Dynamics of the Local Group in different theories of gravity

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Overview

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- Modified Newtonian Dynamics
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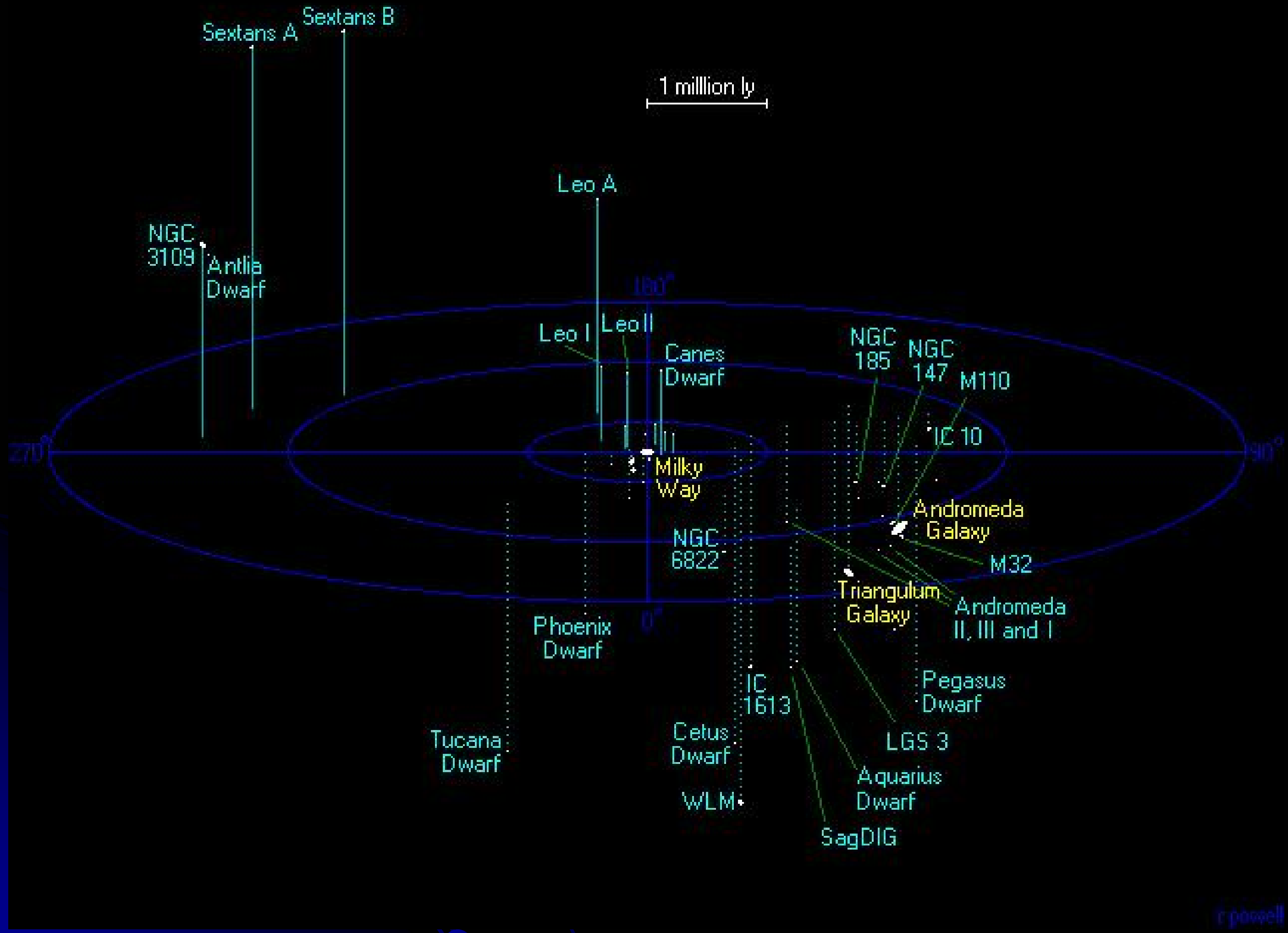
- Some nice pictures (if there is some time left)

Local Group



members:

Milky Way
M31

LMC
SMC
M33

+40 known dwarf galaxies

by Richard Powell

- mass: 2-5 10^{12} M_{sol}

- contains two large spiral galaxies (which make up most of its mass)

