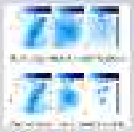
Dark plasma - a possible lighthouse in the morass of the dark sector

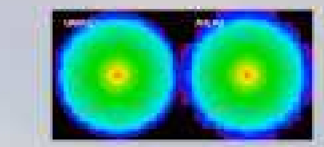
Tiit Sepp

09.03.2016

Tartu Observatory seminar

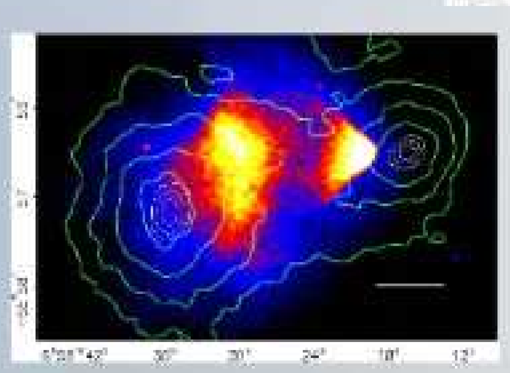
- Both 2 halo mergers
- Halos simple NFW
- Testing parameter variations

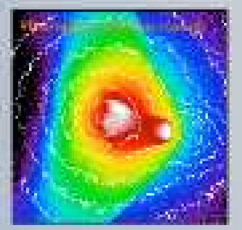


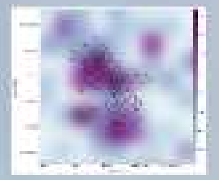


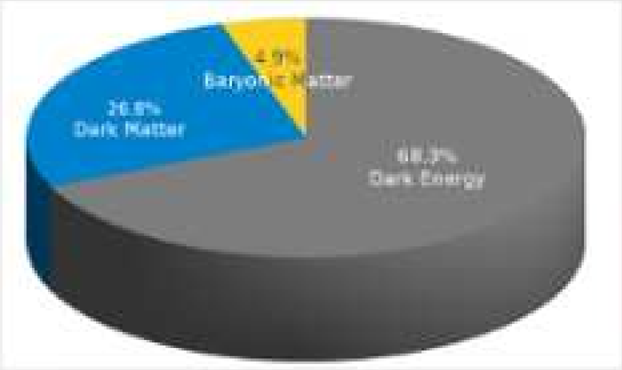
let's look to the bright side!

...nderstood with the wisdom of darkness."

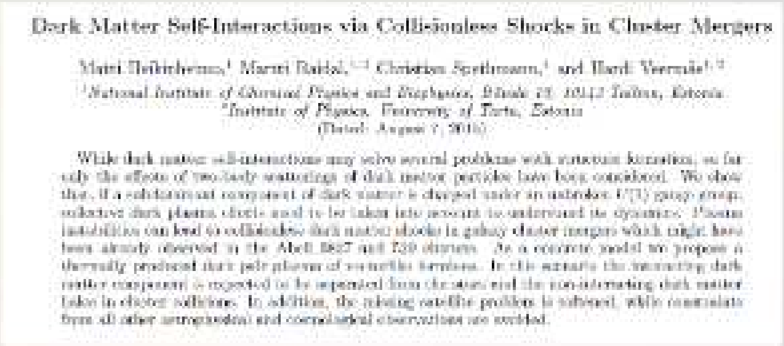




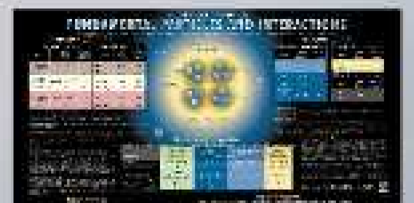


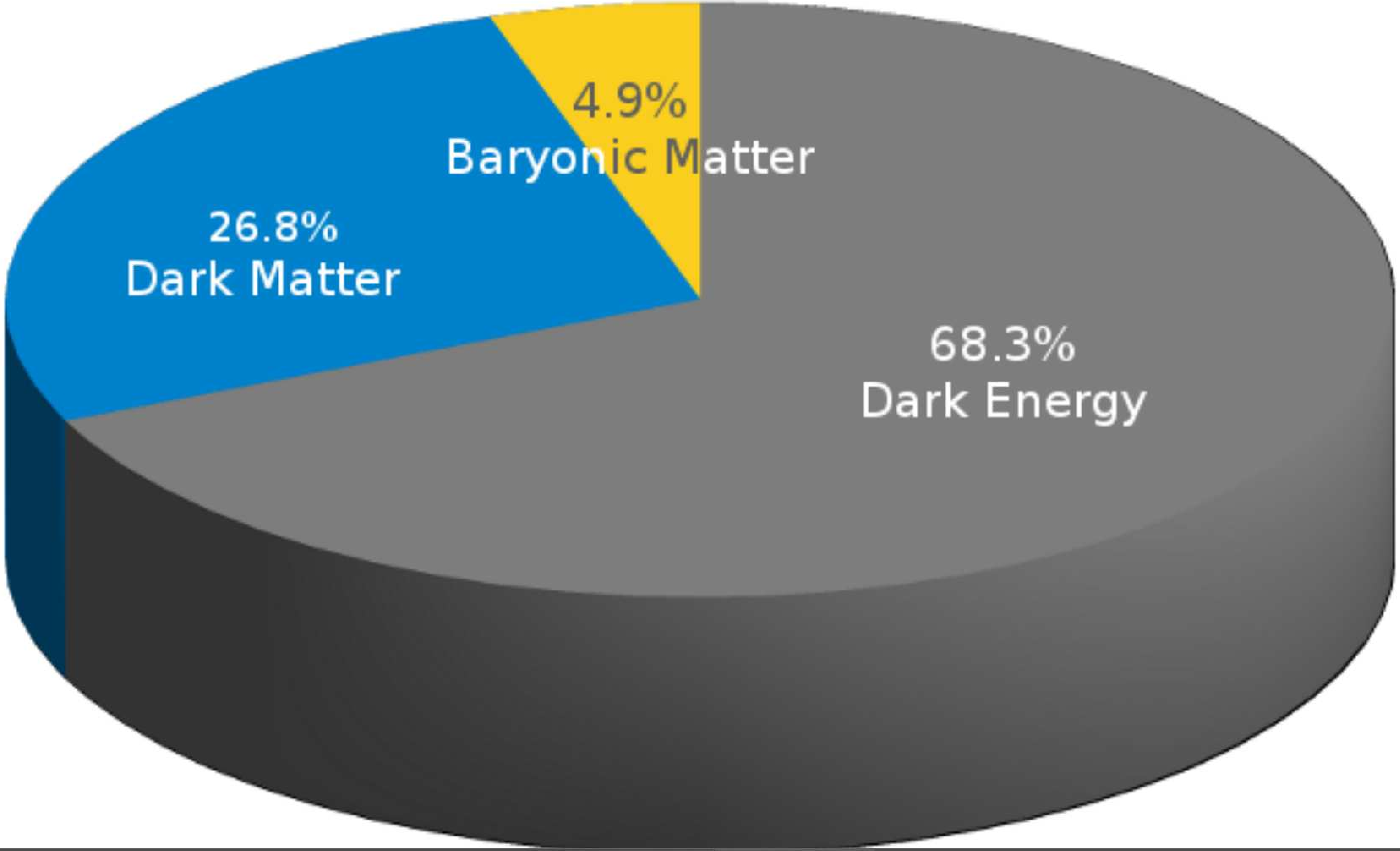


"(Always Look on) The Bright Side of Space"



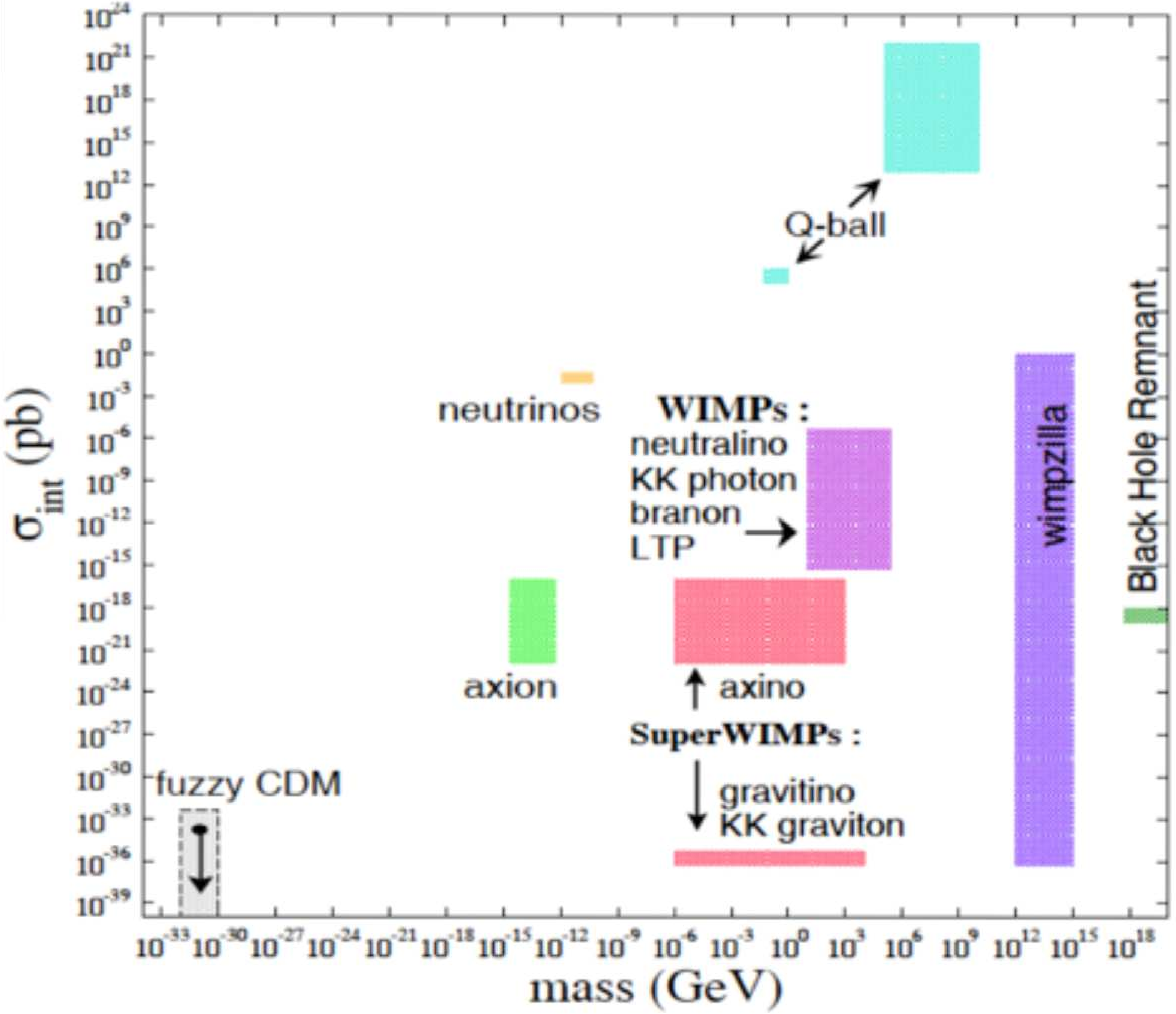
Dark Matter Self-Interactions via Collisionless Shocks in Cluster Mergers



