Seminar Katedre za astronomiju, 30.01.2018.

Radio-evolucija ostataka supernovih i nelinearno difuzno ubrzavanje čestica

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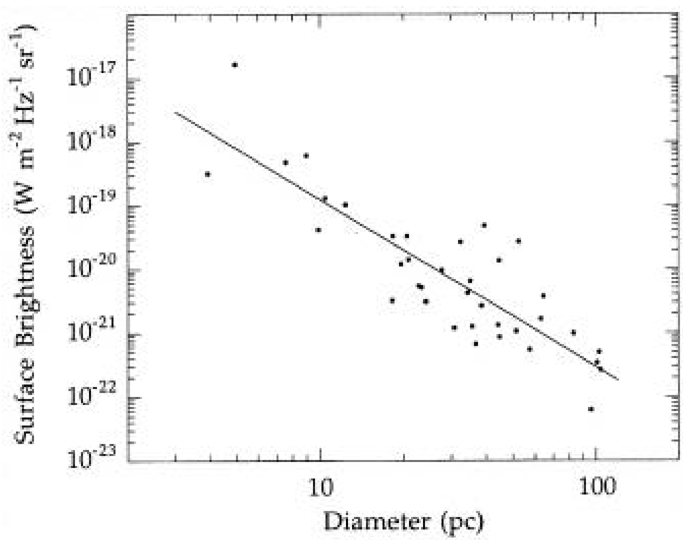
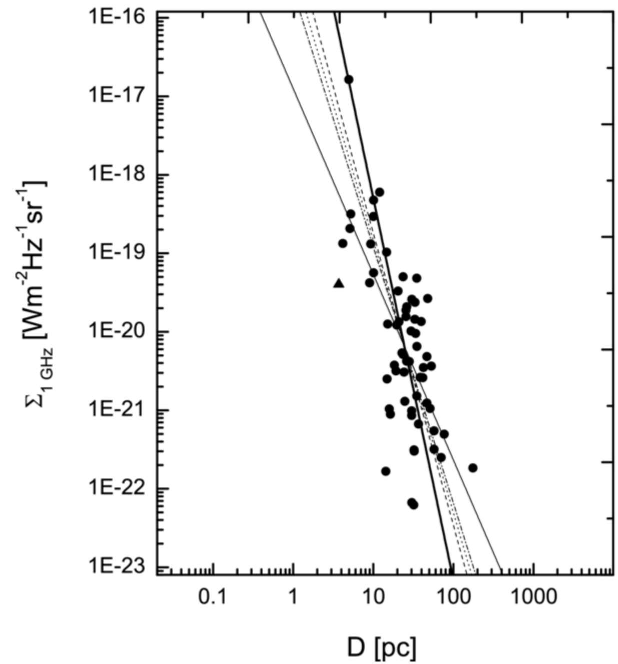
    3.3 Ekviparticija u OSN
4. Zakljuļak
5. Planovi za dalji rad
6. Pitanja i diskusija

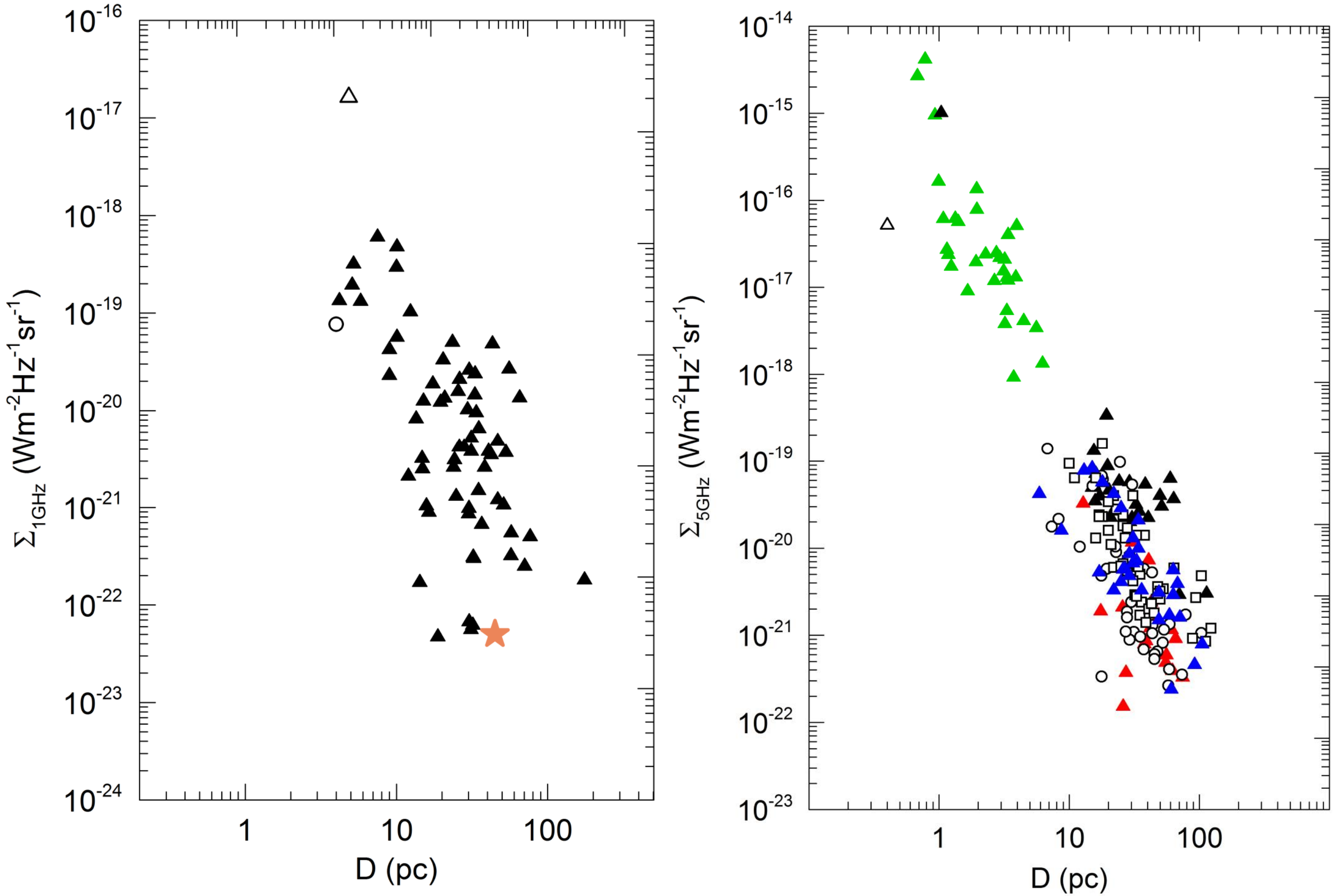
1.1 Zašto radio-evolucija?



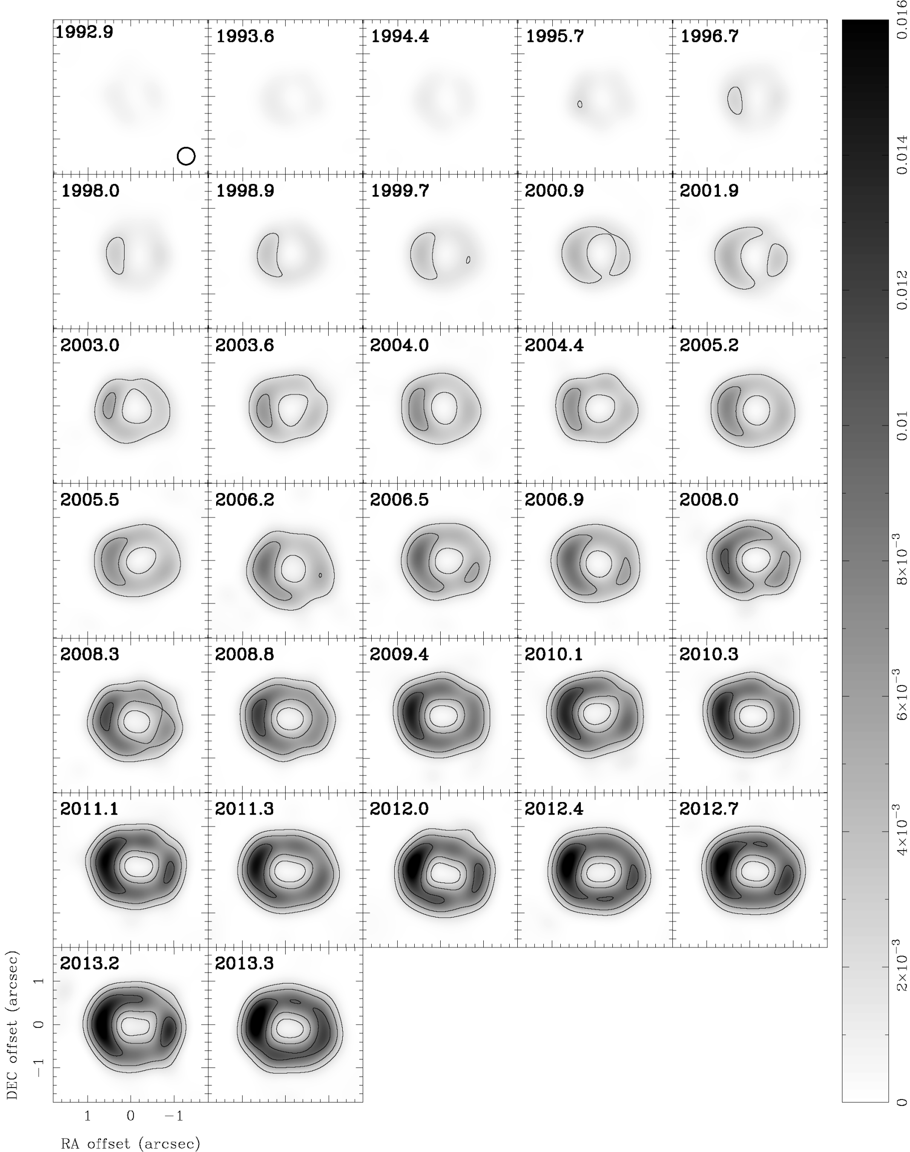
Case & Bhattacharya (1998)



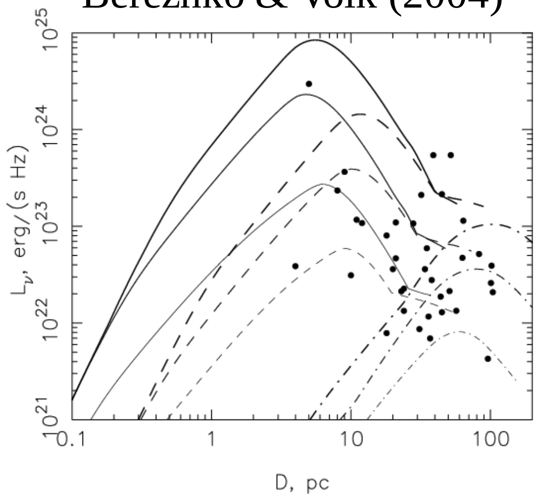
Uroġeviĺ at al. (2003); Arbutina and Uroġeviĺ (2009); Uroġeviĺ et al. (2009); Uroġeviĺ et al. (2010); Pavloviĺ et al. (2013); Vukotiĺ et al. (2014); Pavloviĺ et al. (2014); Kostiĺ et al. (2016); Bozzetto et al. (2017)



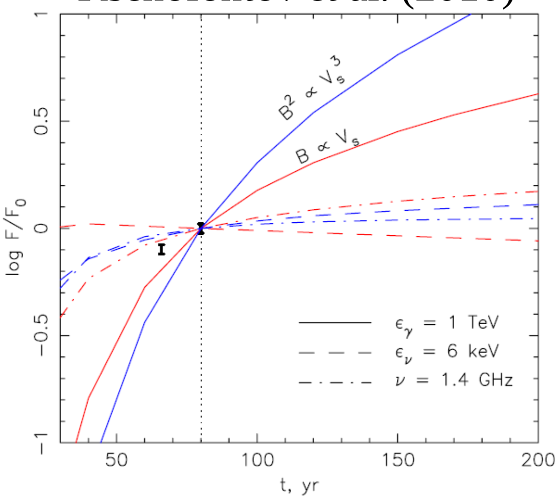
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Σ_{1GHz} (Wm^{-2}Hz^{-1}sr^{-1})
1
10
100
D (pc)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
Σ_{5GHz} (Wm^{-2}Hz^{-1}sr^{-1})
1
10
100
D (pc)

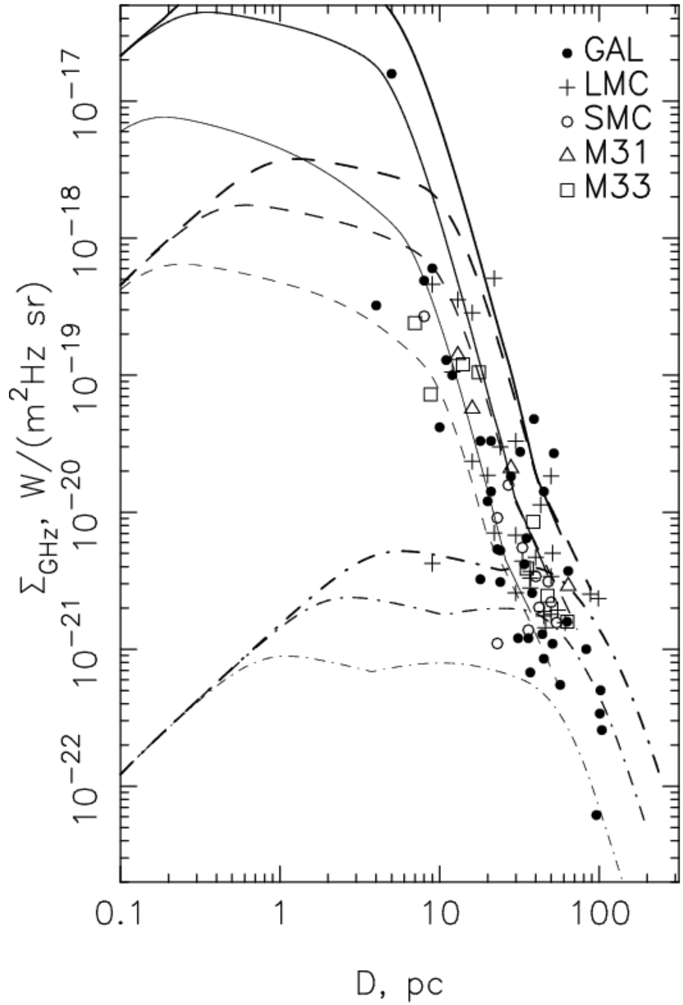

1992.9
1993.6
1994.4
1995.7
1996.7
1998.0
1998.9
1999.7
2000.9
2001.9
2003.0
2003.6
2004.0
2004.4
2005.2
2005.5
2006.2
2006.5
2006.9
2008.0
2008.3
2008.8
2009.4
2010.1
2010.3
2011.1
2011.3
2012.0
2012.4
2012.7
2013.2
2013.3
DEC offset (arcsec)
1
0
−1
1
0
−1
RA offset (arcsec)
0
2×10^{-3}
4×10^{-3}
6×10^{-3}
8×10^{-3}
0.01
0.012
0.014
0.016

Berezhko & Volk (2004)

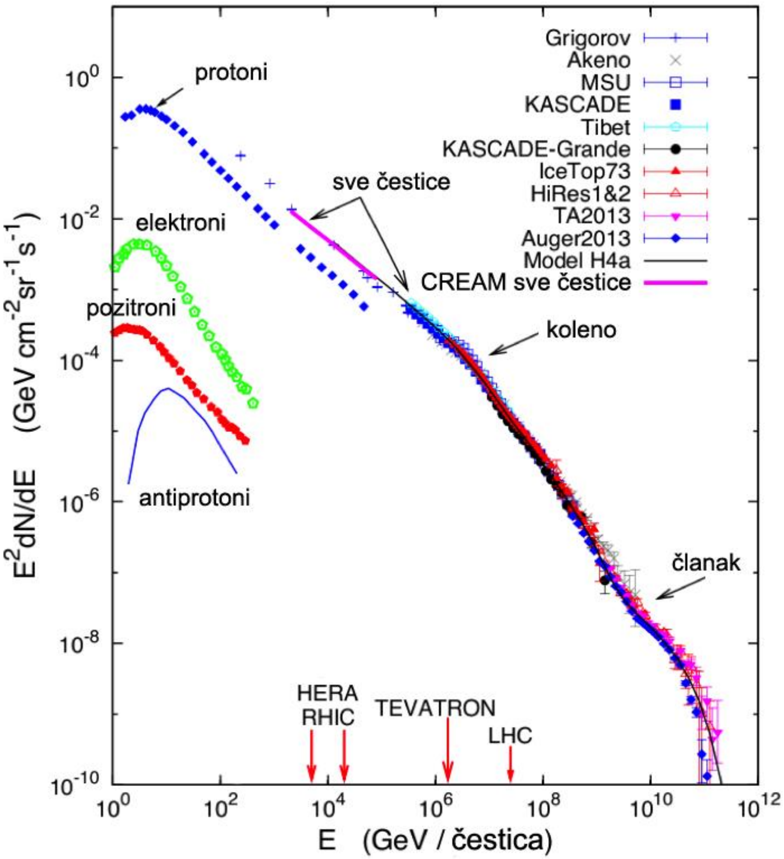


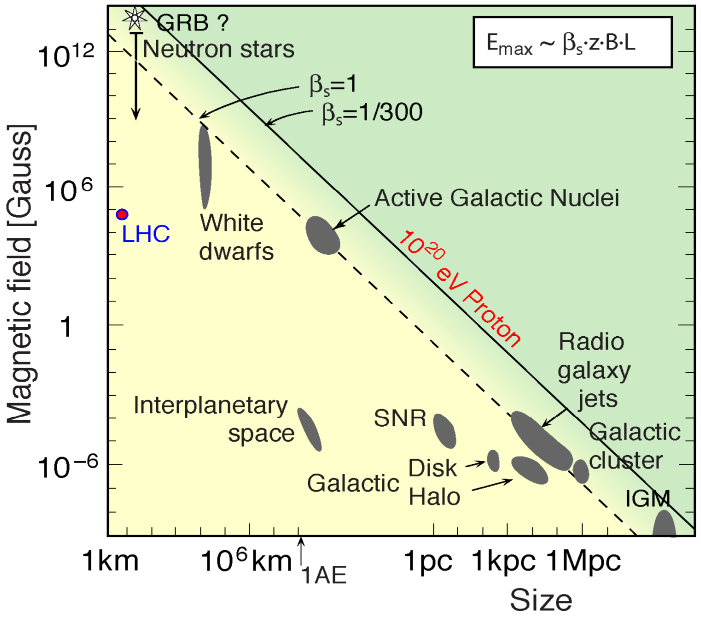
Ksenofontov et al. (2010)





1.2 Zašto ubrzavanje čestica?



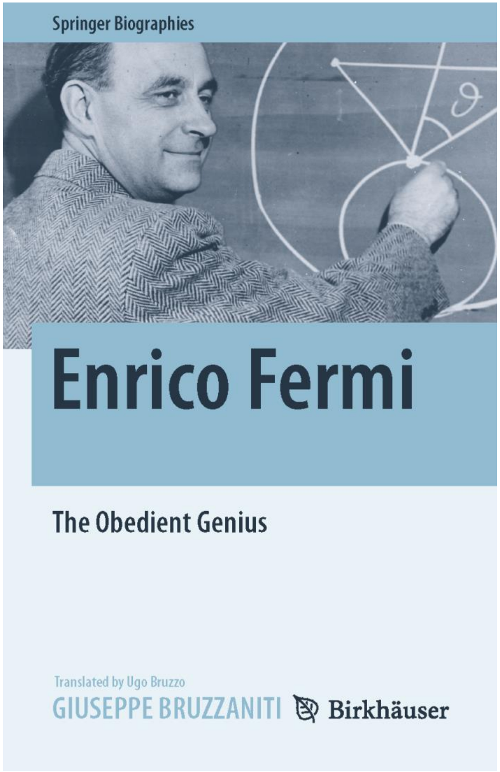


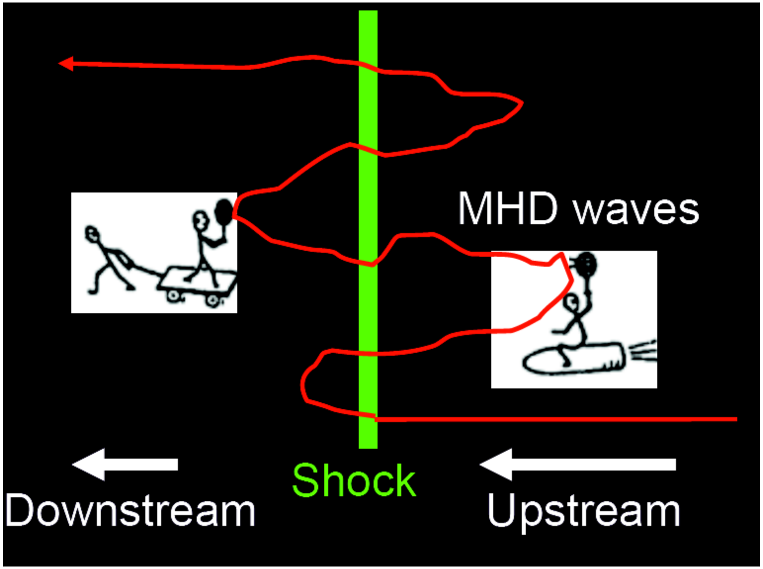
Baade & Zwicky 1934

Bell 1978a, b

Fermi 1949

Axford et al. 1977, Krymsky 1977
Blandford & Ostriker 1978





2. Model

Dwarkadas and Chevalier 1998

Poļ etni uslovi OSN:
eksponencijalni profil
odbaļ enog materijala u
eksploziji SN

