Interstellar Medium in the Nearby Universe
Bamberg, 26-28 March 2018

Radio evolution of supernova remnants including cosmic ray acceleration

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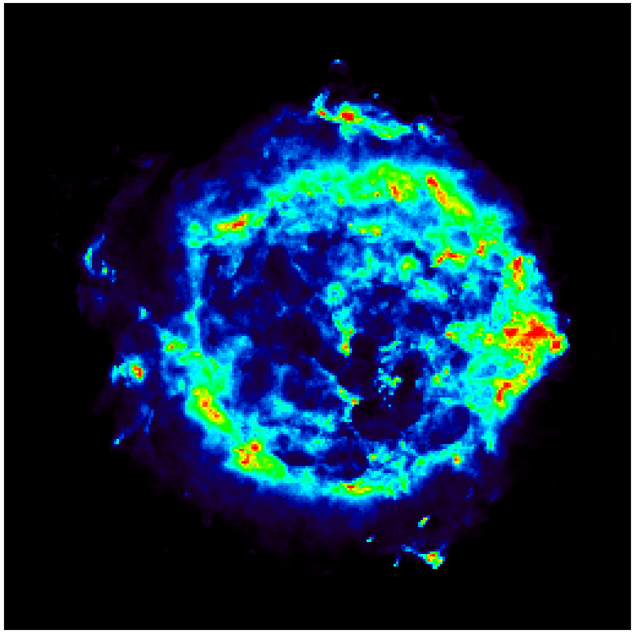
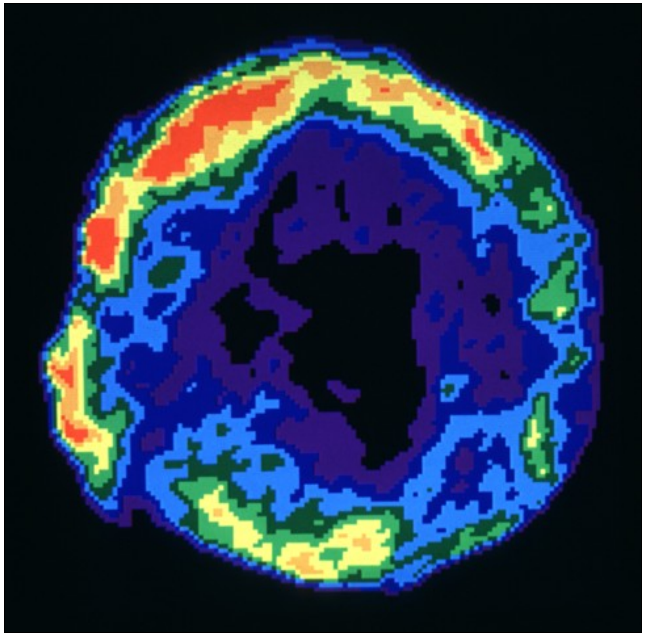
The University of New South Wales

Motivation



Cas A supernova remnant (NRAO/AUI)

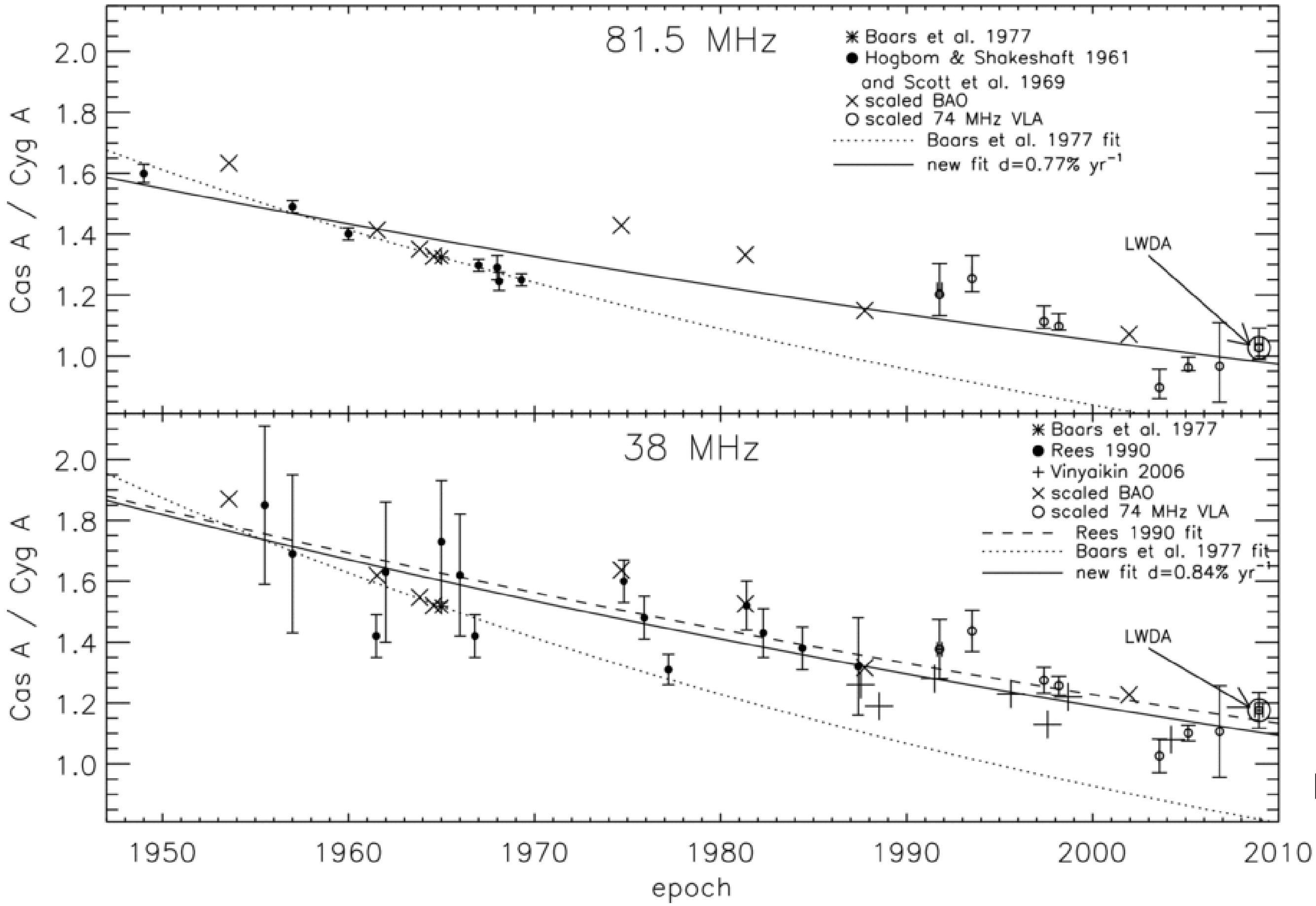


Tycho's supernova remnant (NRAO/AUI)

- So far, about 300 Galactic supernova remnants (SNRs) have been observed in the radio band (Green 2017).
- Radio emission can be interpreted as synchrotron radiation from relativistic electrons accelerated by diffusive shock acceleration.
- Radio is the best tool for detecting new SNRs!

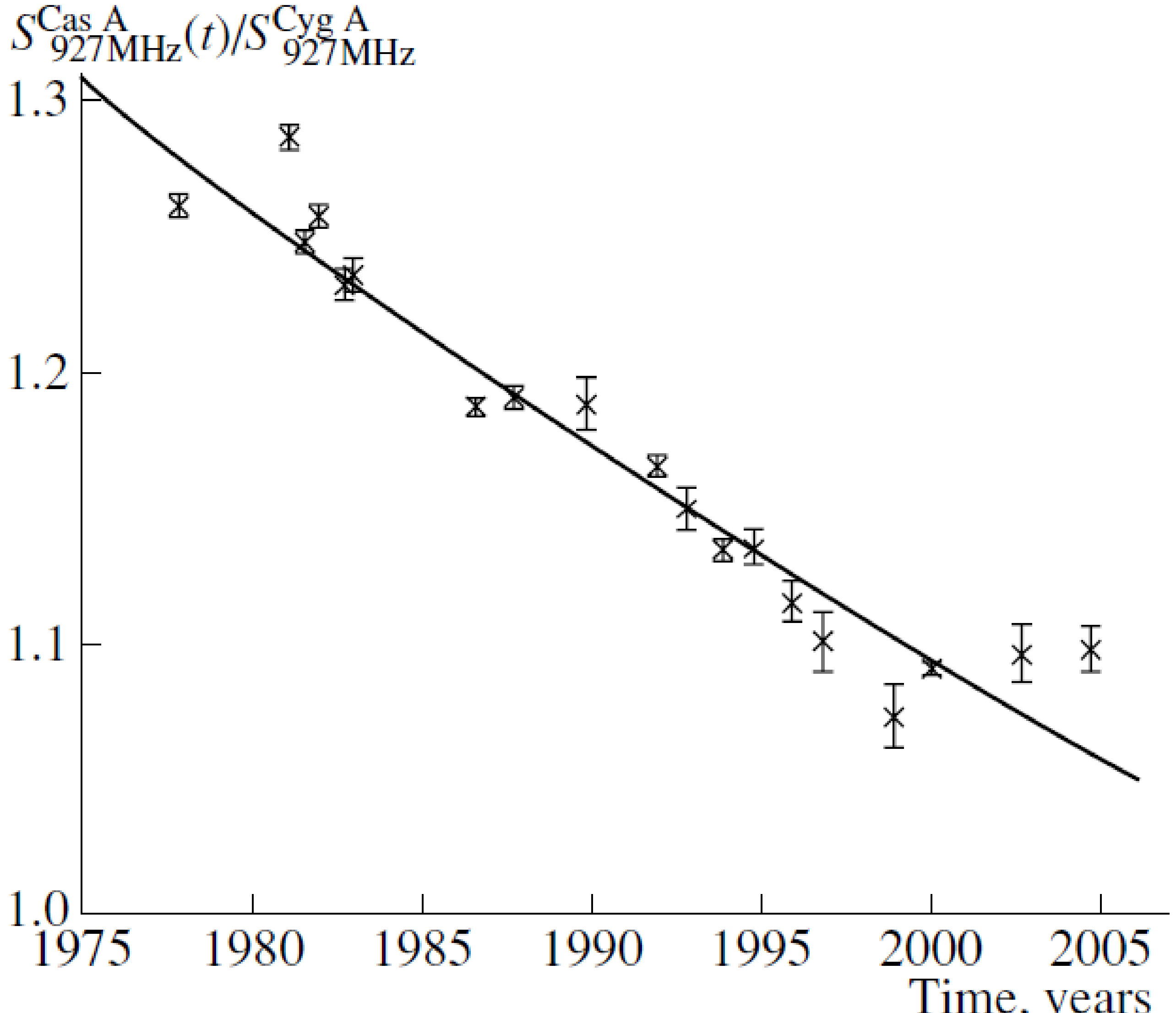
The beginning of the mystery...

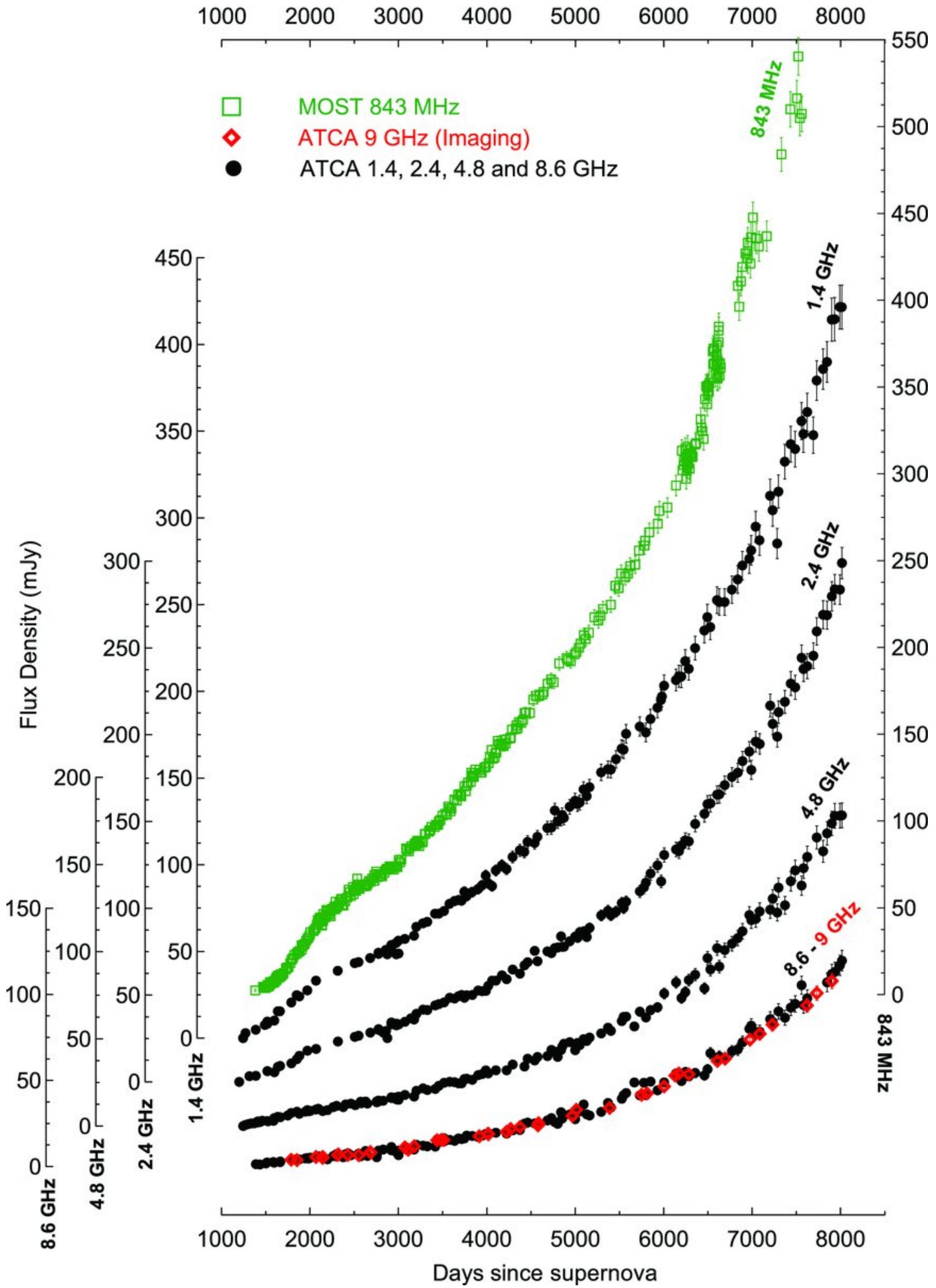
- Time evolution of radio fluxes is observed in some young supernova remnants.
- The radio flux of Cas A has been observed for 50 yr and decreases with time.
- Magnetic field or the number of CR electrons decreases with time?



