Dark Energy in the Local Universe

Arthur D. Chernin
Sternberg Astronomical Institute
Moscow University

Collaborators:

P. Teerikorpi, M.J. Valtonen, G.G. Byrd, V.P. Dolgachev, L.M. Domozhilova

GLOBAL DARK ENERGY

Einstein (1917): Cosmological constant $\Lambda \equiv$ Global antigravity, if $\Lambda>0$

Static universe $\rightarrow$ Gravity + Antigravity = 0

Friedmann (1922-24): Exact GR solutions with Λ

Expanding universe $\rightarrow$ Gravity + Antigravity = f (t)

Riess et al. (1998), Perlmutter et al. (1999): Global acceleration

$\Lambda > 0$

ΛCDM

Standard ΛCDM Model: DE ≡ Einstein's Λ

Observations (WMAP-2006, etc.):

DE contributes 70-75% to the present total mass/energy of the universe

$$\rho_\Lambda = (c^2/8\pi G)\,\Lambda = (0.72 \pm 0.03) \bullet 10^{-29}\ \mathrm{g/cm}$$

DE antigravity dominates at

$$z < z_\Lambda \approx 0.7; \quad t > t_\Lambda \approx 7\ \mathrm{Gyr}$$

VACUUM

MACROSCOPIC DESCRIPTION: **Einstein-Gliner vacuum**

Gliner (1965):

- **Equation of state** $p_\Lambda = - \rho_\Lambda$
- **Perfectly uniform**
- **Density ρ_Λ is constant in any reference frame**

WMAP (2006): $p_\Lambda / \rho_\Lambda = -1 \pm 0.1$

Planck (launched 14 apr 2009): ±0.03-0.02

ANTIGRAVITY

GR: **effective gravitating density**

$$\rho_{\mathbf{eff}} = \rho + 3\,p$$

DE: $\rho_{\mathbf{eff}} = -2\,\rho_{\Lambda} < 0 \rightarrow$ **antigravity**

PHYSICAL NATURE???

MICROSCOPIC STRUCTURE:

Severe challenge to fundamental physics

Zeldovich (1967): $\Lambda \equiv$ **Quantum Vacuum**

Arkani-Hamed et al. (2001): $\rho_\Lambda \sim (M_{EW}/M_P)^8 \rho_P$

$M_{EW} \sim 1$ TeV, $M_P \sim 10^{15}$ TeV

$\rho_p \sim M_p^4$

LOCAL DARK ENERGY

DE is discovered at near-horizon distances of ~ 1 000 Mpc

Does DE act on relatively small local scales?

In principle, yes -- if DE = Λ

Specifically:

* ***How strong may local DE antigravity be?***
* ***May DE antigravity dominate locally?***

LOCAL GRAVITY-ANTIGRAVITY

Schwarzschild-de Sitter static spacetime:

point-like mass on DE background

$$ds^2 = A(R)\, dt^2 - R^2\, d\,\Omega^2 - A^{-1}\, dR^2$$

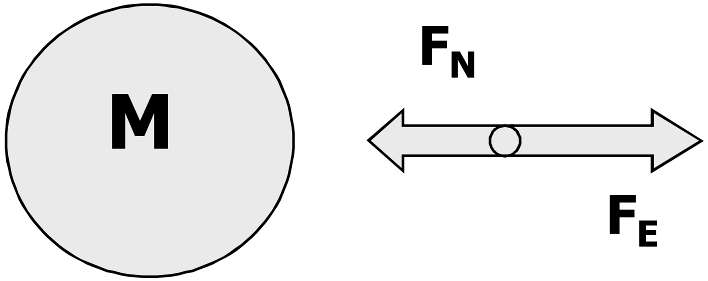
$$A\,(R) = 1 - 2GM/R - (8\pi G/3)\,\rho_\Lambda\, R^2$$

Newtonian limit:

$$1 + U \approx A^{1/2} \approx 1 - GM/R - (4\pi G/3)\,\rho_\Lambda\, R^2$$

$$F\,(R) = -\,\mathrm{grad}\,U = -\,GM/R^2 + (8\pi G/3)\,\rho_\Lambda\, R$$

LOCAL DYNAMICS



Newton Law $F_N = - G M/R^2$

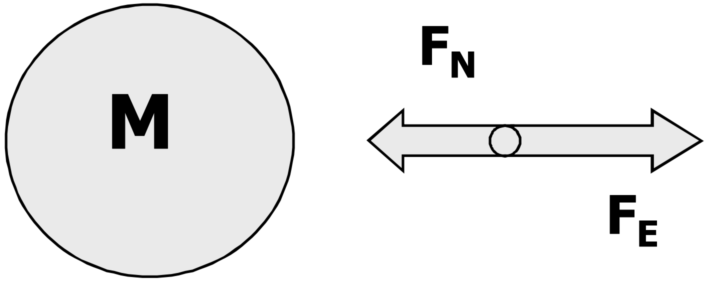
Einstein Law $F_E = - GM_{eff}/R^2$

$$M_{eff} = (4\pi/3)\, \rho_{eff}\, R^3 = (4\pi/3)\, (\rho + 3p)\, R3 = - (8\pi/3)\, G\, \rho_\Lambda\, R^3$$

$$F_E = + (8\pi/3)\, G\, \rho_\Lambda\, R$$

(per unit mass)