Mignone et al. 2007
Orlando et. al 2012
Pavloviĺ 2017
Pavloviĺ et al. 2018

Dinamiļ ka evolucija:
2D/3D hidrodinamika
PLUTO

detekcija udarnog talasa +
uticaj kosmiļ kih zraka

Ferrand et al. 2010
Ellison et al. 2007

Ubrzavanje ļ estica:
NLDSA

Blasi et al. 2002, 2005

Pojaļ anje magnetnog polja

Caprioli et al. 2008, 2009, Pavloviĺ et al. 2017

Mignone et al. 2007
Orlando et. al 2012
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Dwarkadas and Chevalier 1998

Poļ etni uslovi OSN: eksponencijalni profil odbaļ enog materijala u eksploziji SN

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Blasi et al. 2002, 2005

Dwarkadas and Chevalier 1998

Poļ etni uslovi OSN: eksponencijalni profil odbaļ enog materijala u eksploziji SN

Å Eksponencijalni profil gustine odbaļ enog materijala:

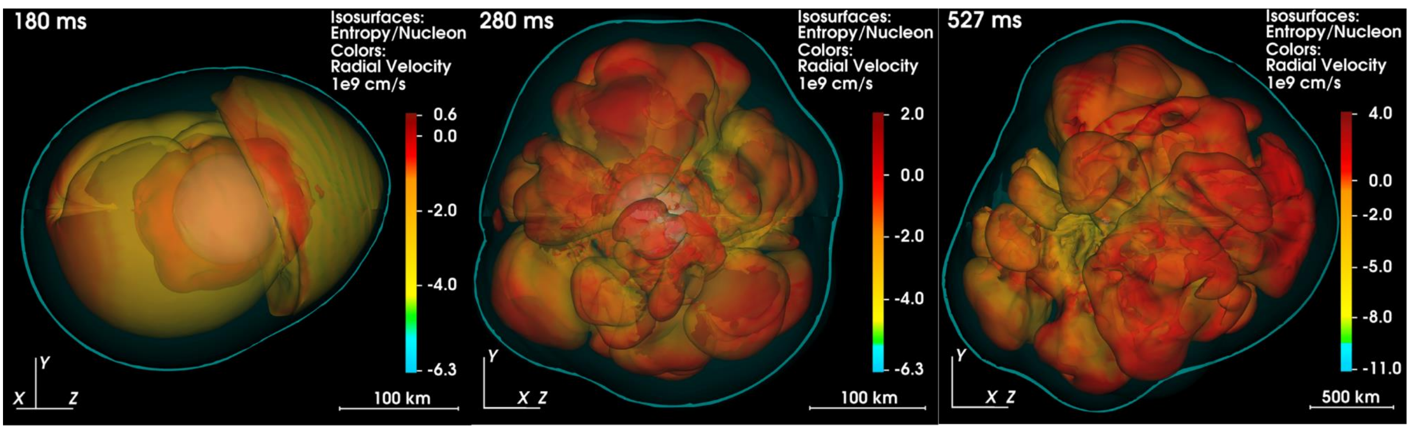
$$\rho_{\mathrm{SN}}(r) \propto t^{-3} e^{-\frac{v(r)}{v_e}}$$

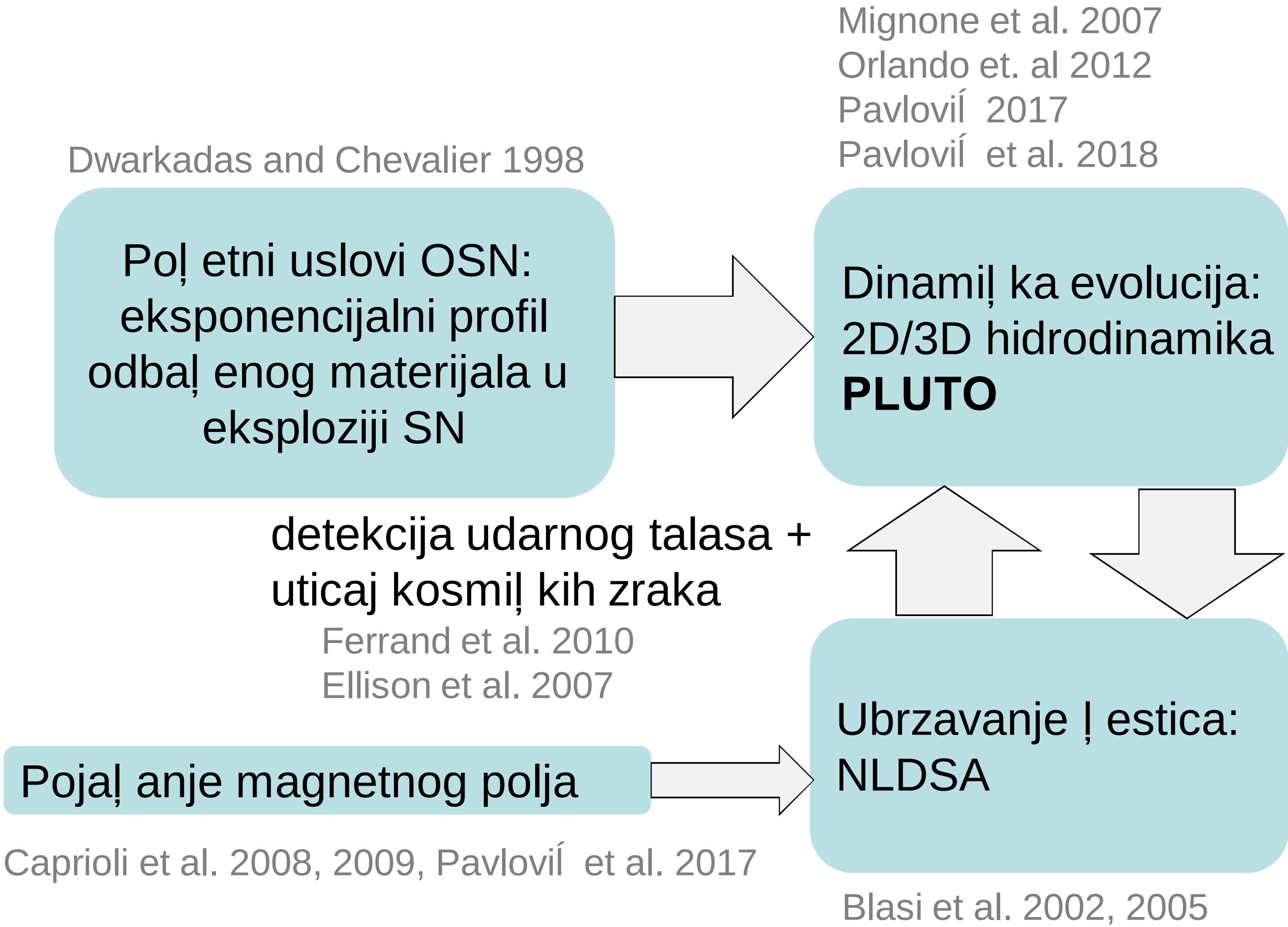
Å Kinetiļ ka energija eksplozije: $E_0 = 10^{51}\mathrm{erg}$

Å Masa odbaļ enog materijala: $M_{\mathrm{ej}} = 1.4 M_{\mathrm{sun}}$

Å Homogena MZM

Melson et al. (2015)

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Ferrand et al. 2010
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Ubrzavanje ļ estica: NLDSA
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Dwarkadas and Chevalier 1998

Poļ etni uslovi OSN:
eksponencijalni profi
odbaļ enog materijala
eksploziji SN

Dinamiļ ka evolucija:
2D/3D hidrodinamika
PLUTO

detekcija uda
uticaj kosmiļ l

Ferrand et al. 2
Ellison et al. 2007

Ubrzavanje ļ estica:
NLDSA

Pojaļ anje magnetnog polja

Caprioli et al. 2008, 2009, Pavloviĺ et al. 2017

Blasi et al. 2002, 2005

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho\boldsymbol{v}\\ E\end{pmatrix}+\nabla\cdot\begin{pmatrix}\rho\boldsymbol{v}\\ \rho\boldsymbol{v}\boldsymbol{v}+\boldsymbol{I}P\\ (E+P)\boldsymbol{v}\end{pmatrix}^{\mathrm{T}}=\begin{pmatrix}0\\0\\0\end{pmatrix}$$

Mignone et al. 2007

Dinamiļ ka evolucija:
2D/3D hidrodinamika
PLUTO

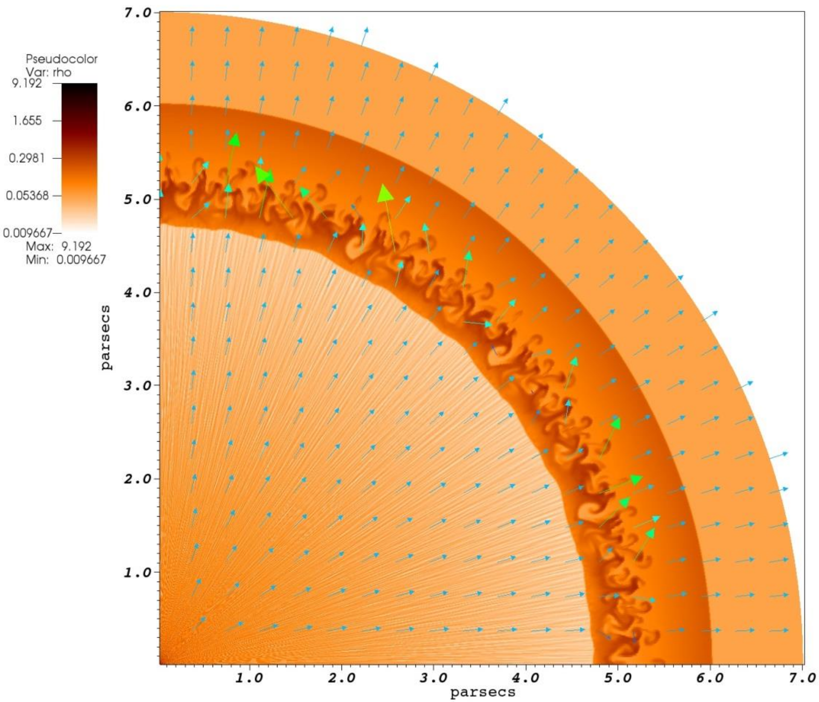
$$P=(\gamma-1)\epsilon$$

Å Vremenska i prostorna zavisnost adijabatskog indeksa plazme:

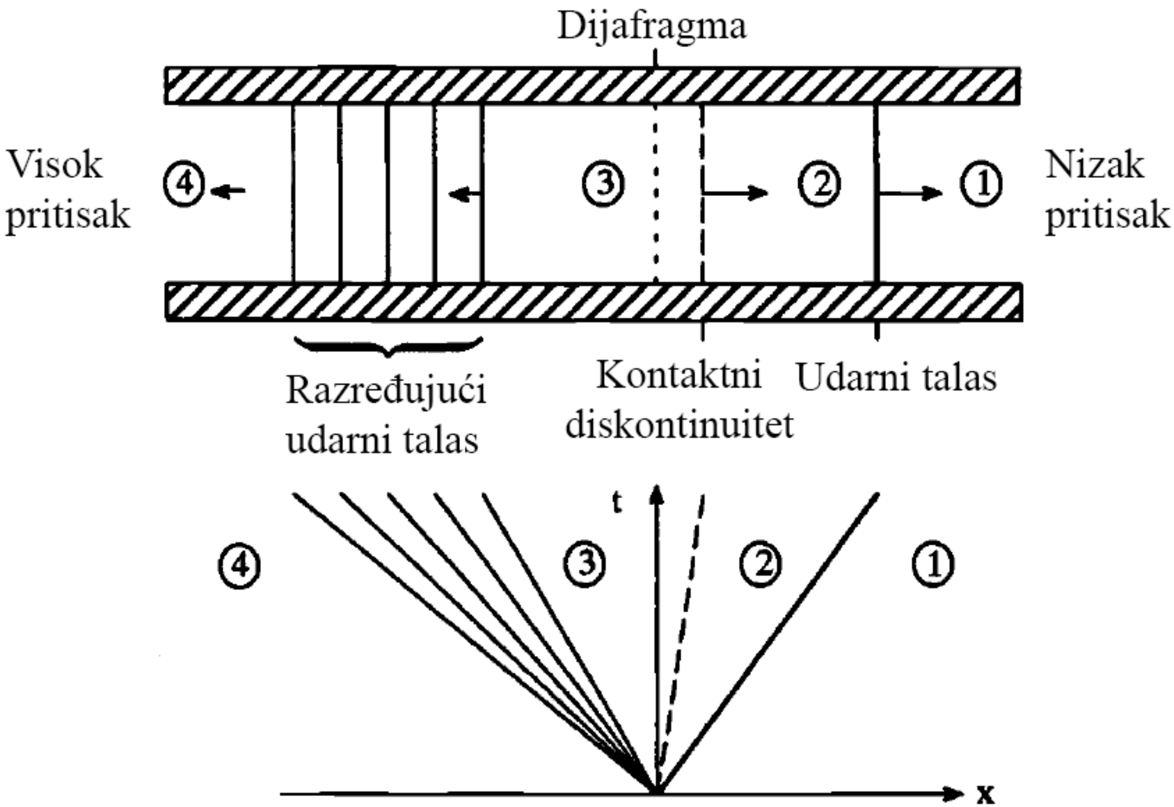
$$E=\frac{P}{\gamma-1}+\frac{1}{2}\rho v^2$$

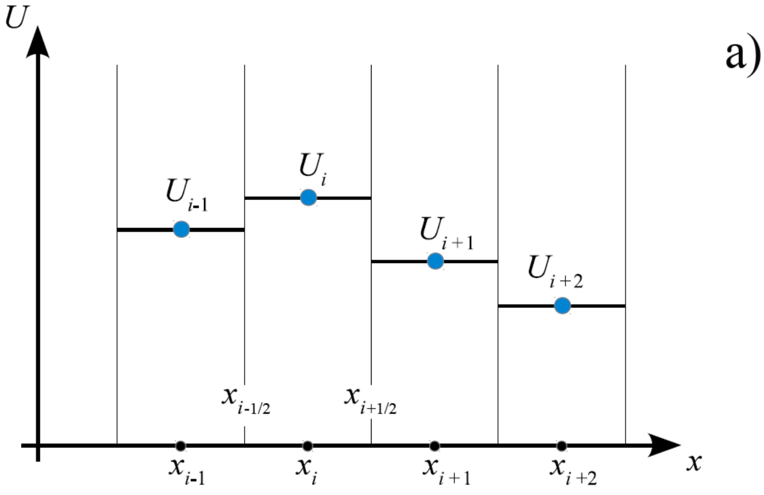
$$\gamma=\gamma(x,y,z,t)$$

Ellison et al. 2004
Ferrand et. al 2010
Orlando et. al 2012

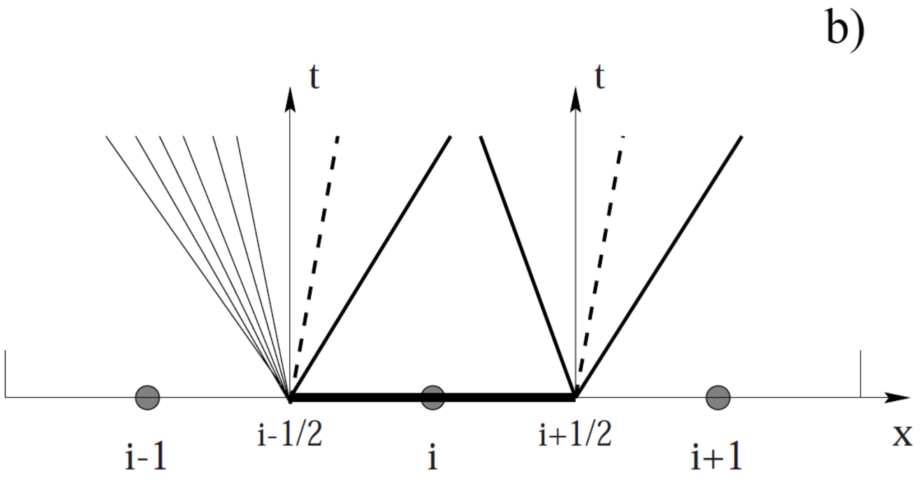


Rimanov problem ← Rimanovi reġavaļ i





Metod Godunova



Mignone et al. 2007

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \rho \boldsymbol{v} \\ E\end{pmatrix} + \nabla \cdot \begin{pmatrix}\rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v} + \boldsymbol{I} P \\ (E+P)\boldsymbol{v}\end{pmatrix}^{\mathrm{T}} = \begin{pmatrix}0 \\ 0 \\ 0\end{pmatrix}$$

Dinamiļ ka evolucija:
2D/3D hidrodinamika
PLUTO

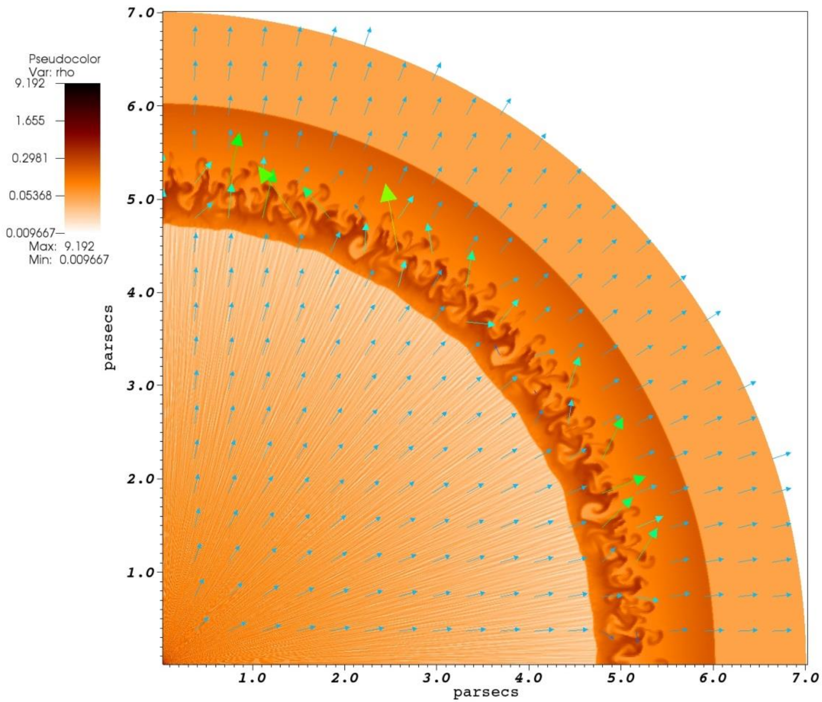
$$P = (\gamma - 1)\epsilon$$

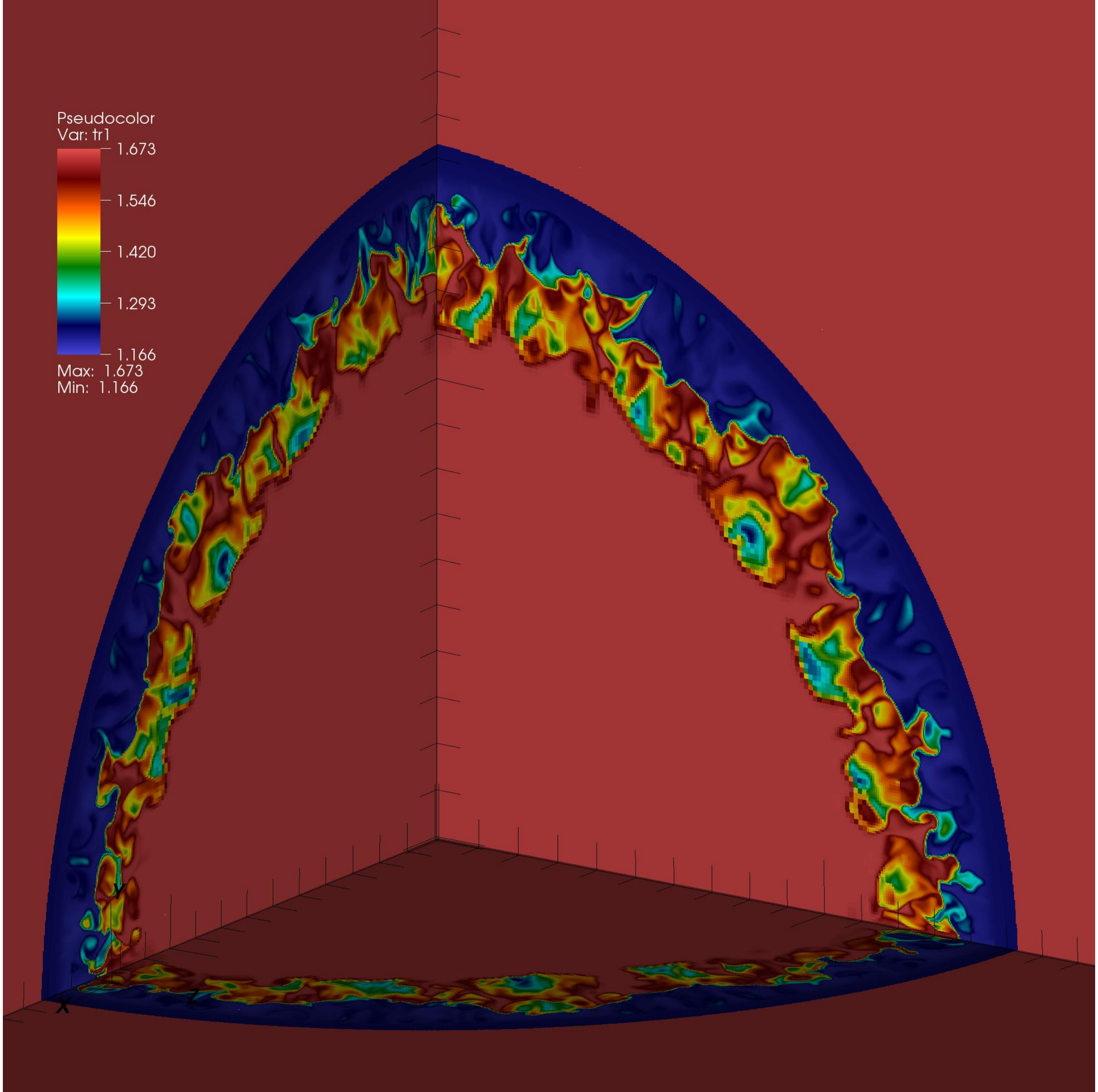
Å Vremenska i prostorna zavisnost adijabatskog indeksa plazme:

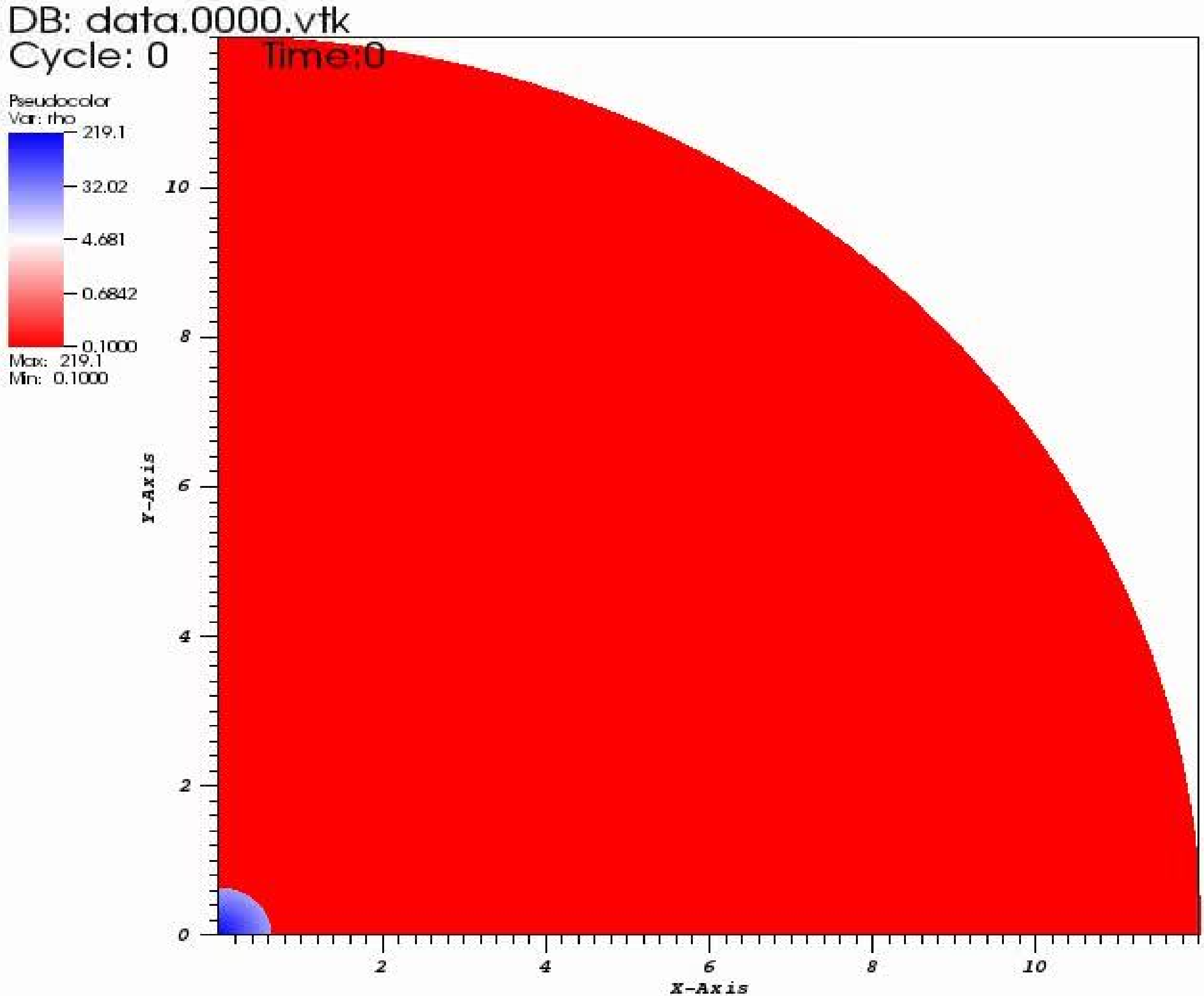
$$E = \frac{P}{\gamma - 1} + \frac{1}{2}\rho v^2$$

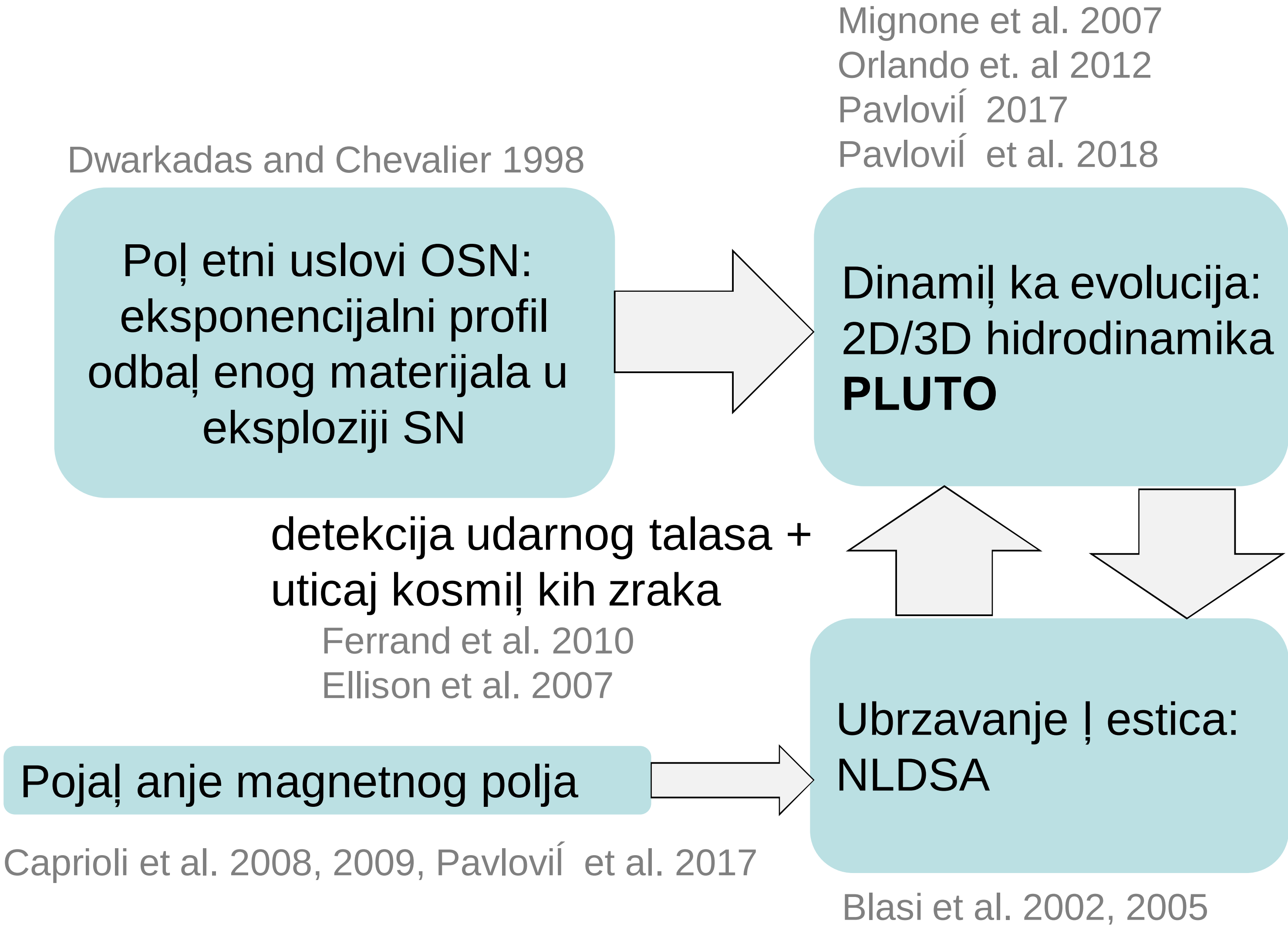
$$\gamma = \gamma(x, y, z, t)$$

Ellison et al. 2004
Ferrand et. al 2010
Orlando et. al 2012




Pseudocolor
Var: tr1
1.673
1.546
1.420
1.293
1.166
Max: 1.673
Min: 1.166


DB: data.0000.vtk
Cycle: 0
Time:0
Pseudocolor
Var: rho
219.1
32.02
4.681
0.6842
0.1000
Max: 219.1
Min: 0.1000
Y-Axis
X-Axis
0
2
4
6
8
10


Mignone et al. 2007
Orlando et. al 2012
Pavloviĺ 2017
Pavloviĺ et al. 2018
Dwarkadas and Chevalier 1998
Poļ etni uslovi OSN: eksponencijalni profil odbaļ enog materijala u eksploziji SN
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Ellison et al. 2007
Ubrzavanje ļ estica: NLDSA
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Blasi et al. 2002, 2005

Mignone et al. 2007
Orlando et. al 2012
Pavloviĺ 2017
Pavloviĺ et al. 2018

Dwarkadas and Chevalier 1998

Poļ etni uslovi OSN:
eksponencijalni profil
odbaļ enog materijala u
eksploziji SN

Dinamiļ ka evolucija:
2D/3D hidrodinamika
PLUTO

detekcija u
uticaj kosm

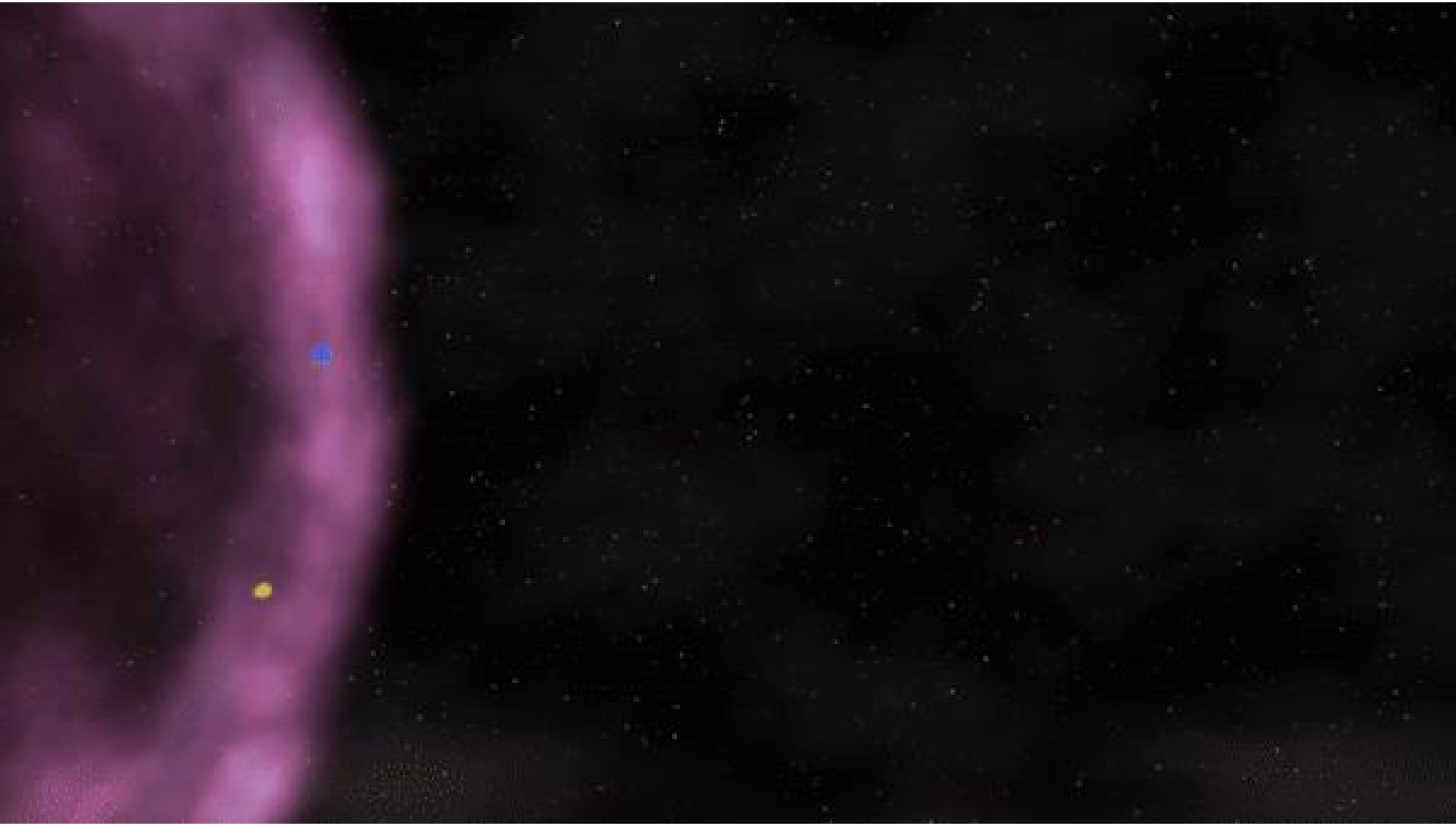
Ferrand et
Ellison et a

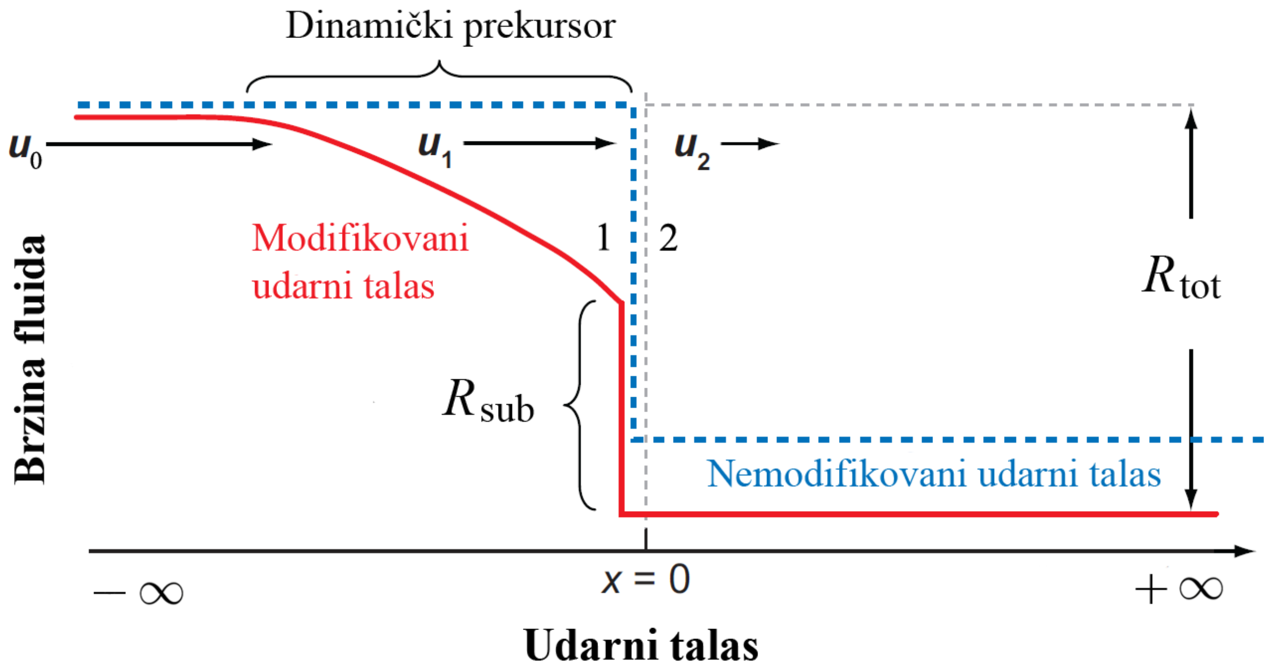
Ubrzavanje ļ estica:
NLDSA

Pojaļ anje magnetnog p

Caprioli et al. 2008, 2009, Pavlovi

Blasi et al. 2002, 2005



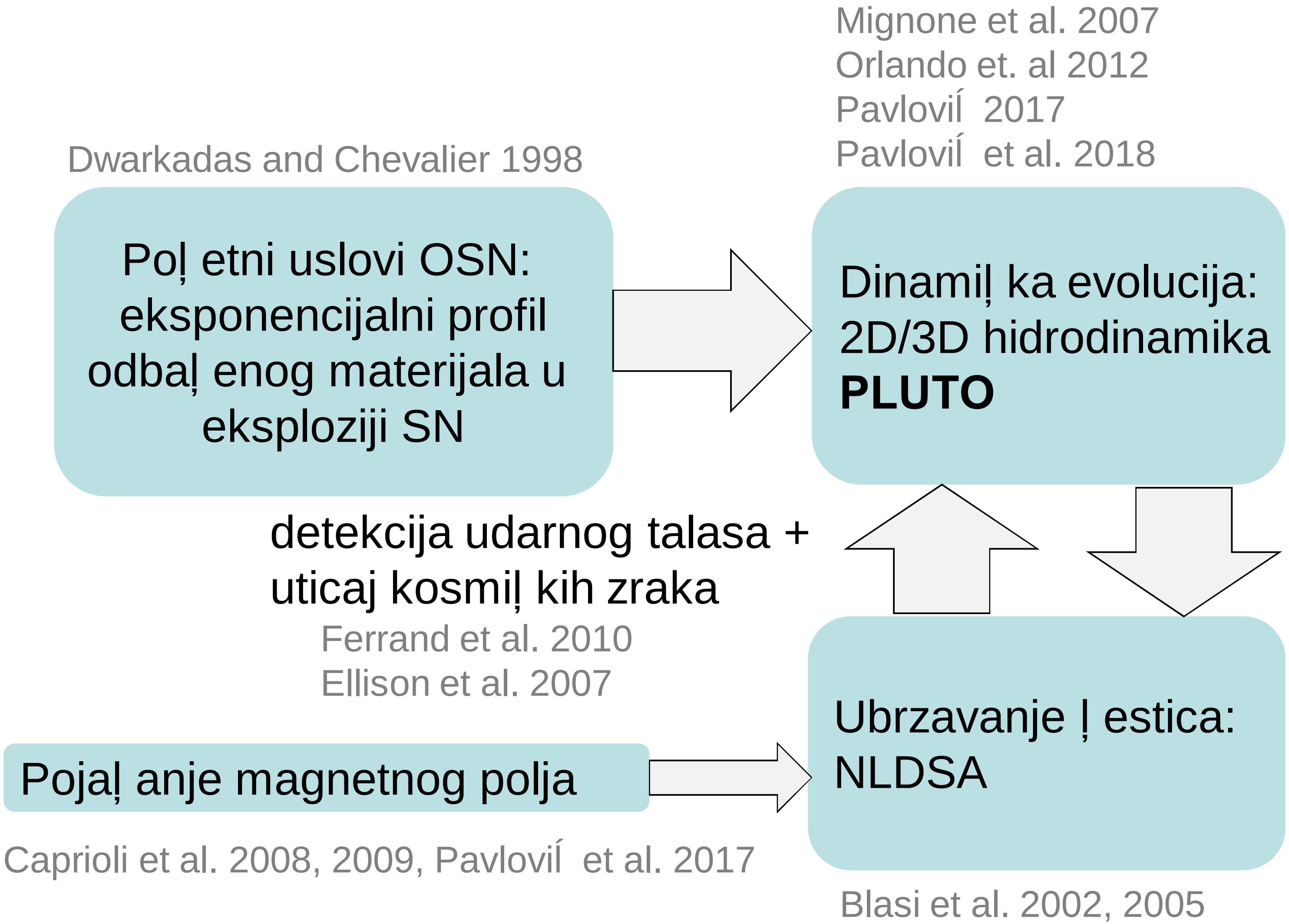


$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f(x,p)}{\partial p} + Q(x,p) = 0$$

$$R_{tot}, R_{prec}, R_{sub}, f(p,x), U(x)$$

Ubrzavanje ¦ estica:
NLDSA

Blasi et al. 2002, 2005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Ferrand et al. 2010

