

# Minimal Dilatonic Gravity from cosmology to compact massive objects

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С подкрепата на: "NewCompStar" COST Action MP1304, фондация ТИФА



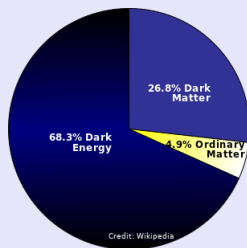
29 март 2015 г.

- 1 Защо имаме нужда от нова теория?
  - Наблюдателни тестове
  - Нерешени проблеми за компактните звезди
  - Как да разширим GR
  - Алтернативни теории на гравитацията
- 2 Минимална дилатонна гравитация
- 3 Приложение за компактни звезди
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# Тестове на общата относителност (GR)

General relativity has been tested on many scales, but mostly in weak to moderate-field regime:

- Laboratory, Earth and Solar System scale ( $v/c \ll 1$  or  $GM/c^2 R \ll 1$ ), upper bound for violations by the Cassini mission –  $10^{-5}$
- Binary pulsars: PSR B1913+16, PSR J0737-3039, PSR J0348+0432 – 0.05%
- Galaxies and galaxies cluster: Sloan Digital Sky Survey III Baryon Oscillations Spectroscopic Survey – 6%



The real probes for the strong field regime ( $v/c > 0.1$  or  $GM/c^2 R \sim 1$ ) are:

- Final stages of binary coalescence of compact objects (WD, NS, BH)
- Cosmological tests of the (early) Universe

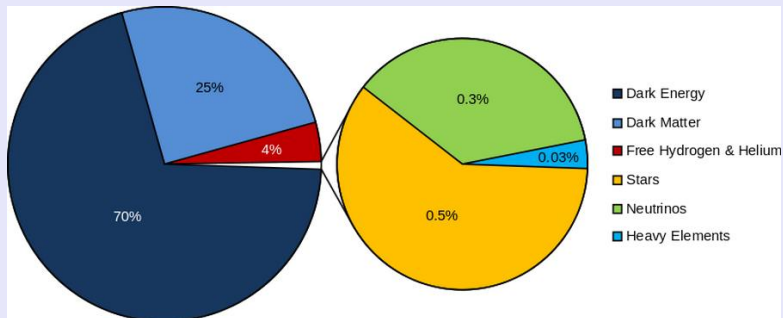
Known problems: Classical theory (not renormalizable), Singularities, Cosmological constant problem, Vacuum fluctuations, Dark Energy, Dark Matter, The initial inflation and initial singularity problem etc.

## Dark Matter

- Orbits of stars in galaxies.
- Motions of galaxies in galaxy clusters.
- Hot gas in galaxy clusters.
- Gravitational lensing

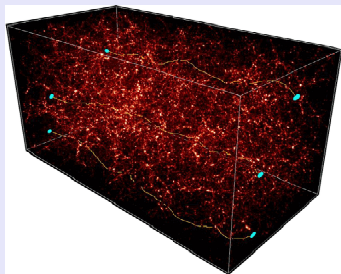
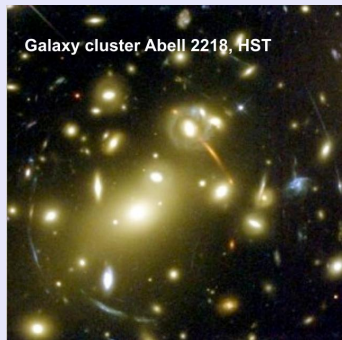
## Dark Energy

- Type Ia SNe
- CMB
- large structures/baryonic oscillations



# Малко повече за тъмната енергия:

- Dark matter candidates:
  - MACHOS (Massive Compact Halo Objects)
  - WIMPS (weakly interacting massive particles).
- An ongoing quest:
  - The Dark Energy Survey (operational),
  - Sloan Digital Sky Survey III (operational, 35% of the sky, with photometric observations of around 500 million objects and spectra for more than 1 million objects),
  - The Euclid Mission (2020, L2 space telescope)
  - HETDEX (2014), DESI (2018), BOSS(operational) etc.

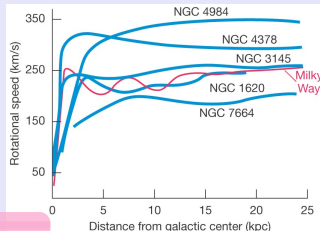
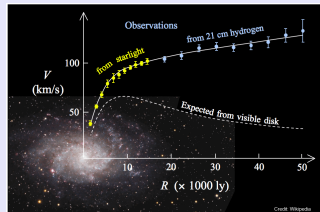


# Как виждаме тъмната материя?

How to do we find the mass? With Kepler's third law:  $M_{encl} = \frac{v \times r^2}{G}$

The rotation curves (for disc galaxies [Corbelli & Salucci (2000)])

- A rotation curve: plot of orbital velocities versus radial distance from galaxy's centre
- Orbital motion traced with:
  - HI emission line (spiral galaxies)
  - broadening of stellar spectral lines (elliptic galaxies)
  - Doppler shift of the galaxies (galactic clusters)
  - Temperature of hot X-ray emitting gas
  - Gravitational lensing (galactic clusters)

