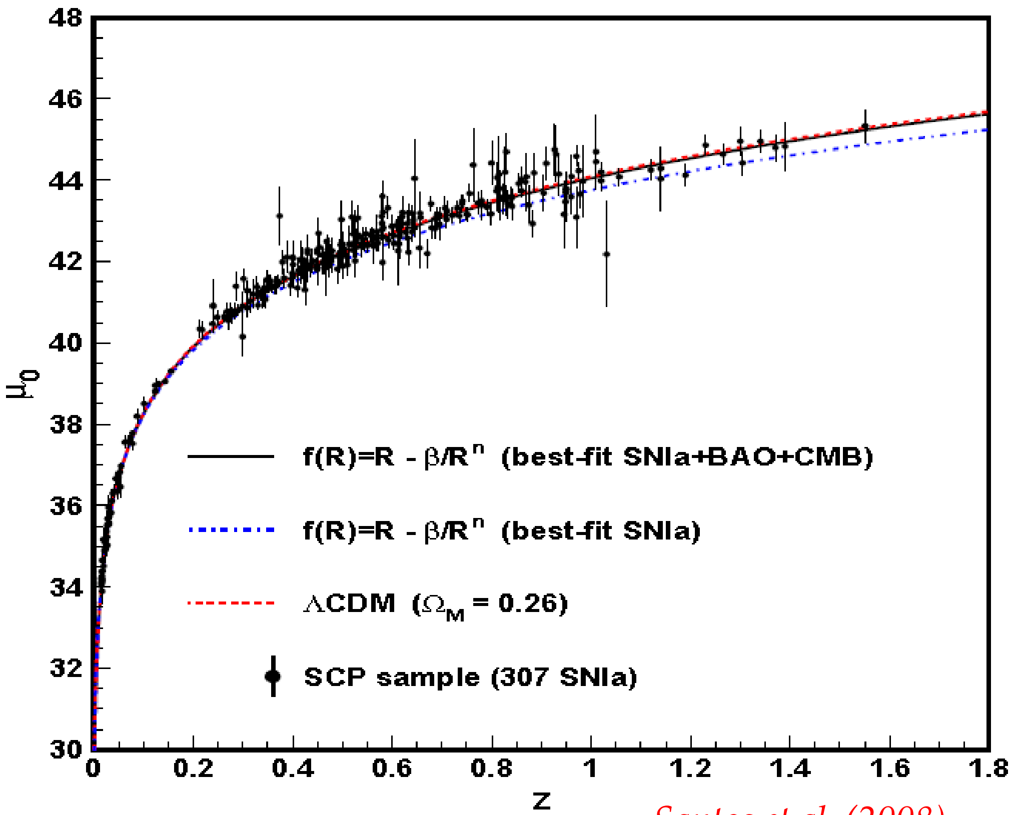
Get acceleration if these terms are positive

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right) + \left[\frac{\partial f}{\partial R}H^2 - \frac{f}{6} - \frac{\ddot{\partial f / \partial R}}{2}\right]$$

Scott Dodelson,
Fermilab/University of Chicago

Easy to fit Supernova Data

The new parameter has dimensions of mass and is of order 10^{-33} eV



Santos et al. (2008)

Resolving the cause of acceleration will be harder than Neptune

- If both Dark Energy and Modified Gravity can re-produce the expansion history, how will we distinguish them observationally?
- Recall the history of the cosmological term (Does it belong on the left or right side of Einstein's Equation?) How do we determine what is a dark energy model and what is a modified gravity model?

Scalar Tensor Models

- *f(R)* models are equivalent to a *scalar-tensor* theory (Starobinsky 1979)
- Challenge the implicit assumption of GR that the metric in the Einstein-Hilbert action is the same as the metric which couples to matter

$$S_{EH} = \frac{1}{16\pi G}\int d^4x\sqrt{-\tilde{g}}R[\tilde{g}] \qquad S_m = \int d^4x\sqrt{-g}L_m$$

- Allow $\tilde{g} = e^{-2\varphi/m_P}g$

- Scalar-Tensor theory then described by dynamics *S[Φ]*

Perturbations in Modified Gravity

Lue, Scoccimarro, and Starkman (2004); Bertschinger (2006); Hu & Sawicki (2007); Tsujikawa et al. (2008); Motohashi, Starobinsky & Yokoyama (2010)

Start with the perturbed FRW metric

$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)(dr^2 + r^2 d\theta + r^2 \sin^2\theta d\phi)$$

Generally two differences between MG and GR:

GENERAL RELATIVITY	MODIFIED GRAVITY
$\Phi - \Psi = 0$	$\Phi - \Psi \neq 0$
$\nabla^2\Phi = -4\pi G \rho_m a^2 \delta$	$\nabla^2\Phi = -4\pi G_{eff}\, \rho_m a^2 \delta$