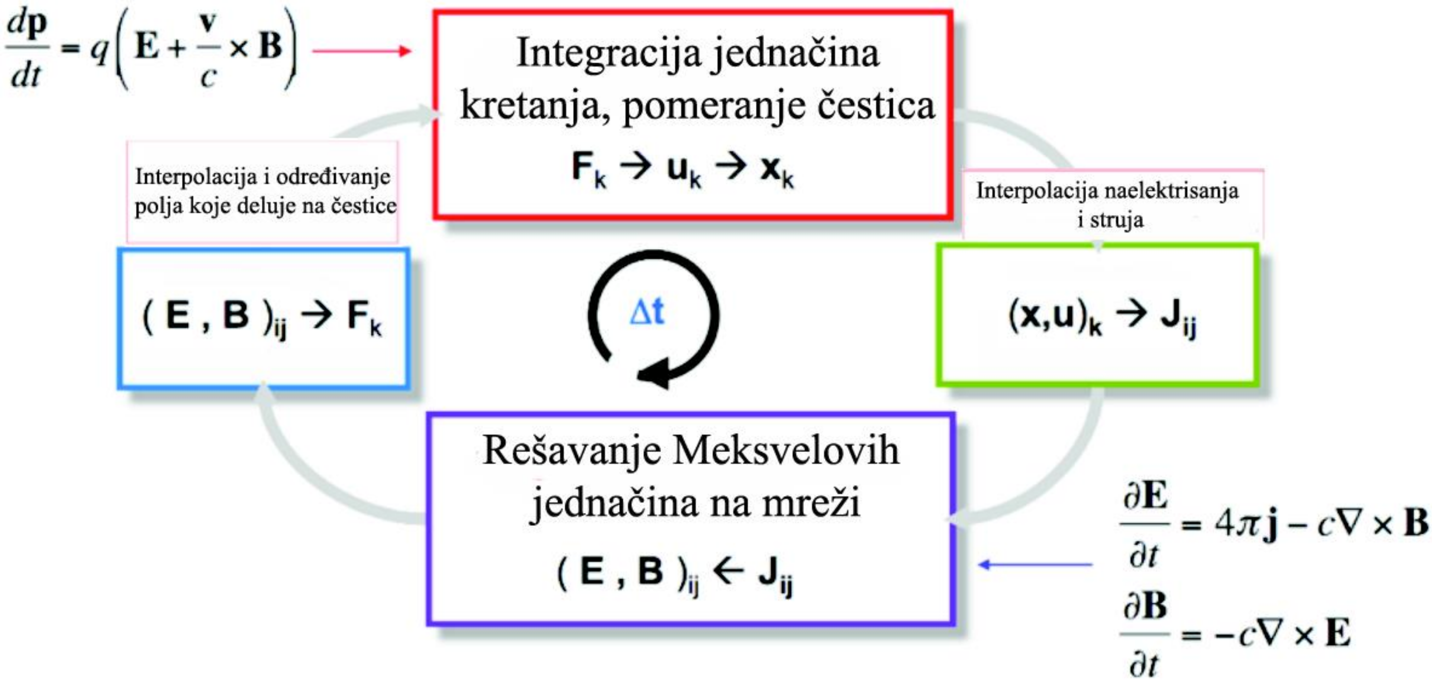
anje ļ estica:

Pojaļ anje magnetnog polja

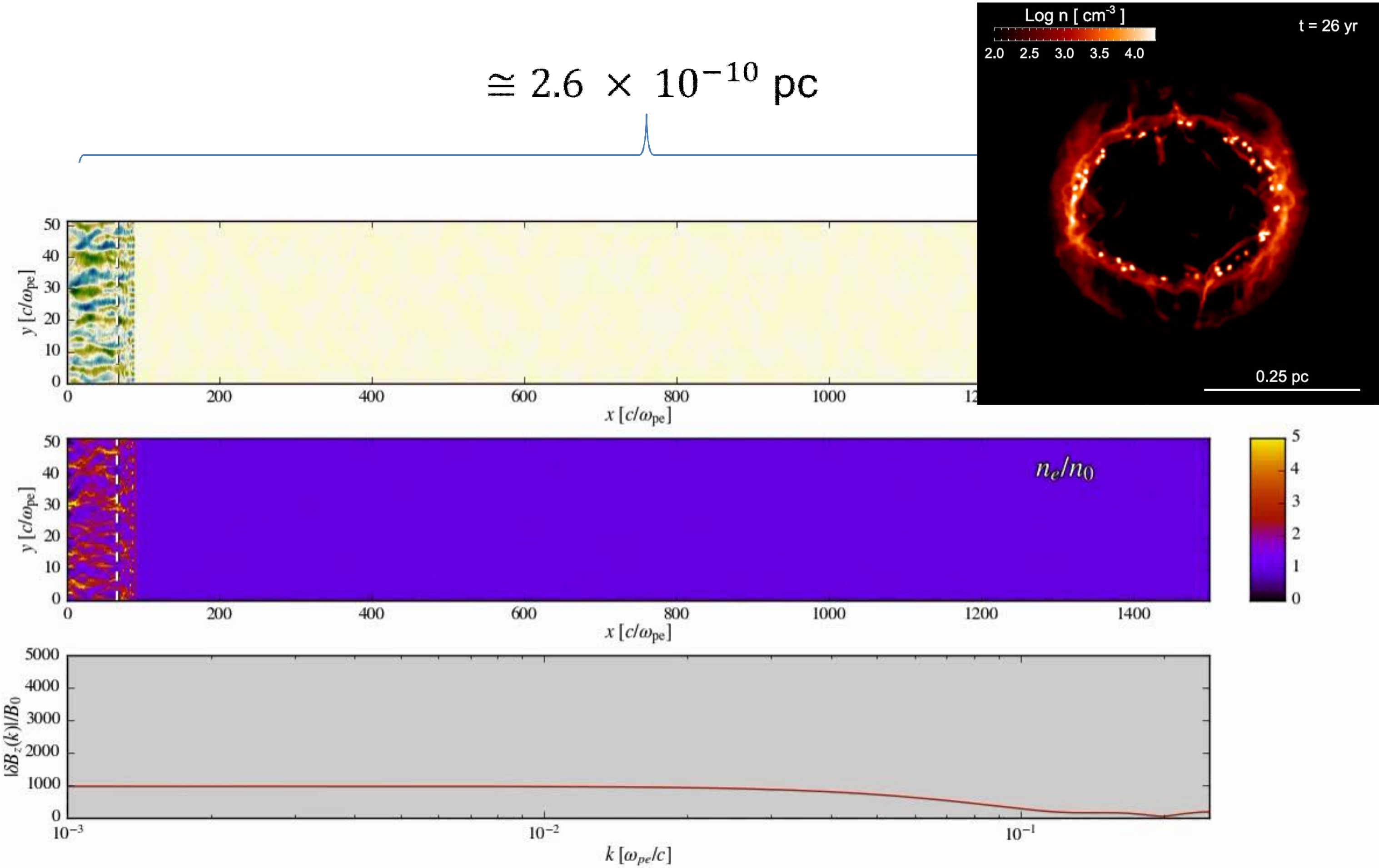
Caprioli et al. 2008, 2009, Pavloviĺ et al. 2017

Blasi et al. 2002, 2005

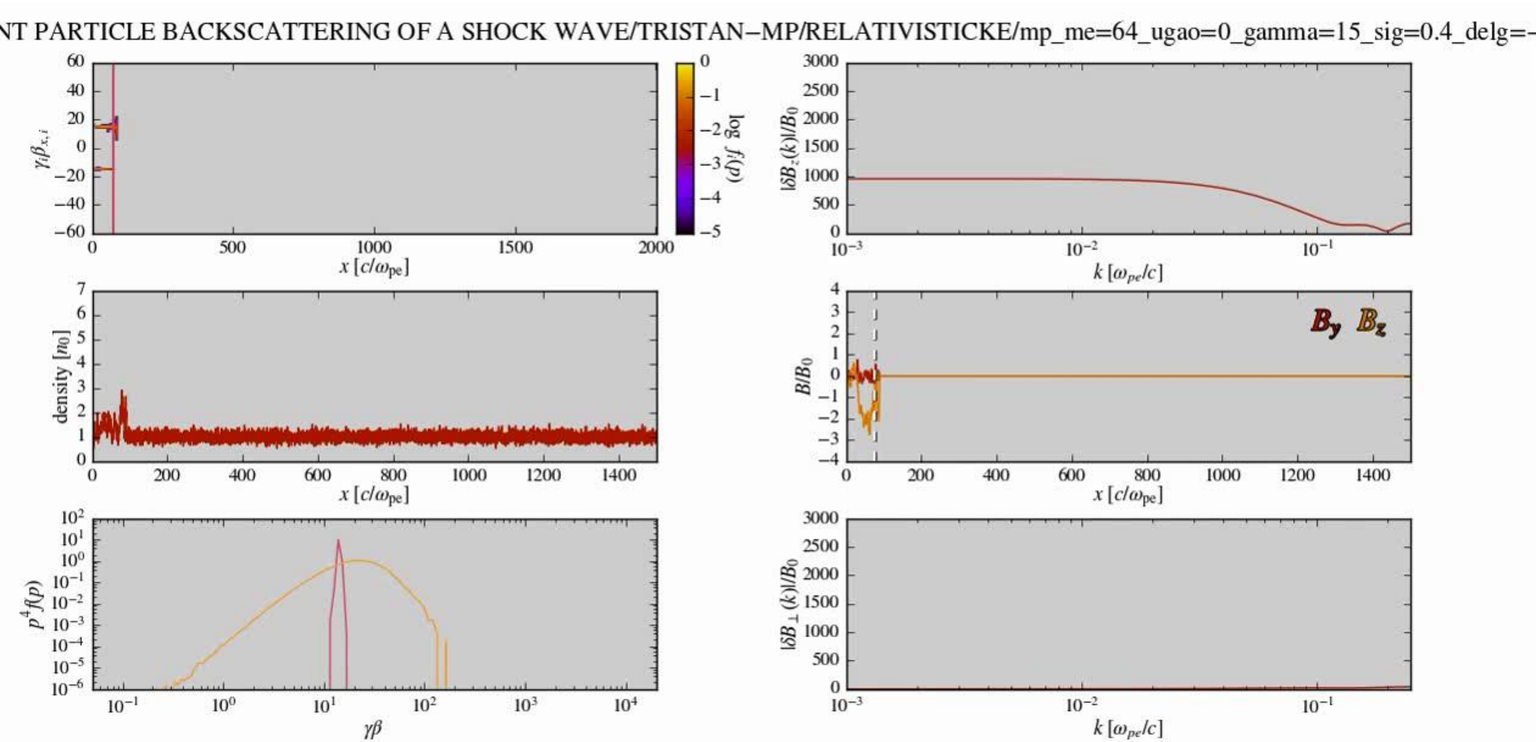
ñParticle-In-Cell (PIC)ò simulacije



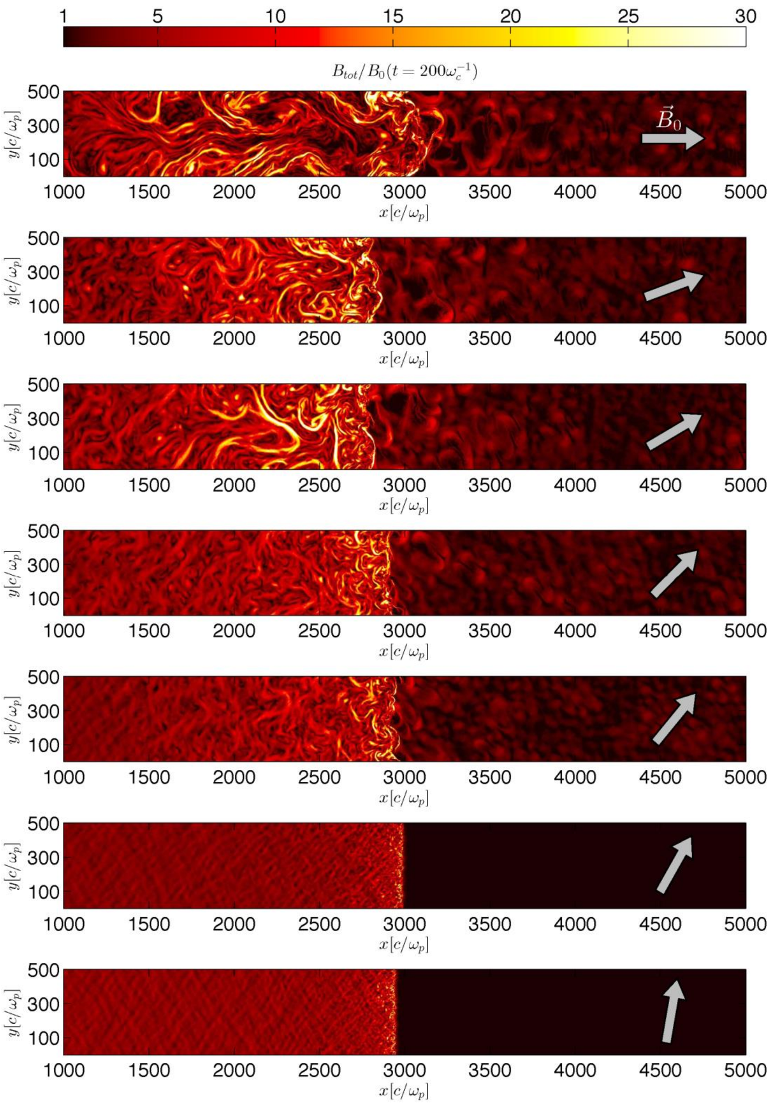
Caprioli and Spitkovsky 2014a,b,c

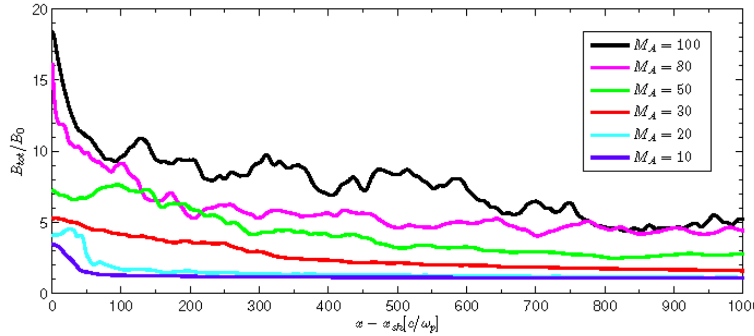


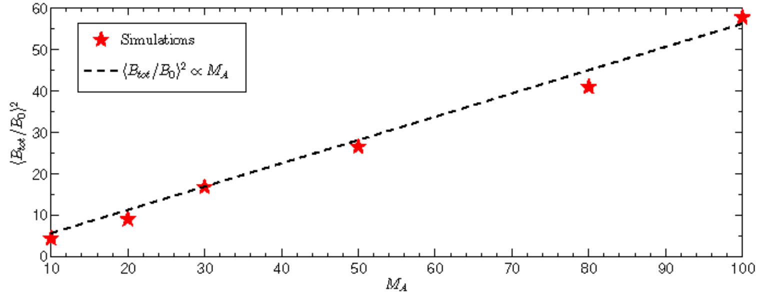
Vladimir Zeković
(privatna komunikacija, rad u pripremi)



Vladimir Zeković
(privatna komunikacija, rad u pripremi)







Caprioli and Spitkovsky 2014a,b,c

Å Pojaļ anje magnetnog polja usled rezonantnih i nerezonantnih nestabilnosti izazvanih tokom kosmiļ kih zraka.

$$\frac{P_{\mathrm{w},p}}{\rho_0 \upsilon_{\mathrm{s}}^2} \cong \frac{1-\zeta}{4M_{\mathrm{A},0}} U_p^{-3/2}(1-U_p^2)(1+\lambda)$$

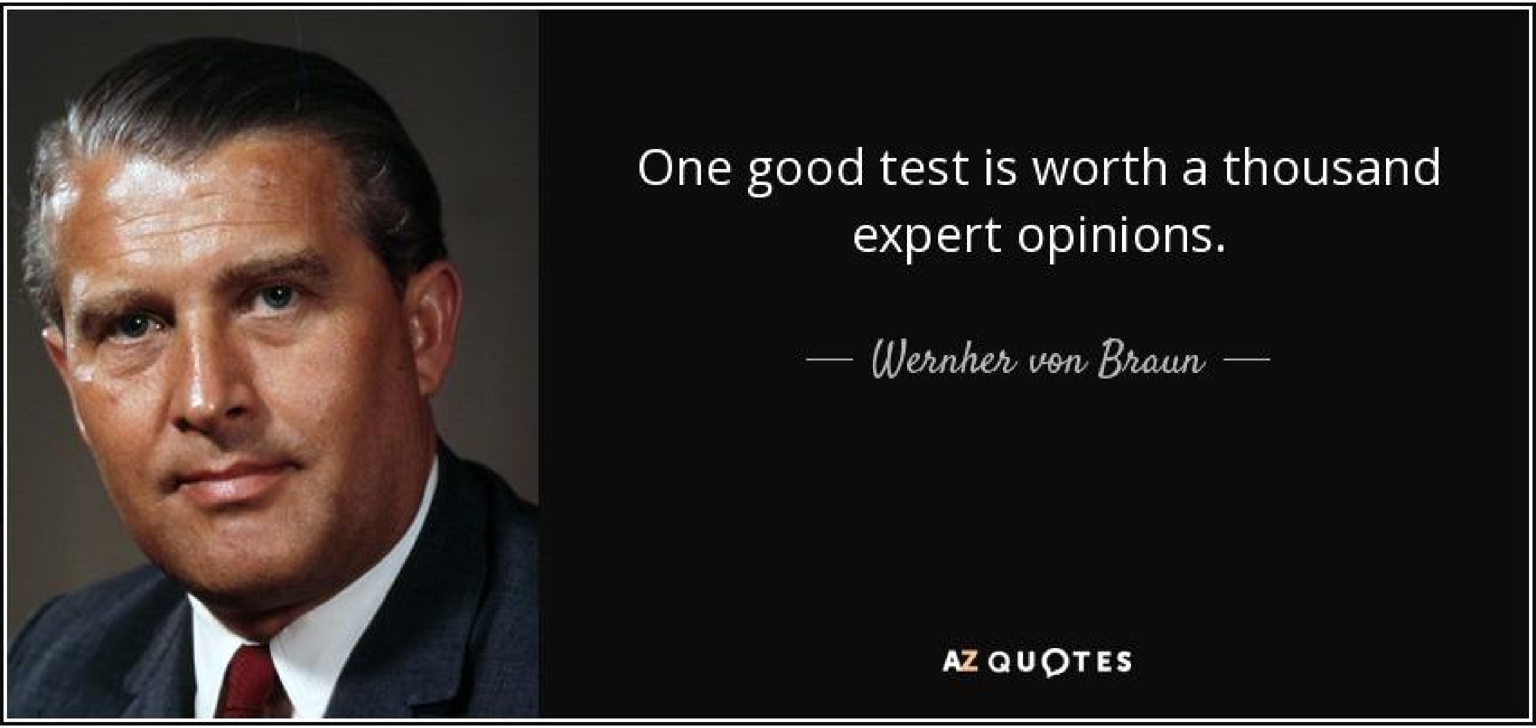
Å Magnetni pritisak Alfenovih talasa u prekursoru.