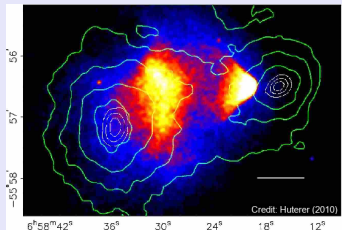
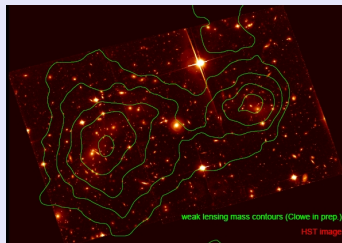


Total mass of galaxies is 10x the visible mass!!!  
Total mass of galactic clusters is 50x the visible mass!!!

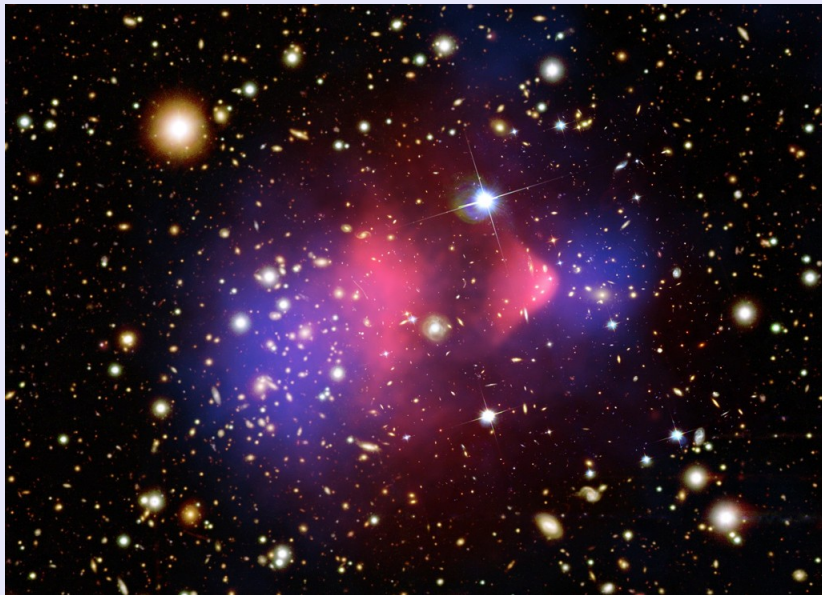
## Model-independent measurements:

- Mass distribution of a galaxy cluster: 2% galaxies, 10 % intergalactic plasma and 88% dark matter
- Weak gravitational lensing results [Clowe et al. (2006), Huterer (2010)]
- “In the absence of dark matter, the gravitational potential will trace the dominant visible matter component, which is the X-ray plasma.

If, on the other hand, the mass is indeed dominated by collisionless dark matter, the potential will trace the distribution of that component, which is expected to be spatially coincident with the collisionless galaxies” (Clowe et al. 2006).

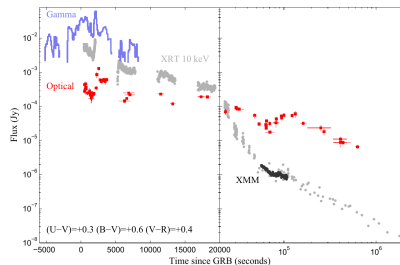
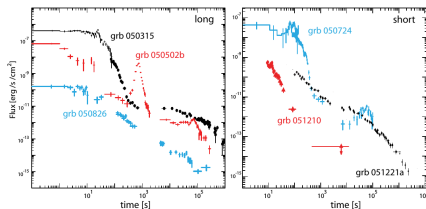


# The Bullet Cluster





# Мистерията на гама избухванията

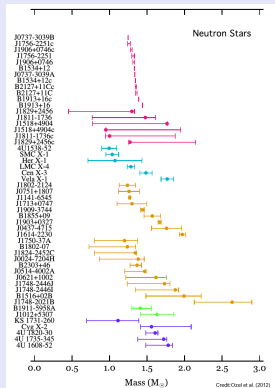


- 1 Energy  $\sim 10^{53}$  erg, two types – Short and Long
- 2 Different variability time-scales – ms, sec, hundreds of seconds
- 3 X-ray plateaus – continued injection of energy ( $\sim 100$ s)
- 4 X-ray flares – multiple rebrightening, happening at up to  $10^5$  s
- 5 Ultralong GRBs (GRB 091024A, GRB 111209A ) – GRBs with  $\gamma$ -emission lasting more than 1000s (APJ, 778:54, 2013, ApJ 766:30, 2013)
- 6 Extended high energy emission (GeV scale, example GRB130427A)
- 7 All those properties call for a long-lasting, extremely powerful central engine
- 8 Figure credit: Gehrels et. al (2009), Gendre et al. (2012), ApJ 766, 30, 2013 (GRB