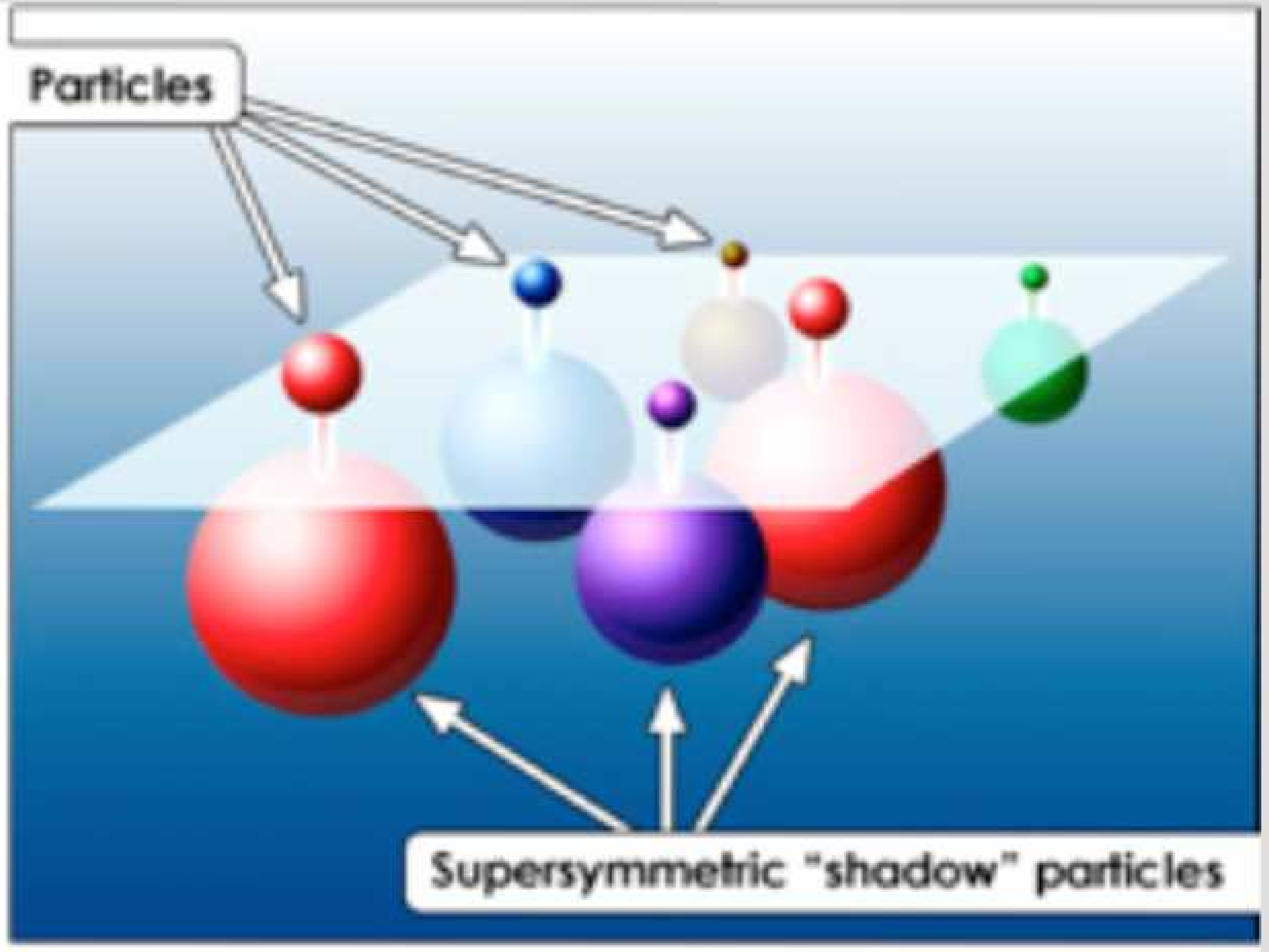

4.9%
Baryonic Matter
26.8%
Dark Matter
68.3%
Dark Energy

Brief history of dark matter

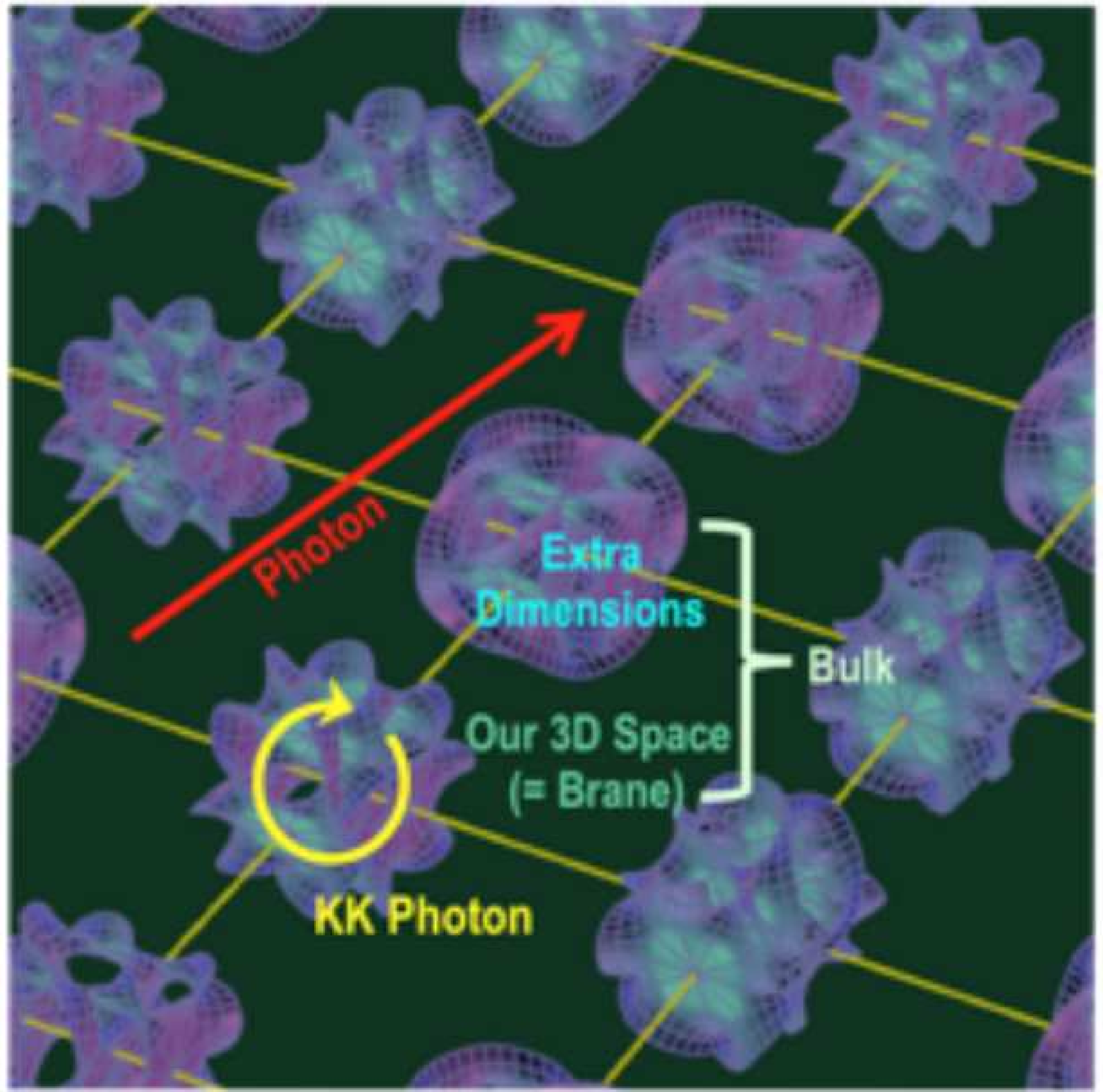
1915 - Öpik total mass estimations
1922 - Kapteyn: "Dark matter" in Milky way
1933, 1937 - Zwicky: "dunkle (kalte) materie" in Coma cluster
1937 - Smith: "Inter-galagtic large mass" in Virgo Cluster
1937 - Holmberg: galaxy masses 500 billion Solar masses
1939 - Babcock M311 rotation curve
1940s -too large velocity dispersions in clusters
1957 - van de Hulst: HI rotation curve in M31
1959 - Kahn & Woltjer: Linnutee-M31 velocities · $M = 1.8 \times 10^{12} M_{Sun}$
1970 - Rubin & Ford: M31 rotation curve
1973 - Ostriker & Peebles: halod around galaxy disks
1974 - Einasto, Kaasik, & Saar; Ostriker, Peebles, Yahil: s M/Lincreases with radii
1975, 78 - Roberts; Bosma: HI rotation curves again
1978 - Mathews: Virgo cluster in X-ray
1980-is - It is generally accepted that we have dark matter



σ_{int} (pb)
mass (GeV)
Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM



Particles
Supersymmetric "shadow" particles



Photon
Extra Dimensions
Bulk
Our 3D Space (= Brane)
KK Photon

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

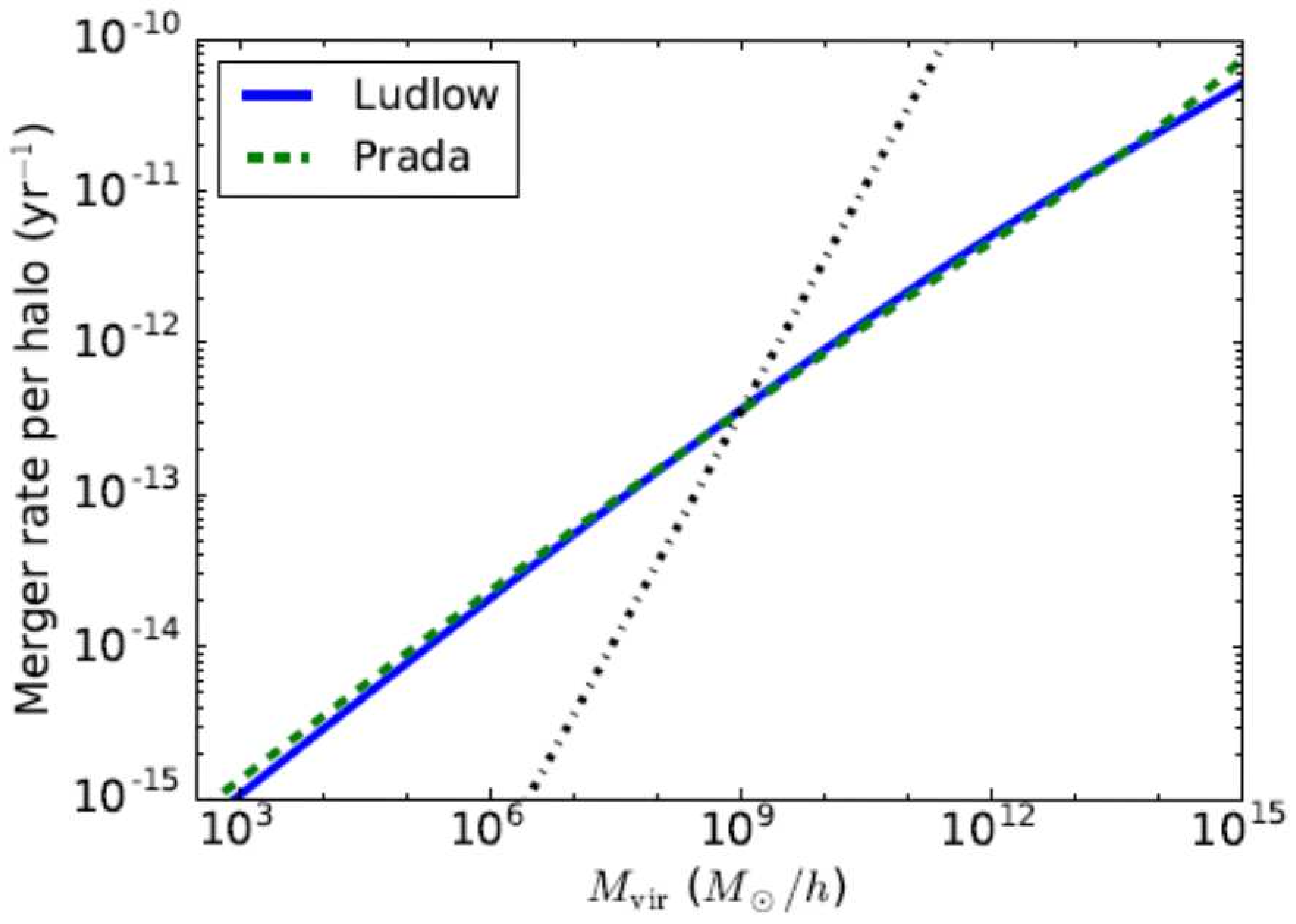


FIG. 1. The PBH merger rate per halo as a function of halo mass. The solid line shows the trend assuming the concentration-mass relation from Ref. [21], and the dashed line that from Ref. [20]. To guide the eye, the dot-dashed line shows a constant BH merger rate per unit halo mass.

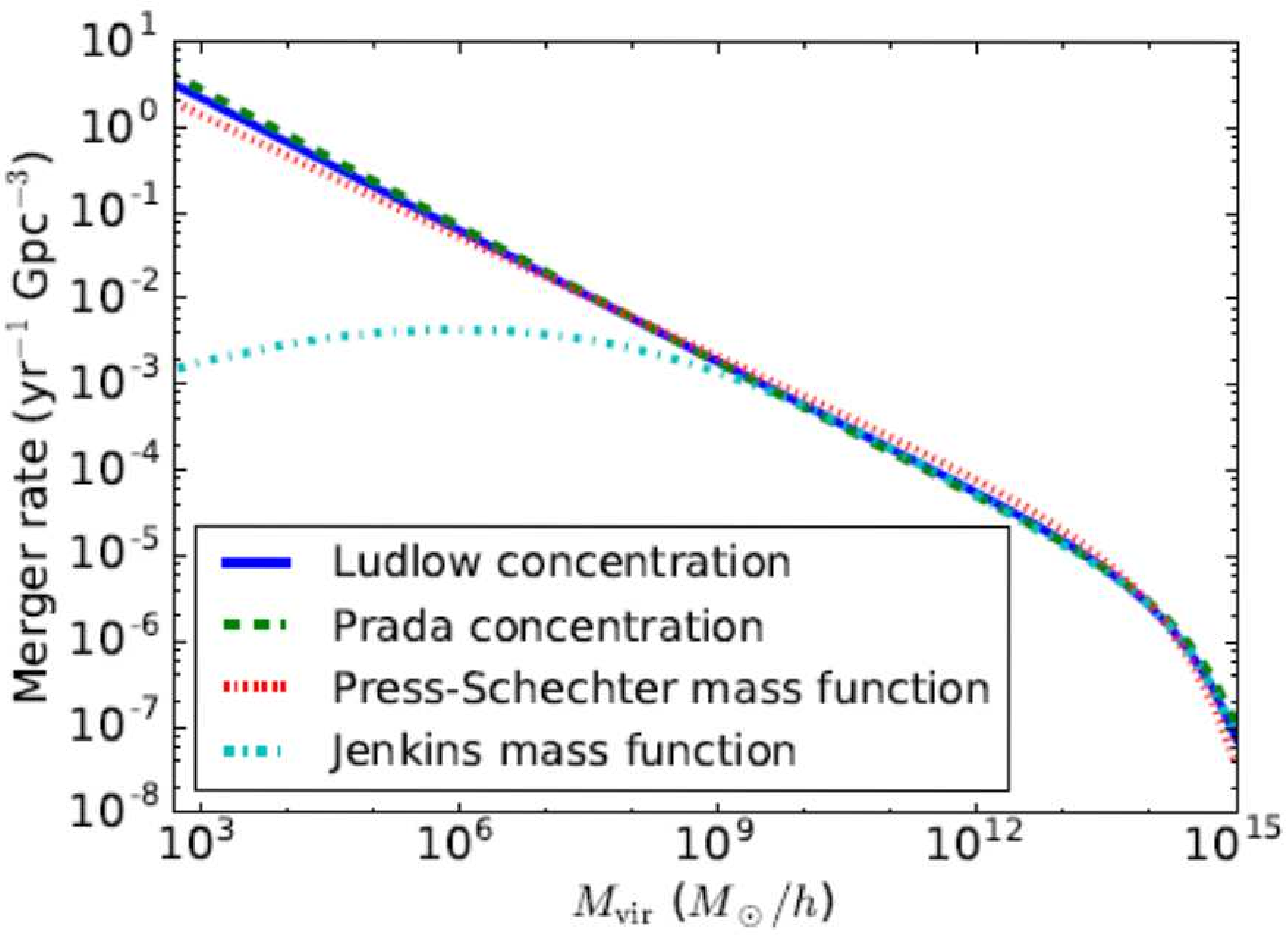


FIG. 2. The total PBH merger rate as a function of halo mass. Dashed and dotted lines show different prescriptions for the concentration-mass relation and halo mass function.