$$P_{\mathrm{w}} = \frac{1}{8\pi}\left(\sum_\mu \delta B_\mu\right)^2$$

Pojaļ anje magnetnog polja

Caprioli et al. 2008, 2009

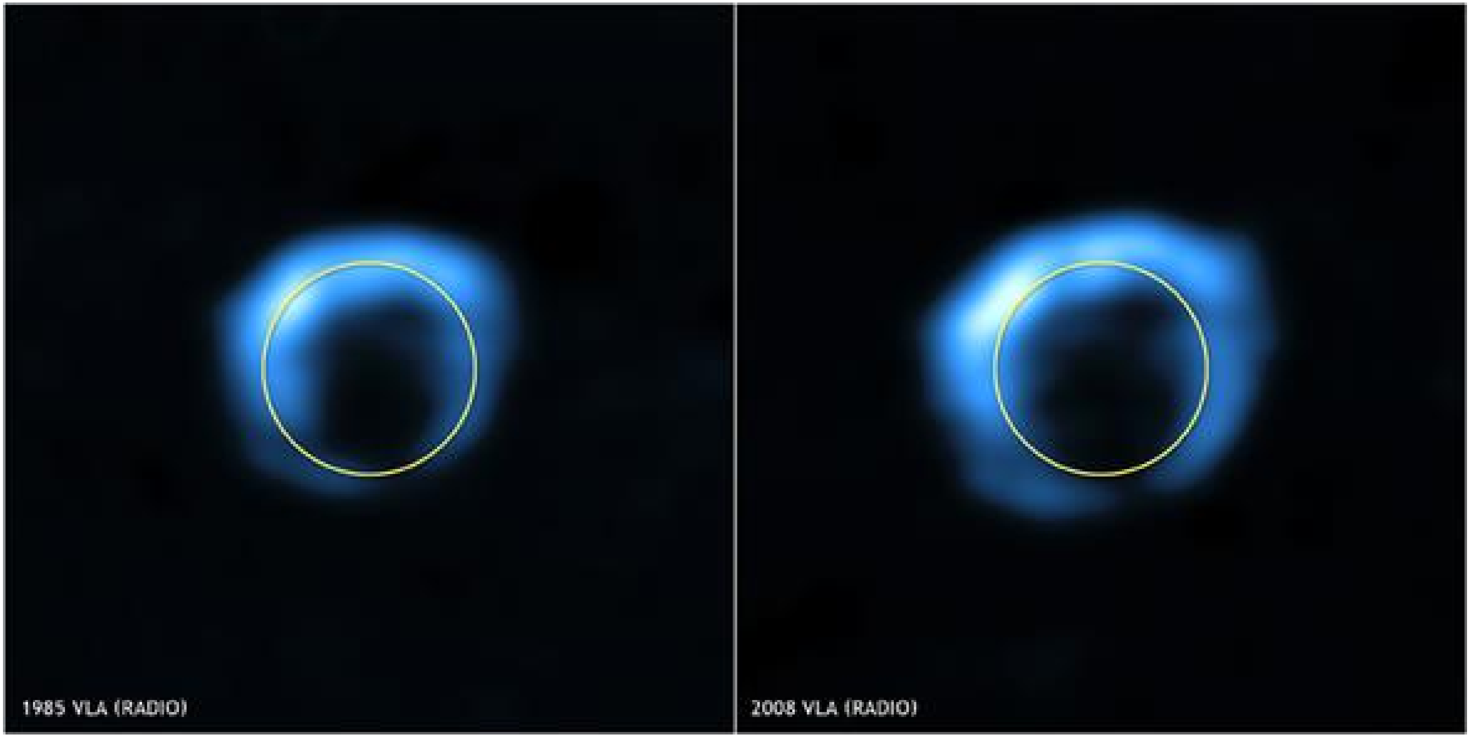
3. Rezultati



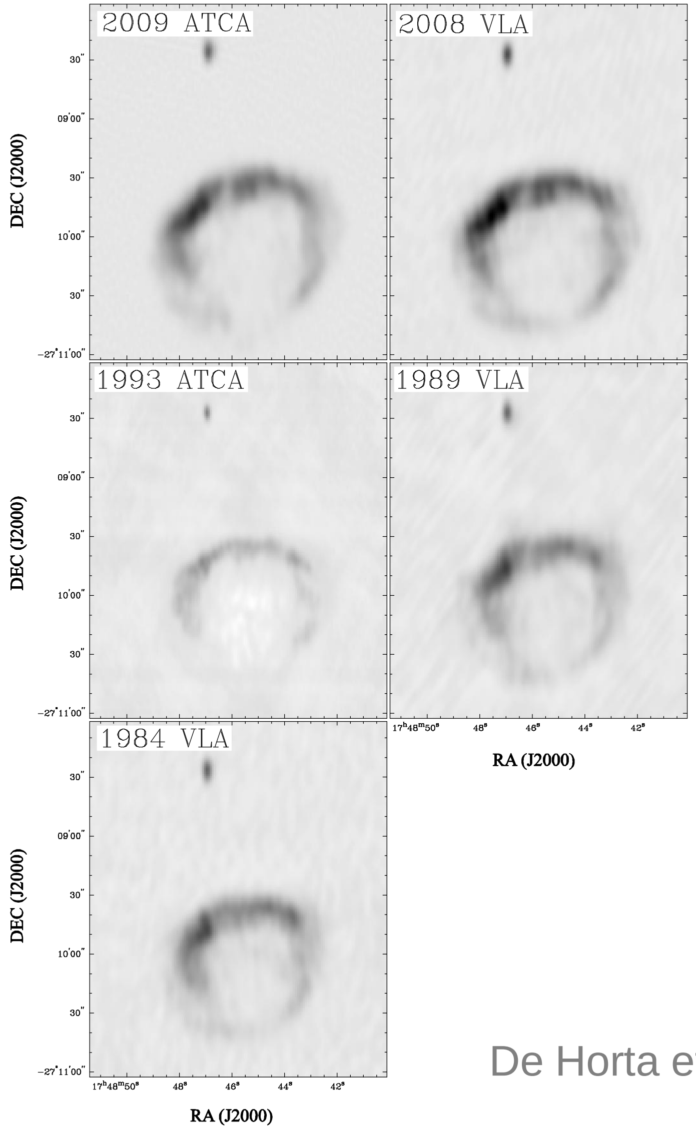
One good test is worth a thousand expert opinions.
— Wernher von Braun —
AZ QUOTES

3.1 Radio-evolucija OSN G1.9+0.3

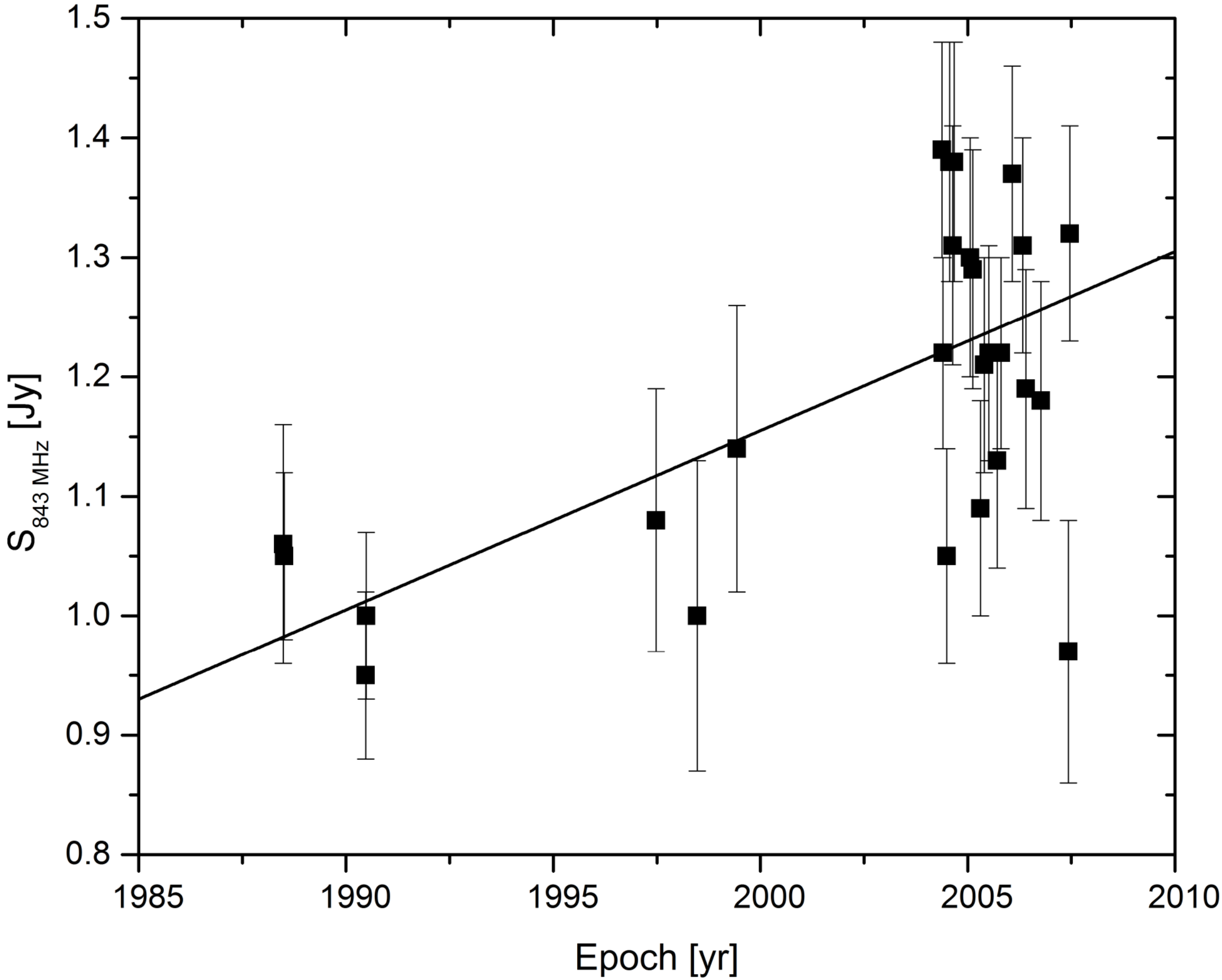
Pavlović, M. Z., MNRAS, 468, 1616 (2017)



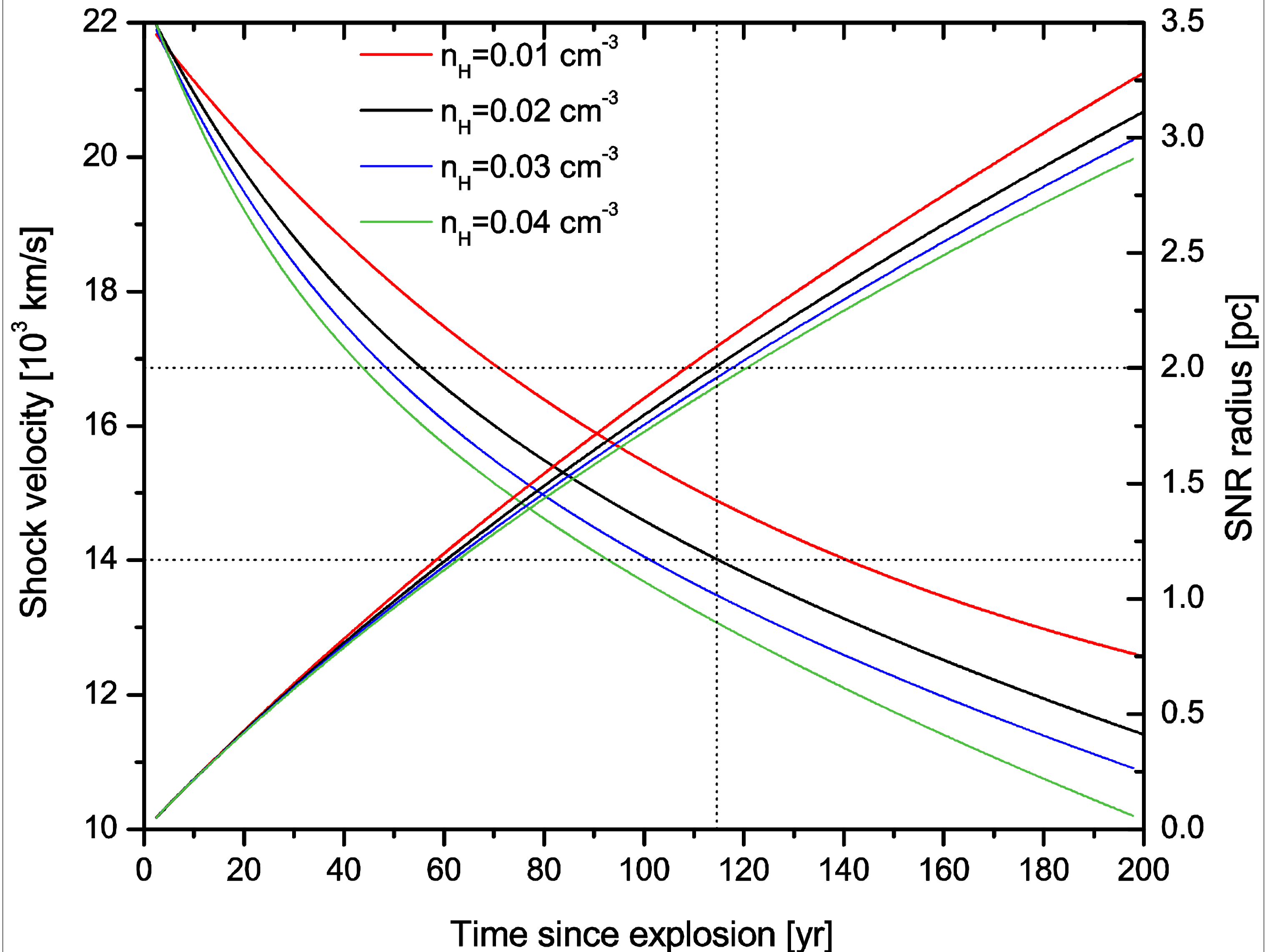
Green & Gull 1984, Green et al. 2008



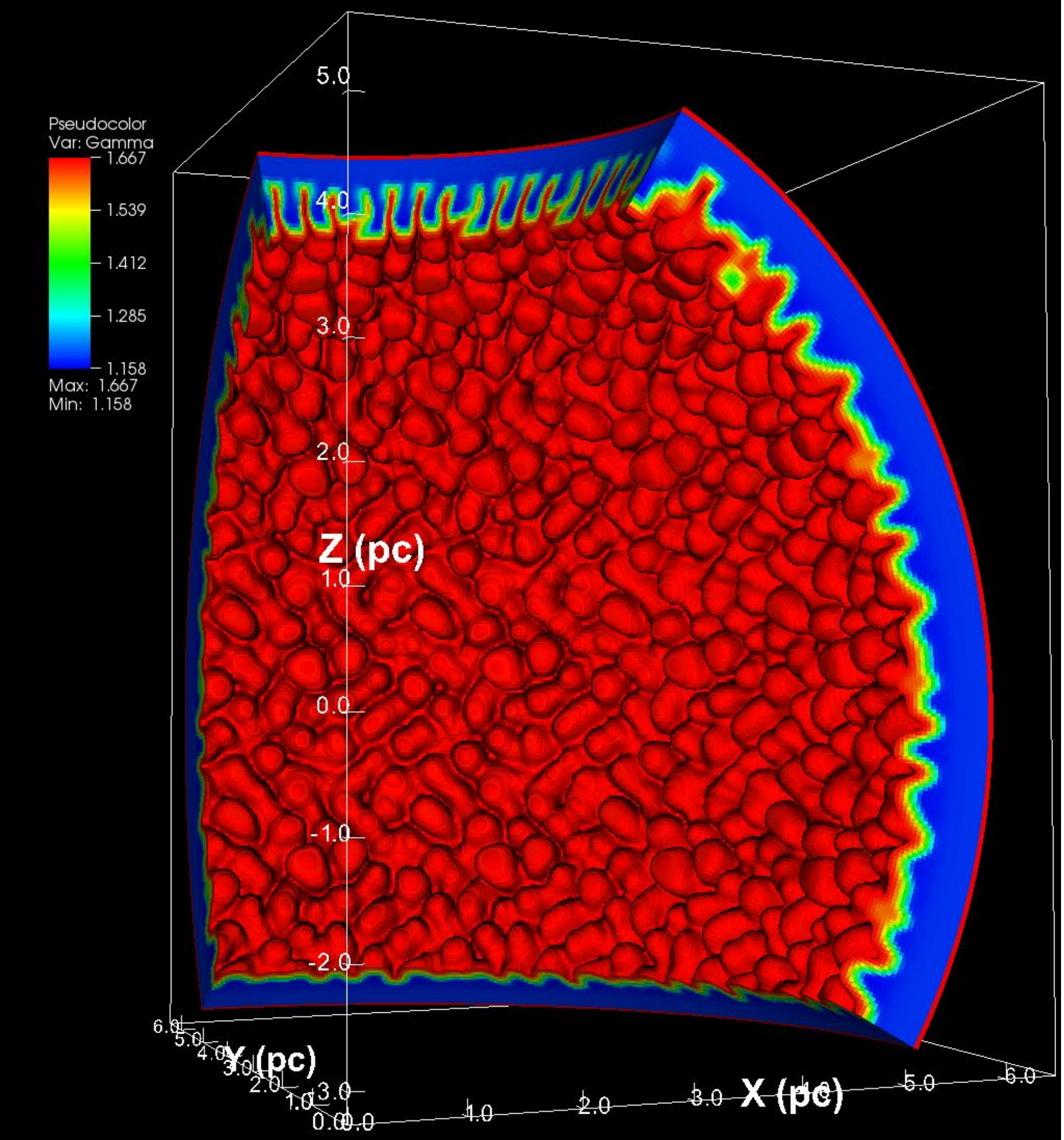
De Horta et al. 2014



Murphy et al. 2008 (MOST)

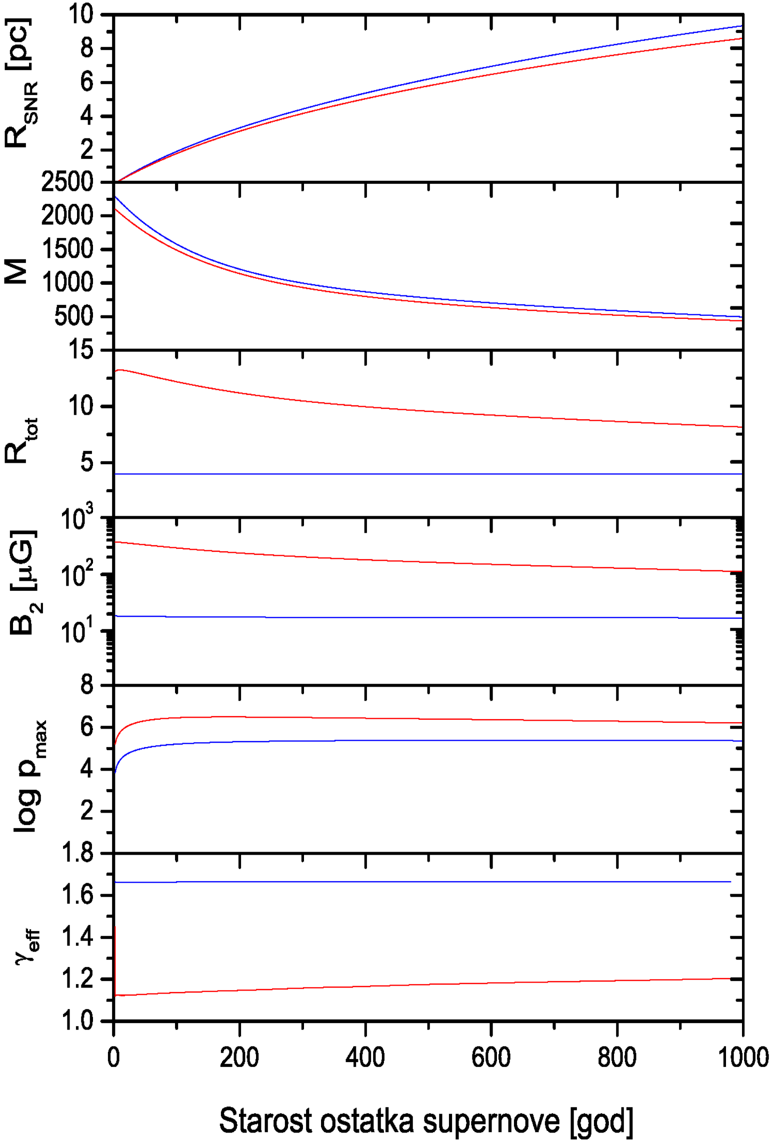


n_H=0.01 cm^-3
n_H=0.02 cm^-3
n_H=0.03 cm^-3
n_H=0.04 cm^-3
Shock velocity [10^3 km/s]
SNR radius [pc]
Time since explosion [yr]
22
20
18
16
14
12
10
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
120
140
160
180
200

