Exotic-singularity-driven dark energy

Mariusz P. Dąbrowski

Institute of Physics
University of Szczecin
Poland

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Content:

- 1. Standard Big-Bang/Crunch versus exotic singularities.
- 2. Phantom dark energy. Big-Rip (type I) as an exotic singularity.
- 3. Sudden Future Singularity (type II) as an exotic singularity.
- 4. Type III (Finite Scale Factor) exotic singularity.
- 5. Generalized Sudden Future, type IV and $w-$singularities.
- 6. Exotic-singularity-driven dark energy.
- 7. Conclusions

1. Standard Big-Bang/Crunch versus exotic singularities.

Standard Einstein-Friedmann equations are two equations for three unknown functions of time $a(t), p(t), \varrho(t)$

$$\varrho = 3\left(\frac{\dot{a}^2}{a^2} + \frac{K}{a^2}\right) , \tag{1}$$

$$p = -\left(2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{K}{a^2}\right) . \tag{2}$$

plus an equation of state, e.g., of a barotropic type ($w =$ const. ≥ -1):

$$p(t) = w\varrho(t) . \tag{3}$$

Since very recently most of cosmologists studied only simplest - say “standard” solutions - each of them starts with Big-Bang singularity in which $a \to 0$, $\varrho, p \to \infty$
– one of them (of $K = +1$) terminates at the second singularity (Big-Crunch) where $a \to 0$, $\varrho, p \to \infty$ – the other two ($K = 0, -1$) continue to an asymptotic emptiness $\varrho, p \to 0$ for $a \to \infty$.

BB and BC exhibit geodesic incompleteness and curvature blow-up.

The paradigm: the obedience of the strong energy condition (SEC)

$$R_{\mu\nu}V^{\mu}V^{\nu} \geq 0, \qquad V^{\mu} - \text{a timelike vector}, \tag{4}$$

($R_{\mu\nu}$ - Ricci tensor) which in terms of the energy density and pressure it is equivalent to

$$\varrho + 3p \geq 0, \qquad \varrho + p \geq 0 . \tag{5}$$

From (1) and (2) one has

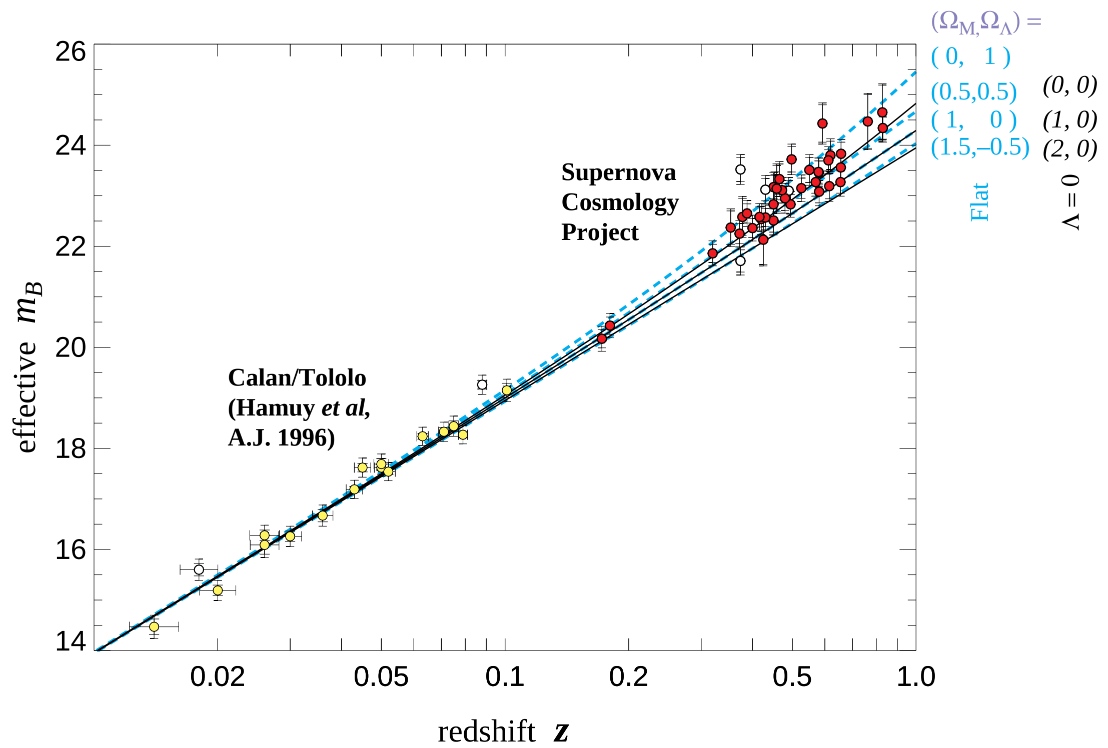
$$-\frac{4\pi G}{3}(\varrho + 3p) = \frac{\ddot{a}}{a} = -qH^2 , \quad (q = -\frac{\ddot{a}a}{\dot{a}^2}; \; H = \frac{\dot{a}}{a}) , \tag{6}$$

which together with (5) means that

$$\ddot{a} \leq 0, \quad \text{or} \quad q \geq 0 , \tag{7}$$

so that the universe was supposed to decelerate its expansion in this “standard”, or better, “pre-supernovae” case.