Scott Dodelson,
Fermilab/University of Chicago

Perturbations in Modified Gravity

To test MG vs. DE, need to measure:

$$g \equiv \Phi - \Psi$$

$$f_G \equiv \frac{G_{eff}}{G} - 1$$

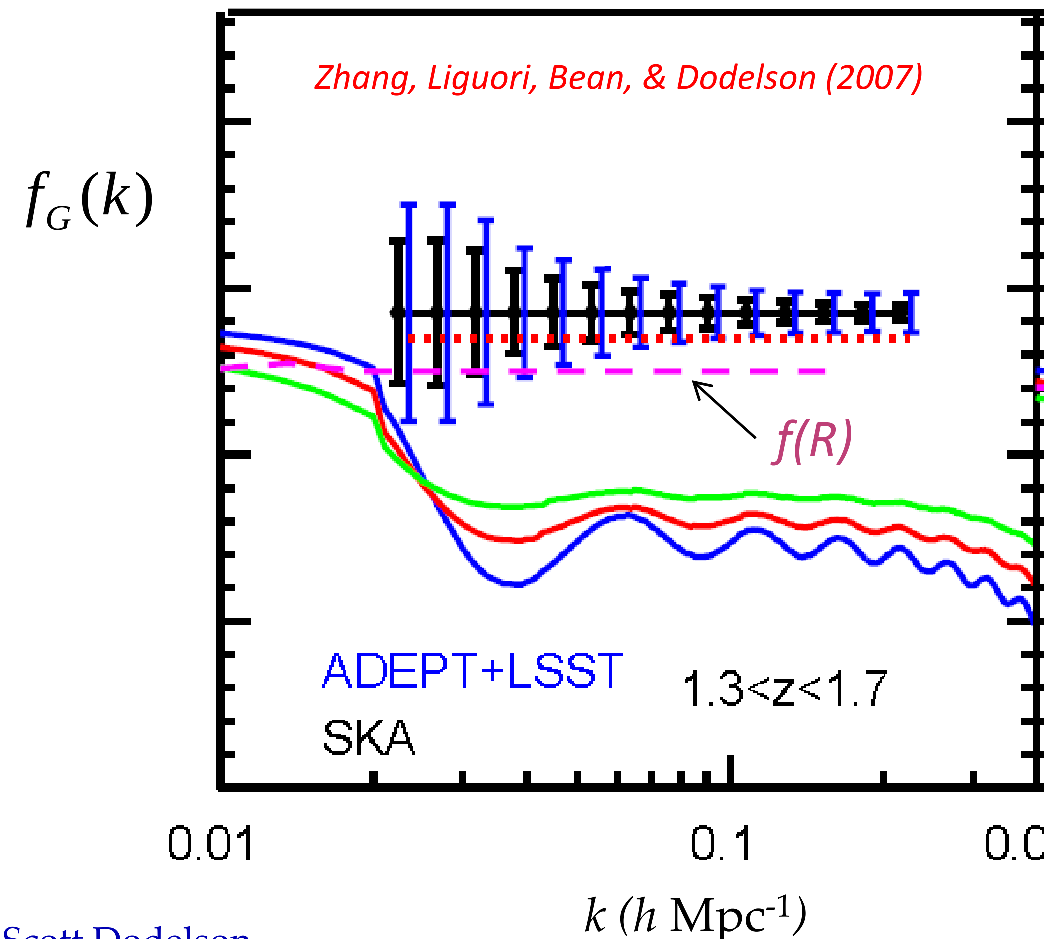
Difference from zero of either of these would indicate MG is responsible for acceleration

Probing *f* and *g*

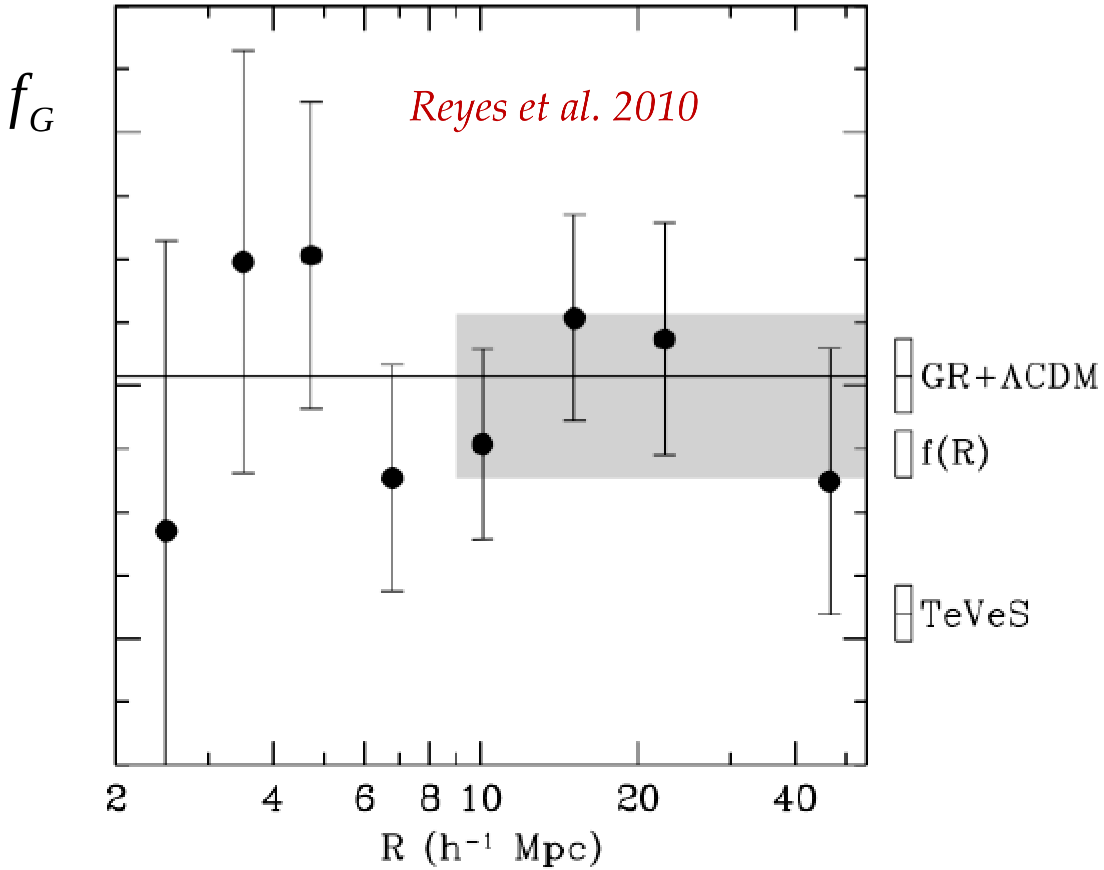
Cross-correlate galaxy density with velocity field