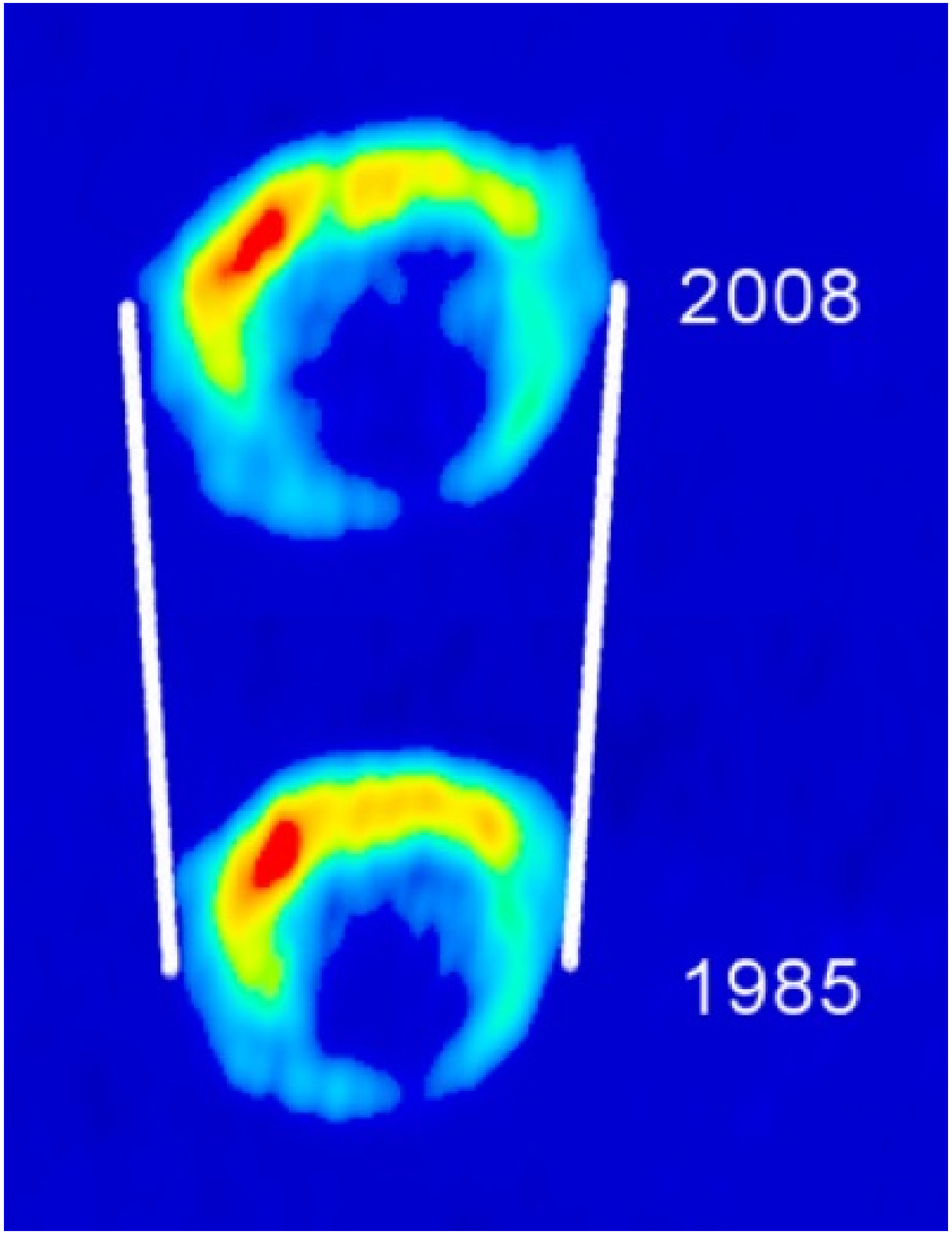
Helmboldt and Kassim 2009

- Flux density ratios of Cas A and Cyg A measured at 927 MHz in 1977–2004 (Vinyaikin 2007)





- Radio flux densities for SN 1987A, integrated over the whole remnant. Plots include data from observations at 1.4, 2.4, 4.8, and 8.6 GHz from 1990 August to 2009 February (Zanardo 2010).



The youngest Galactic SNR G1.9+0.3 (NRAO / VLA)

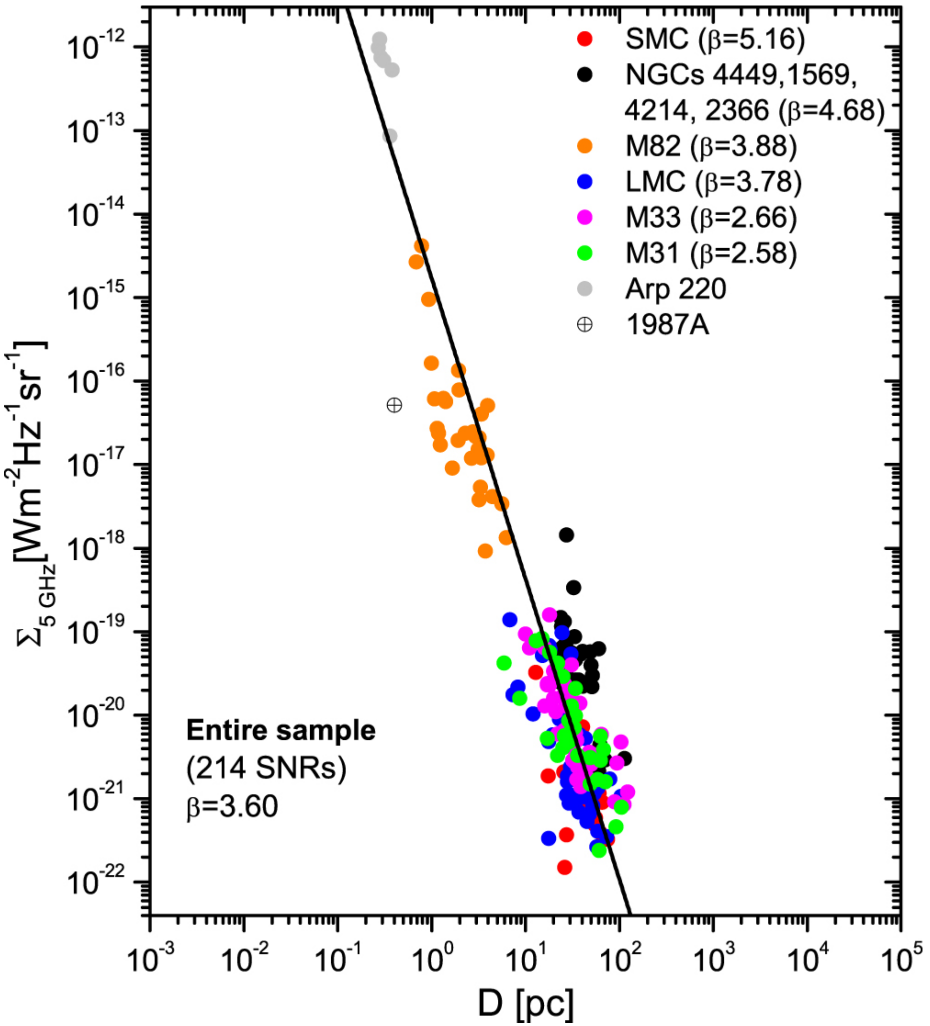
- Not only the evolution of radio flux but also the evolution of the radio size is observed for very young supernova remnants

- The radio expansion and brightening of the very young supernova remnant G1.9+0.3 (Green 2008)

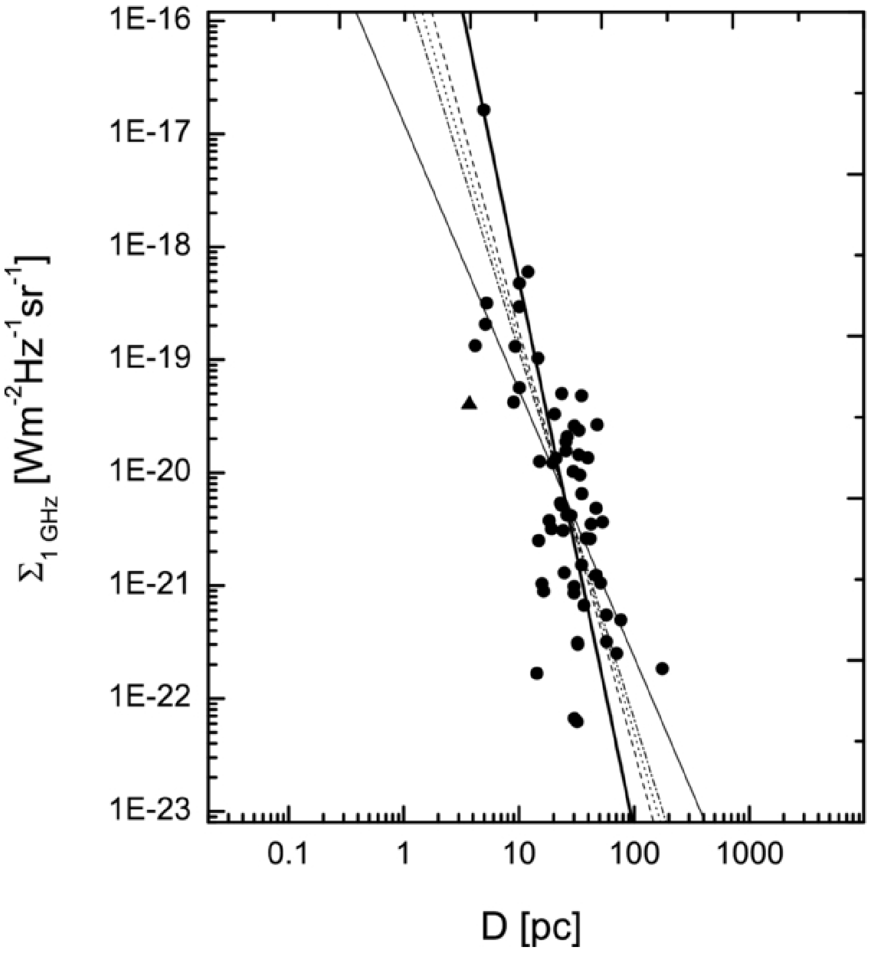
- If G1.9+0.3 is now ∼100 yr old, the observed flux increase by a factor of 1.25 over 13 yr.

- A growing radio flux density requires special conditions?

- Spatially integrated radio synchrotron flux increases with time, essentially due to the rapidly increasing total number of accelerated electrons in the increasing SNR volume $\propto R^3$ (Ksenofontov et al. 2010)?



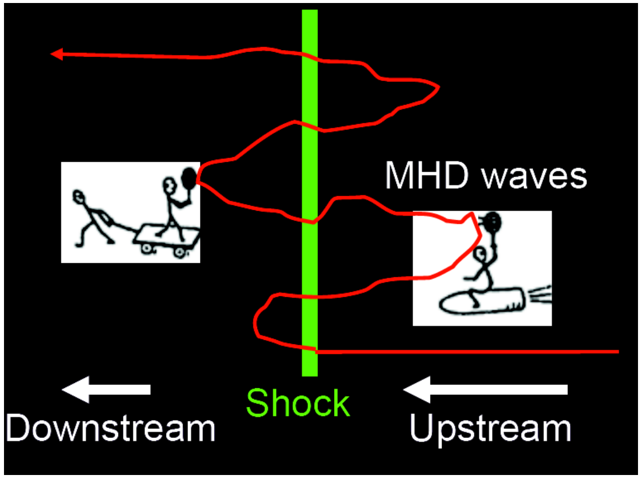
Bozzetto et al. (2017)

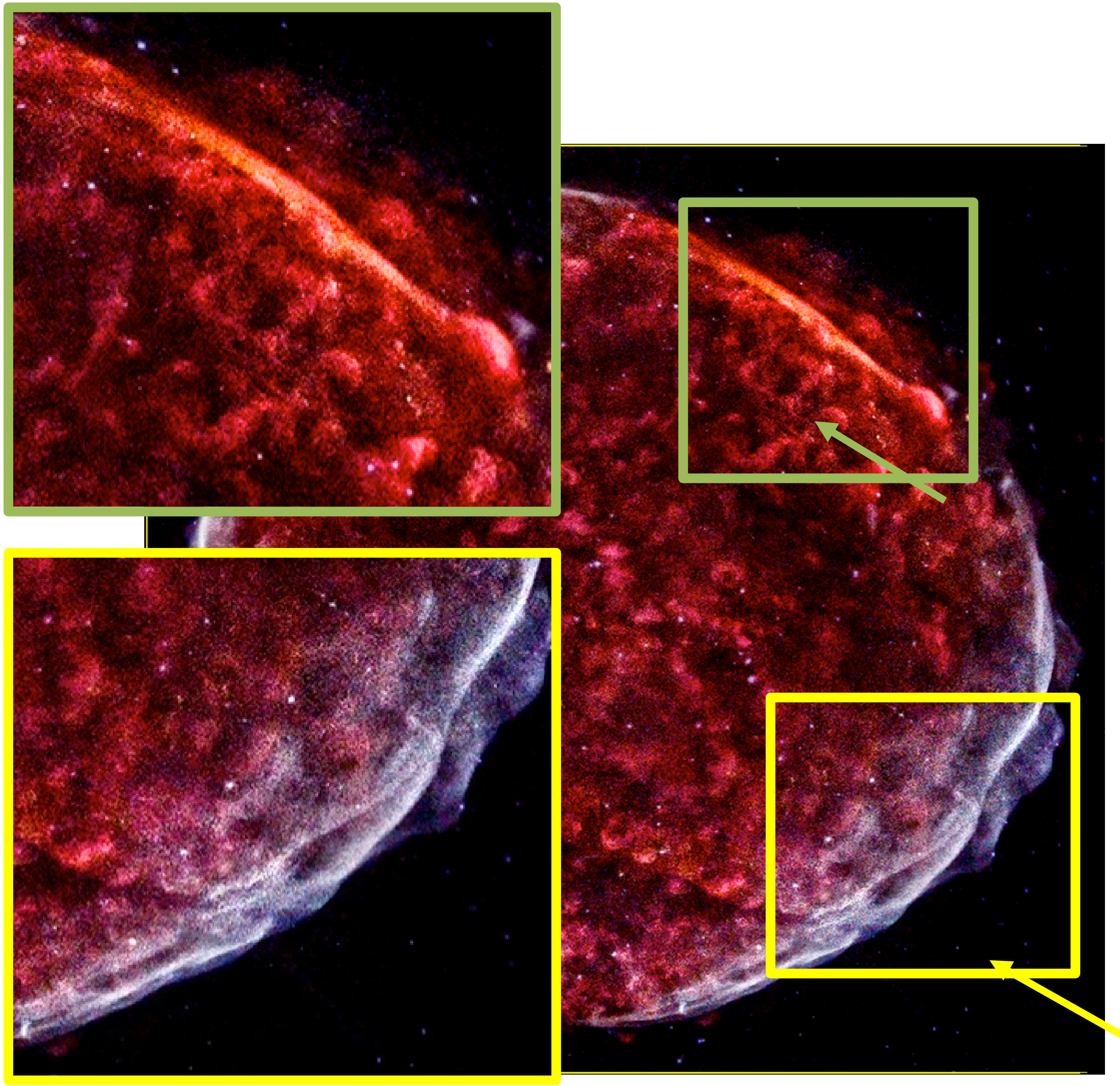


Urošević at al. (2003); Arbutina and Urošević (2009); Urošević et al. (2009); Urošević et al. (2010); Pavlović et al. (2013); Vukotić et al. (2014); Pavlović et al. (2014); Kostić et al. (2016);

SNRs accelerate particles

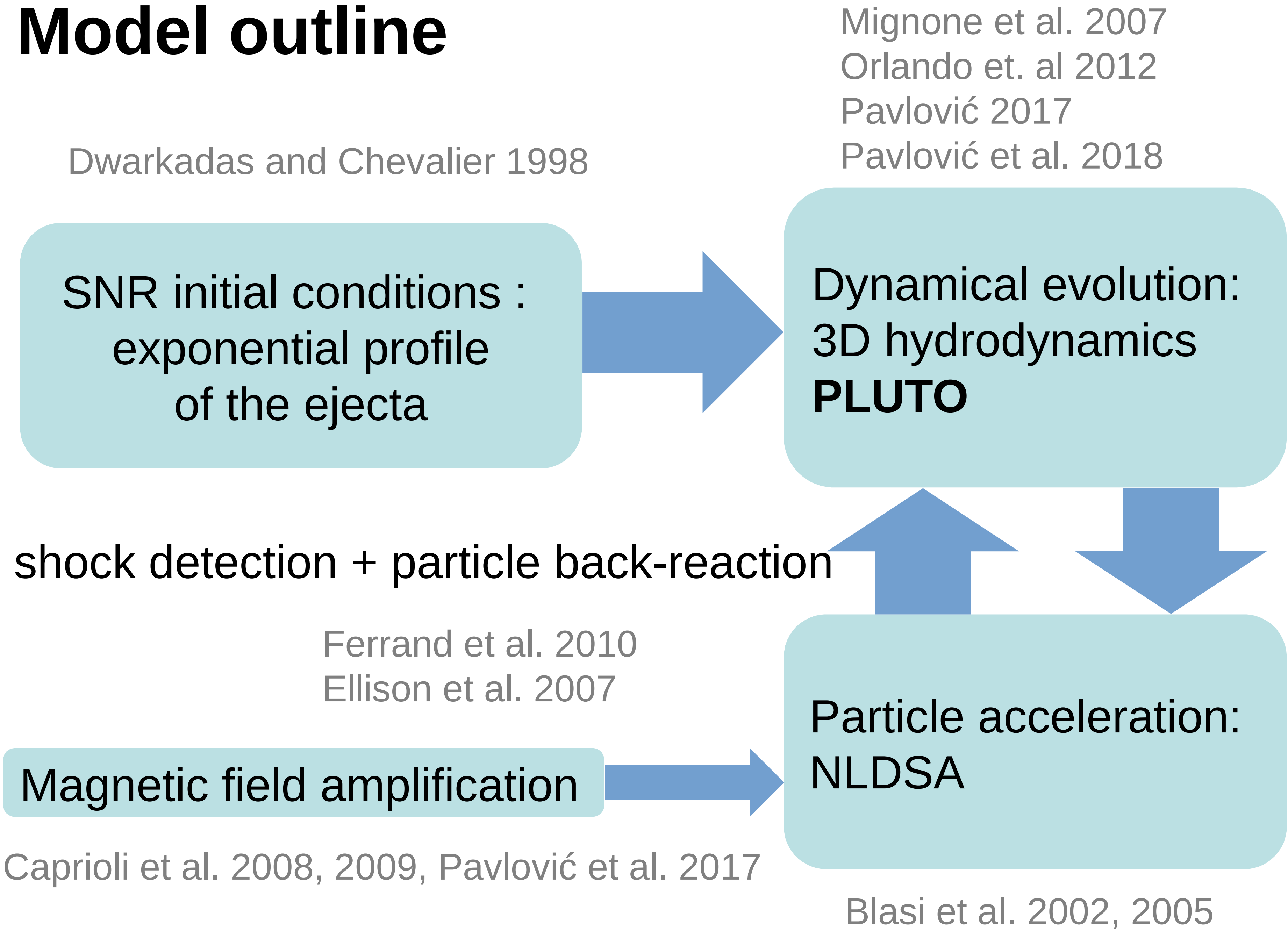
- Forward shock (and reverse shock?) of a SNR accelerate CRs, e.g. SN1006).
- Diffusive shock acceleration (DSA) operating in SNRs is probably the source of Galactic cosmic rays (Krymskii 1977 Axford et al. 1977, Bell 1978a,b, Blandford & Ostriker 1978