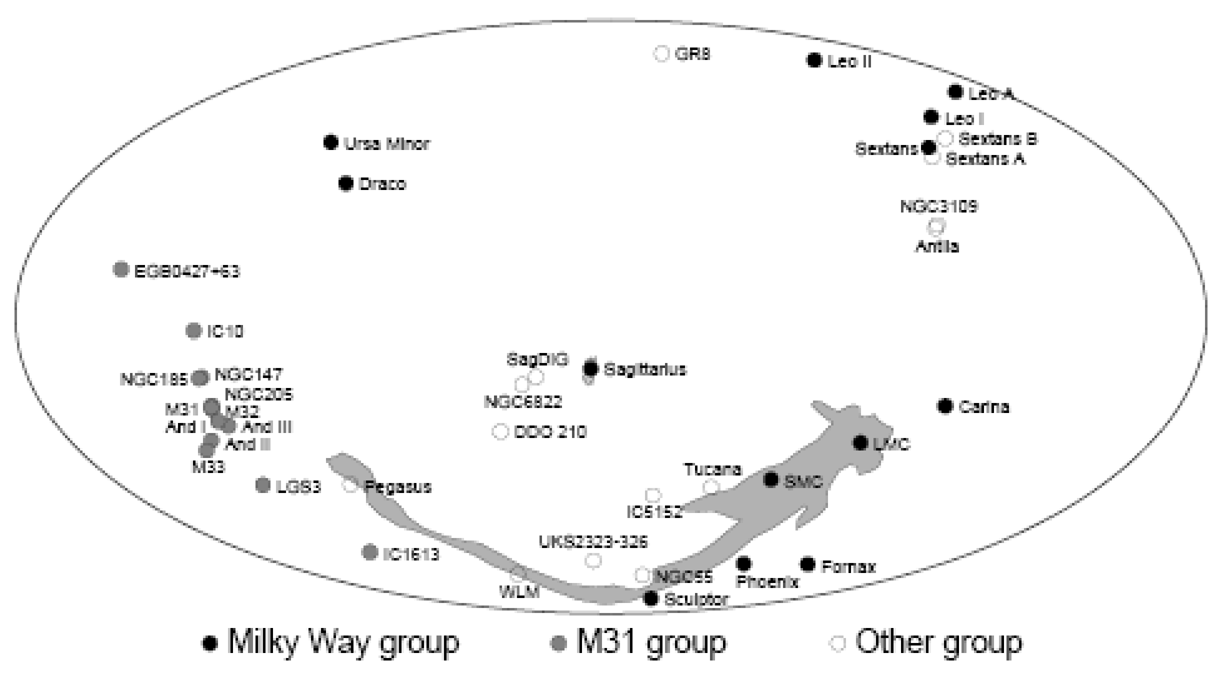
- diameter: >2 Mpc

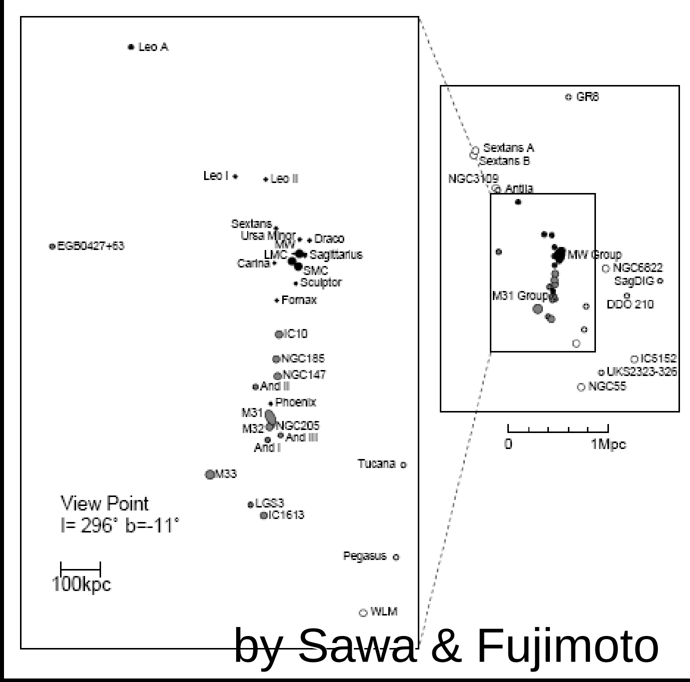
- moves to the Virgo cluster with (200 ± 50)km/s