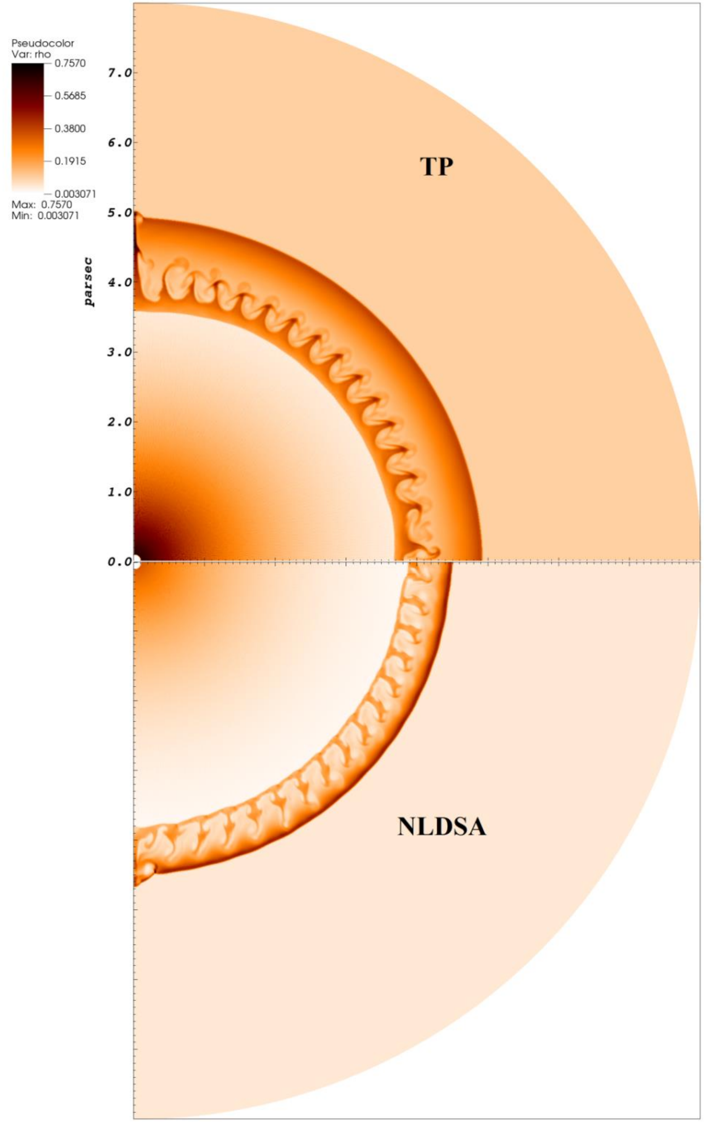


$$\gamma = \gamma(x, y, z, t)$$

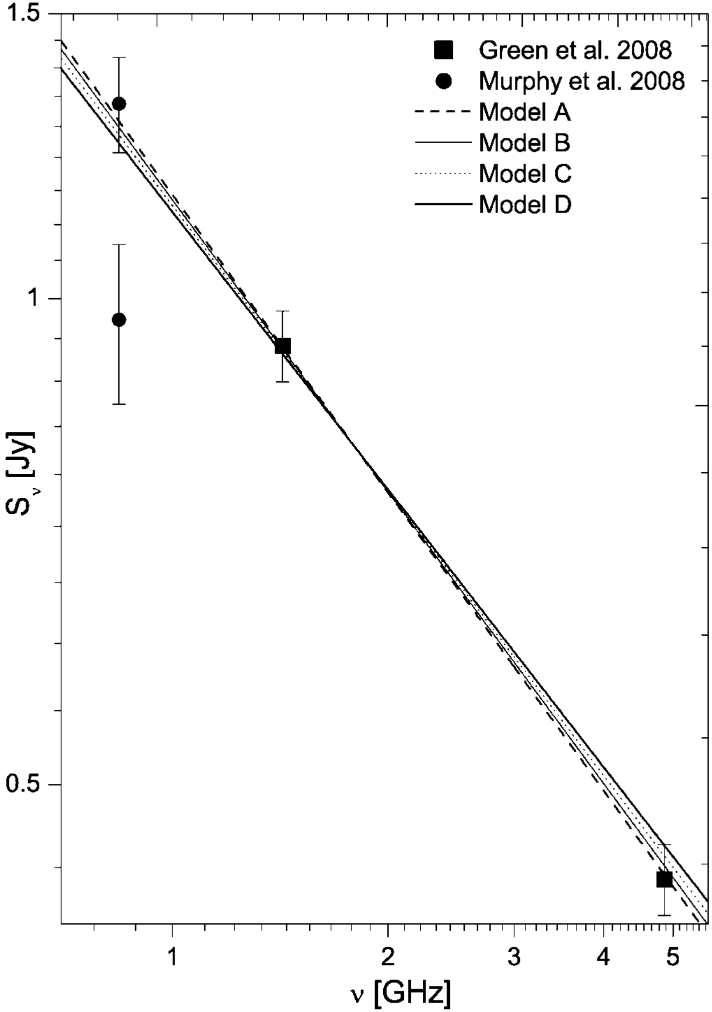
$$P = (\gamma - 1)\epsilon$$



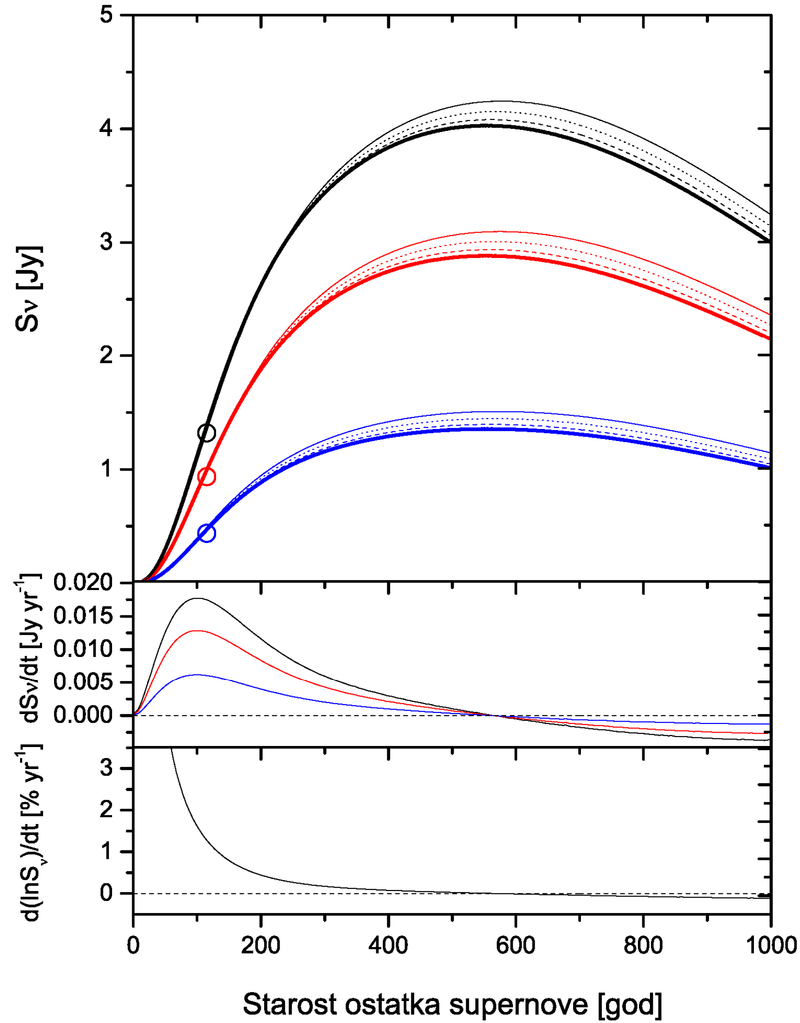
R_{SNR} [pc]
M
R_{tot}
B_2 [μG]
log p_{max}
γ_{eff}
Starost ostatka supernove [god]



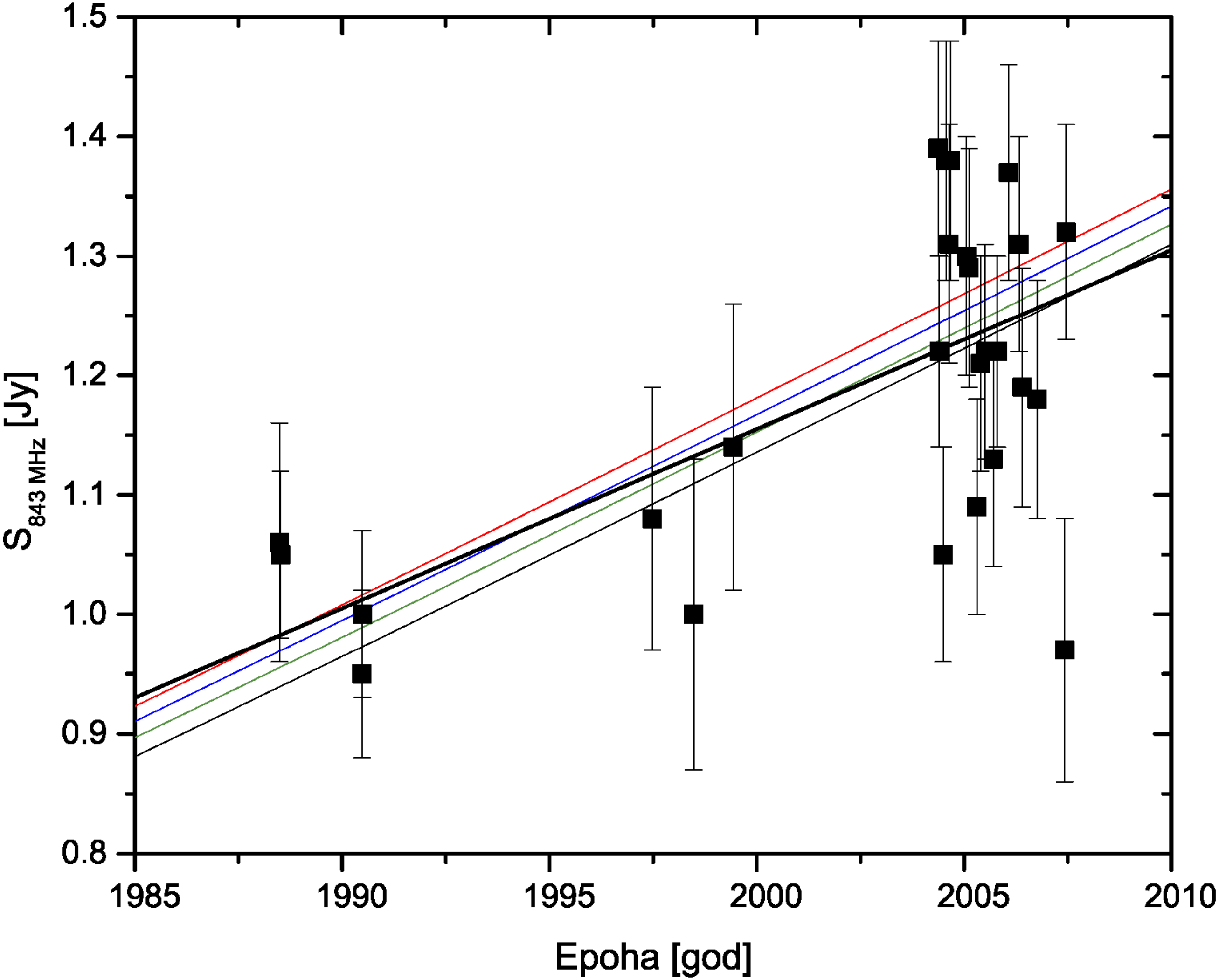
Pseudocolor
Var: rho
0.7570
0.5685
0.3800
0.1915
0.003071
Max: 0.7570
Min: 0.003071
parsec
TP
NLDSA



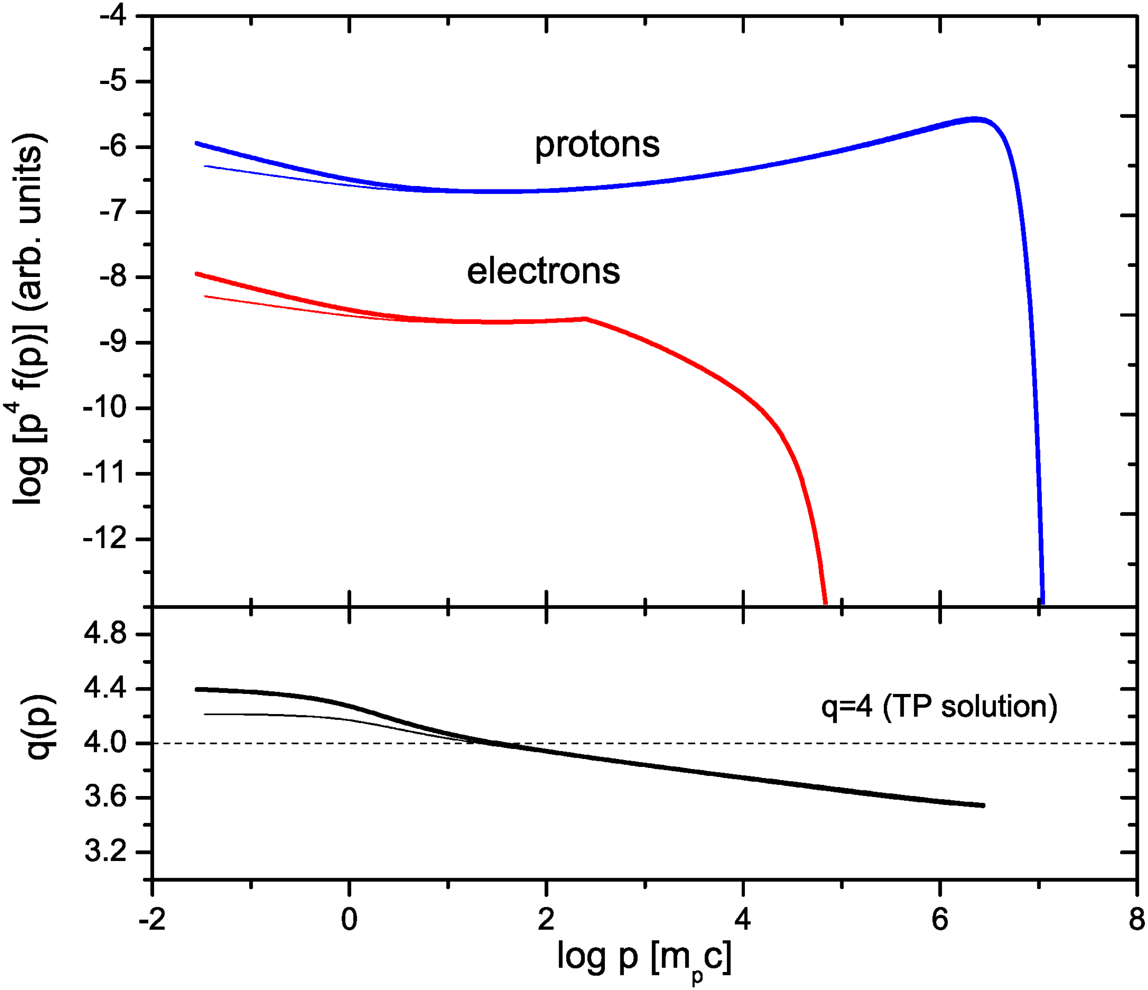
1.5
1
0.5
S_ν [Jy]
1
2
3
4
5
ν [GHz]
Green et al. 2008
Murphy et al. 2008
Model A
Model B
Model C
Model D



5
4
3
2
1
Sν [Jy]
0.020
0.015
0.010
0.005
0.000
dSν/dt [Jy yr^{-1}]
3
2
1
0
d(lnS_ν)/dt [% yr^{-1}]
0
200
400
600
800
1000
Starost ostatka supernove [god]



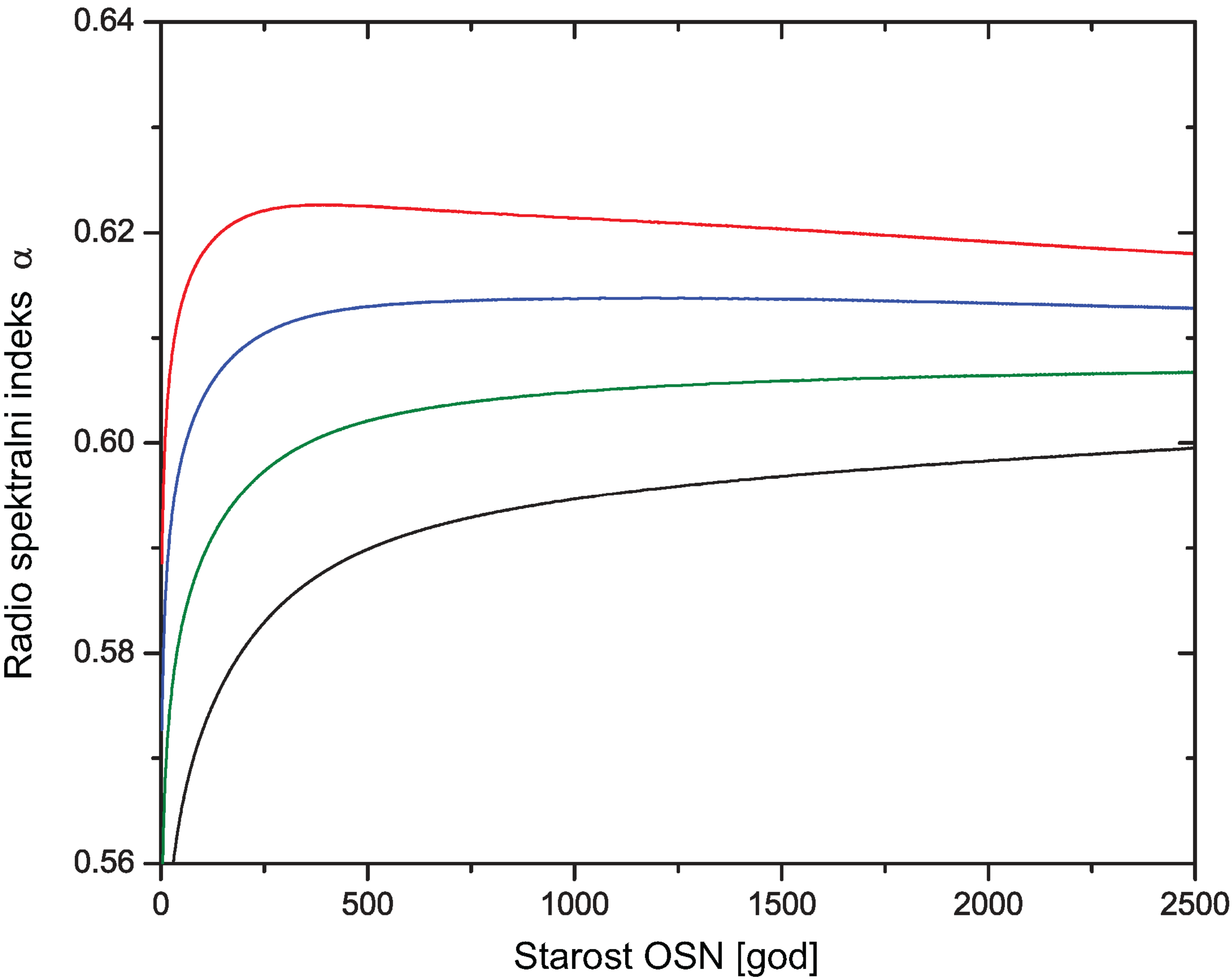
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
S843 MHz [Jy]
1985
1990
1995
2000
2005
2010
Epoha [god]



