# A New Perspective on Milgrom's MOND

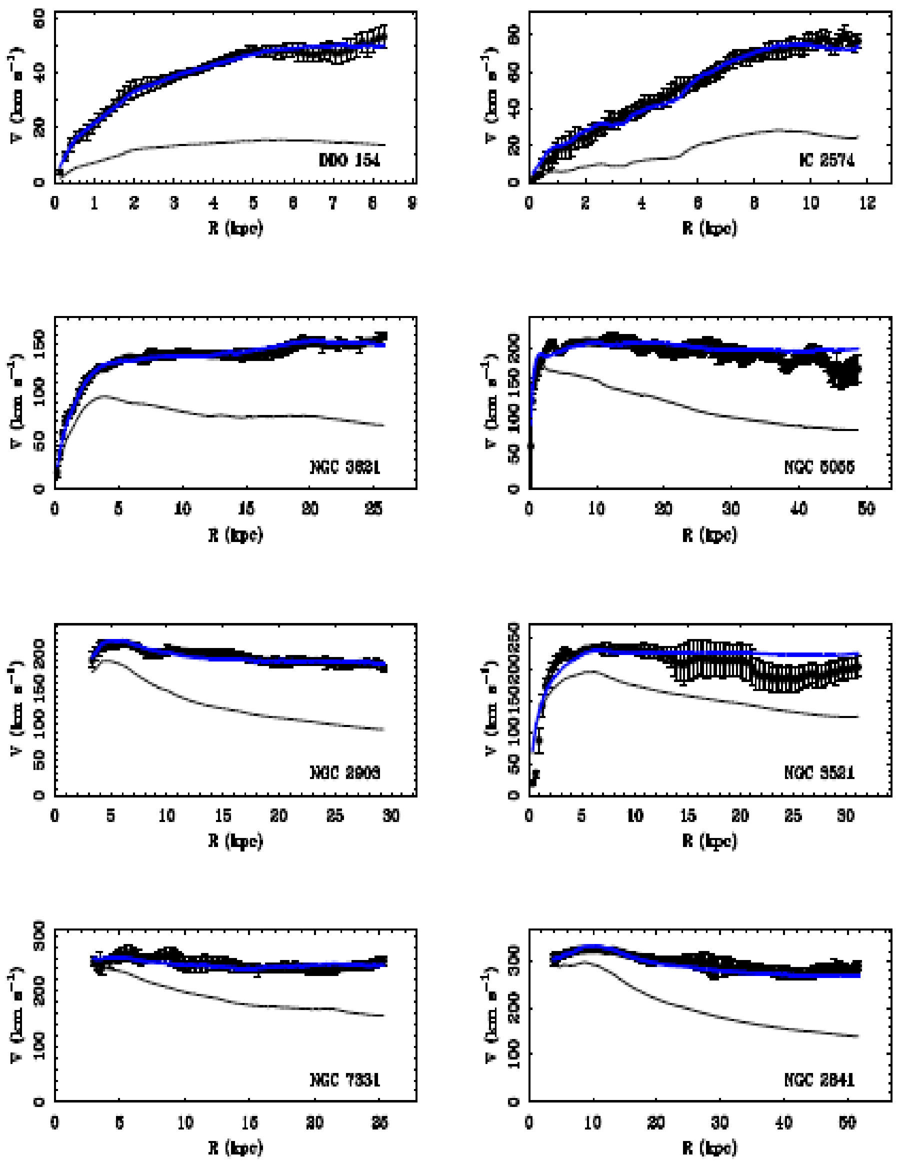
D V Bugg, Queen Mary, London

In many/most galaxies, stellar velocities at their edges disagree with Newtonian gravity which requires

$$mv^2/r = GMm/r^2 \quad \text{hence} \quad v \propto 1/r^{1/2}$$

WHY are galaxies different?

# Famaey and McGough, 1112.3960 (160pp)



- Condensates are ordered systems.
- Ferromagnets, Ferrimagnets
- Liquid Helium
- Superconductors
- Semi-conductors

The essential point is that all have spontaneously broken symmetries. The condensate has a LOWER symmetry than the Hamiltonian.

The objective of the talk is to suggest that galaxies are likewise condensates – that we can see through a telescope!

And I believe I can see how the broken symmetry arises!

There are five clues that galaxies are Fermi-Dirac condensates.