ZERO-GRAVITY RADIUS



$F(R=R_\Lambda) = F_N + F_E = 0$:

$$R_\Lambda = [\, 3\,M/(8\pi\,\rho_\Lambda)\,]^{1/3}$$

$\approx 1\,[\,M/10^{12}\,M_{sun}]^{1/3}$ **Mpc** (Chernin et al. 2000)

Groups of galaxies: $M = (1\text{-}10)\;10^{12}\,M_{sun} \rightarrow R_\Lambda = 1\text{-}2$ **Mpc**

Clusters of galaxies: $M = (1\text{-}10)\;10^{14}\,M_{sun} \rightarrow R_\Lambda = 5\text{-}10$ **Mpc**

R_Λ is local counterpart of global redshift $z_\Lambda \approx 0.7$

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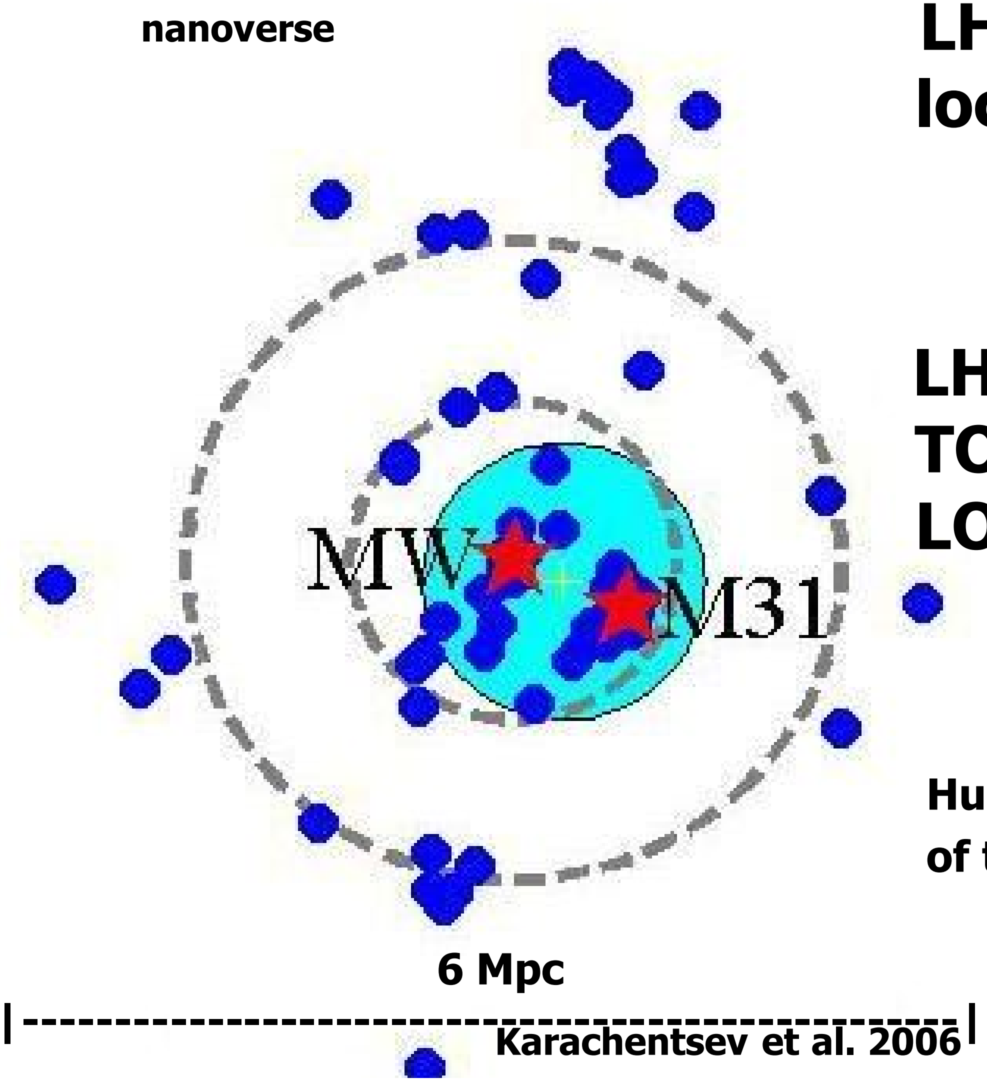
LOCAL HUBBLE CELL (LHC)