- 4 subgroups (MW-subgroup, M31-subgroup, Local Group Cloud and NGC 3109-subgroup)

A plane of galaxies

- Most galaxies in the local group are distributed in a thin plane (see Sawa & Fujimoto 2005)
- This plane doesn’t correspond to a galactic plane of the two large spirals galaxies.





by Sawa & Fujimoto

➢ **Sawa & Fujimoto**	➢ **My own results**

❖ Normal vector in galactic coordinates

l=206°, b=-11° (Milky Way on plane)	l=200°, b=-20° (A) l=203°, b=-27° (2σ-clipping) l=200°, b=-20° (Milky Way and M31 on plane) (B)

❖ Thickness of the Local Group plane

About 50-100 kpc	21 galaxies within 100kpc (A) 28 galaxies within 100kpc (B)

Results basically similar but no perfect match

Origin of the Local Groups satellites

- Cosmological dark matter sub-halos

  - Problem: expected distribution would be spherical symmetric

- Infall and scattering of a filament

  - Problem: expected plane would be too thick

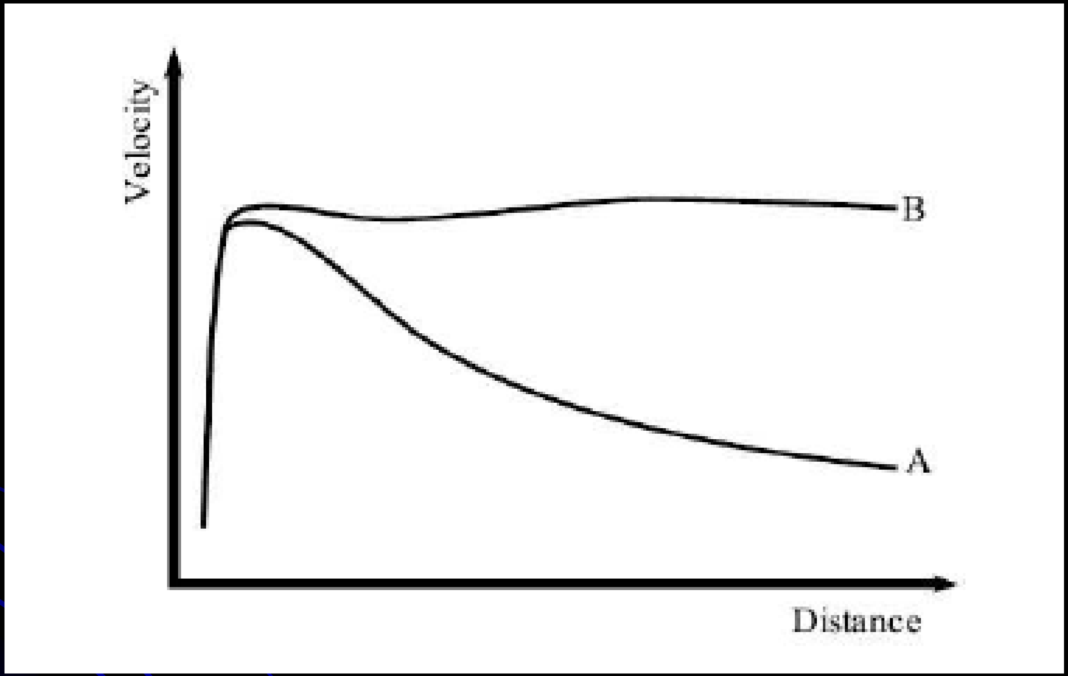
- Early interaction of extended gas-rich discs of Milky Way and M31

  - reproduces observed distribution very well

  - Problem: missing satellite problem, except in MOND, because no dark matter

Dark Matter

- galaxies rotate too fast



by Wikipedia

- need additional matter to explain rotation curves
- same problem appears also in clusters

- WIMPs (or MACHOs)

