Galaxy clusters in presence of Dark Energy:

a gravitational approach

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Outline

The past

- Something about galaxy clusters.
- The introduction of the cosmological constant.
- The ΛCDM model: constraints on Dark Energy.

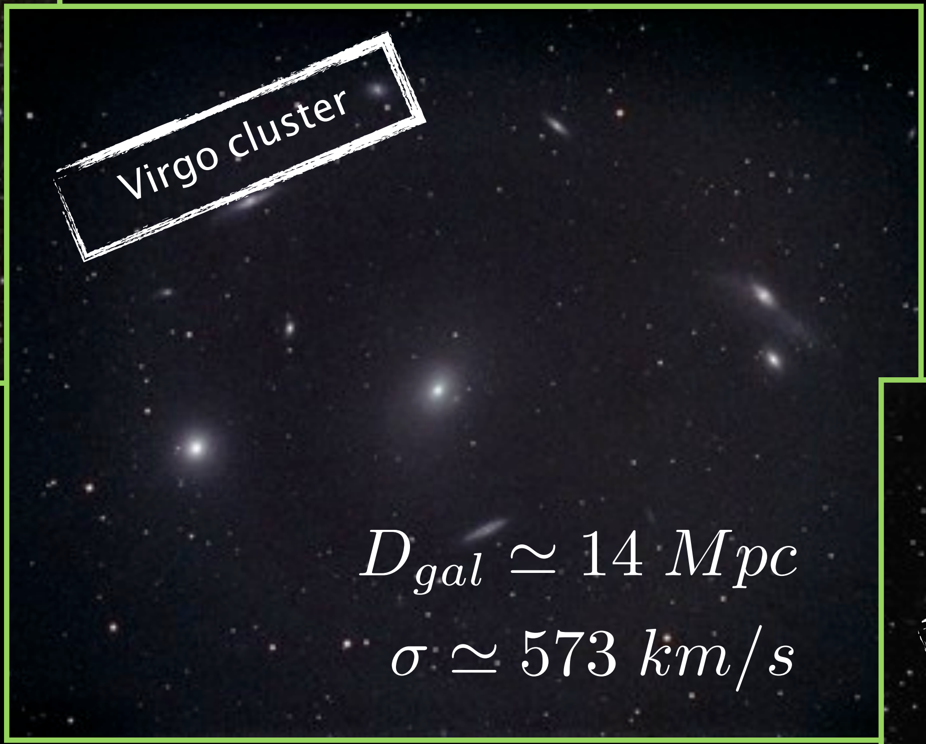
The present

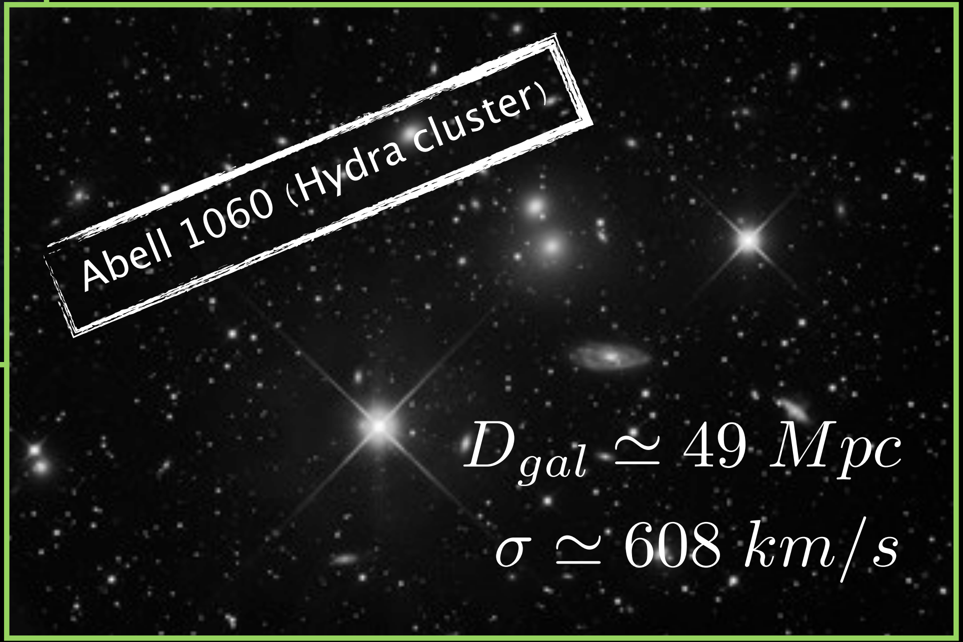
- Our approach to the problem: the investigation of the gravitational equilibrium.
- A brief analysis of the numerical results.
- Zero gravity radius: two important cases.

Conclusions and future perspectives

About galaxy clusters

The past





$$M \simeq (10^{14} - 10^{15})\ M_\odot$$

$$R \simeq (1 - 10)\ Mpc$$

$$T \simeq (10^{7} - 10^{8})\ K$$

- They contains 50-1000 galaxies, gas and dark matter
  - Only 5% - barionic matter
  - 95% - dark matter and gas
- Nowadays we know about 10.000 galaxy clusters

The "biggest blunder"…

The past

Einstein field equation

+

Λ term (1917)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

By using FLRW metric

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -dt^2 + a^2(t) d\sigma^2$$

$$\begin{cases} \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\varepsilon - \frac{kc^2}{R^2 a^2} + \frac{\Lambda}{3} \\ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3P) + \frac{\Lambda}{3} \end{cases}$$

… Riess et al (1998)
Perlmutter et al. (1999)

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). (1)

identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is $t_0^{\text{flat}} = 14.9^{+1.4}_{-1.1}(0.63/h)$ Gyr for a flat cosmology. The size of our sample allows us to perform a variety of (2)

(1) Riess et al, 1998, 116-1009, ApJ

(2) Perlmutter et al, 1999, 517-565, ApJ

Why Dark Energy is the cosmological constant Λ?

The past

If the origin of dark energy is not the cosmological constant, we need some alternatives models to explain the cosmic acceleration today

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

l.h.s
geometry of the spacetime

r.h.s
energies and momenta of the matter components

- First approach: modify l.h.s.
  (f(R) gravity, S-T theories, braneworld models)

- Second approach: modify r.h.s.
  (quintessence, k-essence, PFM)

E.O.S. of Dark Energy

$$w_{DE} \equiv P_{DE}/\rho_{DE}$$

→ $w_{DE} = w_{DE}(t)$ for the other models

→ = -1 Λ CDM model

Gravitational equilibrium →

$$\nabla^2\phi = 4\pi G\rho$$

$$\nabla^2\phi + \Lambda c^2 = 4\pi G\rho$$

$$\varepsilon_\Lambda \equiv \frac{c^2}{8\pi G}\Lambda$$ → Density

$$P_\Lambda = -\varepsilon_\Lambda$$ → Pressure

How we can detect DE?

The past

Cosmological parameters

Hubble's constant $$H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$

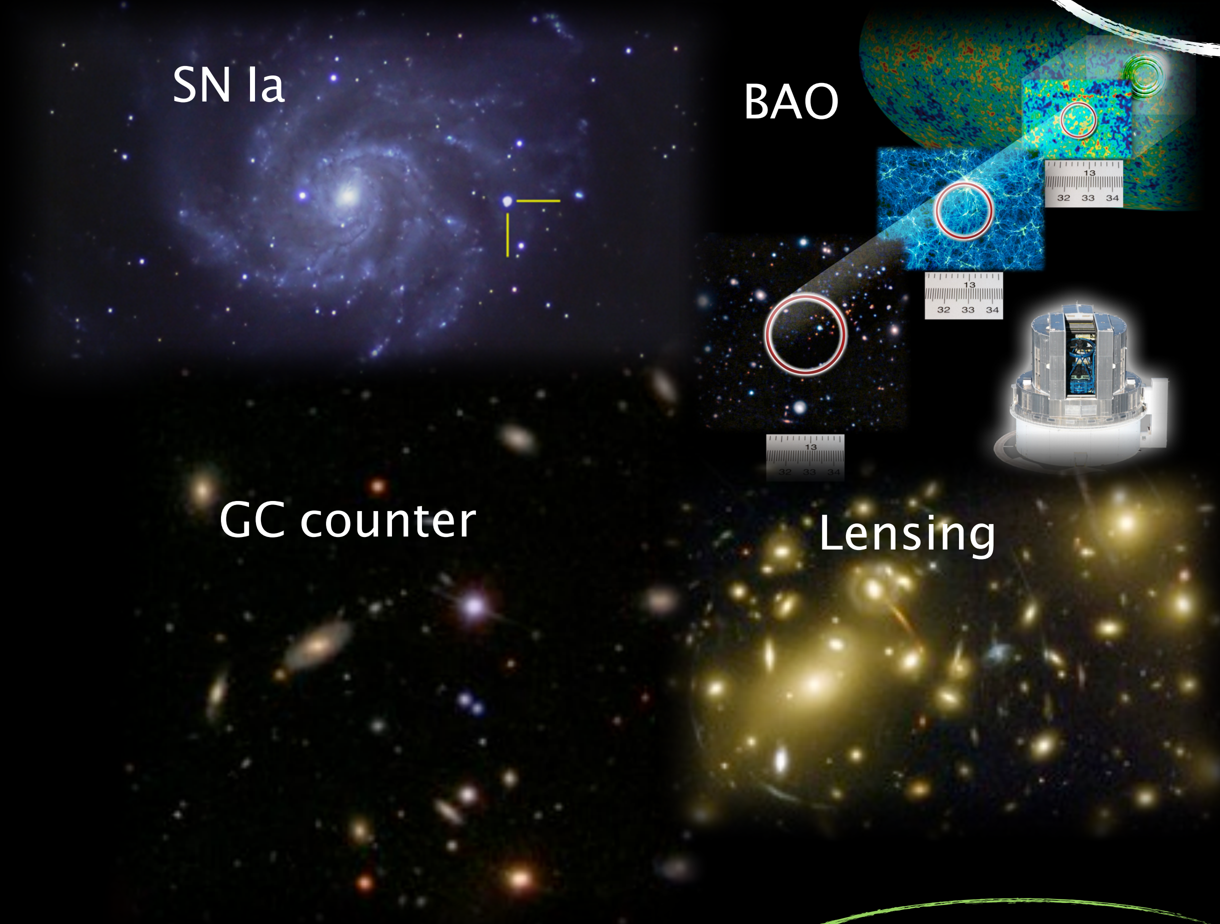
Deceleration parameter $$q(t) \equiv -\frac{a(t)\ddot{a}(t)}{[\dot{a}(t)]^2}$$

Density parameters $$\Omega_k \quad \Omega_\Lambda \quad \Omega_m \quad \Omega_{rad}$$

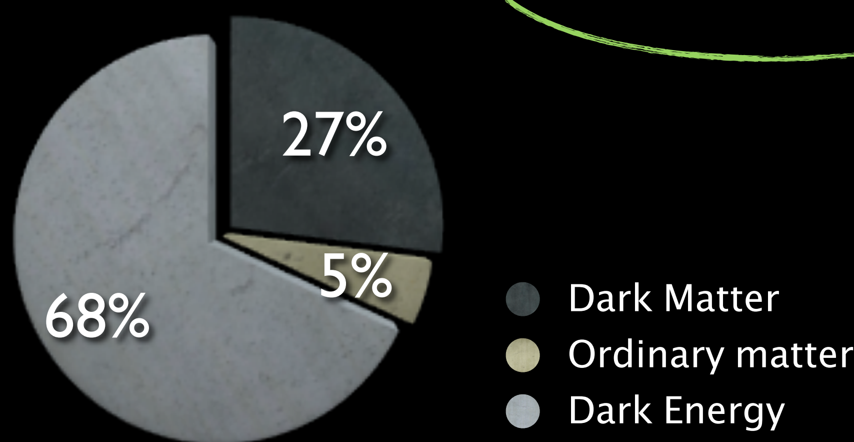
BOOMERanG (1997)

WMAP(2009) (SN Ia + CMB + BAO)

$$0.6 < \Omega_\Lambda < 0.85$$



Planck(2013) → $$\Omega_\Lambda \simeq 0.68$$



The cosmological constant is well consistent with the current observational data while some dark energy models have been already excluded from observations.