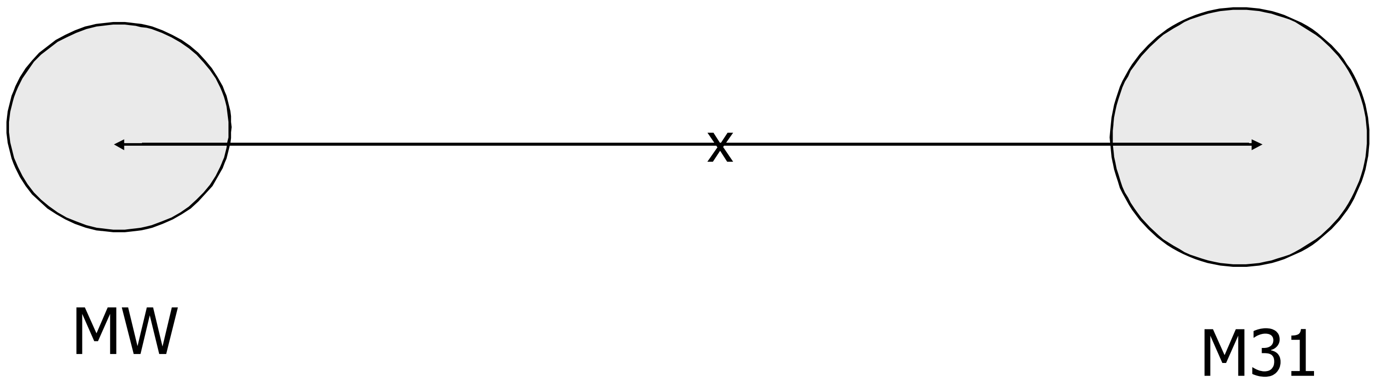


LHC = Local Group + local expansion outflow

LHC IS NATURAL SETUP TO DETECT AND MEASURE LOCAL DARK ENERGY

Hubble cells are typical population of the Local Universe (Hubble 1936)