- different profiles for its distribution

isothermal halo (simple):

$$\rho(r) = \frac{M_0}{4\pi r_0} \frac{1}{r^2}$$

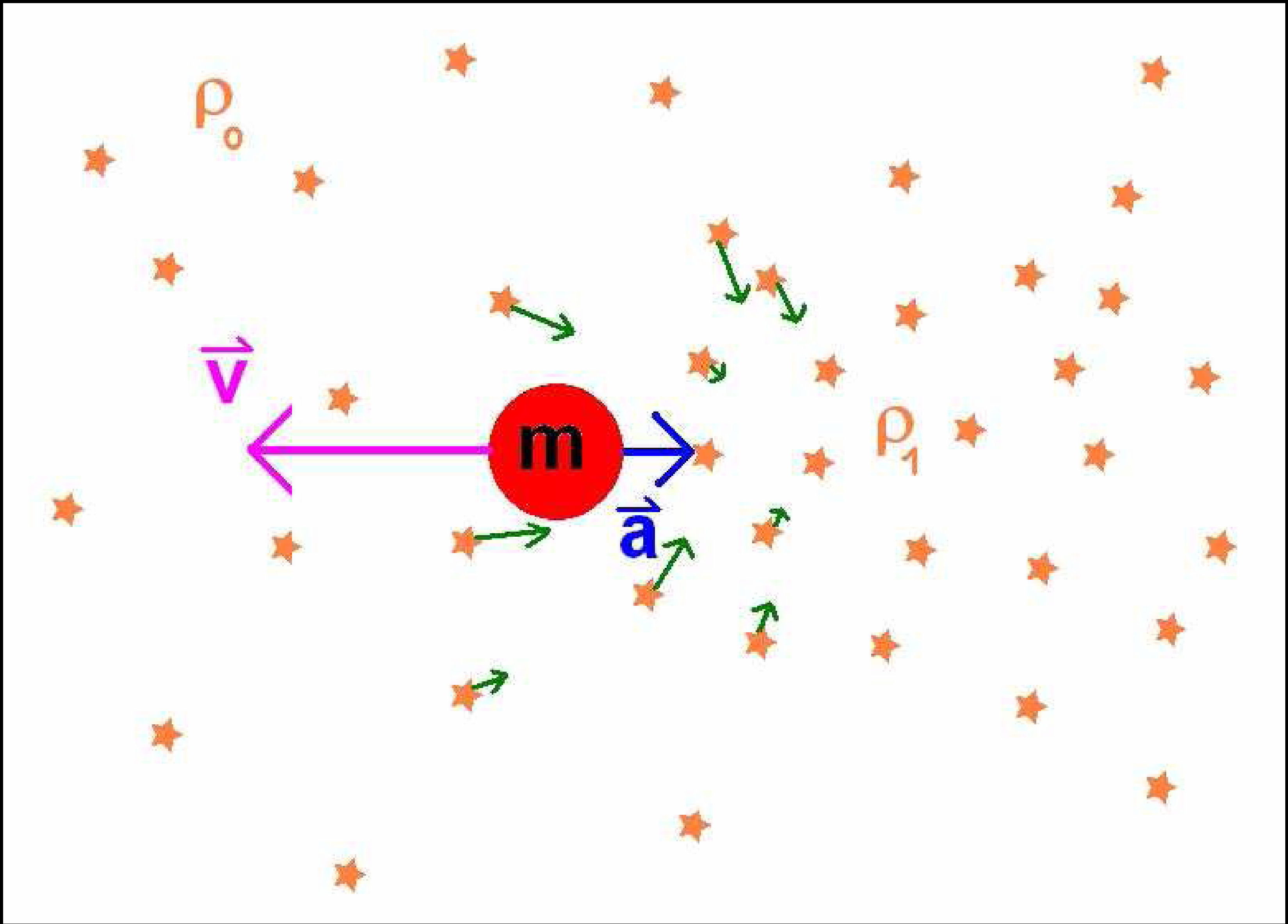
NFW profile (most common):

$$\rho(r) = \frac{\rho_s}{\left(r/r_s\right)\left(1 + r/r_s\right)^2}$$

- problem: particles haven’t been found yet

- other problems: missing satellites, tidal dwarfs, …

Dynamical friction



- General formula:

$$\frac{d\vec{v}}{dt} = -16\pi^2 \ln(\Lambda) G^2 \mu(m+\mu) \frac{\vec{v}}{v^3} \int_0^v f(w) w^2 dw$$

- Usual formula (after some assumptions):

$$\frac{d\vec{v}}{dt} = -4\pi^2 \ln(\Lambda) G^2 \rho m \frac{\vec{v}}{v^3} \left[erf\left(\frac{v}{\sqrt{2}\sigma}\right) - \frac{\sqrt{2}v}{\sqrt{\pi}\sigma} e^{\frac{v^2}{2\sigma^2}} \right]$$