Galaxy clusters and Dark Energy

The present

The effects of Dark Energy are mainly related to large scale structures

The observed growth of the most X-ray luminous galaxy clusters provide to give new contraints on dark energy (cosmological constant model, w-model …)

These are all cosmological views of the problem

… BUT …

we can approach to Dark Energy from another point of view

We introduce two important concepts

- The gravitational equilibrium
- The Zero Gravity Radius

The gravitational equilibrium

The present

What we need

Cosmological model: ΛCDM $\qquad \rho_\lambda = \frac{c^2}{8\pi G}\Lambda$

Maxwell- Boltzmann distribution function with cutoff * $\qquad f = Ae^{-\frac{E}{T}}$

Matter density $\qquad \rho = m\int_0^{p_{max}} f 4\pi p^2 dp$

It is convenient to define a dimensionless Dark Energy density $\qquad \hat{\rho}_\Lambda = \frac{\rho}{\hat{\rho}}\rho_\Lambda$

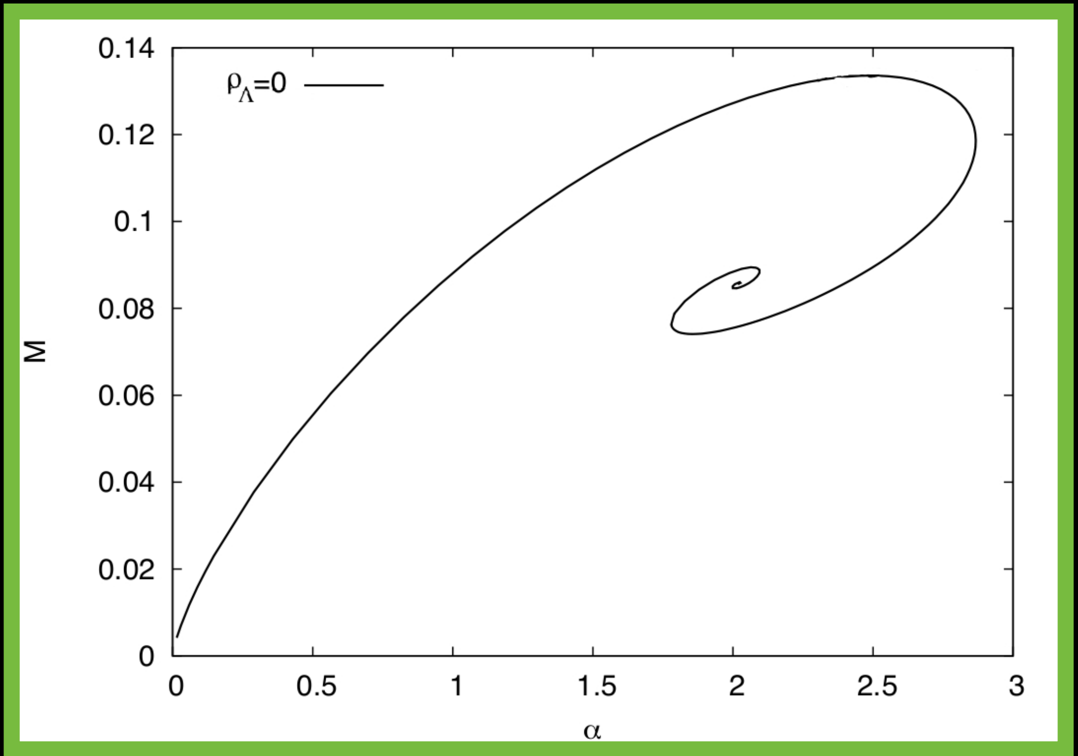
Following ZP (1965)[1], BMRV (1993, 1998)[2,3]

*Energy cutoff

$$E_{cut} = \epsilon_c + m\phi = -\frac{\alpha T}{2}$$

Cutoff parameter

$$\alpha = \frac{2GMm}{RT}\left(1 + \frac{c^2R^3}{6GM}\Lambda\right)$$



(1) Zel'dovich & Podurets 1965, AZh, 42, 963
(2) Bisnovatyi-Kogan et al.,1993, ApJ, 414, 187
(3) Bisnovatyi-Kogan et al.,1998, ApJ, 500, 217

The gravitational equilibrium: the presence of the cosmological constant

The present

Equilibrium equation (Poisson equation)

$$\begin{cases} \nabla^2\phi = \dfrac{1}{r^2}\dfrac{d}{dr}\left(r^2\dfrac{d\phi}{dr}\right) = 4\pi G\rho \\ \phi = \phi_G + \phi_\Lambda \end{cases}$$

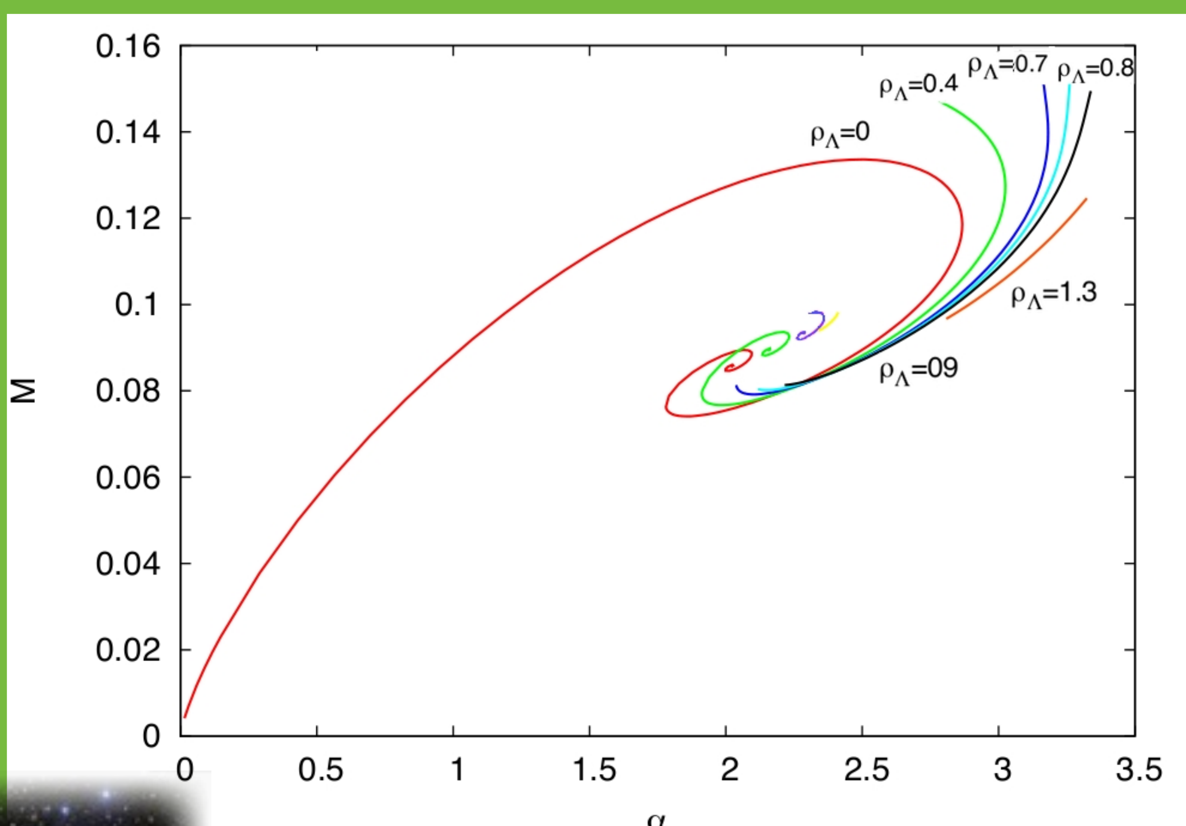
$$\phi_\Lambda = -\frac{\Lambda c^2}{6} r^2$$ From ΛCDM model

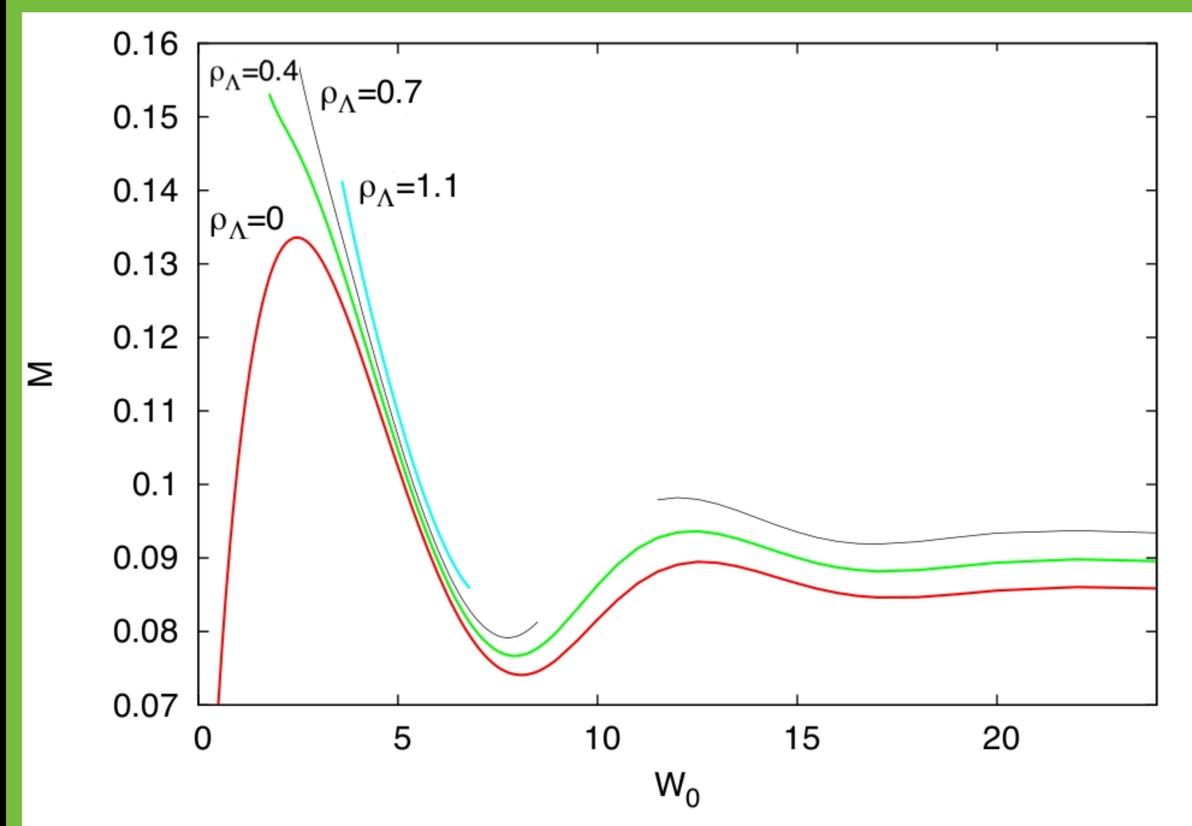
By introducing the following variables

$$W = \frac{m}{T}(\phi_R - \phi)$$ dimensionless potential

$$\sigma^2 = \frac{2T}{m}$$ velocity dispersion

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\phi}{dr}\right) = -\frac{8\pi G}{\sigma^2}(\rho - 2\rho_\Lambda)$$





