The Pros and Cons of Invisible Mass and Modified Gravity

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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 nonbaryonic cold dark matter.
Spiral Galaxy Rotation Curve

Longer arrows represent larger orbital velocities.
Galaxy Cluster
Large Scale Structure
A tree diagram with various branches and nodes, including:

- **Axions**
- **WIMPs**
- **Newton Stars**
- **White Dwarf**
- **Strange Magnet**
- **Fast Stars**
- **Brown Dwarf**
- **Jupiters**
- **Asymmetric Gravity**
- **Weyl Gravity**
- **MACHOs**
- **Dark Clusters**
- **Cold Gas**
- **MOND**
- **MASS**
- **Cold DM**
- **Hot DM**
- **Non Baryonic**
- **Baryonic**
- **Einstein**
- **Dynamics**
- **Gravity**
- **Mass**
- **MOND**
- **Disk DM**
- **Oort Discrepancy**
- **Spiral Galaxy Flat Rotation Curves**
- **Cluster Velocity Dispersions**
- **Large Scale Structure**
- **Bulks Flows**
- **Ω = 1**

The diagram includes mathematical expressions:

\[
\frac{M_*}{M_T} \times 0.1
\]

\[
\frac{M_*}{M_T} \times 0.2
\]
Axions
WIMPs
Neutron Stars
White Dwarfs
Strange Quark
Einstein
Dark Clusters
MACHOs
Cold Gas
MOND
Asymmetry
MOND
Cold DM
Hot DM
Non-Baryonic
Baryonic

Disk DM
Spiral galaxy
flat rotation curves
Cluster Velocity dispersions
Large Scale Structure
Bulk flows

Ω = 1

M* / M* x 0.1
M* / M* x 0.2
Pruning the tree

Baryonic Dark Matter

Many candidates:
- brown dwarfs
- Jupiters
- very faint stars
- very cold molecular gas
- warm ($\sim 10^5$ K) ionized gas

Can usually figure out a way to detect them: most have been ruled out.
Pruning the tree

**Hot Dark Matter**

Obvious candidate:
neutrinos

...but not enough.

Also
- neutrinos suppress structure formation
- can’t crowd together closely enough
  (phase space constraint)
Pruning the tree

Cold Dark Matter

Some new particle, usually assumed to be **WIMPs** (Weakly Interacting Massive Particle) don’t interact electromagnetically, so very dark.

Two big motivations:

1) total mass outweighs normal mass from BBN
   \[ \Omega_m \approx 6 \Omega_b \]
2) needed to grow cosmic structure
There isn’t enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

\[ t = 1.8 \times 10^5 \text{ yr} \]

\[ t = 1.4 \times 10^{10} \text{ yr} \]

very smooth: \( \frac{\delta \rho}{\rho} \sim 10^{-5} \)

very lumpy: \( \frac{\delta \rho}{\rho} \sim 1 \)

\( \frac{\delta \rho}{\rho} \propto t^{2/3} \)

Both (1) and (2) hold only when gravity is normal.
Constraints predating SN, CMB

age = 13 Gyr

$H_0$

$\Omega_m$

$\Lambda$CDM

$\Omega_m = 1$
$\Lambda$CDM

- Baryons
- Dark Matter 23%
- Dark Energy 73%
Pros - Invisible Matter

- Apparently required by wide array of data
- Provides self-consistent cosmology
- Explains large scale structure
- $\Lambda$CDM model parameters well constrained
We have direct knowledge of < 1% of this stuff.

“Cosmologists are often wrong, but never in doubt”
- Lev Landau
Baryonic Mass

\( M_b \left( M_\odot \right) \)

\( 10^6, 10^7, 10^8, 10^9, 10^{10}, 10^{11}, 10^{12}, 10^{13}, 10^{14}, 10^{15} \)

Circular Velocity

\( V_c \) (km s\(^{-1}\))

\( 10^1, 10^2, 10^3 \)

\( \Lambda CDM \) problematic → \( \Lambda CDM \) OK

Slope and normalization wrong

Small scatter poses a fine-tuning problem
On Galaxy Scales...

