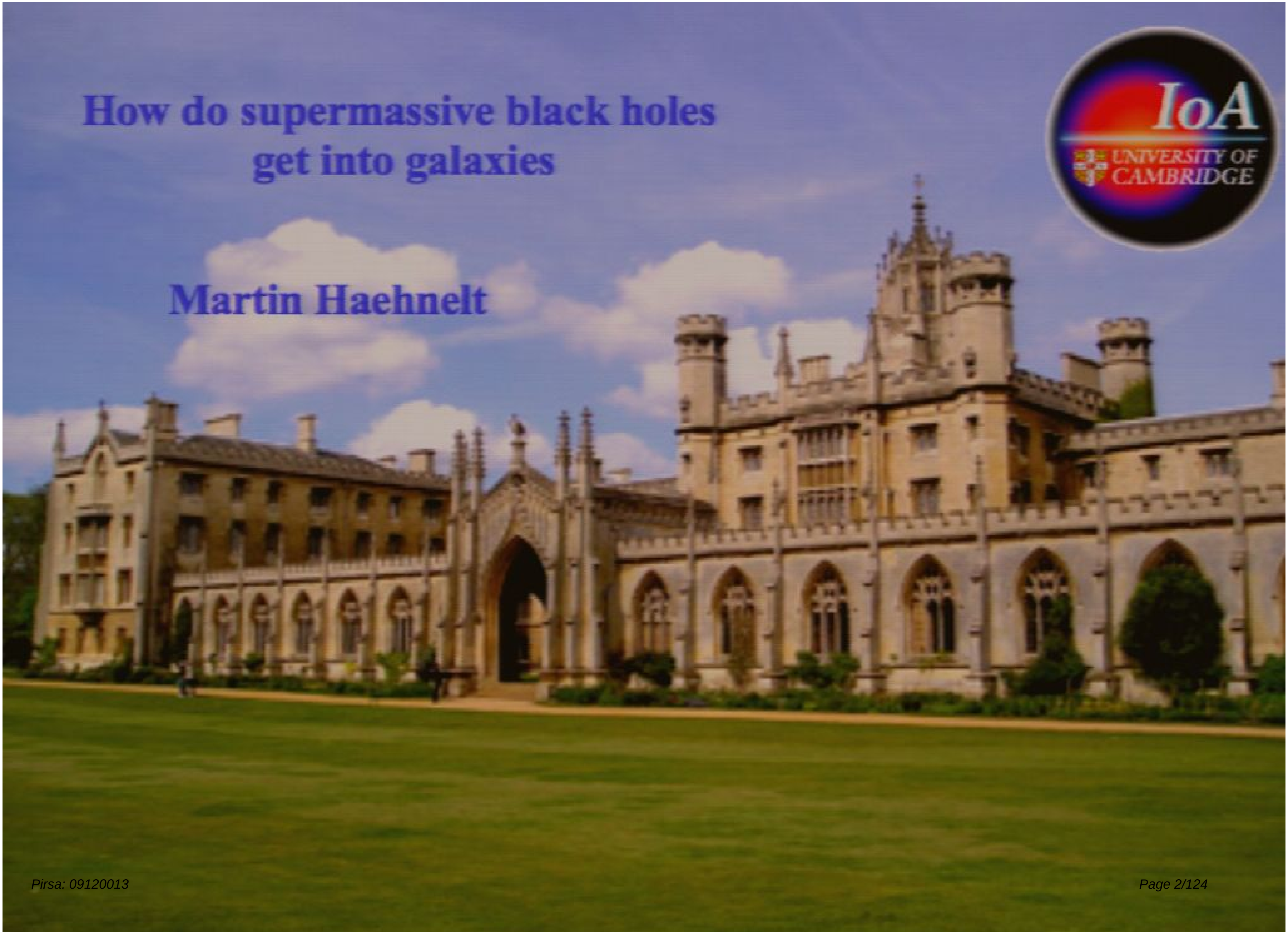
Title: How do supermassive black holes get into galaxies?