Dark Matter Self-Interactions via Collisionless Shocks in Cluster Mergers

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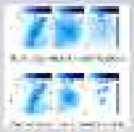
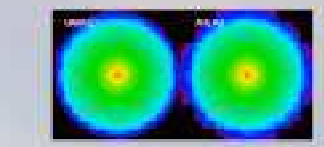
[1]*National Institute of Chemical Physics and Biophysics, Rävala 10, 10143 Tallinn, Estonia*
[2]*Institute of Physics, University of Tartu, Estonia*

(Dated: August 7, 2015)

While dark matter self-interactions may solve several problems with structure formation, so far only the effects of two-body scatterings of dark matter particles have been considered. We show that, if a subdominant component of dark matter is charged under an unbroken $U(1)$ gauge group, collective dark plasma effects need to be taken into account to understand its dynamics. Plasma instabilities can lead to collisionless dark matter shocks in galaxy cluster mergers which might have been already observed in the Abell 3827 and 520 clusters. As a concrete model we propose a thermally produced dark pair plasma of vectorlike fermions. In this scenario the interacting dark matter component is expected to be separated from the stars and the non-interacting dark matter halos in cluster collisions. In addition, the missing satellite problem is softened, while constraints from all other astrophysical and cosmological observations are avoided.

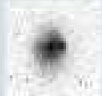
- Both 2 halo mergers
- Halos simple NFW
- Testing parameter variations

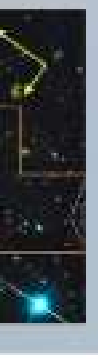


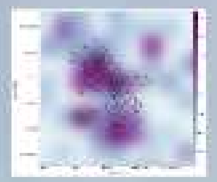


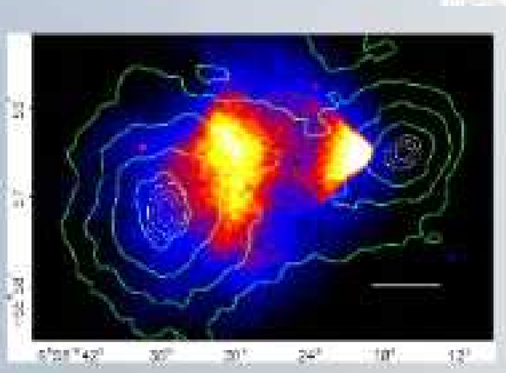
let's look to the
right side!

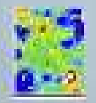
nderstood with the wisdom of darkness."

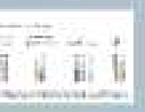


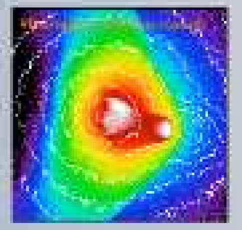






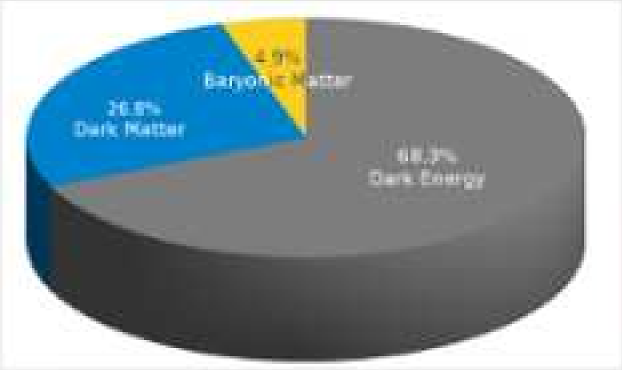






: ESO R. Massey

Brief history of dark matter



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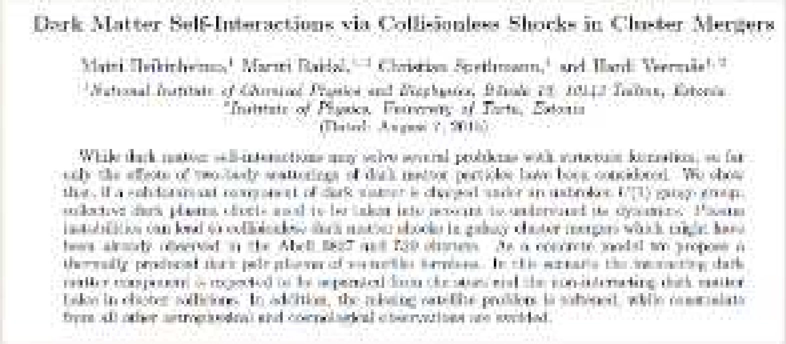
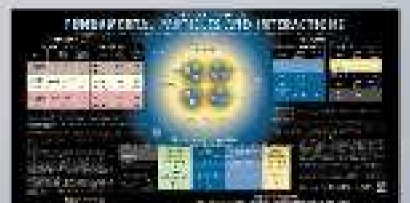
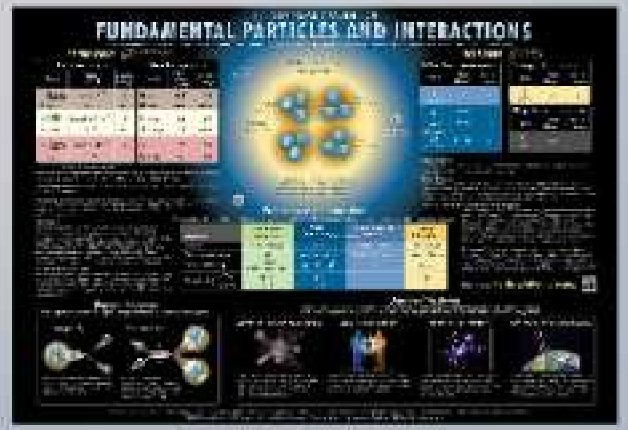


Dark Matter Self-Interactions via Collisionless Shocks in Cluster Mergers





So you have dark plasma you say....

(not to confuse with regular plasma)

- Dark Plasma gives…
  - ..an interacting component to Dark matter
- Dark plasma needs to have….
  - …the interacting subcomponent has long range self-interactions mediated by a dark photon
  - …the elastic scattering rate of the interacting particles is small
  - …the radiative cooling of the interacting component is ineffective

THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

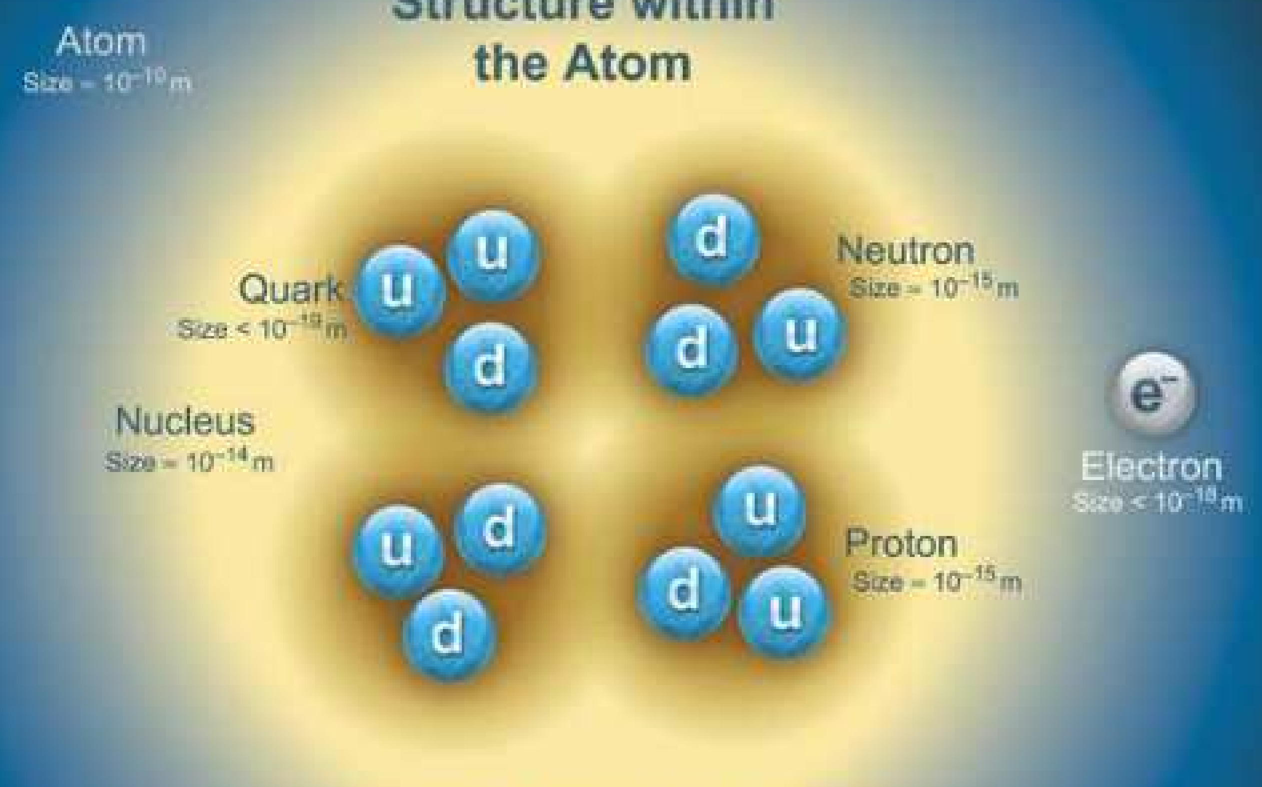
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

Properties of the Interactions

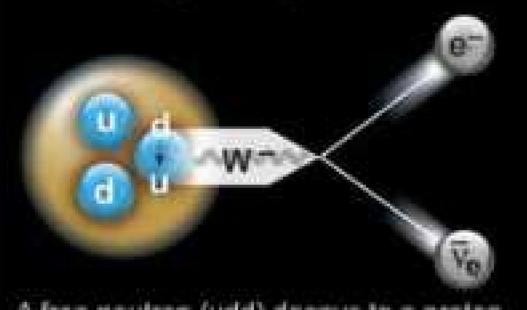
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

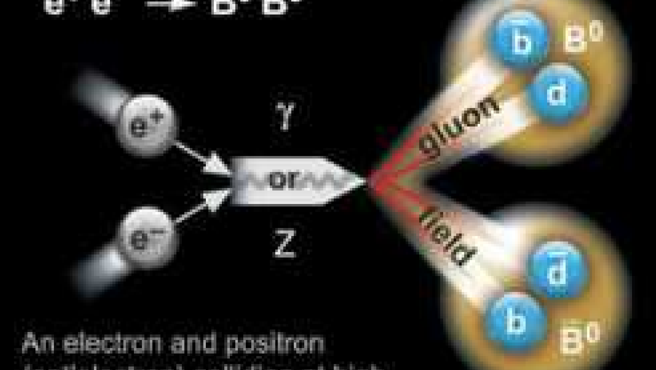
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^- \bar{\nu}_e$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

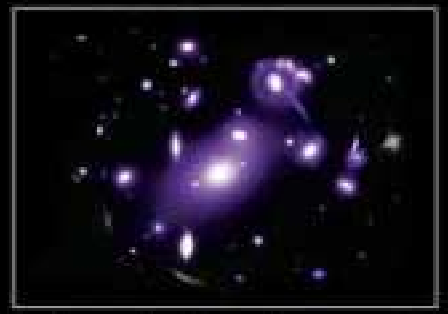
Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?



Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

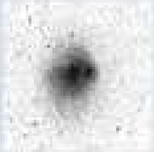
Are there Extra Dimensions?

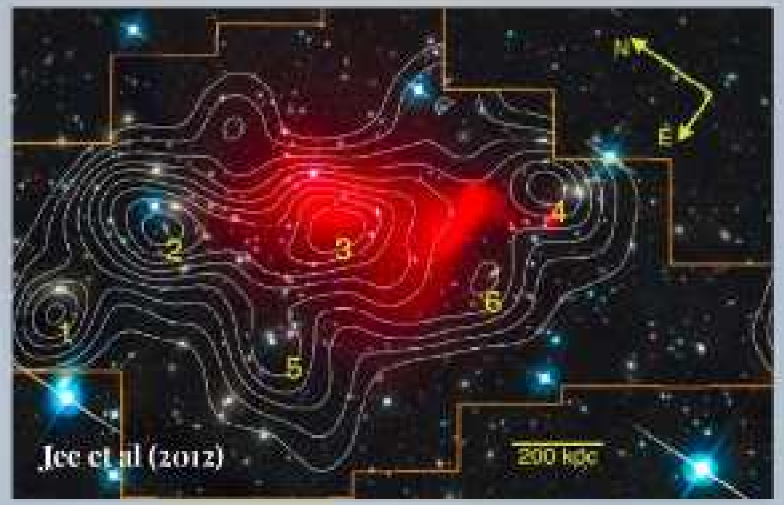
An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

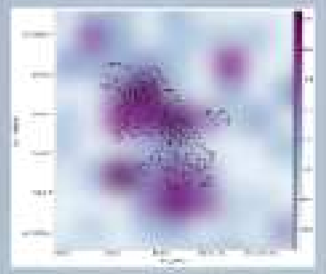
Made possible by the generous support of:
U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

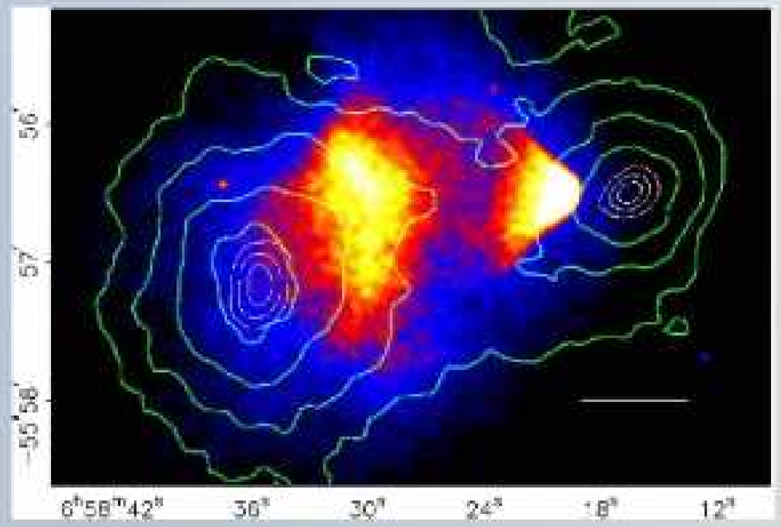
...now let's look to the bright side!