# Компактните звезди в GR:

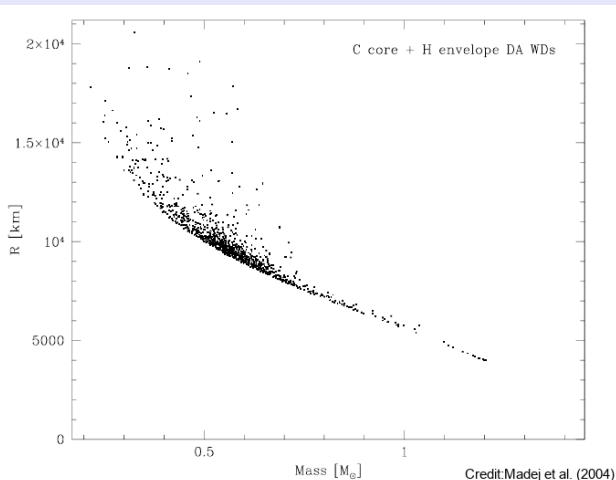
White dwarfs (WD) and neutron stars (NS) – significant observational data and modelling efforts, but still inconsistencies:

- The ultra-massive white dwarfs: SNLS-03D3bb (Nature 443 (2006) 308) and SN2007if (ApJ 713 (2010)), type Ia SN with progenitor exceeding the  $M_{Ch} = 1.4M_{\odot}$  (up to  $2.4-2.8M_{\odot}$ )
- Stiff  $M(R)$  dependence for neutron stars or a dispersion in the observed masses?
- The question of the maximal NS mass and its relation to stellar black holes and astrophysical jets
- The Gamma-Ray Bursts mystery: huge energies, short characteristic time-scales, long life of the central engine



There are numerous approaches towards solving these problems – better MHD modeling, stronger and more complicated magnetic fields, better and richer equation of states etc.

# White Dwarfs $M(R)$ “curve”



**Fig. 2.** Mass – radius relation for 1175 hot white dwarfs of the same sample. The relation does not extend to masses  $M$  higher than  $1.2 M_{\odot}$ , or rather to the highest surface gravities  $\log g > 9.0$ .

# Как да разширим GR

## Requirements:

- reproduce the Minkowski spacetime in the absence of matter and cosmological constants,
- be constructed from only the Riemann curvature tensor and the metric,
- follow the symmetries and conservation laws of the stress-energy tensor of matter,
- reproduce Poisson's equation in the Newtonian limit.

Starting from the Einstein-Hilbert action, one can:

- increase the spacetime dimensions
- change the functional dependence of the Lagrangian density on the Ricci scalar  $R$
- include other scalars generated from the Riemann curvature in the Lagrangian density,
- include additional scalar, vector, or tensor fields.

# Алтернативни теории на гравитацията

Some of the more popular alternatives of GR ( $A_E = \int \frac{1}{2\kappa} R \sqrt{-g} d^4x$ ) :

- **Gaus Bonnet theory** – includes a term of the form:

$G = R^2 - 4R^{\mu\nu} R_{\mu\nu} + R^{\mu\nu\rho\sigma} R_{\mu\nu\rho\sigma}$  in the action  $A = \int d^Dx \sqrt{-g} G$ . ( no additional dynamical degrees of freedom)

- **Lovelock theory** – a natural generalization of GR to  $D > 4$ .

$$\mathcal{L} = \sqrt{-g} (\alpha_0 + \alpha_1 R + \alpha_2 (R^2 + R_{\alpha\beta\mu\nu} R^{\alpha\beta\mu\nu} - 4R_{\mu\nu} R^{\mu\nu}) + \alpha_3 \mathcal{O}(R^3))$$

- **$f(R)$  theories** – a family of theories in which the arbitrary function  $f(R)$  may lead to the accelerated expansion and structure formation of the Universe /dark energy or dark matter alternative/.  $A = \int \frac{1}{2\kappa} f(R) \sqrt{-g} d^4x$

- **Brans-Dicke scalar-tensor theory** – the gravitational interaction is mediated by a scalar field ( $\phi = 1/G$ ) – i .e. a varying  $G$ , as well as the tensor field of general relativity. Contain a tunable, dimensionless Brans-Dicke coupling constant  $\omega$ .

$$A = \int d^4x \sqrt{-g} \left( \frac{\phi R - \omega \frac{\partial_\alpha \phi \partial^\alpha \phi}{\phi}}{16\pi} + \mathcal{L}_M \right)$$

- **Chameleon scalar-tensor theory** – Introduces a scalar particle (the chameleon) which couples to matter, with a variable effective mass, an increasing function of the ambient energy density  $m_{eff} \sim \rho^\alpha$ , where  $\alpha \simeq 1$ . ( $m_{eff} \sim mm - pc$ ).