$$\frac{\langle \delta_g \theta \rangle}{\langle \delta_g \kappa \rangle} \sim \frac{\delta}{\Phi - \Psi} \sim 1 + f_G$$

Cross-correlate galaxy density with convergence field

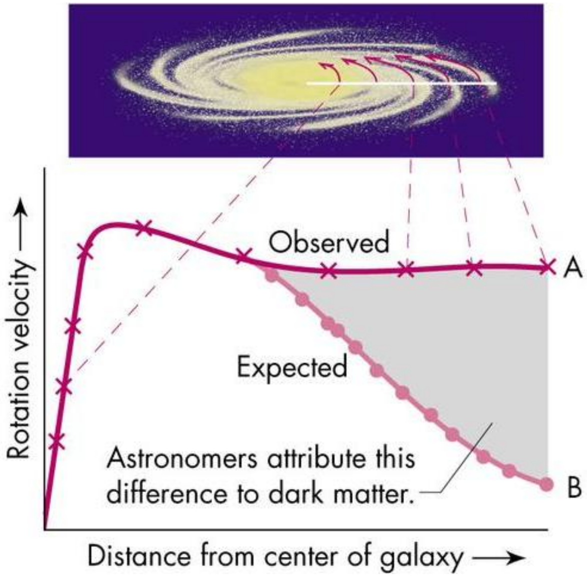


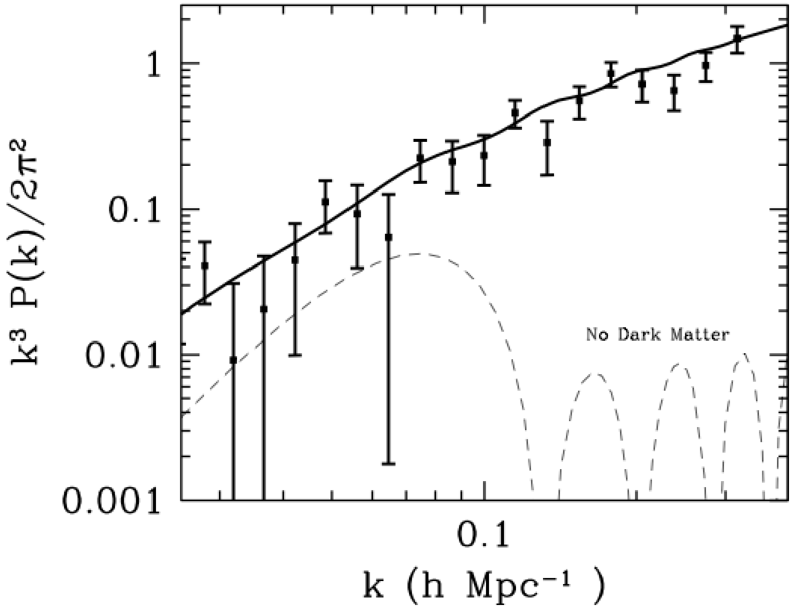
This test has been applied using SDSS



Scott Dodelson,
Fermilab/University of Chicago

Is Dark Matter needed for potential wells?





Scott Dodelson,
Fermilab/University of Chicago

Modified Newtonian Dynamics (MOND) (Milgrom 1983):

$$a_g F(a_g / a_0) = a_N = \frac{MG}{r^2}$$

Acceleration due to gravity
(v^2/r for circular orbit)