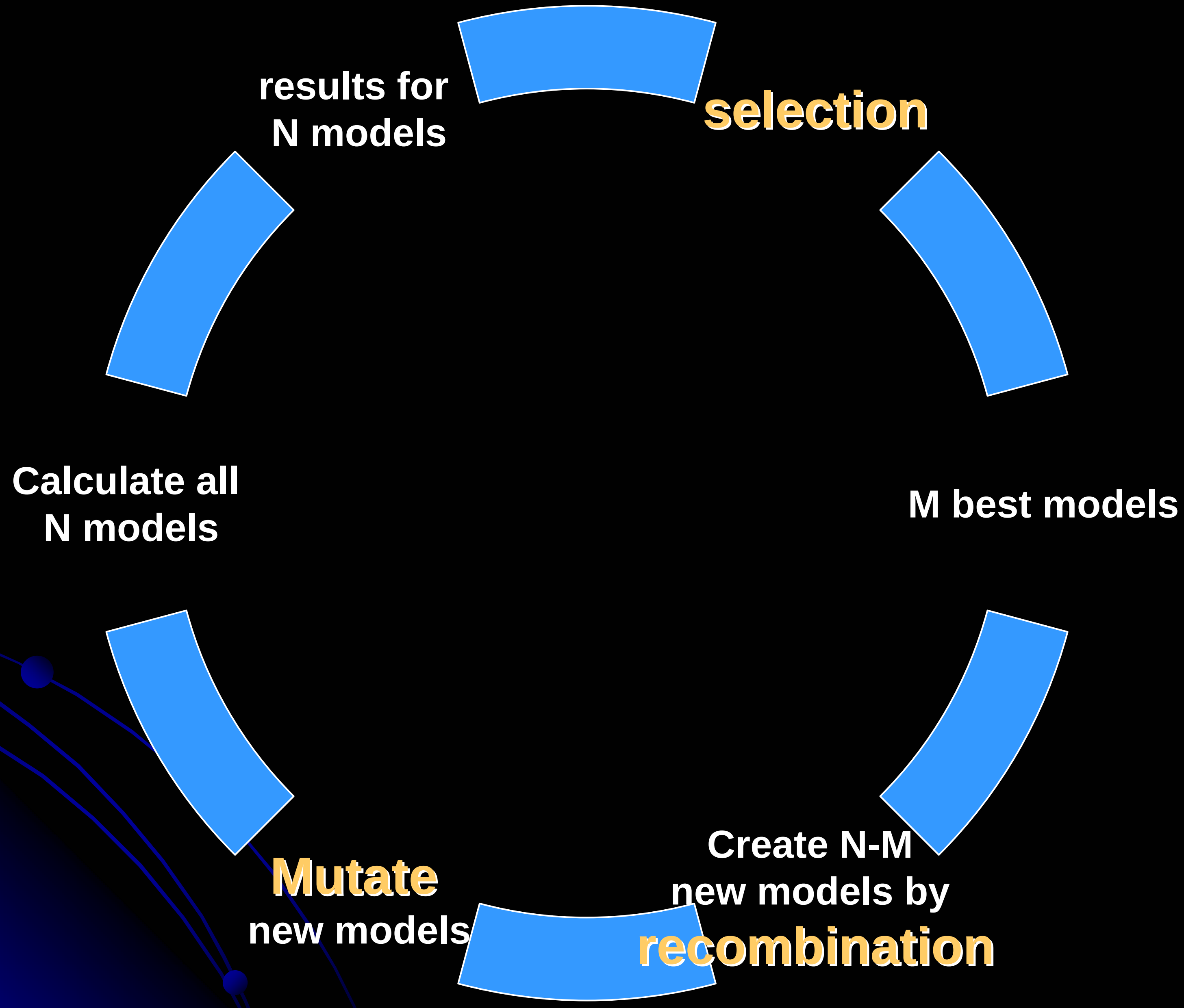
- In an isothermal halo:

$$\rho(r) = \frac{M_H}{4\pi r_H} \frac{1}{r^2}$$

$$\frac{d\vec{v}}{dt} = -\frac{Mm \ln\left(1 + \frac{M_r}{r_H m}\right)}{r_H r^2 v^2} \left[erf\left(\frac{v\sqrt{r_H}}{\sqrt{M}}\right) - \frac{2v\sqrt{r_H}}{\sqrt{\pi}M} e^{\frac{v\sqrt{r_H}}{\sqrt{M}}} \right] \vec{d}_{DF} s$$