Chandra X-ray image(NASA/CXC/Middlebury College/F.Winkler)

Model outline



Model outline

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

Dwarkadas and Chevalier 1998

SNR initial conditions : exponential profile of the ejecta

Dynamical evolution: 2D/3D hydrodynamics **PLUTO**

shock detection + particle

Ferrand et al. 2
Ellison et al. 2007

Magnetic field amplification

Particle acceleration: NLDSA

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

Blasi et al. 2002, 2005

Mignone et al. 2007

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

Dynamical evolution:
2D/3D hydrodynamics
PLUTO

neglecting radiative cooling and thermal conduction

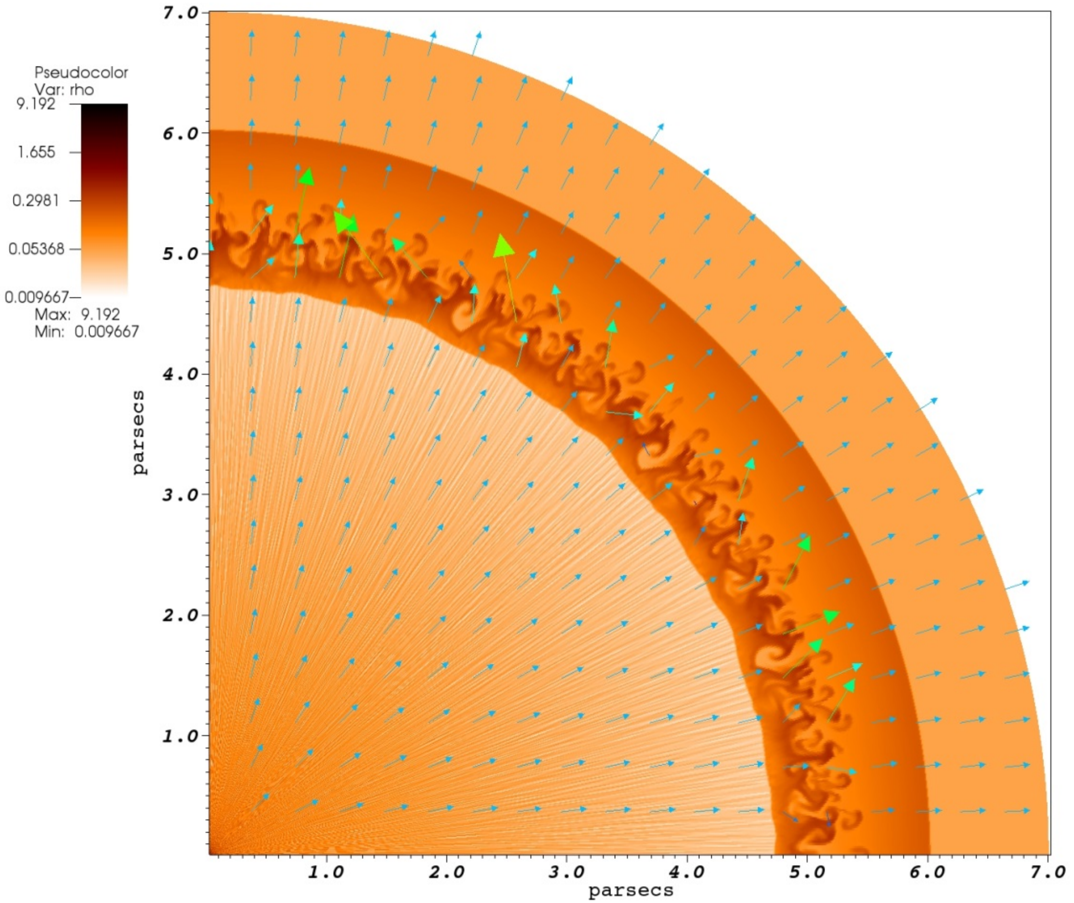
$$P = (\gamma - 1)\epsilon$$

- Time and space-dependent adiabatic index of plasma:

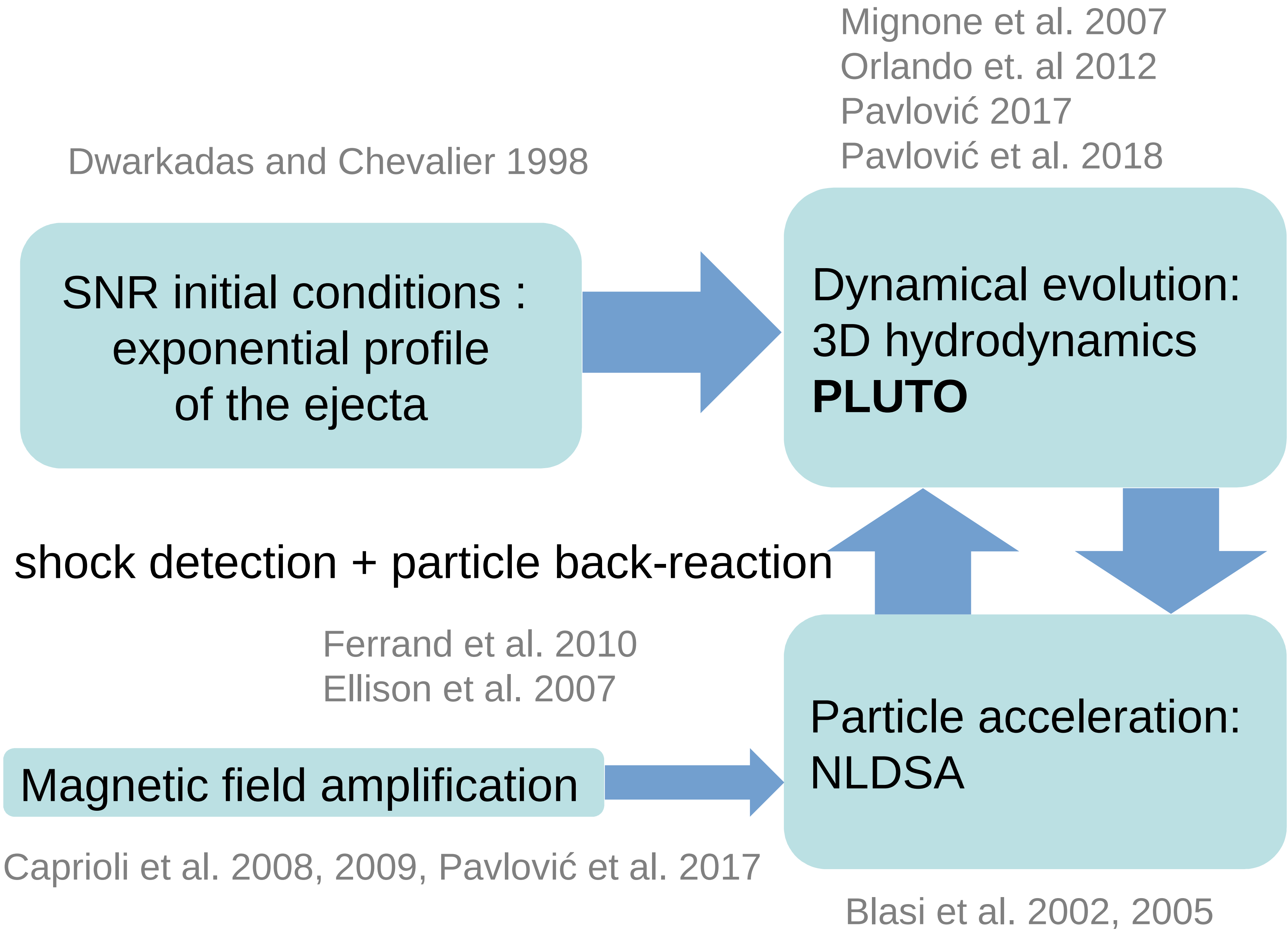
$$E = \frac{P}{\gamma - 1} + \frac{1}{2}\rho v^2$$

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

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



PARADOX Cluster at the Scientific Computing Laboratory of Institute of Physics Belgrade: 106 compute nodes (2 x 8 core Sandy Bridge Xeon 2.6GHz processors with 32GB of RAM + NVIDIA® Tesla™ M2090)


Mignone et al. 2007
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Dwarkadas and Chevalier 1998
SNR initial conditions :
exponential profile
of the ejecta
Dynamical evolution:
3D hydrodynamics
PLUTO
shock detection + particle back-reaction
Ferrand et al. 2010
Ellison et al. 2007
Particle acceleration:
NLDSA
Magnetic field amplification
Caprioli et al. 2008, 2009, Pavlović et al. 2017
Blasi et al. 2002, 2005

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

Dwarkadas and Chevalier 1998

SNR initial conditions :
exponential profile
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shock detection + partic

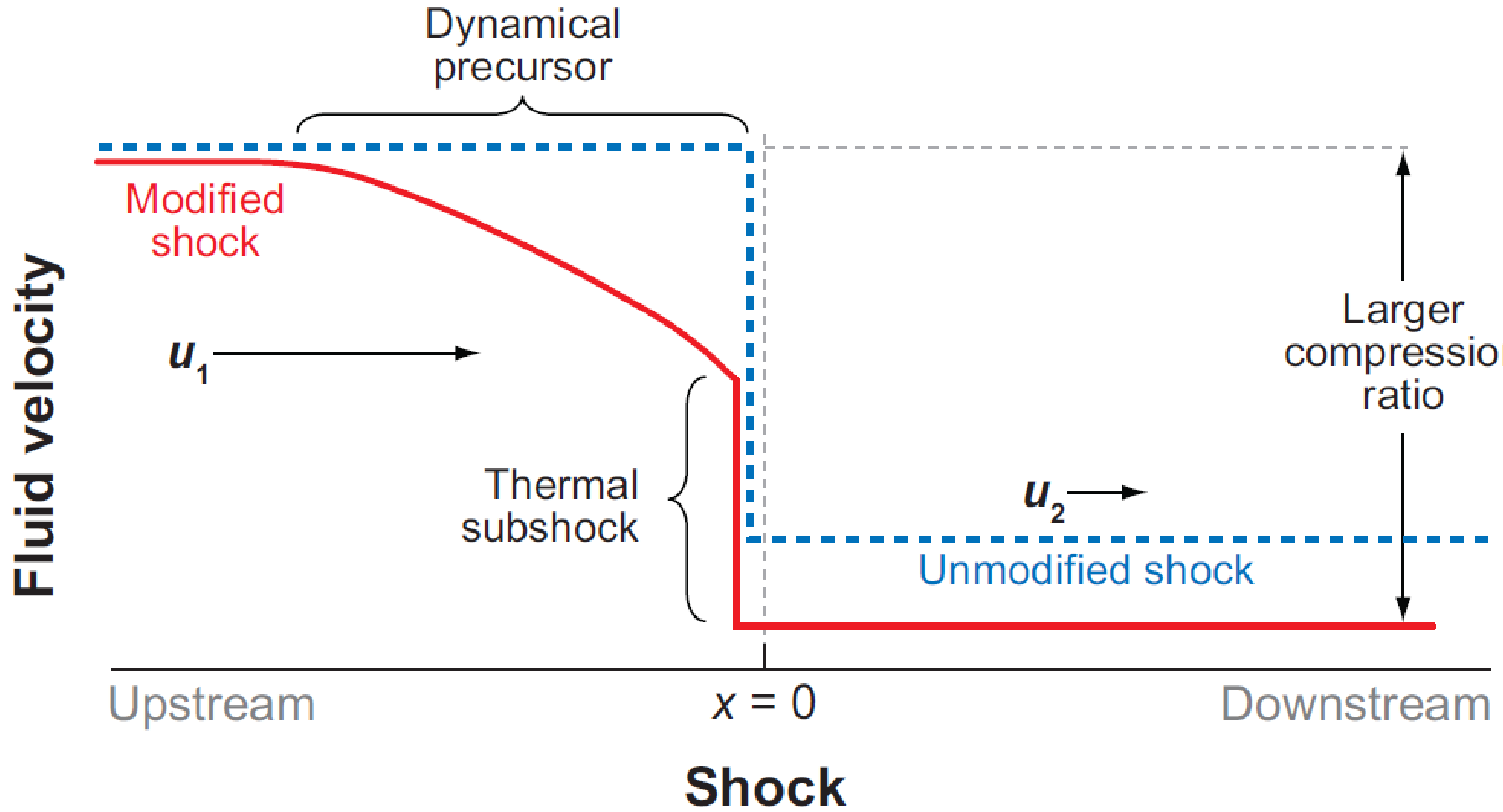
Ferrand et
Ellison et a

Magnetic field amplifica

Caprioli et al. 2008, 2009, Pavlo

Particle acceleration:
NLDSA

Blasi et al. 2002, 2005

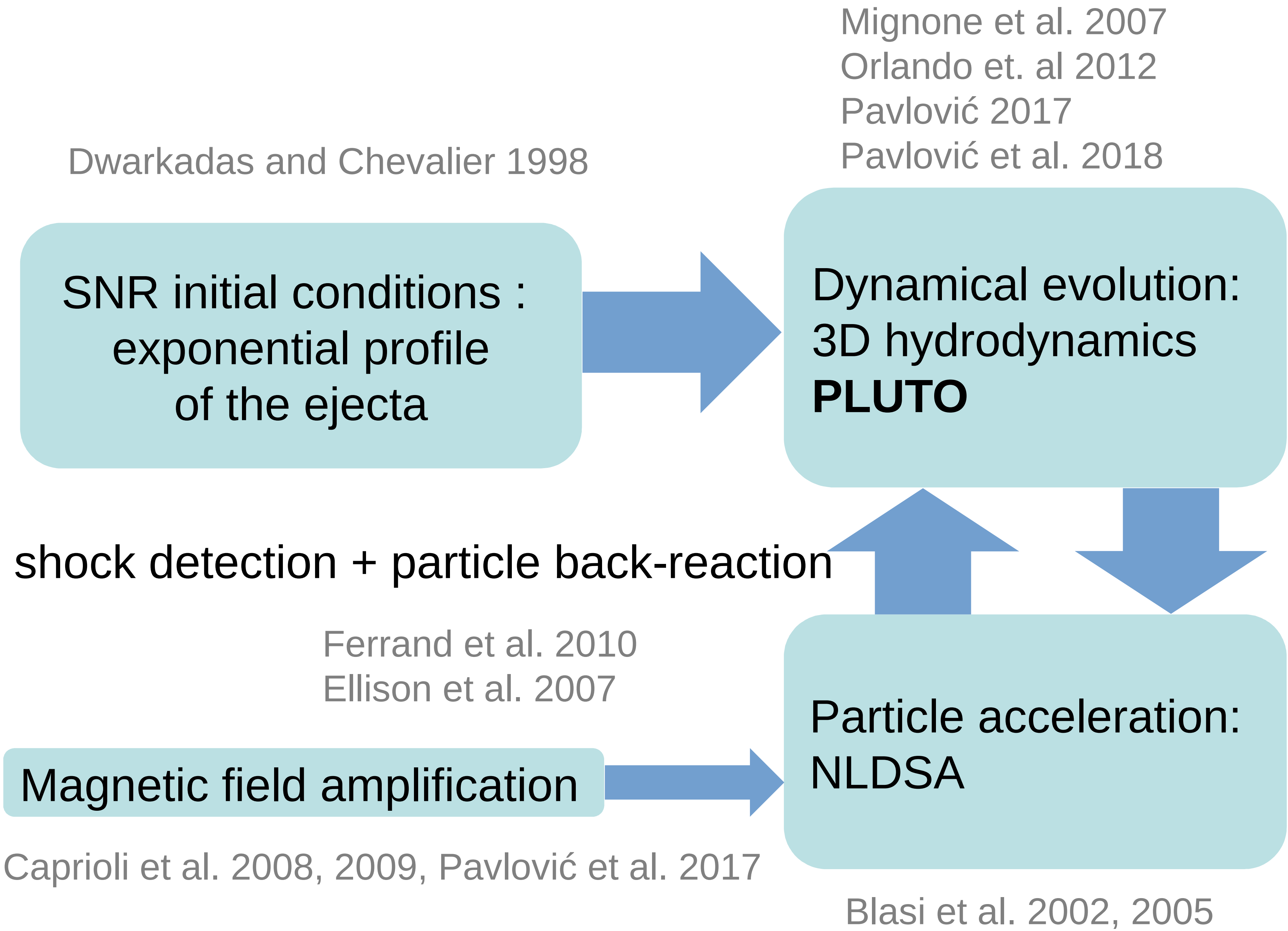


$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f(x,p)}{\partial p} + Q(x,p) = 0$$