New,fundamental scale

For a point mass

$$F(x) = \begin{cases} 1, & x >> 1 \\ x, & x << 1 \end{cases}$$

$$\boxed{\frac{(v^2/r)^2}{a_0} = \frac{MG}{r^2}}$$

This leads to a simple prediction

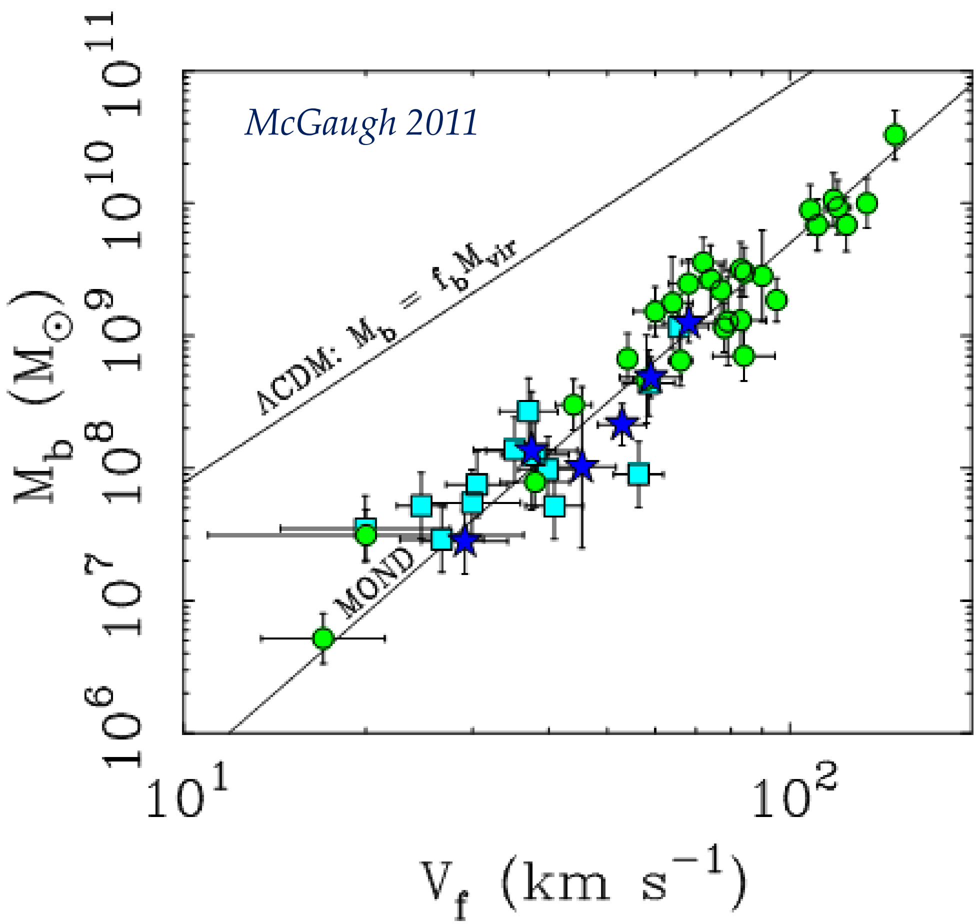
$$\frac{v^2}{r} = \sqrt{\frac{a_0 M G}{r^2}} \Rightarrow v^4 = a_0 M G$$

So MOND predicts

$$M = \frac{v^4}{a_0 G}$$

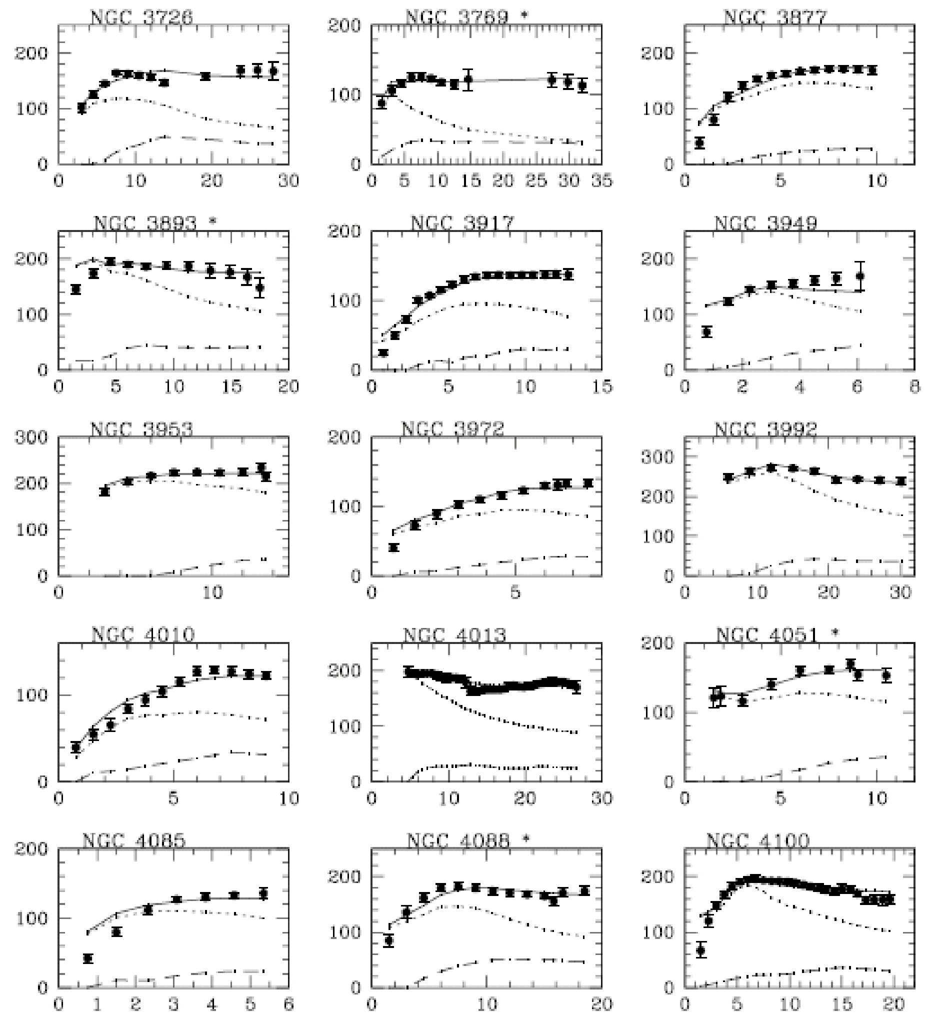
When the acceleration scale is fixed from rotation curves, this is a zero-parameter prediction!