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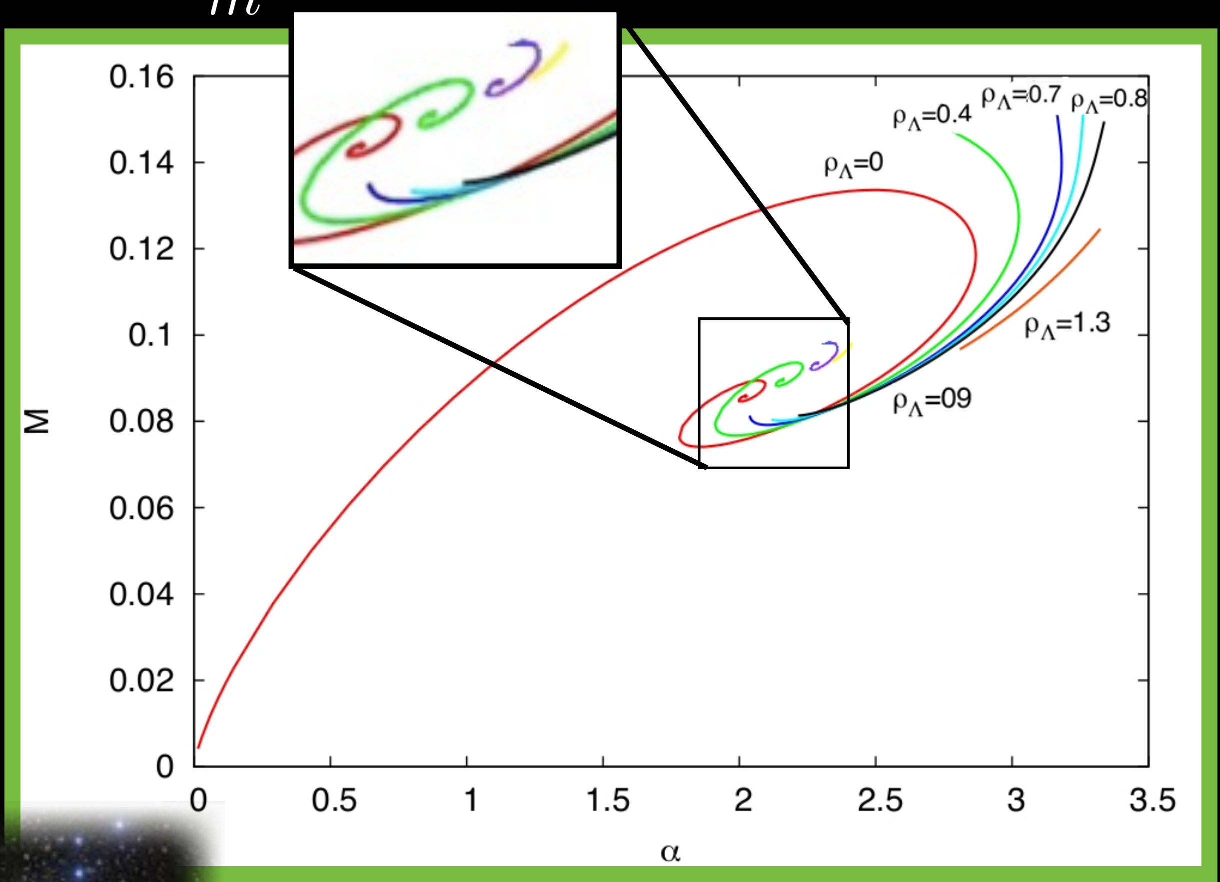