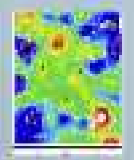
(“Light can only be understood with the wisdom of darkness.”
· Ka Chinery)

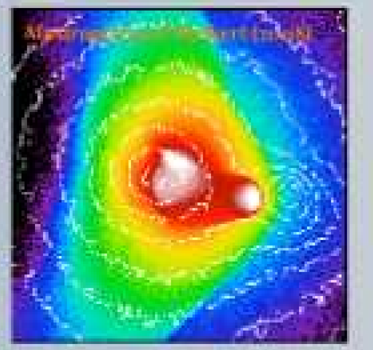


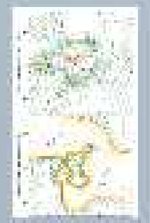












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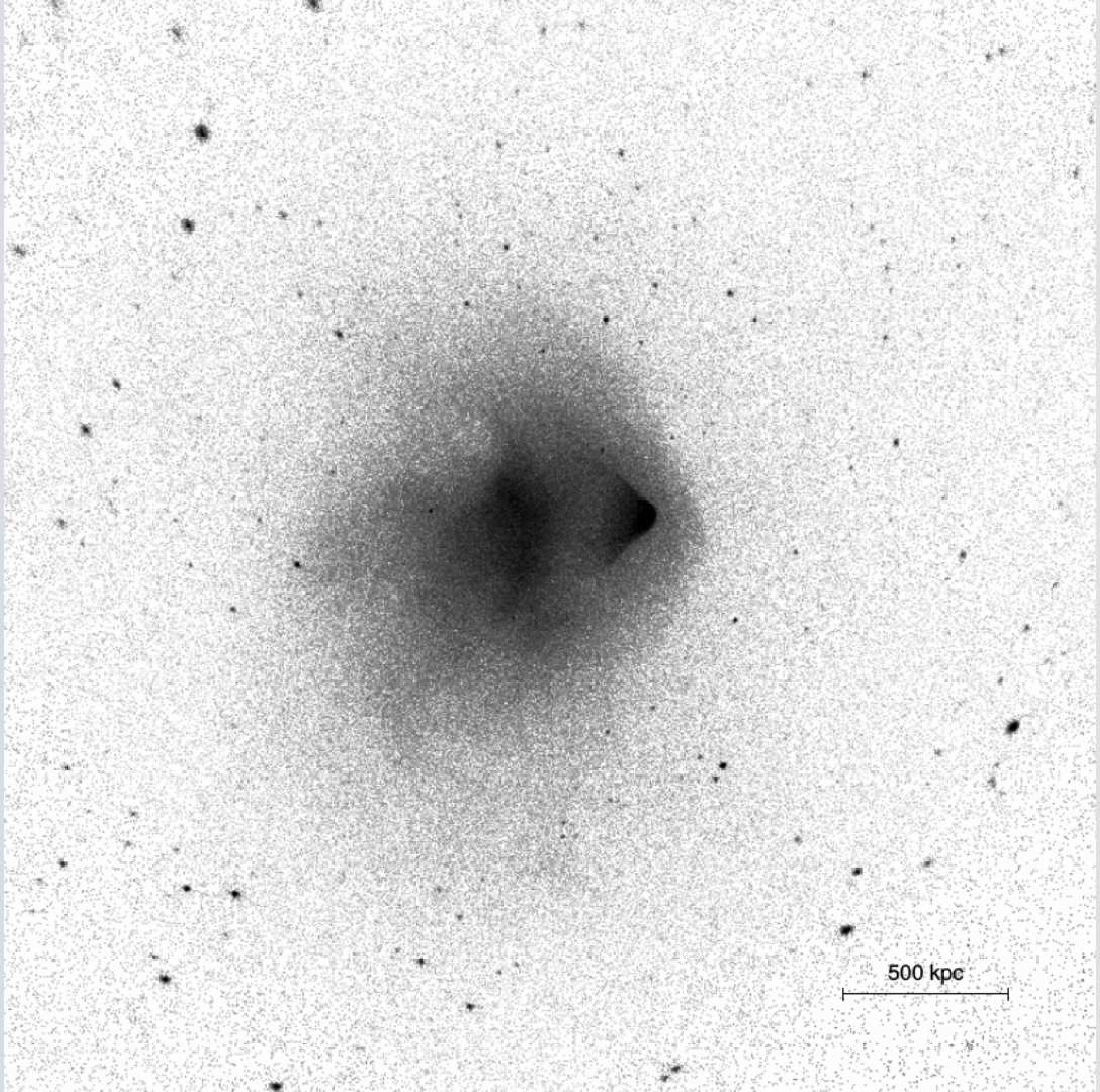
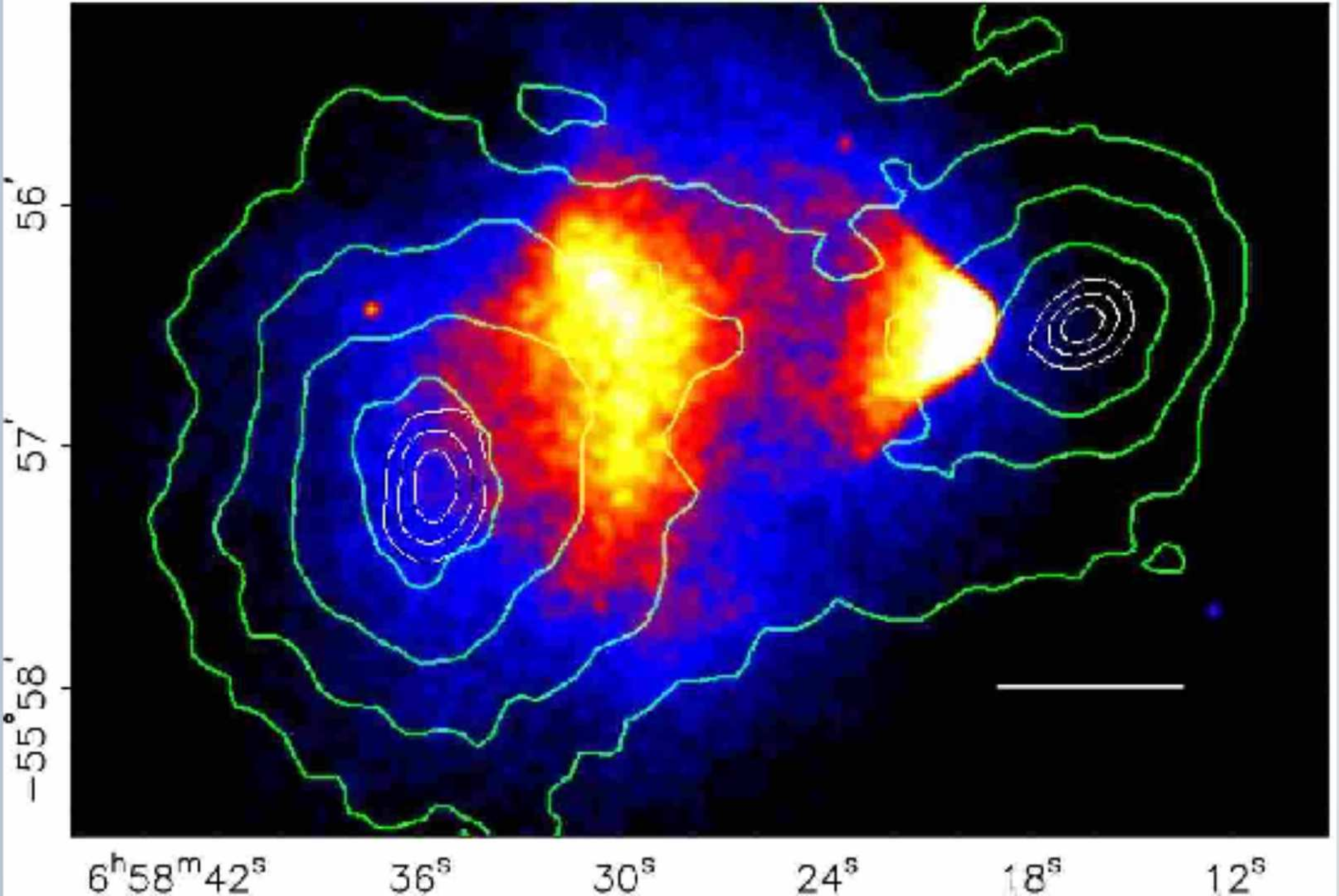
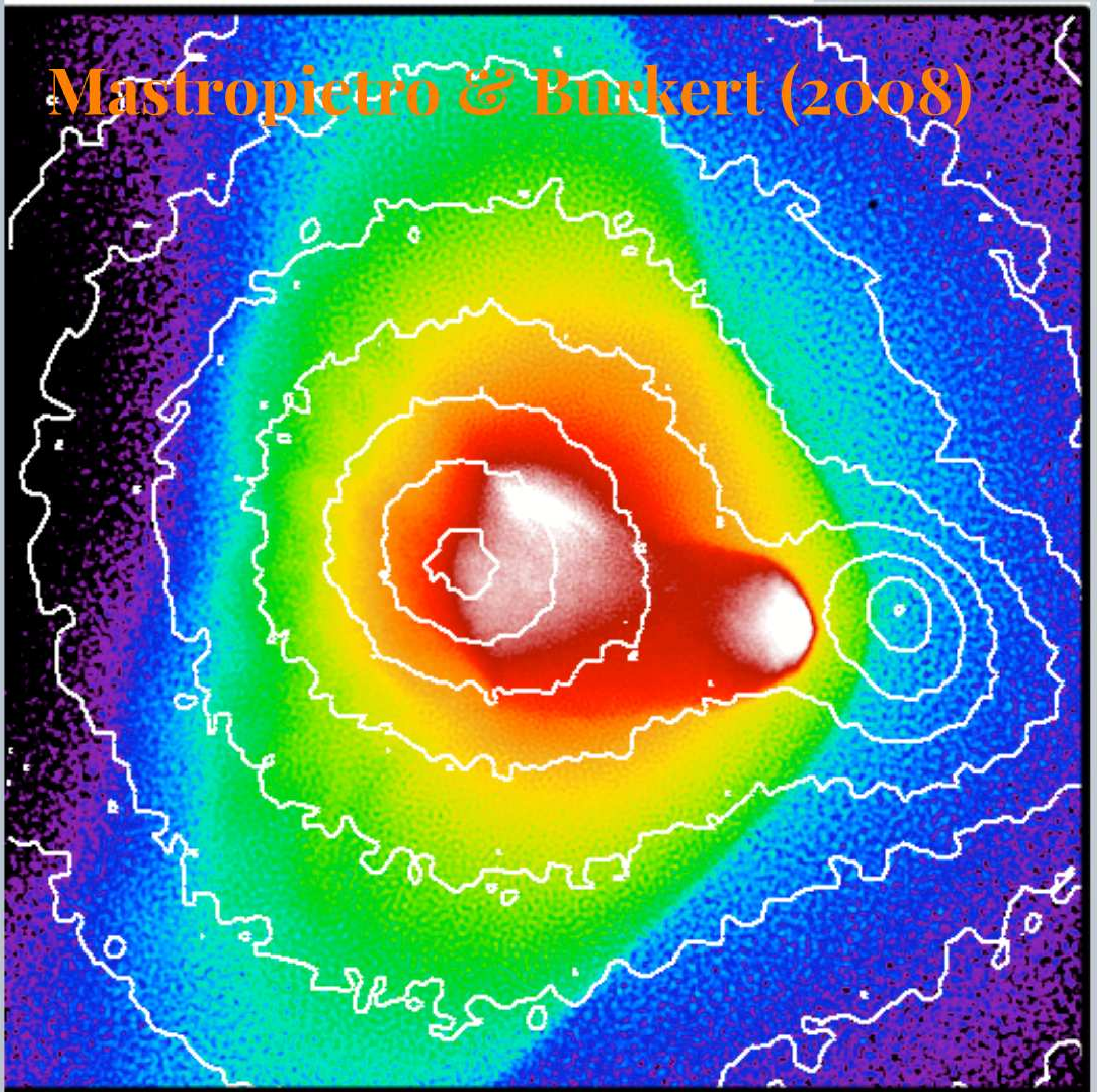
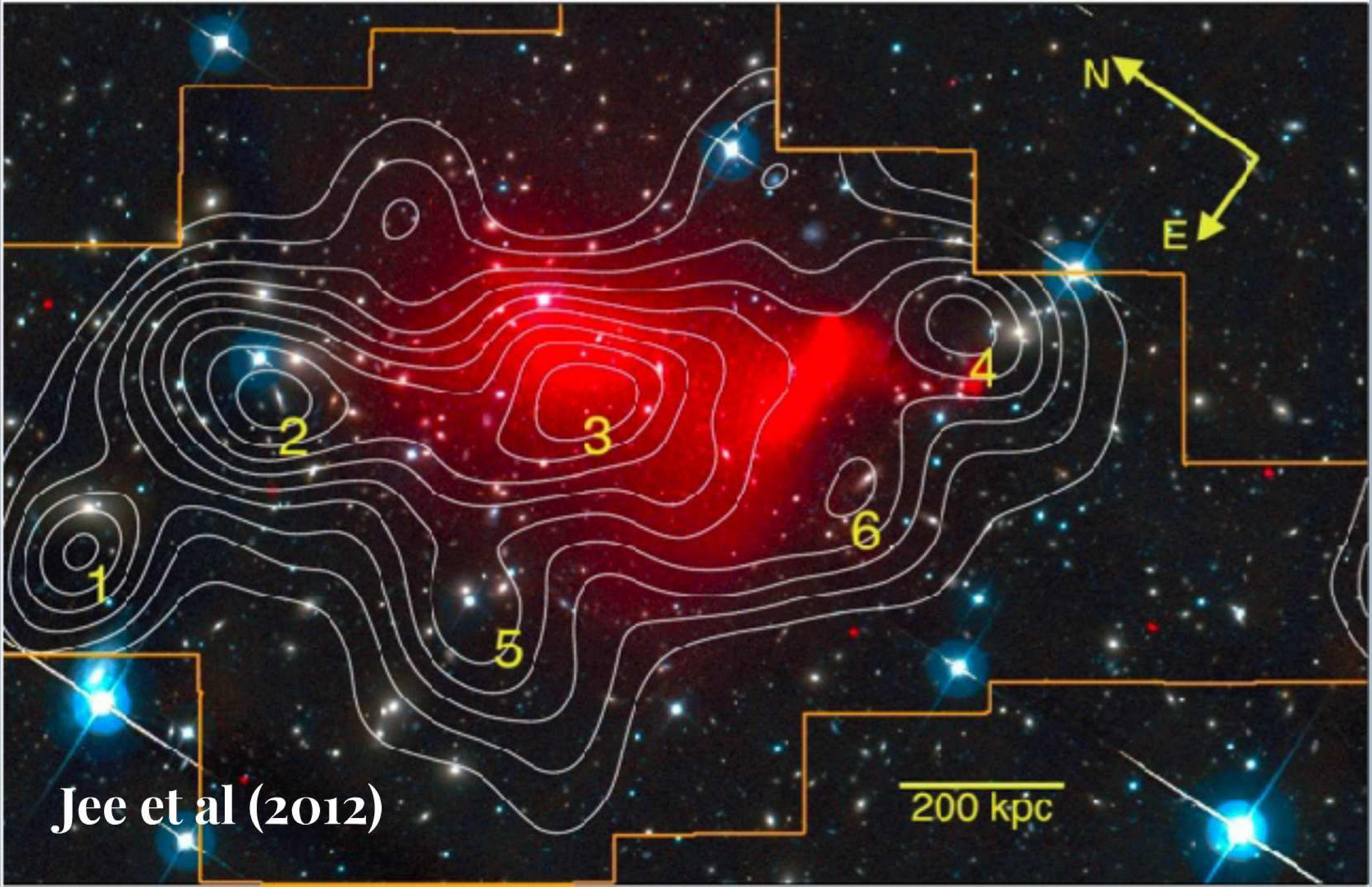