SCP + High-z Team ('98-'99) made the plot to determine q_0

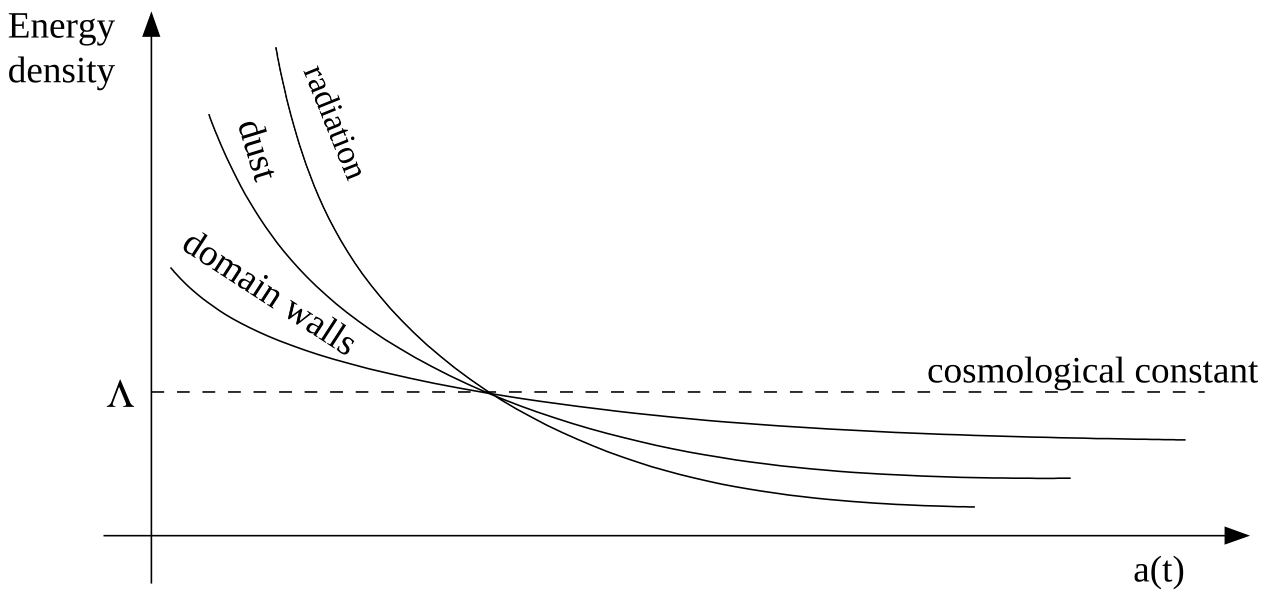


and showed that the best-fit model is for $q_0 = \Omega_M/2 - \Omega_\Lambda < 0$, so that $\ddot{a} > 0$ - favours dark energy with negative pressure ($-1 \leq w \leq 0$).

This gave evidence for the strong energy condition (5) violation, but **the paradigm of the "standard" Big-Bang/Crunch singularities remained untouched.**

This is no wonder in view of the cosmic “no-hair” theorem which says that

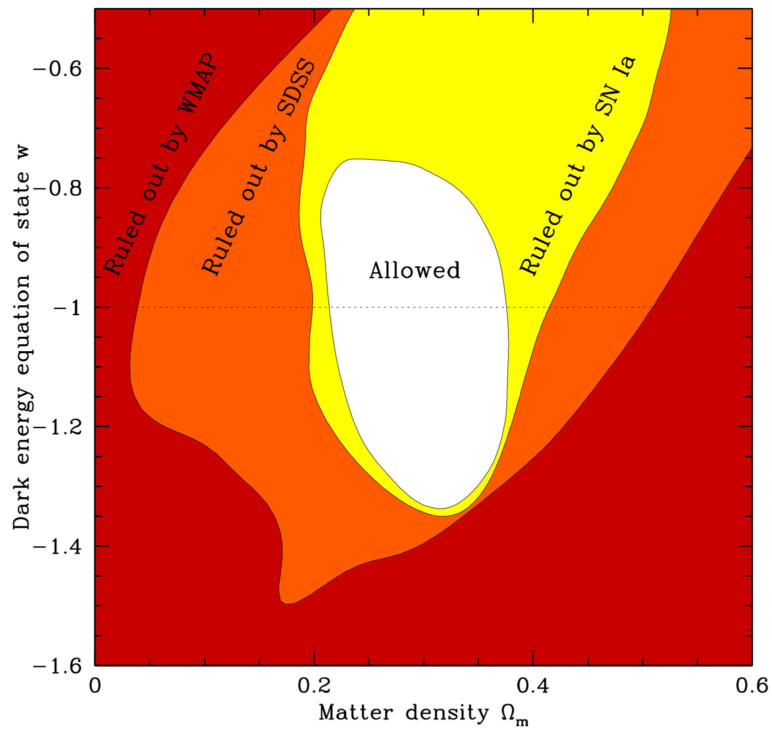
if only $w = \text{const.} \geq -1$ matter appears in the universe (just the strong energy condition is violated), the cosmological constant ($w = -1$) of any small fraction will always dominate



Then: any combination of dark energy with $w = \text{const.} \geq -1$ leads to “standard” Big-Bang/Crunch cosmological singularities: (or rather to emptiness - de Sitter).

2. Phantom dark energy. Big-Rip (type I) - an exotic singularity.

WMAP + SDSS + Supernovae **combined bound on the dark energy barotropic index** w (Tegmark et al. (2004)):



- **There is no sharp cut-off of the data at $p = -\varrho$!!!**
- **Dark energy with $p < -\varrho$ (phantom) can be admitted!**

More recent data:

- Knop et al. 2003 (from SNe + CMB + 2dFGRS combined) – $w = -1.05^{+0.15}_{-0.20}$ (statistical) ± 0.09 (systematic)
- Riess et al. 2004 ($w < -1$)
- Seljak et al. astro-ph/0604335 – $w = -1.04 \pm 0.06$
- though more recently Kowalski et al. (arXiv:0804.4142) analyzed 307 supernovae (Sne + BAO + CMB) – $w = -1.001^{+0.059}_{-0.063}$ (statistical) $^{+0.063}_{-0.066}$ (systematic)

Evidence for cosmic “no-hair” theorem violation - **even a small fraction of phantom dark energy will dominate the evolution** (see later)

Phantom dark energy.