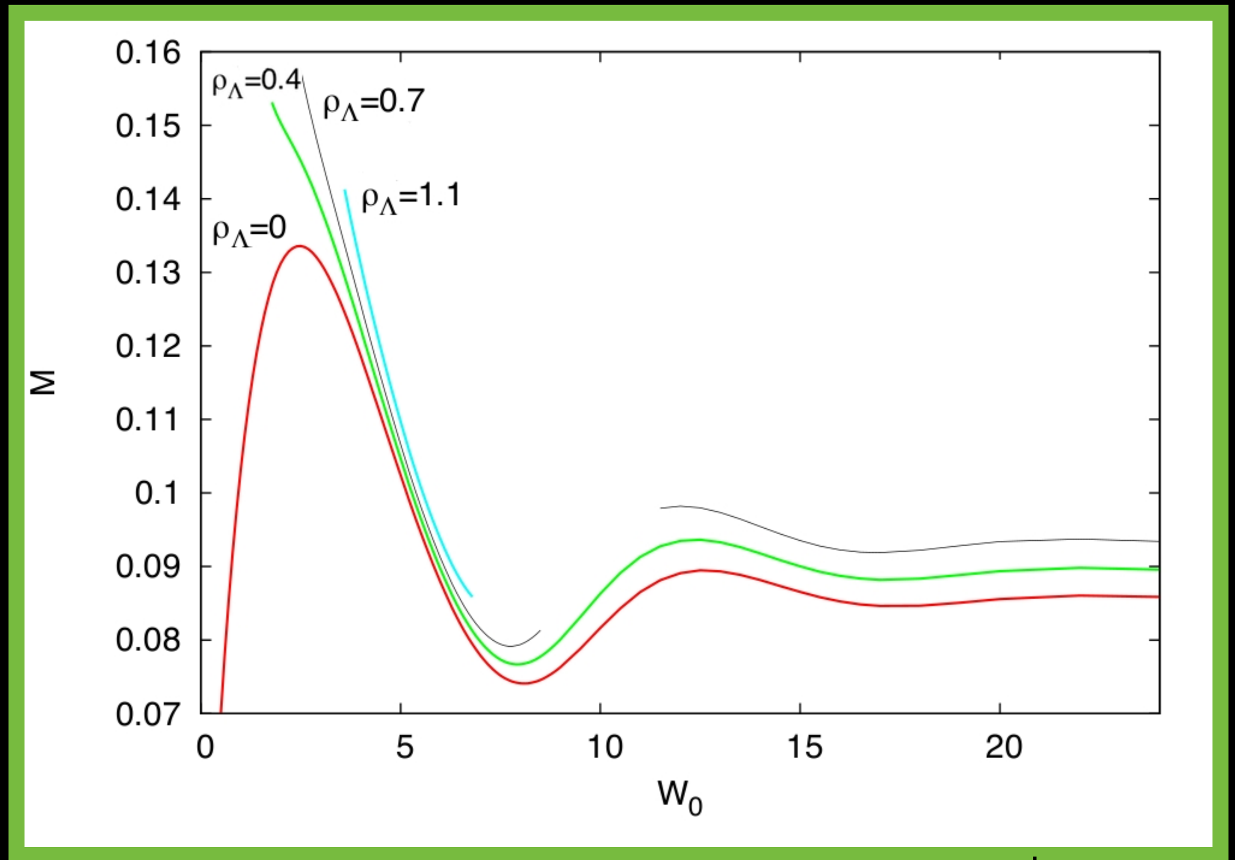

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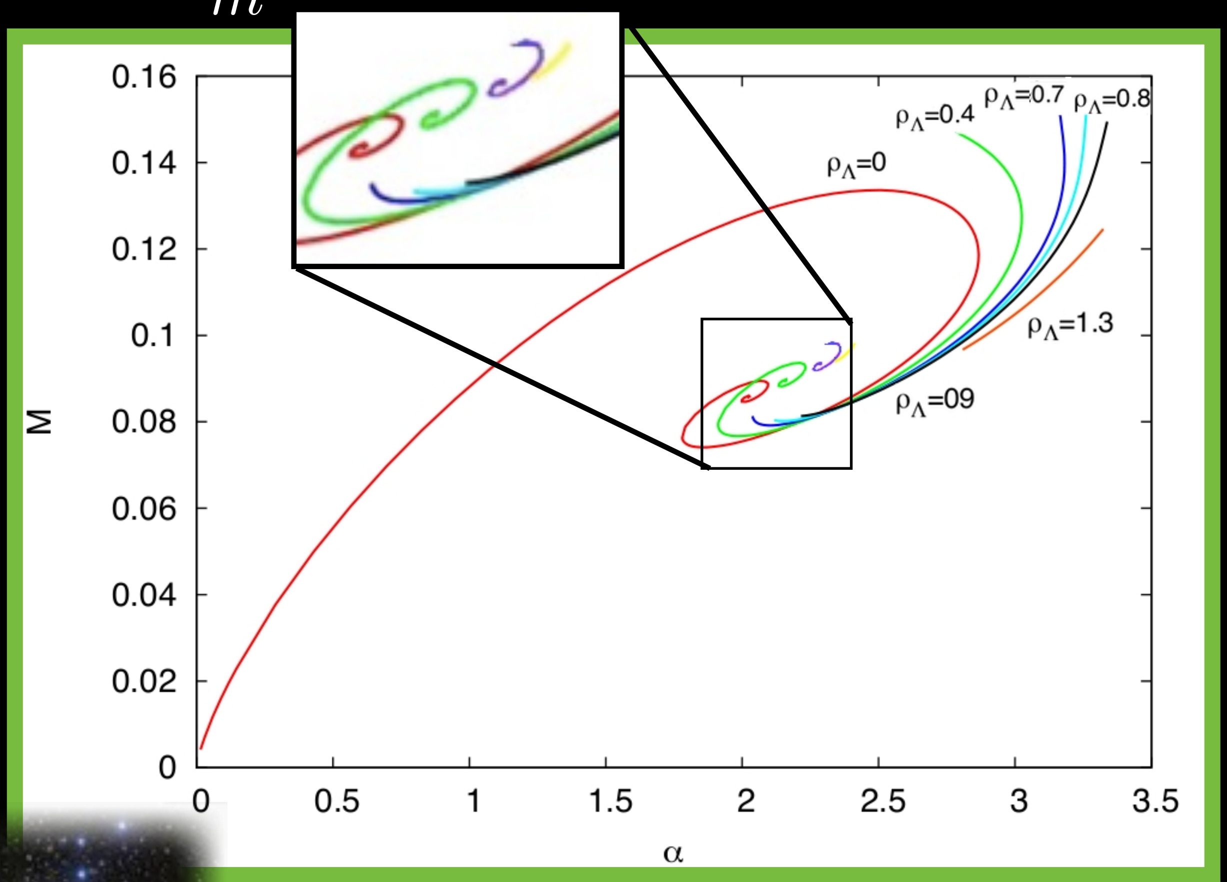
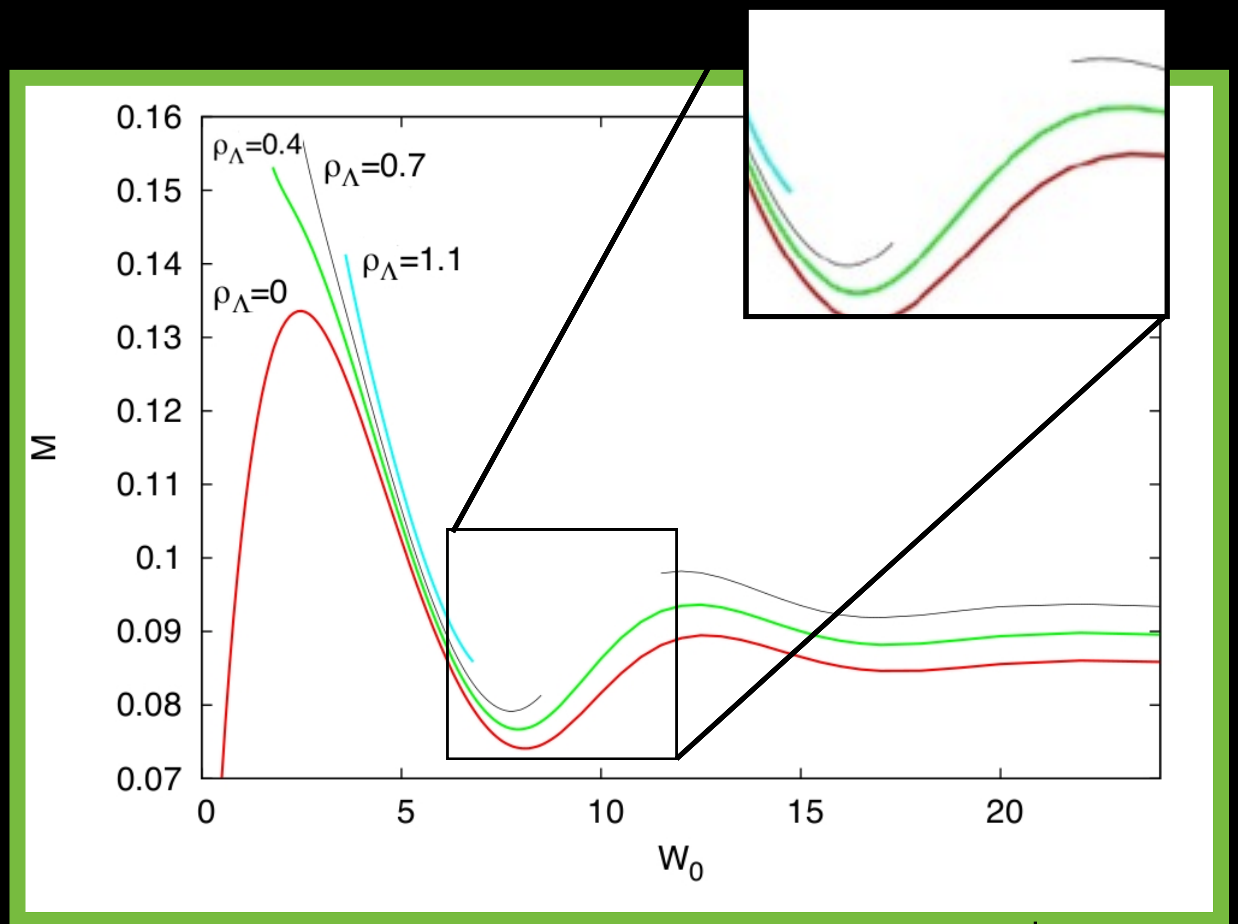
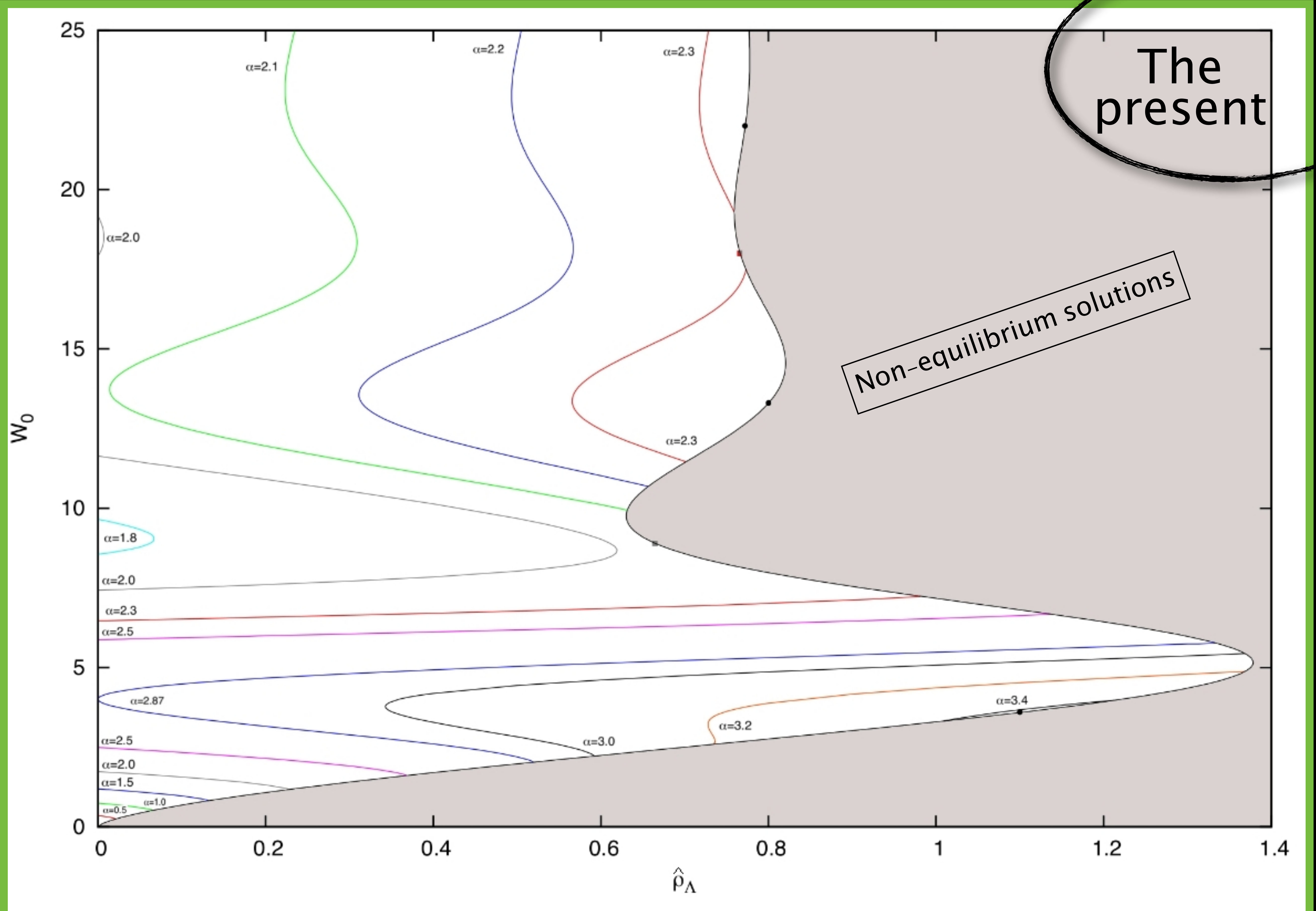