# Минимална Дилатонна Гравитация (MDG)

The action, following Fiziev, PRD **87**, 044053 (2013)

$$A_{g,\phi} = \frac{c}{2\kappa} \int d^4x \sqrt{|g|} (\Phi R - 2\Lambda U(\Phi))$$

Here,  $\Phi \in (0, \infty)$  is the new scalar field called “dilaton”,  $\Lambda > 0$  is the cosmological constant and  $\kappa = 8\pi G_N/c^2$  is the Einstein constant.

## Effects

Clearly, the introduction of the scalar **dilaton**  $\Phi$  leads to varying gravitational constant  $G(\Phi) = G_N/\Phi$ , while the introduction of the cosmological potential  $U(\Phi)$  leads to a variable cosmological factor instead of a constant  $\Lambda$ .

Note: In order to keep gravity as existing and attractive force  $\Phi > 0$ .

## The action

$$A_{g,\phi} = \frac{c}{2\kappa} \int d^4x \sqrt{|g|} (\Phi R - 2\Lambda U(\Phi))$$

This action corresponds to the Brans-Dicke theory with  $\omega = 0$ .  
GR is recovered for  $\Phi = 1$ ,  $U(1) = 1$ .

Some of the properties of the MDG model already demonstrated:

- 1 The inflation and the graceful exit to the present day accelerating de Sitter expansion of the Universe ( $U(\Phi)$  can be reconstructed from  $a(t)$ ).
- 2 Avoids any conflicts with the existing solar system and laboratory gravitational experiments when  $m_\phi \sim 10^{-3} \text{ eV}/c^2$ .
- 3 The time of inflation as a reciprocal quantity to the mass of dilaton  $m_\phi$ .

Field equations obtained by variations with respect to scalar field  $\Phi$  and the metric  $g_{\alpha\beta}$  (trace and traceless part).

## Крайният вид на полевите уравнения:

If we include the standard action of the matter fields  $\Psi$ , based on the minimal interaction with gravity:

$$A_{\text{matt}} = \frac{1}{c} \int d^4x \sqrt{|g|} L_{\text{matt}}(\Psi, \nabla\Psi; g_{\alpha\beta}) \quad (1)$$

we get the final form of the field equations in cosmological units  $\Lambda = 1, \kappa = 1, c = 1$ :

$$\begin{aligned} R &= 2\Lambda U_{,\Phi}(\Phi) \\ \square\Phi + 2/3(\Phi U_{,\Phi}(\Phi) - 2U(\Phi)) &= \frac{1}{3}T \\ \Phi \widehat{R}_{\alpha}^{\beta} &= -\widehat{\nabla}_{\alpha}\nabla^{\beta}\Phi - \widehat{T}_{\alpha}^{\beta} \end{aligned} \quad (2)$$

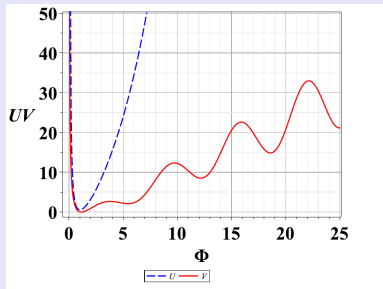
Note: The dilaton  $\Phi$  does not interact directly with the matter and thus it is a good candidate for the dark matter. Its interaction with the usual matter goes only through the gravitational interaction.



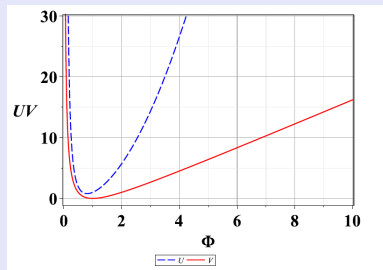
- 1 MDG and  $f(R)$  theories are related by the Legendre transform (i.e. there is a dictionary between the two models).
- 2 The witholding property: In order to guarantee that  $\Phi \in (0, \infty)$ , we require that  $V(0) = V(\infty) = +\infty$ , i.e. infinite potential barriers at the end of the interval.
- 3 From  $U(\Phi) = \frac{3}{2}\Phi^2 \int_1^\Phi \Phi^{-3} V_{,\Phi} d\Phi + \Phi^2$  (from  $U(1) = 1$ ), if we assume that  $V(\Phi) \sim v\Phi^n$ , it follows that  $U(0) = U(\infty) = +\infty$ .
- 4 Additional requirement:  $U(\Phi) > 0$ , for  $\Phi \in (0, \infty)$  (the cosmological term needs to have a definite positive sign).
- 5 From the convex condition  $U_{,\Phi\Phi} > 0$ , for  $\Phi \in (0, \infty)$  (ensures the uniqueness of the Einstein vacuum).
- 6 The uniqueness of the deSitter vacuum is not guaranteed:

$$V_{,\Phi\Phi} = \frac{2}{3}(\Phi U_{,\Phi\Phi} - U_{,\Phi}), \quad V_{,\Phi\Phi\Phi} = \frac{2}{3}\Phi U_{,\Phi\Phi\Phi}$$

Thus we can have  $V(\Phi)$  with several minima in the domain.