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

Particle acceleration:
NLDSA

Blasi et al. 2002, 2005


Mignone et al. 2007
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SNR initial conditions :
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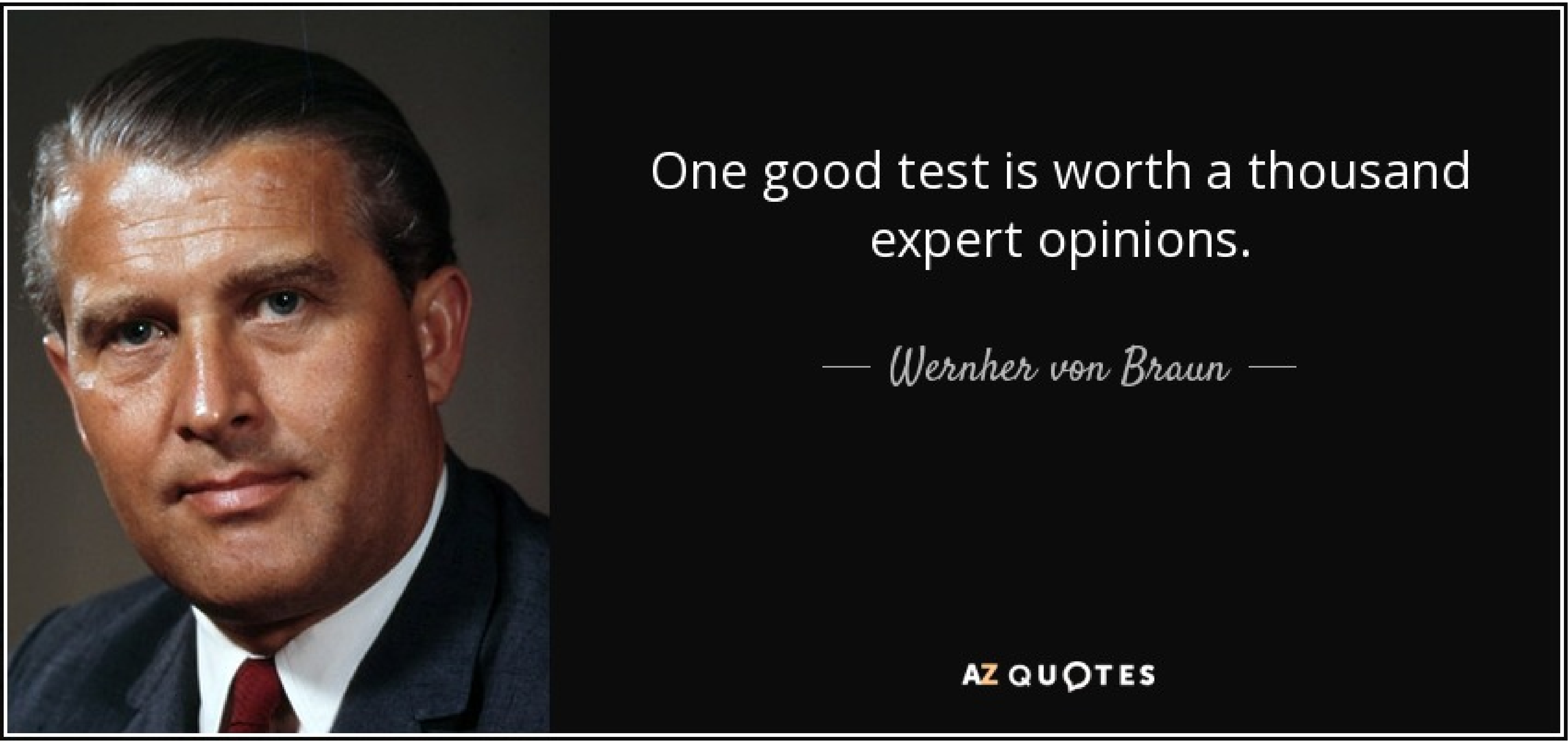
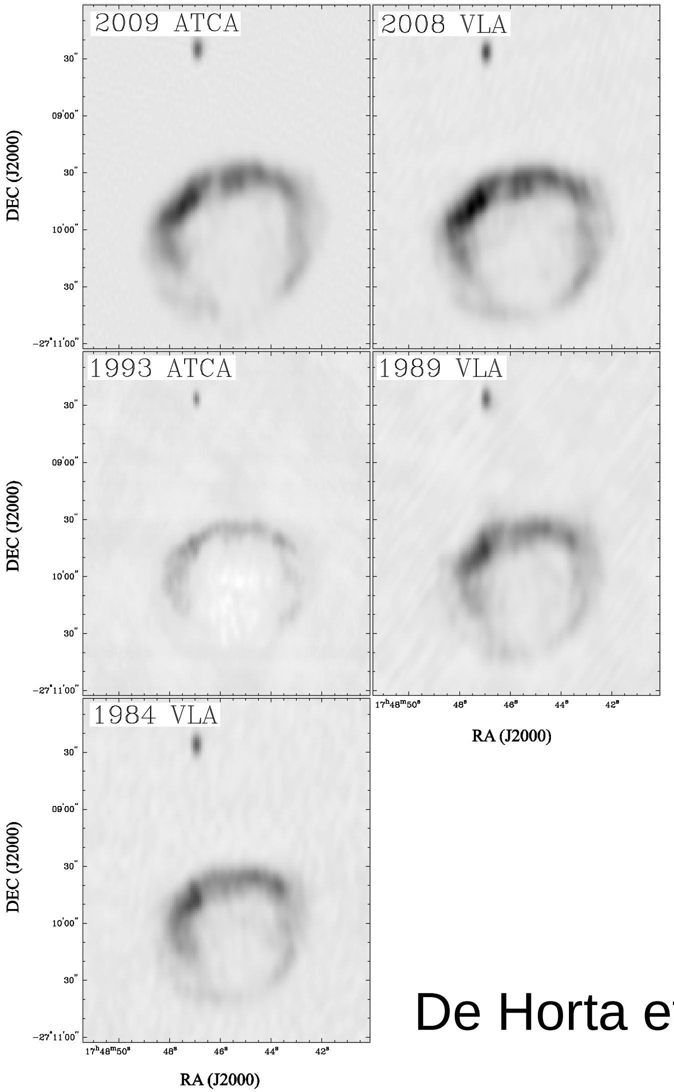
Particle acceleration:
NLDSA
Magnetic field amplification
Caprioli et al. 2008, 2009, Pavlović et al. 2017
Blasi et al. 2002, 2005

Results



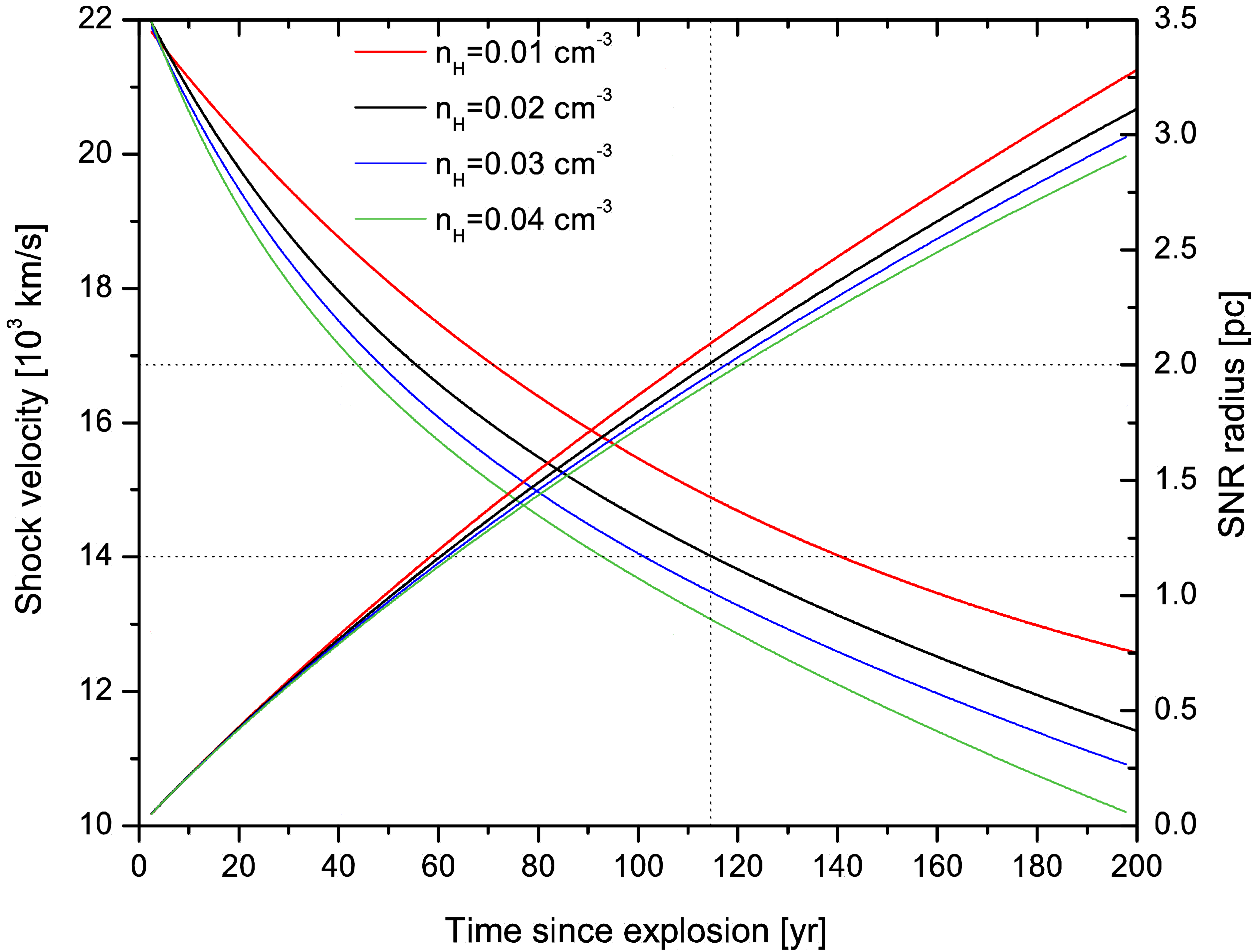
One good test is worth a thousand expert opinions.
— Wernher von Braun —
AZ QUOTES

Radio evolution of SNR G1.9+0.3

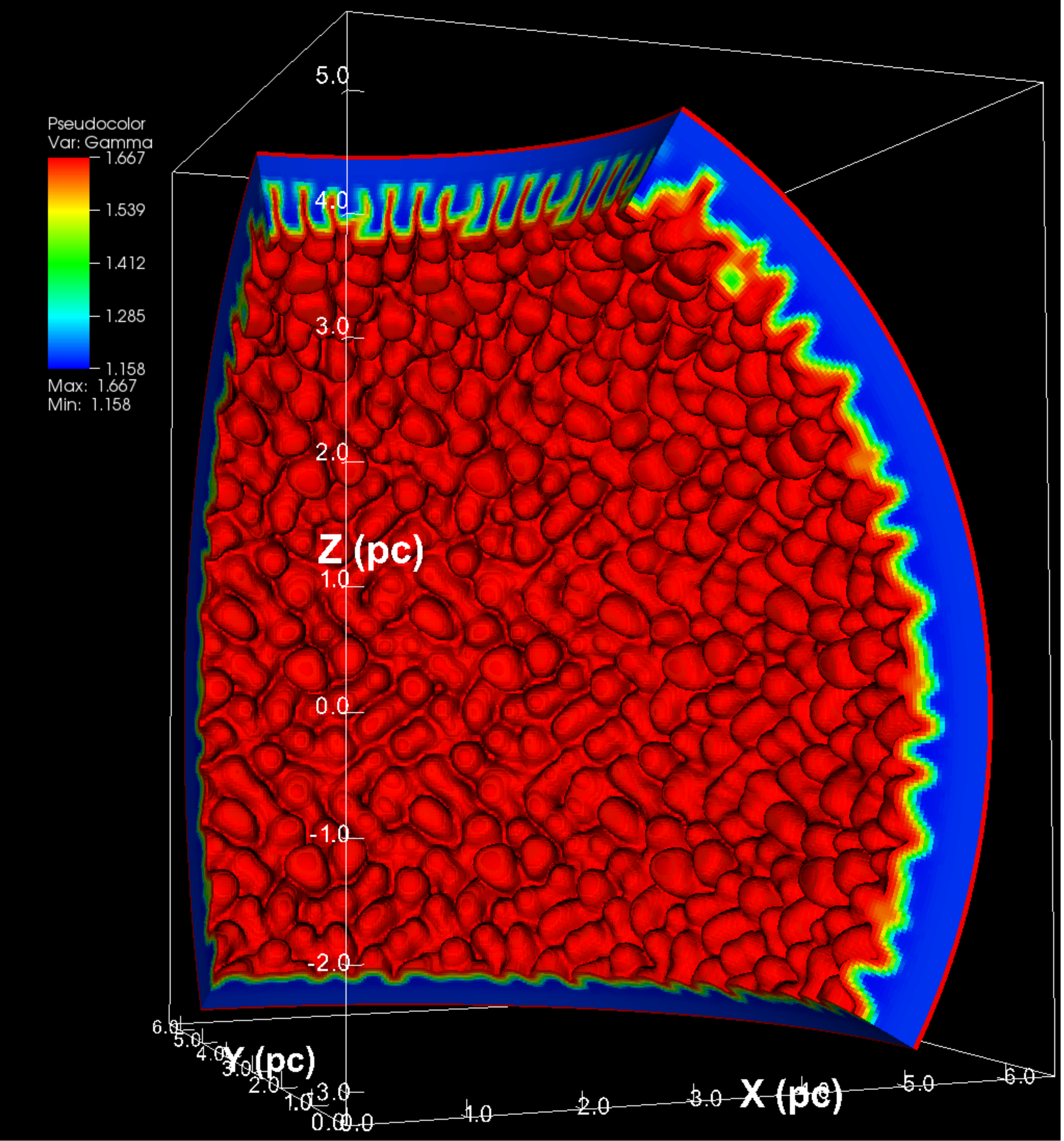


- Green et al. (2008) compared their VLA radio observations of the SNR G1.9+0.3 at 4.86 GHz and 1.43 GHz with earlier observations of a comparable resolution.
- Evidence that this SNR has been brightening over the past few decades in the radio emission at a rate of ≈ 2 per cent yr^{-1}.