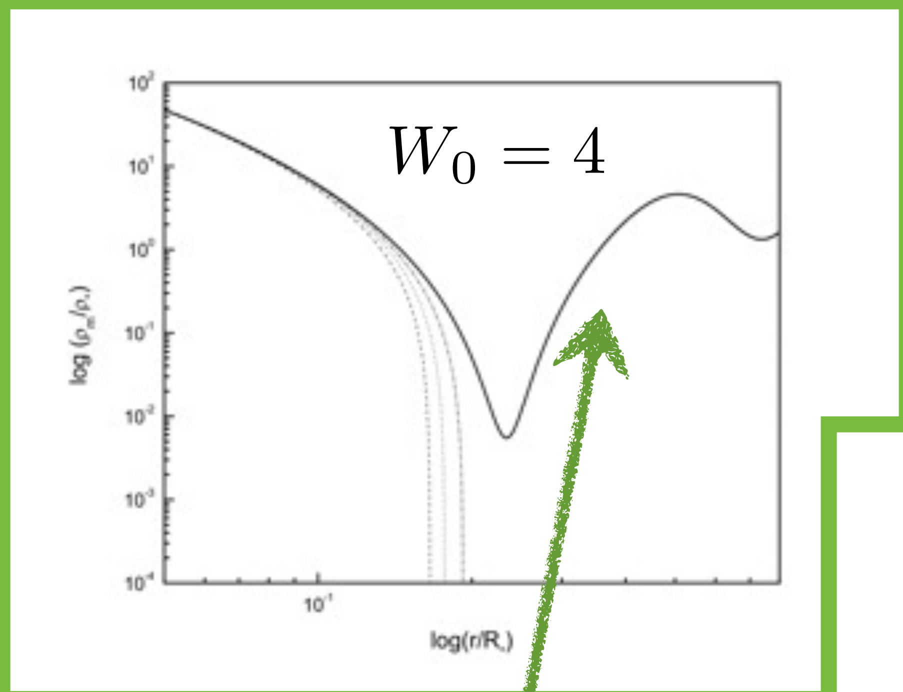


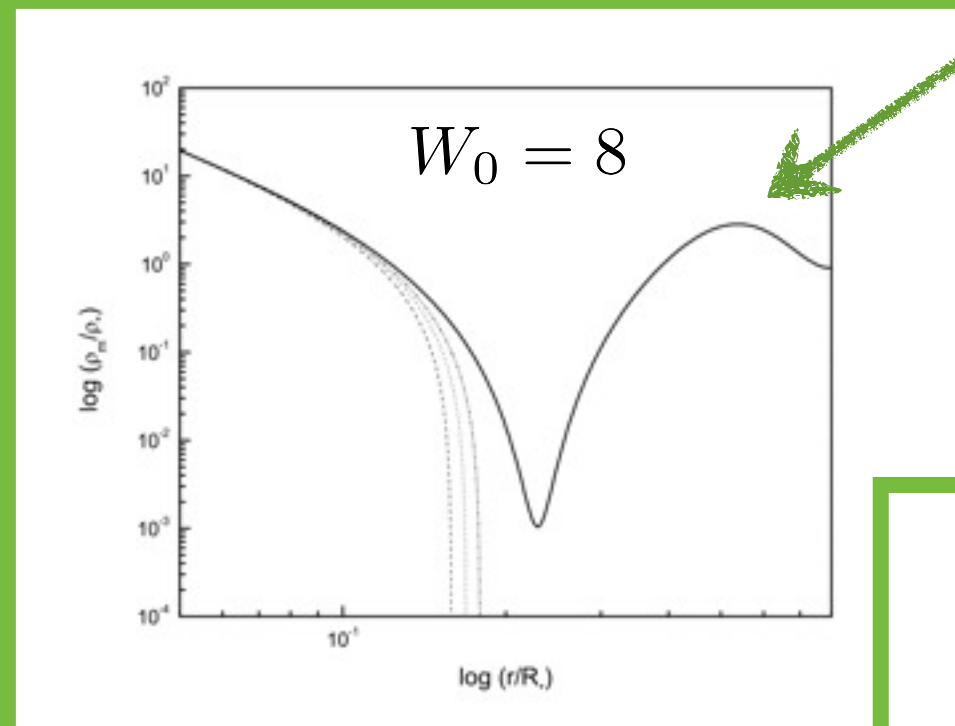


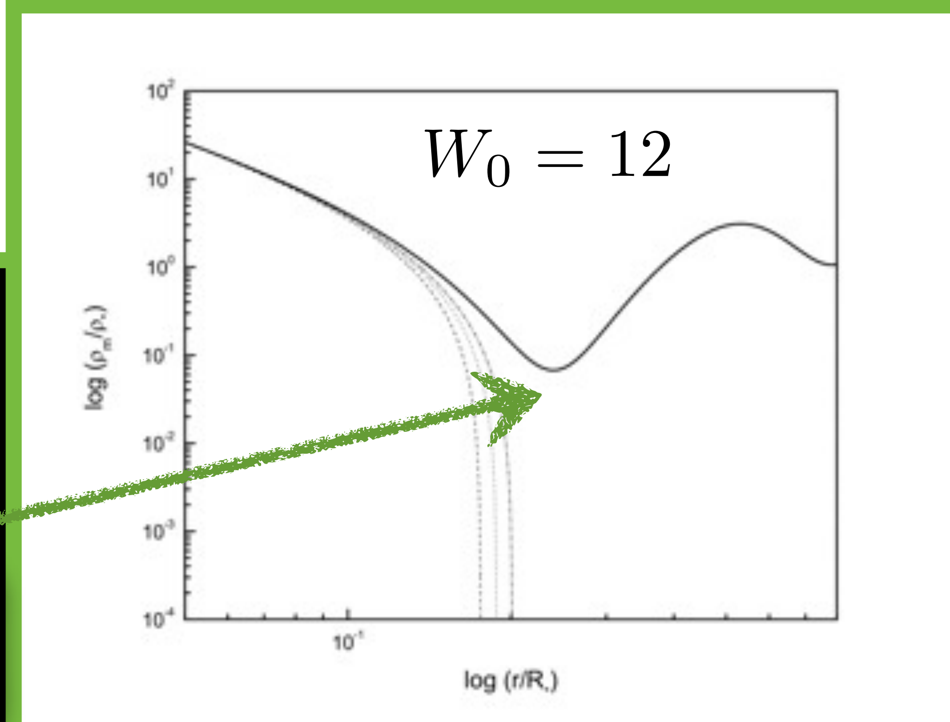
The present
Non-equilibrium solutions
α=2.1
α=2.2
α=2.3
α=2.0
α=1.8
α=2.0
α=2.3
α=2.5
α=2.87
α=2.5
α=2.0
α=1.5
α=1.0
α=0.5
α=3.0
α=3.2
α=3.4
α=2.3
W_0
$\hat{\rho}_\Lambda$

The gravitational equilibrium: density profiles

The present



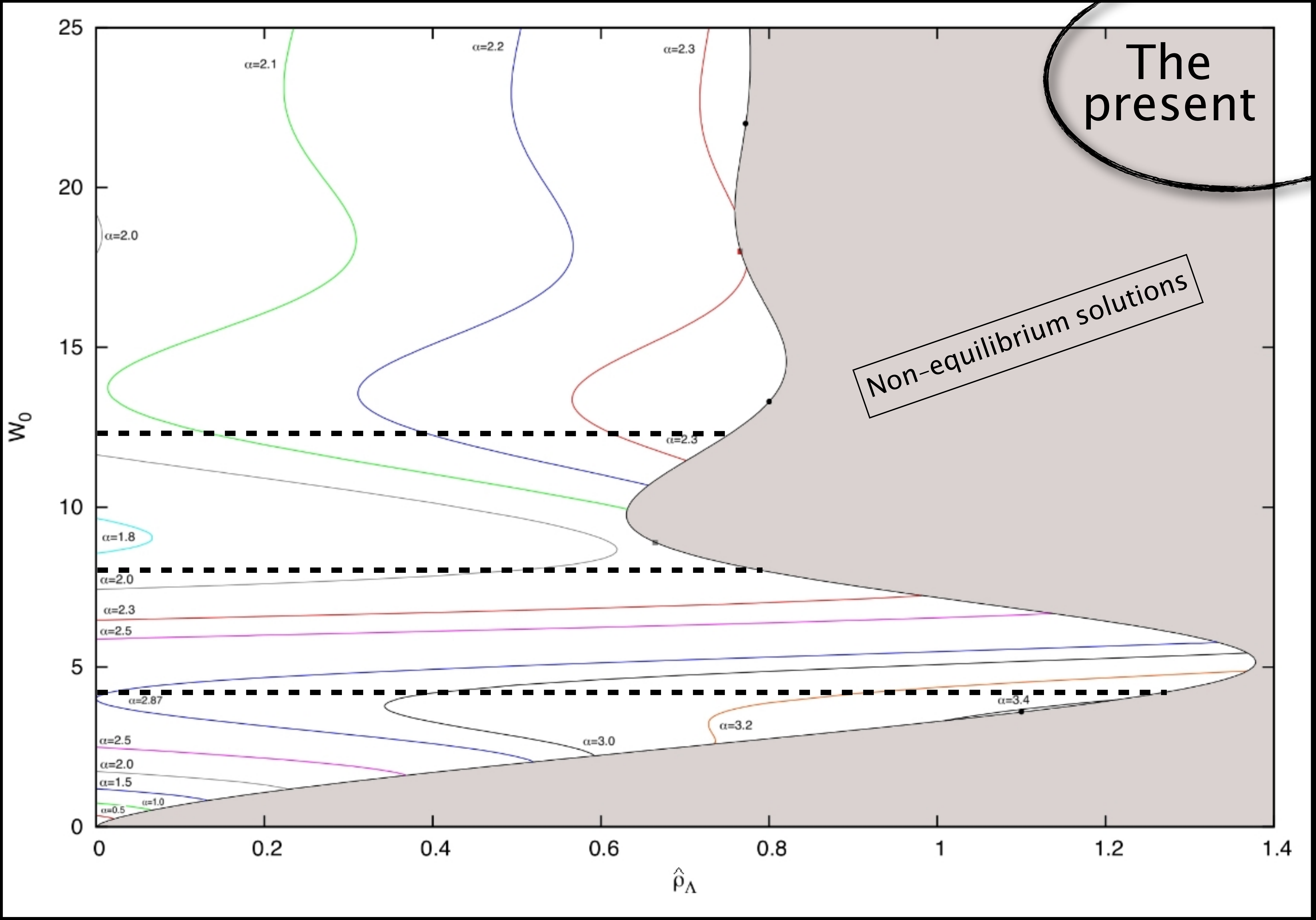




$\hat{\rho}_\Lambda \simeq 1.3$

$\hat{\rho}_\Lambda \simeq 0.8$

$\hat{\rho}_\Lambda \simeq 0.9$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α=1.5
α=1.0
α=0.5
α=3.0
α=3.2
α=3.4
α=2.3
W_0
$\hat{\rho}_\Lambda$
0
5
10
15
20
25
0
0.2
0.4
0.6
0.8
1
1.2
1.4

The Zero Gravity Radius

The present

of $\simeq 10-30$ Mpc from the cluster center. On both scales of 1 and 10 Mpc, the key physical parameter of the system is its "zero-gravity radius" which is the distance (from the system center) where the matter gravity and the dark energy antigravity balance each other exactly. The gravitationally bound system can exist only within the sphere of this radius; outside the sphere the flow dynamics is controlled mostly by the dark energy antigravity. [1]

$$F_{G\Lambda} = F_G + F_\Lambda = -\frac{GM}{r^2} + \frac{8\pi\rho_\Lambda}{3} r$$

- If the Dark Energy and the gravity balance each other $F_{G\Lambda} = 0$ →

$$r = R_\Lambda = \left(\frac{3M}{8\pi\rho_\Lambda}\right)^{1/3}$$

- The gravity dominates at distances $r \leq R_\Lambda$
- The antigravity (DE) is stronger than the gravity at $r > R_\Lambda$ →

