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“What Comes Beyond the Standard Models?"
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Numerical solution of Einstein field equations with Planck core boundary condition

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Thanks for hosting: Virtual Institute of Astroparticle physics

Short bio

Igor Nikitin:

- graduated from Moscow Institute for Physics and Technology 1991

- worked in Institute for High Energy Physics, Protvino, Russia 1993-1997
- PhD topic: Anomaly free quantization of string theory in 4 dimensions (special types of motion)
- Doc.Sci topic: Anomaly free quantization of string theory in 4 dimensions (general case)

- Currently working in Fraunhofer Institute for Algorithms and Scientific Computing, Sankt Augustin, Germany

  Field of work: energetics

Content

Planck stars

Spherically symmetric models with Planck core in the center

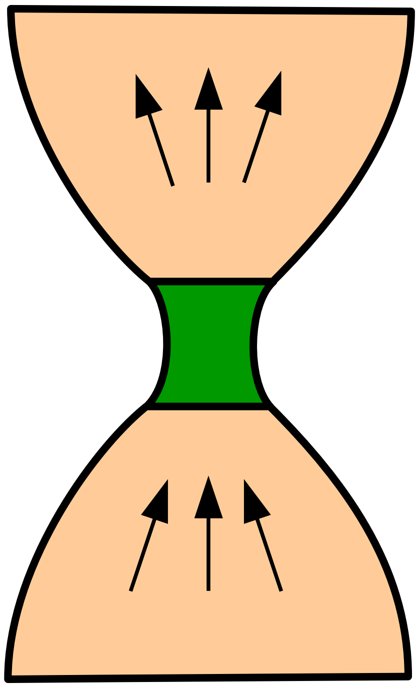
- white holes: questions of stability
- RDM-stars: galactic rotation curves and fast radio bursts
- QG-bubbles: one more candidate to the fast radio bursts

Hypotheses: What is astrophysical dark matter made of?

arXiv:
1701.01569
1811.03368
1812.11801
1903.09972
1906.09074

Planck stars

- calculations in quantum gravity (QG) for a cosmological model with a scalar field (Ashtekar et al. 2006) give a correction to the mass density: $\boldsymbol{\rho_X = \rho\ (1\text{-}\rho/\rho_c),\ \rho_c \sim \rho_P}$
- $\rho = \rho_c \Rightarrow \rho_X = 0$ at critical density the gravity is switched off
- $\rho > \rho_c \Rightarrow \rho_X < 0$ in excess of critical density the effective negative mass appears (**exotic matter**), with gravitational repulsion (a quantum bounce phenomenon)



Planck star

- Planck star model: Rovelli, Vidotto (2014), Barceló et al. (2015)
- collapse of a star replaced by extension, black hole turns white

- in this talk we consider a stationary version of Planck star, stabilized under the pressure of the external matter (a Planck core)
- 3 spherically symmetric models with Planck core in the center will be considered
- the question is related with the stability of white holes, the shape of galactic rotation curves and the origin of fast radio bursts

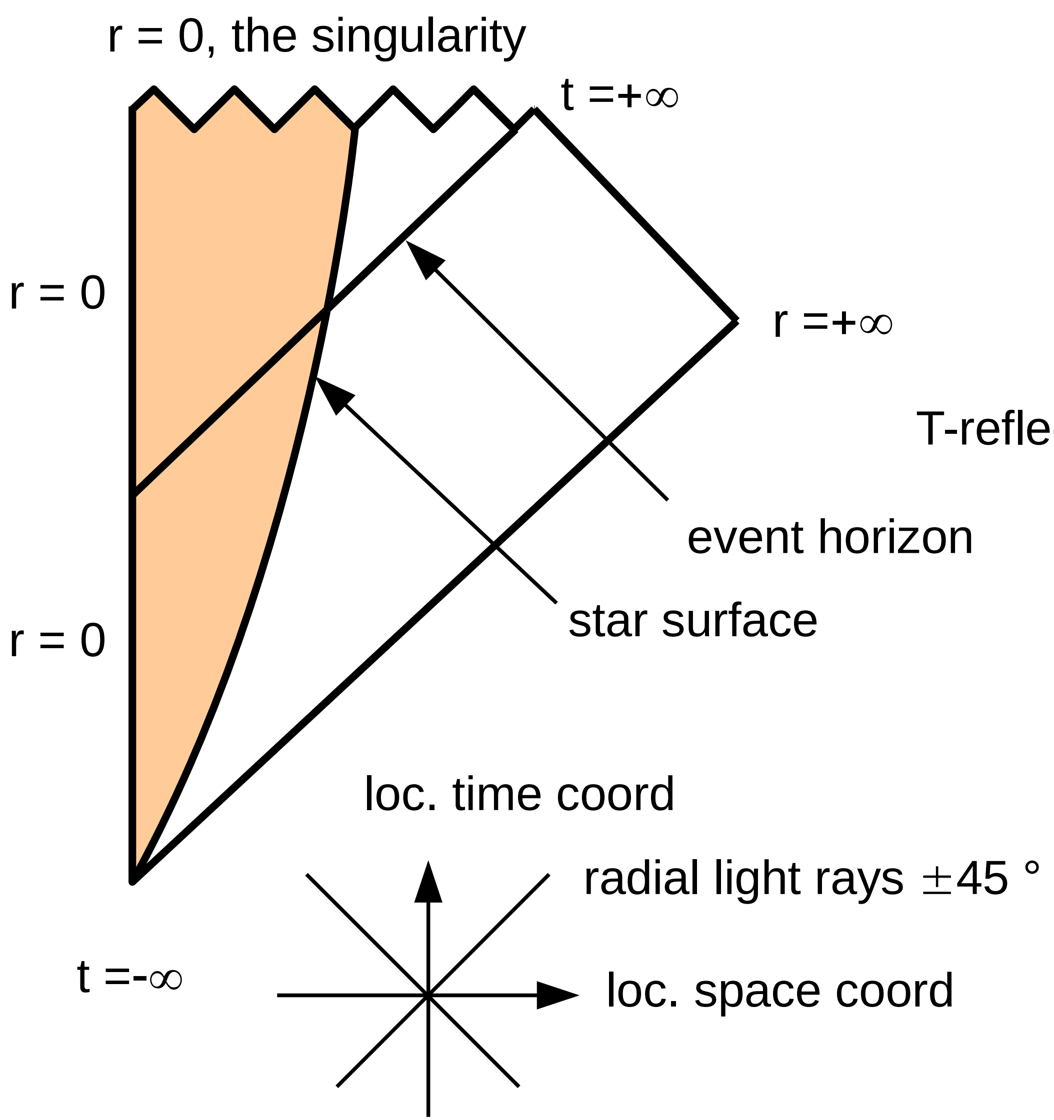
General remark on negative masses

Evolution of viewpoint:

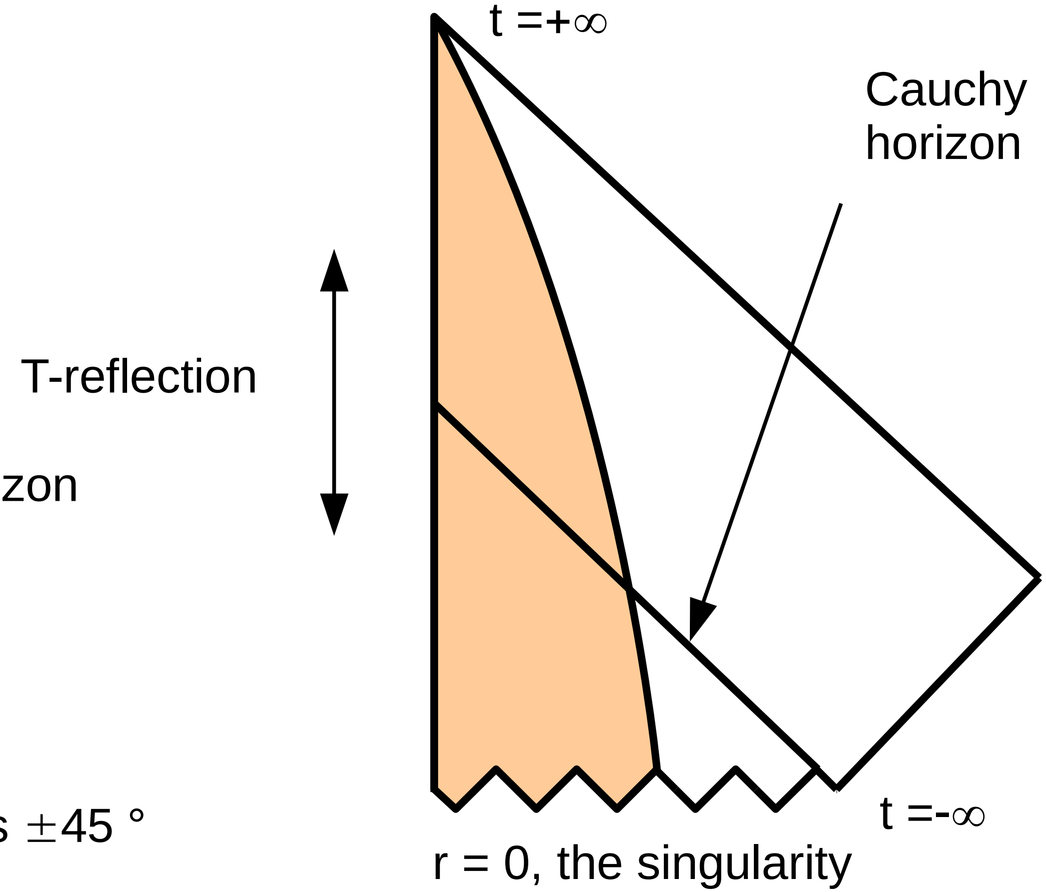
- Energy conditions (Einstein, Hawking): there are ***NO*** negative masses
- 't Hooft (1985): "... negative mass solutions unattractive to work with but ***perhaps they cannot be completely excluded***."
- negative masses ***are needed*** to create the wormholes (Morris-Thorne 1988), warp drives (Alcubierre 1994), time machines (Visser 1996)
- Barceló, Visser (2002), ***Twilight for the energy conditions?***
- Rovelli, Vidotto (2014), Barceló et al. (2015): negative masses ***can be obtained*** effectively by an excess of Planck density
- alternative way: Tippett, Tsang (2017), many interesting solutions can be obtained with non-exotic matter in **f(R)-gravity** (examples are wormholes and accelerating cosmology)
- **…**

White hole on Penrose diagram

collapse of a star into a black hole
(Oppenheimer-Snyder model)

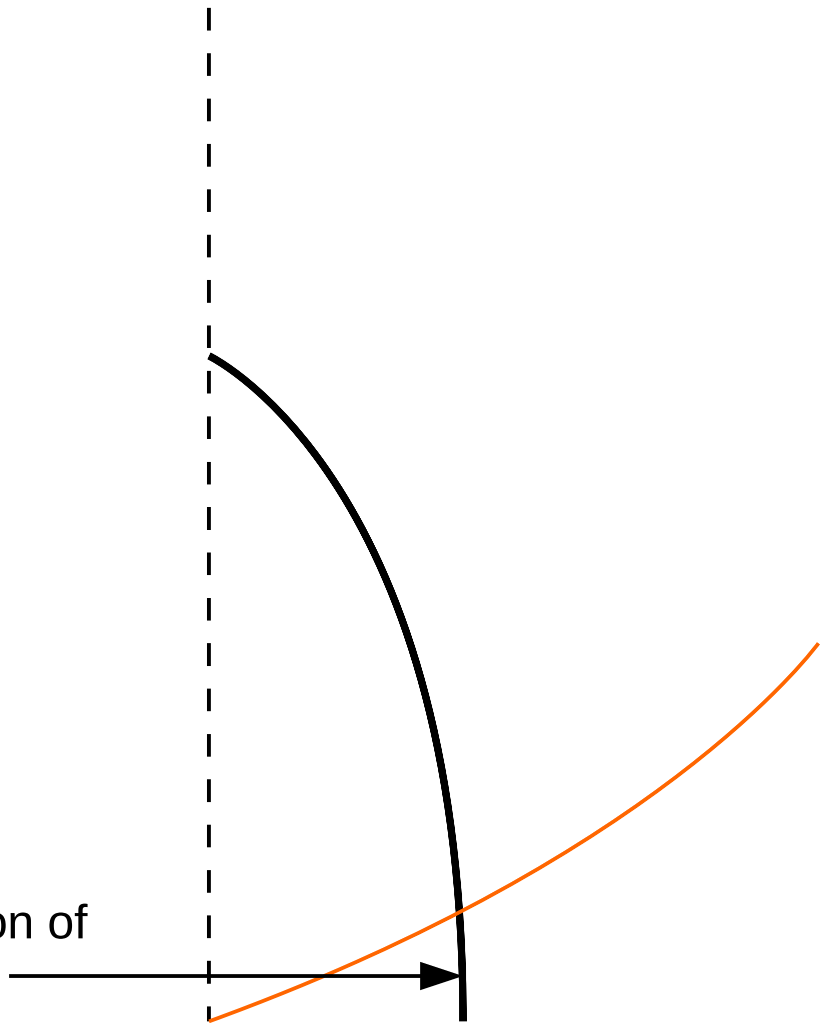


the eruption of a white hole
(Lemaître-Tolman model)

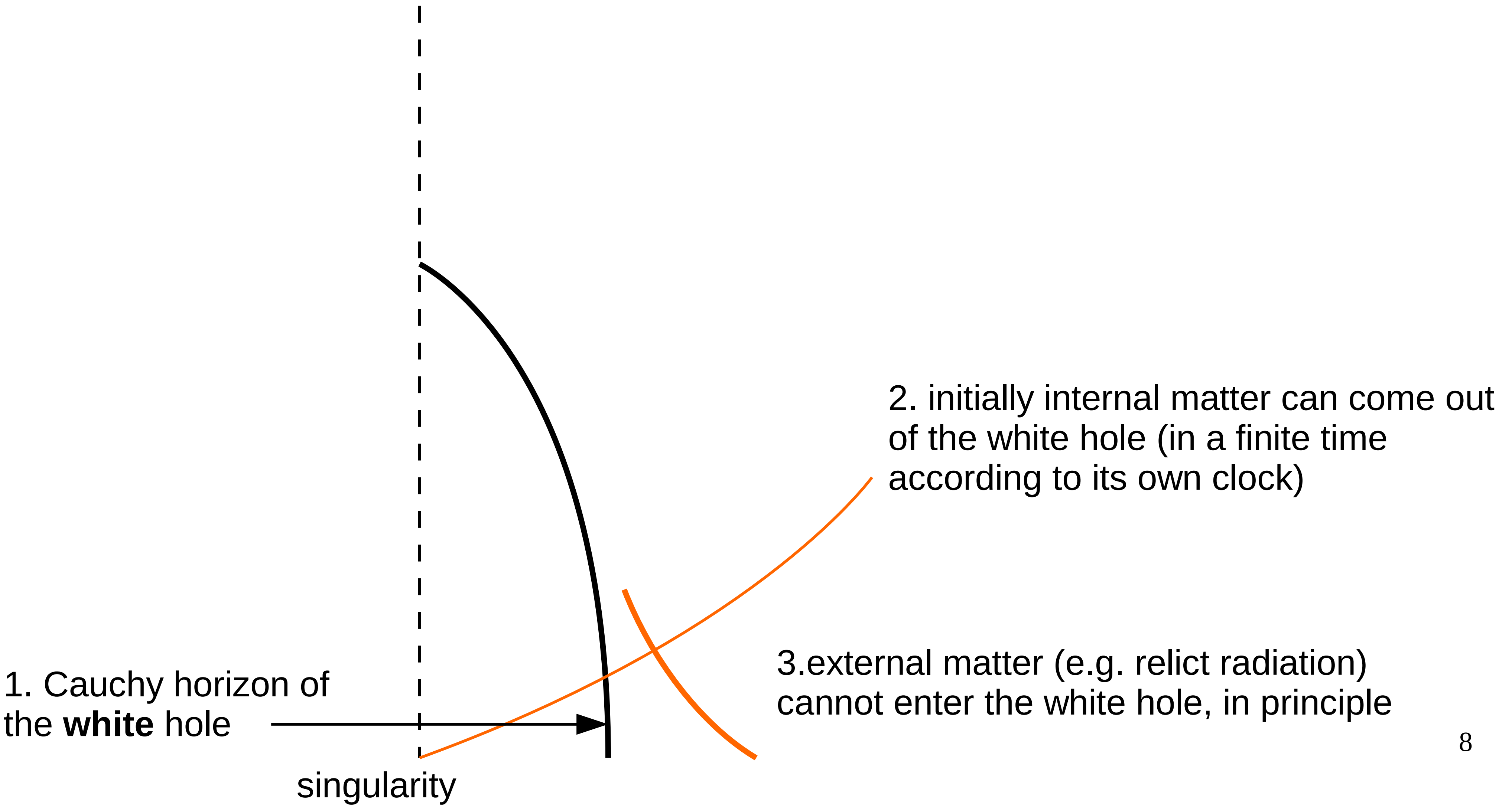


White hole (it is not as simple)

- Eardley instability (1974) – one should take into account the interaction with external matter