Phantom is dark energy of a very large negative pressure (Caldwell astro-ph/9908168 - published in PLB 2002; after 2002 tens of refs which are not listed)

$$p < -\varrho, \quad \text{or} \;\; w < -1 \, , \tag{8}$$

which violates all the remained energy conditions, i.e., the null (NEC)

$$T_{\mu\nu} k^{\mu} k^{\nu} \quad \geq \quad 0, \qquad k^{\mu} - \text{a null vector} \, , \;\; \text{i.e.,} \qquad \varrho + p \geq 0 \, , \tag{9}$$

the weak (WEC)

$$T_{\mu\nu} V^{\mu} V^{\nu} \quad \geq \quad 0, \;\; V^{\mu} - \text{a timelike vector} \, , \;\; \text{i.e.,} \; \varrho + p \geq 0, \;\; \rho \geq 0 \, , \tag{10}$$

and the dominant energy (DEC)

$$T_{\mu\nu} V^{\mu} V^{\nu} \quad \geq \quad 0, \;\; T_{\mu\nu} V^{\mu} - \text{not spacelike} \, , \;\; \text{i.e.,} \; \mid p \mid \leq \varrho, \;\; \varrho \geq 0 \, . \tag{11}$$

Big-Rip (type I) as an exotic singularity.

For convenience take

$$| w + 1 | = -(w + 1) > 0 , \quad (12)$$

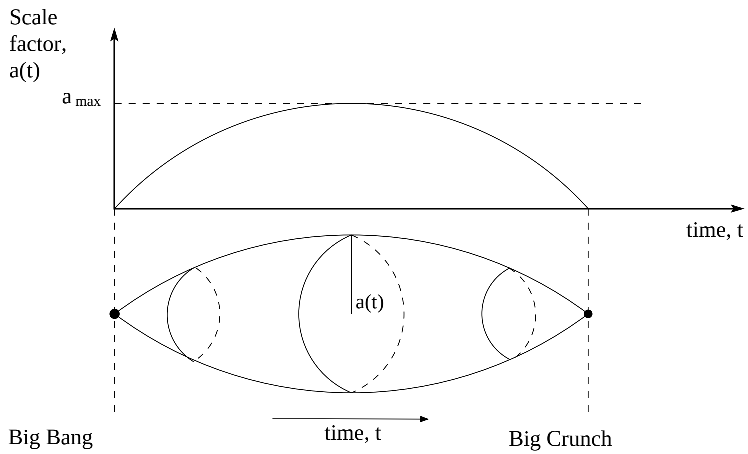
so that the conservation law for phantom gives

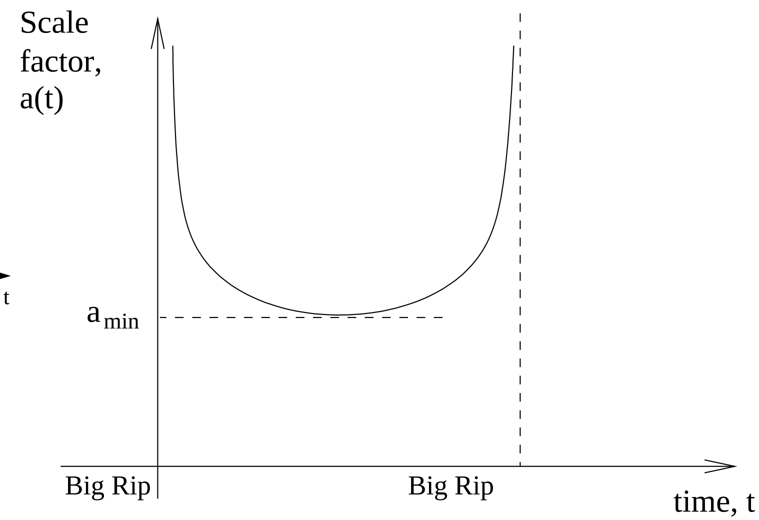
$$\varrho \propto a^{3|w+1|} . \quad (13)$$

- Conclusion: the bigger the universe grows, the denser it is, and **it becomes dominated by phantom (overcomes Λ-term)** – an exotic future singularity appears – Big-Rip $\varrho, p \to \infty$ for $a \to \infty$
- Curvature invariants R^2, $R_{\mu\nu}R^{\mu\nu}$, $R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$ diverge at Big-Rip
- Only for $-5/3 < w < -1$ the null geodesics are geodesically complete; for other values of w, including all timelike geodesics, there is a geodesic incompleteness (Lazkoz et al. gr-qc/0607073, PRD ’07) - the singularity is reached in a finite proper time.

Phantom duality

BR to BR model as dual to standard BB to BC model (MPD et al. 2003)





Duality: Standard matter ($p > -\varrho$) $\leftrightarrow$ Phantom ($p < -\varrho$)

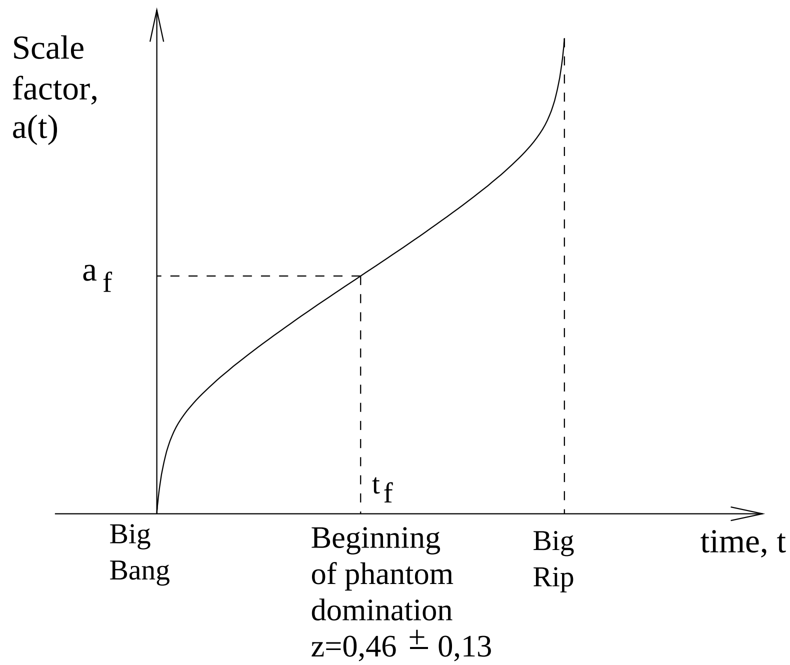
$$w \leftrightarrow -(w+2) \qquad \text{or better} \;\; \gamma \leftrightarrow -\gamma \,, \quad \gamma = w + 1 \tag{14}$$

i.e.

$$a(t) \leftrightarrow \frac{1}{a(t)} \tag{15}$$

Phantom and Big-Rip-singularity-driven dark energy.