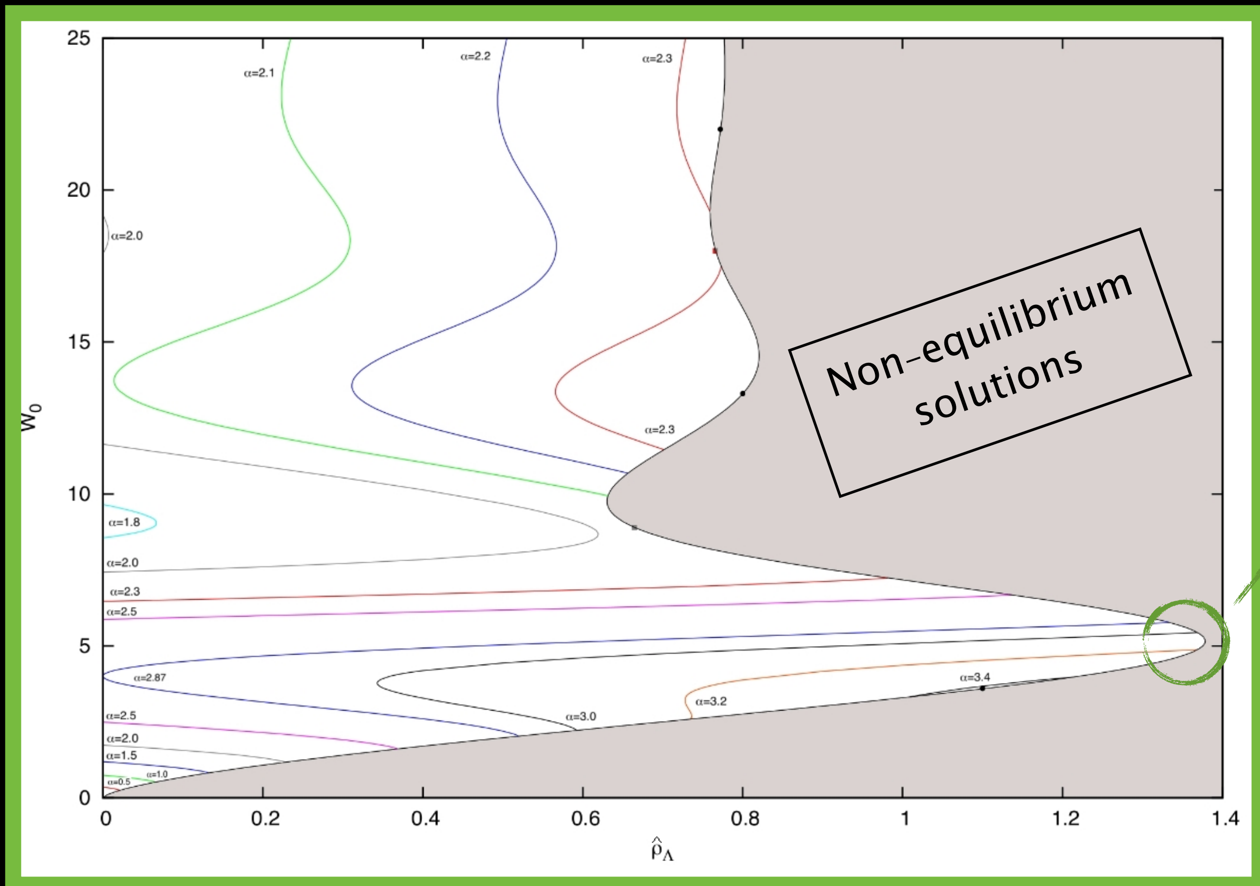
Galaxy clusters are known as the largest gravitationally bound systems, thus, ZGR is in absolute upper limit for the radial size R of a STATIC cluster

$$R < R_\Lambda$$

(1) Bisnovatyi-Kogan & Chernin- Astrp-Ph.CO, 2012

The Zero Gravity Radius

The present

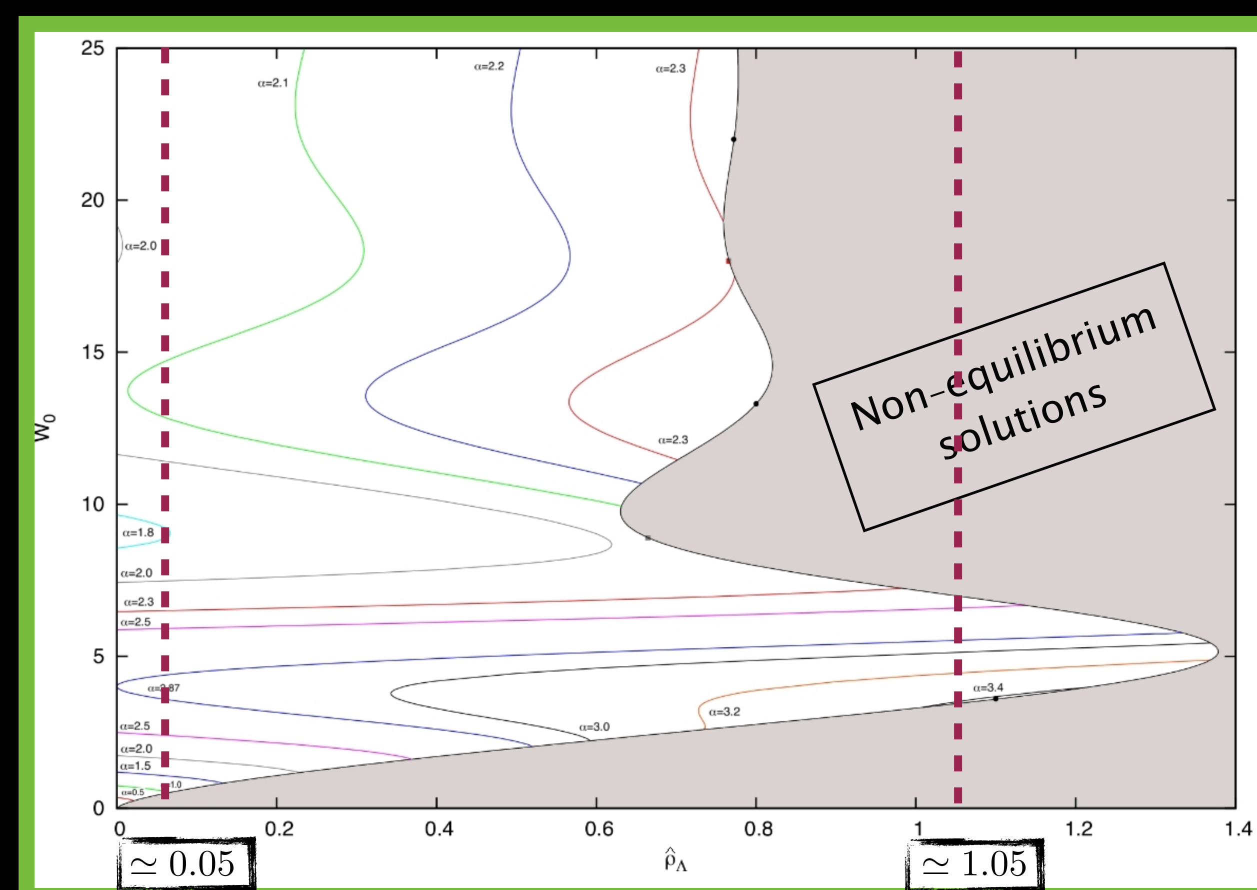


$$\rho_\Lambda \leq 0.48 \times 10^{-28} \left[\frac{\sigma}{1000\ km/s}\right]^2 \left[\frac{R}{1\ Mpc}\right]^{-2} \quad g/cm^3$$

$$R_{scale} = 15\ Mpc$$

$$R_{clust} = (1 - 18)\ Mpc$$

$$\sigma_{clust} = (300 - 1200)\ km/s$$



The Zero Gravity Radius: Virgo cluster

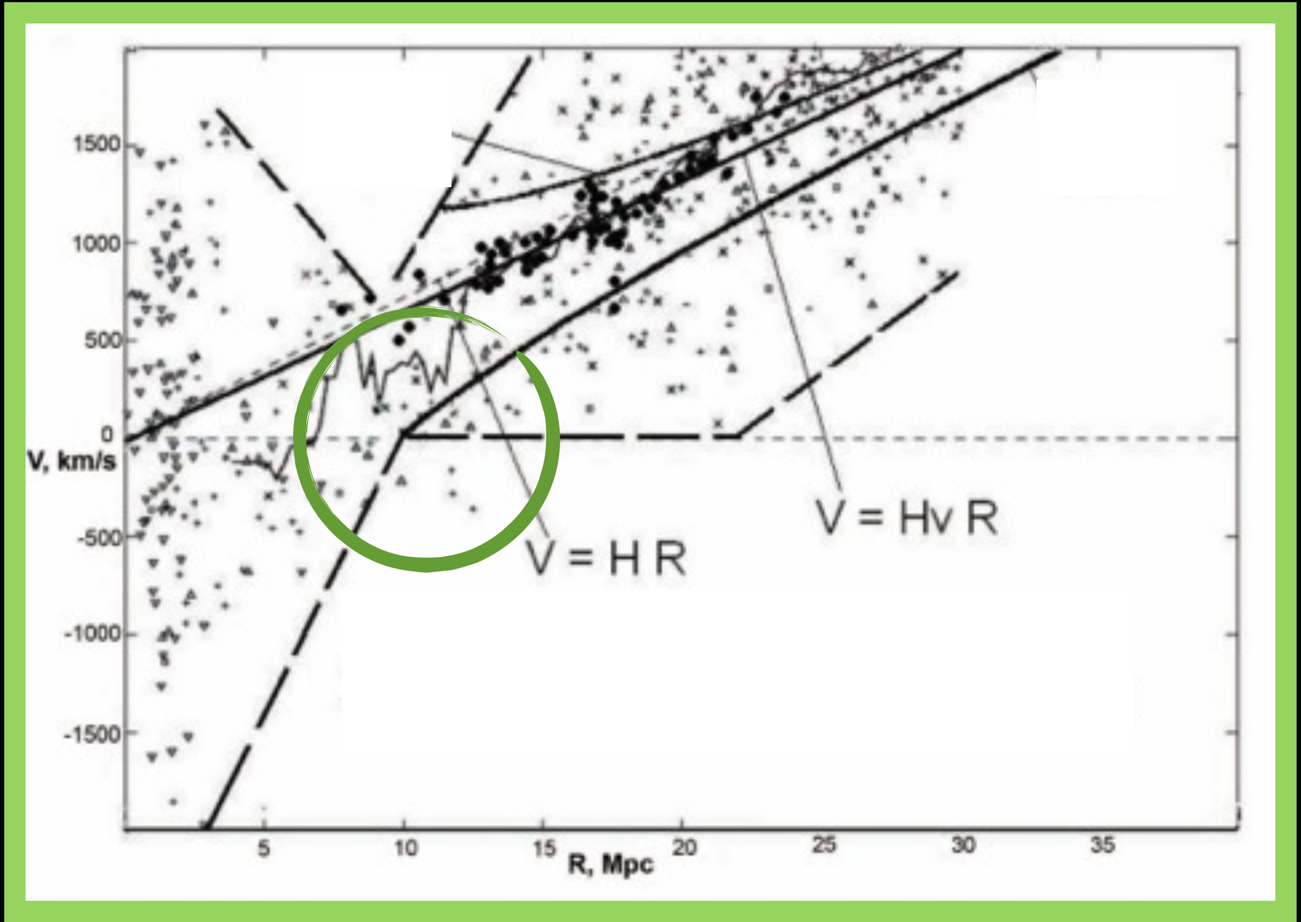
The present

$$M_{VC} = (2.7 \div 8.9) \times 10^{14}\, M_\odot \; ^{(1)}$$

$$M_{VC} = 1.2 \times 10^{15} M_\odot \; ^{(2)}$$

$$M_{VC} = (0.6 \div 1.2) \times 10^{15}\; M_\odot$$

$$\rho_\Lambda = 0.7 \times 10^{-29} g/cm^3 \; ^{(4)}$$



(4)