(d) Unique Einstein Vacuum and many deSitter vacuums:  $U_{,\Phi\Phi} > 0$



(e) Unique Einstein Vacuum and unique deSitter vacuums:  $U_{,\Phi\Phi} > 0, V_{,\Phi\Phi} > 0$

## Пример за МДГ с единствен dSV

If we postulate a unique deSitter vacuum, then the function  $V(\Phi)$  will be convex for  $\Phi \in (0, \infty)$  and the function  $\frac{2}{3}(\Phi U_{,\Phi\Phi} - U_{,\Phi}) > 0$  is strictly positive.

A simple example of such pair of withholding potentials is:

$$V(\Phi) = \frac{1}{2}p^{-2}(\Phi + 1/\Phi - 2) \quad (3)$$

$$U(\Phi) = \Phi^2 + \frac{3}{16}p^{-2}(\Phi - 1/\Phi)^2 \quad (4)$$

where  $p$  is a small parameter related with the dilaton mass.

We are going to use these withholding potentials in our study of compact stars.

Some of the works where details on the MDG model have been worked out.

## A theory in development

Fiziev, arXiv:1402.2813 [gr-qc], "Frontiers of Fundamental Physics 14 Marseille, France, July, 15-18, 2014, PoS(FFP14)080

P.P. Fiziev, Physical Review D 87, 044053 (2013)

P. Fiziev, Georgieva D., Phys. Rev. D 67 064016 (2003).

Plamen P. Fiziev, arXiv:gr-qc/0202074

Fiziev P. P., Yazadjiev S., Boyadjiev T., Todorov M., Phys. Rev. D 61 124018 (2000).

P. P. Fiziev, Mod. Phys. Lett. A, 15 1077 (2000)

The pioneering work on the MDG model is by O'Hanlon, Phys. Rev. Lett. 29 137 (1972).

We follow the first application to the case of neutron stars published in [Fiziev (2013)]:

Let us consider a static, spherically symmetric metric of the type:

$$ds^2 = e^{\nu(r)} dt^2 - e^{\lambda(r)} dr^2 - r^2 d\Omega^2, \quad (5)$$

where  $r$  is the luminosity distance to the center of symmetry, and  $d\Omega^2$  describes the space-interval on the unit sphere.

The equations are the MDG field equations:

$$\begin{aligned} \square\Phi + 2/3(\Phi U_{,\Phi}(\Phi) - 2U(\Phi)) &= \frac{1}{3}T \\ \Phi \hat{R}_\alpha^\beta &= -\widehat{\nabla_\alpha \nabla^\beta \Phi} - \hat{T}_\alpha^\beta \end{aligned} \quad (6)$$

Then, if we assume the perfect fluid stress-energy tensor  $T^{\mu\nu} = \text{diag}(\epsilon, p, p, p) / c = 1/$  we obtain:

# Уравненията

1. For the inner domain  $r \in [0, r_*]$ :

$$\frac{dm}{dr} = 4\pi r^2 \epsilon_{eff} / \Phi \quad (7)$$

$$\frac{dp}{dr} = -\frac{p + \epsilon}{r} \frac{m + 4\pi r^3 p_{eff} / \Phi}{\Delta - 2\pi r^3 p_\Phi / \Phi} \quad (8)$$

$$\frac{d\Phi}{dr} = -4\pi r^2 p_{eff} / \Delta \quad (9)$$

$$\frac{dp_\Phi}{dr} = -\frac{p_\Phi}{r\Delta} \left( 3r - 7m - \frac{2}{3}\Lambda r^3 + 4\pi r^3 \epsilon_{eff} / \Phi \right) - \frac{2}{r} \epsilon_\Phi \quad (10)$$

Additionally, we have:

$$\epsilon_\Lambda = -p_\Lambda - \frac{\Lambda}{12\pi} \Phi,$$

$$\epsilon_\Phi = p - \frac{1}{3}\epsilon + \frac{\Lambda}{8\pi} V'(\Phi) + \frac{p_\Phi}{2} \Pi$$

$$\epsilon = \epsilon(p)$$

where

$$\Delta = r - 2m - \frac{1}{3}\Lambda r^3, \epsilon_{eff} = \epsilon + \epsilon_\Phi + \epsilon_\Lambda, p_{eff} = p + p_\Phi + p_\Lambda, \Pi = \frac{m + 4\pi r^3 p_{eff} / \Phi}{\Delta - 2\pi r^3 p_\Phi / \Phi}$$

and

$$\epsilon_\Lambda = \frac{\Lambda}{8\pi} (U(\Phi) - \Phi), p_\Lambda = \frac{\Lambda}{8\pi} (U(\Phi) - \frac{1}{3}\Phi)$$

...

The 4 unknown functions are  $m(r), p(r), \Phi(r), p_\Phi(r)$ .