De Horta et al. 2014



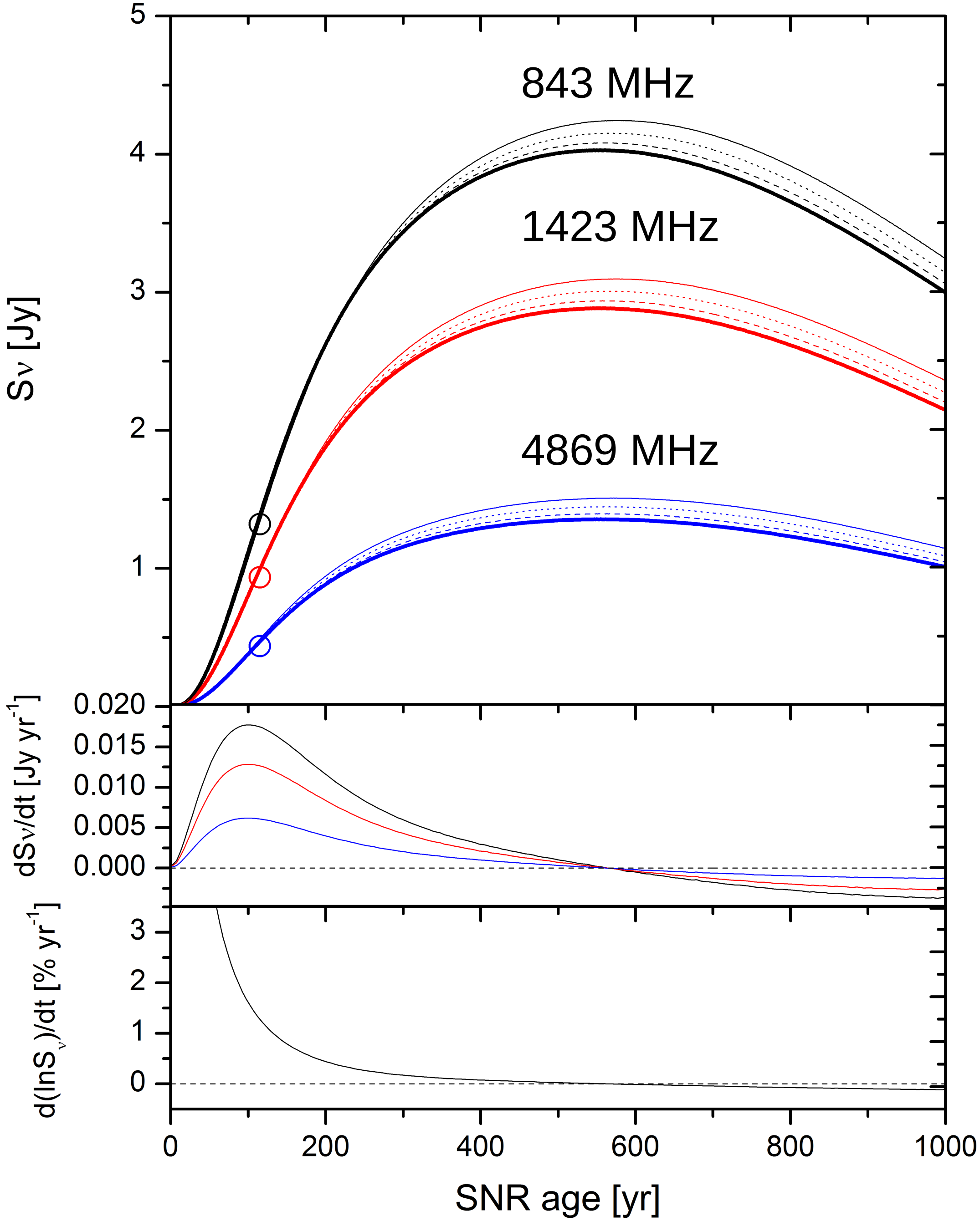
n_H=0.01 cm^{-3}
n_H=0.02 cm^{-3}
n_H=0.03 cm^{-3}
n_H=0.04 cm^{-3}
Shock velocity [10^3 km/s]
SNR radius [pc]
Time since explosion [yr]
22
20
18
16
14
12
10
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
120
140
160
180
200



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

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

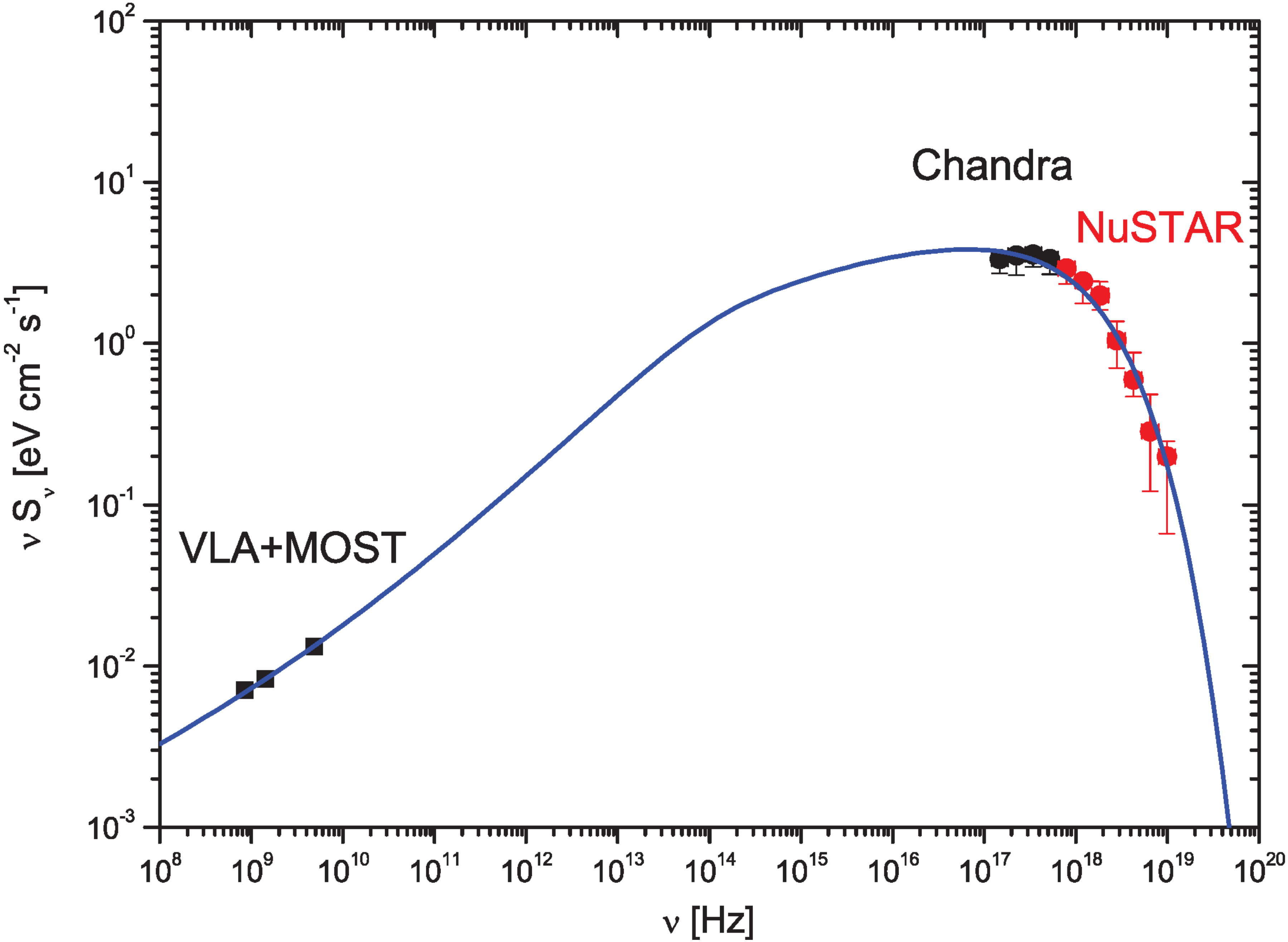
Pavlović 2017



- We predict increasing radio emission from G1.9+0.3 during the free expansion phase, reaching its maximum value around the age of 600 yr and then decreasing during late free expansion and beginning of Sedov phase around 1700 yr after initial explosion.

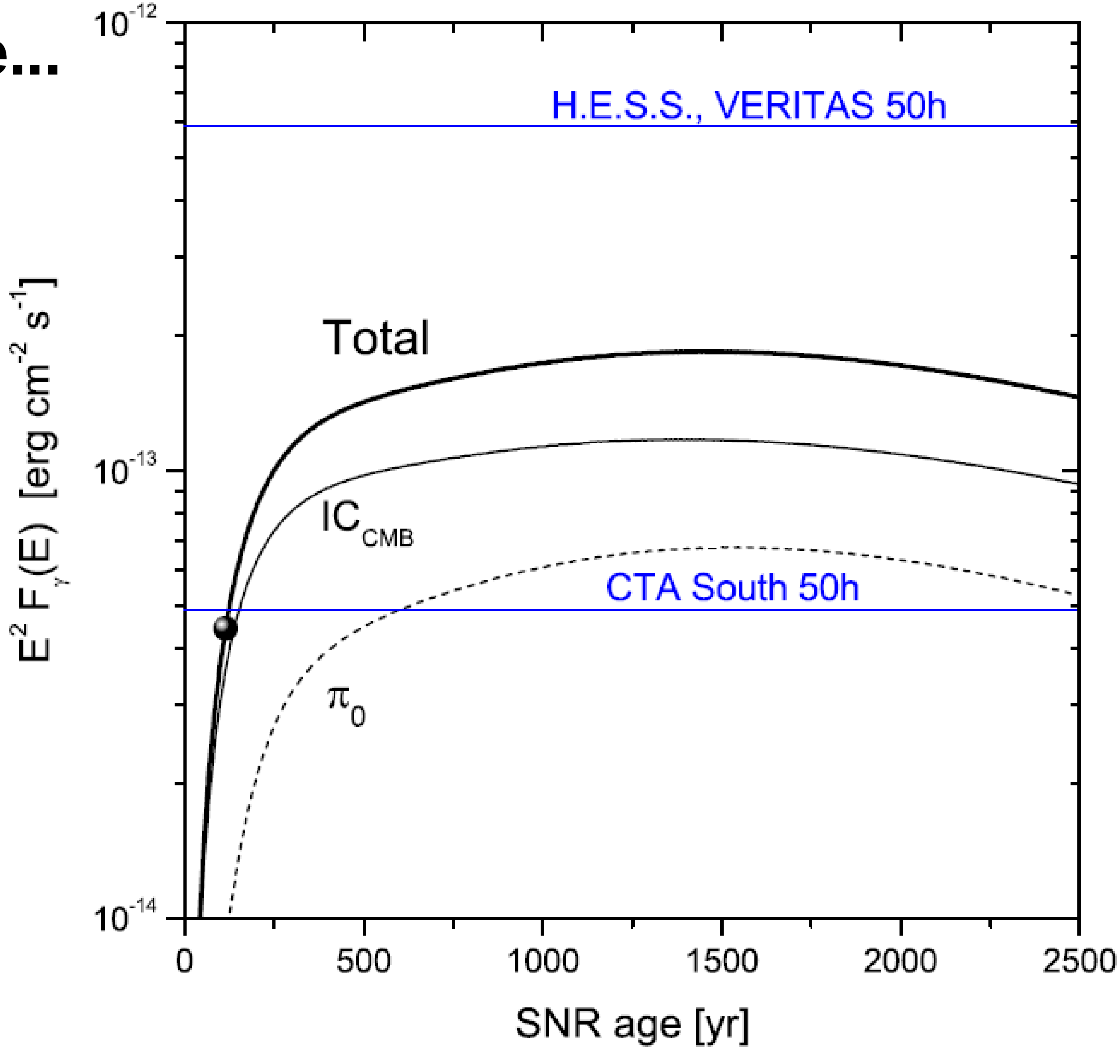
- It seems that we are currently witnessing approximately the fastest radio emission increase than it will ever be.

- The steep radio spectral index of ≈ 0.6 (steeper than linear DSA prediction of $\alpha = 0.5$) for young SNRs is explained only by means of efficient NLDSA and accompanying strong MFA.



Chandra
NuSTAR
VLA+MOST
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
νS_{ν} [eV cm^{-2} s^{-1}]
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}
ν [Hz]

Hope...



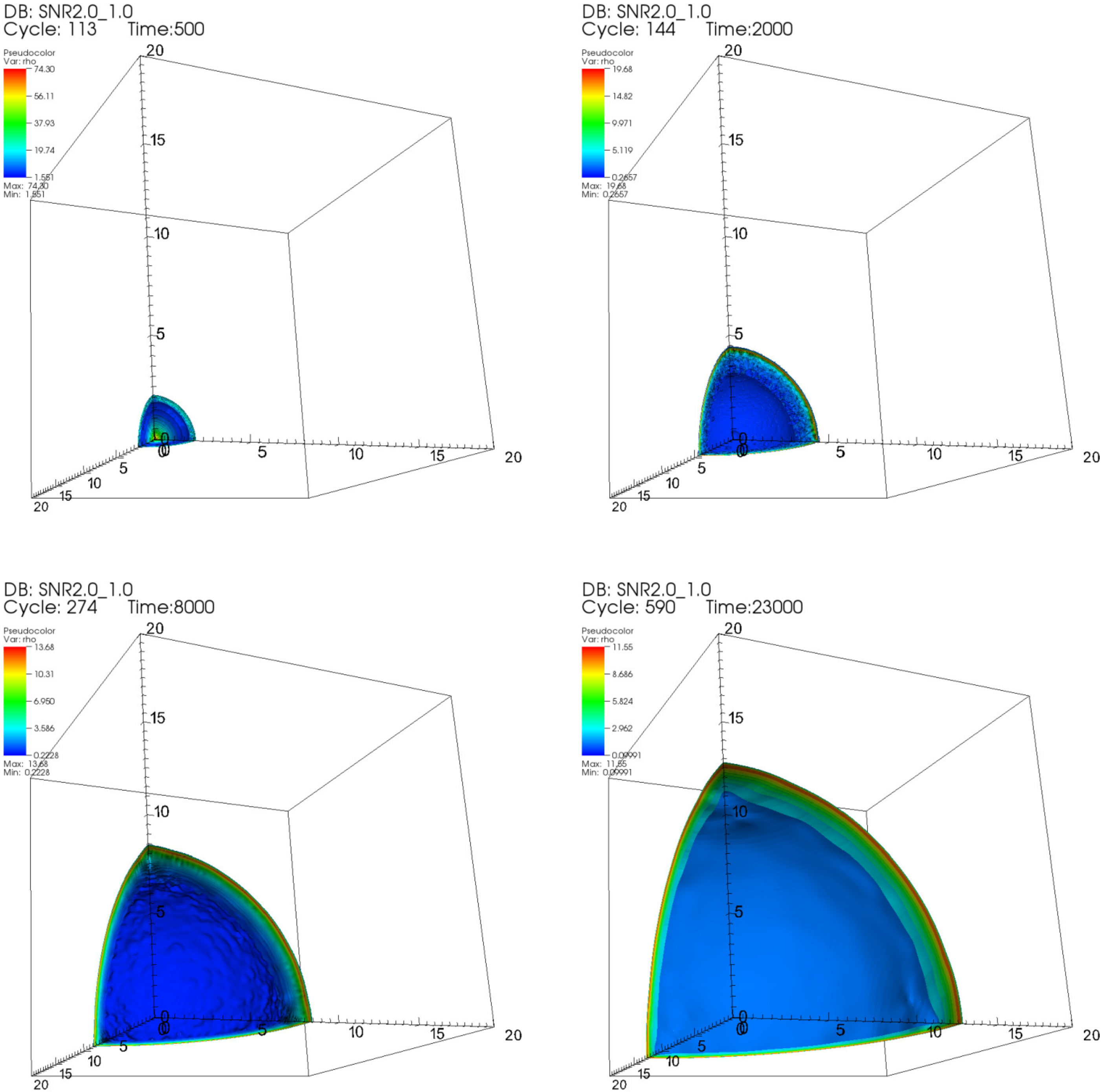
H.E.S.S., VERITAS 50h
Total
IC_{CMB}
CTA South 50h
π_0
10^{-12}
10^{-13}
10^{-14}
$E^2 F_\gamma(E)$ [erg cm^{-2} s^{-1}]
0
500
1000
1500
2000
2500
SNR age [yr]