- Measure rotation velocity; find
- Properties depend systematically on
  - Total Baryonic Mass
  - Baryon Distribution
  - Acceleration
High Surface Brightness (HSB)

Low Surface Brightness (LSB)

\[ \Sigma(R) = \Sigma_0 e^{-R/h} \]

Azimuthally averaged light distribution typically exponential for spiral disks.
NGC 6822 (Weldrake & de Blok 2003)

\[ V \sin i = V_{sys} + V_c \cos \theta + V_r \sin \theta \]
NGC 6946

Stars

H\textsubscript{i} gas

Boomsma 2005
NGC 6946: $M_* / L_B = 1.1 \, M_\odot / L_\odot$
Newton says
\[ V^2 = GM/R. \]
Equivalently,
\[ \Sigma = M/R^2 \]
\[ V^4 = G^2 M \Sigma \]

Therefore
\[ \text{Different } \Sigma \text{ should mean different TF normalization.} \]
NGC 2403

UGC 128

Same global L,V

Very different mass distributions
$R_p \approx 2.2h$
No Residuals from TF rel’n

Not even where disk contribution is maximal
Requires fine balance between dark & baryonic mass

Cons - Invisible Matter

- Serious fine-tuning problems
- Halo-by-halo missing baryon problem
- Cusp/core problem
- Missing satellite problem
- Do dark matter particles actually exist?
\( \Lambda \text{CDM} \) predicts too much dark mass at small radii.
Cons - Invisible Matter

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M31 (Gendler)
Juerg Diemand "Via Lactea" simulation

Kravtsov et al. 2004
Cons - Invisible Matter

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CDMS, LHC, & GLAST should all see something soon
One begins to worry that...

GRAVITY IS ARBITRARY!
MOND
M Odified Newtonian Dynamics
introduced by Moti Milgrom in 1983

instead of dark matter, suppose the force law changes such that

\[ \text{for } a \gg a_o, \quad a \Rightarrow g_N \]
\[ \text{for } a \ll a_o, \quad a \Rightarrow \sqrt{g_N a_o} \]

where

\[ g_N = \frac{GM}{R^2} \]

is the usual Newtonian acceleration.

More generally, these limits are connected by a smooth interpolation fcn \( \mu (a/a_o) \) so that

\[ \mu (a/a_o) a = g_N. \]

MOND can be interpreted as a modification of either inertia (\( F = ma \)) or gravity (the Poisson eqn).
**MOND predictions**

- The Tully-Fisher Relation
  - Slope = 4
  - Normalization = \( \sqrt{a_0 G} \)
- No Dependence on Surface Brightness
- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

**Disk Galaxies with low surface brightness provide particularly strong tests**

None of the following data existed in 1983.

At that time, LSB galaxies which were widely thought not to exist.
The Tully-Fisher Relation

- Slope = 4
- Normalization = $1/(a_0G)$
- Fundamentally a relation between Disk Mass and $V_{flat}$
- No Dependence on Surface Brightness

- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density $\sim$ Surface Brightness
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$M_d (M_\odot)$ vs. $V_{flat}$
In MOND limit of low acceleration

\[ a = \sqrt{g_N a_0} \]

\[ \frac{V^2}{R} = \sqrt{\frac{GM}{R^2}} a_0 \]

\[ V^4 = a_0 GM \]

observed TF!
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MOND predictions

\[ \xi = \frac{V^2}{G\mu_o} \]

Not a fit
Residuals of MOND fits

All data

$\sigma_{V/V} < 5\%$

$R$ (kpc)
The Tully-Fisher Relation

- Slope = 4
- Normalization = $1/(a_0 G)$
- Fundamentally a relation between Disk Mass and $V_{\text{flat}}$
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MOND predictions

- The Tully-Fisher Relation
  - ✔️ Slope = 4
  - ✔️ Normalization = $1/(a_0 G)$
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- ✔️ Rotation Curve Shapes

- ✔️ Surface Density ~ Surface Brightness

- ✔️ Detailed Rotation Curve Fits

- ✔️ Stellar Population Mass-to-Light Ratios
Line: stellar population model (mean expectation)
The Tully-Fisher Relation

- Slope = 4
- Normalization = 1/(a_0G)
- Fundamentally a relation between Disk Mass and V_{flat}
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- Rotation Curve Shapes
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios
Those are the pros.

What are the cons?

• You don’t know the Power of the Dark Side

• Can MOND explain large scale structure?

• Can it provide a satisfactory cosmology?

• Can it be reconciled with General Relativity? TeVeS

• Does it survive other tests?

Clusters problematic
1E 0657-56 - “bullet” cluster  (Clowe et al. 2006)

direct proof of dark matter?
bullet cluster shows same baryon discrepancy in MOND as other galaxy clusters

MOND suffers a missing mass problem! unseen baryons? heavy neutrinos?
observed shock velocity

bullet cluster collision velocity

observed shock velocity

MOND

bullet cluster collision velocity

MOND works too well in galaxies to be a coincidence. Either

MOND is correct, or

Dark Matter mimics MOND

Either way, new physics is implicated:

- gravity?

\[ a_0 \sim cH_0 \sim c\Lambda^{1/2} \]

- new properties of dark matter?

"I think you should be more explicit here in step two."
BBN: \[ \omega_b = \Omega_b h^2 \propto \eta_{10} \]