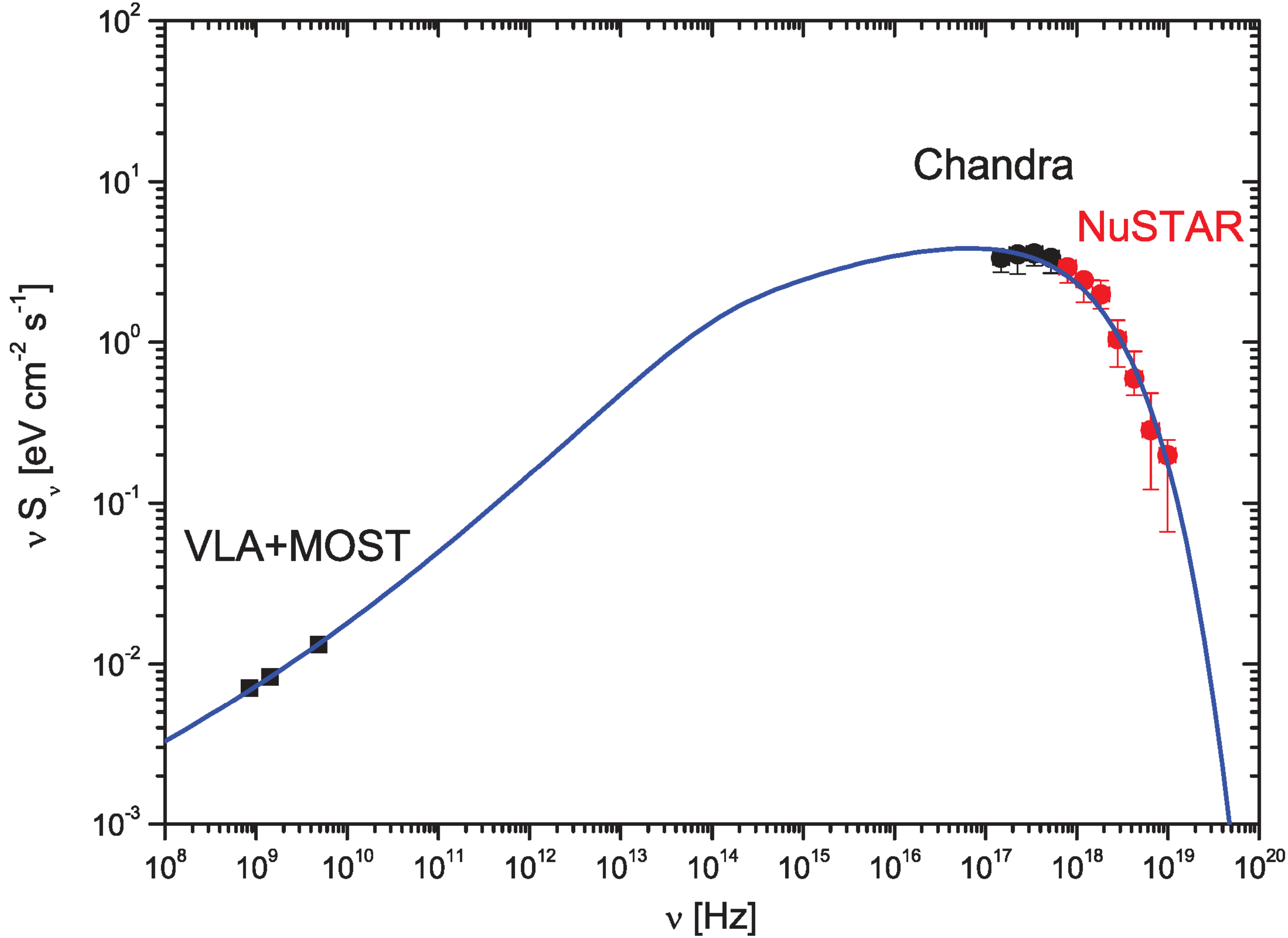
$$f(p) \propto p^{q}$$

$$E(p) \propto p^{q+2}$$

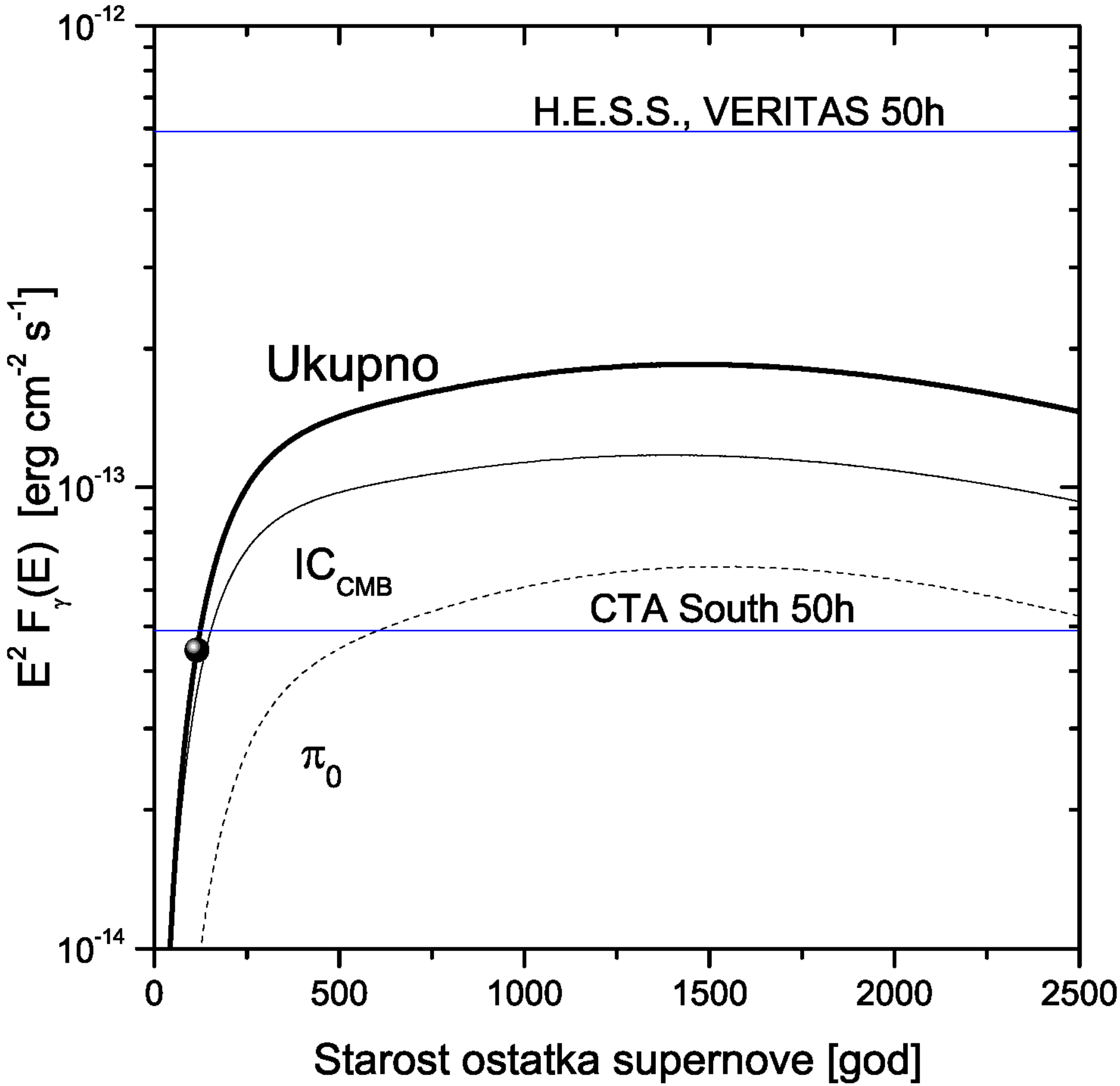
$$q(p) = \frac{d \ln f(p)}{d \ln p}$$



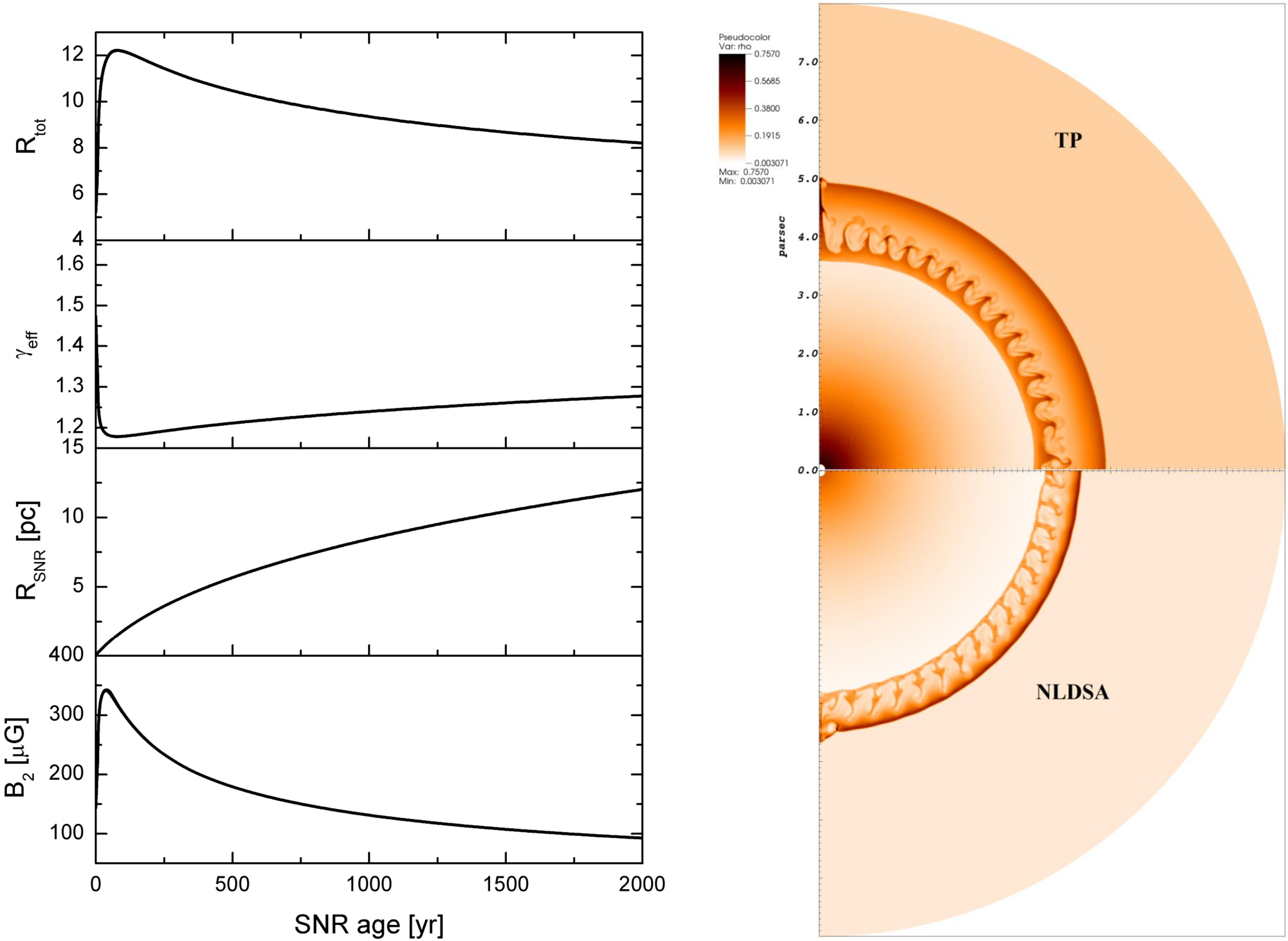
0.64
0.62
0.60
0.58
0.56
0
500
1000
1500
2000
2500
Radio spektralni indeks α
Starost OSN [god]



Chandra
NuSTAR
VLA+MOST
νS_ν [eV cm^{-2} s^{-1}]
ν [Hz]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}



H.E.S.S., VERITAS 50h
Ukupno
IC$_{CMB}$
CTA South 50h
π_0
10^{-12}
10^{-13}
10^{-14}
$E^2 F_\gamma(E)$ [erg cm^{-2} s^{-1}]
0
500
1000
1500
2000
2500
Starost ostatka supernove [god]



R_tot
12
10
8
6
4
γ_eff
1.6
1.5
1.4
1.3
1.2
R_SNR [pc]
15
10
5
B_2 [μG]
400
300
200
100
0
500
1000
1500
2000
SNR age [yr]
Pseudocolor
Var: rho
0.7570
0.5685
0.3800
0.1915
0.003071
Max: 0.7570
Min: 0.003071
parsec
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
TP
NLDSA

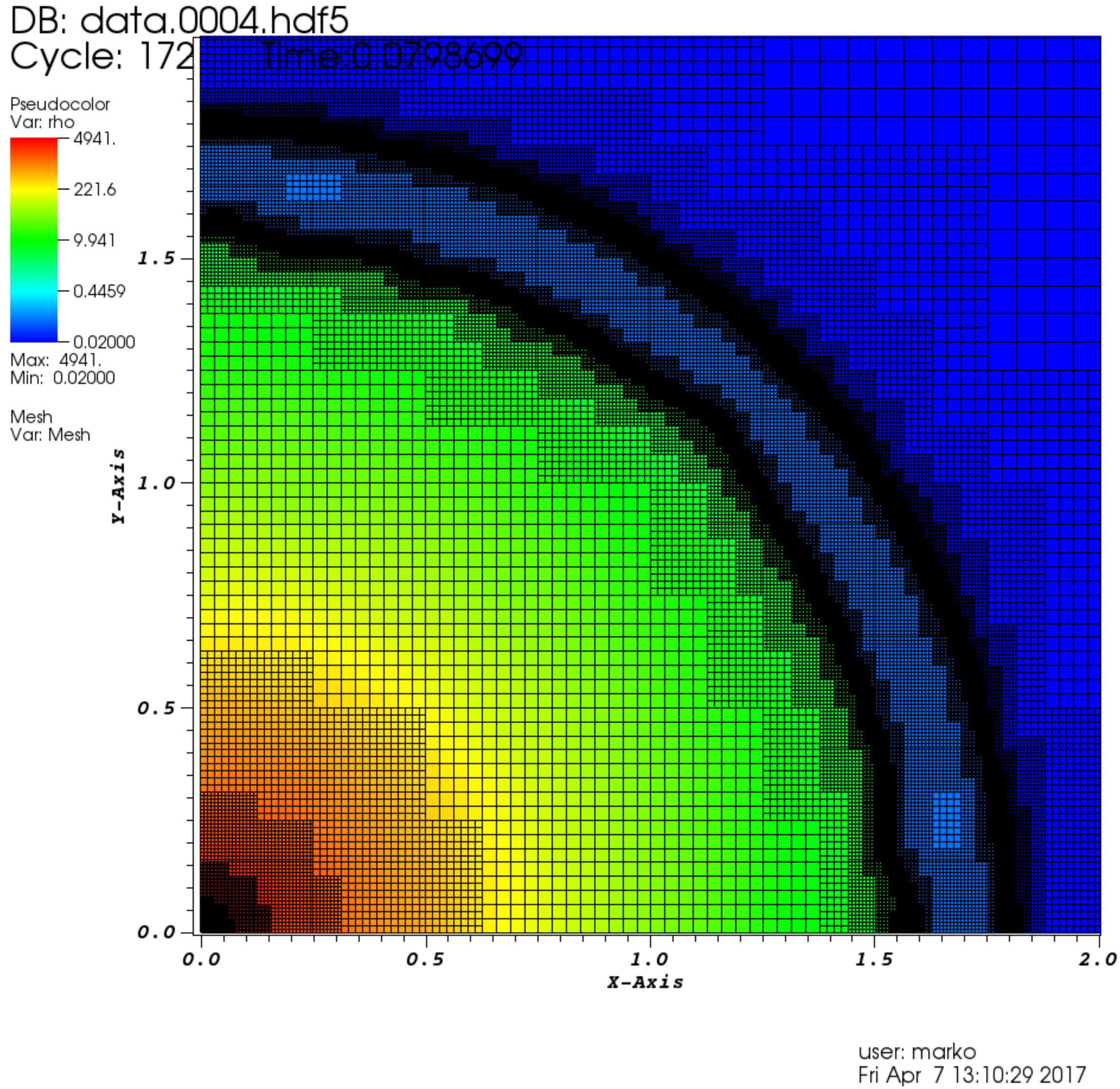
3.2 Opšti model radio-evolucije OSN

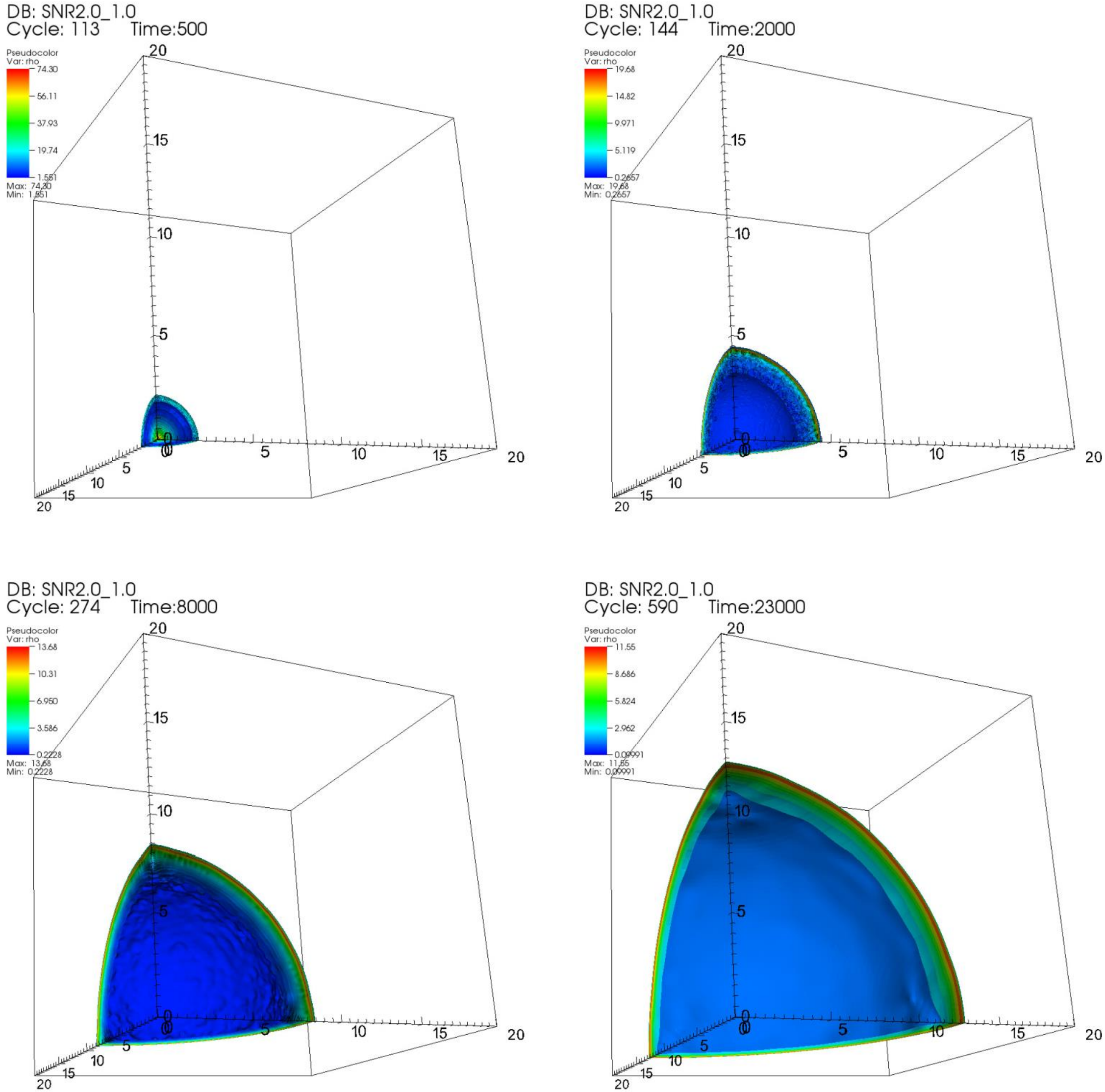
Pavlovil̍ , M. Z., Uroġevil̍ , D., Arbutina, B., Salvatore, O., Maxted, N., Filipovil̍ , M., ApJ, 852, 84 (2018)

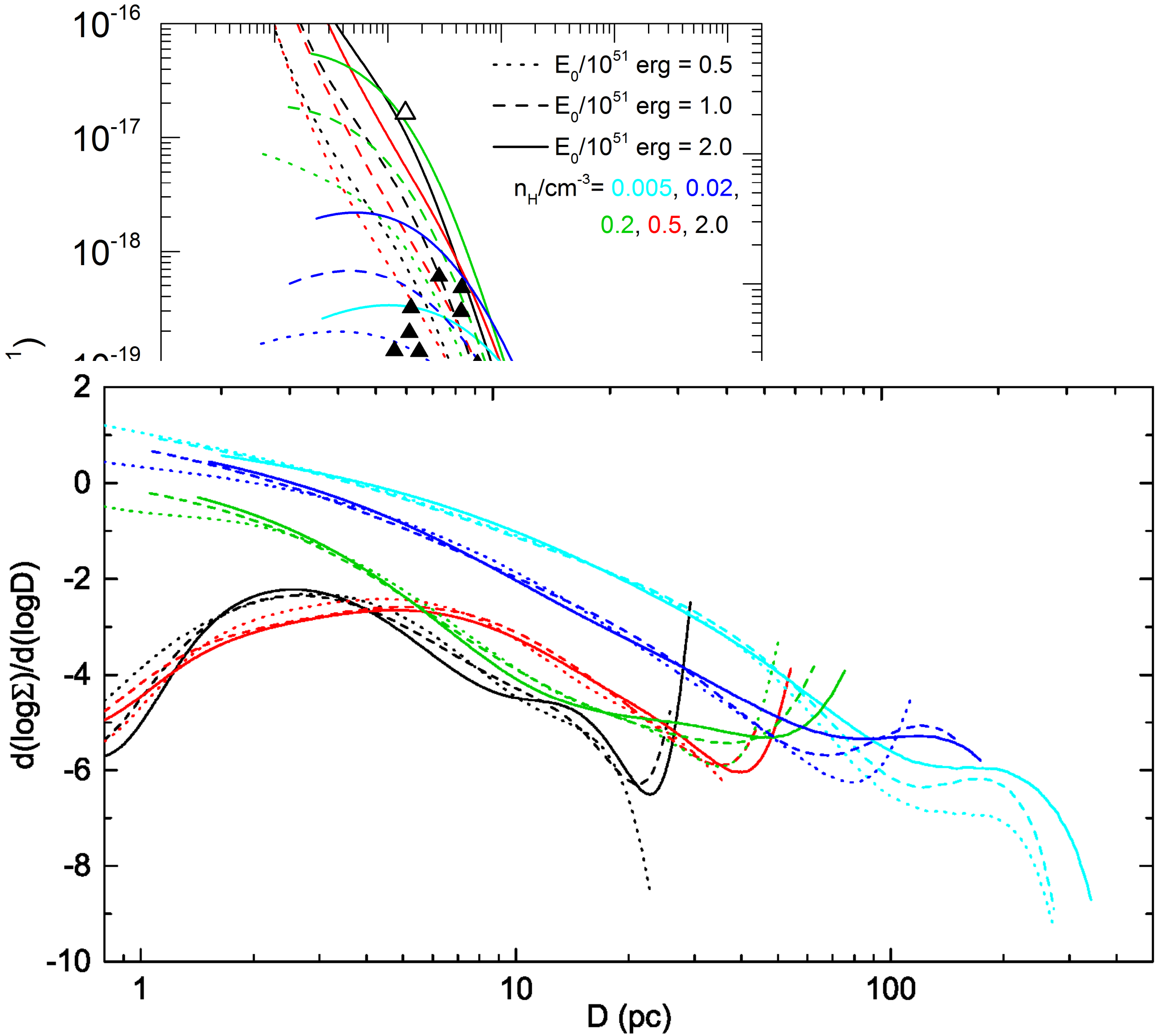
Table 1

Adopted Parameters and Initial Conditions for the Hydrodynamic Models Used to Obtain Radio Evolution of Different SNRs