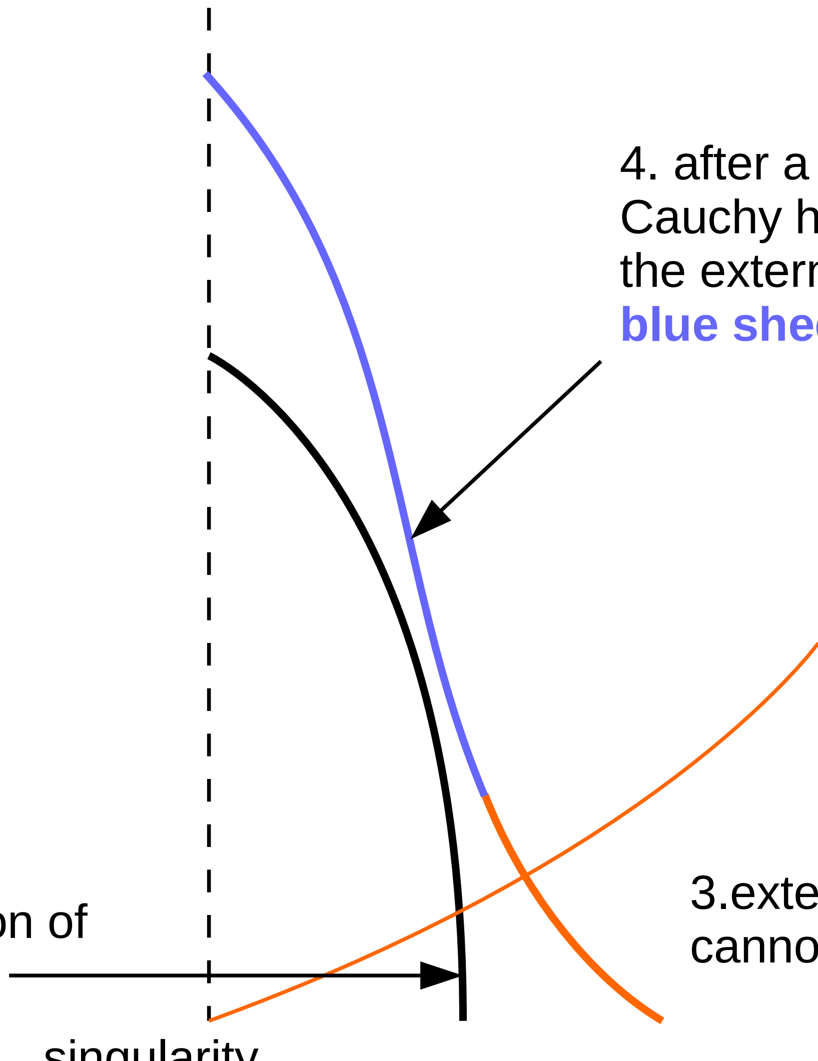


White hole (Eardley instability)



White hole (Eardley instability)

the exponential process:
(value doubled every minute)
r_s=1.2*10^{10}m, t=13.8 Gyears,
$A^{-1/2}$~exp(tc/(2r_s))~**exp(10^{16})!!!**



White hole (Eardley instability)

the exponential process:
(value doubled every minute)
$r_s=1.2*10^{10}$m, t=13.8 Gyears,
$A^{-1/2}\sim\exp(tc/(2r_s))\sim$ **$\exp(10^{16})$!!!**

5. as a result, a **black** hole is formed, under the event horizon of which the blue sheet falls, together with the internal matter that didn't had time to escape the white hole

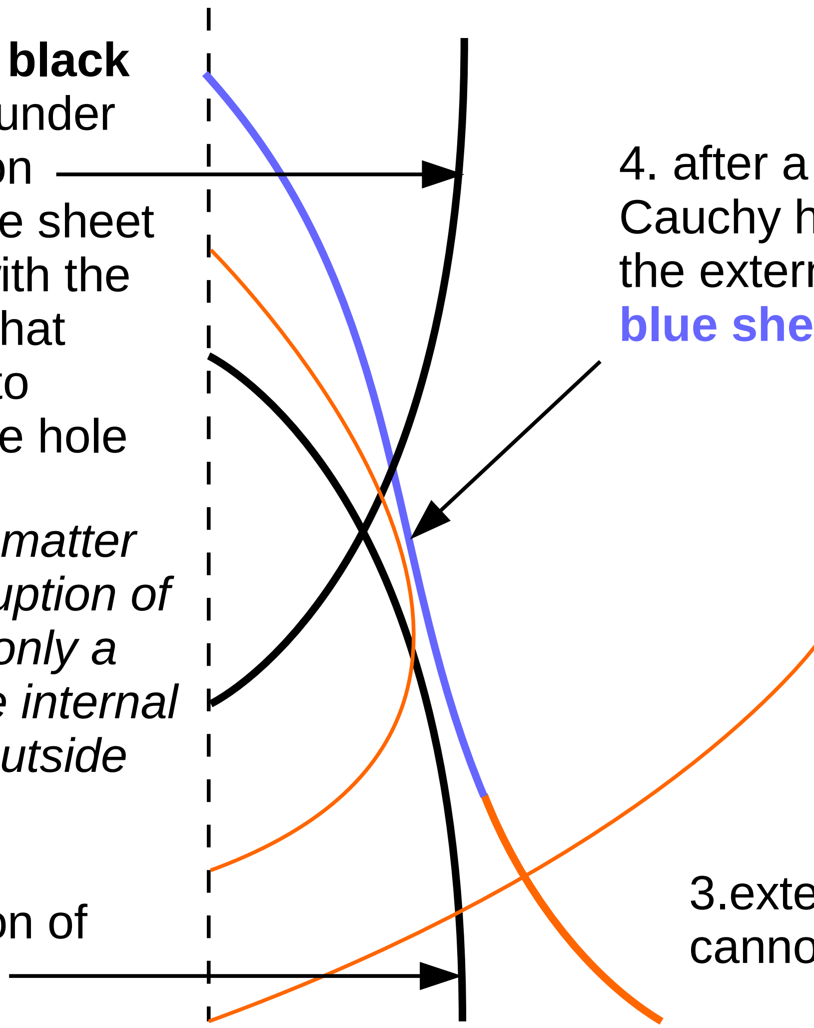
4. after a long (13.8 billion years) wait at the Cauchy horizon and superstrong blue shifting the external matter forms a thin super-energetic **blue sheet**

=> the external matter prevents the eruption of the white hole, only a small part of the internal matter can go outside

2. initially internal matter can come out of the white hole (in a finite time according to its own clock)

3.external matter (e.g. relict radiation) cannot enter the white hole, in principle

1. Cauchy horizon of the **white** hole

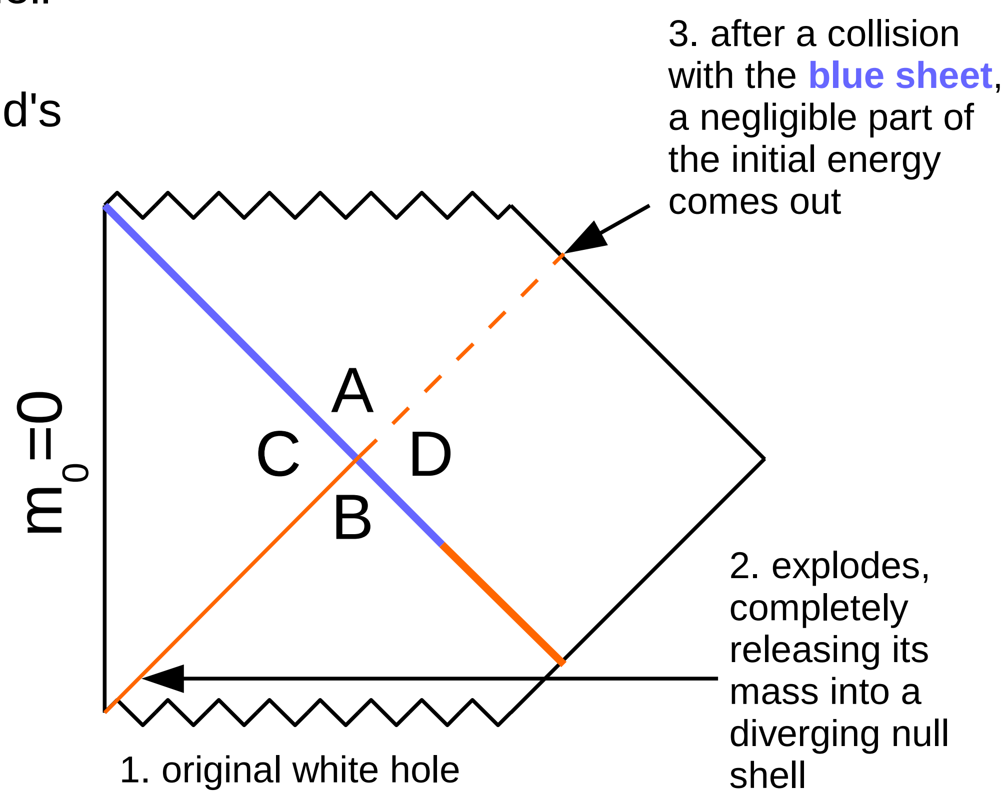


White hole (null shell model)

- Ori-Poisson model (1994)
- gravitational interaction of null shells
- M is the mass of the white hole,
  dm is the mass of the input shell,
  E is the mass / energy of output shell
  (G = c = 1), m_0 – remainder
- solution consists of 4 Schwarzschild's patches ABCD

$$m_A = M - E,\ m_B = M - dm,$$

$$m_C = m_0,\ m_D = M$$



White hole (null shell model)

The proof uses Dray-'t Hooft-Redmount (DTR) relation:

$$f_A f_B = f_C f_D, \; f_i = 1 - 2m_i/R, \; i = A, B, C, D$$

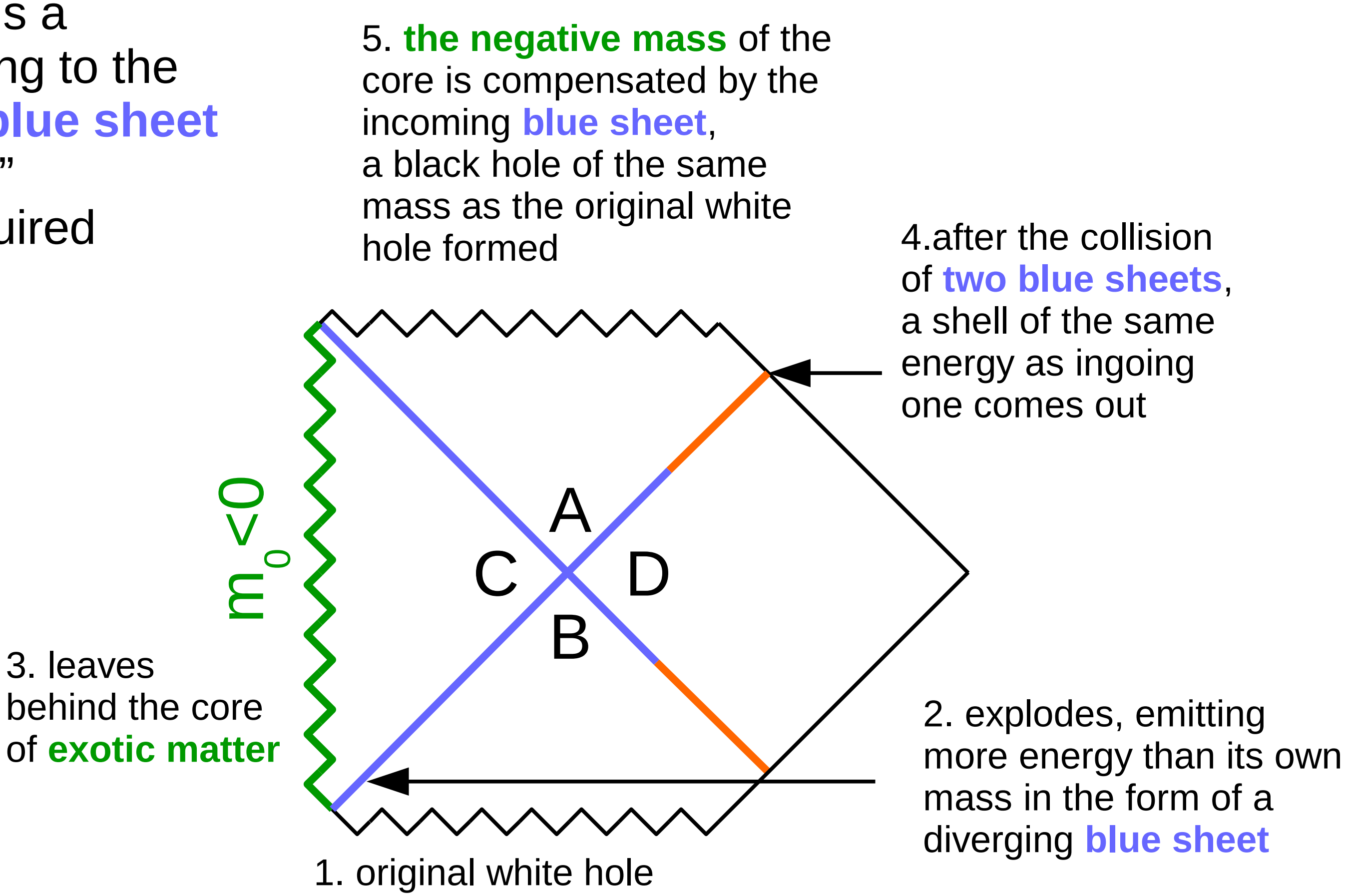
$$\xi = R/(2M) - 1, \; \alpha = dm/M,$$
$$\beta = m_0/M, \; \eta = E/M,$$ ← efficiency of white hole eruption

$\xi = \xi_0 \exp(-\tau/(4M))$ ~ **exp(-10^{16})** $\eta \sim \xi/\alpha$ ~ **exp(-10^{16})**

exponential process of approaching of the ingoing null shell
to the Cauchy horizon

White hole (null shell model)

- so, the black holes are stable, but the white holes aren't ... **what is about T-symmetry?**
- the paradox resolution: there is a T-symmetric scenario according to the principle "for every incoming **blue sheet** there is **the same** outgoing ..."
- negative mass remainder required in solution (**exotic matter**)



White hole (null shell model)

- calculation with β<0 shows self-consistency of the solution:

$$\eta = (1 - \alpha - \beta)\,\xi/(\alpha + \xi)$$

$\beta \sim -\alpha/\xi$ $\qquad \eta \sim 1$ (100% efficiency)

T-symmetric case:

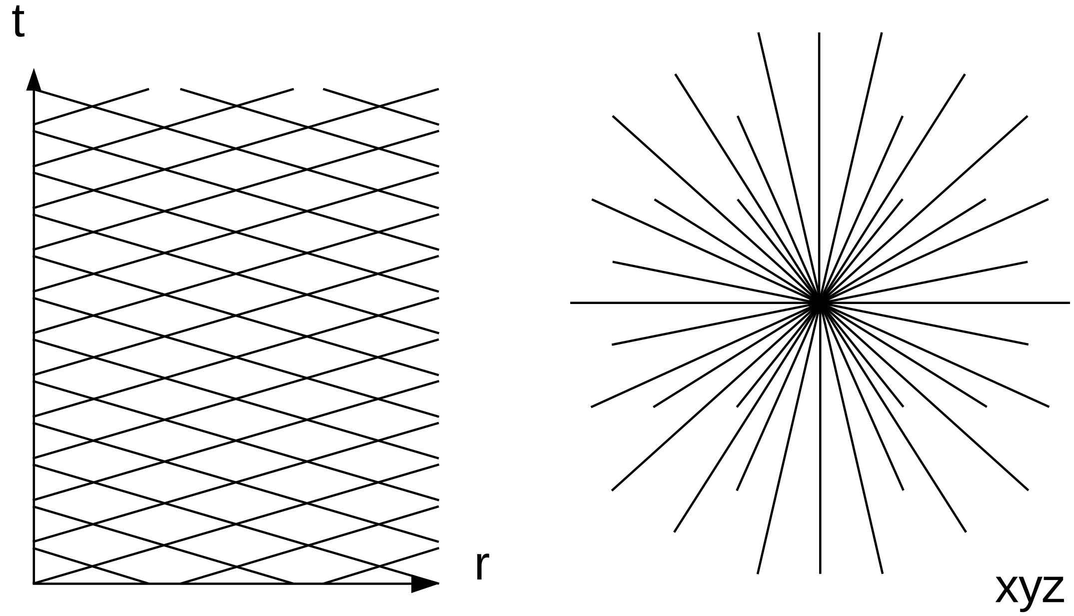
$$\eta = \alpha, E = dm,\ \beta = -(\alpha^2 - \xi + 2\alpha\xi)/\xi$$

Conclusion1: in Ori-Poisson model, Eardley instability can be eliminated if the system has a core of negative mass

Dark Stars

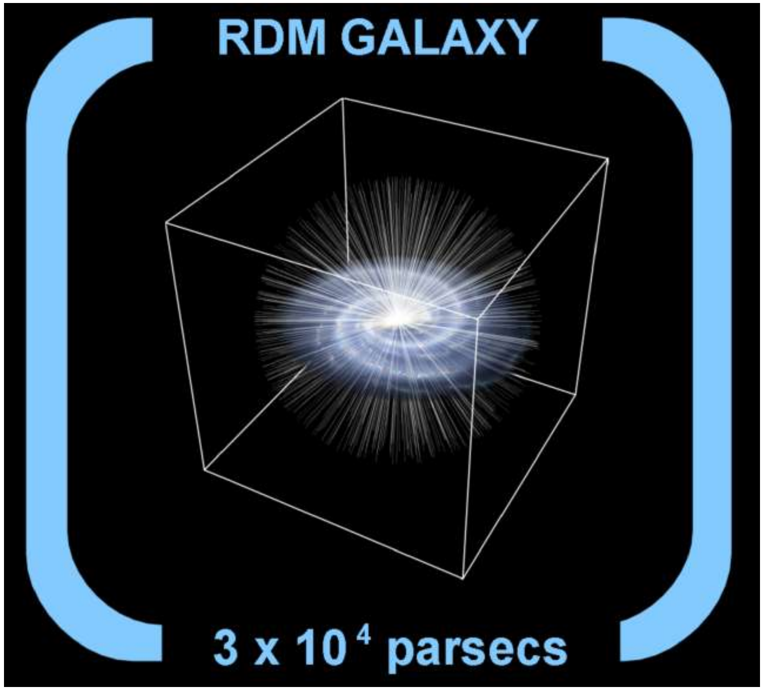
- also known as ***quasi black holes***, boson stars, gravastars, fuzzballs ...
- solutions of general theory of relativity, which first follow Schwarzschild profile and then *are modified*
- outside are similar to black holes, inside are constructed differently (depending on the model of matter used)
- review of the models: Visser et al., ***Small, dark, and heavy: But is it a black hole?***, arXiv: 0902.0346
- our contribution to this family: *RDM stars* (quasi black holes coupled to Radial Dark Matter)

Stationary solution, including T-symmetric superposition of ingoing and outgoing radially directed flows of dark matter