- <u>The gauge bosons</u> (all massless)
- gluons which `dress' themselves with quarks
- photons which couple to charges.
- gravitons which are described classically by General Relativity. They form Black Holes. Their very short-range behaviour is still a mystery.

I shall be talking about their very long range behaviour on the scale of galaxies.

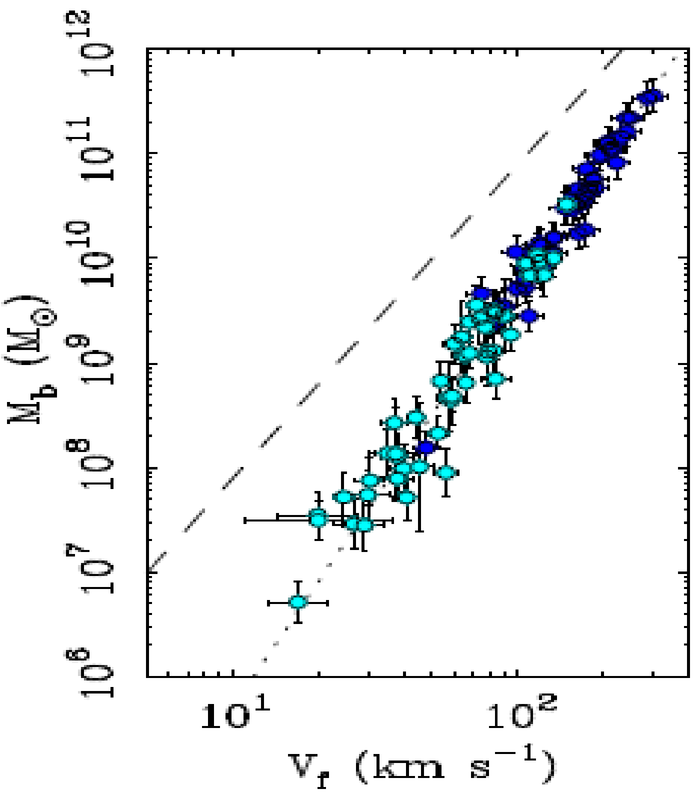
Milgrom (1983): $a(\text{total}) = g_N/\mu(a/a_0)$; $\mu$ is an empirical function of <u>acceleration</u> (not radius).

For small $g_N < 10^{-12}$ m s$^{-2}$, $a \to (g_N a_0)^{1/2}$; $a_0 = 10^{-10}$ m s$^{-2}$.

Then $v^2/r \to (GMa_0)^{1/2}/r$

or $v^4 \to GMa_0$.

Luminosity $L \propto M$, so $v^4 \propto L$ (Tully,Fisher 1977).




McGough, astro-ph/0510620, summing all baryons: stars + gas.

One popular form for Milgrom's $\mu$ function is

$$\mu(x) = \sqrt{1 + 1/4x^2} - 1/2x$$

With some algebra

$$\left(g_N + \frac{a_0}{2}\right)^2 = a^2 + \left(\frac{a_0}{2}\right)^2.$$

total acceleration $a = (g^2 + a_0 g)^{1/2}$; the previous formula applies when $g^2$ is negligible.

This formula gives the smoothest parametrisation of MOND symmetrical about $a_0$.

IMPORTANT new data on globular clusters. Their equilibrium is controlled by Jeans' Law, which relates the velocity dispersion of stars to their acceleration.

Scarpa et al. (1008.3526) measured this dispersion for 8 GC's and Hernandez, Jimenez and Allen (1108.4121) show that the velocity dispersion deviates rather abruptly from Newton's Law as it drops through $a_0$.

Cannot be explained by tidal effects which are too weak.

Jeans-> velocity dispersion $\alpha$ Mass$^{-4}$, like Tully-Fisher.

IMPORTANT: in galaxies mass variations with radius are often not well determined from luminosity. In GCs, there is no such problem.