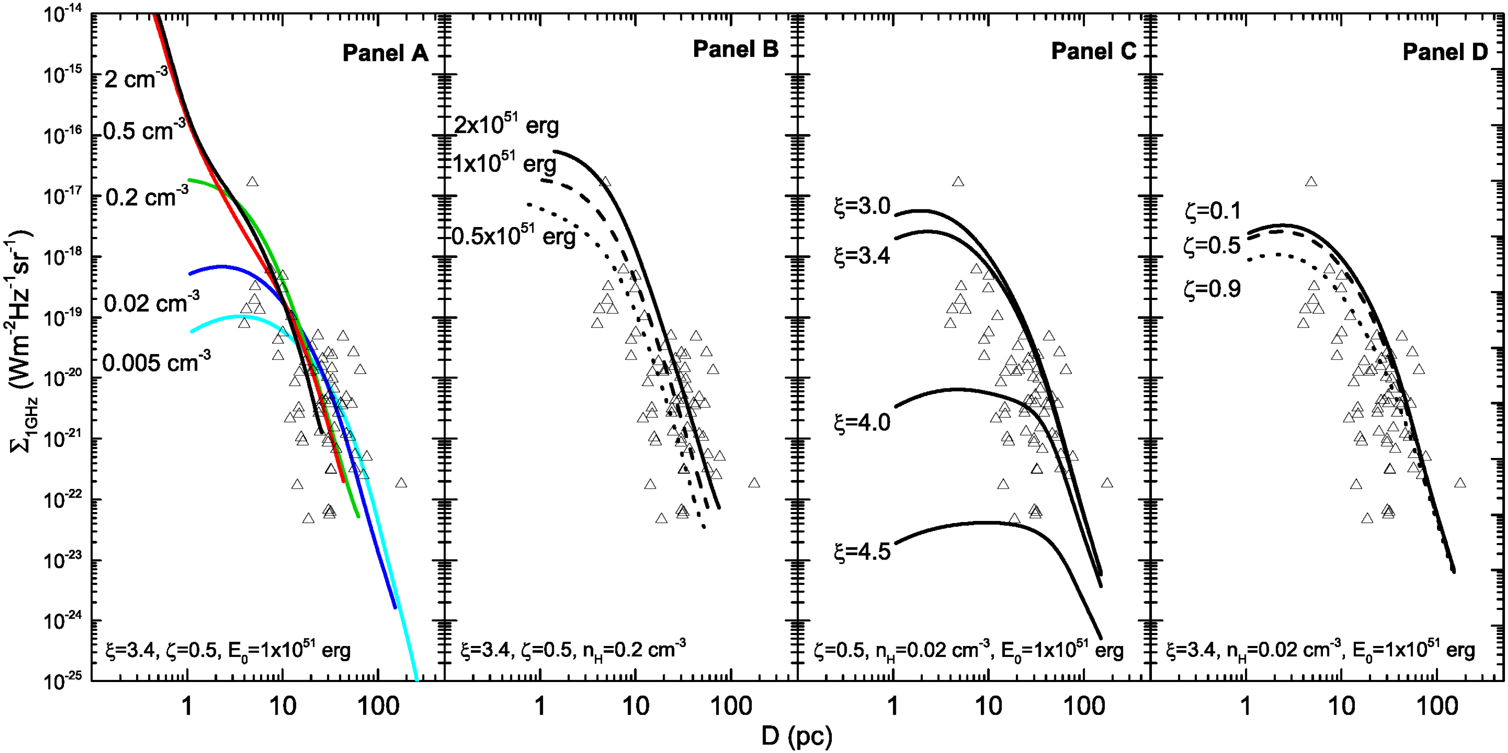
Model Abbreviation (1)	Ejecta Mass ($M_\odot$) (2)	Explosion Energy (10^{51} erg) (3)	Ambient Density (cm^{-3}) (4)	Maximum Age (kyr) (5)	Maximum Size of Physical Grid (pc) (6)
SNR0.005_0.5	1.4	0.5	0.005	400	140
SNR0.005_1.0	1.4	1.0	0.005	400	160
SNR0.005_2.0	1.4	2.0	0.005	500	200
SNR0.02_0.5	1.4	0.5	0.02	150	80
SNR0.02_1.0	1.4	1.0	0.02	150	80
SNR0.02_2.0	1.4	2.0	0.02	150	90
SNR0.2_0.5	1.4	0.5	0.2	60	35
SNR0.2_1.0	1.4	1.0	0.2	60	35
SNR0.2_2.0	1.4	2.0	0.2	70	35
SNR0.5_0.5	10	0.5	0.5	35	20
SNR0.5_1.0	10	1.0	0.5	40	25
SNR0.5_2.0	10	2.0	0.5	50	32
SNR2.0_0.5	10	0.5	2.0	23	20
SNR2.0_1.0	10	1.0	2.0	23	20
SNR2.0_2.0	10	2.0	2.0	23	20


DB: data.0004.hdf5
Cycle: 172
Time:0.0798699
Pseudocolor
Var: rho
4941.
221.6
9.941
0.4459
0.02000
Max: 4941.
Min: 0.02000
Mesh
Var: Mesh
Y-Axis
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
X-Axis
user: marko
Fri Apr 7 13:10:29 2017

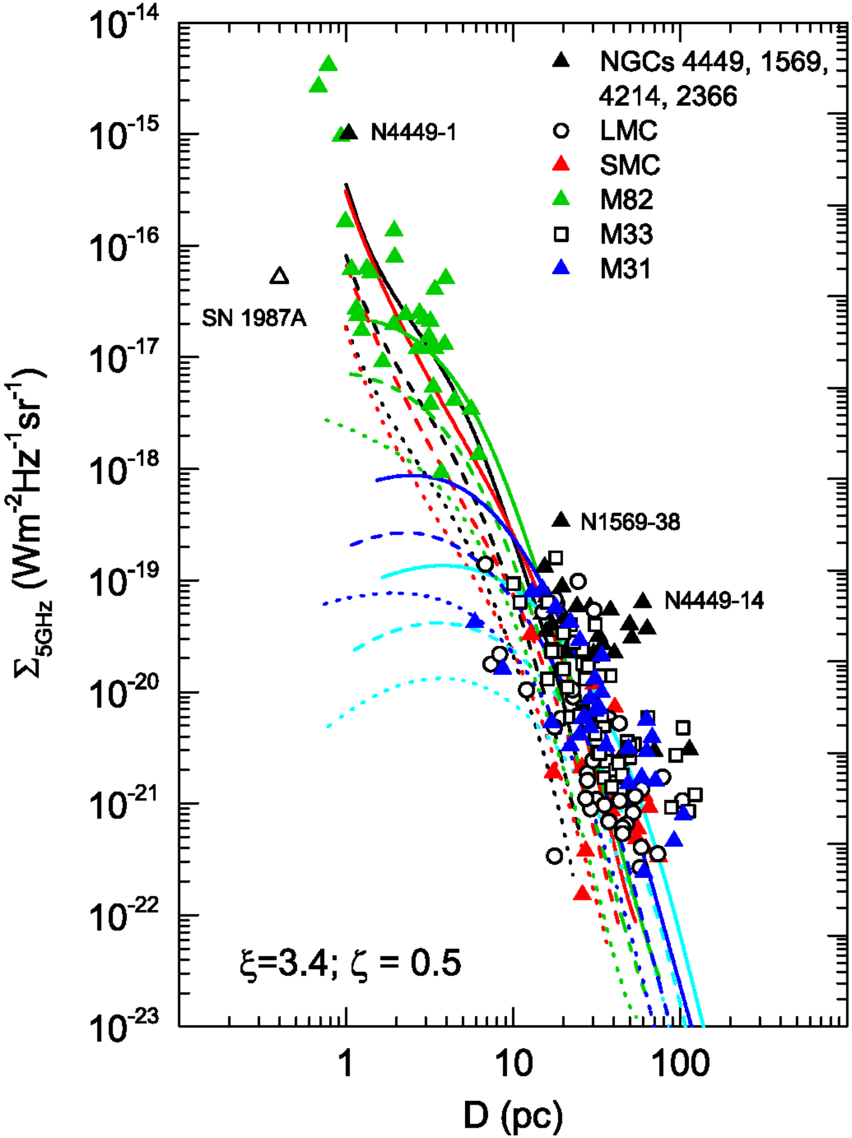

DB: SNR2.0_1.0
Cycle: 113 Time:500
Pseudocolor
Var: rho
74.30
56.11
37.93
19.74
1.551
Max: 74.30
Min: 1.551
DB: SNR2.0_1.0
Cycle: 144 Time:2000
Pseudocolor
Var: rho
19.68
14.82
9.971
5.119
0.2657
Max: 19.68
Min: 0.2657
DB: SNR2.0_1.0
Cycle: 274 Time:8000
Pseudocolor
Var: rho
13.68
10.31
6.950
3.586
0.2228
Max: 13.68
Min: 0.2228
DB: SNR2.0_1.0
Cycle: 590 Time:23000
Pseudocolor
Var: rho
11.55
8.686
5.824
2.962
0.09991
Max: 11.55
Min: 0.09991



E0/10^51 erg = 0.5
E0/10^51 erg = 1.0
E0/10^51 erg = 2.0
nH/cm^-3= 0.005, 0.02,
0.2, 0.5, 2.0
d(logΣ)/d(logD)
D (pc)



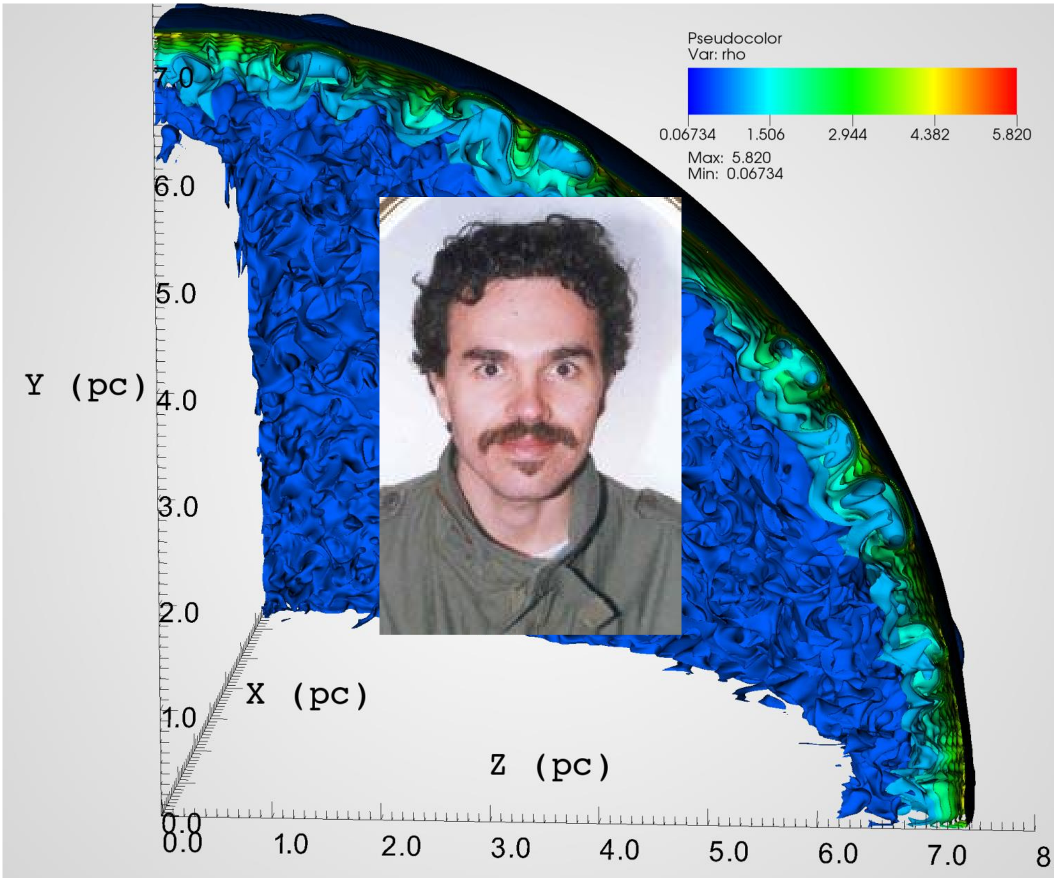
Panel A
Panel B
Panel C
Panel D
2 cm-3
0.5 cm-3
0.2 cm-3
0.02 cm-3
0.005 cm-3
2x10^51 erg
1x10^51 erg
0.5x10^51 erg
ξ=3.0
ξ=3.4
ξ=4.0
ξ=4.5
ζ=0.1
ζ=0.5
ζ=0.9
ξ=3.4, ζ=0.5, E0=1x10^51 erg
ξ=3.4, ζ=0.5, nH=0.2 cm-3
ζ=0.5, nH=0.02 cm-3, E0=1x10^51 erg
ξ=3.4, nH=0.02 cm-3, E0=1x10^51 erg
Σ1GHz (Wm-2Hz-1sr-1)
D (pc)

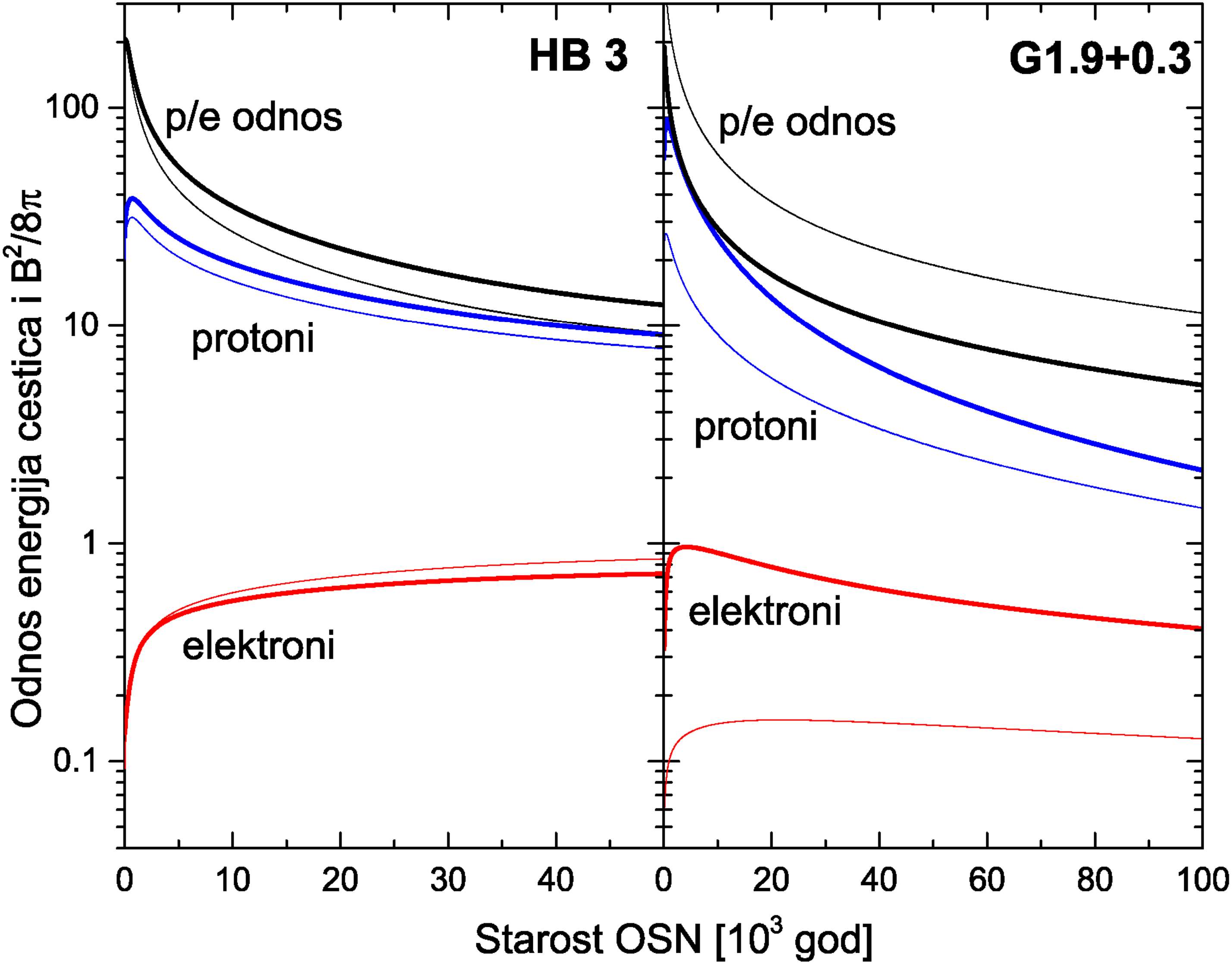


NGCs 4449, 1569, 4214, 2366
LMC
SMC
M82
M33
M31
N4449-1
SN 1987A
N1569-38
N4449-14
ξ=3.4; ζ = 0.5
Σ_{5GHz} (Wm^{-2}Hz^{-1}sr^{-1})
D (pc)

3.3 Ekviparticija u OSN

Uroġeviĺ , D., Pavloviĺ , M. Z., Arbutina, ApJ, u ġtampi (2018)





HB 3
G1.9+0.3
p/e odnos
protoni
elektroni
p/e odnos
protoni
elektroni
100
10
1
0.1
0
10
20
30
40
0
20
40
60
80
100
Odnos energija cestica i $B^2/8\pi$
Starost OSN [10^3 god]

4. Zaključak

1) Efikasno difuzno ubrzavanje ļ estica modifikuje strukturu udarnog talasa, znaļ ajno pojaļ ava meĽuzvezdano magnetno polje, ļ ime proces ubrzavanja i radio-emisije ubrzanih elektrona postaje nelinearan i zahteva primenu numeriļ kih simulacija.

2) Modelovali smo specifiļ nu radio-evoluciju najmlaĽeg poznatog Galaktiļ kog OSN G1.9+0.3. Procenjena starost ovog OSN iz naġeg modela iznosi oko 120 godina, dok gustina okolne MZM iznosi 0.02 cm^{-3}. Strmiji spektralni indeksi (standardna DSA teorija predviĽa oko 0.5) kod mladih OSN dobijaju se putem efikasnog NLDSA mehanizma i odgovarajuĺ eg pojaļ anja magnetnog polja.

3) Radio-emisija ostatka G1.9+0.3 raste tokom faze slobodnog ġirenja, dostiġe maksimalnu vrednost 600 godina posle eksplozije da bi zatim ukupan sjaj opadao do kraja faze slobodnog ġirenja i u fazi Sedov-Tejlora. Numeriļ ki model pokazuje da je porast radio-emisije uobicajena pojava kod mladih OSN.

4) Pored radio-emisije, implementiran je i jednostavan model za sintezu sinhrotronskog spektra OSN G1.9+0.3 od radio do X-podruļ ja, koji pokazuje dobro slaganje sa posmatranjima.

5) Evolutivne trake, dobijene u ovom radu, mogu biti veoma korisne za radio-posmatraį e. Oni ih mogu primeniti na odreĽivanje evolutivnog statusa svih posmatranih Galaktiį kih i vangalaktiį kih OSN, za koje je nepoznata starost ili parametri okoline.

6) Radio evolutivne trake za OSN koji evoluiraju u razliį itoj gustini seku se izmeĽu 10 pc i nekoliko desetina parseka. Sigma-D trake za vecu gustinu MZM se posle toga nalaze ispod traka koje odgovaraju retkoj sredini. Stoga korelacija izmeĽu okolne gustine i poloġaja na Sigma-D dijagramu nije uvek jednoznaį na.

7) U naġim simulacijama se dobijaju Sigma-D nagibi izmeĽu -4 i -6 za potpuni reġim Sedov-Tejlora, koji se dobro slaġu sa teorijskim predviĽanjima i vrednostima za posmatrane uzorke OSN.

8) Zakljuį ujemo da je ekviparticija opravdana pretpostavka za energiju elektrona i magnetnog polja u starijim OSN, tokom faze Sedov-Tejlora. TakoĽe, simulacije nude moguĺ e objaġnjenje za ekviparticiju izmedju kosmiį kih zraka i magnetnog polja u MZM.

5. Planovi za dalji rad

1) Neophodan je rad na razvoju numeriļ kih modela hidrodinamiļ ke evolucije OSN u radijativnoj fazi.

2) Od velikog znaļ aja, posebno kod mladih OSN, bi bilo ukljuļ ivanje Alfenovog drifta u model NLDSA.

3) Planirano je povezivanje simulacija OSN razvijenih u ovom radu sa simulacijama eksplozija supernovih na znatno manjim skalama.

4) Planiramo da analizu ekviparticije proģirimo na sve OSN za koje postoji dovoljno posmatranja u razliļ itim oblastima elektromagnetnog spektra.

5) Kao jedan od glavnih nereģenih problema u oblasti vidimo injekciju i ubrzavanje elektrona na udarnim talasima.

Acknowledgements

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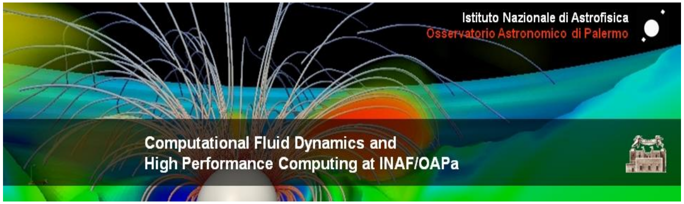
- M. P. also thanks **Gilles Ferrand** for extremely helpful discussions, advices and help during this work. We are indebted to **Brian Reville** for his valuable comments on different approaches in SNR modeling.




Hvala na pažnji