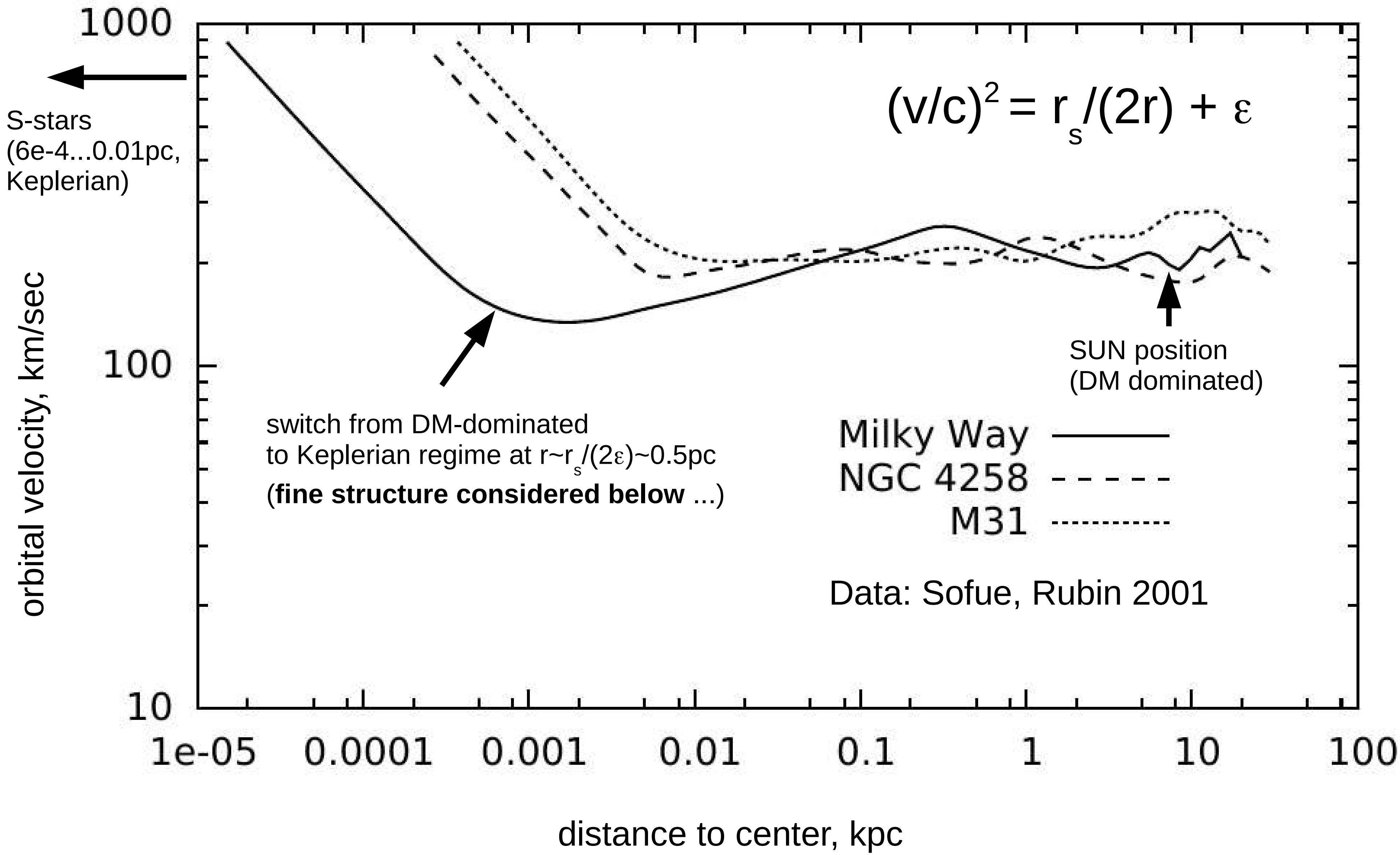
Galactic model with radial dark matter

- The simplest model of a spiral galaxy
- 30kpc level (for MW)
- Dark matter flows radially converge towards the center of the galaxy
- The limit of weak gravitational fields, one-line calculation: $\rho \sim r^{-2}$, $M \sim r$, $v^2 = GM / r = Const$
- Qualitatively correct behavior of galactic rotation curves (asymptotically flat shape at large distances)
- The orbital velocity of the stars and interstellar gas consisting of Kepler and constant terms
- Q1: How to describe the deviation of rotation curves from the flat shape? (the model of distributed RDM-stars will be considered)
- Q2: What is happening in the center of the galaxy? (the calculation in the limit of strong fields will be done)



$$v^2 = GM/r + Const$$

Typical behaviour of galactic rotation curves (Kepler + constant)



Rotation curves of galaxies, in details

- Universal Rotation Curve (URC, Salucci et al. 1995-2017)

- represents averaged exp. rotation curves of >1000 galaxies
- before averaging: galaxies are subdivided to bins over magnitude mag
- curves V(R,mag) are normalized to the values at optical radius: V / Vopt, R / Ropt
- the averaging smoothes the individual characteristics of the curves (loc. minima / maxima)

- detailed modeling of rotation curves in RDM model
- based on the assumptions: (1) all black holes are RDM-stars; (2) their density is proportional to the concentration of the luminous matter in the galaxy
- in this case, the dark matter density is given by the integral (Kirillov, Turaev 2006)

constant

$$\rho_{dm}(x) = \int d^3x'\, b(|x-x'|)\, \rho_{lm}(x'), \quad b(r) = 1/(4\pi L_{KT})/r^2$$

Freeman 1970 model

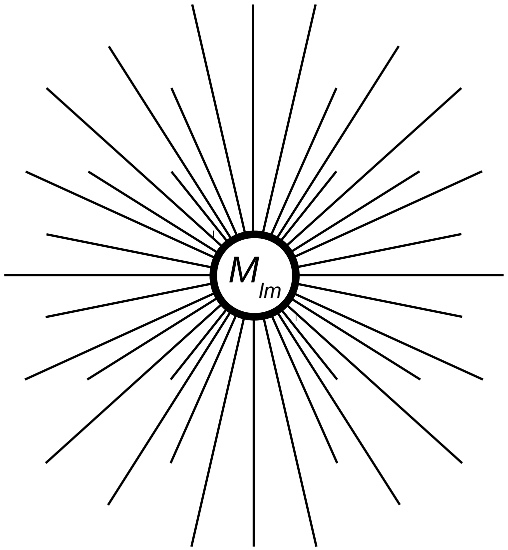
the contribution of one RDM-star

$$\sim \delta(z)\exp(-r/R_D),\, R_{opt} = 3.2 R_D$$

optical radius of the galaxy
encompassing 83% of the light

Rotation curves of galaxies, in details

The physical meaning of KT-integral: every element of luminous matter (i.e., RDM-stars contained in it) gives additive contributions to dark matter density, mass, gravitational field, orbital velocity, gravitational potential...



$$\rho_{dm}(r) = M_{lm}/(4\pi L_{KT})/r^2,$$

$$M_{dm}(r) = 4\pi \int_0^r dr' r'^2 \rho_{dm}(r') = M_{lm} r / L_{KT},$$

$$a_{r,dm} = GM_{dm}(r)/r^2 = GM_{lm}/(rL_{KT}),$$

$$v_{dm}^2 = GM_{dm}(r)/r = GM_{lm}/L_{KT},$$

$$\varphi_{dm} = GM_{lm}/L_{KT} \cdot \log r.$$

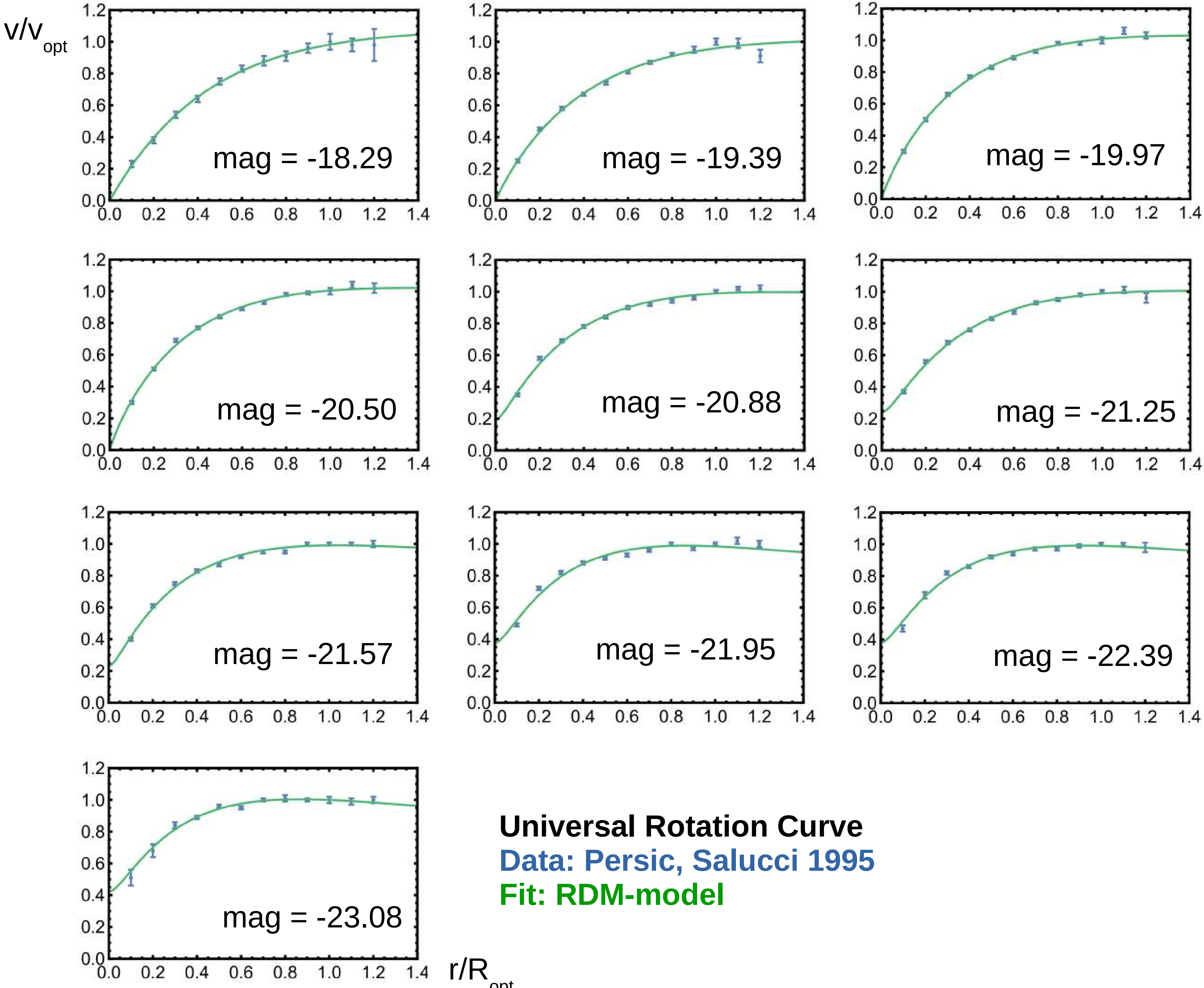
L_{KT} is the distance at which the mass of dark matter equals to the mass of the luminous matter, to which it is coupled

Rotation curves of galaxies, in details

the integrals are evaluated analytically and lead to the following model:

$$
\begin{aligned}
&v^2_{center,lm} = \alpha_0 v^2_{opt}\, R_{opt}/r,\ \ v^2_{center,dm} = \alpha v^2_{opt},\\
&v^2_{disk,lm} = \beta v^2_{opt}\, F_{disk}(r/R_D)/F_{disk}(3.2),\\
&F_{disk}(x) = x^2(I_0(x/2)K_0(x/2) - I_1(x/2)K_1(x/2)),\\
&v^2_{disk,dm} = \gamma v^2_{opt}\, F_{disk,dm}(r/R_D)/F_{disk,dm}(3.2),\\
&F_{disk,dm}(x) = 1 - e^{-x}(1+x),\ \ R_{opt} = 3.2 R_D,\\
&v^2 = v^2_{center,lm} + v^2_{center,dm} + v^2_{disk,lm} + v^2_{disk,dm},\\
&v^2_{opt} = v^2(r \to R_{opt}),\ \ \alpha_0 + \alpha + \beta + \gamma = 1,
\end{aligned}
$$

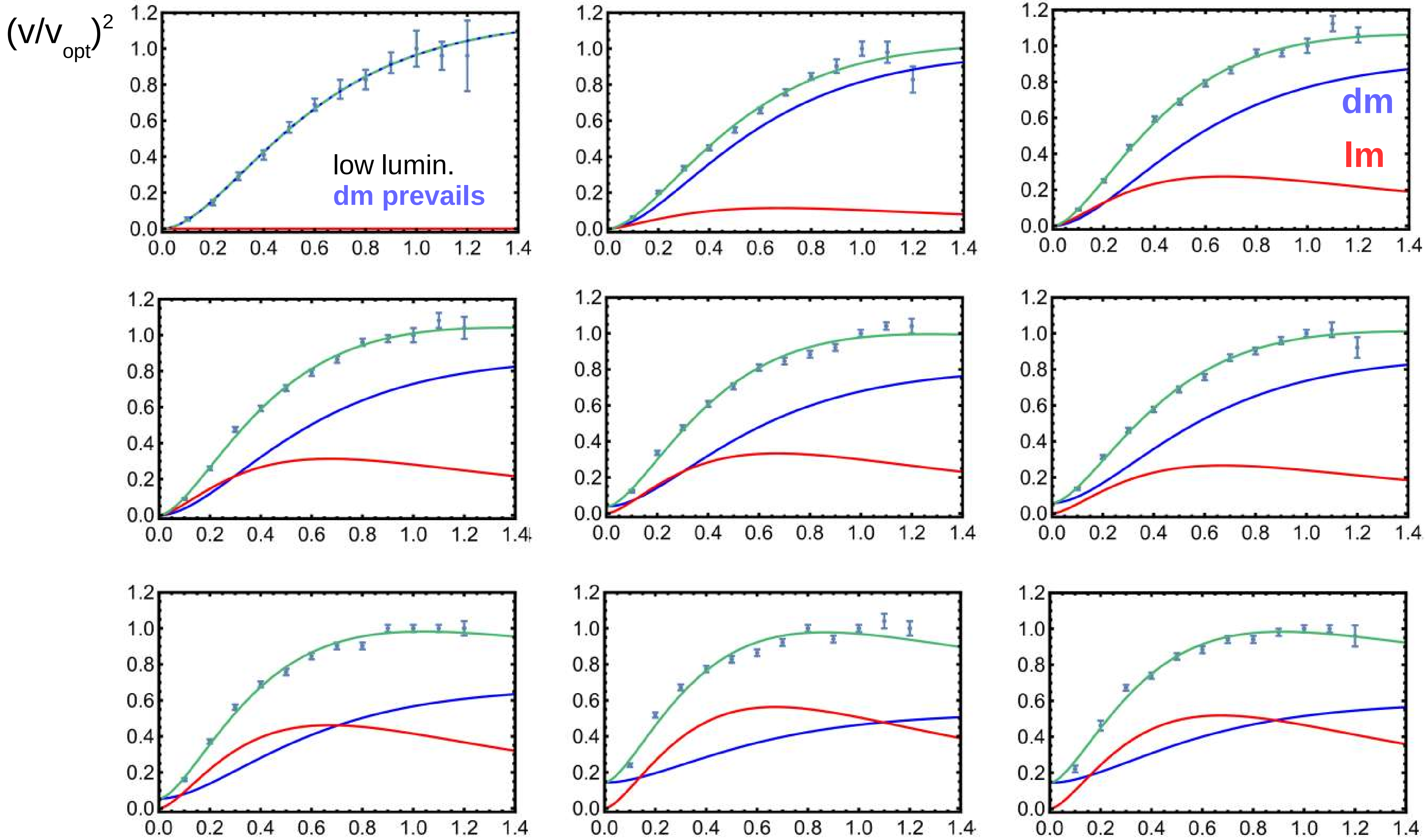
the contributions are separated for the galactic center (unresolved), disk, visible and dark matter; I_n, K_n - modified Bessel functions; coeff. at basis shapes selected as fitting parameters

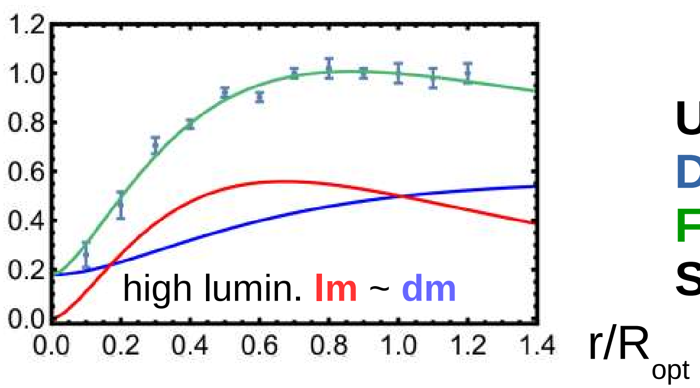


Universal Rotation Curve

Data: Persic, Salucci 1995

Fit: RDM-model





Universal Rotation Curve (v squared)

Data: Persic, Salucci 1995

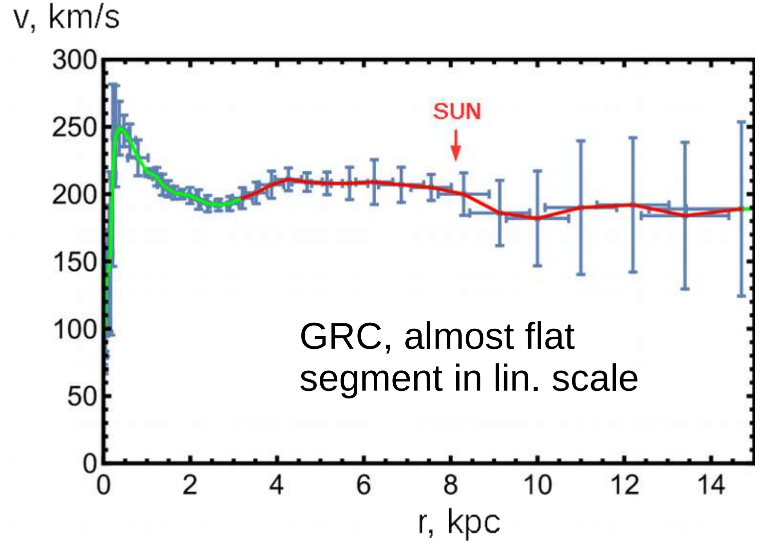
Fit: RDM-model

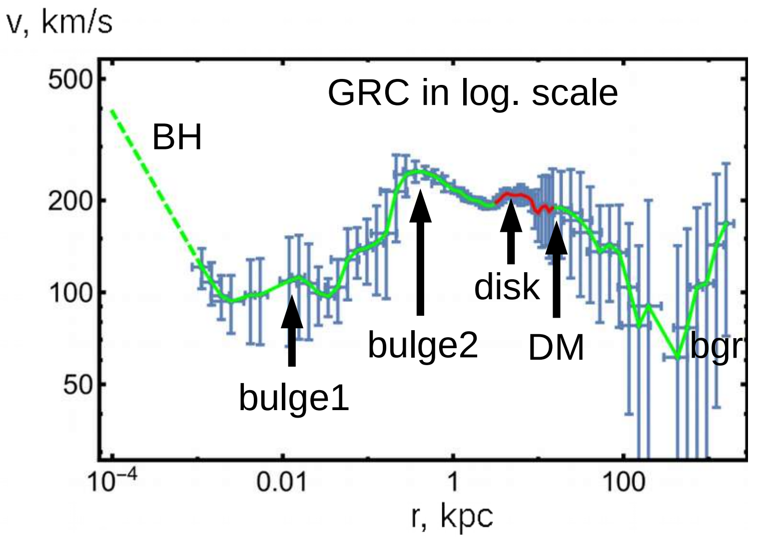
Separation of the contributions:

dark matter / luminous matter

Rotation curves of galaxies, in details

- rotation curve for the Milky Way in a large range of distances (Grand Rotation Curve, GRC, Sofue et al. 2009-2013)
- shows individual structures typical for a particular galaxy (MW)
- structures are clearly visible in log.scale (central black hole, the inner, outer bulges, disk, dark matter halo, the background contribution)
- in the fitting procedure each structure is represented by its own basis function
- we consider several scenarios with fixed coupling constants of dark matter to separate structures