$$r = R_\Lambda = \left(\frac{3M}{8\pi\rho_\Lambda}\right)^{(1/3)}$$

$$R_{\Lambda Virgo} = (9 \div 11)\; Mpc$$

(1) Karachentsev & Nasonova 2010, MNRAS 405, 1075

(2) Tully & Mohayee 2004, IAU p.205

(3) Bisnovatyi-Kogan & Chernin- Astrp-Ph.CO, 2012

(4) Spergel et al., 2007, ApJ suppl., 170, 377

The Zero Gravity Radius: Coma

The present

Density profiles

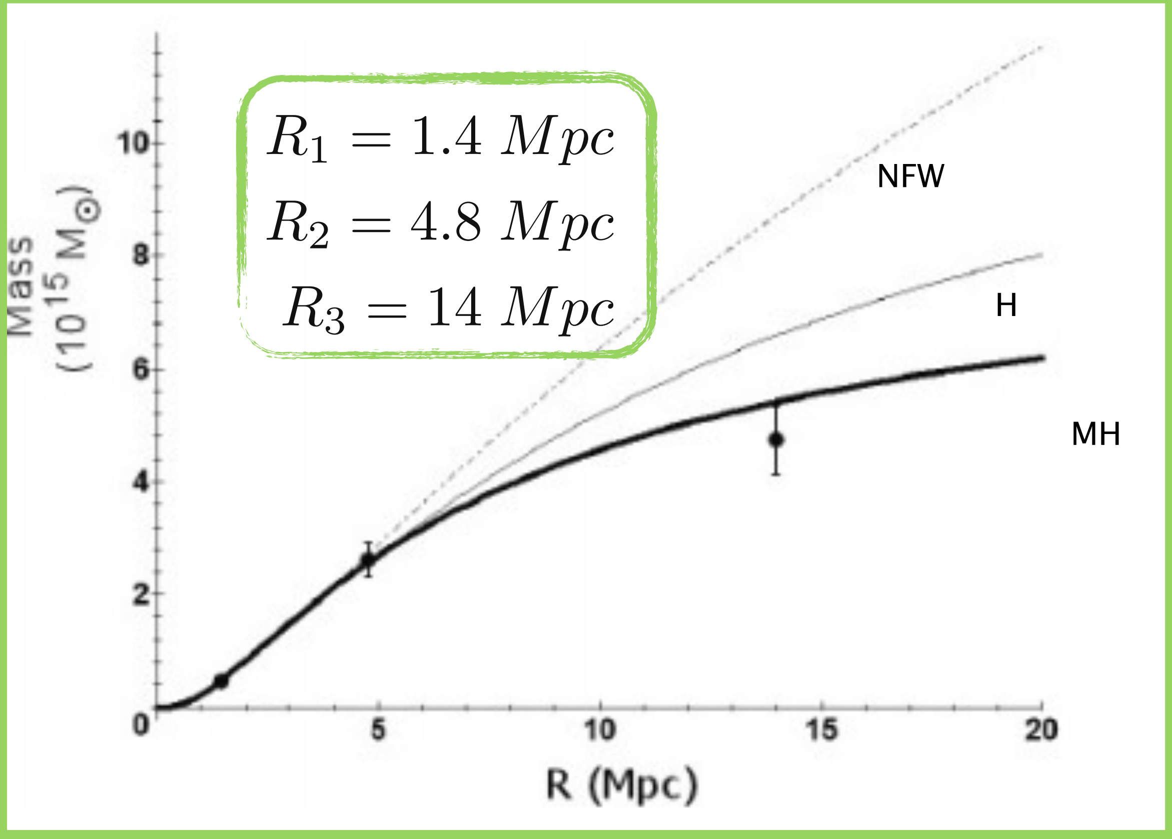
NFW [2]
$$\rho = \frac{4\rho_s}{R/R_s(1+R/R_s)}$$

Hernquist [3]
$$\rho(R) \propto \frac{1}{R(R+\alpha)^3}$$

Modified Hernquist
$$\rho = \frac{3}{4\pi} M_* R_* (R+R_*)^{-4}$$

Only for R › R_3 the dark energy anitgravity affect strongly the structure of the Coma cluster

$$M_\Lambda = -2.3 \times 10^{15} M_\odot$$
$$M_M = 4.7 \times 10^{15} M_\odot$$



(1)

The available observational data and the MH mass profile give upper limits for the Coma cluster total size

$$R \leq 20\ Mpc$$
$$M_m \leq 6.2 \times 10^{15} M_\odot$$

(1) Chernin et al. 2013, A&A 553, A101
(2) Navarro, Frenk, White, 2005, ApJ, 671, 563
(3) Hernquist, 1990 ApJ, 356, 359

Conclusions

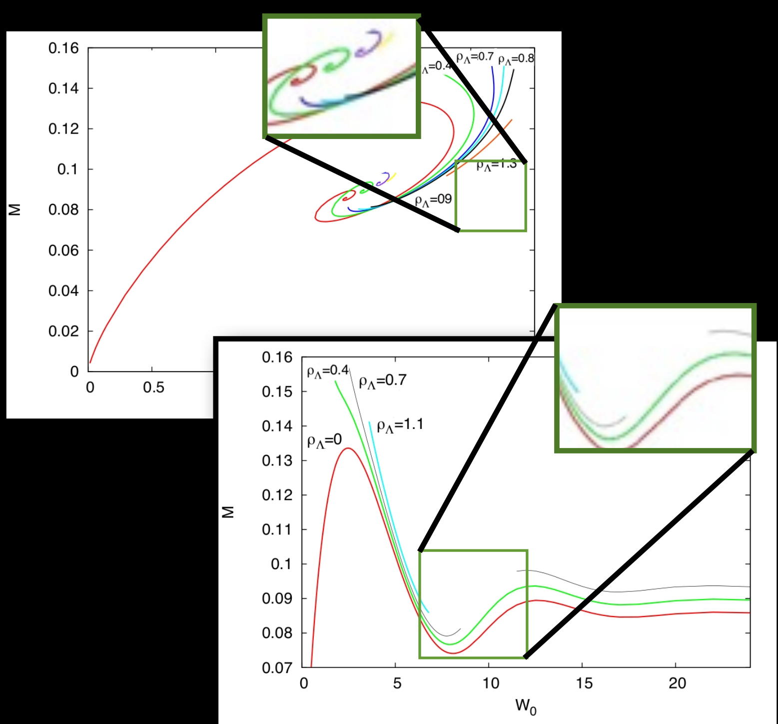
The future

Where we started?

- The ΛCDM model allows us to identify the acceleration of the Universe with the Einstein cosmological constant.
- We studied the problem from a gravitational point of view keeping the same DF and changing the equilibrium equation.

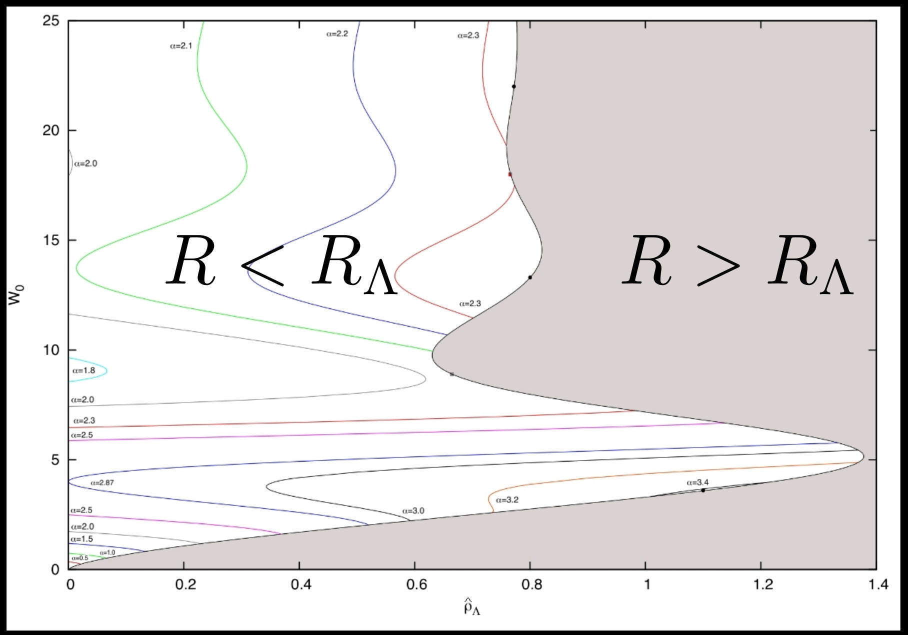
Where we arrived?

- We found peculiar density profiles, characteristic of each model.



- In $W_0 - \hat{\rho}_\Lambda$ diagram it is possible to define two regions

permitted	$F_g > F_\Lambda$
forbidden	$F_g < F_\Lambda$



- We introduced the Zero Gravity Radius

$$R_\Lambda = \left(\frac{3M}{8\pi\rho_\Lambda} \right)^{1/3}$$

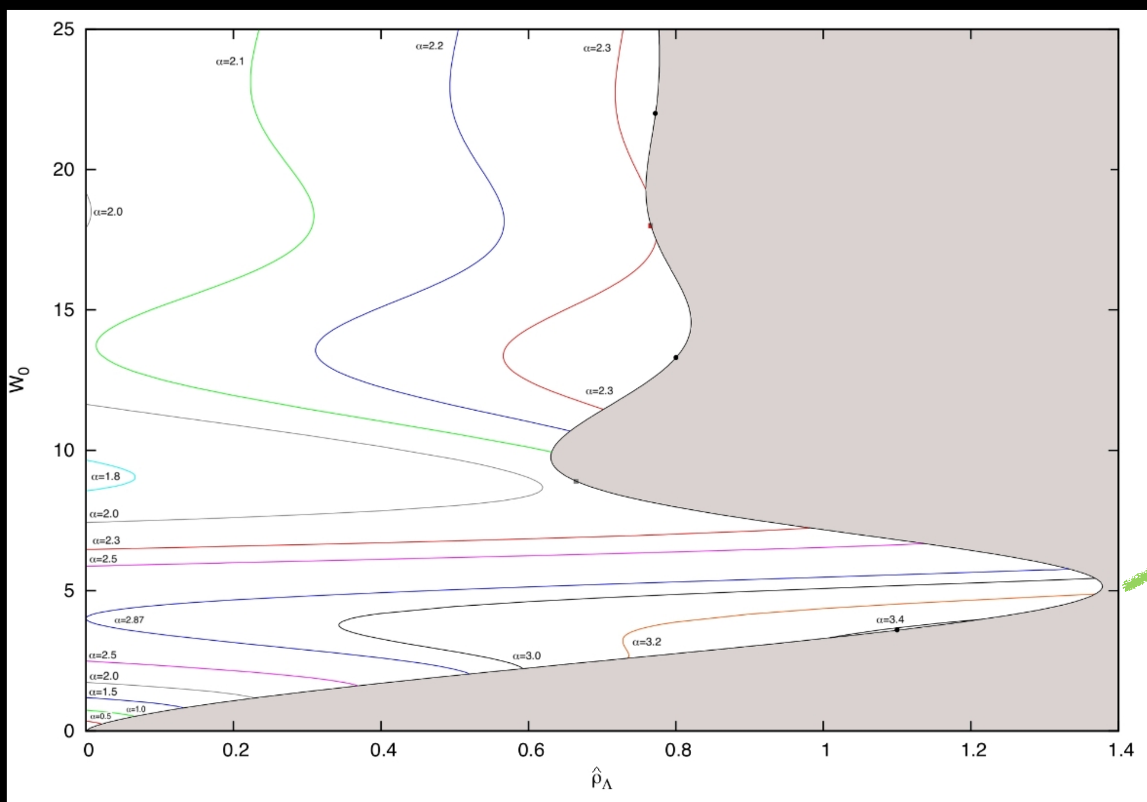
Conclusions

The future

What we said about the boundary?