## Начални и гранични условия:

$$m(0) = m_c = 0, \Phi(0) = \Phi_c, p(0) = p_c$$
$$p_\Phi(0) = p_{\Phi c} = \frac{2}{3} \left( \frac{\epsilon(p)}{3} - p_c \right) - \frac{\Lambda}{12\pi} V'(\Phi_c)$$

On the star's edge ( $p(r^*) = 0$ ) we have

$$m^* = m(r^*; p_c, \Phi_c), \Phi^* = \Phi(r^*, p_c, \Phi_c), p_\Phi^* = p_{\Phi c}(r^*, p_c, \Phi_c)$$

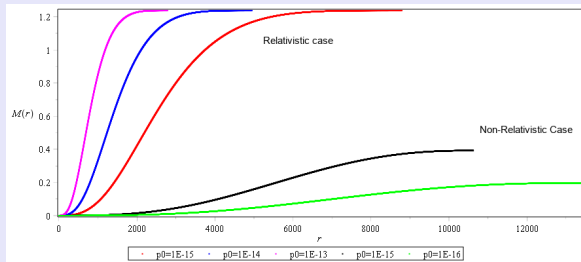
2. For the outer domain: a boundary value problem for  $\Phi$ :

$$p = 0, \epsilon = 0, \Phi_\Delta = 1$$

After introducing the EOS, we solve the ODE system + the initial and boundary conditions for the unknown functions  $m(r), p(r), \Phi(r), p_\Phi(r)$ .

# TOV уравнения за бели джуджета

In the case of GR, the white dwarfs are described well even in the polytropic approximation:



Here the integration has been performed using Maple.  $M(r)$  is in  $M_{\odot}$ ,  $r$  in [km]/

$$M_{WD} = 0.17 - 1.3M_{\odot}$$

$$R_{WD} = 0.008 - 0.02R_{\odot}$$

$$\rho_{WD} = 10^5 - 10^9 \text{ gr/cm}^3$$

Composition:

He, C, O

The ODE system:

$$\frac{dM(r)}{dr} = \beta r^2 \epsilon$$

$$\frac{dp(r)}{dr} = \frac{\alpha \epsilon M(r)}{r^2}$$

$$\epsilon = (p(r)/K)^{1/\nu}$$



## Бели джуджета в MDG (за $A/Z = 2.15$ )

In the case of white dwarfs, we use the polytropic EOS in the two regimes  
– the relativistic case ( $k_F \gg m_e$ ) and the non-relativistic case  $k_F \ll m_e$ :

$$\rho_{nonrel} = K_{nonrel} \epsilon^{\frac{5}{3}}, \rho_{rel} = K_{rel} \epsilon^{\frac{4}{3}},$$

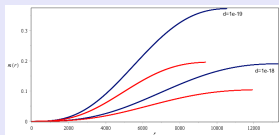
where

$$K_{nonrel} = \frac{\hbar^2}{15\pi^2 m_e} \left( \frac{3\pi^2 Z}{Am_N c^2} \right)^{5/3}, K_{rel} = \frac{\hbar c}{12\pi^2} \left( \frac{3\pi^2 Z}{Am_N c^2} \right)^{\frac{4}{3}}$$

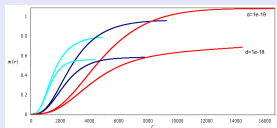
We make the equation dimensional following [Sibar and Reddy (2004)].

Model	$r_{MDG}$	$m_{MDG}$	$r_{GR}$	$m_{GR}$
Relativistic WD ( $\rho_0 = 10^{-14}$ )	4 947	1.2406	4840	1.2431
Relativistic WD ( $\rho_0 = 10^{-15}$ )	8 799	1.2419	8600	1.2432
Relativistic WD ( $\rho_0 = 10^{-16}$ )	15 648	1.2427	15 080	1.2430
Non-Relativistic ( $\rho_0 = 10^{-15}$ )	10 603	0.3929	10 620	0.3941
Non-Relativistic ( $\rho_0 = 10^{-16}$ )	13 349	0.1969	13 360	0.1974

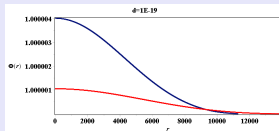
# Бели джуджета в МДГ ( $M$ в слънчеви маси, $r$ в km, $\rho$ в $ergs/cm^3 * 10^{38}$ )



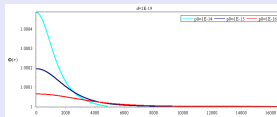
(з) Non-relativistic case



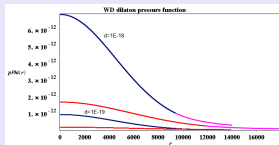
(и) Relativistic case



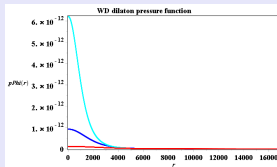
(к) Non-relativistic case



(л) Relativistic case

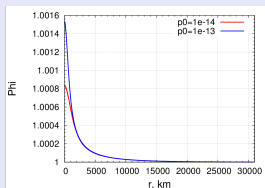
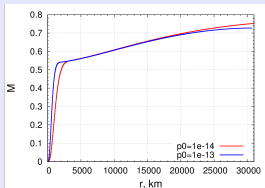
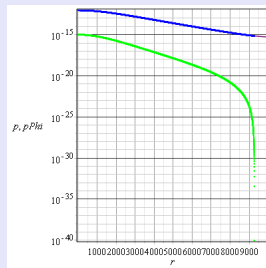
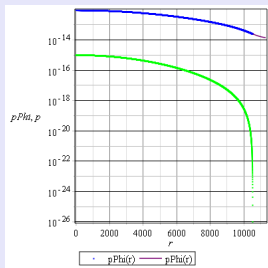