λ_{KT}	s1	s2	s3
λ_{bh}	0	1	10^3
λ_1	0	1	10^2
λ_2	0	1	2
λ_{disk}	1	1	1

$$v_{bh}^2 = G_m M_{bh}/r,\ \ G_m = 4.3016 \cdot 10^{-6}\ (km/s)^2 (kpc/M_\odot),$$

$$v_{sph,i}^2 = G_m M_i/r \cdot F_{sph}(r/a_i),\ \ i = 1, 2,$$

$$F_{sph}(x) = 1 - e^{-x}(1 + x + x^2/2),$$

$$v_{disk}^2 = G_m M_{disk}/(2R_D) \cdot F_{disk}(r/R_D),$$

$$F_{disk}(x) = x^2(I_0(x/2)K_0(x/2) - I_1(x/2)K_1(x/2)),$$

$$v_{lm}^2 = v_{bh}^2 + v_{sph1}^2 + v_{sph2}^2 + v_{disk}^2,$$

$$v_{dm,bh}^2 = G_m M_{bh} \lambda_{bh}/L_{KT},$$

$$v_{dm,sph,i}^2 = G_m M_i \lambda_{sph,i}/L_{KT} \cdot F_{dm,sph}(r/a_i),\ \ i = 1, 2,$$

$$F_{dm,sph}(x) = (6x + (3 - 3x + x^2)e^x Ei(-x)$$
$$-(3 + 3x + x^2)e^{-x} Ei(x))/(4x),$$

$$v_{dm,disk}^2 = G_m M_{disk} \lambda_{disk}/L_{KT} \cdot F_{dm,disk}(r/R_D),$$

$$F_{dm,disk}(x) = 1 - e^{-x}(1 + x),$$

$$v_{dm,sum}^2 = v_{dm,bh}^2 + v_{dm,sph1}^2 + v_{dm,sph2}^2 + v_{dm,disk}^2,$$

$$v_{dm,cut}^2 = v_{dm,sum}^2(r \to r_{cut}) \cdot r_{cut}/r,\ \ v_{bgr}^2 = 4\pi G_m \rho_0 r^2/3,$$

$$v_{dm}^2 = ((v_{dm,sum}^2)^p + (v_{dm,cut}^2)^p)^{1/p},$$

$$v^2 = v_{lm}^2 + v_{dm}^2 + v_{bgr}^2.$$

the contributions: central BH, 2-component bulge, disc, visible and dark matter, homogeneous background density

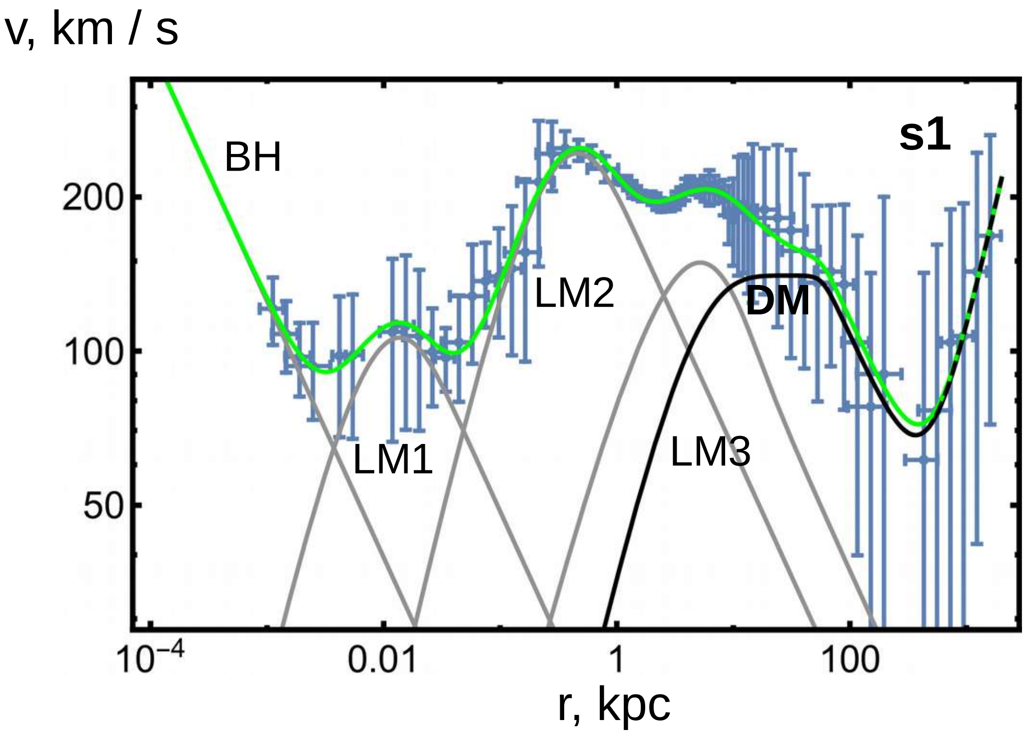
the fitting parameters: coefficients at basis shapes (or masses of components), geom. dimensions of the components

Ei - exponential integral function

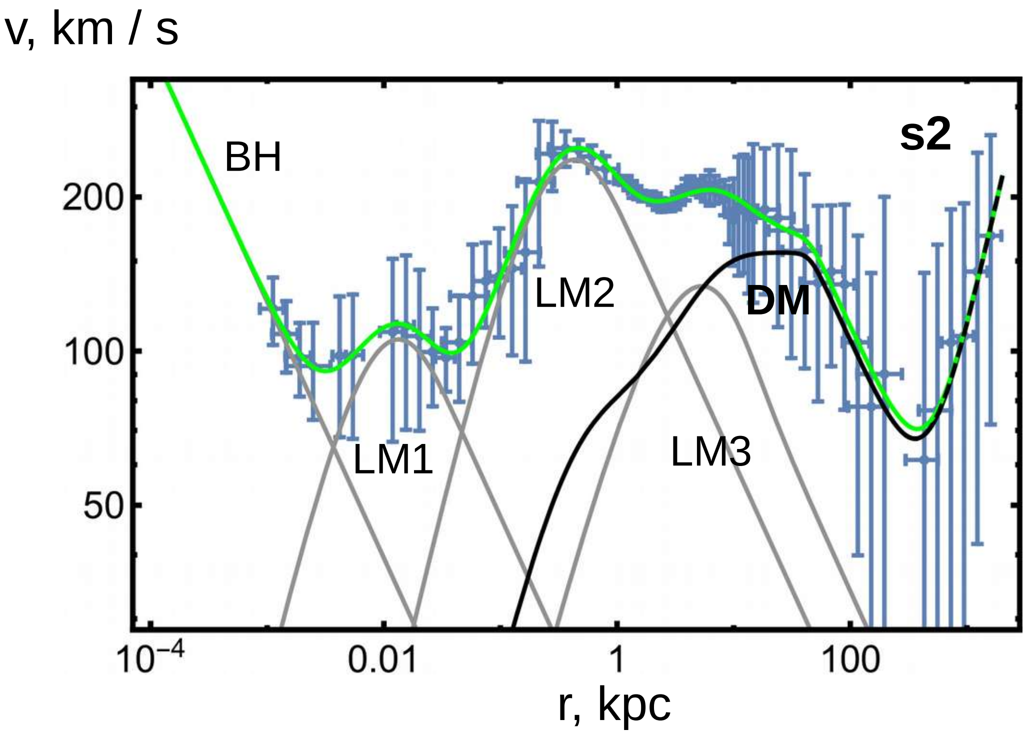
dark matter halo is cut on the outer radius rcut, analogous to termination shock phenomenon at the boundary of Solar sys., where solar wind stops meeting the uniform interstellar env.

background contribution, similar to uniform cosmological distr. (Hubble flow), with a possible local overdensity above the critical

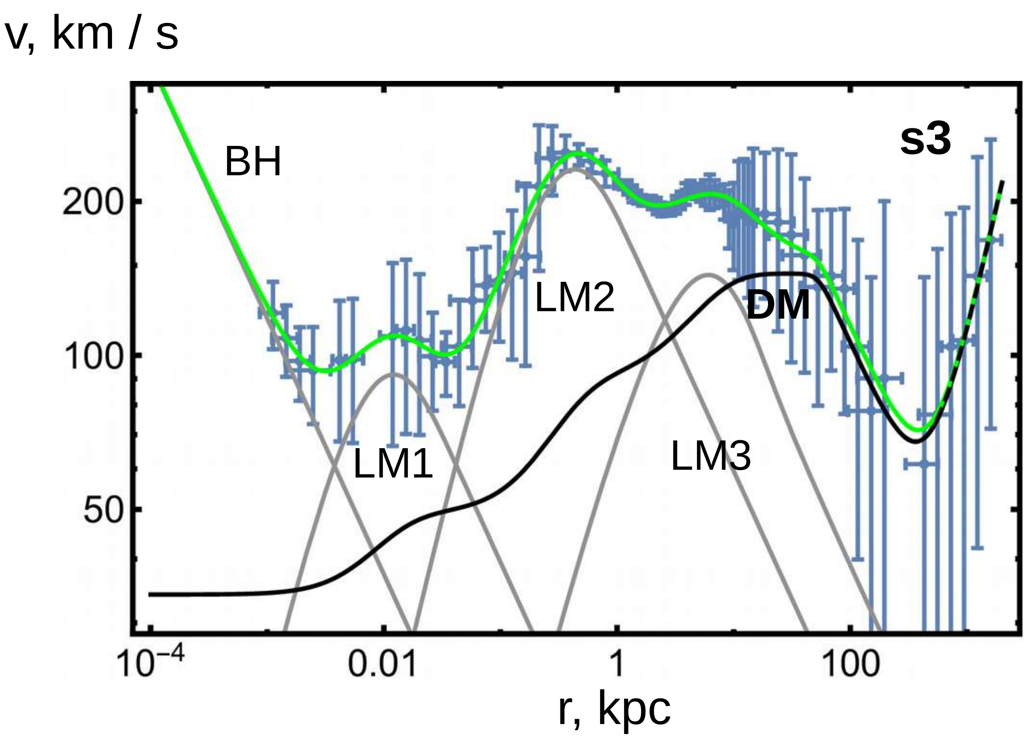
Rotation curves of galaxies, in details



Rotation curves of galaxies, in details



Rotation curves of galaxies, in details



Rotation curves of galaxies, in details

GRC: fitting results, central values of parameters*

par	s1	s2	s3
M_{bh}	3.6×10^6	3.6×10^6	3.2×10^6
M_1	5.5×10^7	5.2×10^7	3.6×10^7
a_1	0.0041	0.0039	0.0036
M_2	9.7×10^9	8.6×10^9	8.2×10^9
a_2	0.13	0.13	0.13
M_{disk}	3.2×10^{10}	2.7×10^{10}	3.5×10^{10}
R_D	2.4	2.5	2.8
L_{KT}	7.0	6.3	12.0
r_{cut}	58	45	53
$M_{dm}(r_{cut})$	2.7×10^{11}	2.5×10^{11}	2.6×10^{11}
ρ_0	646	653	649

* masses in $M_\odot$, lengths in kpc, density in $M_\odot/kpc^3$

approx equal for all scenarios

5x greater than critical density (local overdensity)

Conclusion2: RDM model can describe galactic rotation curves of both URC and GRC type

What happens inside RDM-star: strong fields

Einstein eqs: relate gravitational field to the distribution of matter

geodesic eqs: relate matter distr. to the gravitational field

$$G^{\mu\nu} = 8\pi G/c^4 \cdot T^{\mu\nu},\ u^\nu \nabla_\nu u^\mu = 0,\ \nabla_\mu \rho u^\mu = 0$$

=> self-consistent PDE system

$$ds^2 = -Adt^2 + Bdr^2 + Dr^2(d\theta^2 + \sin^2\theta\ d\phi^2)$$

standard metric for spherically symmetric stationary case, A>0, B>0, D=1

matter distribution in the RDM model: the energy-momentum tensor

$$T^{\mu\nu} = \rho(u_+^\mu u_+^\nu + u_-^\mu u_-^\nu),\ u_\pm = (\pm u^t, u^r, 0, 0)$$

mass density > 0, pressure p = 0 (dust)

radial velocity flows: incoming / outgoing

Note: steady-state solution requires energy balance of the flows

- zeroing total energy flux through r-spheres: $T^{tr} = 0$
- satisfied in the particular case with T-symmetric flow, above
- (arXiv:1906.09074): general case

RDM equations, derived with computer algebra

The geodesic eqs:

$$(\rho u^r)' + (4/r + A'/A + B'/B)\rho u^r/2 = 0,$$
$$(u^t A'/A + (u^t)')u^r = 0,$$
$$(u^t)^2 A' + (u^r)^2 B' + 2Bu^r(u^r)' = 0,$$

Analytical solution:

$$\rho = c_1/\left(r^2 u^r \sqrt{AB}\right),$$
$$u^t = c_2/A,\ \ u^r = \sqrt{c_2^2 + c_3 A}/\sqrt{AB}$$

$c_{1,2,3}$ – integration consts,
$c_{1,2}>0$, $c_3=-1,0,+1$

RDM equations, derived with computer algebra

Einstein's equations:

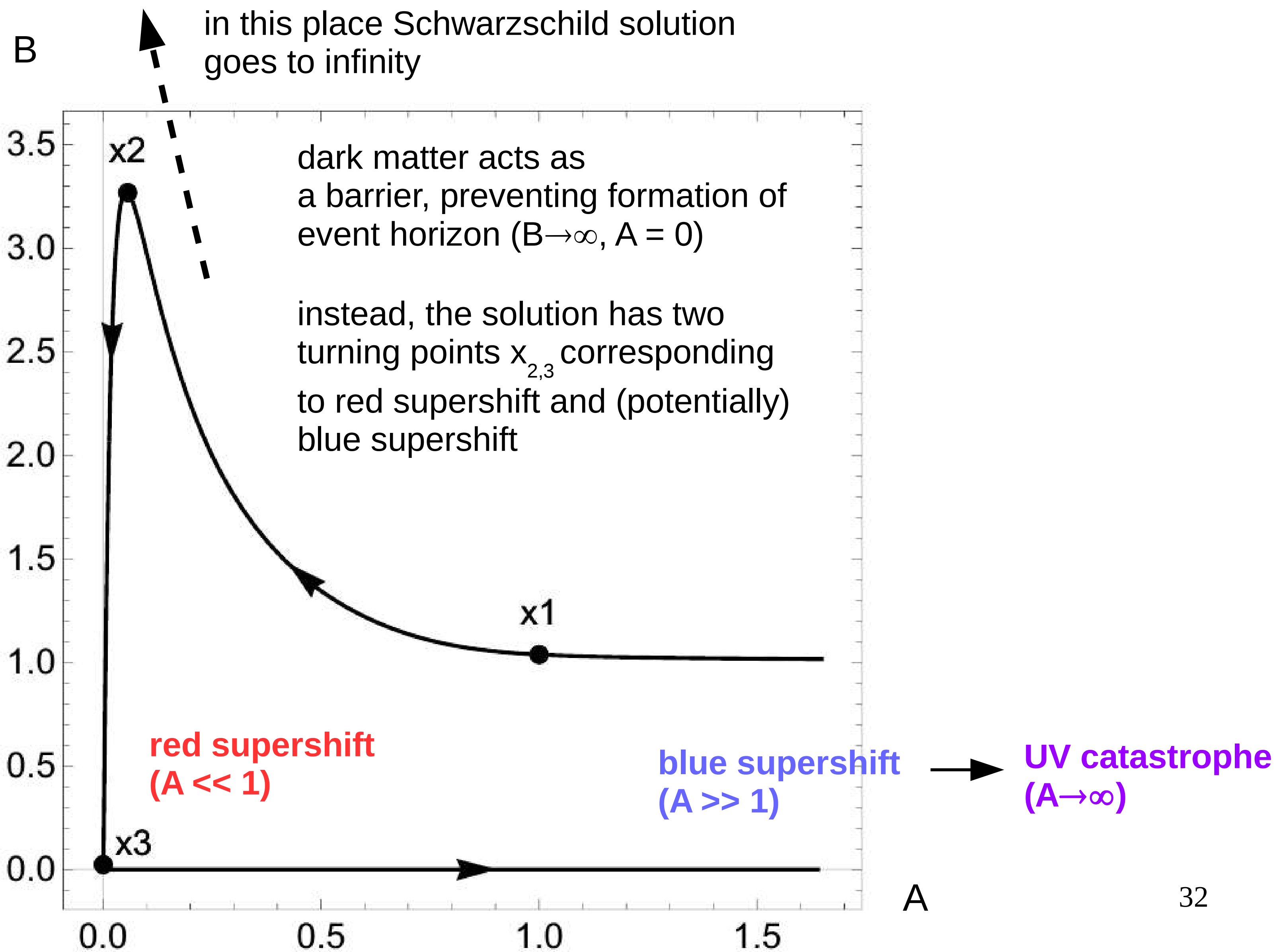
$$rA' = -A + AB + 4c_1 B\sqrt{c_2^2 + c_3 A},$$
$$rB' = B/A\left(A - AB + 4c_1 c_2^2 B/\sqrt{c_2^2 + c_3 A}\right)$$

in the limiting case $c_1 = 0$, dark matter switched off, the analytical solution in the form of a Schwarzschild black hole

in general, there is no analytical solution (system solved numerically)