… which has been verified (Tully-Fisher Law)



Scott Dodelson,
Fermilab/University of Chicago

MOND does a good job doing what it was constructed to do



McGaugh

Fit Rotation Curves of many galaxies w/ only one free parameter (instead of 3 used in CDM).

MOND is not a complete theory but can be placed in a scalar-tensor theory

$$L_\varphi = \frac{a_0{}^2}{8\pi G} F(\varphi_{,\mu}\varphi^{,\mu} / a_0{}^2)$$

Bekenstein & Milgrom 1984

There is a new fundamental mass scale in the Lagrangian

$$\frac{a_0}{c} \approx \frac{v_{gal}{}^2}{c r_{gal}} \approx \frac{(200 km/\sec)^2}{(3\times 10^5 km/\sec)(0.005 Mpc)} = 27\frac{km}{\sec Mpc} \approx H_0 \approx 10^{-33} eV$$

TeVeS (Bekenstein 2004)

- Scalar-Tensor Models fail because of lensing constraints
- Add also a vector field (to get more lensing w/o dark matter)
- Scalar action:

$$S_\varphi = -\frac{1}{16\pi G}\int d^4x\sqrt{-\tilde{g}}\left[\chi(\tilde{g}^{\mu\nu} - A^\mu A^\nu)\varphi_{,\mu}\varphi_{,\nu} + V(\chi)\right]$$

Auxiliary scalar field added *(χ)* to make kinetic term standard; two parameters in potential *V. V(χ)* is related to the MOND function μ.

- We can now do cosmology: is there enough clustering w/o dark matter?

Inhomogeneities in TeVeS

Skordis 2006
Skordis, Mota, Ferreira, & Boehm 2006
Dodelson & Liguori 2006

Perturb all fields: (metric, matter, radiation)
+ (scalar field, vector field)

E.g., the perturbed metric is

$$g_{\mu\nu} = diag[-a^2(1-2\Psi), a^2(1+2\Phi), a^2(1+2\Phi), a^2(1+2\Phi)]$$

where *a* depends on time only and the **two** potentials depend on space and time.

Inhomogeneities in TeVeS

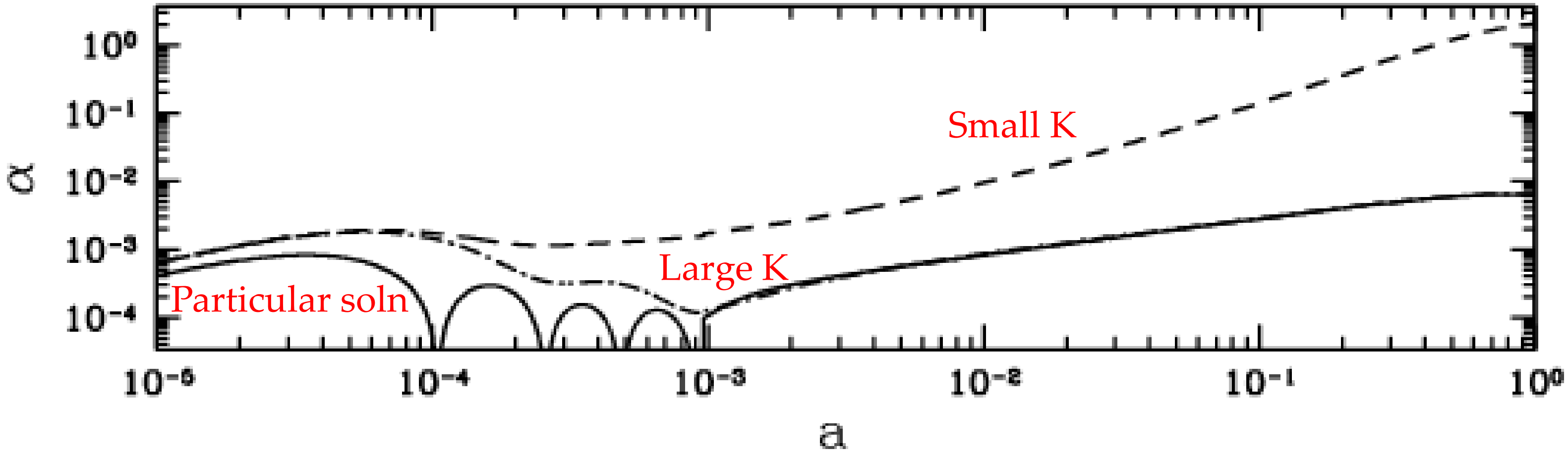
Other fields are perturbed in the standard way; only the vector perturbation is subtle.