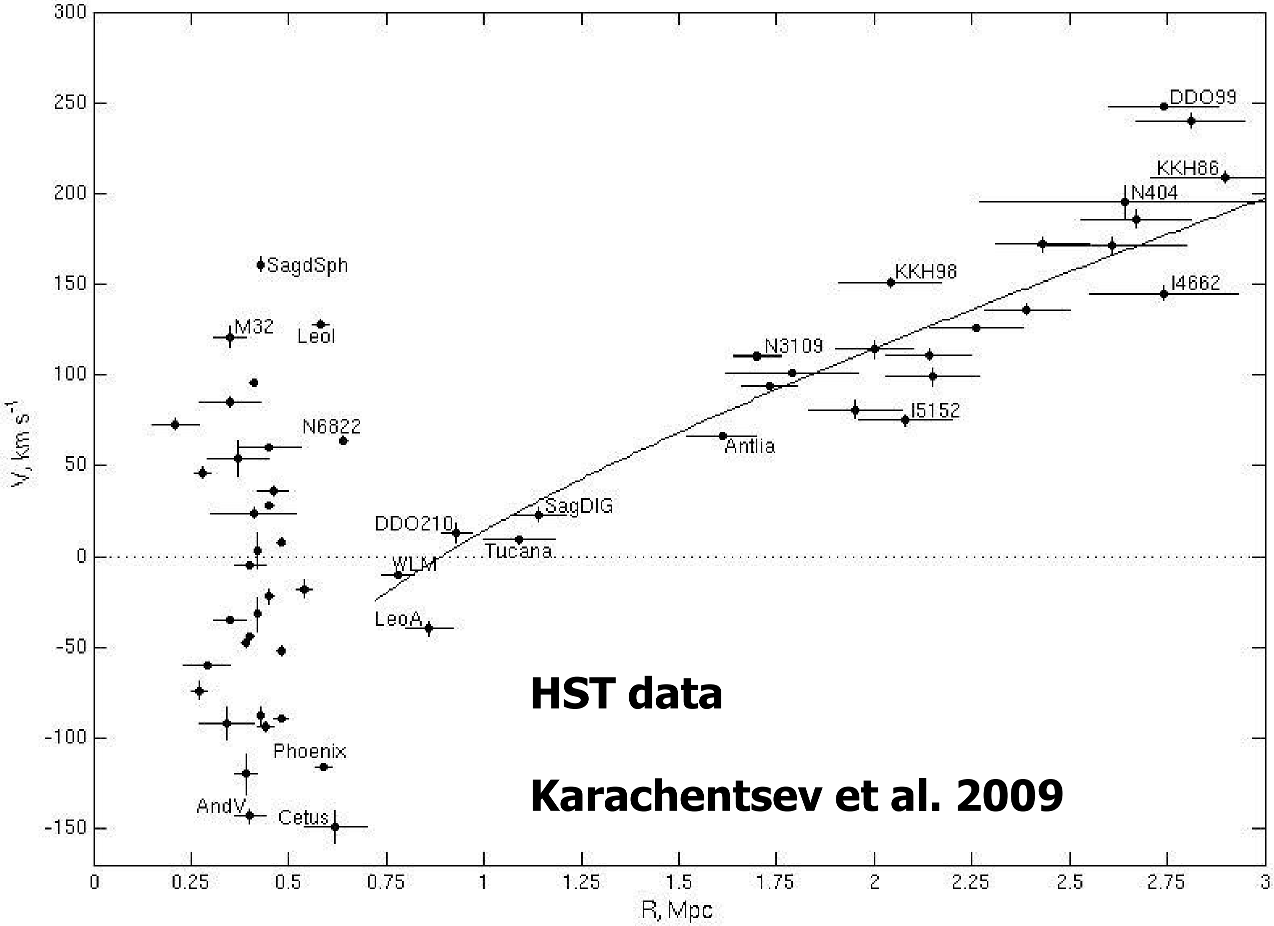
LOCAL GROUP



Giant MW-M31 binary and ≈ 50 dwarf galaxies

MW and M31 are separated by distance of 0.7 Mpc and move toward each other with relative velocity – 120 km/s now

LHC PHASE PORTAIT



HST data

Karachentsev et al. 2009

Group:

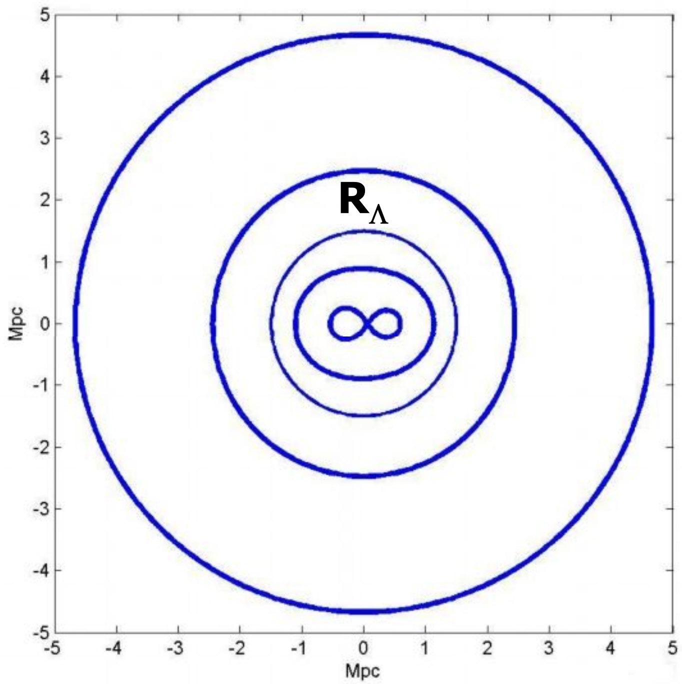
R < 1.2 Mpc

Outflow:

R > 1.6 Mpc

LHC ZERO-GRAVITY RADIUS

LHC gravity-antigravity potential



Gravitationally bound group

$R < R_\Lambda$: **gravity dominates**

Expansion outflow

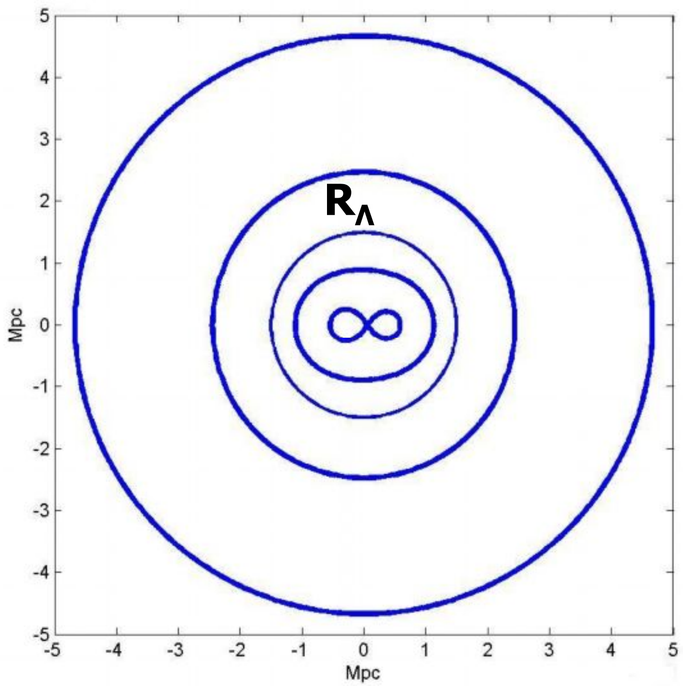
$R > R_\Lambda$: **antigravity dominates**

Antigravity makes outflow cool: linear velocity-distance relation with low dispersion

(Chernin et al. 2000-04, Maccio' et al. 2005, Sandage et al. 2006)

LHC MODEL

LHC gravity-antigravity potential



Group:

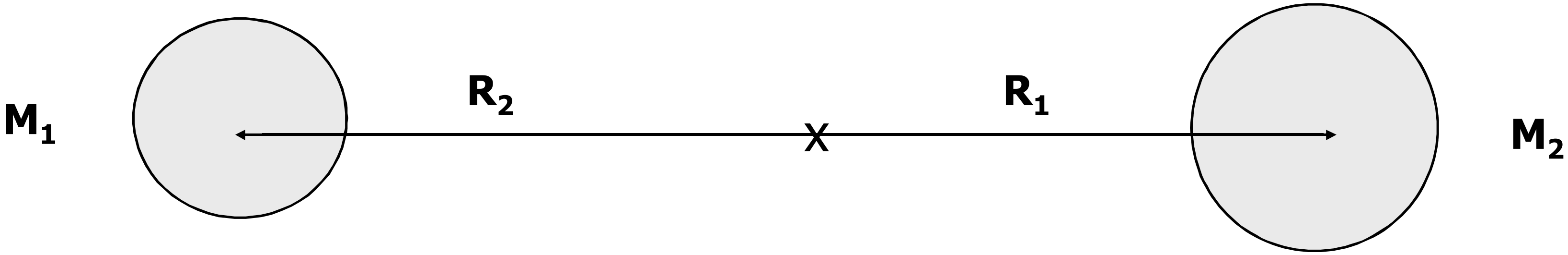
MW_M31 binary as bound linear two-body system

Expansion outflow:

dwarf galaxies as test particles moving in a spherical gravity-antigravity static potential

The cell is embedded in the uniform DE background

MW-M31 BINARY



D = R_1+ R_2 = 0.7 Mpc; V = -120 km/s

Linear two-body problem on DE background: equations of motion

$$d^2R_1/dt^2 = - G M_2/D^2 + G (8\pi/3)\rho_\Lambda R_1$$

$$- d^2R_2/dt^2 = G M_1/D^2 - G (8\pi/3)\rho_\Lambda R_2$$

(barycenter reference frame)

GRAVITY-ANTIGRAVITY POTENTIAL

$$d^2D/dt^2 = - GM/D^2 + G(8\pi/3)\rho_\Lambda D$$

$(M = M_1+M_2 , D = R_1+R_2)$

The first integral

$$(1/2) V^2 = GM/D + G (4\pi/3) \rho_\Lambda D^2 + E,$$

(E =Const)

Effective potential : $U = - GM/D - G (4\pi/3) \rho_\Lambda D^2$

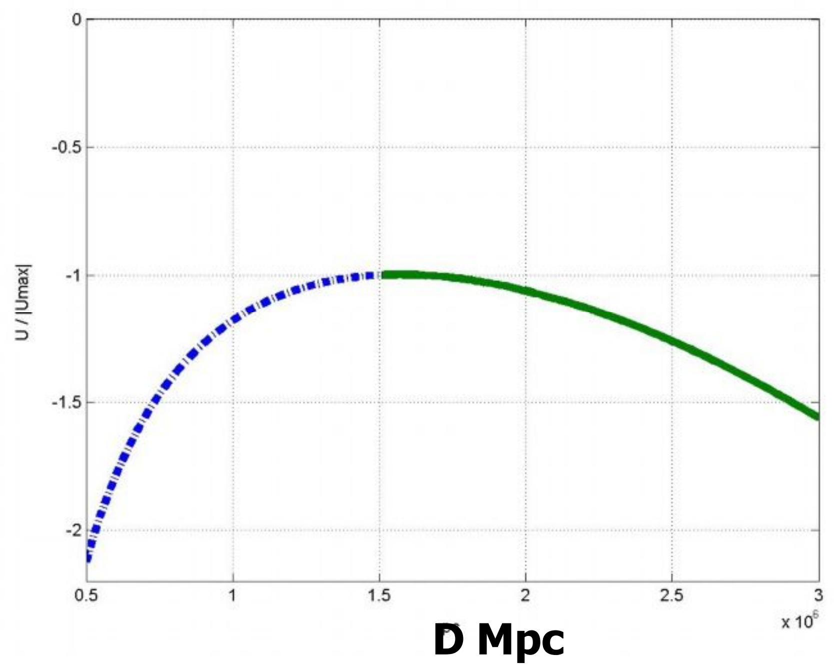
BINDING CONDITION

Binary is gravitationally bound, if

$$E < U_{max} = -(3/2)\, GM^{2/3} [(8\pi/3)\, \rho_\Lambda]^{1/3}$$

Binding condition + first integral

$$(1/2)\, V^2 = GM/D + G\,(4\pi/3)\, \rho_\Lambda D^2 + E$$



lead to lower limit to mass

$$M > M_1 = 3.3\ 10^{12}\, M_{sun}$$

(KW: M_1 =1.1)

TIMING ARGUMENT

Gravitational instability in ΛCDM model is terminated when antigravity becomes stronger than gravity at $t = t_\Lambda = 7$ Gyr (e.g. Chernin et al. 2003)