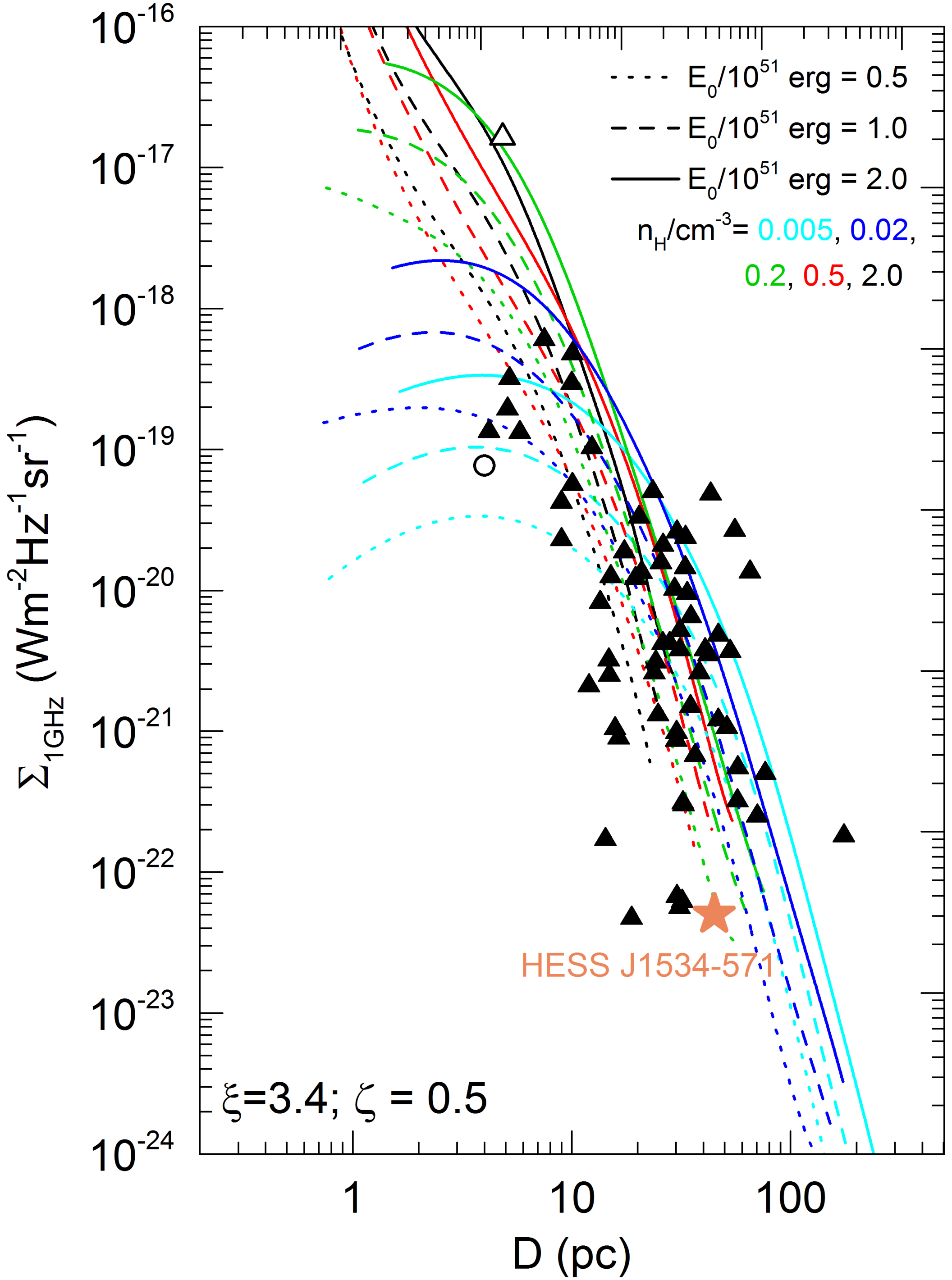
General model of radio evolution

Pavlović, M. Z., Urošević, D., Arbutina, B., Salvatore, O., Maxted, N., Filipović, M. 2018

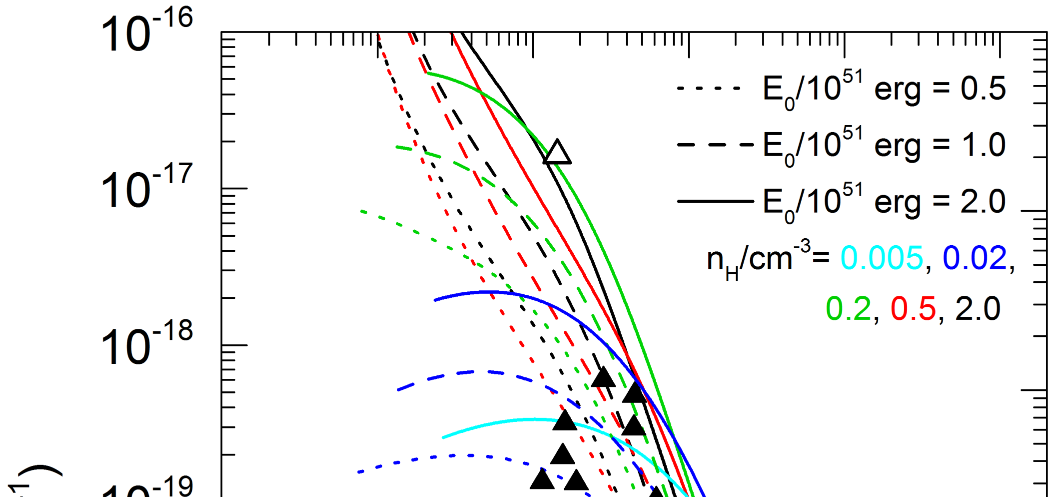
Table 1
Adopted Parameters and Initial Conditions for the Hydrodynamic Models Used to Obtain Radio Evolution of Different SNRs

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: 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



- 65 Galactic SNRs with known distances (Pavlovic et al. 2013).
- Four prominent SNRs - CTB 37A, Kes 67, CTB 37B and G65.1+0.6. Observations suggest that all of them are interacting with molecular clouds (Maxted et al. 2013, Dubner et al. 2004, Paron 2012, Froebrich et al. 2015 etc).
- Intersecting evolutionary tracks!



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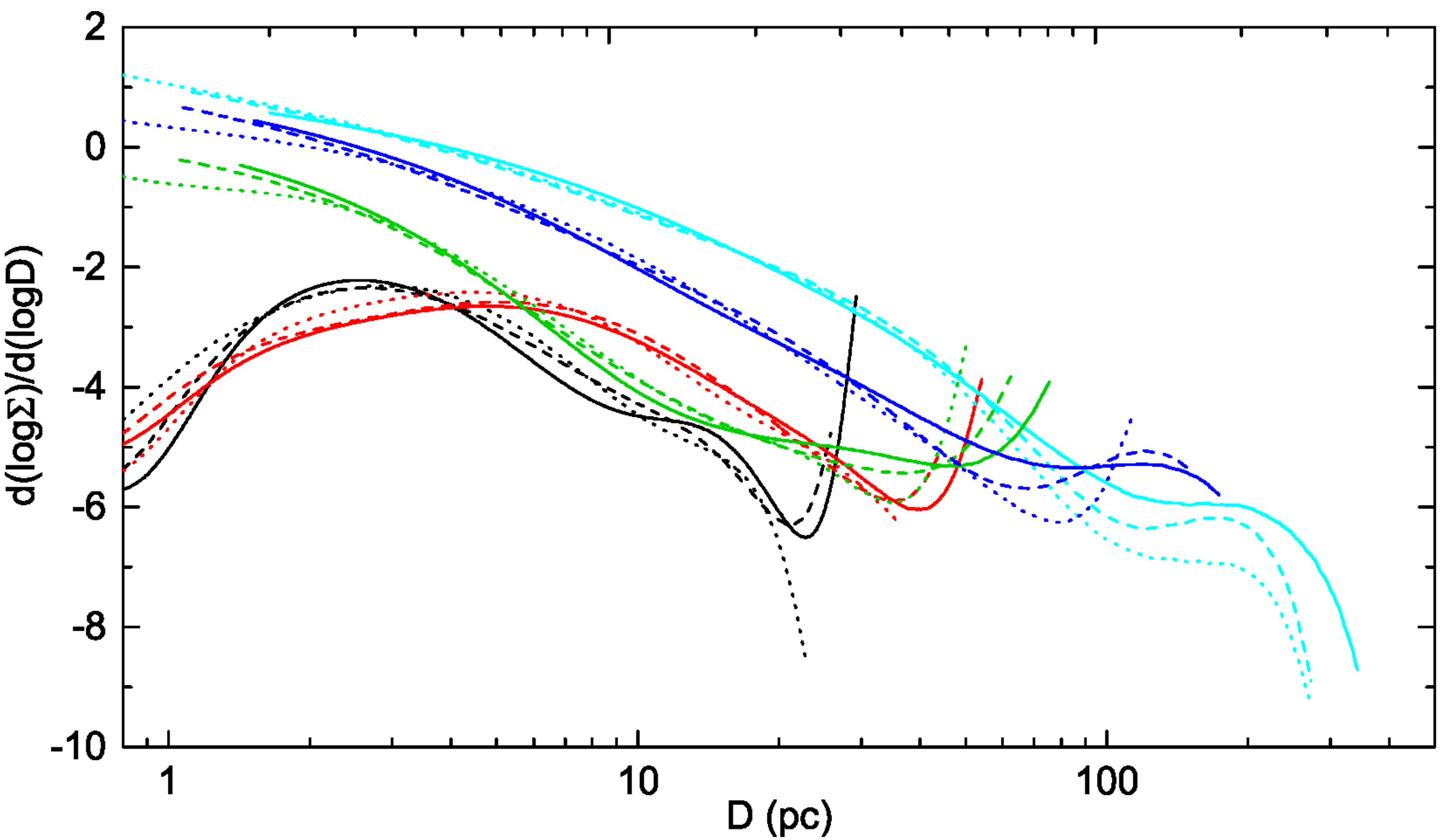
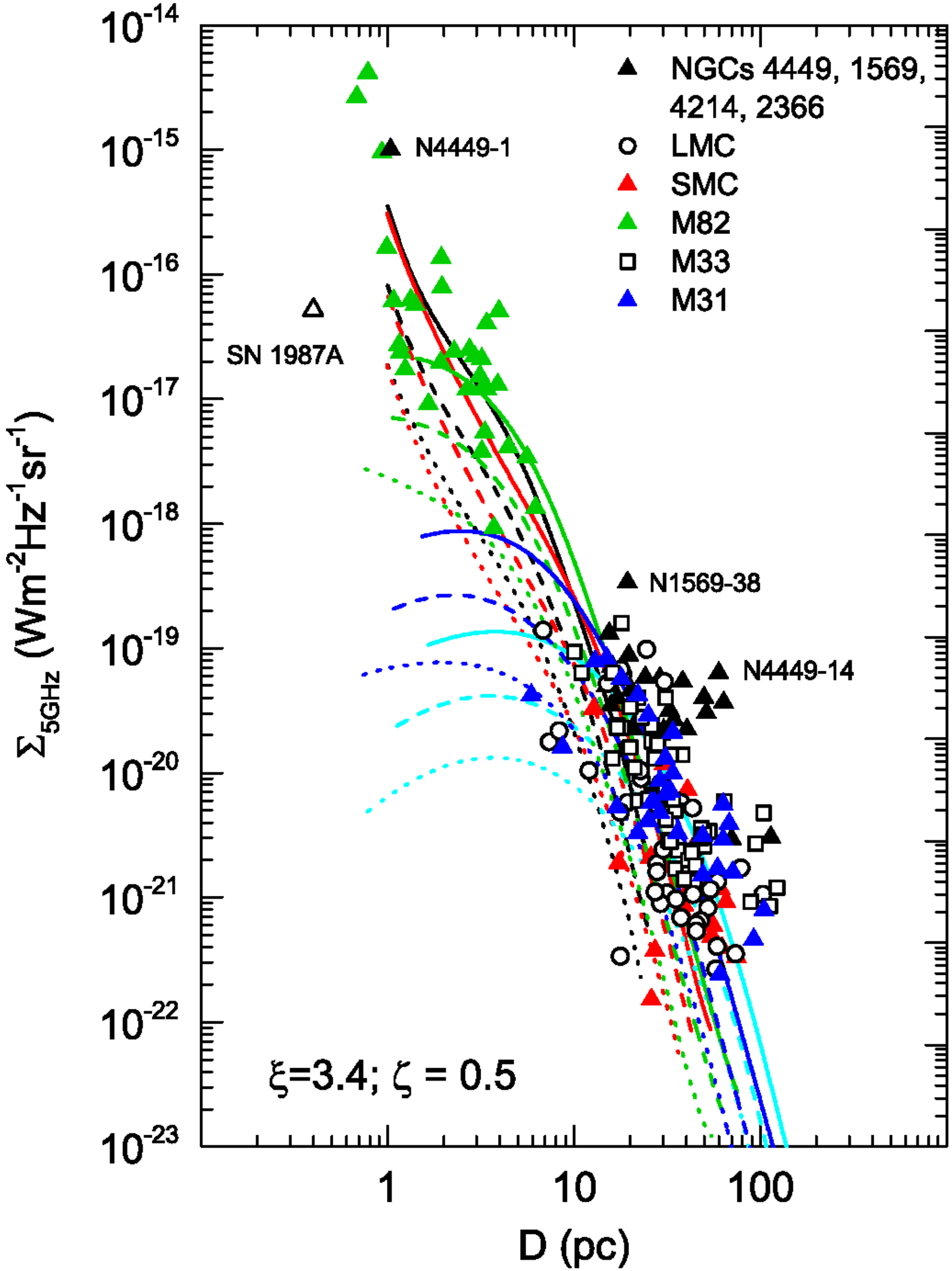
ubner et
Froebrich

ary tracks!





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)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
1
10
100

Results and Summary

1) We have presented a 3D hydrodynamical modeling of SNRs, also accounting for nonlinear DSA, MFA, and shock modifications. We are mainly studying the properties of the radio synchrotron emission of SNRs and its evolution..

2) Following our models, it can be concluded that radio emission increasing brightness is a common property of young SNRs.

3) Numerical model predicts increasing radio emission from G1.9+0.3 during the free expansion phase, reaching its maximum value around the age of 600 yr and then decreasing during late free expansion and beginning of Sedov phase around 1700 yr after theSN explosion. Interestingly, it seems that we are currently witnessing approximately the fastest radio emission increase than it will ever be.

4) We have validated our model on available Galactic and extragalactic observational samples. The simulated dependence of SNR radio evolution is consistent with the range of parameters observed in nature.

5) The evolutionary tracks presented here can be very useful for radio observers. This type of modeling is expected to be a useful apparatus for future observers working on powerful radio telescopes such as ALMA, MWA, ASKAP, SKA, and FAST.

Acknowledgements

- This work is part of Project No. 176005 "Emission nebulae: structure and evolution" supported by the Ministry of Education, Science, and Technological Development of the Republic of Serbia.

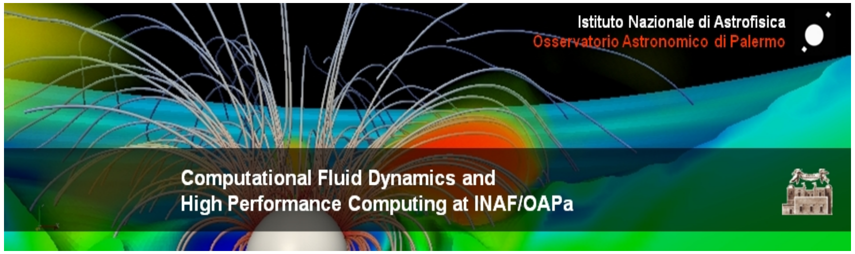
- Numerical simulations were run on the **PARADOX-IV** supercomputing facility at the Scientific Computing Laboratory of the Institute of Physics Belgrade, supported in part by the Ministry of Education, Science and Technological Development of the Republic of Serbia under project No. ON171017.

- We acknowledge the hospitality of the Observatory Astronomico di Palermo where part of this work was carried out.