$$A_\mu = ae^{-\varphi}\left(1+\Psi+\delta\varphi,\vec{\alpha}\right)$$

Constraint leaves only 3 DOF's. Two of these decouple from scalar perturbations, so we need track only the longitudinal component defined via:

$$\vec{\nabla}\alpha \equiv \vec{\alpha}$$

Inhomogeneities in TeVeS



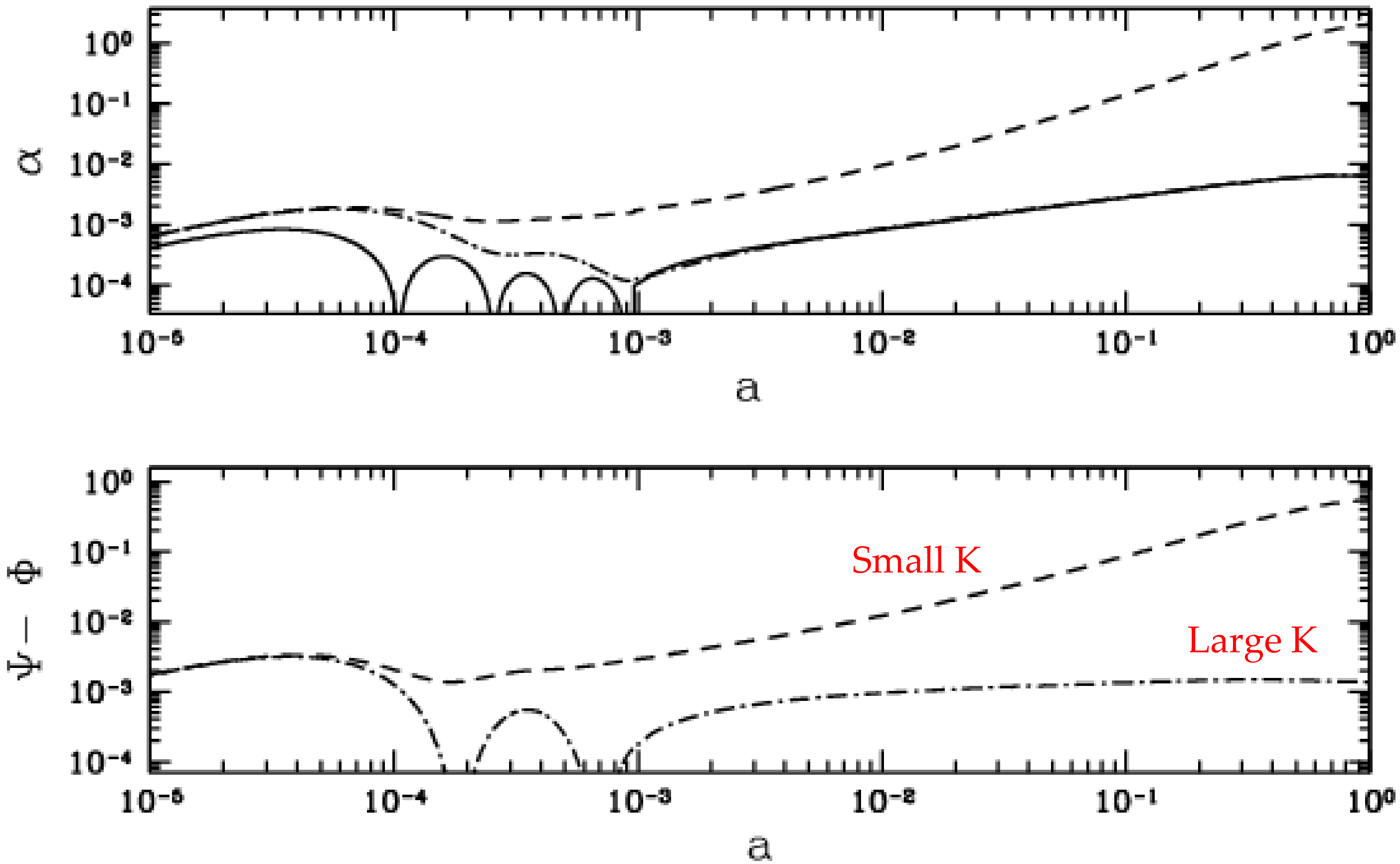
For large K, no growing mode: vector follows particular solution.

For small K, growing mode comes to dominate.