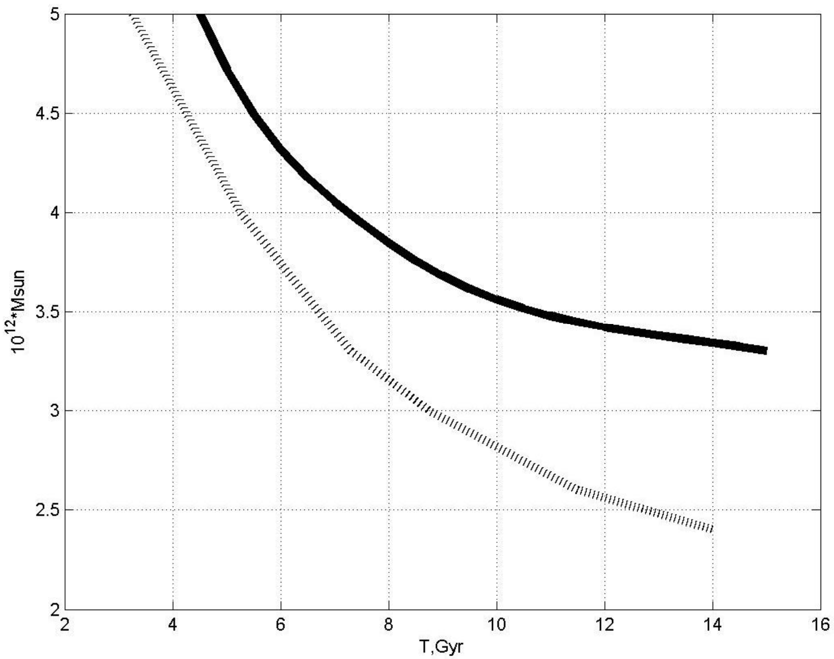
Therefore binary collapse time

$$T > t_0 - t_\Lambda \approx 7 \text{ Gyr}$$

M-T relation leads to upper limit to mass:

$$M < M_2 = 4.1 \; 10^{12} \, M_{sun}$$

(KW: $M_2 = 3.2$)



M-T relation comes from second integration of equation of motion

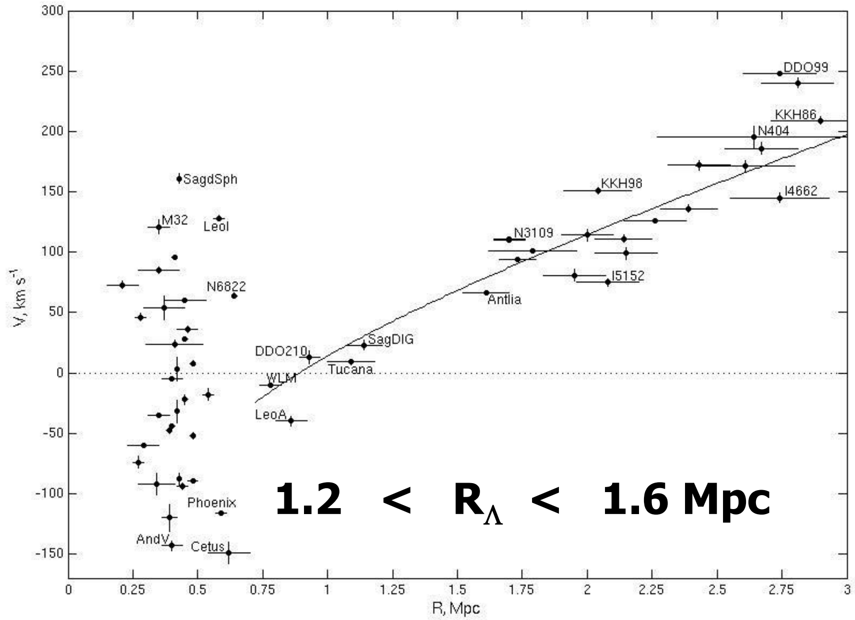
LIMITS TO ZERO-GRAVITY RADIUS

$$R_\Lambda = [\,3\,M/(8\pi\,\rho_\Lambda)]^{1/3} \quad \rightarrow \quad M = (8\pi/3)\,\rho_\Lambda\,R_\Lambda^{3}$$