Genetic Algorithm

- Simulate evolution (selection – recombination – mutation)
- Many different implementations
- Fast way to find minima in large number parameter spaces
- May get caught in local minima


results for N models
selection
M best models
Create N-M new models by recombination
Mutate new models
Calculate all N models

MOdified Newtonian Dynamics

- Alternative theory to explain observed rotations curves of galaxies
- Avoids dark matter (on galactic scales)
- First suggested by Milgrom in 1983
- Relativistic extension by Bekenstein in 2004

- Modified Poisson-equation

$$\vec{\nabla}\left(\mu\left(\frac{a}{a_0}\right).\vec{\nabla}\Phi\left(\vec{r}\right)\right)=4\pi G.\rho\left(\vec{r}\right)$$

- Interpolating function μ(x)

$$\mu\left(x\right)=\frac{x}{\sqrt{1+x^2}}$$

alternative: $$\mu\left(x\right)=\frac{x}{1+x}$$

- No longer superposition of accelerations possible

- Force on particle depends on absolute acceleration

$$F = m.\mu\left(\frac{a}{a_0}\right).a$$

$$\frac{G.M}{r^2} = \mu\left(\frac{a}{a_0}\right).a$$

central potential

$$a >> a_0 \quad \rightarrow \mu \sim 1$$

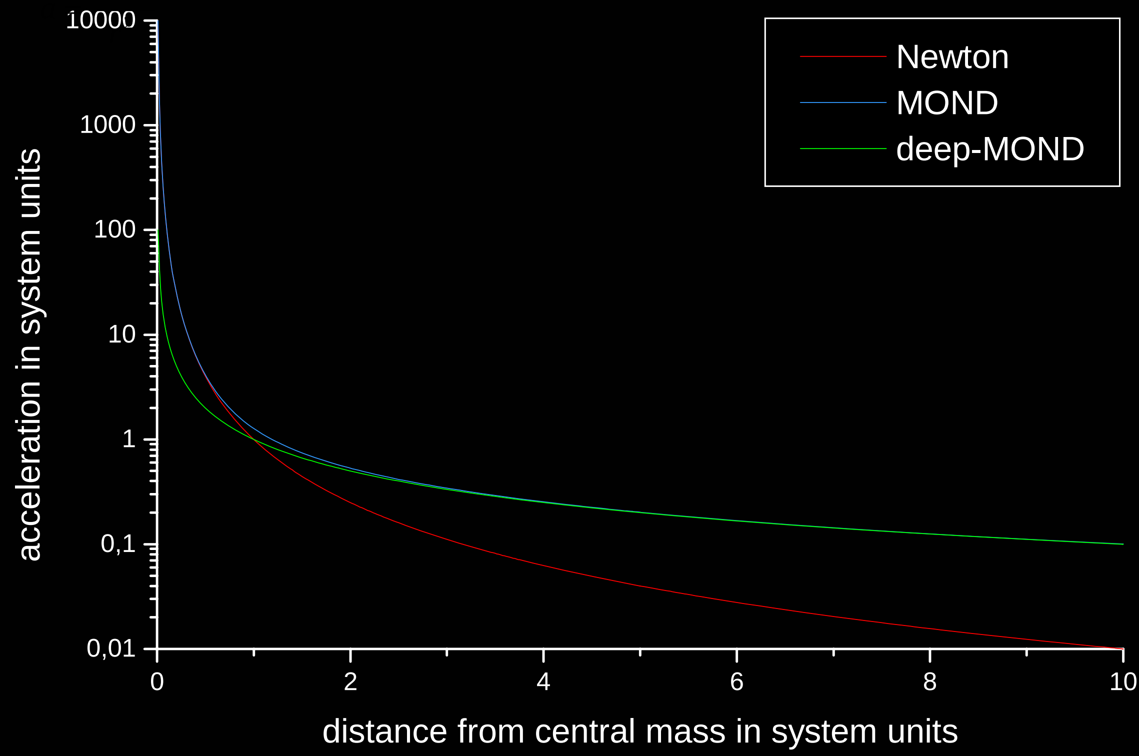
$$a = \frac{G.M}{r^2}$$

Newtonian limit

$$a << a_0 \quad \rightarrow \mu \sim a/a_0$$

$$a = \frac{\sqrt{G.M.a_0}}{r}$$

Deep-MOND limit



Advantages

- No Dark Matter on galactic scales
- Some observed relations follow naturally from MOND, like the Tully-Fisher relation
- Fits rotation curves very well with only one free parameter $a_0 \sim 1.2\ 10^{-10}$ m/s² $\sim c\ H_0 / 2\pi$
- Can explain rotation curves of LSB and HSB galaxies in one model

Problems

- merging is less likely in MOND, but it also takes much longer → observed merging rate?