Mathematica NDSolve

The numerical solution of RDM equations



The numerical solution of RDM equations

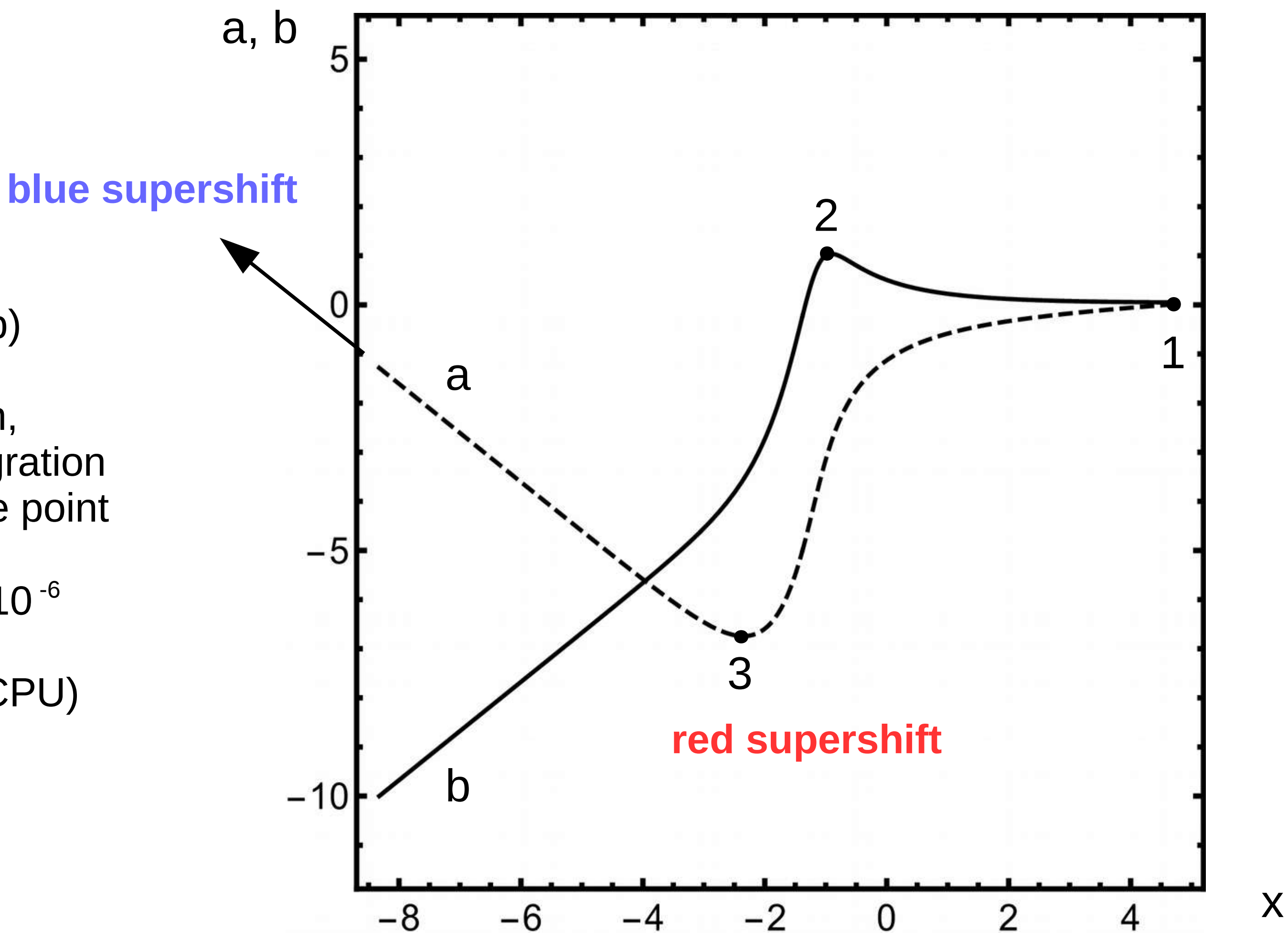
details in the log. scale

to improve the accuracy of integration the autonomy of the system is used and the system is reduced to a single eq db/da=f(a,b)

due to nonmonotonicity of solution, it is necessary to change the integration variable a <-> b at an intermediate point

relative accuracy of integration ~ 10^{-6}

time of solution 0.006sec (3GHz CPU)



$$x = \log r, \ \ a = \log A, \ \ b = \log B$$

The physical meaning of the constants

$$c_3 = u_\mu u^\mu = -1, 0, +1$$

matter type: massive, null, tachyonic (M/N/T-RDM)

solution *in strong fields (A<<1)* does not depend on matter type, since the term $c_3 A$ becomes small

solution *in weak fields (A~1)* depends on combination of constansts:

$$c_4 = 4c_1c_2,\ c_5 = c_3/c_2^2,$$

$$c_6 = c_4\sqrt{1+c_5},\ c_7 = c_4/\sqrt{1+c_5},$$

parameter c_5 defines *asymptotic radial velocity* of dark matter:
c_5<-1, MRDM flow has a turning point, the matter cannot escape
c_5>-1, all matter types, the matter can escape to large distances (the case further considered)

$$\epsilon = (c_6 + c_7)/2$$

parameter, defining *asymptotic gravitating density* (ρ_{eff}+p_{eff}) of dark matter flow

$$\rho_{\rm eff} = c_4/(2r^2)/\sqrt{1+c_5}, \quad p_{\rm eff} = c_4/(2r^2)\cdot\sqrt{1+c_5}$$

directly measurable parameter: $\varepsilon = (v/c)^2$, where v is the orbital velocity of stars at large distances from the galaxy center, for Milky Way v ~ 200 km/s, ε = $4\text{x}10^{-7}$

Comparison of RDM model with parameters of Milky Way

model parameters	$\epsilon = 4 \cdot 10^{-7}$, $r_0 = 1.2 \cdot 10^{10}$ m
a border of the galaxy (starting point)	$r_1 = 3.1 \cdot 10^{21}$ m, $a_1 = 0$, $b_1 = 2.67 \cdot 10^{-7}$
data at Earth location	$r_E = 2.57 \cdot 10^{20}$ m, $a_E = -2 \cdot 10^{-6}$, $b_E = b_1 + 4 \cdot 10^{-11}$
switch from DM-dominated to Keplerian regime	$r_{1a} = 1.5 \cdot 10^{16}$ m, $a_{1a} = -1.05 \cdot 10^{-5}$, $b_{1a} = 9.91 \cdot 10^{-7}$
switch to Schwarzschild regime	$r_{1b} = 3.33 \cdot 10^{10}$ m, $a_{1b} = -b_{1b} - 2.06 \cdot 10^{-5}$, $b_{1b} = 0.404$
begin of the supershift	$r_2 = 1.11 \cdot 10^{10}$ m, $a_2 = -14.79$, $b_2 = 13.40$
switch of integration $b(a) \to a(b)$	$r_{2a} = r_2 - 1.2 \cdot 10^{4}$ m, $a_{2a} = -16.79$, $b_{2a} = 12.54$
end of the supershift	$r_3 = 6.8 \cdot 10^{6}$ m, $a_3 = b_3 - 14.79$, $b_3 = -1.33 \cdot 10^{6}$
redshift at the minimal radius (Planck length)	$r_{Pl} = 1.62 \cdot 10^{-35}$ m, $a_{Pl}/a_3 - 1 = -7.19 \cdot 10^{-5}$

100kpc

DM domination

Sun-Earth
8.3kpc

S-stars
Kepl.orbits
$10^{13\text{-}15}$m

circular orbits
become instab.

gravit.
radius

supershift
(mass
inflation)

naked
singularity

=> supershift remains **red** until Planck length (no UV-catastrophe)

RDM and TOV stars

- static spherically symmetric solutions of Einstein field equations (EFE)
- differ by the equation of state (EOS)

  $\rho = p_r$, $p_t = 0$, null radial dark matter (NRDM), in particular

  $w\rho = p_r = p_t$, Tolman-Oppenheimer-Volkoff (TOV), w=1/3 photon gas, presented later
- in the considered scenarios, both contain a core of negative mass
- behave like T-symmetric combination of black and white hole solutions
- permanently absorb and eject (dark) matter
- similarity with Planck star model: QG bounce repeats continuously
- similarity with Ori-Poisson null-shell model: T-symmetric ingoing and outgoing shells repeat continuously, blue sheet formation equivalent to mass inflation phenomenon
- mass inflation (Hamilton, Pollack 2005): a positive feedback loop in black hole solutions with counterstreaming matter flows: (a) increasing energy of the crossing flows => (b) increasig pressure => (c) increasing gravity => (a); leads to an accumulation of very large mass in the counterstreaming region

RDM-stars: Misner-Sharp mass

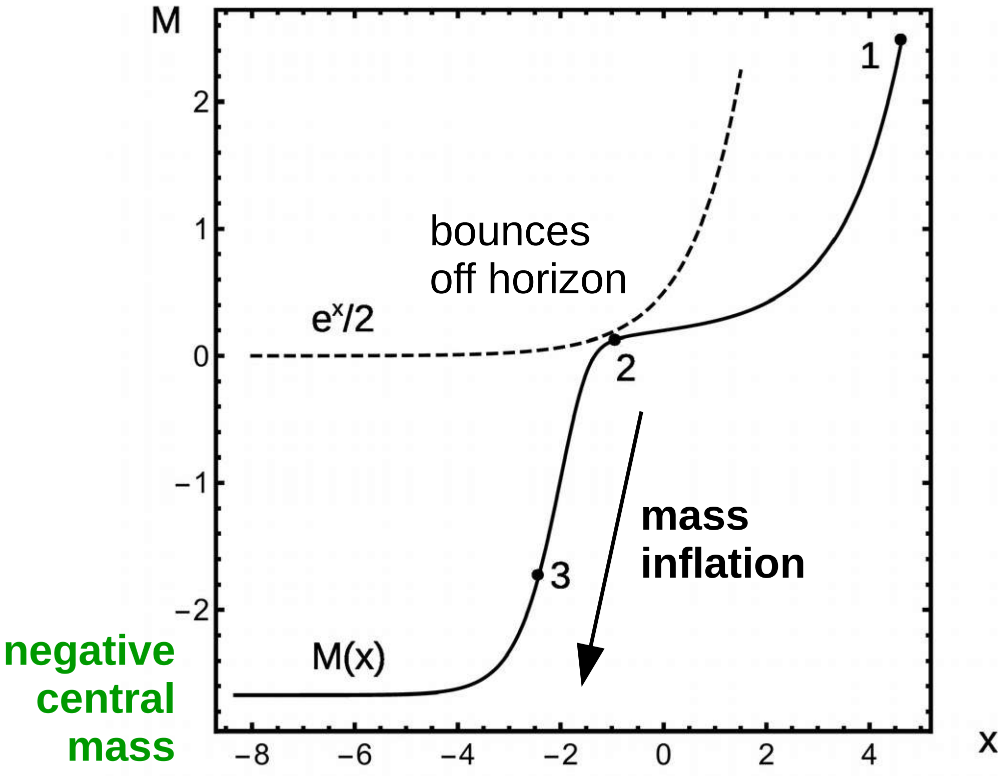
$$M = r/2\ (1 - B^{-1})$$

(1) decreases with decreasing r (imagine positive mass layers removed from the star)

(2) when approaching the horizon (2M = r), decreases faster 2M<r, the horizon is erased

(3) decreases very rapidly in supershift region, **mass inflation**

(4) possesses **negative central value**, corresponding to Schwarzschild's naked singularity



RDM stars: QG cutoff

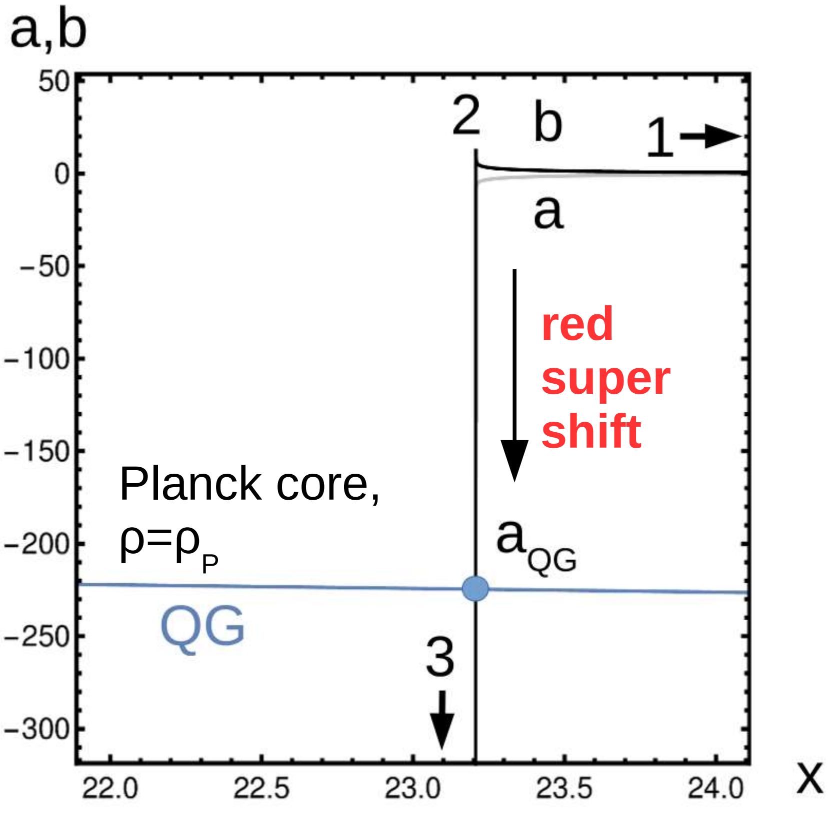
considering NRDM: $\rho = \varepsilon/(8\pi r^2 A)$

Planck core condition: $\rho=\rho_P$

the most of the structures are cut before reaching the naked singularity, in supershift/mass inflation region

$A_{QG} = \varepsilon(L_P/r_s)^2/(8\pi)$

MW: $\mathbf{A_{QG}^{1/2} \sim 10^{-49}}$



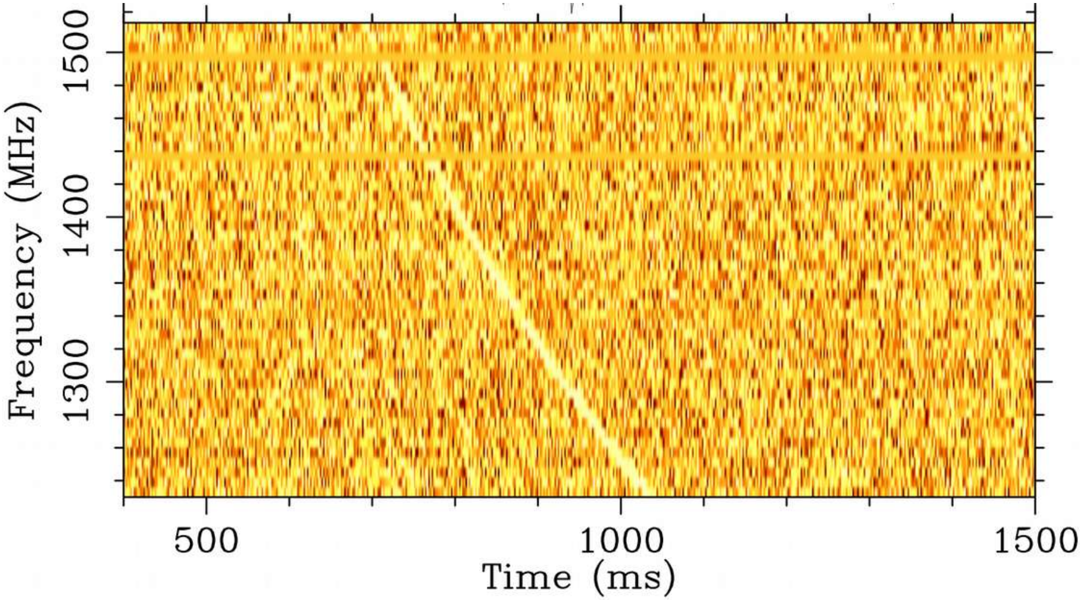
calculation for the Milky Way galaxy

$$x = \log r, \;\; a = \log A, \;\; b = \log B$$

Relation to Fast Radio Bursts

Fast Radio Bursts (FRB), powerful flashes of extragalactic origin

Big Scanning Antenna (BSA), Pushchino, Russia, registered 11 FRB of lowest frequency **111MHz**

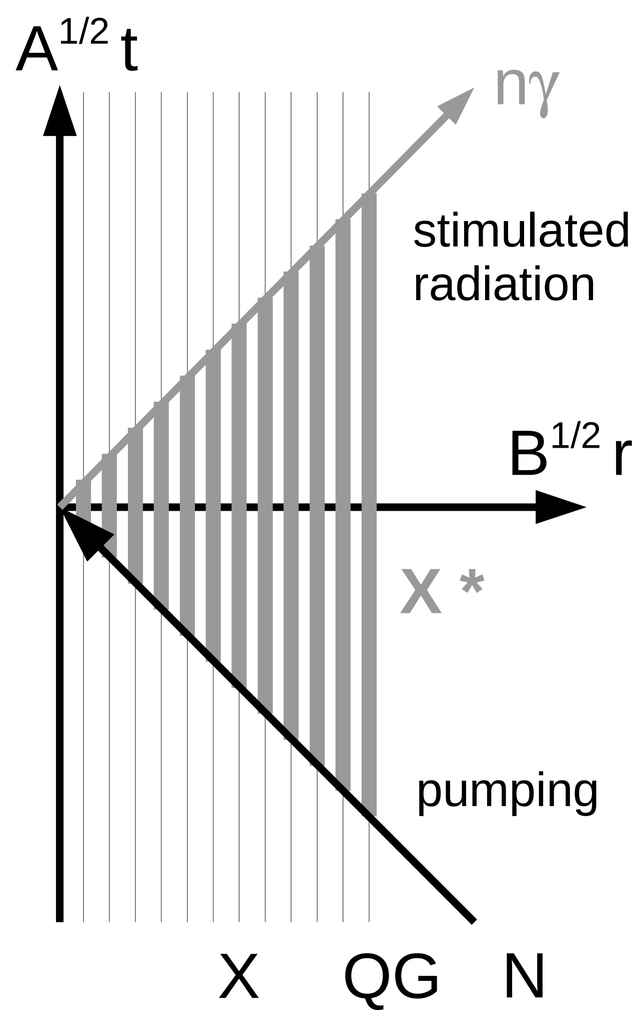


typical signature of FRB (the first registered flash FRB010724, Lorimer et al. 2007, frbcat.org)
the slope indicates high dispersion shift (extragalactic distance)