The universe begins with a Big-Bang and terminates at a Big-Rip:



so that standard Hot-Big-Bang cosmology is preserved (with a turning point at z = 0.46 (since $j_0 > 0$) Riess et al. 2004).

Data shows that a Big -Rip is possible in the far future: $t = t_{BR} \approx 20$ Gyr.

4. Sudden Future Singularity (type II) as an exotic singularity.

Strange properties of a Big-Rip gave a push to studies some other exotic (or just "non-standard") types of singularities and the sources of dark energy which can be related to them. One of such singularities is:

A Sudden Future Singularity (SFS) (or type II - Nojiri, Odintsov, Tsujikawa 2005) which:

– manifests as a singularity of pressure (or $\ddot{a}$) only

– leads to the dominant energy condition violation only

The hint (Barrow '04):

release the assumption about the imposition of an equation of state

$$p \neq p(\varrho), \qquad \text{no analytic form of this relation is given} \tag{16}$$

Choose a special form of the scale factor (may be motivated in fundamental cosmologies) as:

$$a(t) = a_s \left[\delta + (1-\delta)\, y^m - \delta\, (1-y)^n\right] , \qquad y \equiv \frac{t}{t_s} \tag{17}$$

There is a Big-Bang at $t = 0$. But what about $t = t_s$?

$$\dot{a} = a_s \left[\frac{m}{t_s} (1-\delta) y^{m-1} + \delta \frac{n}{t_s} (1-y)^{n-1} \right] , \tag{18}$$

$$\ddot{a} = \frac{a_s}{t_s^2} \left[m(m-1)(1-\delta) y^{m-2} - \delta n (n-1)(1-y)^{n-2} \right] . \tag{19}$$

If we assume that

$$1 < n < 2, \tag{20}$$

then using Einstein equations (38)-(40) we get

$$a = \mathrm{const.}, \qquad \dot{a} = \mathrm{const.} \qquad \varrho = \mathrm{const.}$$
$$\ddot{a} \to \mp\infty \qquad p \to \pm\infty \qquad \mathrm{for} \qquad t \to t_s \tag{21}$$

Friedmann limit - “nonstandardicity” parameter δ

Friedmann limit is easily obtained in the limit of “nonstandardicity” parameter $\delta \to 0$.

The parameter m can be taken to be just a form of the w parameter present in the barotropic equation of state:

- $0 < m \leq 1$ when $w \geq -1/3$ (standard matter);
- $m > 1$ when $-1 < w < -1/3$ (quintessence);
- $m < 0$ when $w < -1$ (phantom).

Near to SFS one has

$$a_{SFS} = a_s \left[1 - \delta(1-y)^n\right] \ , \tag{22}$$

and n plays the role in making a pressure blow-up.

Important point:

Unless we take $m > 1$ or $m < 0$ as an independent source of energy, acceleration is possible only for $\delta < 0$!

We will call it pressure-driven dark energy (whatever it is!).

SFS as a “weak” singularity

SFS are determined by a blow-up of the Riemann tensor and its derivatives

Geodesics do not feel SFS at all, since geodesic equations are not singular for $a_s = a(t_s) =$ const. (Fernandez-Jambrina, Lazkoz PRD 74, 064030 (2006) ((gr-qc/0607073))

$$\left(\frac{dt}{d\tau}\right)^2 = A + \frac{P^2 + KL^2}{a^2(t)} , \tag{23}$$

$$\frac{dr}{d\tau} = \frac{P_1 cos\phi + P_2 \sin\phi}{a^2(t)} \sqrt{1 - Kr^2} , \tag{24}$$

$$\frac{d\phi}{d\tau} = \frac{L}{a^2(t) r^2} . \tag{25}$$

Geodesic deviation equation

$$\frac{D^2 n^\alpha}{d\lambda^2} + R^\alpha_{\beta\gamma\delta} u^\beta n^\gamma u^\delta = 0 , \tag{26}$$

feels SFS since at $t = t_s$ we have the Riemann tensor $R^\alpha_{\beta\gamma\delta} \to \infty$.

No geodesic incompleteness.

- No geodesic incompleteness ($a =$ const. and r.h.s. of geodesic eqs. do not diverge) $\Rightarrow$ SFS are not the final state of the universe
- Point particles do not even see SFS while extended objects may suffer instantaneous infinite tidal forces but still may not be crushed.
- They are weak curvature singularities i.e. in-falling observers or detectors are not destroyed by tidal forces:
- Tipler's (Phys. Lett. A64, 8 (1977)) definition (of a weak singularity):
  $\int_0^\tau d\tau' \int_0^{\tau'} d\tau'' R_{ab} u^a u^b$
  does not diverge on the approach to a singularity at $\tau = \tau_s$
- Królak's (CQG 3, 267 (1988)) definition (of a weak singularity):
  $\int_0^\tau d\tau' R_{ab} u^a u^b$
  does not diverge on the approach to a singularity at $\tau = \tau_s$
- A singularity may be weak acc. to Tipler, but strong according to Królak
- Conclusion: a Big-Rip and an SFS are of different nature.

5. Type III (Finite Scale Factor - FSF) exotic singularity.

Type III singularities (Nojiri et al. PRD 71, 063004 (2005)) which we will call Finite Scale Factor singularities are characterized by the following conditions:

$$a = a_s = \text{const.}, \varrho, \dot{a}_s \to \infty, |p|, \ddot{a}_s \to \infty$$

The simplest way to get them is to apply the scale factor as given previously for SFS, i.e.,

$$a(t) = a_s \left[\delta + (1-\delta)\, y^m - \delta\, (1-y)^n\right] , \qquad y \equiv \frac{t}{t_s} \tag{27}$$

where $a_f \equiv a(t_f) =$ const. and $\delta, A, m, n =$ const., but with the range of parameter n changed from $1 < n < 2$ into

$$0 < n < 1$$

FSF singularities are weak according to Tipler's definition, but strong according to Królak's.