- violation of strong equivalence principle → Lyman α forest problem
  → maybe solved by TeVeS

- Requires (hot) dark matter on cluster scale (remaining mass discrepancy of a factor of 2-3 with MOND)

- Galaxy cluster 1E0657-558 (a.k.a. **Bullet Cluster**) → separation of visible matter and Dark matter by a high velocity collision

- Timing of the Local Group: Milky Way and M31 cannot be on their first orbit in MOND → too much visible matter already found

- Physical motivation and consequences: new theory of gravity or new theory of inertia? Is it the best way to modify gravity?

Simulations

- Several simulations with Newtonian gravity (including Dark Matter) and deep MOND
- Wrote a lot of new programs
- Aim: to reproduce today's distribution of galaxies in the Local Group

  and to see if Dark Matter or MOND is true

Working hypothesis

- Most dwarf galaxies has been formed by an encounter of the gaseous discs of Milky Way and M31 more than 10 Billion years ago
- Scattered across the Local Group
- Orbits dominated by the two main galaxies
- Dwarfs are located now near the movement plane of Milky Way and Andromeda-galaxy

My main model

- Milky Way and M31 on an elliptical orbit (parameters optimized by 2body simulations)
- LMC, SMC and M33 are also massive
- All other dwarf galaxies are test particles
- Simulation starts with MW and M31 separated only by 24 - 150 kpc about 12 Gyr in the past

- Initial positions of other galaxies are located relatively near MW and M31
- In case of Newtonian gravity it includes dynamical friction, extended halos and the Hubble expansion.
- In case of MONDian gravity it includes the Hubble expansion.
- 20 generation with 1000 individual models per generation

Programs

- Written in Fortran90
- Using a NEMO-compatible file format
- Although all programs has been developed for a special problem, but most of them can be used for other problems as well (with some modifications).
- Controlled by a Shell-Script

Interplay of my programs

mkinput

Loop for N generations (

mkmodel

NewHExl or DeMonl

extracting required information after integration

GeneAl)

tidy up the results

NewHExI and DeMonI

- Stellar dynamical integrators for Newtonian and MONDian gravity
- NewHExI can perform calculations using Newtonian gravity, extended halos, dynamical friction and the Hubble expansion.
- DeMonI can perform calculations using deep-MOND gravity and the Hubble expansion.

GeneAl

- 237 variable starting parameters
- 158 fitting parameters
- Normal parameter scan unreasonable
- Fast alternative: genetic algorithm
- Partly restricted N-body problem → can do some tricks to increase its performance

- For every model:
  - Calculate fitness parameter for massive galaxies: position and radial velocity
  - Find the best test particle for every massless galaxy → origin of a new test particle cloud
  - Calculate total fitness of the model
- Create children by recombination of all parents (one child can have >2 parents)
- Choose mutating children randomly
- Mutate single parameters of a model within reasonable values

Results

- 11 different setups (6 Newtonian, 5 MONDian)
- MOND can fit the positions of the Local Group dwarf galaxies very well
- But MOND totally fails at the velocities, everything moves to fast (by several 100 km/s)
- In MOND the Milky Way and the Andromeda Galaxy are on their second orbit

- Newtonian gravity fits moderately (mainly due to problems in the outermost regions of the Local Group)
- Very extended Dark Matter halos are preferred for MW and M31 (r > 250 kpc)
- Early interaction about 12 Gyr ago is possible
- Minimal distance between MW and M31 at early encounter was about 50 – 100 kpc (Sawa and Fujimoto: 150 kpc)

- M33, LMC and SMC shouldn’t get to close to one of the large spirals → danger of merger
- Orbital plane of MW and M31 doesn’t has to correspond with the plane of dwarf galaxies
- Initial distribution: compact (diameter ~100 kpc) agglomeration around the two main galaxies, but with a tail like structure extending in the orbital plane several 100 kpc.
- Many ideas for further improvement of the simulation and the model

Conclusions

- The working hypothesis is possible model to explain the observed distribution.
- MOND has significant problems to reproduce the dynamics of our galaxy group.
- The plane of galaxies doesn’t have to correspond with the orbital plane of the Milky Way and the Andromeda galaxy.