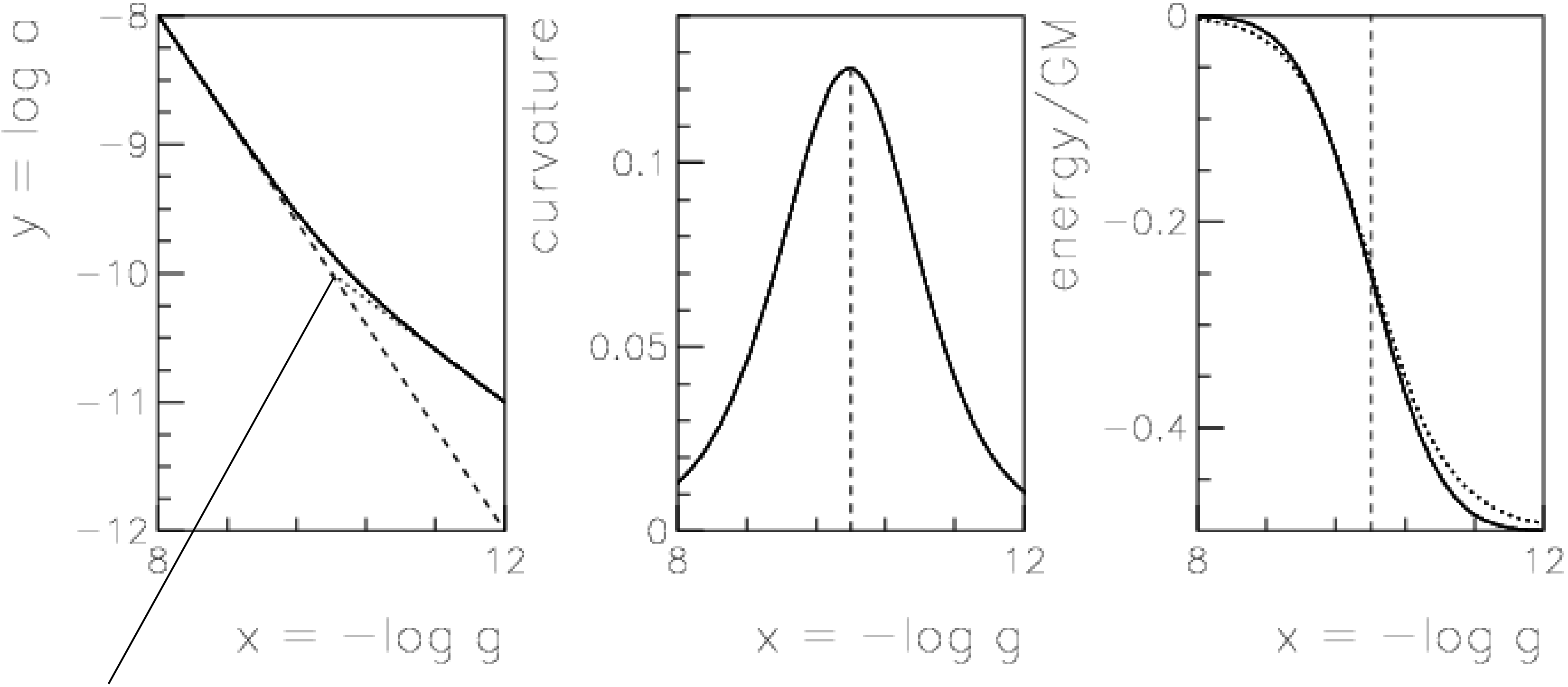
Values of $a_0$:

Gentile et al. 1011.4148 -> $(1.22 +- 0.33) \times 10^{-10}$ m s$^{-2}$

McGaugh, 1102.3912: $(1.24 +- 0.14) \times 10^{-10}$ m s$^{-2}$

$cH_0/2\pi = (1.113 +- 0.046) \times 10^{-10}$ m s$^{-2}$

For simplicity, I will round this off to $10^{-10}$ m s$^{-2}$. It looks unlikely that this relation is accidental and it will play a key role eventually.