(м) Non-relativistic case



(н) Relativistic case

# Двете безразмерни налягания и малко забавления с метода на Rosenbrock във FORTRAN



# Случаят на TOV неутронна звезда

If one uses the Tolman-Oppenheimer-Volkov (TOV) model for EOS (ideal Fermi neutron gas at zero temperature):

$$\begin{aligned}M &= 1.4 - 2M_{\odot} \\ R &= 12 - 13 \text{ km} \\ \rho &= 10^9 - 10^{17} \text{ kg/m}^3 \\ \text{Composition: } &n^0(\dots)\end{aligned}$$

$$\epsilon = \frac{1}{4\pi} K(\sinh(t) - t), \quad p = \frac{1}{12\pi} K(\sinh(t) - 8 \sinh(t/2) + 3t)$$

Here  $K = \pi \frac{m^4 c^5}{4\hbar^2}$ ,  $t = 4 \log \left( \frac{p_F}{mc} + \left( 1 + \left( \frac{p_F}{mc} \right)^2 \right)^{1/2} \right)$  and

$p = \sqrt{\Lambda \hbar} / cm_{\phi} = 10^{-21}$  (the dilaton mass parameter, for observational consistency,  $p < 10^{-30}$ ),  $\Lambda \sim 10^{-44} \text{ km}^{-2}$ ,

EOS in the original notations of [Oppenheimer & Volkoff (1939)], see also [Rezzola & Zanotti (2013)].

We use MAPLE to solve the ODE system using the shooting method for the BC and the rosenbrock method for the integration.

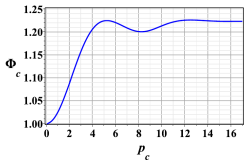


FIG. 1: The specific MDG-curve  $F_{\Lambda}(p_c, \Phi_c) = 0$

(T)

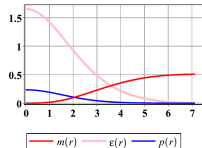


FIG. 2: The MDG-SSSS interior in accord with MEOS

(y)

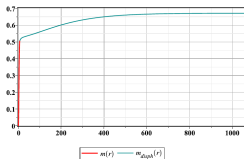


FIG. 3: The SSSS-disphere-mass-dependence on  $r$

(phi)

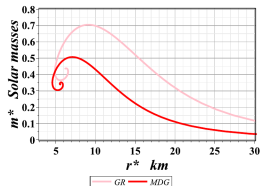


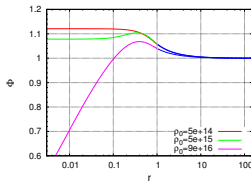
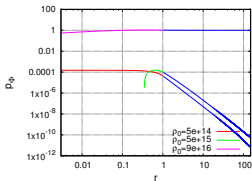
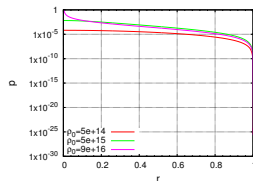
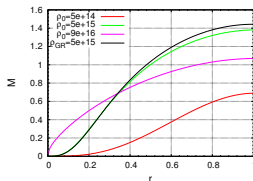
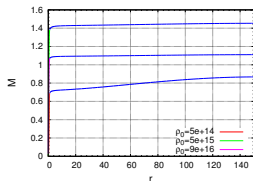
FIG. 7: Mass - radius relations for IFNG0T in GR ( $m_{max}^* \approx .7051 m_{\odot}$ ,  $r_{max}^* \approx 9.209$  km) and in MDG ( $m_{max}^* \approx .5073 m_{\odot}$ ,  $r_{max}^* \approx 7.092$  km)

(x)

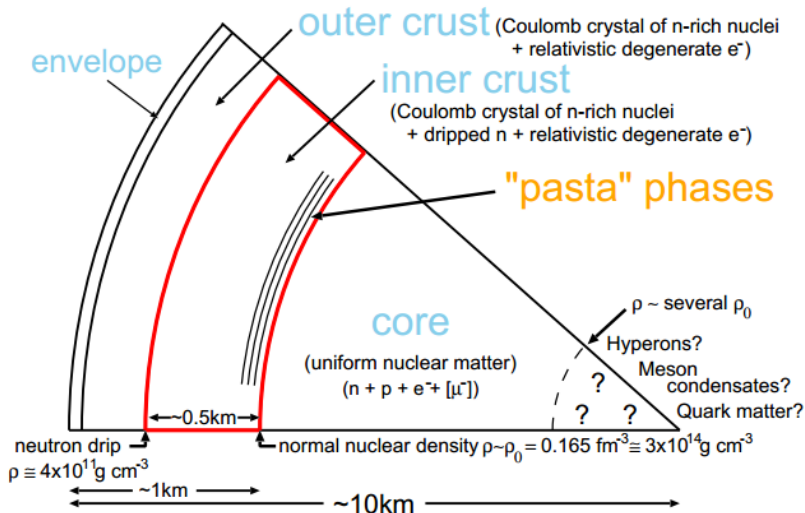
# Включването на уравненията в COCAL, с Antonios Tsokaros, ITP