6. Generalized Sudden Future, type IV and $w-$ singularities.

Sudden future singularities may be generalized to GSFS.

Take a general scale factor time derivative of an order r:

$$a^{(r)} = a_s \left[\frac{m(m-1)...(m-r+1)}{t_s^r} (1-\delta)\, y^{m-r} + (-1)^{r-1} \delta \frac{n(n-1)...(n-r+1)}{t_s^r} (1-y)^{n-r} \right] , \qquad (28)$$

Choosing (Barrow '04, Lake '04) $r-1 < n < r$, for any integer r we have a singularity in the scale factor derivative $a^{(r)}$, and consequently in the appropriate pressure derivative $p^{(r-2)}$.

Note that it fullfils all the energy conditions for any $r \geq 3$!!!

Type IV - Big Separation (BS)

Type IV singularity according to Nojiri et al. ’05 is when:

$$a = a_s \text{ = const.}, \varrho \to 0, p \to 0, \dddot{a}, \ddot{H} \to \infty \text{ etc.}$$

and so it is similar to Generalized Sudden Future singularity with only one exception: it also gives the divergence of the barotropic index in the barotropic equation of state

$$p(t) = w(t)\varrho(t)$$

i.e.,

$$w(t) \to \infty$$

Barotropic index $w-$singularity

Another exotic is a $w-$singularity only (without the divergence of the higher-derivatives of the scale factor). (Apparently, it appears in physical theories such as $f(R)$ gravity (Starobinsky '80), scalar field gravity (Setare, Saridakis '09, and brane gravity Sahni, Shtanov '05)). We choose

$$a(t) = A + B\left(\frac{t}{t_s}\right)^{\frac{2}{3\gamma}} + C\left(D - \frac{t}{t_s}\right)^{n} \ , \tag{29}$$

where A, B, C, D, γ, n, and t_s are constants and impose the conditions:

$$a(0) = 0, \ a(t_s) = const. \equiv a_s, \ \dot{a}(t_s) = 0, \ \ddot{a}(t_s) = 0 \ , \tag{30}$$

which finally leads to the following form of the scale factor:

$w-$singularity

$$
\begin{aligned}
a(t) &= \frac{a_s}{1-\frac{3\gamma}{2}\left(\frac{n-1}{n-\frac{2}{3\gamma}}\right)^{n-1}} \\
&+ \frac{1-\frac{2}{3\gamma}}{n-\frac{2}{3\gamma}} \frac{na_s}{1-\frac{2}{3\gamma}\left(\frac{n-\frac{2}{3\gamma}}{n-1}\right)^{n-1}} \left(\frac{t}{t_s}\right)^{\frac{2}{3\gamma}} \\
&+ \frac{a_s}{\frac{3\gamma}{2}\left(\frac{n-1}{n-\frac{2}{3\gamma}}\right)^{n-1} - 1} \left(1-\frac{1-\frac{2}{3\gamma}}{n-\frac{2}{3\gamma}}\frac{t}{t_s}\right)^{n} ,
\end{aligned} \tag{31}
$$

with the admissible values of the parameters: $\gamma > 0$ and $n \neq 1$.

$w-$duality

We have a blow-up of the effective barotropic index, i.e.,

$$w(t_s) = \frac{c^2}{3}\left[2q(t_s) - 1\right] \rightarrow \infty \ , \tag{32}$$

accompanied by

$$p(t_s) \rightarrow 0; \quad \varrho(t_s) \rightarrow 0 \ . \tag{33}$$

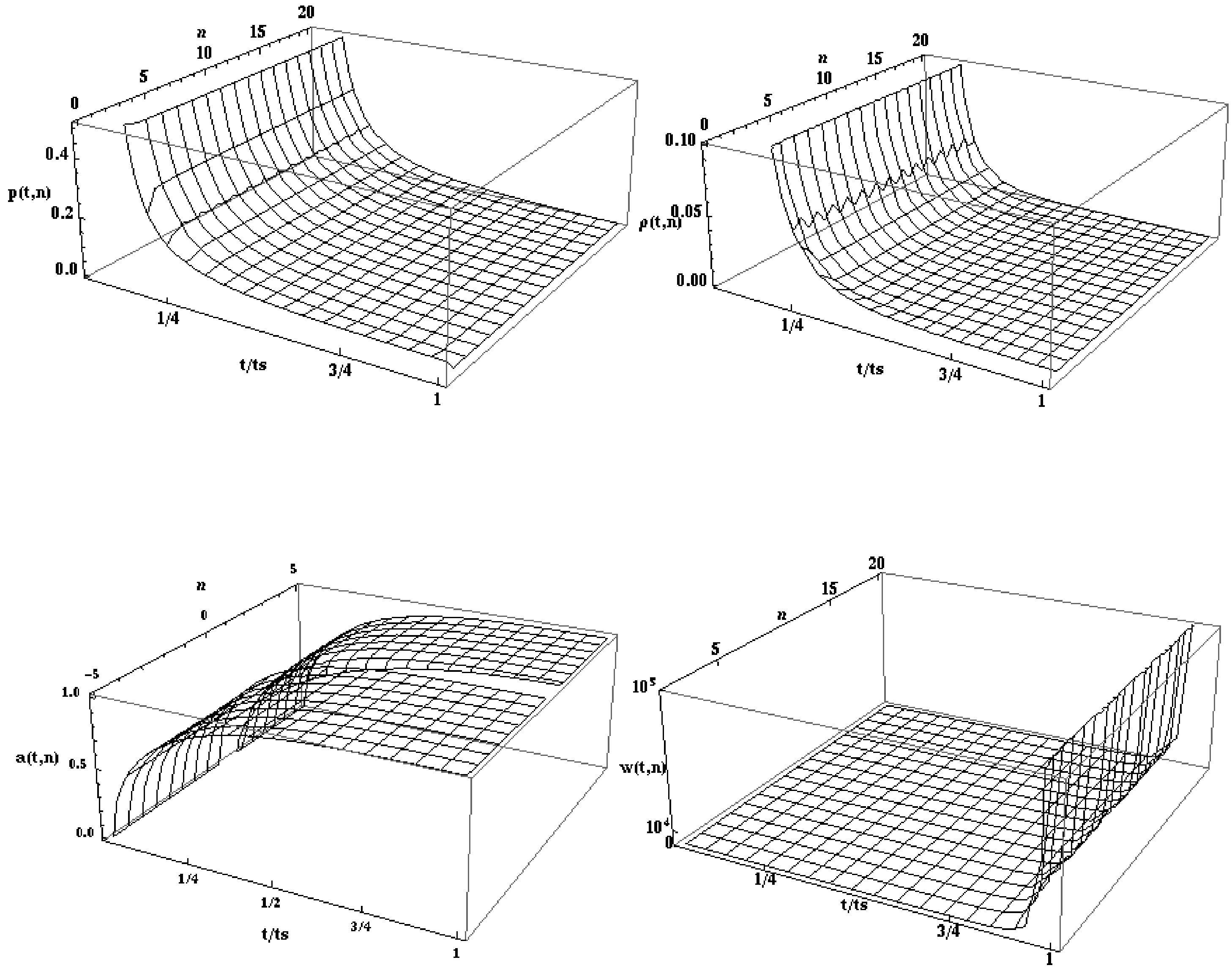
There is an amazing duality between the Big-Bang and the w-singularity in the form