Scott Dodelson,
Fermilab/University of Chicago

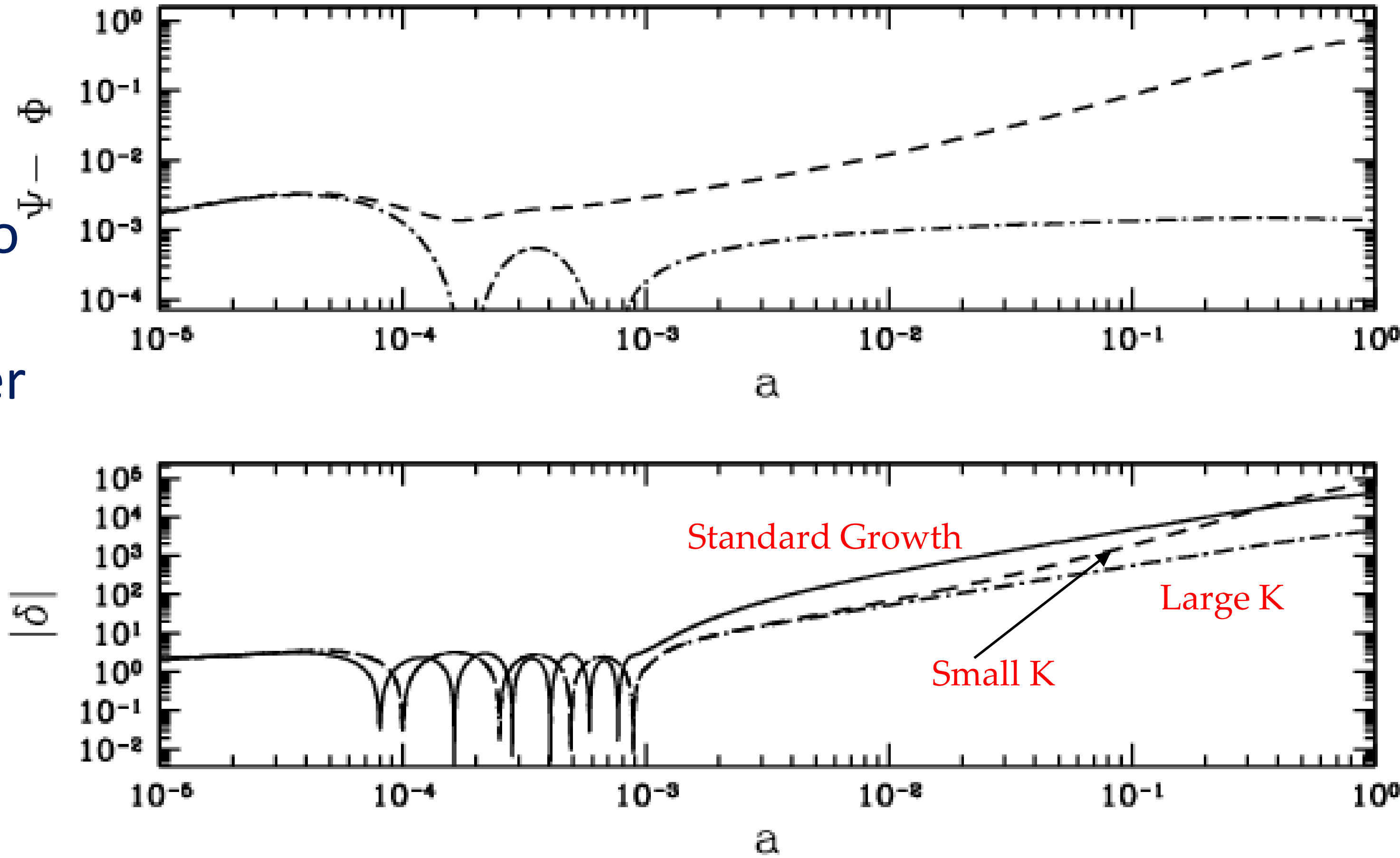
Inhomogeneities in TeVeS

This drives difference in the two gravitational potentials …

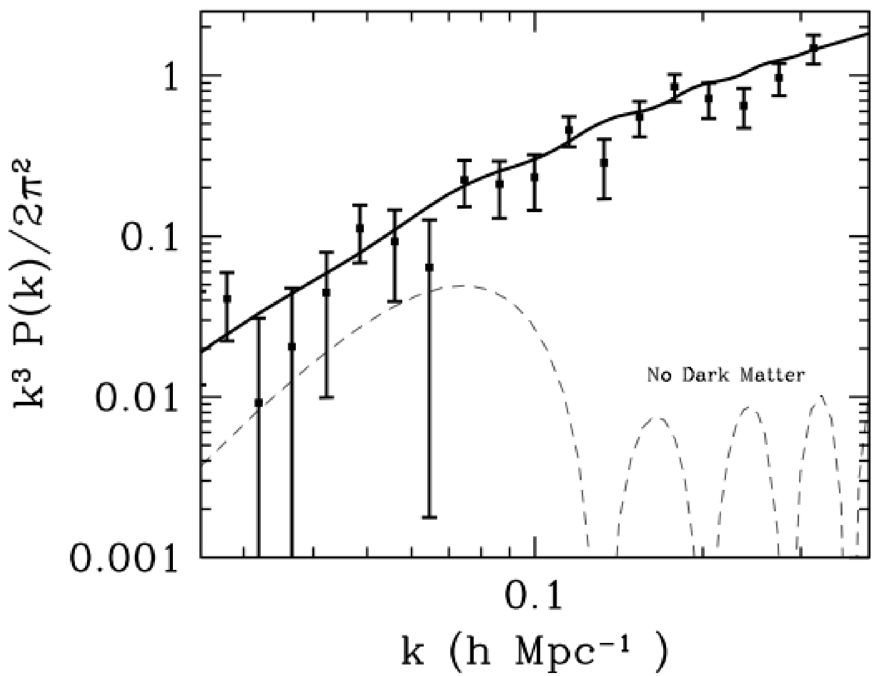


Inhomogeneities in TeVeS

… which leads to enhanced growth in matter perturbations!



Biggest Challenge to TeVeS or any no-Dark Matter model



Why do we not observe large oscillations in the power spectrum?