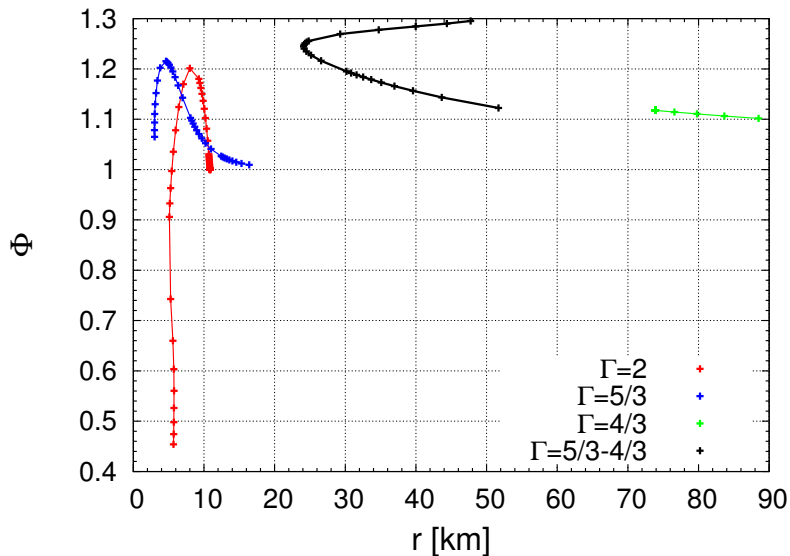
As part of my COST visit at the ITP, the MDG static equations were implemented in the Compact Object CALculator (Tsokaros et al. in prep (2014)).

Some preliminary results for the NS case /here  $\gamma = 2$ /:

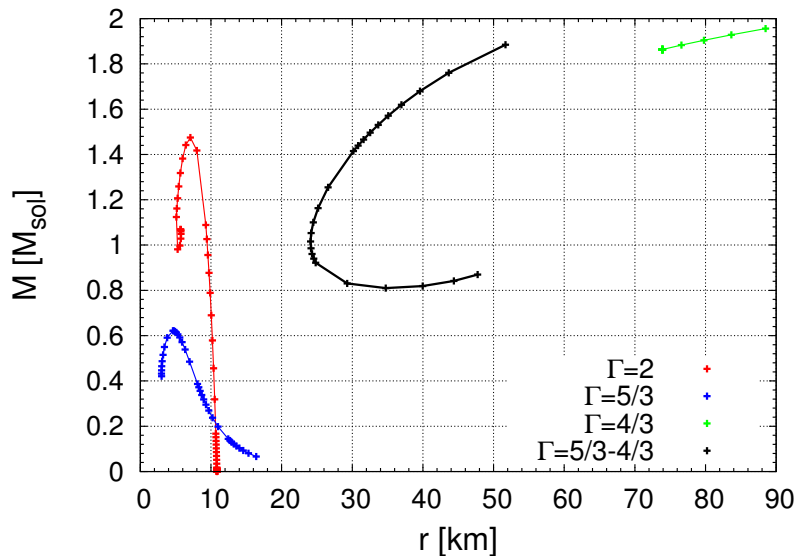


# Структура на НЗ



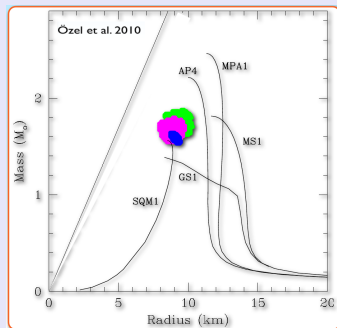






# Резултатите на кратко

- 1 Уравненията в МДГ възстановяват GR с добра точност ( $\Phi = 1$ ,  $U(1) = 1$ ,  $\Lambda = 0$ )
- 2 За масивен дилатон, кривите на  $M(R)$  са подобни на тези в GR
- 3 В случая на неутронни звезди, общата маса е 30% от тази на НЗ
- 4 За бели джуджета, масата на диласферата е около  $\sim 27\%$  от тази на звездата
- 5 Масата на белите джуджета расте с включването на масивен дилатон
- 6 Достигнатата маса за дилатона към момента е ( $d \sim 10^{-20}$ ), което е доста над нужното  $\sim 10^{-30}$ .



Резултатите в случаите на тези просто уравнения на състоянията са обещаващи, но са нужни нови кодове, за да се решат уравненията за много лек дилатон!

Благодаря за вниманието!

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