- reported totally 111 FRB sources, 11 of which are repeating (data of 06.06.2020, frbcat.org)
- duration: *0.08ms (fast) - 5s,* frequency: **111MHz-8GHz** (radio band)
- typical isotropic energy of the flash ~ $10^{32\text{-}34}$J, corresp. $E = mc^2$ for a small asteroid
- the nature of bursts is currently unknown, 59 theories exist (06.06.2020, frbtheorycat)

Relation to Fast Radio Bursts

- FRB generation mechanism in RDM model
- object of an asteroid mass falls onto the RDM-star
- grav. field acts as an accelerator with super-strong **ultrarelativistic factor $\gamma \sim 10^{49}$**
- nucleons N composing the asteroid enter in the inelastic collisions with particles X forming the Planck core, producing the excited states of a typical energy **$E(X^*) \sim \mathrm{sqrt}(2m_X E_N)$**
- high-energy photons formed by the decay of X* $E(\gamma,in) \sim E(X^*)/2$ are subjected to super-strong **red shift factor γ^{-1}**
- outgoing energy $E(\gamma,out) \sim \mathrm{sqrt}(m_X m_N/(2\gamma))$, wavelength $\lambda out = \mathrm{sqrt}(2\lambda_X \lambda_N \gamma)$, where $\lambda_X \sim 1.6\times10^{-35}$m (Planck length), $\lambda_N \sim 1.32\text{x}10^{-15}$m (Compton wavelength of nucleon)
- **$\lambda out = 2 (2\pi)^{1/4} \mathrm{sqrt}(r_s \lambda_N) / \varepsilon^{1/4}$**, for Milky Way parameters $r_s = 1.2\text{x}10^{10}$m, $\varepsilon = 4\text{x}10^{-7}$, $\lambda out = 0.5$m, $\nu out =$ **600MHz**
- falls in the observed range **111MHz-8GHz**
- a common mechanism of stimulated emission (aka LASER) generates a short pulse of ***coherent radiation***



Relation to Fast Radio Bursts

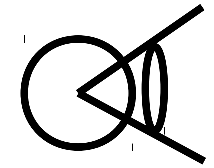
- other parameters of FRBs, arXiv:1812.11801
- ***spectral index*** $E|dn/dE| \sim E^{\alpha}$, $\alpha = -2$, observed $-10.4...13.6$
- temporal characteristics influenced by external effects
- ***pulse width*** $W \sim \nu^{\beta}$, $\beta = -4... -4.4$ scatter broadening
  (a) $t_{in} \sim T_P$, $t_{out} \sim T_P A_{QG}^{-1/2} = 3*10^{-12}$ s << $t_{exp} \sim$ ms, then the scattering on intergalactic, destination and host galaxy medium stretches a picosecond pulse to the observed ms
  (b) $t_{in} \sim 10^9 T_P$, $t_{out} \sim$ ms (scenario without scattering)
- ***pulse delay*** $dt \sim \nu^{\gamma}$, $\gamma = -2$, dispersion on interstellar medium
- ***polarization*** of some FRBs can indicate the presence of strong magnetic fields near the source
- ***repeating bursts*** can appear in the passage of a massive object through the asteroid field
- **periodicity** detected for FRB 180916 (16d) and FRB 121102 (157d), can be related with an orbital motion
- ***total energy*** of the burst: isotropic estimation $\sim 10^{15\text{-}17}$ kg corresponds to a mass of an asteroid; narrow beam geometry can reduce this mass; loss of energy to small frequencies (where the signal becomes undetectable due to large scatter broadening) can increase this mass

supermassive BH

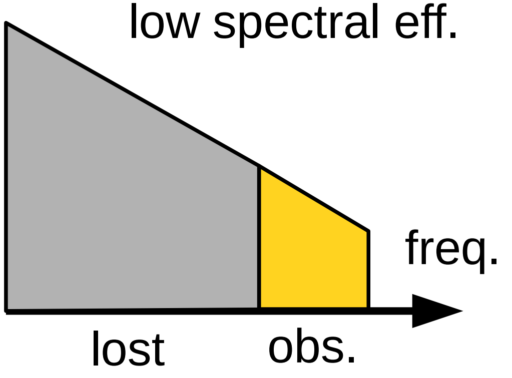
high beam eff.

stellar BH

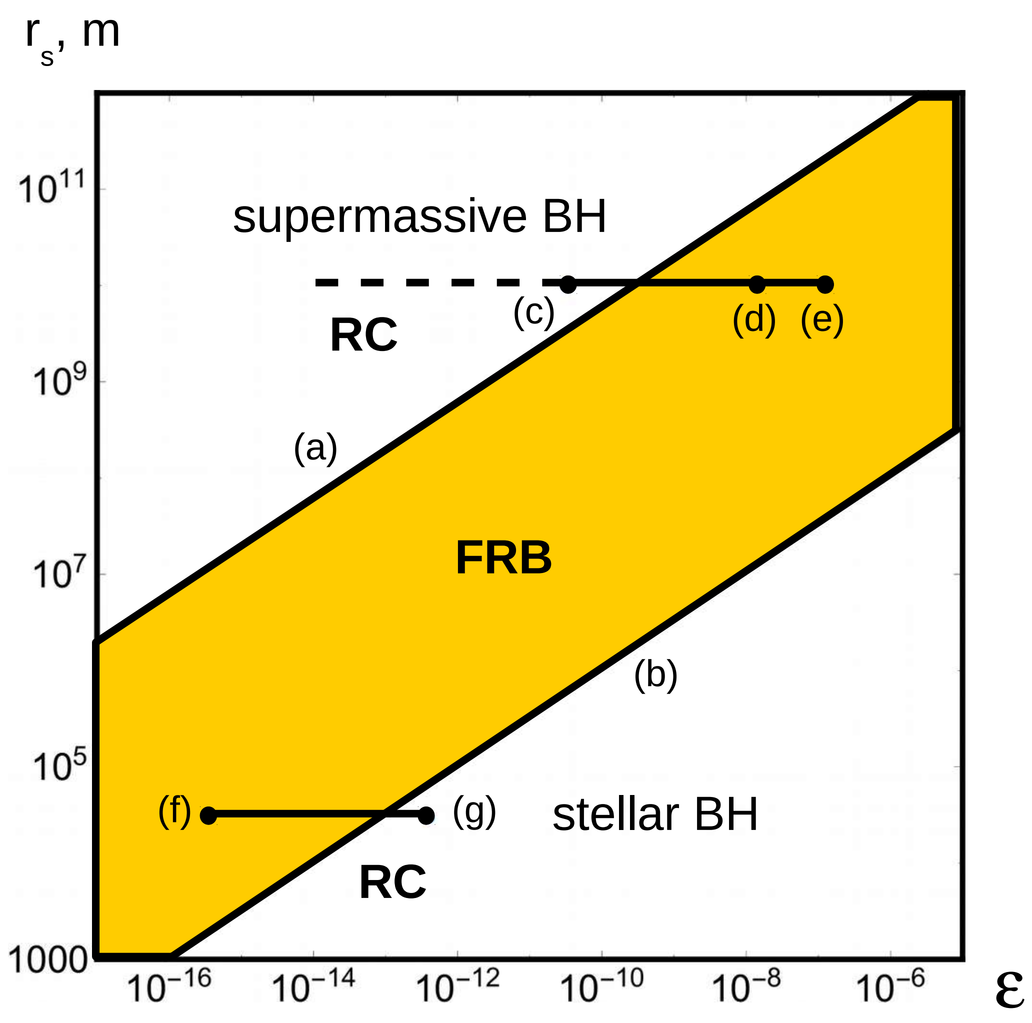
low beam eff.



low spectral eff.



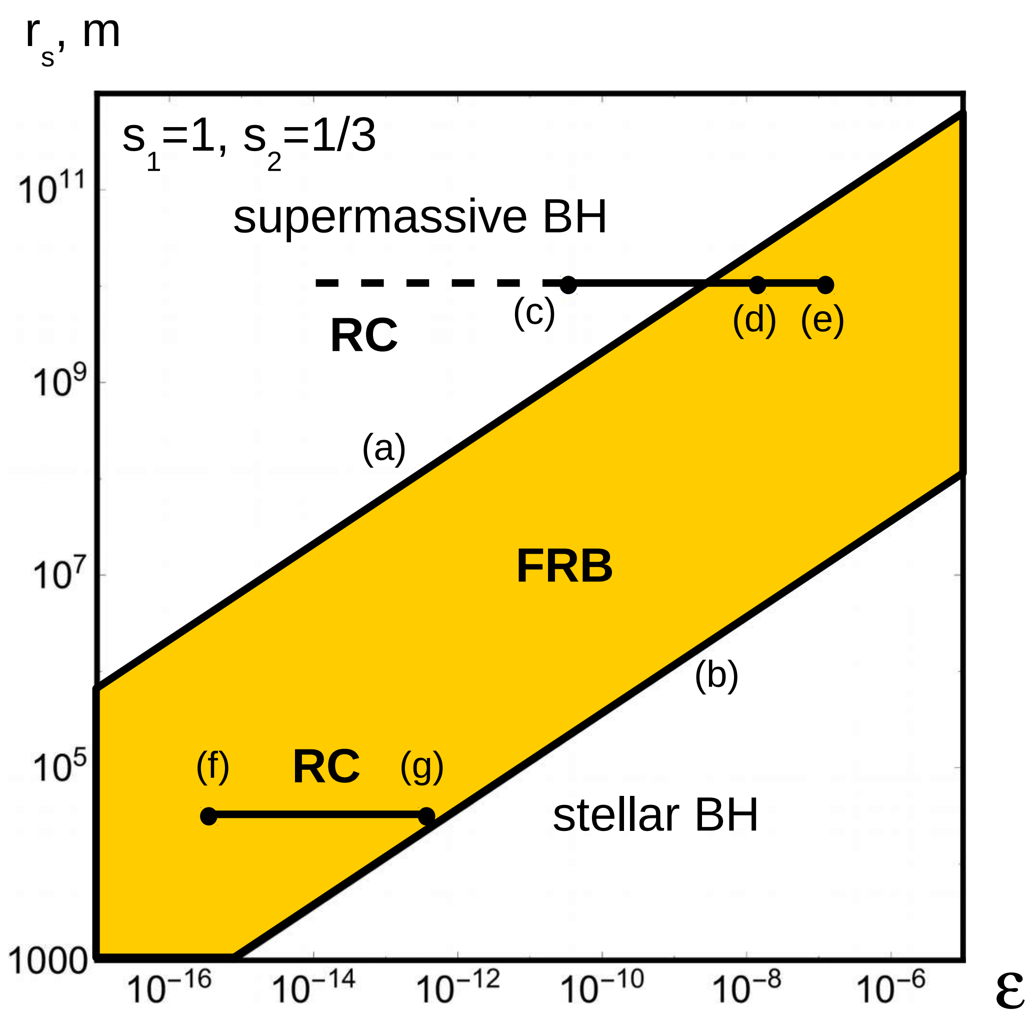
Combined analysis of RCs and FRBs



two solutions for FRB sources: supermassive and stellar BH (here MW estimations)

(a) νout=111MHz, (b) νout=8GHz, (c) MWs2,
(d) MWs3, (e) MWmax for V(smbh,dm)=100km/sec,
(f) $\varepsilon=4\times10^{-7}$ div to $Nsbh=10^9$, (g) same with $Nsbh=10^6$
(Wheeler, Johnson, 2011)(arxiv:1107.3165)

Combined analysis of RCs and FRBs



(a) νout=111MHz, (b) νout=8GHz, (c) MWs2,
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(f) $\varepsilon=4\times10^{-7}$ div to Nsbh=10^9, (g) same with Nsbh=10^6
(Wheeler, Johnson, 2011)(arxiv:1107.3165)

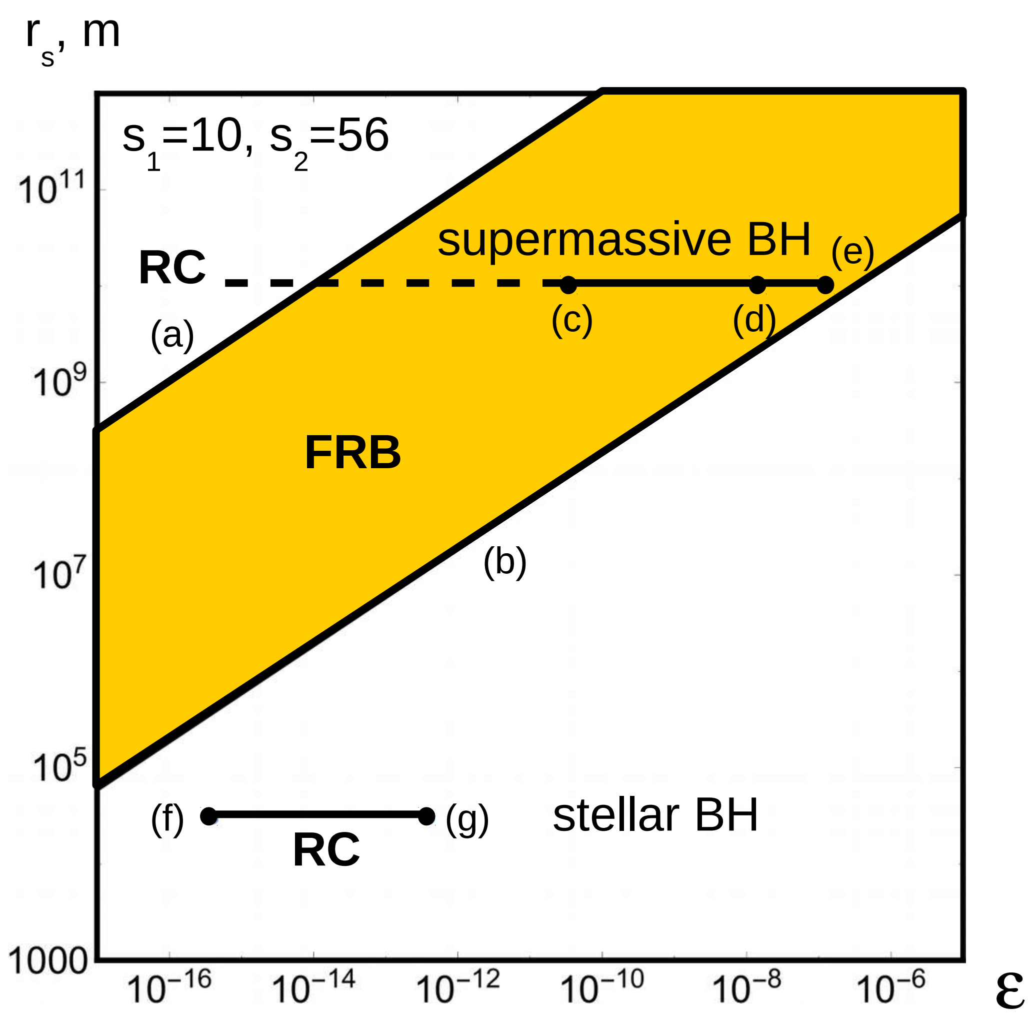
FRB adjustment factors:

earlier onset of QG effects: $\rho \rightarrow \rho_P/s_1$

nucleon fragmentation factor: $\lambda_N \rightarrow \lambda_N/s_2$

s_1=1, s_2=1/3 (constituent quarks)

Combined analysis of RCs and FRBs



(a) νout=111MHz, (b) νout=8GHz, (c) MWs2,
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(Wheeler, Johnson, 2011)(arxiv:1107.3165)

FRB adjustment factors:

earlier onset of QG effects: $\rho \rightarrow \rho_P/s_1$

nucleon fragmentation factor: $\lambda_N \rightarrow \lambda_N/s_2$

s_1=10, s_2=56 (iron nuclei)

=> RDM descriptions of RCs and FRBs are compatible

Conclusion3: RDM model with Planck core can decribe simultaneously the shape of galactic rotation curves and the properties of fast radio bursts

TOV stars with QG core (QG-bubbles)

TOV equations:

$$w\rho'_r = -(\rho M/r^2)(1+w)(1+4\pi r^3 w\rho/M)(1-2M/r)^{-1}$$
$$M'_r = 4\pi r^2\rho,\ h'_r = 4\pi r(1-2M/r)^{-1}\rho(1+w)$$

metric: $A = e^{2h}f,\ B = f^{-1},\ f = 1 - 2M/r$

- EFE for static spherically-symmetric solution with $w\rho = p_r = p_t$ EOS
- usually solved assuming regularity in the center: $M(0)=0$
- this condition relates background density and total mass: $\rho(r_1)$, $M(r_1)$, at large r_1
- we will solve the eqs without this precondition
- a concentrated mass can be located in the center