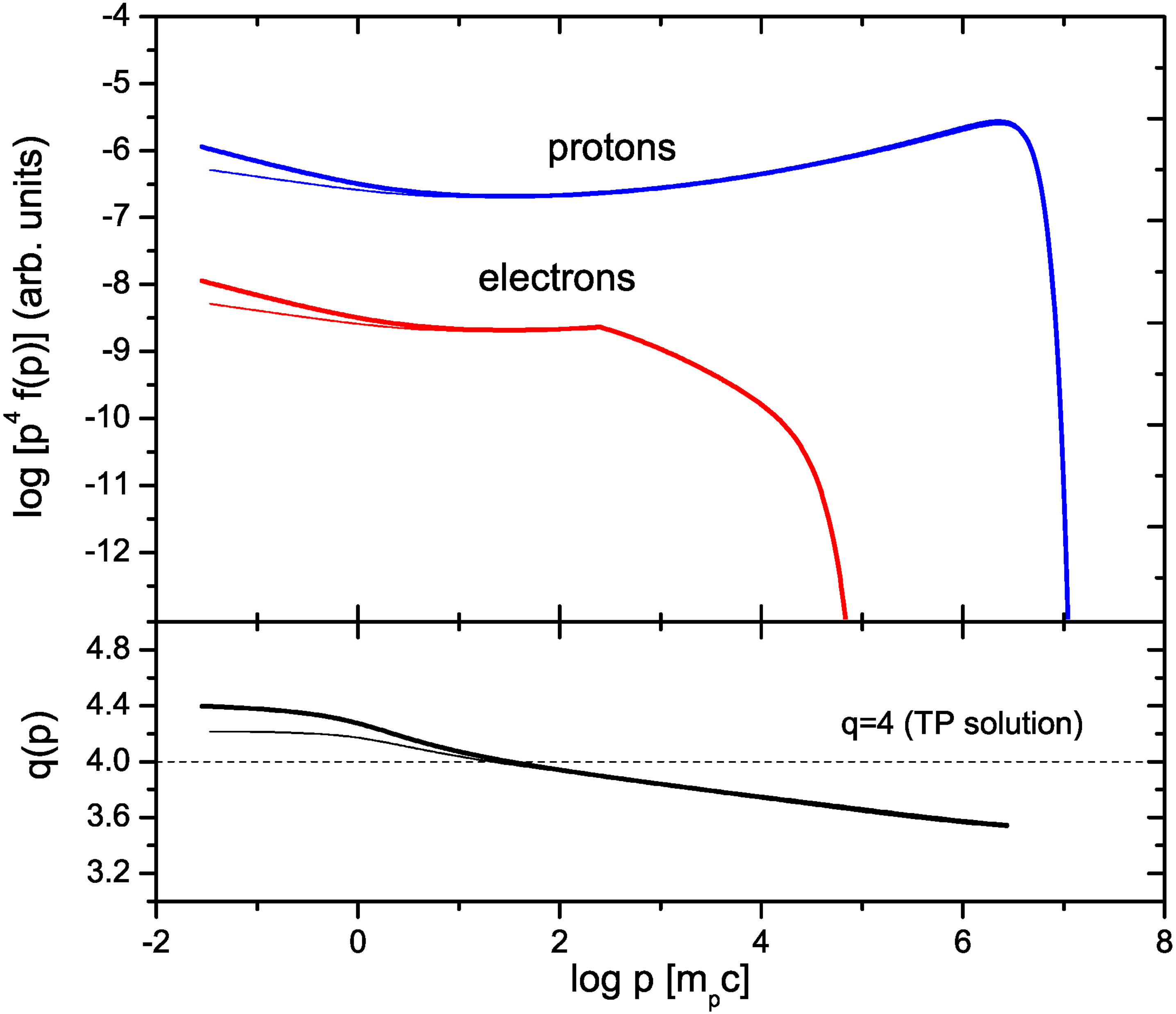
- M. P. also thanks **Gilles Ferrand** for extremely helpful discussions, advices and help during this work.

University of Belgrade
Faculty of Mathematics

SCIENTIFIC COMPUTING LABORATORY



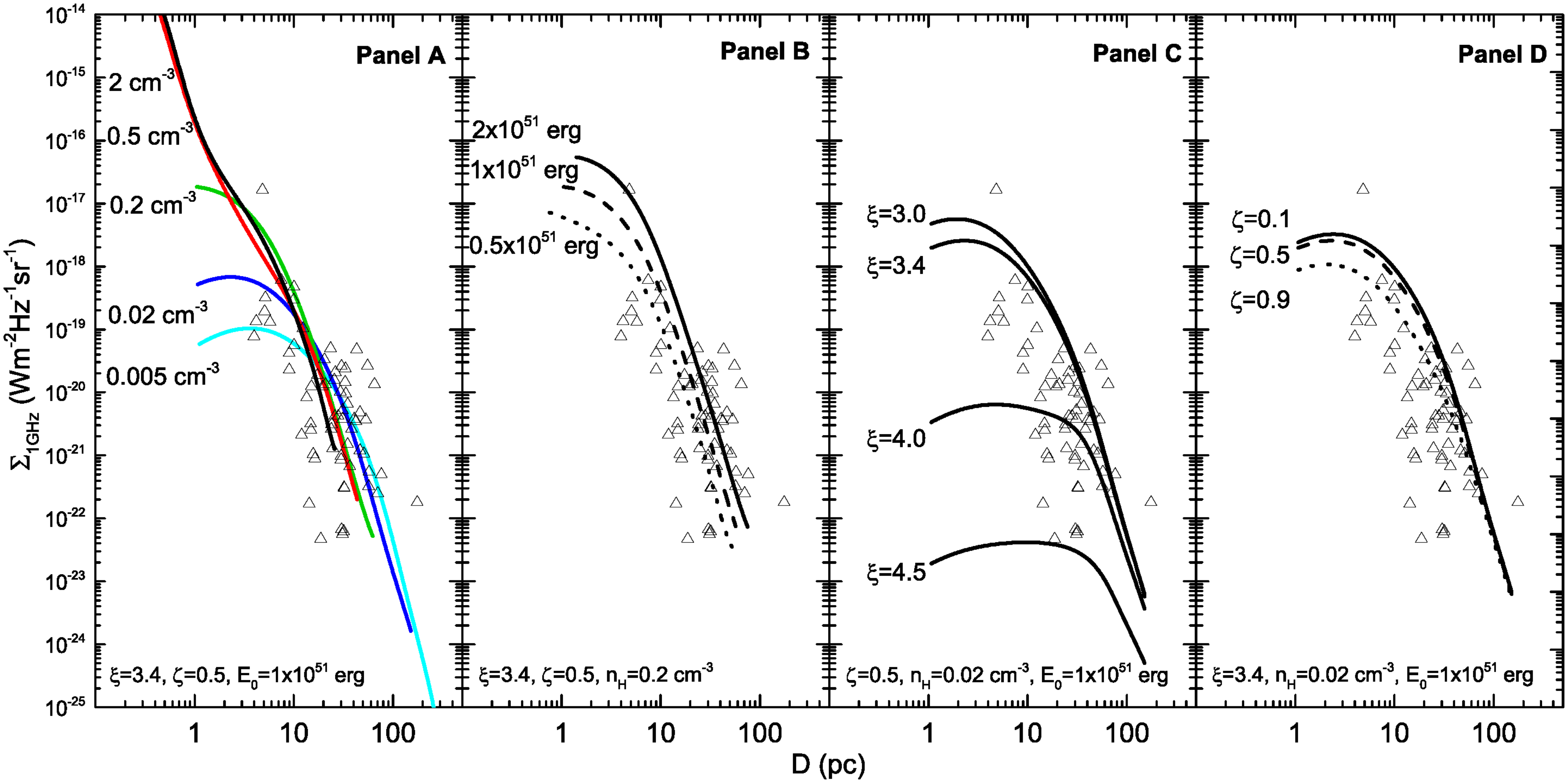
THANK YOU FOR YOUR ATTENTION!



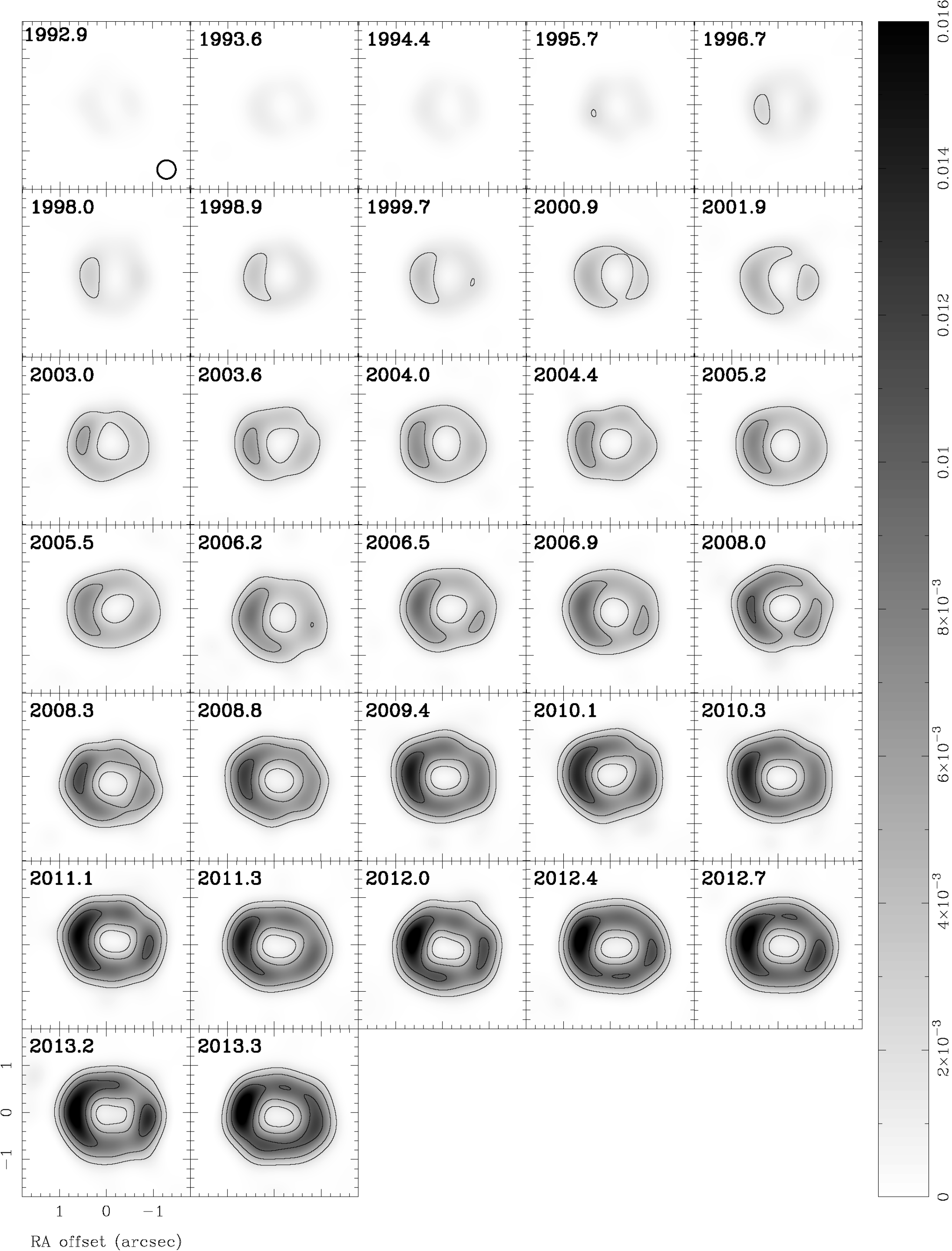
$$f(p) \propto p^{q}$$

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

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



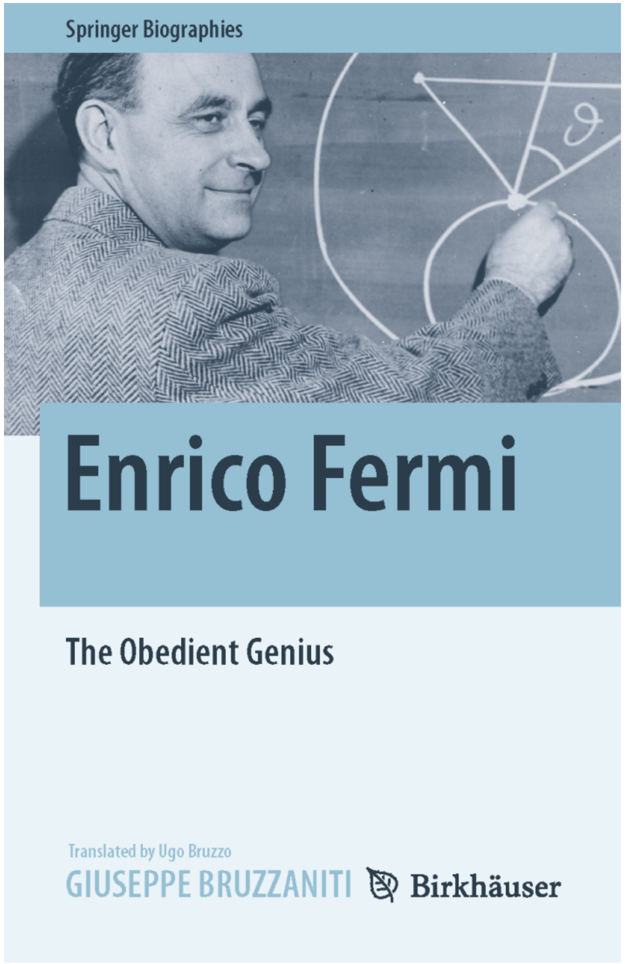
Panel A
Panel B
Panel C
Panel D
2 cm-3
0.5 cm-3
0.2 cm-3
0.02 cm-3
0.005 cm-3
2x10^51 erg
1x10^51 erg
0.5x10^51 erg
ξ=3.0
ξ=3.4
ξ=4.0
ξ=4.5
ζ=0.1
ζ=0.5
ζ=0.9
ξ=3.4, ζ=0.5, E0=1x10^51 erg
ξ=3.4, ζ=0.5, nH=0.2 cm-3
ζ=0.5, nH=0.02 cm-3, E0=1x10^51 erg
ξ=3.4, nH=0.02 cm-3, E0=1x10^51 erg
Σ1GHz (Wm-2Hz-1sr-1)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



- Not only the evolution of radio flux but also the evolution of the radio size is observed for very young supernova remnant
-
- Left: 9 GHz ATCA images of SN1987A, obtained between 1992 and 2013 (Ng et al. 2013)