Scott Dodelson,
Fermilab/University of Chicago

The Dark Sector vs. Modified Gravity

- The simplest version of the Dark Matter hypothesis will be tested this decade
- Our views on what the new phenomena might mean are evolving
- This is a new incarnation of an age-old debate:

We do not understand the Laws	We understand the Laws but are missing some components

[redacted]

Constraints on f(R)

$$\left[f_R H^2 - \frac{f}{6} - \frac{\ddot{f}_R}{2} \right] > 0$$

at late times

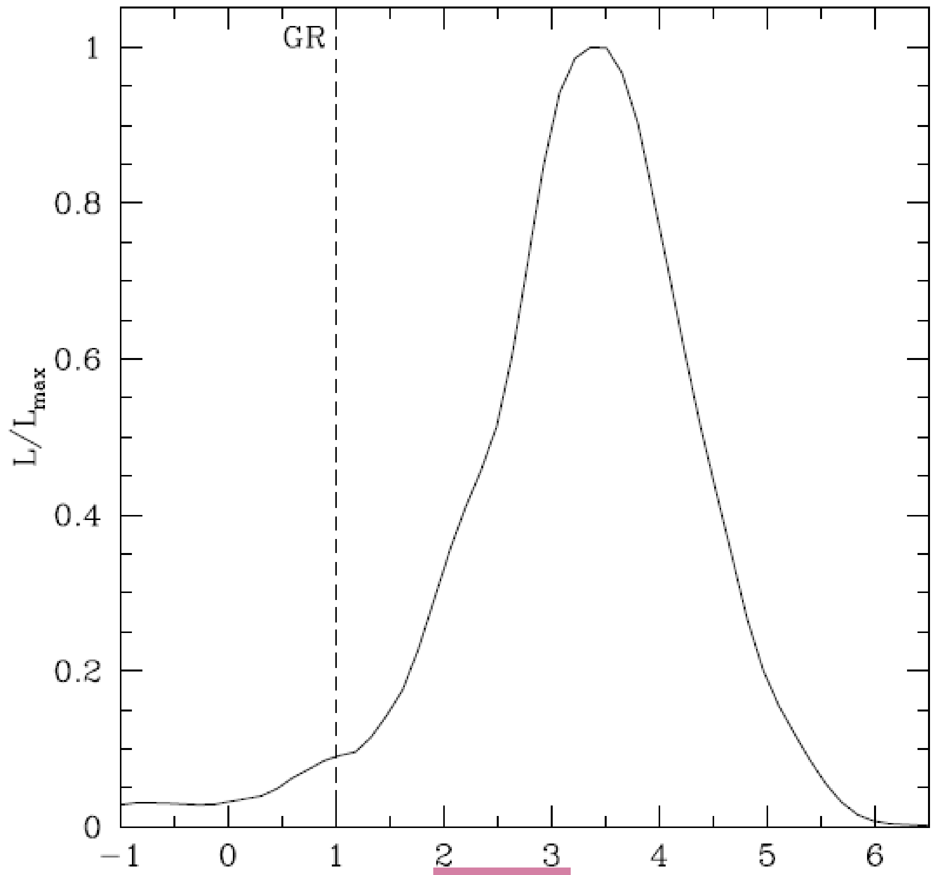
Note: f,R have dimensions of mass squared and $R \sim H^2$

Require

$$f = \frac{M^{2(1+n)}}{R^n}$$

Need to introduce new mass scale of order $M \sim H_0 \sim 10^{-33}$ eV

Observed deviation from GR from lensing?

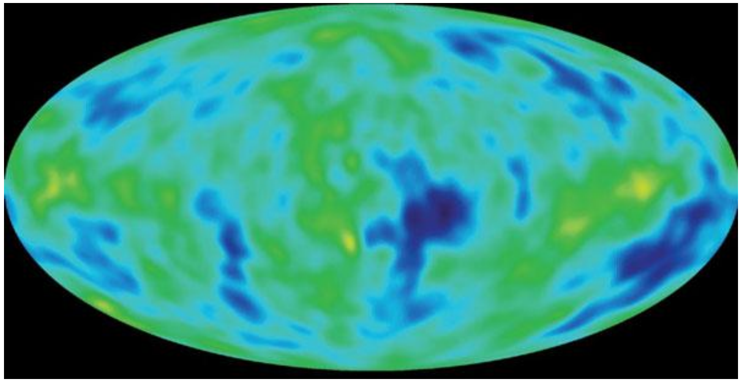


$1+g$

Bean (2009)

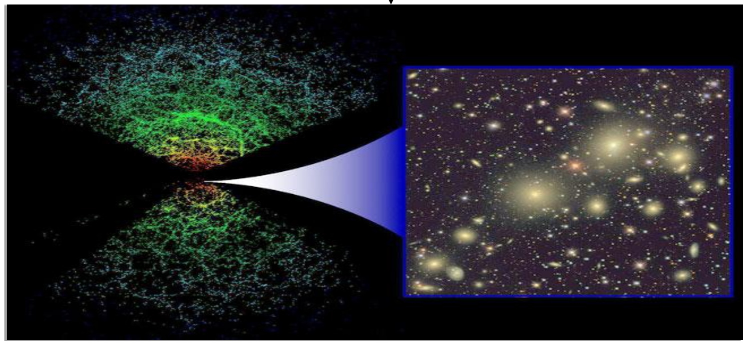
Primordial Gravitational Potentials Not Deep Enough to Produce Structure

Map of the photons, electrons, & protons when the Universe was 400,000 years old



COBE

Map of the galaxy distribution in the Universe today



Sloan Digital Sky Survey (SDSS)