QG-bubbles

Equivalent form:

$$r(p+\rho)A'_r + 2Arp'_r = 0$$

hydrostatic equation
(a consequence of TOV system)

$$4\pi w\rho = k_3 A^{k_4}$$

analytical solution

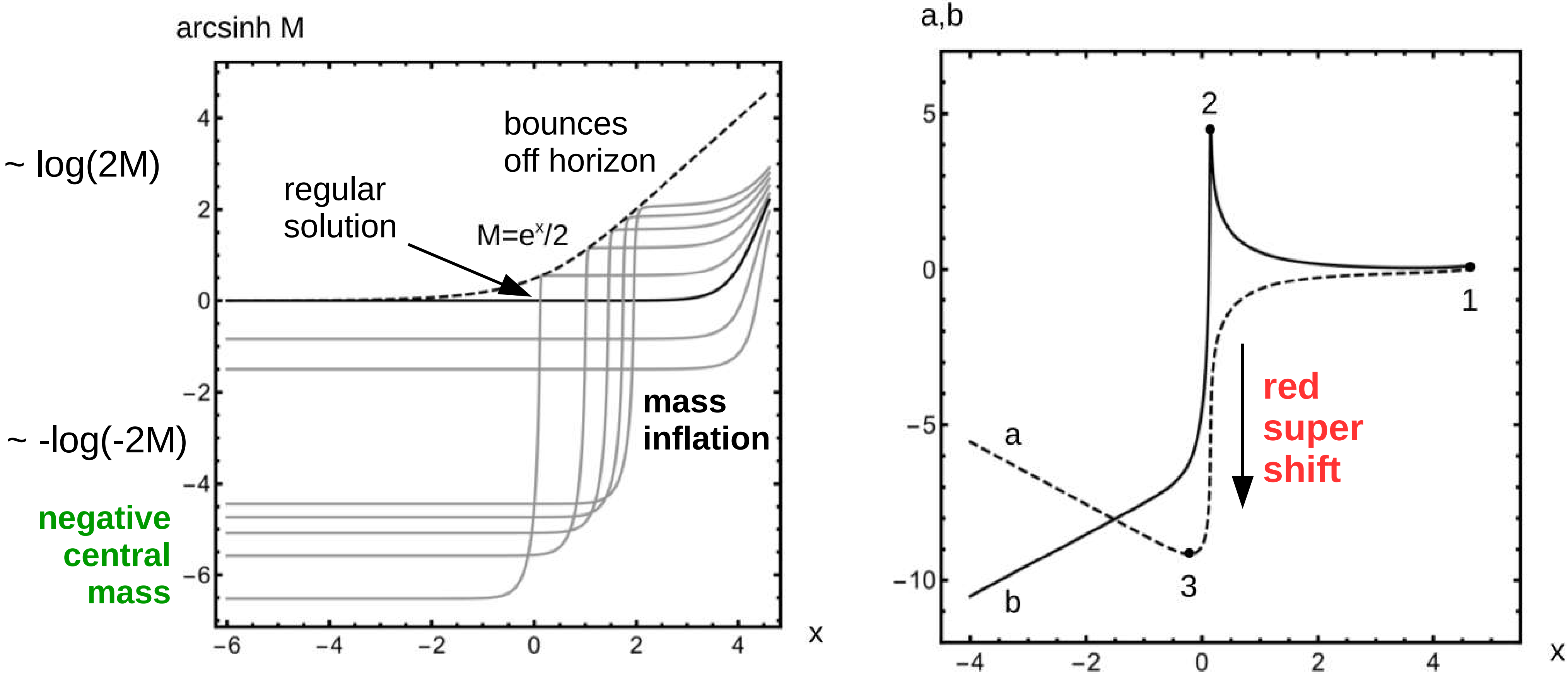
$$k_1 = 1/w,\ k_3 = 4\pi\rho_1 w,$$
$$k_4 = -(1+k_1)/2,\ k_6 = \log k_3$$

photon gas: w=1/3, k_4=-2

$$a'_x = -1 + e^b + 2e^{2x+k_4 a+b+k_6},$$
$$b'_x = 1 - e^b + (2/w)e^{2x+k_4 a+b+k_6}$$

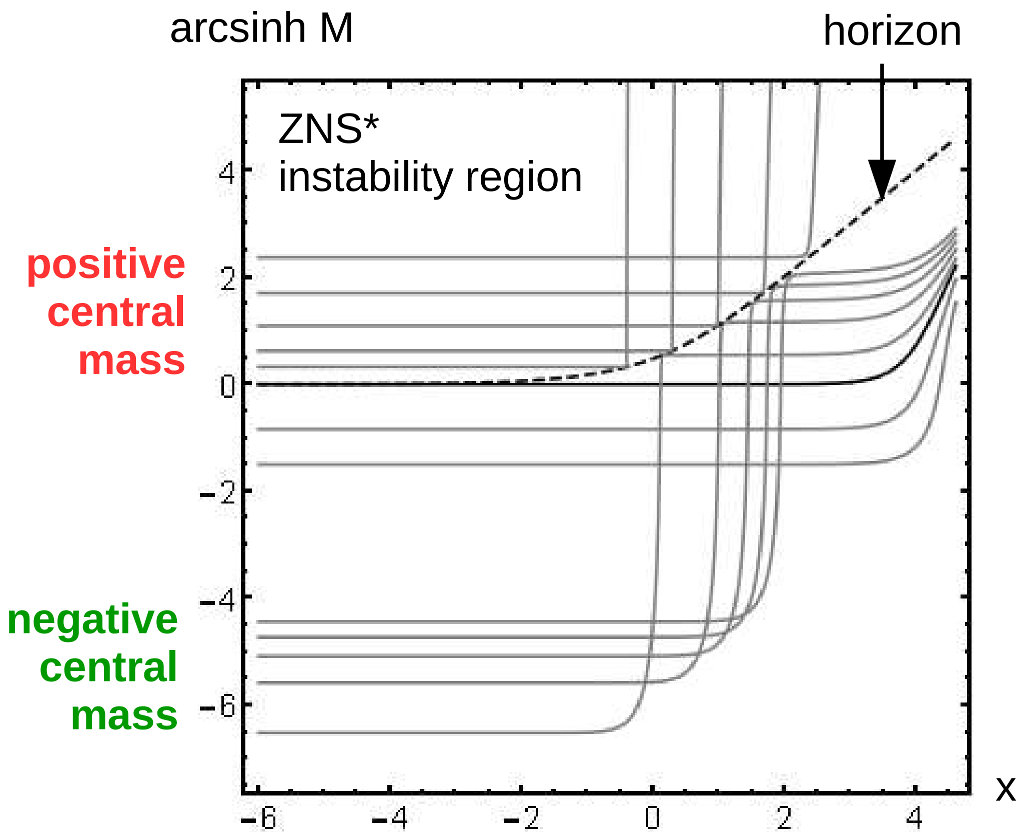
ODE system in logarithmic vars, more convenient for numerical solution

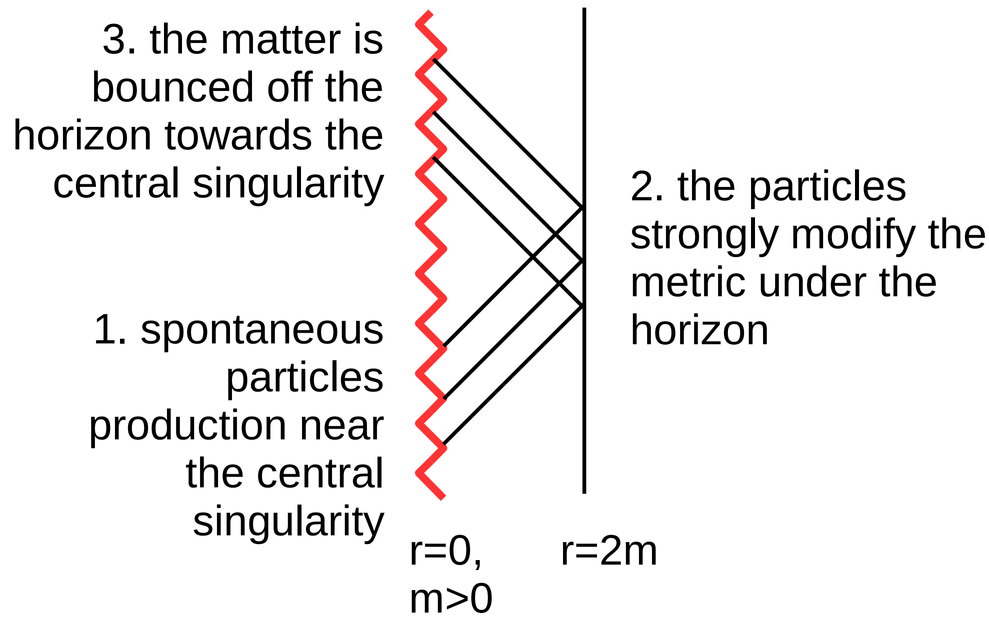
QG-bubbles



- the regular solution subdivides the set of solutions to two regions
- for solution with initial mass smaller than regular value, the solution just goes to the negative mass in the center
- for solution with initial mass larger than regular value, instead of forming the black hole, the solution bounces of horizon, goes through the mass inflation and ends in even more negative mass in the center
- behavior is similar to RDM-star, just the achieved (a,b,M) values are more moderate

QG-bubbles





- solving TOV-alike system at r<2M for diff. EOS
- solutions resemble: FLRW cosmology of closed type; NRDM model at r<2M
- common property : the matter bounces off horizon and cannot go outside

- *Zeldovich, Novikov, Starobinskiy, Quantum effects in white holes (1974)
- describes the other type of white holes instability
- white hole with the space-like singularity (**m>0**) is unstable, the ejected matter modifies the equations in a way that it cannot come out of the horizon
- we consider the solution with time-like singularity (**m<0**), outside of the instability region

QG-bubbles

Table : TOV model scenario with a stellar mass compact object in cosmic microwave background

model parameters	$M_1 = 10 M_\odot$, $w = 1/3$, $\rho_1 = \rho_{cmb} = 4 \cdot 10^{-14}$ J/m^3
starting point of the integration	$r_1 = 10^6$m, $a_1 = 0$, $b_1 = 0.0299773$, $M_1/M_\odot = 10$
supershift begins	$r_2 = 29532.4$m, $a_2 = -54.2719$, $b_2 = 53.7265$, $M_2/M_1 - 1 = -3.64729 \cdot 10^{-23}$, $\boxed{r_2 - 2GM_2/c^2 = 1.37139 \cdot 10^{-19}\text{m}}$
supershift ends	$r_3 = 20638.1$m, $a_3 = -107.522$, $b_3 = -104.685$, $\boxed{\log_{10}(-M_3/M_\odot) = 46.3087}$
minimal radius (Planck length), end of the integration	$r_4 = 1.62 \cdot 10^{-35}$m, $a_4 = -17.6594$, $b_4 = -195.278$, $M_4 = 1.728\ M_3$

QG-bubbles

Comments:

- **$r2-rs \sim 10^{-19}$m**, the extremely small gap separating the object from the gravitational collapse. At this distance initially inactive matter terms, describing relict radiation, wake up and begin to influence strongly the structure of the solution. This is the result of purely classical model, quantum considerations can change this number.

- log10(-M3/Msun)~46, for comparison: log10(Muni/Msun)~23. Thus, QG-bubble contains a core of negative mass **|M3| >> Muni**, compensated by the coat of TOV matter with (almost) the same positive mass. The numbers for null shell and RDM models are even larger: log10(-M3/Msun)~10^{15}, 10^{5}.

- These enormous numbers could be the result of model idealization. Their origin is the unrestraint phenomenon of **mass inflation**. It can be changed if a (non-gravitational) interaction between the counterstreaming flows and corresponding corrections to EOS will be taken into account.

QG-bubbles

Comments:

- The other origin of large numbers is Planck density: $\rho_P = c^5/(\hbar G^2)$ = **5×10^{96} kg/m^3**. Straightforward estimation for the Planck density core of only **R = 1mm** radius gives the mass $M = (4/3)\pi R^3 \rho_P = 2 \times 10^{88}$kg, gravitational radius: $Rs = 2GM/c^2 = 3 \times 10^{61}$m, compare to the mass and the radius of the observable universe Muni = 10^{53}kg, Runi = 4×10^{26}m => such a core will immediately cover the universe by its gravitational radius, with a large margin. A mechanism for mass compensation is necessary to place such objects in our universe.

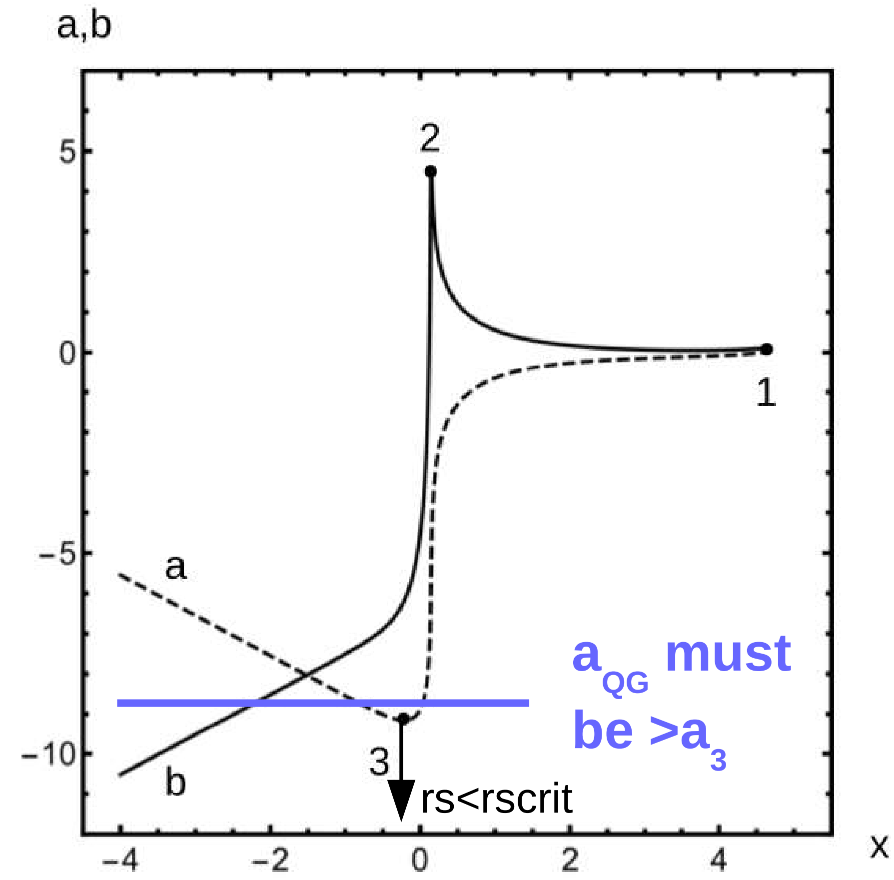
- Enormous reserve of energy hiding inside QG-bubble can fuel extremely high-energy phenomena. *If a QG bubble bursts somewhere, the consequences can be felt throughout the universe.*

QG-bubbles as possible sources of FRBs

- take solution of TOV hydrostatic equation: $\rho \sim A^{-2} \Rightarrow \rho_P/\rho_{cmb}=A_{QG}^{-2}$
- consider $\rho_P=4.633*10^{113}$ J/m^3; $\rho_{cmb}=4.19*10^{-14}$ J/m^3, in energetic units $\Rightarrow A_{QG}=(\rho_{cmb}/\rho_P)^{1/2}=3*10^{-64}$
- consider a photon of initially Planck energy, $E_{in} \sim E_P$, $\lambda_{in} \sim L_P$ $\Rightarrow$ after applying the redshift, outgoing wavelength $\lambda_{out}=L_P\, A_{QG}^{-1/2}$=**0.9mm**
- compare with λ_{exp}=**37.5mm** (for the highest 8GHz FRB detection of FRB121102) deviation $\lambda_{exp}/\lambda_{out}$ **~40**
- can be considered as a good hit, taking into account 127 orders of difference in the input density parameters
- technically can be compensated by an attenuation factor $E_{in}= E_P/N$, the initial photon is N~40 weaker than Planck energy
- a part of this factor can be related with (1+z) Hubble redshift, z~0.2-0.3, N~30

QG-bubbles as possible sources of FRBs

- **can the Planck density be reached?**
- in point 3 solution has a minimum of the redshift factor
- reachability of Planck density: $a_{QG}>a_3$
- fixing $\rho_{bgr}=\rho_{cmb}$ and varying solution mass, this condition is satisfied at $M<7.6*10^{22}$ kg ~ Moon's mass, rs<rscrit=0.11mm (micro QG-bubbles)



QG-bubbles as possible sources of FRBs

$$\text{Table: micro QG-bubble, the critical case}$$

model parameters	$w = 1/3,\ \rho_1 = \rho_{cmb} = 4 \cdot 10^{-14}\ \text{J/m}^3,\ \boxed{a_{QG} = -146.264}$
starting point of the integration	$r_1 = 1.13042 \cdot 10^{-2}\text{m},\ a_1 = 0,\ b_1 = 0.0100503,$ $M_1 = 7.61132 \cdot 10^{22}\text{kg}$
supershift begins	$\boxed{r_2 = 1.13042 \cdot 10^{-4}\text{m},}$ $a_2 = -73.6529,\ b_2 = 73.0876,$ $r_2 - 2GM_2/c^2 = 2.04973 \cdot 10^{-36}\text{m}$
supershift ends	$r_3 = 7.89967 \cdot 10^{-5}\text{m},$ $\boxed{a_3 = -146.264,}\ b_3 = -143.408,$ $\log_{10}(-M_3/M_\odot) = 54.7085$
minimal radius (Planck length), end of the integration	$r_4 = 1.62 \cdot 10^{-35}\text{m},$ $a_4 = -75.7824,\ b_4 = -214.619,$ $M_4 = 1.72898\ M_3$

QG-bubbles as possible sources of FRBs

- **can the bursts repeat?**
- there is an inner reserve of energy for $7.6*10^{22}$kg*c^2/(10^{32-34}J)~10^{6-8} bursts
- the energy can be also refilled from the environment (e.g., a companion, an asteroid belt,...)
- in this refilling, when the threshold is rs>rscrit passed, the conditions for QG-core existence disappear; this can trigger the FRB, that will return the system to rs<rscrit state (autonomous oscillations)

Conclusion4: QG-bubbles can be the sources of FRB, with a possibility of autogeneration

5 DM Hypotheses

Hypothesis1: galactic DM can be cold, hot, or (theoretically) tachyonic, producing *the same rotation curves*

- in RDM model, orbital v depends only on intensity factor ε, not on matter constitution (cold/hot, M/N/T cases, controlled by the constant c_5 above)
- comparison with Barranco et al. 2015 (arXiv:1301.6785), where a particular solution of TOV eqs was considered and the conclusion was drawn that galactic DM 'must be cold'
- **short explanation:** TOV vs RDM, different EOS, different structure of solutions
- **in more details:** a particular analytical solution of TOV eqs possessing a property of selfsimilarity $\rho \sim 1/r^2$ was considered
- the same pattern as RDM, produces flat rotation curves, but with a different amplitude
- for this particular TOV solution, cold matter produces non-relativistic v, hot matter – relativistic v
- the observed v is non-relativistic, from here is the conclusion