- The boundary is the region in which

  This means that the radius of the configuration is equal to its zero gravity radius



$$\rho_\Lambda \leq 0.48 \times 10^{-28} \left[\frac{\sigma}{1000\ km/s}\right]^2 \left[\frac{R}{1\ Mpc}\right]^{-2} g/cm^3$$

- From observational data if we assume that Virgo cluster has $M_{VC} = (0.6 \div 1.2) \times 10^{15}\ M_\odot$ we are able to estimate its ZGR $R_{\Lambda Virgo} = (9 \div 11)\ Mpc$

$$R_{VC} \simeq R_{\Lambda VC}$$

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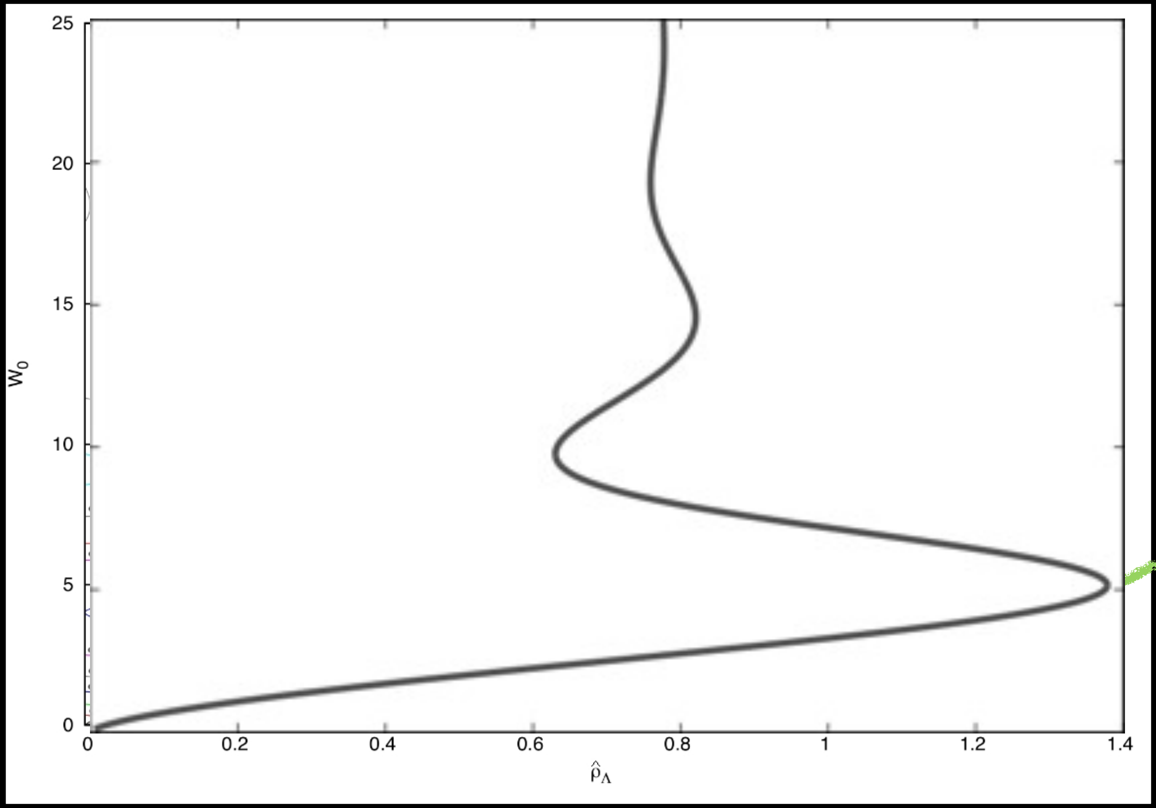

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$$R_{VC} \simeq R_{\Lambda VC}$$

Future perspectives (1/2)

The future

- Change the starting point, by using other distribution functions
- Taking into account all the components of the clusters

Gas and visible matter → Beta-model [1] $\rho(r) = \frac{\rho_0}{[1 + (r/R_c)^2]^{3\beta/2}}$

Dark Matter → NFW and Hernquist profile [2,3] $\rho(r) \propto \left[\frac{r}{a}\left(1 + \frac{r}{a}\right)^{-\alpha}\right]$

- $\alpha = 2$ NFW
- $\alpha = 3$ Hernquist

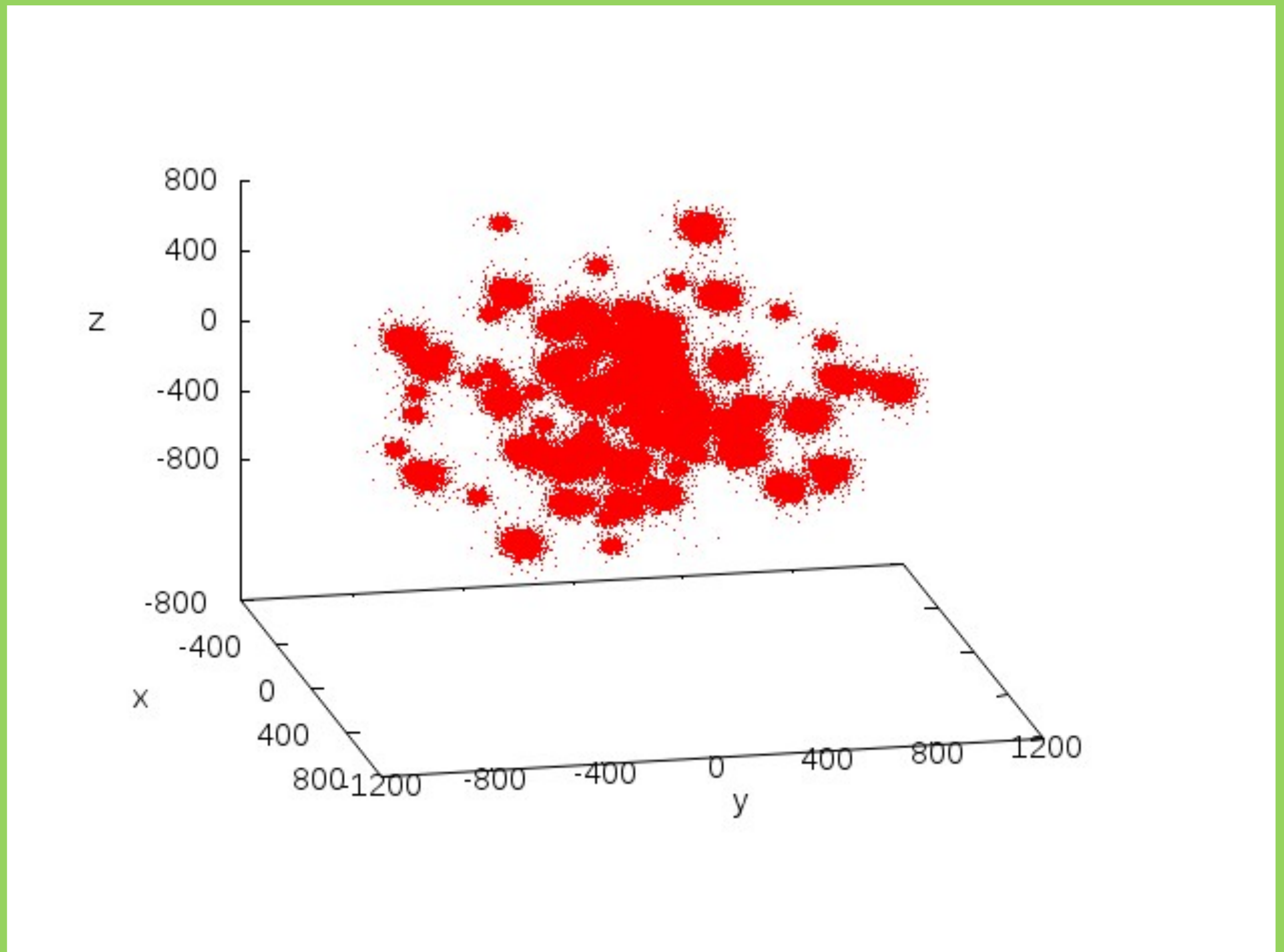
(1) Girardi et al. 1998 Apj, 505-64

(2) Navarro, Frenk, White, 2005, ApJ, 671, 563

(3) Hernquist, 1990 ApJ, 356, 359

Future perspectives (2/2)

The future

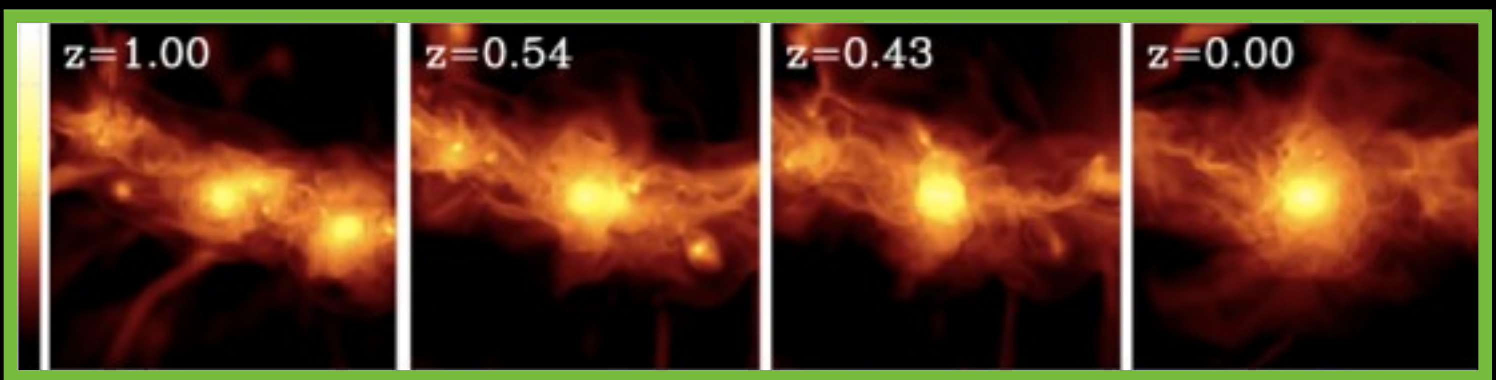


- Make N-body simulations to study the dynamic of the galaxies in cluster

↓

Obtain more physical observables in order to make a comparison with the observational data present in literature.

- Hydrodynamical studies with existing codes (es. GADGET2)



(4)

(4) Borgani & Kravtsov, 2009 arXiv: 0906.4370v1