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ANY QUESTIONS?

The Milky Way

by Digital Sky LLC

The Andromeda Galaxy

by John Lanoue

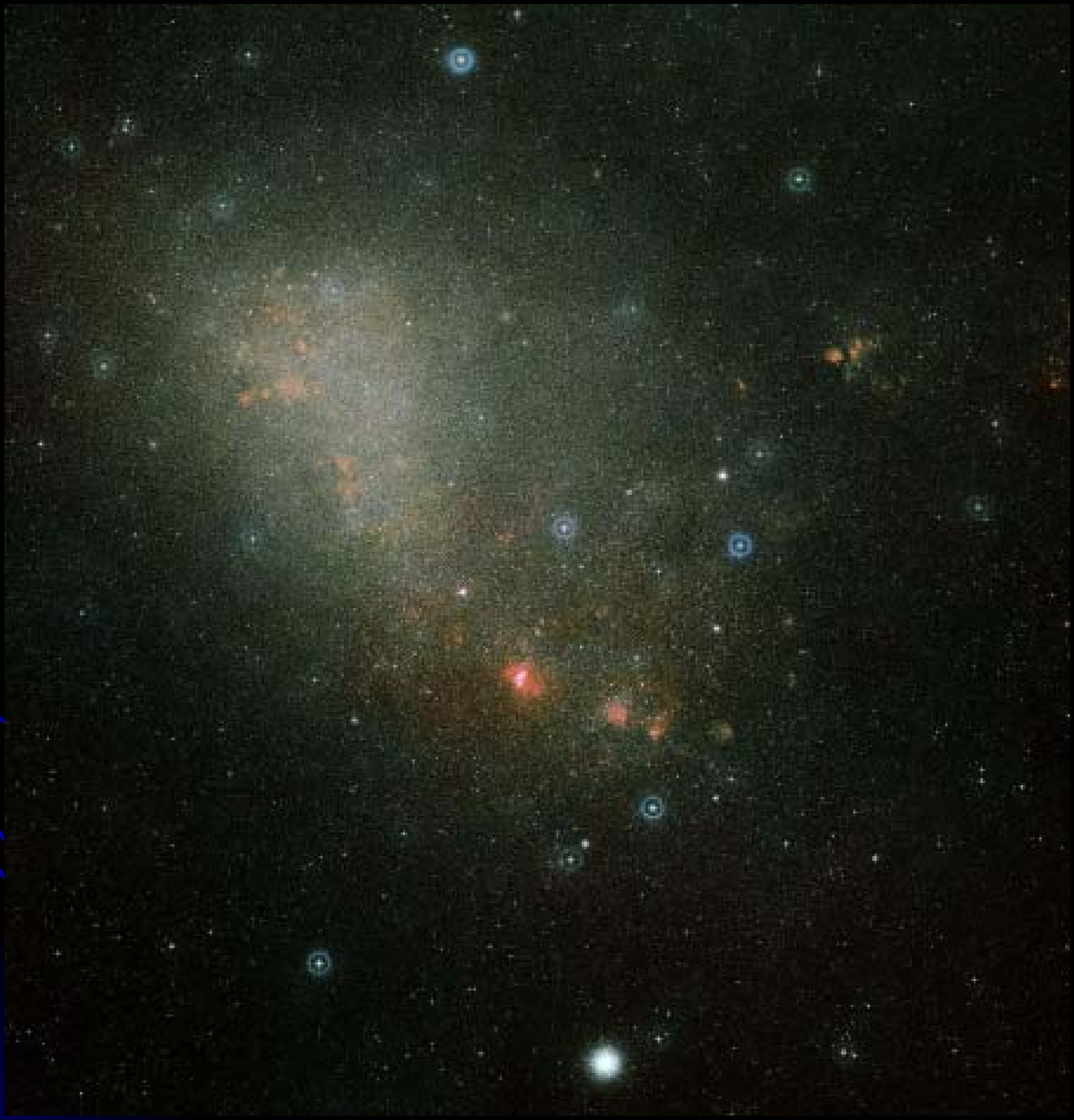
The Triangulum-Nebula

by Hewholooks

The Large Magellanic Cloud

by NASA

The Small Magellanic Cloud



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