500 kpc

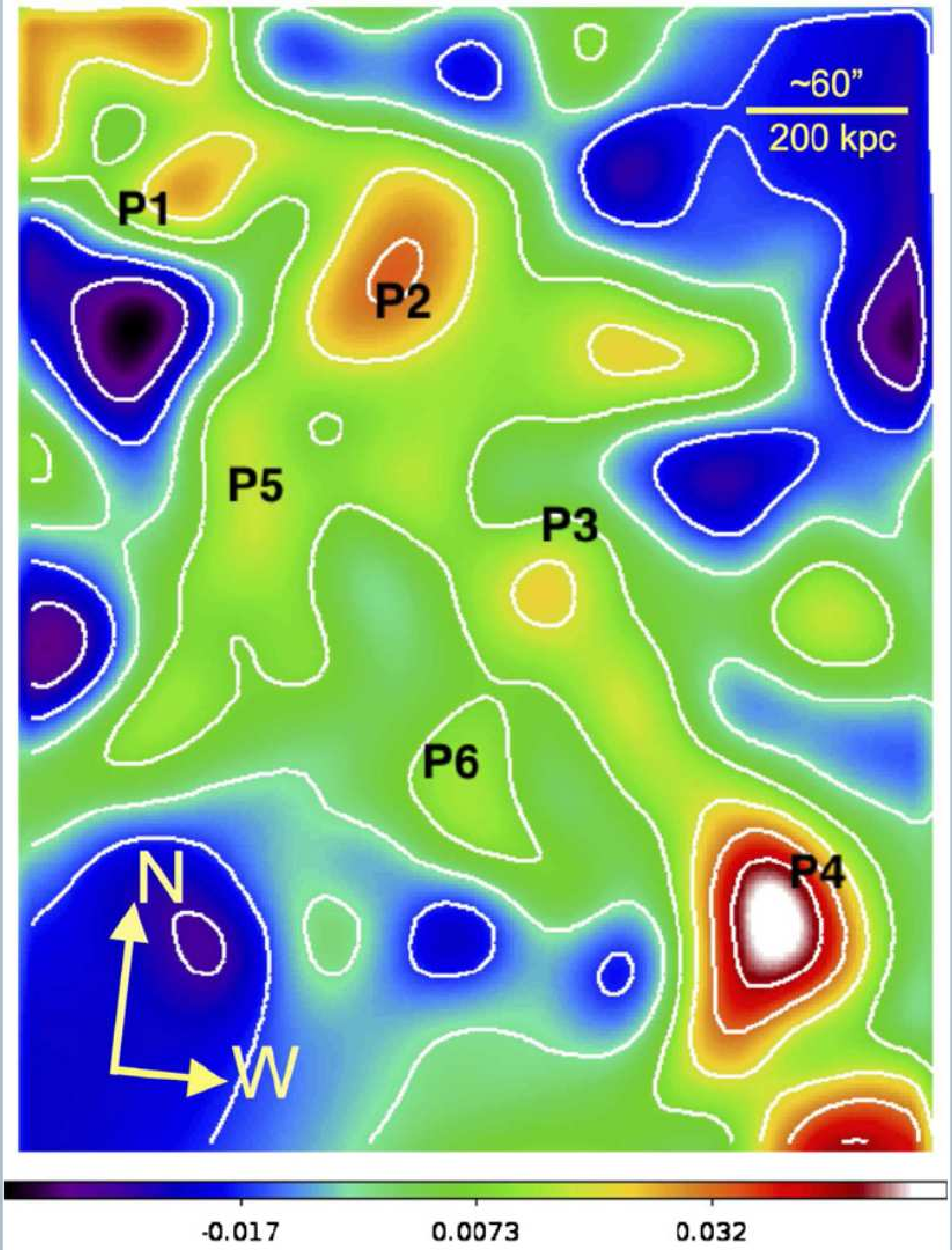


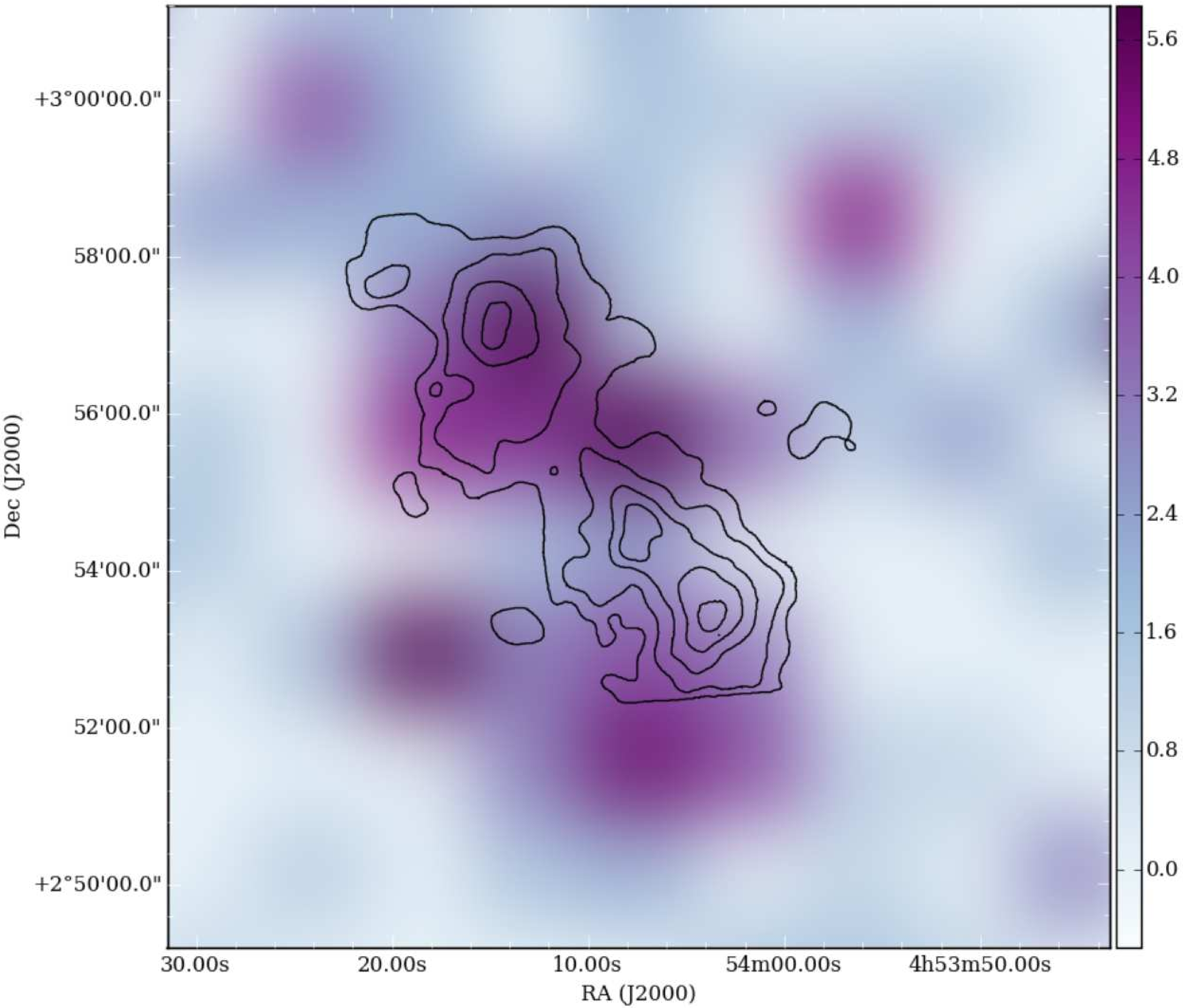
56′
57′
−55°58′
6h58m42s
36s
30s
24s
18s
12s


Mastropietro & Burkert (2008)



Jee et al (2012)


~60"
200 kpc
P1
P2
P3
P4
P5
P6
N
W
-0.017
0.0073
0.032



+3°00'00.0"
58'00.0"
56'00.0"
54'00.0"
52'00.0"
+2°50'00.0"
Dec (J2000)
30.00s
20.00s
10.00s
54m00.00s
4h53m50.00s
RA (J2000)
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0

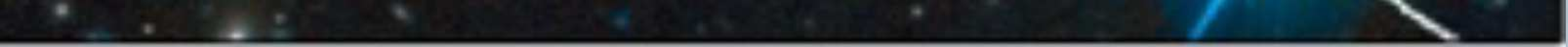
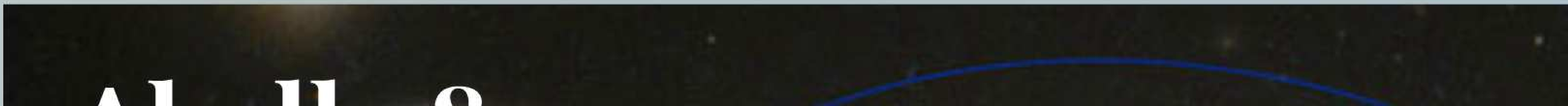
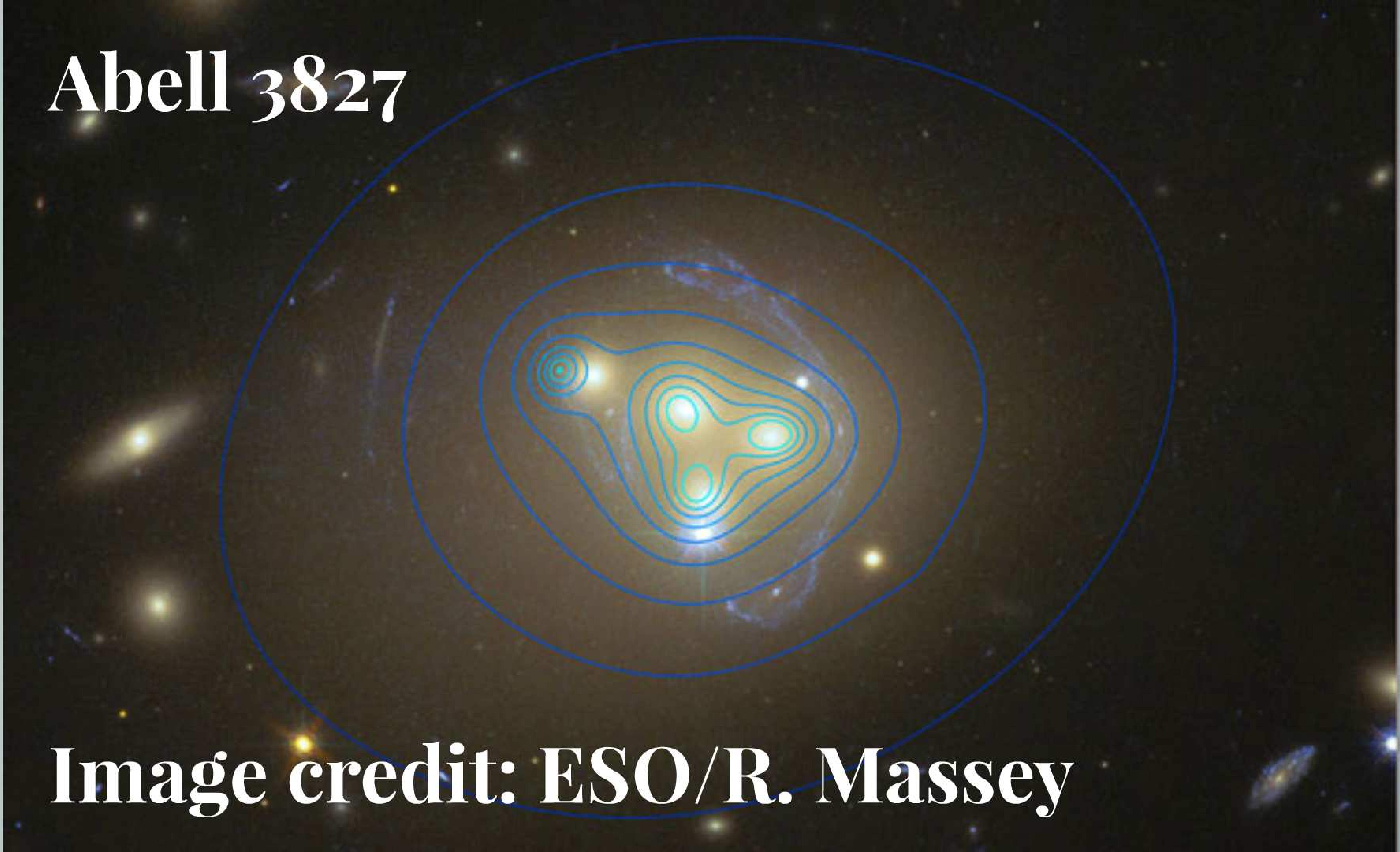