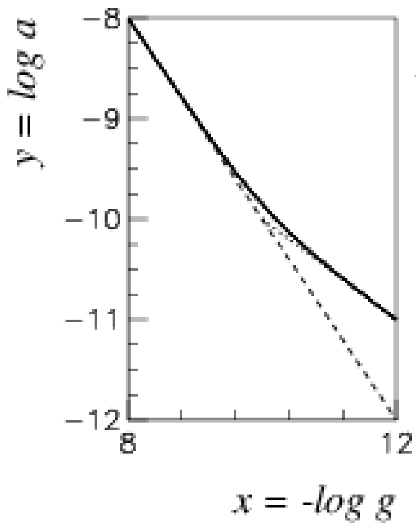


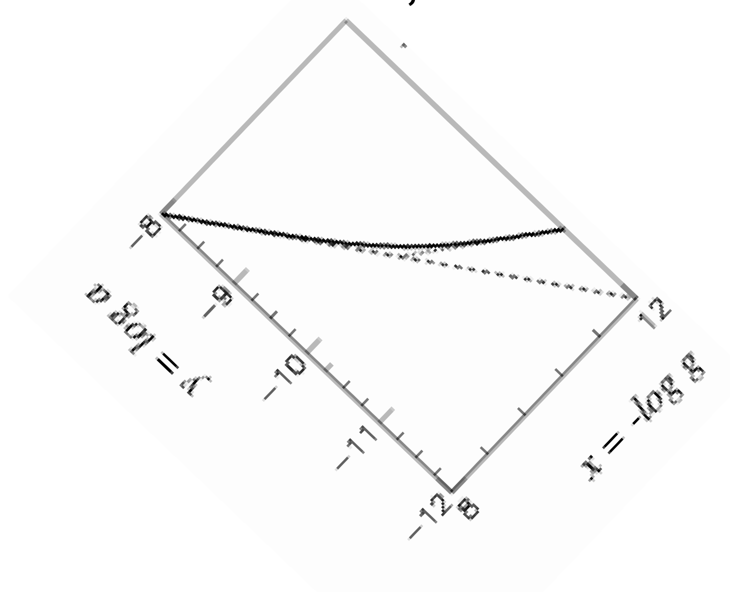

cross-over between 2 regimes: Newtonian and ? Hubble?

The curvature is centred on $a_0$. I take this acceleration and integrate it to determine the `Extra' Energy above Newtonian Energy. It is negative like Newtonian energy. It fits accurately to a Fermi function with an Energy Gap -0.5 GM; analogous to those in superconductors and doped semi-conductors . Evidence for a condensate??

- My proposal:

Rotation angle = mean of $45^0$ and $\tan^{-1} 0.5$; result = $35.8^0$

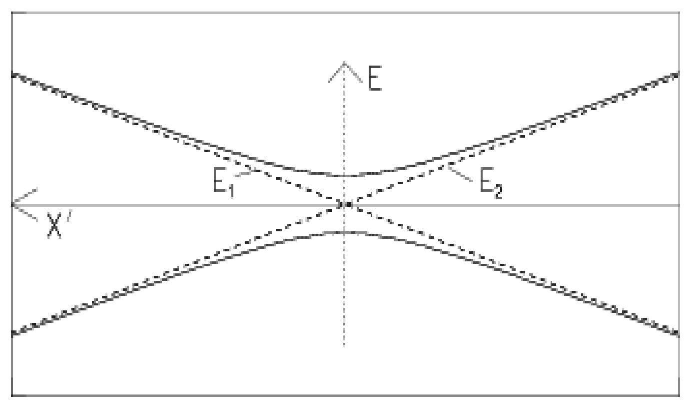



Atomic lines in a magnetic field:

L=1,s=1/2->J=3/2

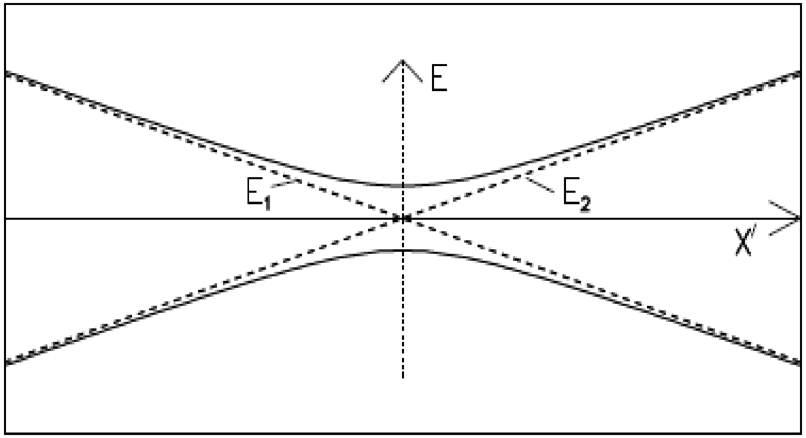
L=2,s=1/2->J=3/2




Dirac: the Hamiltonian tells you the basis states

The Breit-Rabi diagram for two crossing eigenstates:

same J = different L + S




$$< H\Psi >= \begin{pmatrix} < H_{11} > & V \\ V & < H_{22} > \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} = E \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}.$$

$$(H_{11} - E)(H_{22} - E) - V^2 = 0.$$

A similar equation describes mixing between the three neutrinos. The relation is quadratic in E if V = constant.