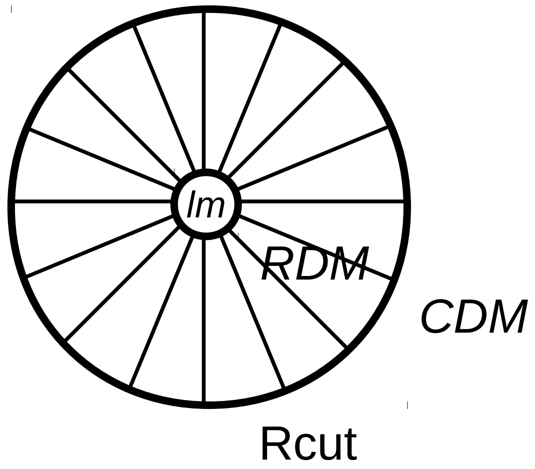
5 DM Hypotheses

- **even more details:** a physical explanation of TOV selfsimilar solution
- a particular, singular and very specific solution, which can appear with an ideal gas in a spherical volume of an arbitrary radius, also a small one, e.g., R=1m
- a common TOV solution with a regular core looks like ρ~const, compare to an (approximately) uniform gas distribution in R=1m balloon at normal conditions
- for creation of the singular solution, very high mass of the gas is needed, which will force it to condense under the action of own gravitational field
- the higher the temperature is, the larger mass is necessary, producing also higher orbital velocities of bodies in its field
- for the photon gas, the mass should be so large that the orbital velocities become relativistic

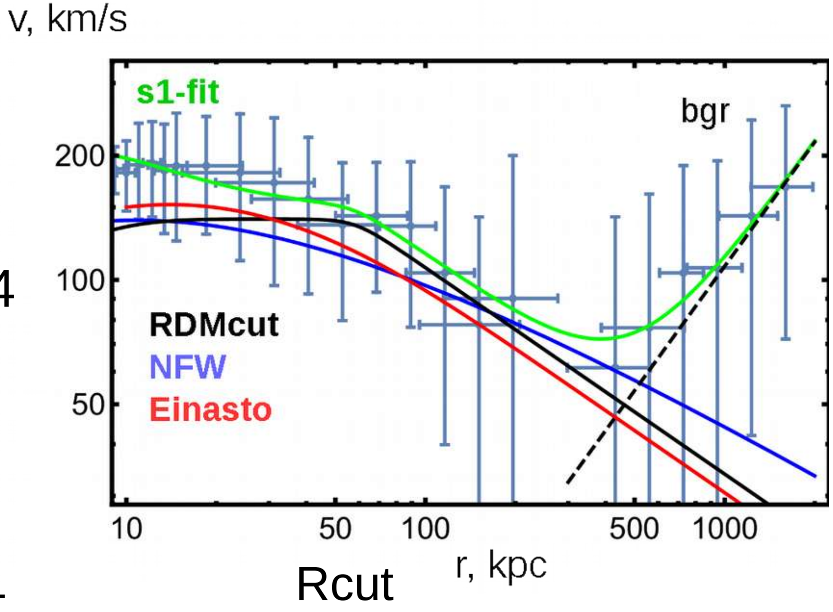
- differently for RDM, where $\rho \sim 1/r^2$ holds always from geometrical reasons and the observed non-relativistic v can be obtained both for cold and hot DM

5 DM Hypotheses

Hypothesis2: (cut&paste approach) galactic DM of any nature stitched at Rcut to cold cosmological DM



- caused by a self-interaction of DM at Rcut limit
- similar to a termination shock on the border of the solar system, where the radially directed solar wind meets the uniform interstellar medium
- GRC fit with RDMcut model gives Rcut~50kpc (although does not distinguish between different models due to high scatter in the outer region)
- *Tully-Fisher relation* can be derived in RDMcut model: Mlm ~ Vmax$^{\beta}$, with β=3-4 (theory), β=3.64 $\pm$ 0.28 (exp, Torres-Flores et al. 2011, arXiv 1106.0505)
- derivation based on KT-integral with Mlm~Rcut^{D}, D=3, classical uniform distribution, D~2, *fractal distribution* (Mandelbrot 1982-1997; Pietronero et al. 1997; Kirillov, Turaev 2006)



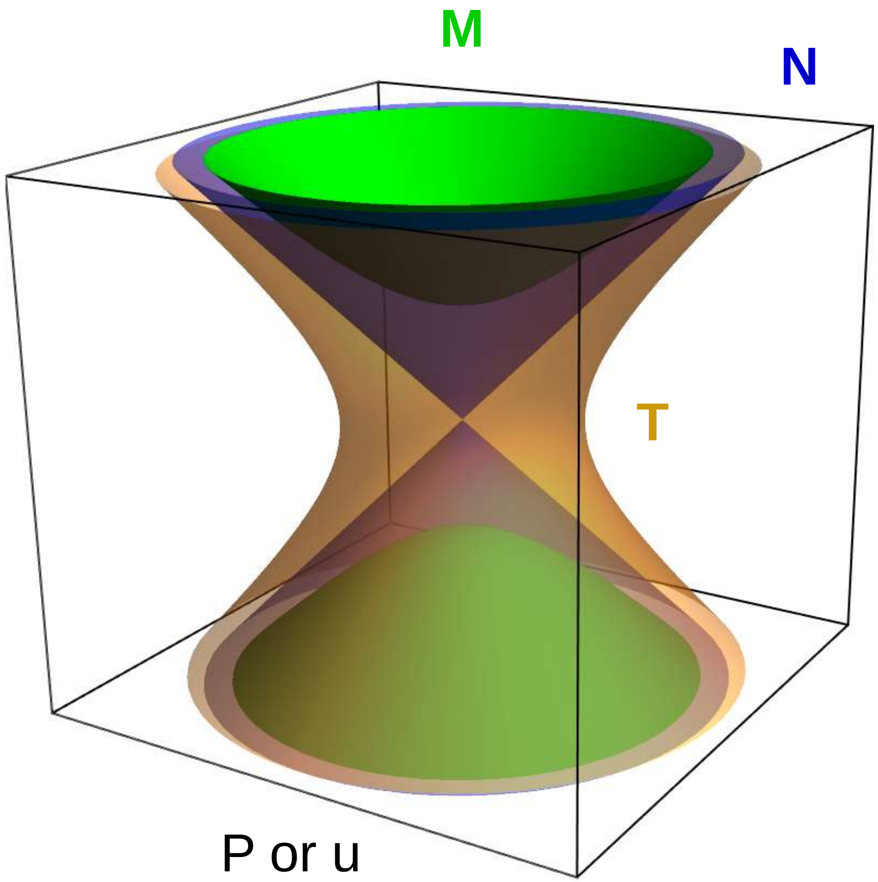
5 DM Hypotheses

Hypothesis3: emission of galactic DM from Planck core can be *acausal*

- RDM star contains two Tsym flows, ingoing and outgoing
- sterile DM, no interaction with the rest of the world (except of non-local gravitational and local high temperature at Planck core)
- can have decoupled termodynamics, with other time arrow or absence of it (T-sym thermodyn., max enthropy, equilibr. state)
- mass shells:

  one-sheet tachyonic, contains both ingoing and outgoing directions

  two-sheet massive/null, T-sym occupied

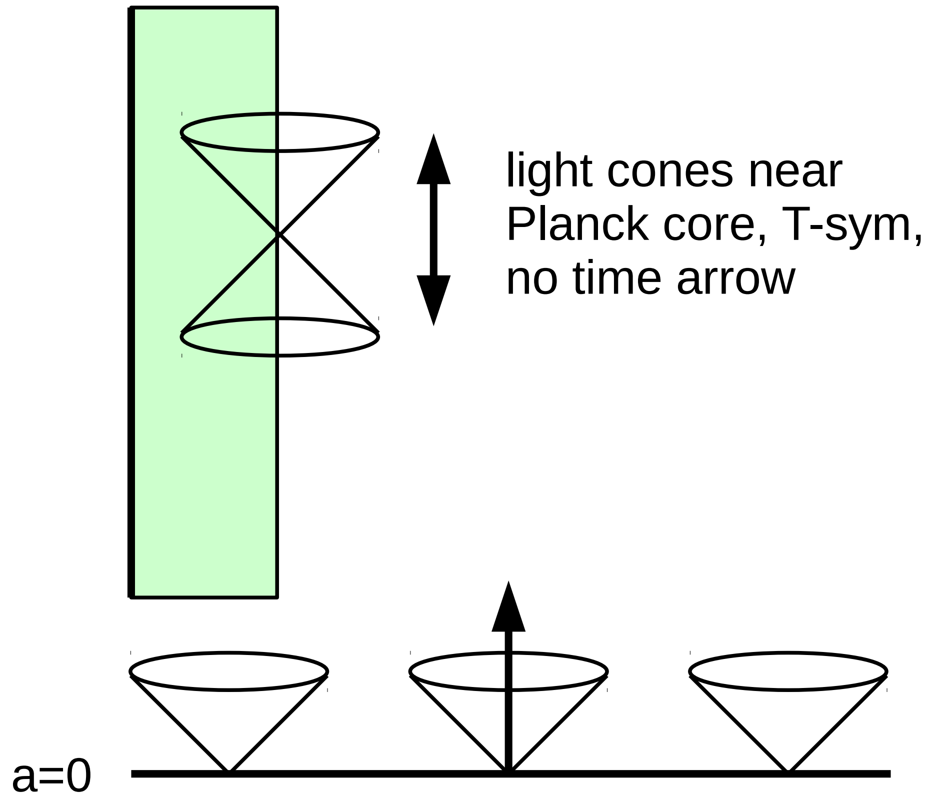


Remark: $P_0<0$ corresponds to T-conj flow of the same particles as $P_0>0$

$A=m\int d\tau\, |x'_\mu x'^\mu|^{1/2}$ and $T^{\mu\nu}=\rho\, u^\mu u^\nu$ are invariant under T-reflection

5 DM Hypotheses

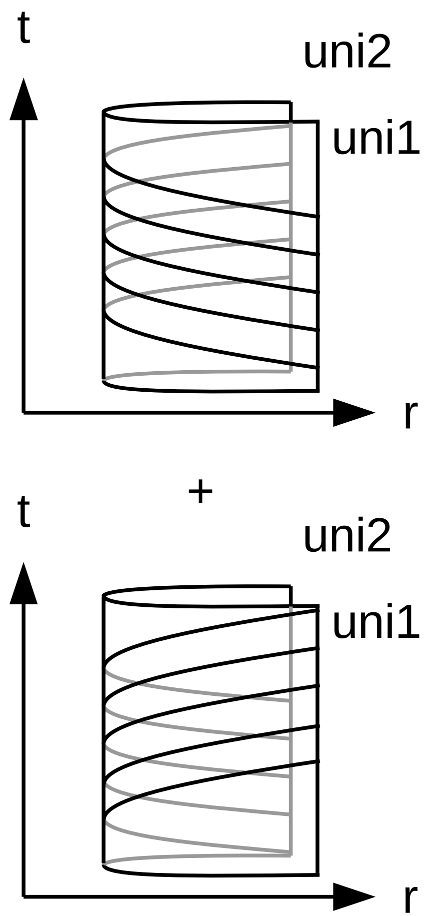
- Planck core temperature conditions are similar to Big Bang
- with a difference that RDM singularity and Planck core are timelike, while Big Bang singularity is spacelike
- different orientation of light cones can lead to the absence of time arrow (recovered T-sym) near Planck core and its presence near/after Big Bang

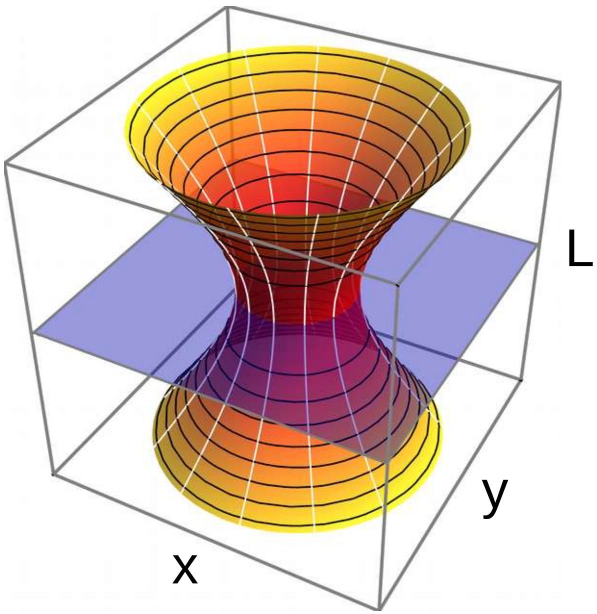


light cones near Big Bang singularity, time arrow

5 DM Hypotheses

- another possibility: in/outgoing RDM world lines catched by a wormhole
- a modification of RDM model with a wormhole in the center: 1707.02764, 1909.08984
- the wormhole can lead to another universe
- uni1/2 can also possess opposite time arrows, so that ingoing flows from our viewpoint are outgoing from their...





Remark: dynamical opening of the wormhole (topology change) is possible (Sorkin 1986, Louko, Sorkin 1997, Horowitz 1991, Ionicioiu 1997, McCabe 2005), see review in my CosmoVIA lecture 2020-03-13...

5 DM Hypotheses

Hypothesis4: sterile DM vs normal matter in *unusual condition*

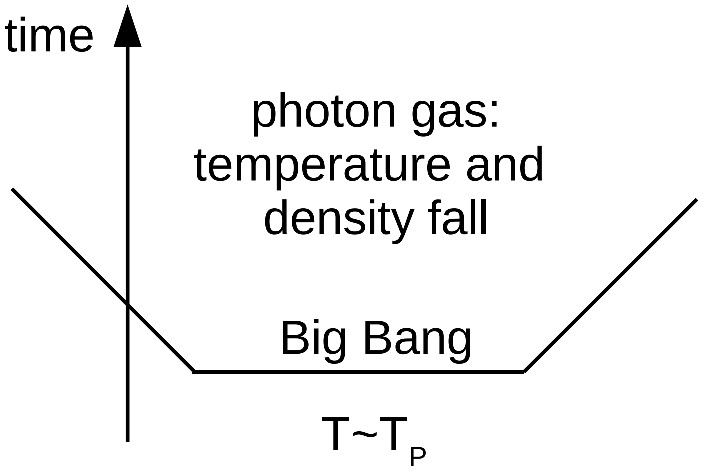
- sterile DM: new type of particles not interacting with the known ones (except of gravitational and Planck temperature interaction)
- alternative are known massless particles (photons, gravitons...) with extremely large wavelength
- in RDM model, at the surface of Planck core the matter has $E \sim E_P$, $\lambda_{in} \sim L_P$
- gravitational redshift $A_{QG}^{1/2} \sim 10^{-49}$, $\lambda_{out} \sim 10^{14}$m~4 light days~16x |Sun-Pluto|
- such longwave particles are not registered by usual means
- DM emission density at Planck core: 1 particle per Planck area per Planck time (corresponds to Planck density and pressure)
- DM density after applying A_{QG} for redshift and gravitational time dilation and geometrical $1/r^2$ factor corresponds to the measured halo mass

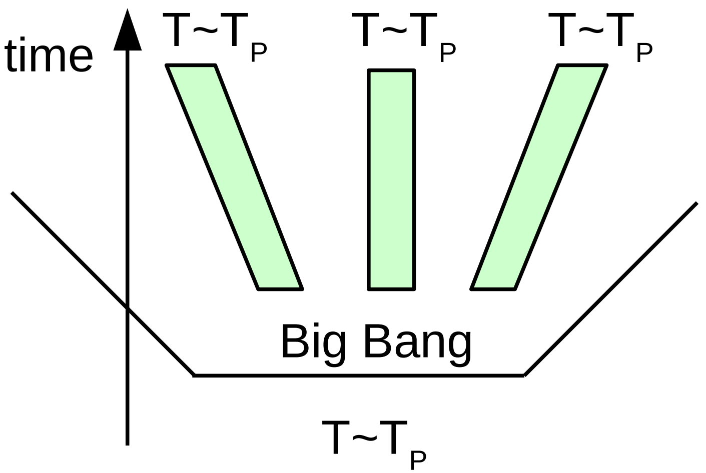
$$A_{QG} = \varepsilon(L_P/r_s)^2/(8\pi), \quad \rho = 1/L_P^2 \, A_{QG} \, (r_s/r)^2 = \varepsilon/(8\pi r^2)$$

5 DM Hypotheses

Hypothesis5: cosmological DM *mimics* CDM

- consider FLRW-cosmology, evolution of uniform photon gas: initial flash, then temperature and density fall in expanding universe
- for CDM only density falls
- differences: RDM model is non-uniform
- thermalization: RDM-stars continuously absorb&inject energy, possess constant $T \sim T_P$
- if they influence DM so that it has a constant T, then in long-range evolution it will behave like CDM



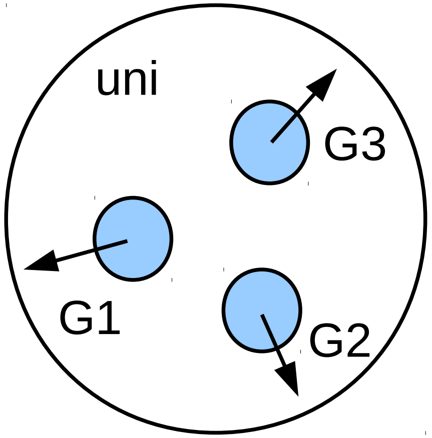


DM: Planck cores support constant local temperature, density falls

5 DM Hypotheses

- other mechanism: EOS of cosmological DM should not be identical to the galactic one
- Swiss cheese model: galaxies and their halos do not change their size and structure under cosmological expansion, move as a whole
- cosmological expansion acts only on the level where the matter distribution can be considered as uniform
- clustering: galaxies coated in massive halos can behave like macro-particles of CDM
- compare with balloons (Dyson spheres) filled with radiation, externally act like cold massive particles
- multiscale / fractal cosmology? Mandelbrot 1982, D=1.23, Pietronero et al. 1987-1997, D~2, recent advances: Einasto et al. 2020, r[Mpc/h] vs D

  r=0 D=1.5, r=2 D=0, r=10 D=2, r=100 D=3



galactic vs cosmological DM: hot inside, cold outside

Conclusion

3 spherically symmetric models with Planck core (effectively negative mass) in the center are considered:

- white holes become stable: both Eardley and ZNS types of instability are fixed
- RDM model can decribe simultaneously the shape of galactic rotation curves and the properties of FRBs
- TOV solutions with Planck core (QG-bubbles) can also generate FRBs

5 Hypotheses about composition of astrophysical DM are put forward

Thank you!