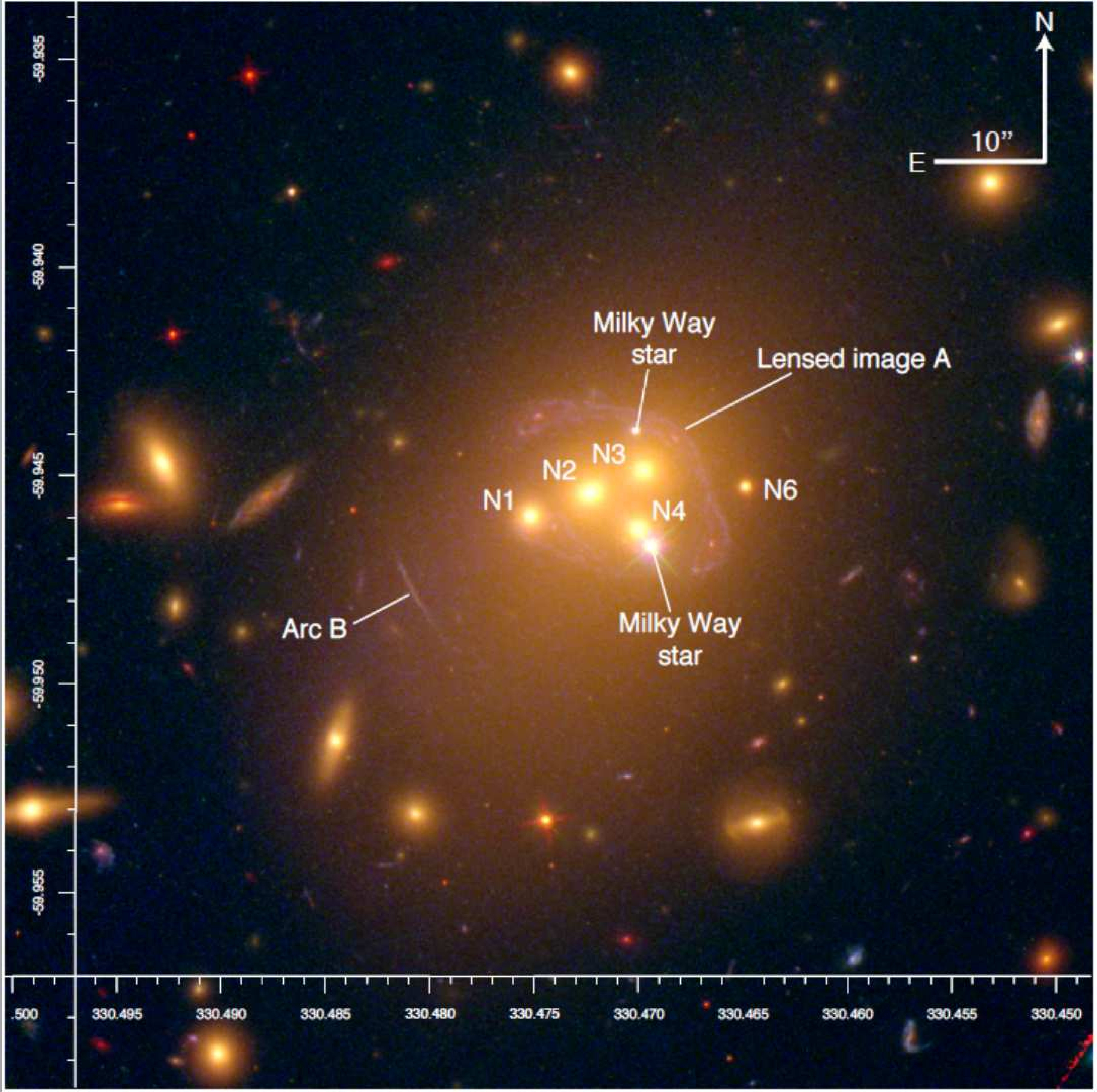
Table 1
Mass and Luminosity Properties of Substructure ($r < 150$ kpc)

Substructure	α, δ ($^{h\ m\ s}, ^{\circ\ \prime\ \prime\prime}$)	$\Delta\alpha, \Delta\delta$ ($^{\prime\prime}, ^{\prime\prime}$)	Projected Mass ($h_{70}^{-1} 10^{13} M_{\odot}$)	Luminosity ($h_{70}^{-2} 10^{11} L_{B\odot}$)	M/L ($h_{70} M_{\odot}/L_{B\odot}$)	f_g ($h_{70}^{-1.5}$)
P1	(04 54 20.76, +02 57 38.4)	(4.4,2.7)	2.63 ± 0.48	1.54	171 ± 31	< 0.06
P2	(04 54 15.02, +02 57 09.2)	(4.0,6.5)	3.83 ± 0.42	3.58	106 ± 12	< 0.08
P3 (dark core)	(04 54 11.07, +02 55 35.3)	(6.7,6.5)	4.00 ± 0.38	0.68	588 ± 56	< 0.14
P4	(04 54 04.32, +02 53 51.0)	(5.1,6.9)	3.64 ± 0.45	2.95	123 ± 15	< 0.08
P5	(04 54 16.53, +02 55 26.7)	(6.5,6.4)	3.03 ± 0.40	2.12	143 ± 19	< 0.05
P6	(04 54 08.85, +02 53 50.2)	(9.6,6.7)	3.33 ± 0.40	1.23	270 ± 33	< 0.06

Note. — The positional uncertainty is estimated from bootstrapping. We estimate the aperture mass based on the method of Fahlman et al. (1994). The mass uncertainties are evaluated from 1000 Monte-Carlo realizations. The gas fraction f_g is derived using Cauchy-Schwartz method in M07




Abell 3827
Image credit: ESO/R. Massey



N
10"
E
Milky Way
star
Lensed image A
N3
N2
N1
N4
N6
Arc B
Milky Way
star
-59.935
-59.940
-59.945
-59.950
-59.955
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330.495
330.490
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330.470
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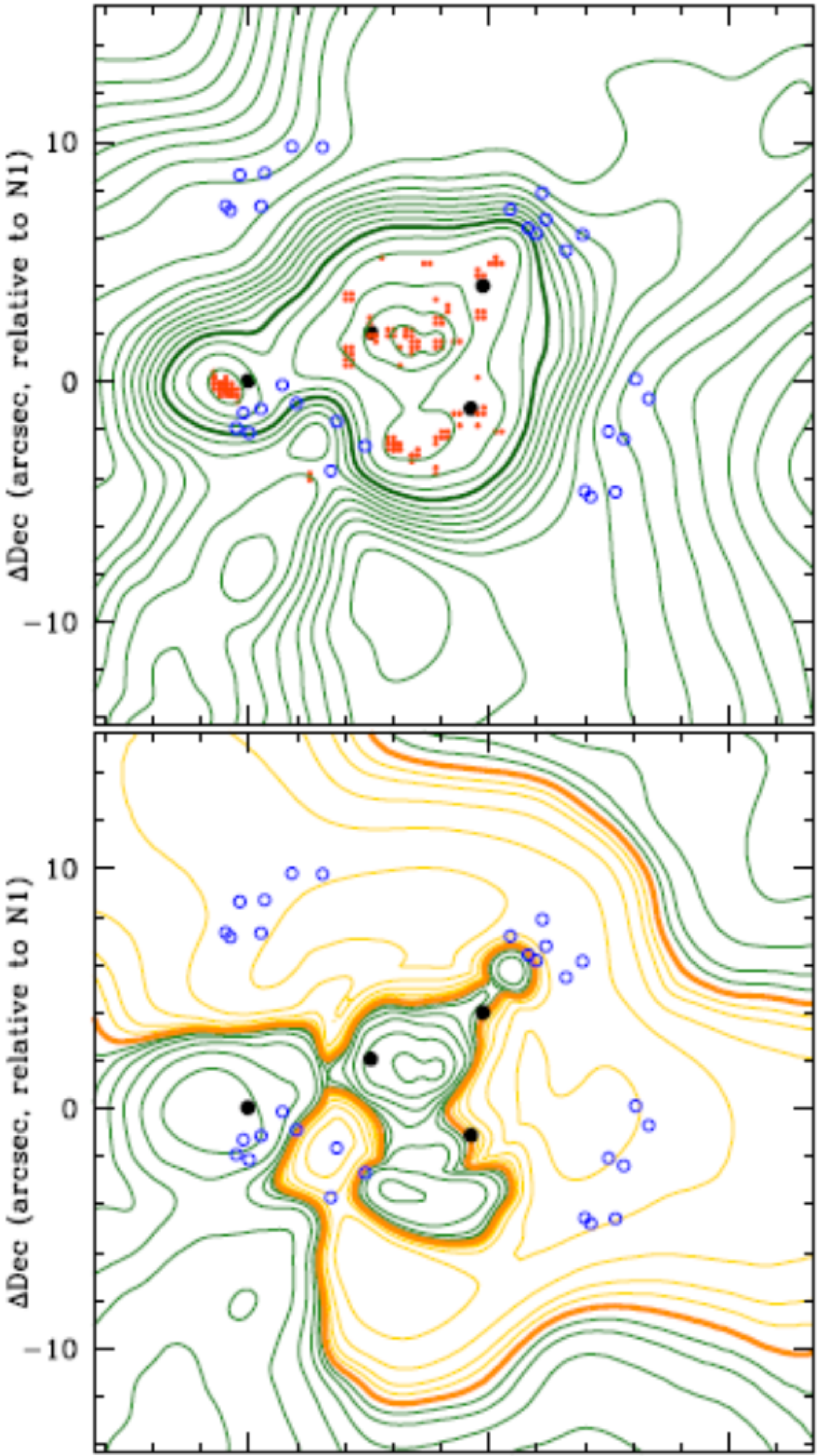
330.460
330.455
330.450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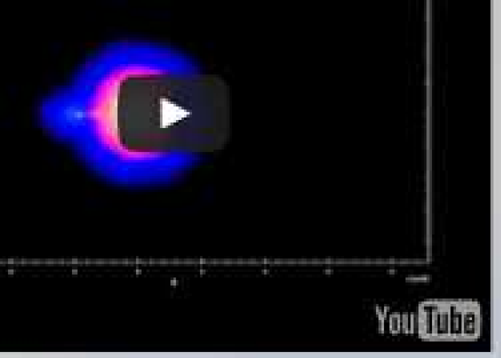
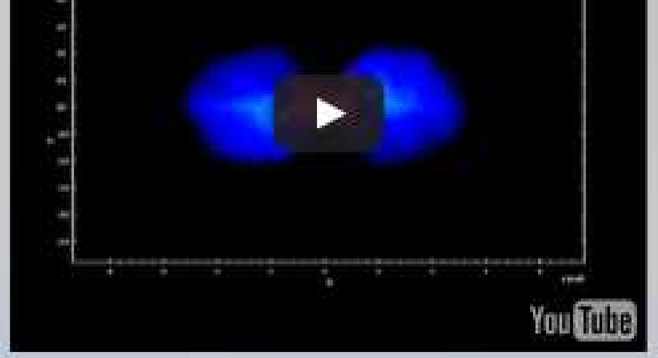
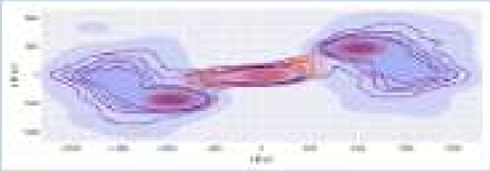
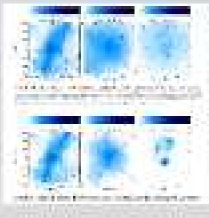
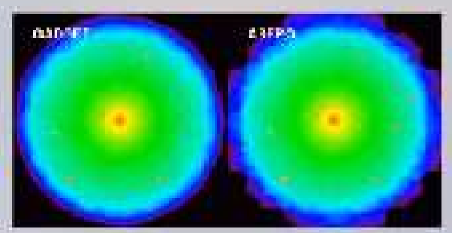
0
−10
ΔDec (arcsec, relative to N1)
10
0
−10