Can we explain galaxies with the same approach?

$H_{11}$ = Newtonian energy; $H_{22}$ = energy from the Hubble acceleration (negligible)

Can rewrite the Breit-Rabi equation as

$$E^2 = E(E_1 + E_2) – E_1E_2 + V^2 \text{ using}$$

$$g = e^{x} = GM/r^2$$

a scale factor

$$e^{x/2} = (GM)^{1/2}/r$$

$$\langle H_{11}\rangle = E_1 = -GM/r = -(GM)^{1/2} e^{x/2}$$

$$E_2 = -(GM)^{1/2} \varepsilon(x)$$

$$V = -(GM)^{1/2} W(x)$$

*to satisfy the Tully-Fisher relation.*

The variation of Hubble acceleration over the radius of the Milky Way = $2 \times 10^{-4}$, so $\varepsilon$ is very small. General Relativity is not needed.

Another important result from MOND: a logarithmic tail to the Newtonian potential.

Asymptotically, the total acceleration from MOND is

$$a = (g_N a_0)^{1/2} = (GMa_0)^{1/2} / r$$

Taking this as the gradient of a potential $\phi$,

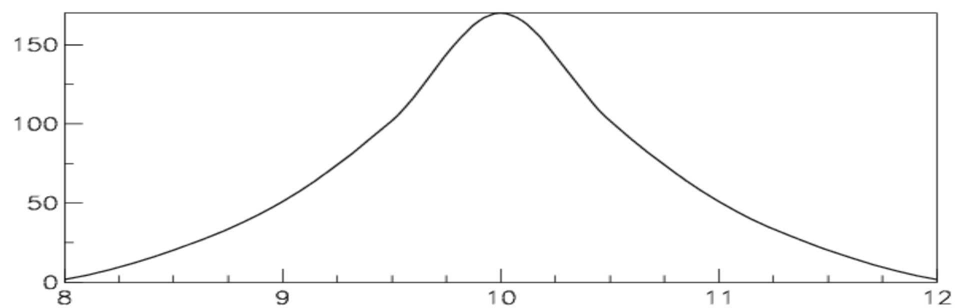
$$\phi = -(GMa_0)^{1/2} \ln_e (r/r_0)$$

where $r_0$ is the radius at acceleration $a_0$. It is quite weak because it depends on $(a_0)^{1/2}$ where $a_0 = 10^{-10}$. It does explain the asymptotic straight line at the edge of my first figure.

The interpretation of this term is simple. Mixing between the Newtonian potential and the condensation mechanism allows the wave-length of gravitons trapped in the Newtonian potential to expand. This lowers the zero-point energy. An analogy is with the covalent bond in chemistry (and mesons).

With $\varepsilon = 0$, the Breit-Rabi equation reads $2E = E_1 - [E_1^2 + 4W^2]^{1/2}$. Its variation with |x| is shown in the figure. <u>This</u> is the clue to how the condensate forms. Gravitons reaching the edge of the galaxy are ~plane waves and interfere <u>coherently</u> with many nucleons (or stars); the sum of squares of amplitudes acts as a large amplifier. Fluctuations at the level of 4% can arise from (a) supernovae which heat large volumes, (b) `chimneys' and `wormholes' which are observed to carry dust and gas through galaxies.

Gravitation is carried by spin 2 gravitons. Their interactions with nucleons generate a Fermi-Dirac condensate.




The x-axis is $-\log(g_n)$; y shows total acceleration/$g_N$

The simplest form for the Fermi function is

$W(x) = 0.25/[1 + \exp\{(E – E_F)/kT\}]^{-1}$,

$E_F$ = energy at the centre of the Fermi function.

A Bose-Einstein condensate does not fit the data:

$W(x) \quad = -B(1 + |x|^{3/2} \exp(-\gamma x^2))$

$dW/dx = B(1.5|x|^{1/2} - 2\gamma |x|^{5/2}) \exp(-\gamma x^2)$.