$$M_3 < M < M_4$$

$$M_3 = 1.7\ \ 10^{12}\,M_{sun}$$

$$M_4 = 3.9\ \ 10^{12}\,M_{sun}$$



$$1.2 < R_\Lambda < 1.6\ \text{Mpc}$$

HST data: Karachentsev et al. 2009

LOCAL GROUP MASS

Four limits to group mass in combination

$$3.3 \quad < \quad M \quad < \quad 3.9 \quad 10^{12}\, M_{sun}$$

If local DE density = global value ρ_Λ

LOCAL DE DENSITY

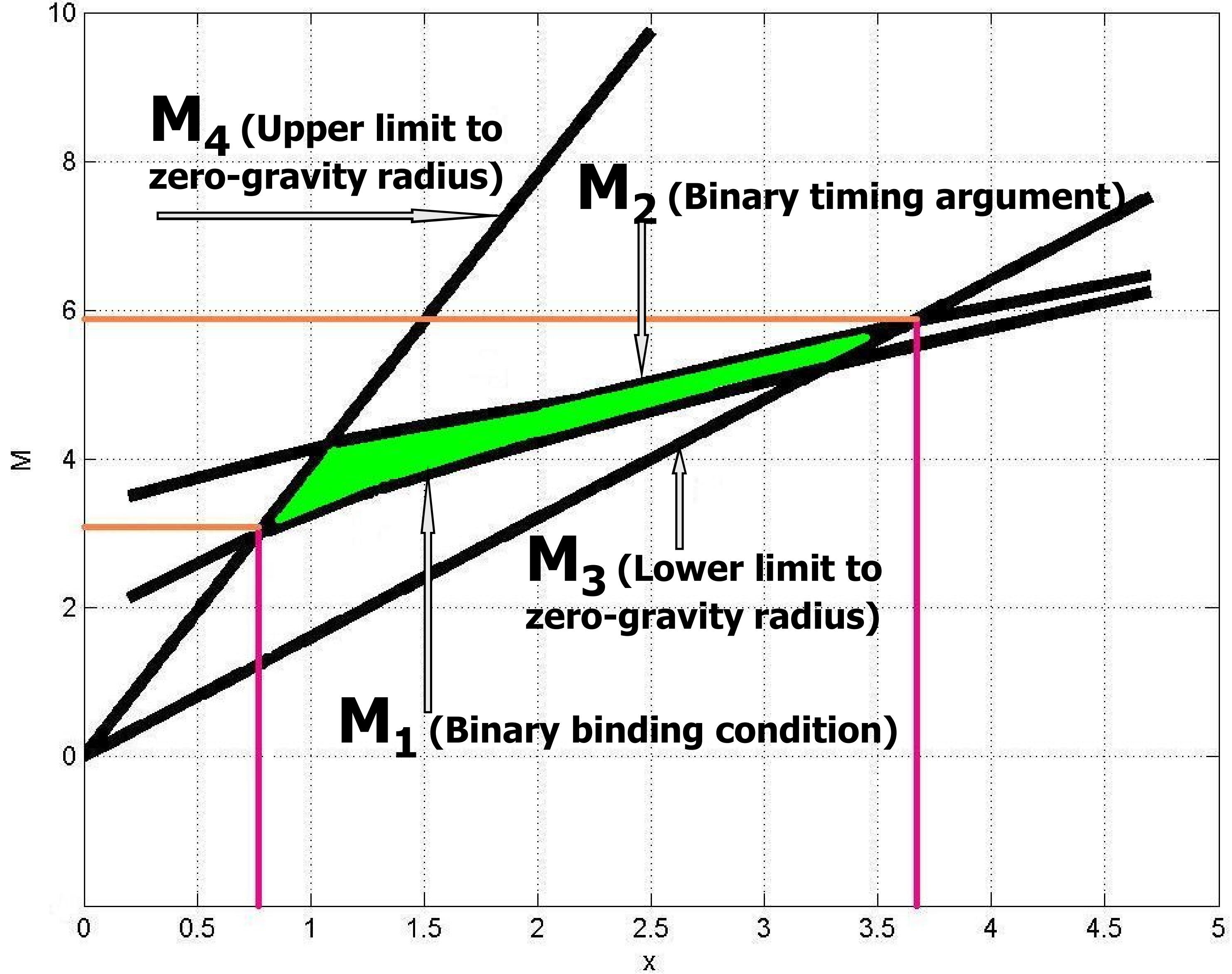
If local DE density is unknown ρ_x , four mass limits are functions of local DE density, or $x = \rho_x / \rho_\Lambda$

$M > M_1(x)$, $M < M_2(x)$,

$M < M_3(x)$, $M_4 > M_4(x)$

Observational data: D= 0.7 Mpc, V = -120 km/s

$1.2 < R_\Lambda < 1.6$ Mpc



x = ρ_x / ρ_Λ

CONCLUSIONS

LHC is natural setup for measuring Local Group mass and local DE density at ~ 1 Mpc in self-consistent way

Total (dark matter + baryons) mass of Local Group

$$3.1 < M < 5.9 \quad 10^{12} \quad M_{sun}$$

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(20-30% accuracy)