$$p_{BB} \leftrightarrow \frac{1}{p_w}, \quad \varrho_{BB} \leftrightarrow \frac{1}{\varrho_w}, \quad w_{BB} \leftrightarrow \frac{1}{w_w} \quad . \tag{34}$$

In other words:

$$p_{BB} \rightarrow \infty; \varrho_{BB} \rightarrow \infty; w_{BB} \rightarrow 0; a_{BB} \rightarrow 0$$
$$p_w \rightarrow 0; \varrho_w \rightarrow 0; w_w \rightarrow \infty; a_w \rightarrow a_s = \text{const.}$$

$w-$duality



p(t,n)
0.4
0.2
0.0
0
5
10
15
20
n
1/4
t/ts
3/4
1
ρ(t,n)
0.10
0.05
0.00
a(t,n)
1.0
0.5
0.0
-5
0
5
1/2
w(t,n)
10^5
10^4

7. Exotic-singularity-driven dark energy.

- We have already mentioned that there is usually some fundamental physical theory (scalar field, higher-oder, string, brane, LQC) which can be related to the models with exotic singularities.
- In other words, the evidence for an exotic singularity may be attached to some form of matter which gives current acceleration of the universe and makes a candidate for the dark energy.
- We now check which of these exotic singularity models can really serve that by checking them against data which favors accelerated universe.
- The best studied models are of course phantom models which still are within the range of observational limit.
- However, we will show that some other models (in particular SFS models) can play a good candidate for the dark energy, too.
- In order to do so one may compare SFS models with observational data from supernovae.

First we test SFS (type II) models against supernovae.

We have

$$m(z) = M - 5\log_{10} H_0 + 25 + 5\log_{10}[r_1 a(t_0)(1+z)], \tag{35}$$

where r_1 comes from null geodesic equation

$$\int_0^{r_1} \frac{dr}{\sqrt{1-kr^2}} = \int_{t_1}^{t_0} \frac{cdt}{a(t)}, 1+z = \frac{a(t_0)}{a(t_1)} = \frac{\delta + (1-\delta)\, y_0^m - \delta\,(1-y_0)^n}{\delta + (1-\delta)\, y_1^m - \delta\,(1-y_1)^n}, \tag{36}$$

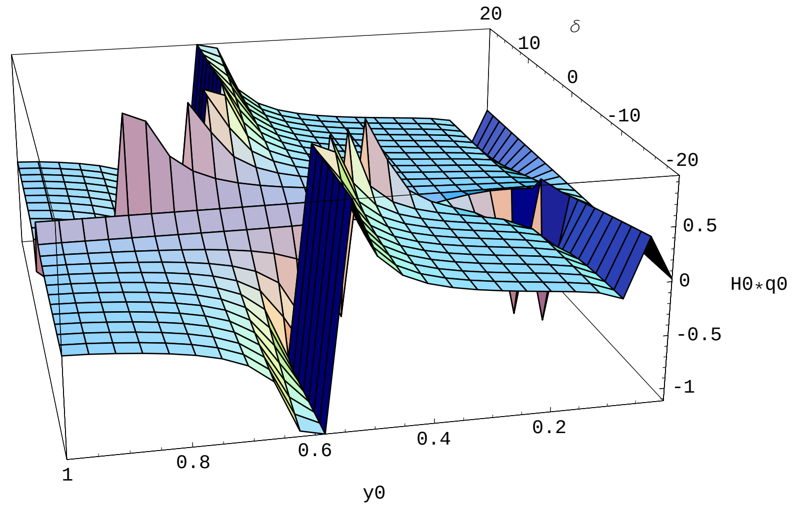
For a rough estimation of the dark energy models (acceleration) we study the product

$$q_0 H_0 = -\left(\frac{\ddot{a}}{\dot{a}}\right)_0 = \tag{37}$$

$$- \quad \frac{y_0}{t_0} \frac{m(m-1)(1-\delta)y_0^{m-2} - \delta n(n-1)\,(1-y_0)^{n-2}}{m(1-\delta)y_0^{m-1} + n\delta\,(1-y_0)^{n-1}},$$

which should be negative.