What about Dark Energy? It is conventional to model the Hubble acceleration as a function of time or red-shift by the Friedmann-Robertson-Walker model which includes Newtonian acceleration on the scale of the Universe + Dark Energy, which is accelerating the expansion of the Universe at late times. If quantum mechanics produces the Energy Gaps of individual galaxies, it is logical that these add and explain Dark Energy: as galaxies evolve with time, their energy gaps grow. A FRW Universe has a very special metric in which the Hubble acceleration appears explicity. We view the universe to the visible horizon with the present $H_0$. At the horizon, the acceleration becomes $cH_0$. In Particle Physics, interaction of gluons with quarks generates Breit-Wigner resonances. Suppose the same happens with Dark Energy.

One will then see a phase variations $2\pi$ over the `resonance', explaining the relation $2\pi a_0 = cH_0$. Speculative, but possible!

What I am modelling is at the edges of galaxies: it is <u>not</u> about structures at their centres. My view is that the condensation mechanism acts as a funnel, channelling gas and dust into galaxies.

There are 3 new papers criticising the <u>non-appearance</u> of $a_0$ in $\Lambda$CDM: (i) Kroupa et al., 1301.3907, (ii) Famaey and McGaugh 1301.0623, (iii) McGaugh and Milgrom, 1301.0822.

Morphologies of galaxies near their centres depend on angular momentum L: for large L, they are flat;

for lower L, bulges and spirals develop;

for low L, large elliptical and dwarf spheroidal galaxies evolve;

for L=0, they collapse as quasars.

I suggest that $\Lambda$CDM is modelling a global average of these morphologies.

There is a very important new paper by Milgrom, 1305.3516. There are many examples of nearby galaxies which are illuminated with light from background galaxies. This light is bent by weak gravitional lensing. Astronomers have selected cases where the lensing is in the extreme periphery of the foreground galaxy. Milgrom compares their data with what is predicted by the Gaussian tail predicted by MOND. It agrees with MOND within experimental error, but is a factor ~70 larger then $\Lambda$CDM predicts near the maximum acceleration!!

I have checked his arithmetic and agree closely. This is evidence that the standard Cosmological Model NEEDS to include MOND effects, i.e. it needs the parameter $a_0$: experimental FACT – MUST take note!!

# SUMMARY up to here:

There are 5 clues that galaxies are Fermi-Dirac condensates:

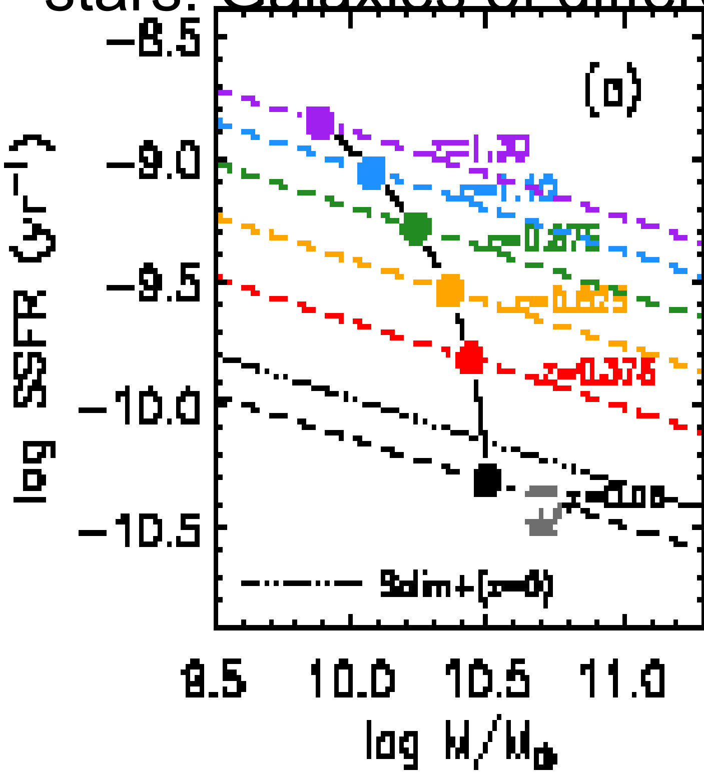
1) Phenomena occur on a log-log scale, consistent with Statistical Mechanics, proportional to log x. Also my first figure can be explained in terms of quantum mechanical mixing between two crossing eigenstates.
2) A Fermi function fits the total energy remarkably well – and very stably. For large variations of the acceleration, only the top and bottom of the Fermi function change by <4%.
3) The asymptotic form of the acceleration generates a logarithmic form, requiring mixing of two eigenstates
4) The rotation of axes of $35.8^0$ is just what is expected from quantum mechanical mixing. A Bose-Einstein condensate does not fit the data.
5) A single long wave-length graviton can form a condensate by interacting coherently with nucleons over a large range: a cooperative effect. The condensate is in the graviton-nucleon interaction, <u>not</u> in the gravitational interaction.