If $\rho_x = \rho_\Lambda$: $\quad 3.3 < M < 3.9 \quad 10^{12} \quad M_{sun}$

ΛCDM Millennium Simulations (2008): $\quad 1.7 < M < 5.1 \quad 10^{12}\ M_{sun}$

CONCLUSIONS

DARK ENERGY EXISTS ON SCALE ~ 1 Mpc

ANTIGRAVITY IS STRONG ON THIS SCALE

Local density of dark energy

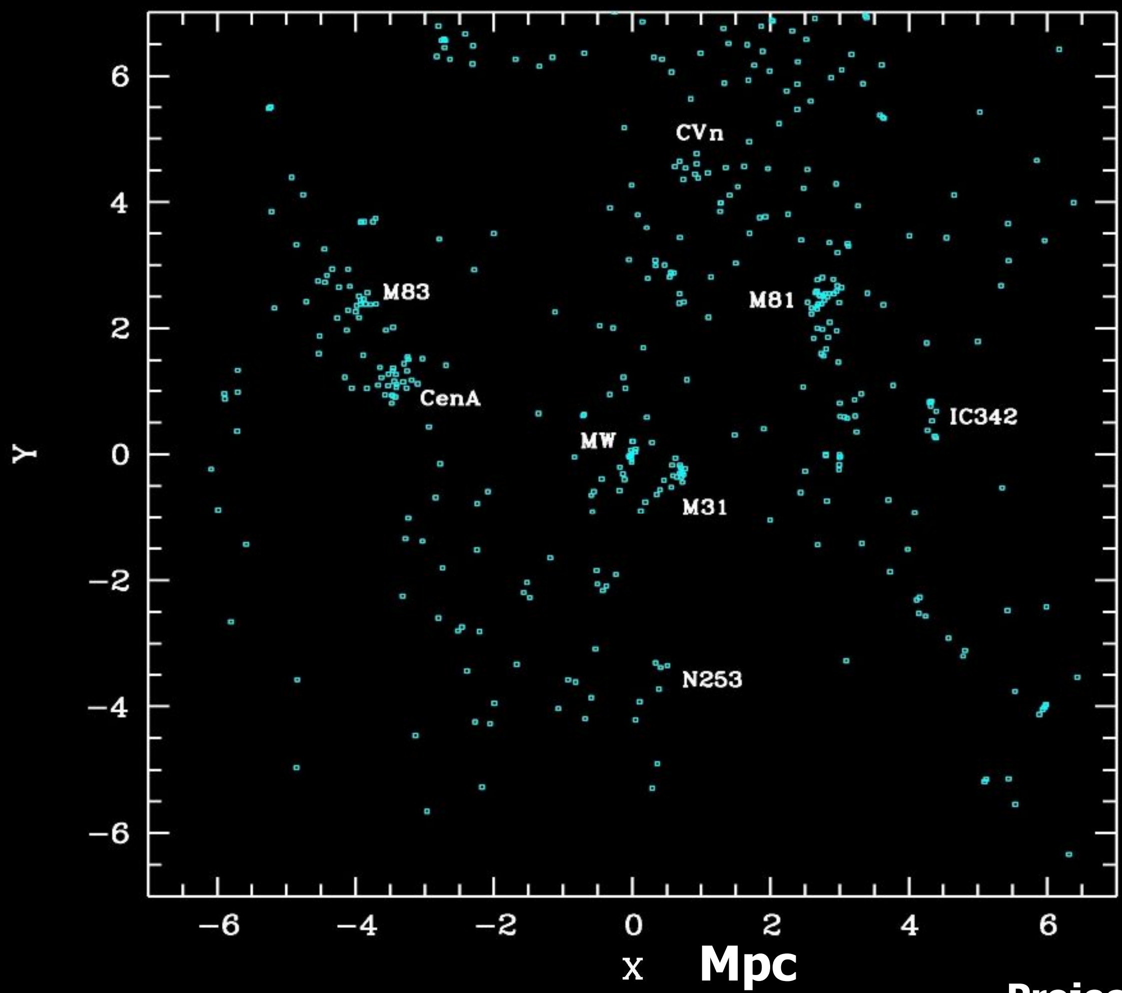
$$0.8 < \rho_x < 3.7 \rho_\Lambda$$

====================== (20-30% accuracy)

Local DE density at R ~ 1 Mpc is close, if not exactly equal, to global DE density at R ~ 1 000 Mpc

NEW INDEPENDENT EVIDENCE FOR EINSTEIN'S IDEA OF UNIVERSAL ANTIGRAVITY

LOCAL UNIVERSE



Karachentsev et al. (2006):

HST map of the local volume of 14 Mpc across

Projection on the Supergalactic plane

LOCAL UNIVERSE

The Local Universe is a network of receding partly overlapping "Hubble cells"

The Hubble cell is a gravitationally bound galaxy system (group or cluster) + an expansion flow of galaxies around it

The network (100-300 Mpc across) is embedded in the uniform dark energy background

KAHN-WOLTJER MODEL

$d^2D/dt^2 = - G M/D^2$ → $\frac{1}{2} V^2 = GM/D + E$

($dD/dt = V$; $D = R_1 + R_2$; $M = M_1 + M_2$)

The first integral and the bound condition E < 0 imply:

$$M > M_{min} = \frac{1}{2} V^2 D/G = 10^{12} M_{sun}$$

$M_{min} \sim 10\ M_L$

First evidence for dark matter in MW and M31