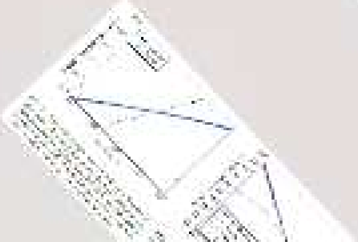




"All the light we cannot see"

A. Doerr

- GADGET-2 (Springel, 2005) simulations
  - Pure Dark matter, dark plasma simulations
- Set up:
  - As simple as possible
  - Both 2 halo mergers
  - Halos simple NFW
- Testing parameter variations



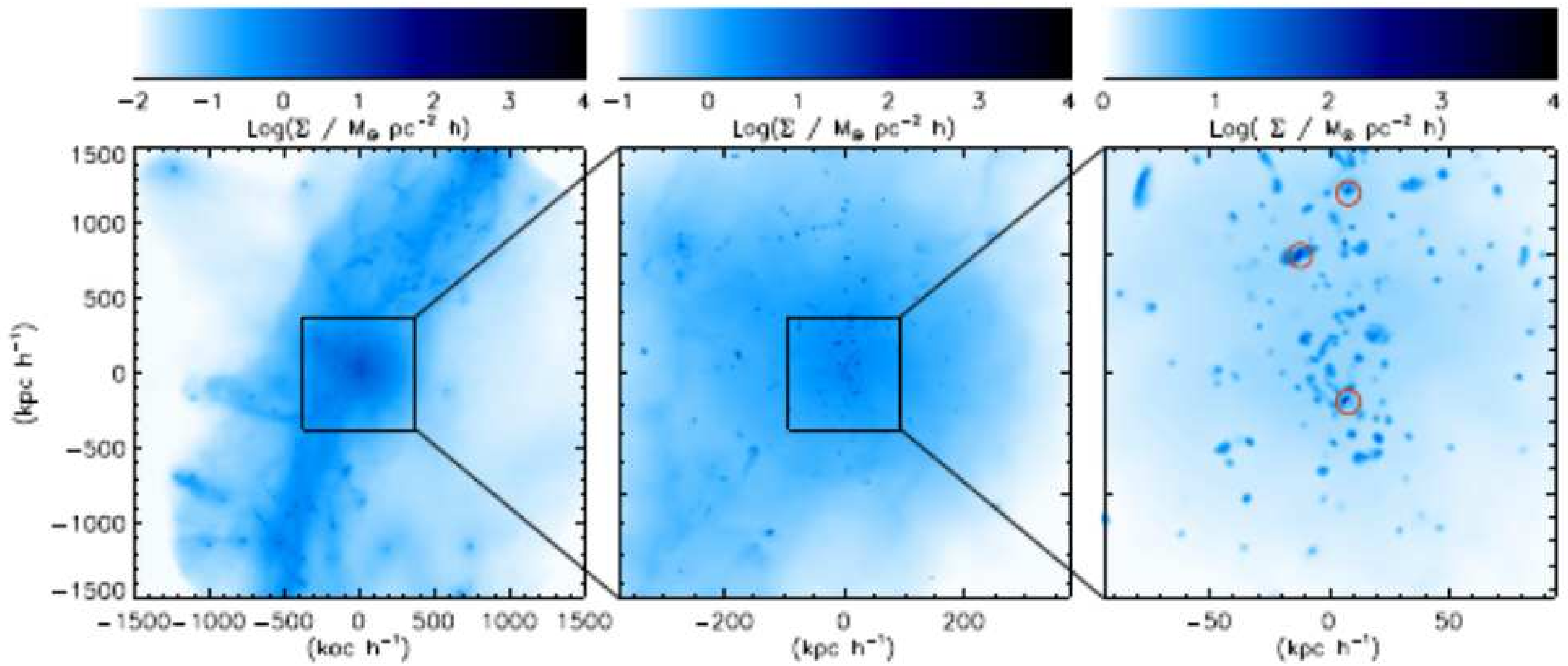



Figure 1. Maps of the projected gas surface density for one object in the GADGET simulation at redshift $z = 1$. The central object has a halo mass of $M = 2 \times 10^{12} h^{-1} M_{\odot}$. Three nested views are shown to give a clear picture of the gas distribution over a large range of spatial scales. In the rightmost panel, the gas distribution around the central galaxy can be seen to be fairly clumpy and the galaxies themselves appear fairly compact. In this image, three galaxies are in the process of merging, which we have identified with red circles. It is helpful to directly compare this plot to Figure 2 which shows the same maps for the AREPO simulation.

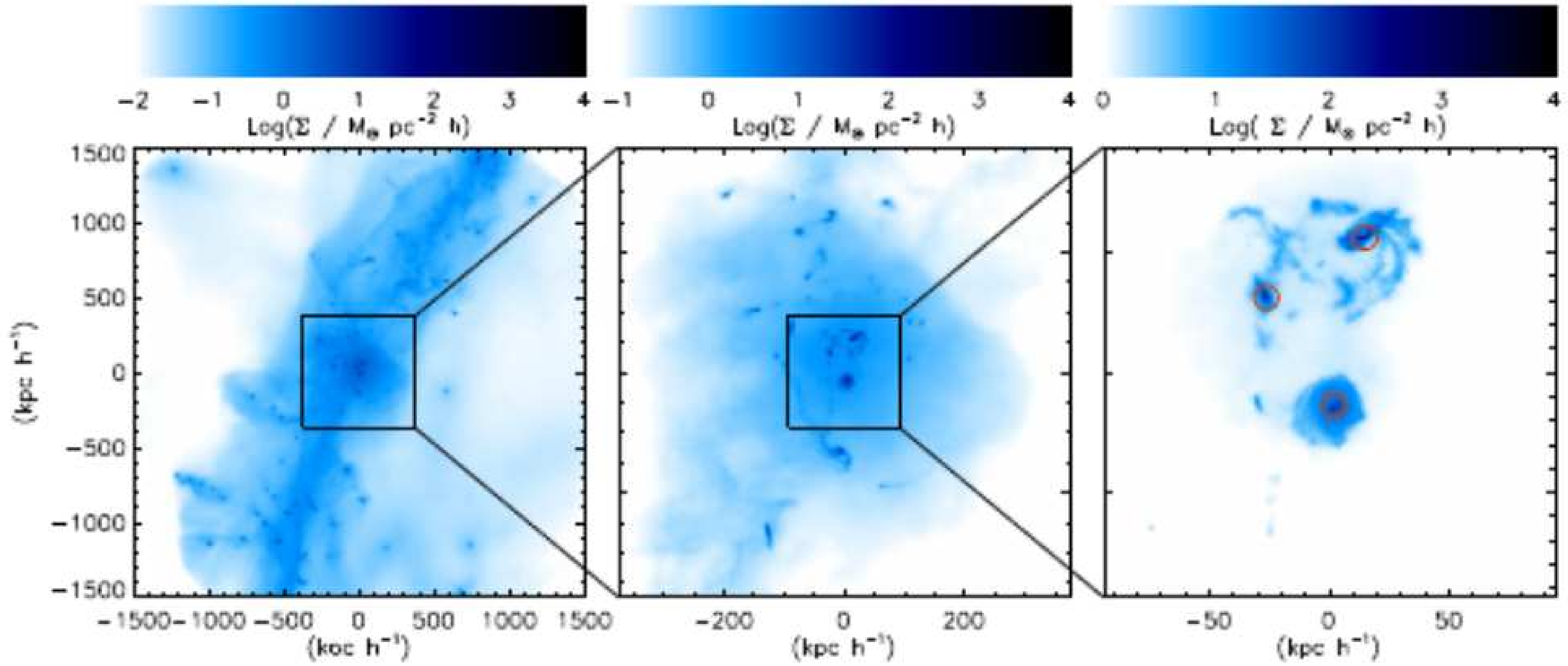
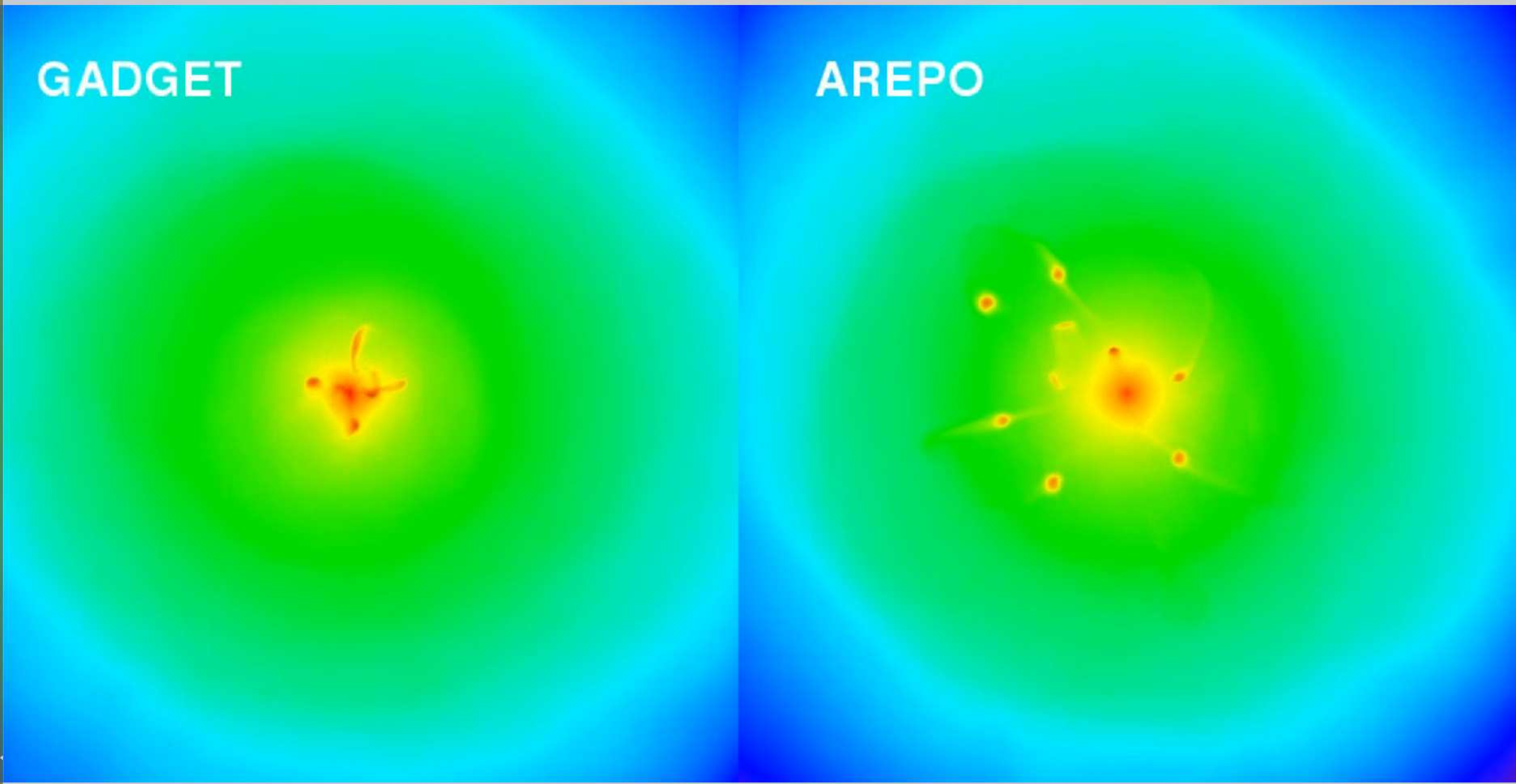


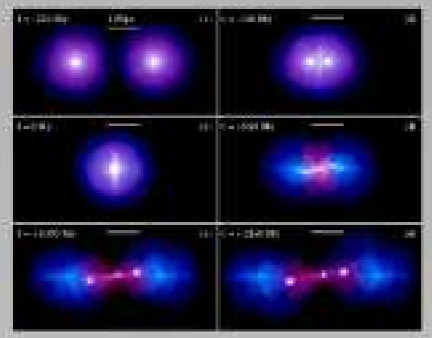
Figure 2. Same as Figure 1, but for the AREPO simulation. In contrast to Figure 1, the gas distribution around the central galaxy in the rightmost panel has much fewer gas clumps. The three galaxies that are in the process of merging are highlighted with red circles.