What about the other branch of the Fermi function? Since the \`upper' branch corresponds to an eigenstate with reduced zero-point energy, the 'lower branch' in fact corresponds to an excited energy level. This is unlikely to survive long enough to be observed.

Over the last year, a great deal of new data has appeared from studies of red-shifted galaxies. There is lots of it over the range z (red-shift) = 0 to 2, some over the range 2 to 4 and a very small amount for z = 6 to 8. Astrophysicists are digesting these data. They study redness (recent star formation enhances redness), metallicity (which measures the development of heavy atoms) and development of morpholgies – e.g. discs, central bulges and spiral arms; also the geometry of satellite galaxies lying close to large galaxies. I will select just one paper as a guide to what emerges.

Patel et al., 1304.2395 have studied the evolution of large galaxies from red-shift z = 1.3 to the present z = 0.

They select star-forming progenitors and analyse the structure evolution of galaxies a bit smaller than the Milky Way from red-shift z =1.3 to now: z=0. Their conclusion in the figure is that a galaxy of $10^{8.5}$ solar masses expands to $10^{10.5}$ solar masses by creating new stars. Galaxies of different types, e.g. ellipticals, evolve in different ways. My hunch is that the present $\Lambda$CDM has the flexibility to fit a wide variety of morphoplogies. That is not part of MOND.



The model I have produced is open to experimental test.

There are two sources of information about Dark Energy. One is the Hubble acceleration as a function of red-shift z.

The second is the Cosmic Microwave spectrum (WMAP). This shows temperature fluctuations observed over the whole sky. The Fourier transform reveals correlations over the whole Universe.

This spectrum arises from condensation of electrons and protons to hydrogen atoms ~380,000 years after the Big Bang. This spectrum is written in terms of Legendre polynomials up to L=2500. A series of peaks appears beginning at L~220 and falling as L -> 2500. A critical issue is HOW to interpret this spectrum.

A paper 1209.4607 of Lopez-Corredoira and Gabrielli presents a toy model of WMAP data. A better name is Baryon Acoustic Oscillations.

They remark that it is necessary to account for the fact that the condensation occurred over a diffuse volume with edges. The slope of the edge governs the magnitudes of successive peaks.