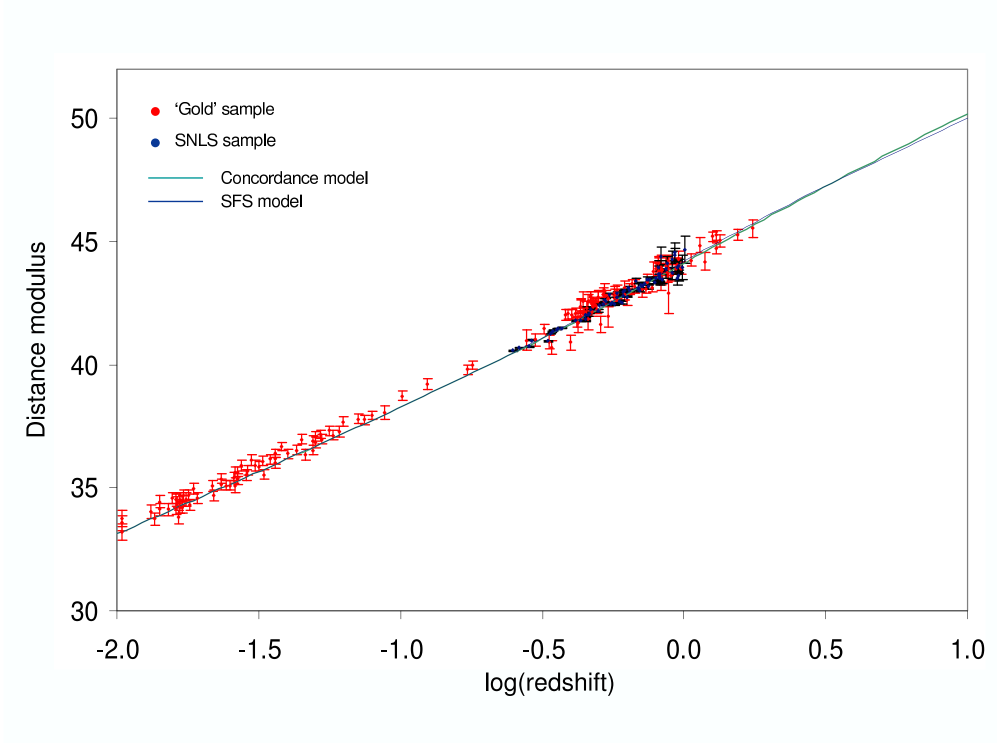
Parameter space for exotic-singularity-driven dark energy



Parameter space $(H_0 q_0, \delta, y_0)$ for fixed values of $m = 2/3, n = 1.9993, t_0 = 13.3547$ Gyr of the sudden future singularity models. There are large regions of the parameter space which admit cosmic acceleration

$$q_0 H_0 < 0 \ . \tag{38}$$

SFS dark energy versus Λ-term dark energy (concordance cosmology - CC)



Distance modulus $\mu_L = m - M$ for the CC model ($H_0 = 72 \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$, $\Omega_{m0} = 0.26$, $\Omega_{\Lambda 0} = 0.74$) (dashed curve) and SFS model ($m = 2/3, n = 1.9999, \delta = -0.471, y_0 = 0.99936$) (solid curve). Open circles are for the 'Gold' data and filled circles are for SNLS data.

Exotic-singularity-driven dark energy surprise.

Surprising remark:
If the age of the SFS model is equal to the age of the CC model, i.e. $t_0 = 13.6$ Gyr, one finds that **an SFS is possible in only 8.7 million years!!!**.

- In this context it is no wonder that the singularities were termed “sudden”.
- It was checked that GSFS (generalized SFS - no energy conditions violation) are always more distant in future. That means the strongest of SFS type singularities is more likely to become reality.
- A practical tool to recognize them well in advance is to measure possible large values of statefinders (deceleration parameter, jerk, snap etc.)!

Interesting point: SFS plague loop quantum cosmology! - see Wands et al. PRL ’08 ;arXiv: 0808.0190.

Big-Brake-exotic-singularity-driven dark energy.

SFS with $a = a_b$ = const., $\dot{a} = 0$ ($\varrho \to 0$), and $\ddot{a} \to -\infty$ ($p \to \infty$) were also termed Big-Brake (Gorini, Kamenschchik et al. PRD 69 (2004), 123512). They fulfill an anti-Chaplygin gas equation of state of the form

$$p = \frac{A}{\varrho} \qquad \mathrm{A} = \mathrm{const.} \quad . \tag{39}$$

They were studied in the context of the tachyon cosmology by Gergely, Keresztes et al. (0901.2292).

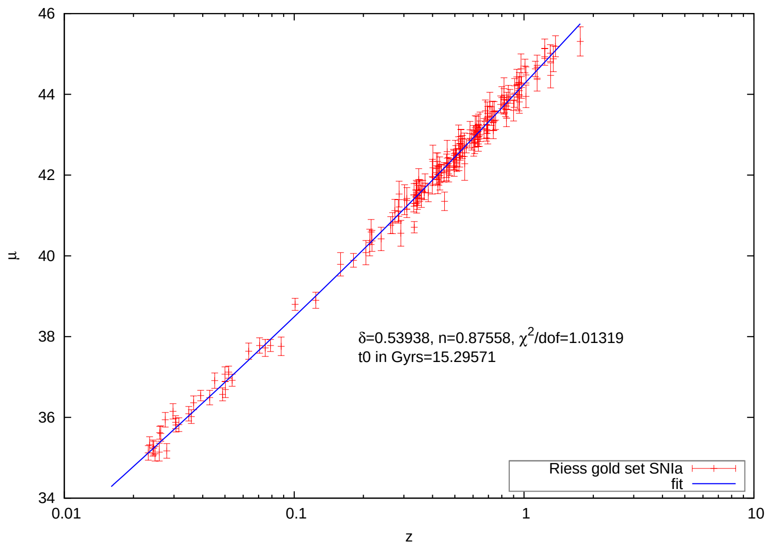
However, due to the imposition of different values of parameters which are given by tachyon constraints (plus anti-Chaplygin gas constraints) the closest singularity in their model appears

– 1 Gyr in future

– and the furthest even 44 Gyr in future.

Despite, they of course can serve as a source of dark energy.

FSF (type III) v. supernovae



We have preliminary found that even the type III (Finite Scale Factor) singularity can be closer than this, i.e.