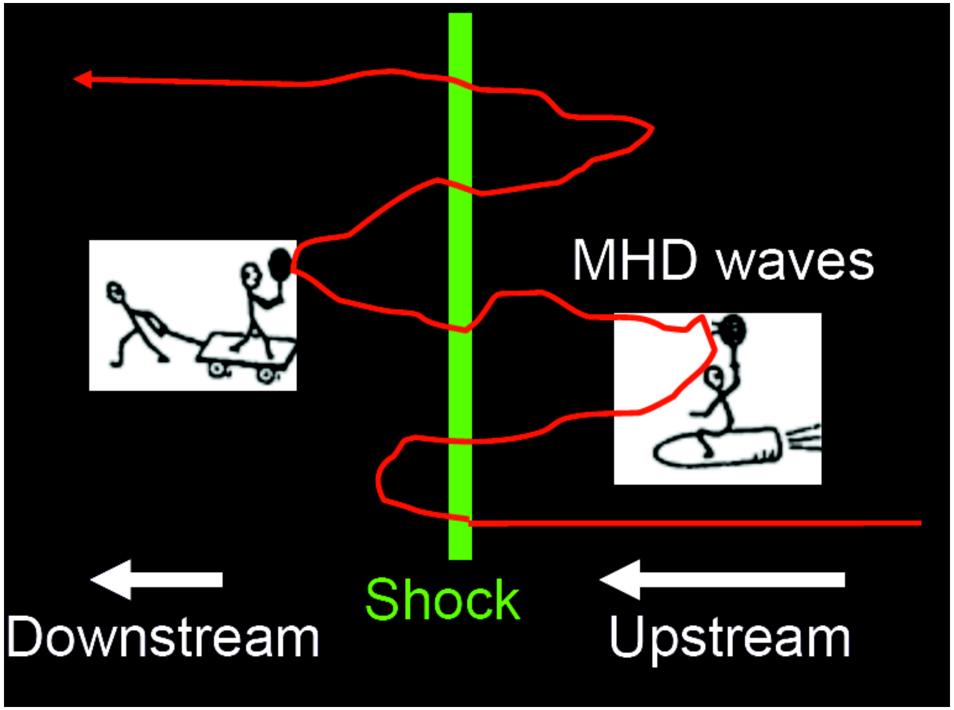
Baade & Zwicky 1934

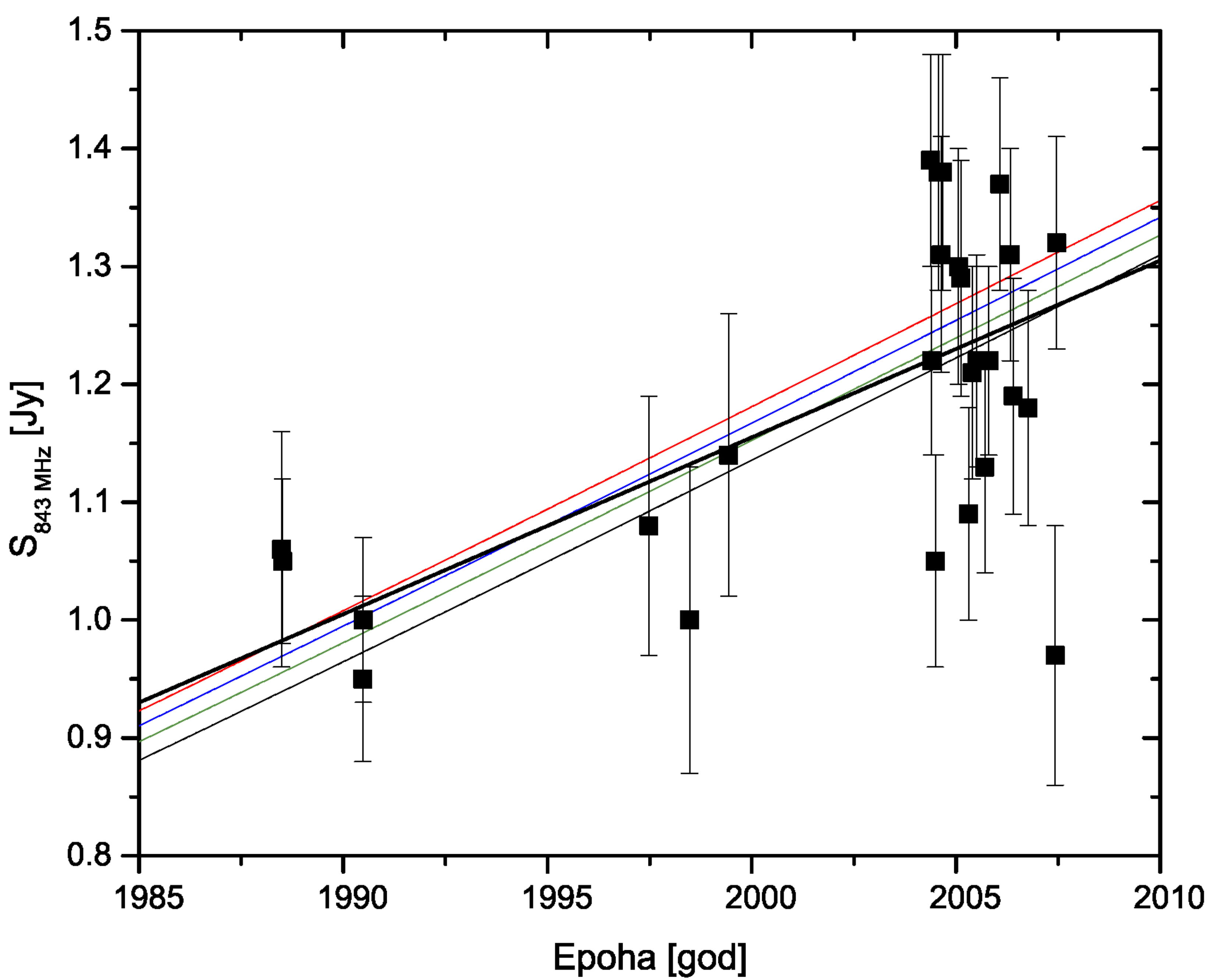
Fermi 1949



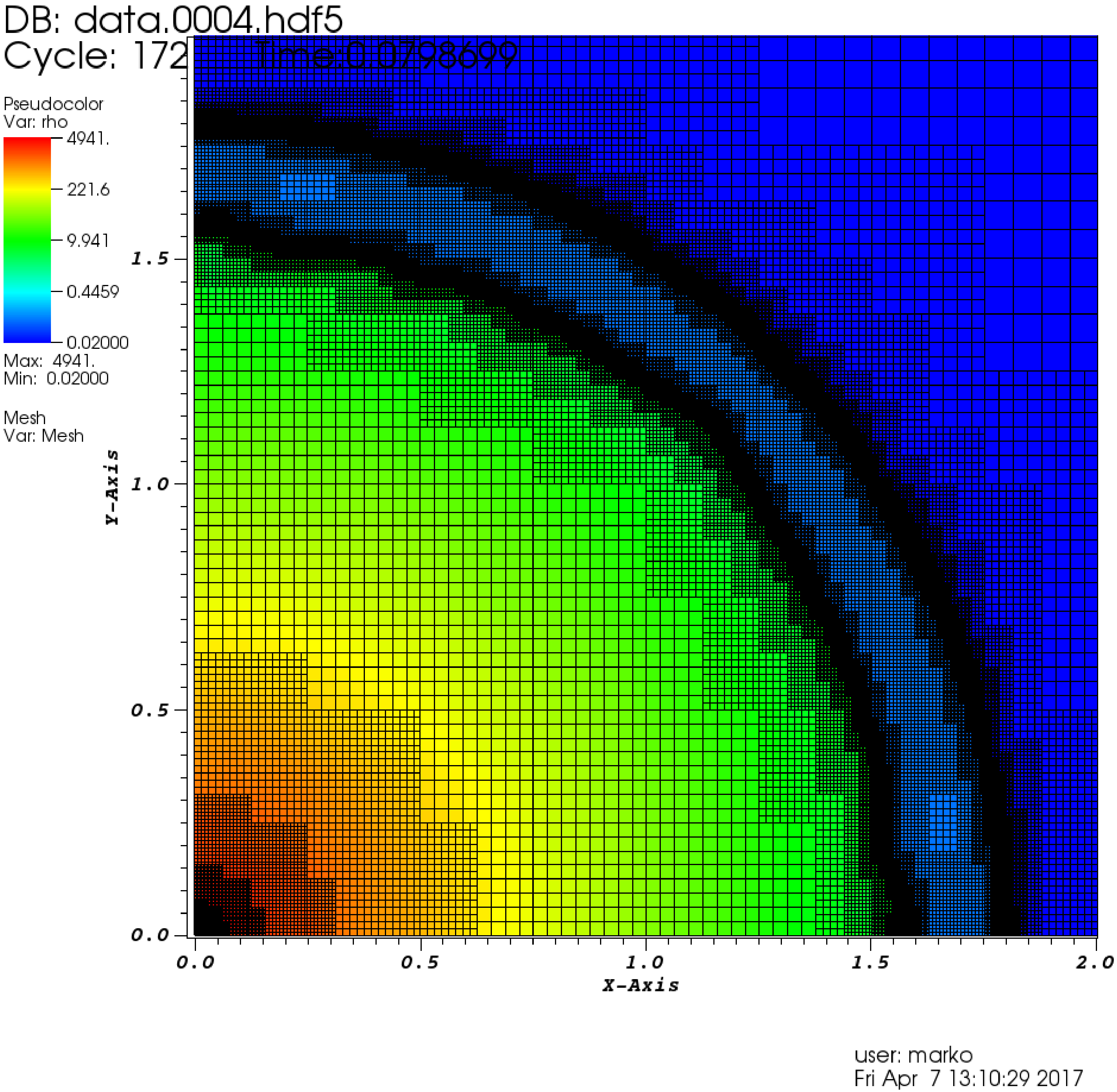
Bell 1978a, b

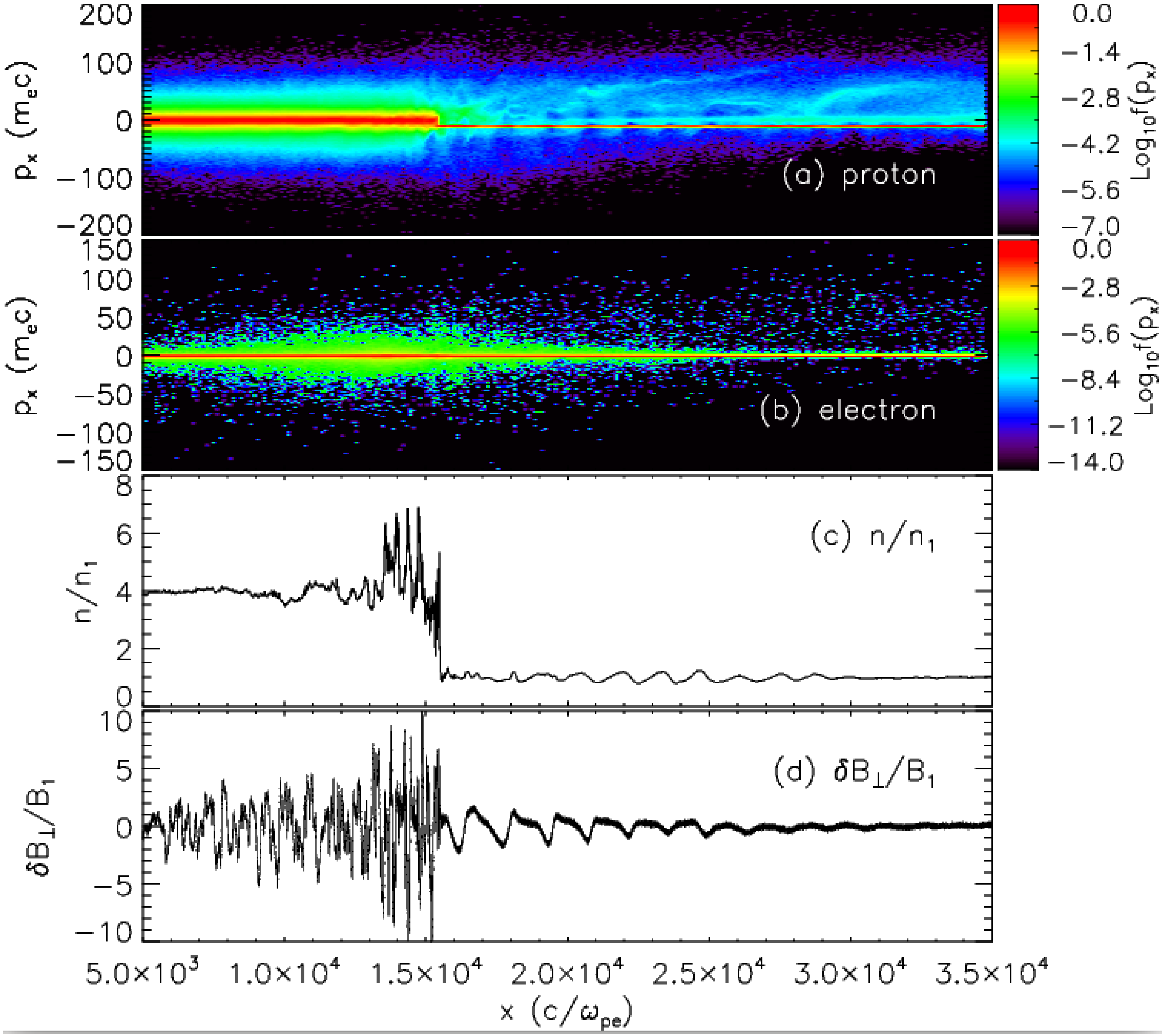
Axford et al. 1977, Krymsky 1977
Blandford & Ostriker 1978



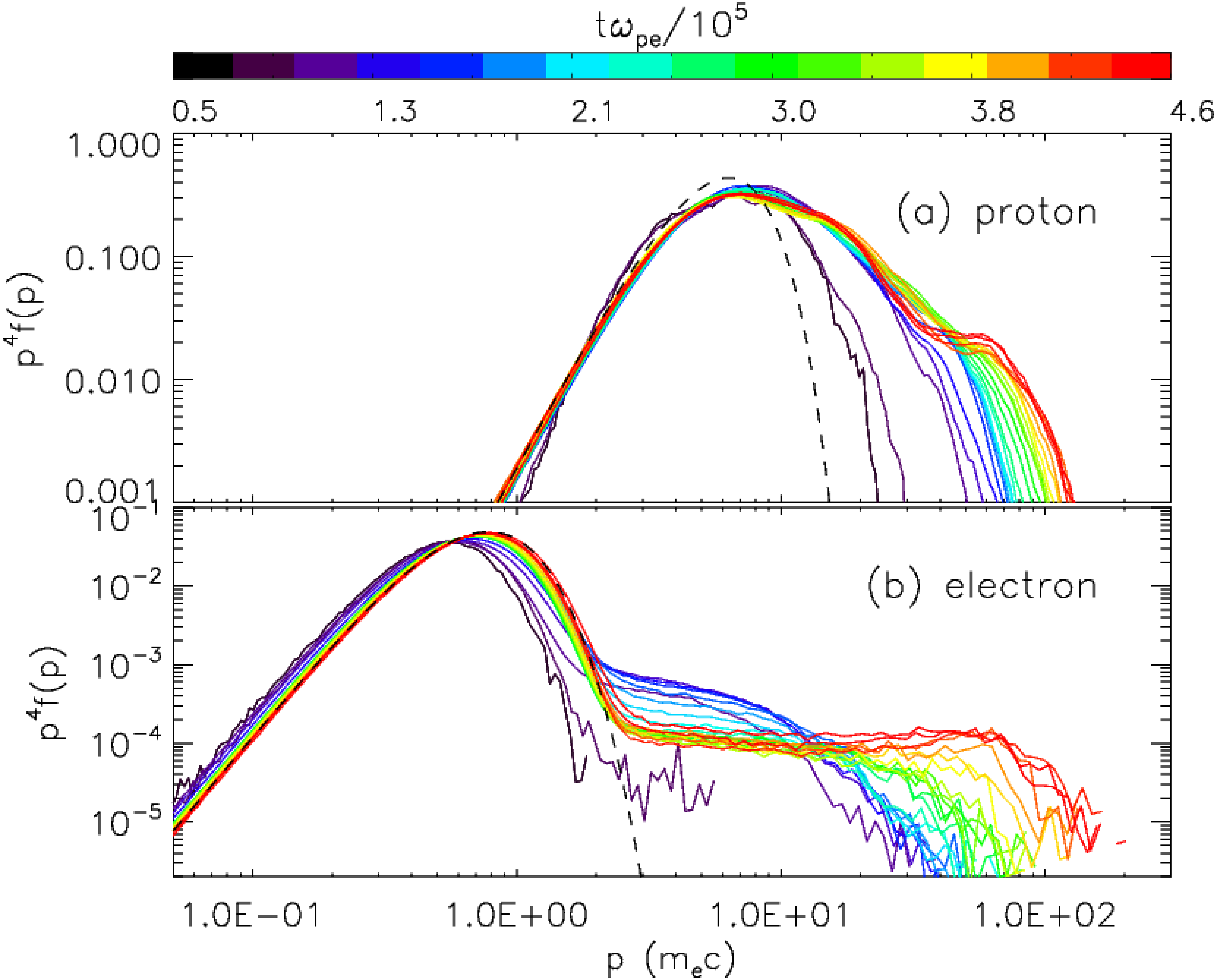


S843 MHz [Jy]
Epoha [god]
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
1985
1990
1995
2000
2005
2010


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
X-Axis
0.0
0.5
1.0
1.5
2.0
user: marko
Fri Apr 7 13:10:29 2017



(a) proton
(b) electron
(c) n/n1
(d) δB⊥/B1
px (mec)
n/n1
δB⊥/B1
Log10f(px)
x (c/ωpe)
200
100
0
−100
−200
150
50
−50
−150
0.0
−1.4
−2.8
−4.2
−5.6
−7.0
−8.4
−11.2
−14.0
8
6
4
2
10
5
−5
−10
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
2.5×10^4
3.0×10^4
3.5×10^4



$t\omega_{pe}/10^5$
0.5
1.3
2.1
3.0
3.8
4.6
1.000
0.100
0.010
0.001
$p^4f(p)$
(a) proton
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$p^4f(p)$
(b) electron
1.0E−01
1.0E+00
1.0E+01
1.0E+02
p (m_ec)