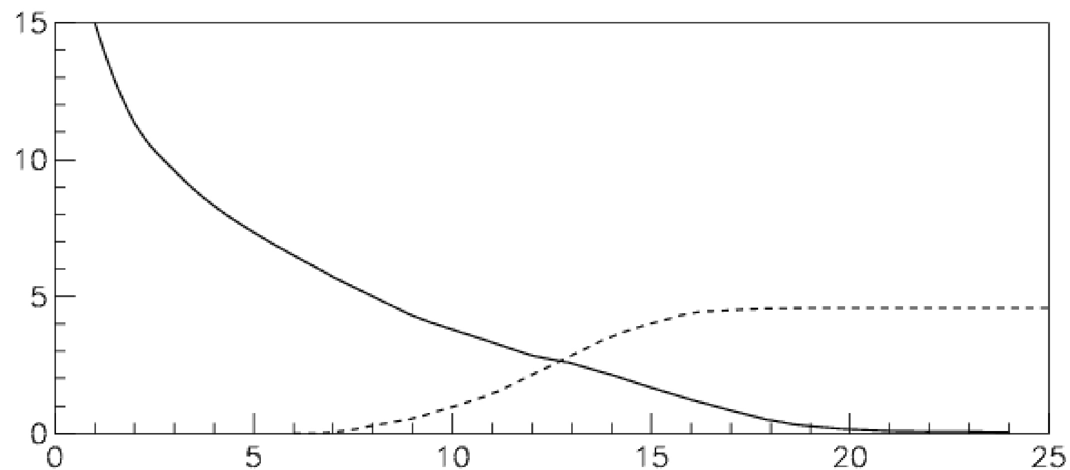
## Friedmann-Lemaitre equations

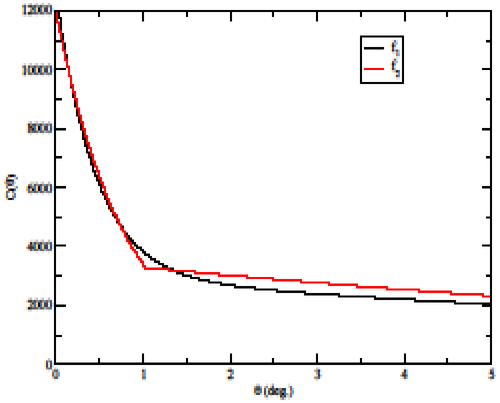
Standard equations are to be found in the Particle Data book. They describe Newtonian acceleration as the Universe expands. Initially the fall is fast, just after the Big Bang, but it gradually slows down. Equations are:

$$H^2 = (\dot{R}/R)^2 = (8\pi G_n \rho)/3 - k/R^2 + \Lambda/3 \quad (1)$$

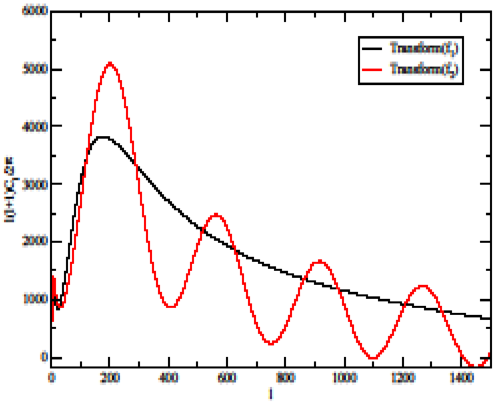
$$\ddot{R}/R = \Lambda/3 - (4\pi G_n/3)(\rho + 3p) \quad (2)$$

$$\dot{\rho} = -3H(\rho + p). \quad (3)$$






angle (deg)




L

Coming back to the toy model of Lopez-Corredoira and Gabrielli, the slope of the spectrum arises from damping due to diffusion of photons from high temperature regions to cooler regions (Silk damping, 1968). They find that 6 parameters are needed to fit the spectrum. That is also the case in the standard $\Lambda$CDM model. But because the $\Lambda$CDM model has been shown by Milgrom to be inconsistent with weak gravitational lensing, it is certain that $\Lambda$CDM needs some modifications. What these are remain to be seen. The essential question is whether results accommodate the model I have fitted to MOND, or something close.

FINI

A detail, which is presently fitted correctly, is that there are correlations called TT (meaning between temperatures in WMAP at different points) and TE(meaning between termperature and observed polarisation of the photons in WMAP. This is presently included in fitting Planck data and I think does not need any significant modification.

NEW result:

A very recent paper 1306.4732, Suyu et al. shows that Strong gravitational lensing of a nearby galaxy producing 4 images of the background galaxy is capable of measuring the Hubble acceleration accurately. Result differ strongly with the standard $\Lambda$CDM model with 0.27 Dark Matter, 0.73 Dark Energy and w=-1 (the usual value for Dark Energy).

• SUMMARY

1) MOND: The difference between observed galactic rotation curves and $g_N$ is close to a Gaussian. Integrating it, the result is close to a Fermi function. It is Negative, requiring an energy gap 0.5 GM. Five clues agree on a Fermi-Dirac condensate in the graviton-nucleon interaction.
2) Milgrom's work on weak gravitational lensing shows that $\Lambda$CDM is certainly wrong by a factor 60-70. Also it does not explain the Tully-Fisher relation.
3) Lughausen, Kroupa et al have studied polar-ring galaxies and shown that Mond explains them. $\Lambda$CDM does not.
4) Top priority is to check whether WMAP data and the expansion of the Universe measured by type 1a supernovae can be fitted along the general lines suggested by Lopez-Corredoira and Gabrielli. Help is needed from groups with Planck data and programs at their finger-tips.
5) It seems logical that the sum total of all galactic energy gaps on the scale of the Universe explains Dark Energy.