$t_s - t_0 \approx 0.3 Gyrs$ (about 30 times larger than the time to an SFS)

with the choice of parameters to be:

$\ddot{a} > 0$ for $\delta > 0$:

$n = 0.87558$; δ = 0.53938; t_0 = 15.29571 Gyrs

8. Conclusions

- Exotic singularities are related to new physical sources of gravity which can serve as the dark energy.
- First example source - phantom - produces an exotic singularity – a Big-Rip in which ($a \to \infty$ and $\varrho \to \infty$) which is different from a Big-Bang/Crunch.
- Investigations of phantom inspired other searches for non-standard singularities (sudden future, generalized sudden future (=Big-Brake), type III (Finite Scale Factor), type IV (Big-Separation), $w-$singularities etc.) which, in fact, are not necessarily the "true" singularities (according to Hawking and Penrose definition), as sources of dark energy.
- Big-Rip and other exotic singularities are, in fact, motivated by fundamental theories of particle physics (scalar-tensor, superstring, brane, loop quantum cosmology etc.).

conclusions contd.

- Big-Rip which serves as dark energy despite it may happen in 20 Gyr, while weak singularities (of tidal forces and their derivatives) may serve as dark energy if they are quite close in the near future. For example an SFS may even appear in 8.7 Myr with no contradiction with data. A GSFS always appears later. Type III (FSF) is possible in about 0.3 Gyr. Finally, a Big-Brake (which is also an SFS) in tachyon cosmology context is at least 1 Gyr away from now.

Phantom trouble:

- classical and quantum instabilities (e.g. Buniy and Hsu hep-th/0502203) - due to negative kinetic energy of phantom particles scattered rather gain than lose energy
- positive mass theorems fail
- black hole thermodynamics is under trouble (cf. Gonzalez-Diaz astro-ph/0407421; Pereira and Lima 0806.0682)
- cosmic censorship conjecture fails (all three above rely on the energy conditions)
- Phantom matter accretion onto a black hole may cause its mass diminishing (Babichev, Dokuchaev, Eroshenko, PRL '04).

But see the papers:
Cline et al. PRD 70 (2004), 043543;
Buniy, Hsu, Murray hep-th/0606091;
Rubakov hep-th/0604153; (no negative kinetic terms, NEC violated)
Creminelli et al. JHEP 0612 080 (2006) (no instabilities, NEC violated)

Big-Rip exotic singularity approach:

In a Big-Rip scenario everything is pulled apart on the approach to a Big-Rip in a reverse order (Caldwell et al. PRL '03).
Specifically, for $w = -3/2$ Big-Rip will happen in 20 Gyr from now and the scenario will be as follows:

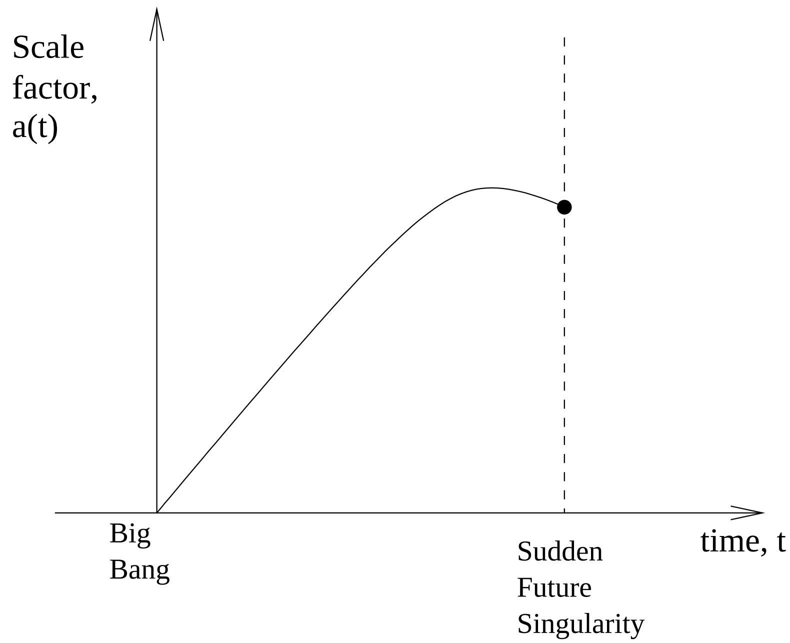
- in 1 Gyr before BR - clusters are erased
- in 60 Myr before BR - Milky Way is destroyed
- 3 months before BR - Solar System becomes unbound
- 30 min before BR - Earth explodes
- 10^{-19} s before BR - atoms are dissociated
- nuclei etc. .....

All this comes from the formula $t \approx P\sqrt{2 \mid w+1 \mid}/[6\pi \mid 1+w \mid]$, where P is the period of a circular orbit around the system at radius R, mass M.

Sudden future singularity

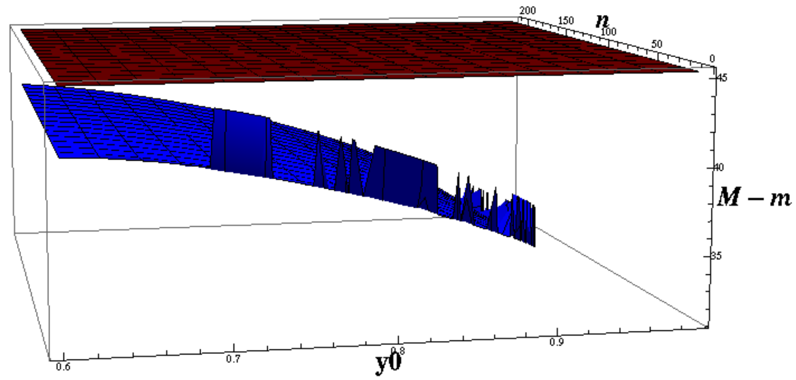
It is only the pressure singularity with finite scale factor and the energy density.

Possible universe evolution scenario:



(or upwards in a similar way as in phantom scenario with an inflection point)

$w-$singularities v. supernovae (in progress)



$w-$ singularity does not fit for parameters chosen so far.

blue surface (theory)

red surface (observations)

do not cross at all