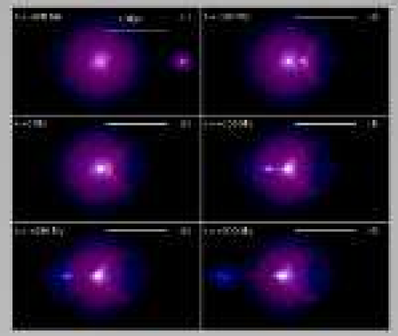

Wine Windows Program Loader
20:49
GADGET
AREPO


GADGET
AREPO

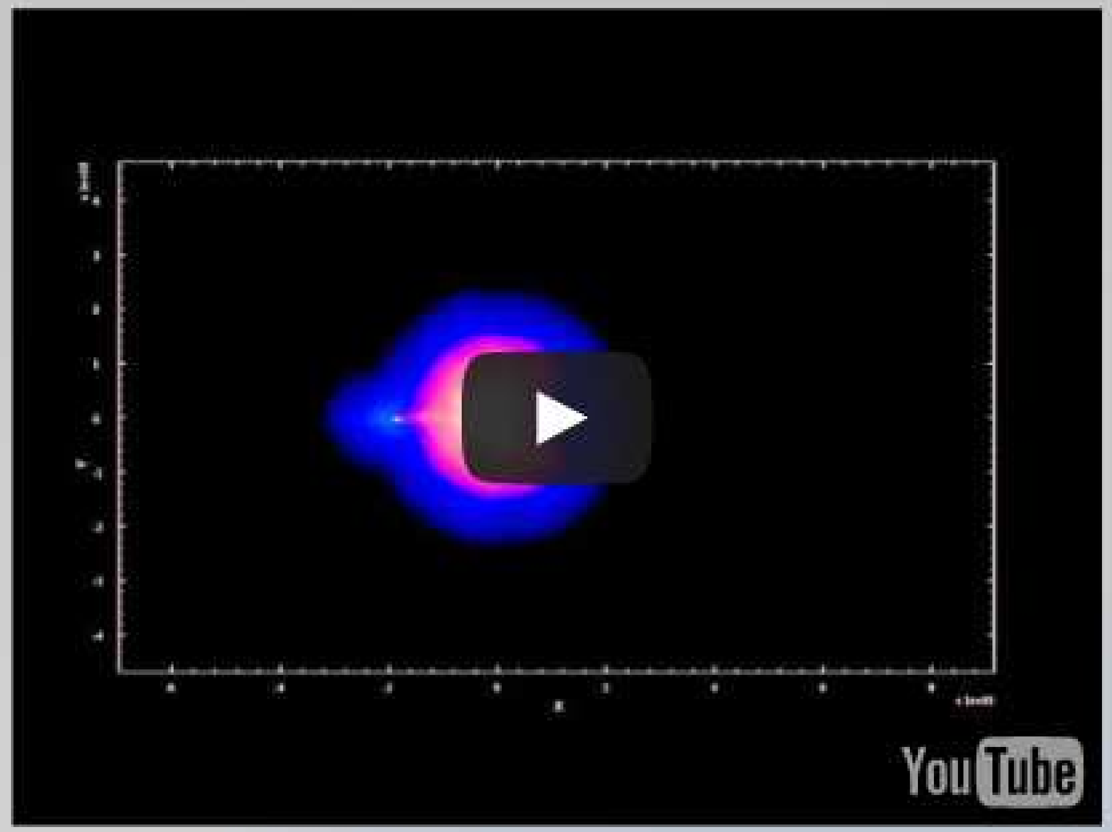

Wine Windows Program Loader
20:50
GADGET
AREPO

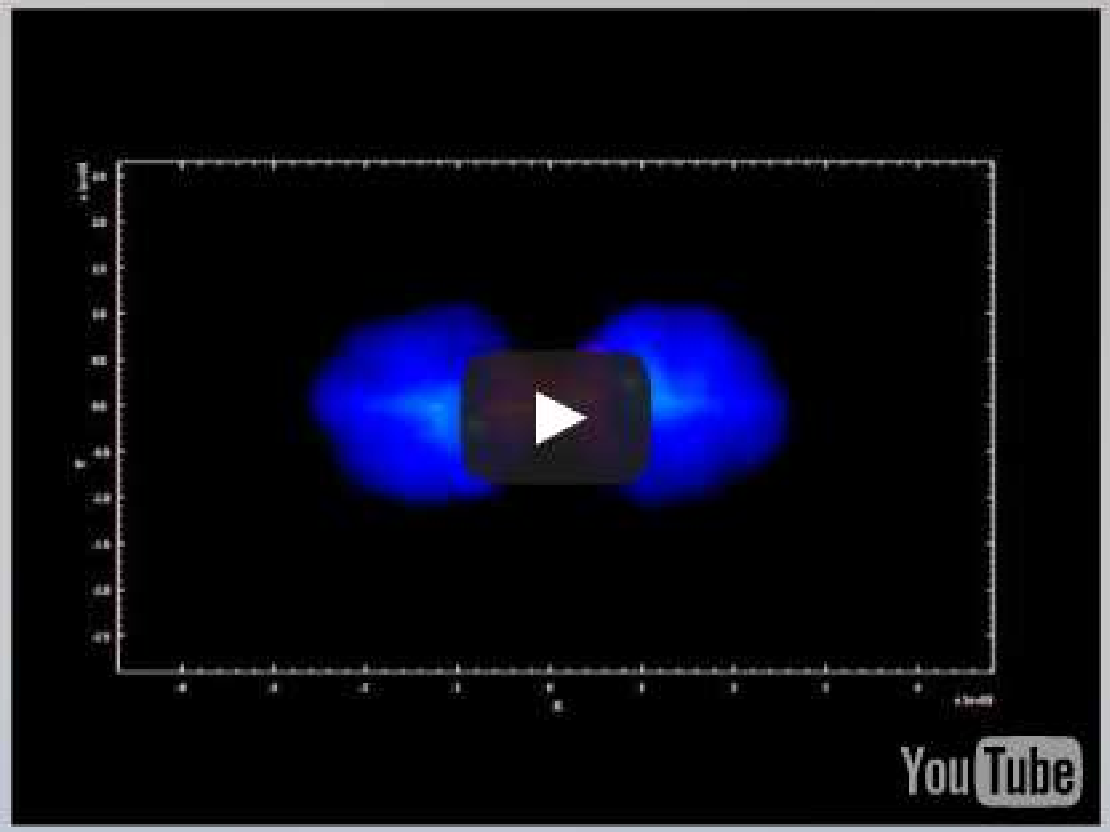

Wine Windows Program Loader
20:51
GADGET
AREPO

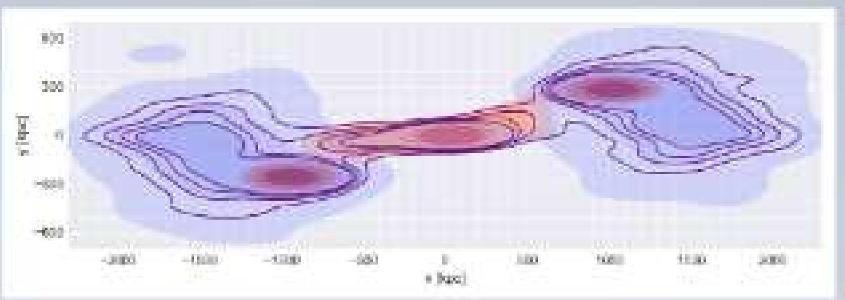




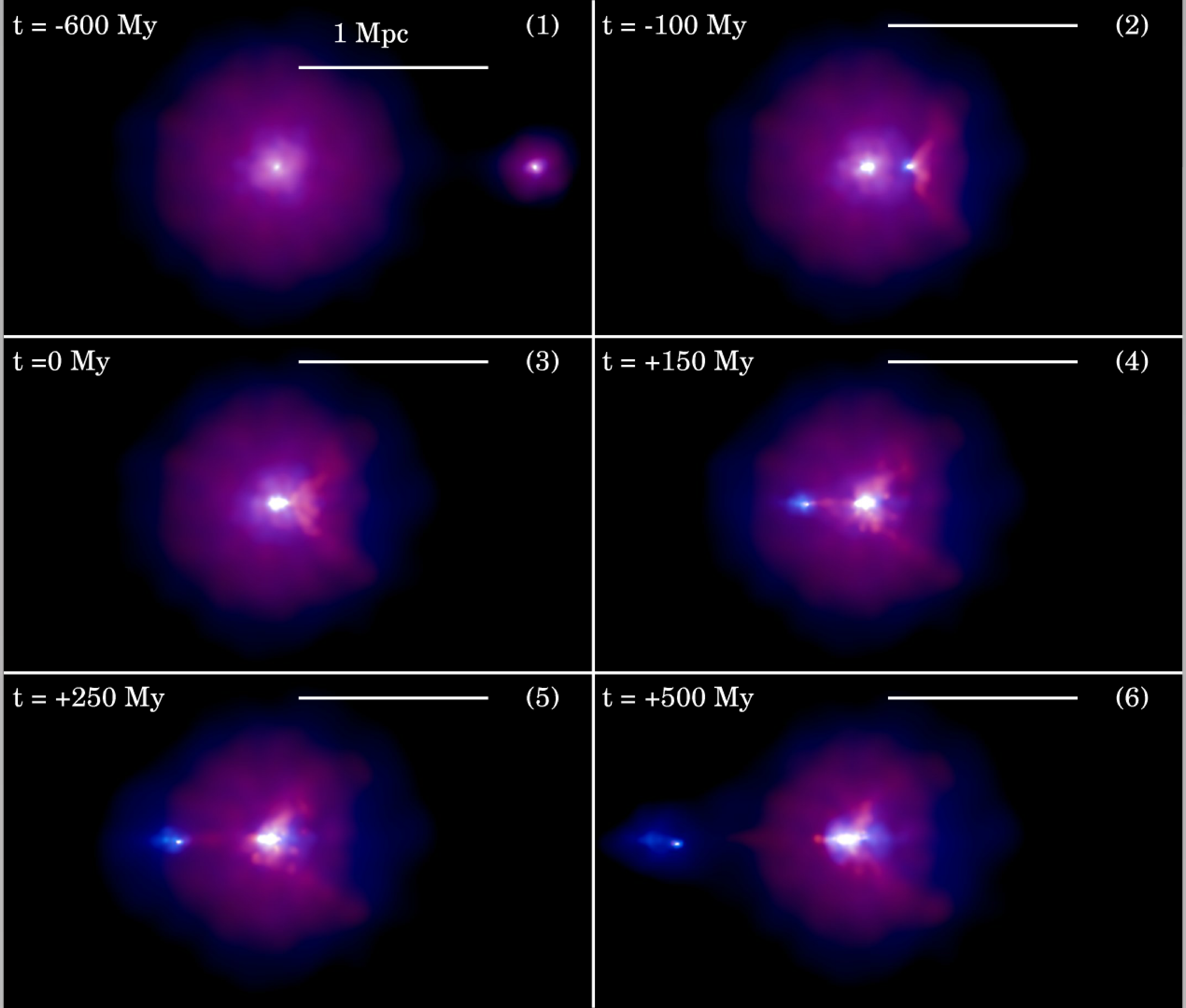
From Bullet to A520







"All the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t = -100 My
(2)
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(3)
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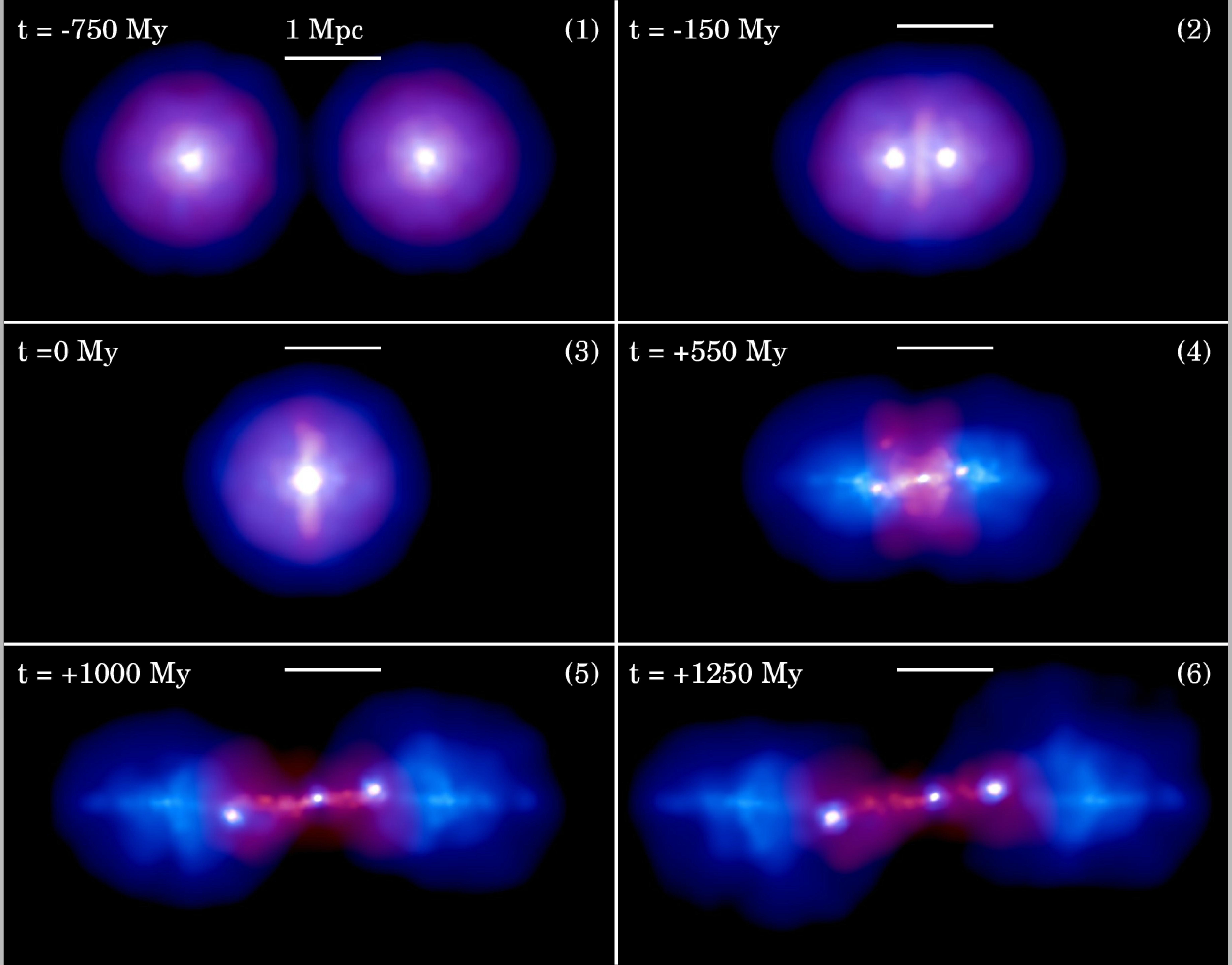
(4)
t = +250 My
(5)
t = +500 My
(6)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(1)
t = -150 My
(2)
t =0 My
(3)
t = +550 My
(4)
t = +1000 My
(5)
t = +1250 My
(6)

600
300
0
−300
−600
y [kpc]
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2000
x [kpc]