Date: Dec 09, 2009 02:00 PM

URL: http://pirsa.org/09120013

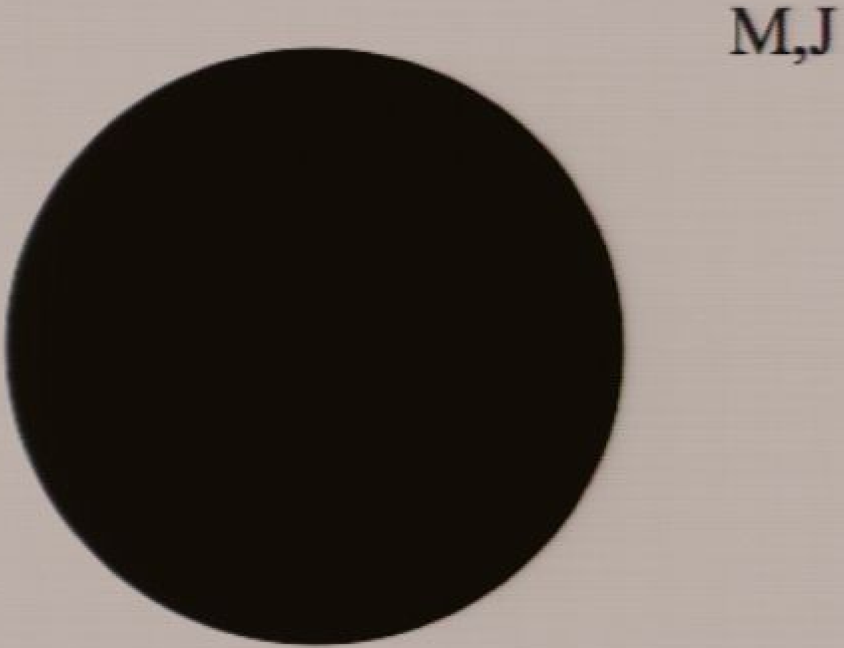
Abstract: I will give an account of our current understanding of the formation and growth of the central supermassive black holes in galaxies from an astrophysical perspective.



How do supermassive black holes get into galaxies

Martin Haehnelt

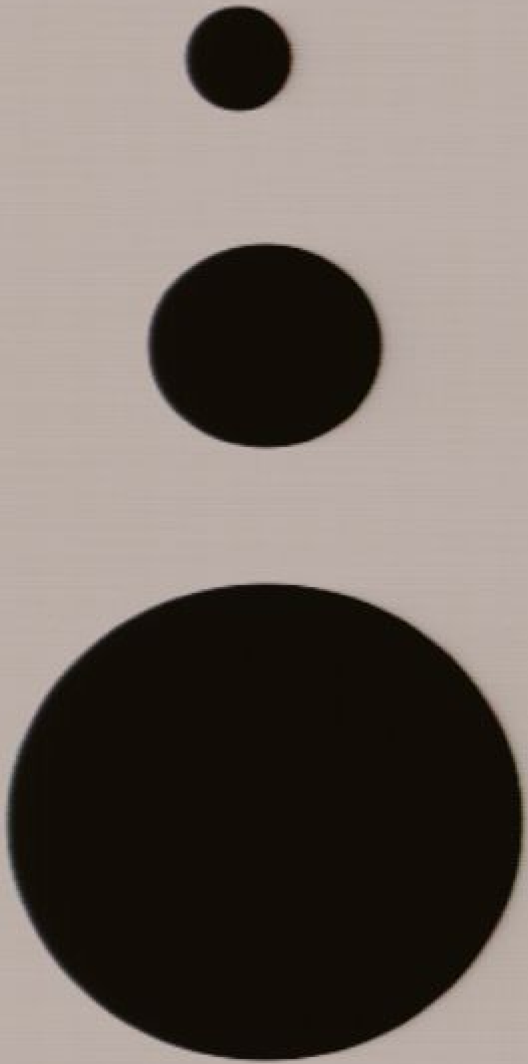
IoA
UNIVERSITY OF CAMBRIDGE



$$ds^2 = \frac{\Delta}{\rho^2}\left(cdt - a\sin^2\theta\, d\phi\right)^2 - \frac{\sin^2\theta}{\rho^2}\left[\left(r^2+a^2\right)d\phi - acdt\right]^2 - \frac{\rho^2}{\Delta}dr^2 - \rho^2 d\theta^2,$$

where Δ and ρ are

$$\left.\begin{array}{rcl}\Delta &=& r^2 - 2\mu r + a^2,\\ \rho^2 &=& r^2 + a^2\cos^2\theta.\end{array}\right\}$$



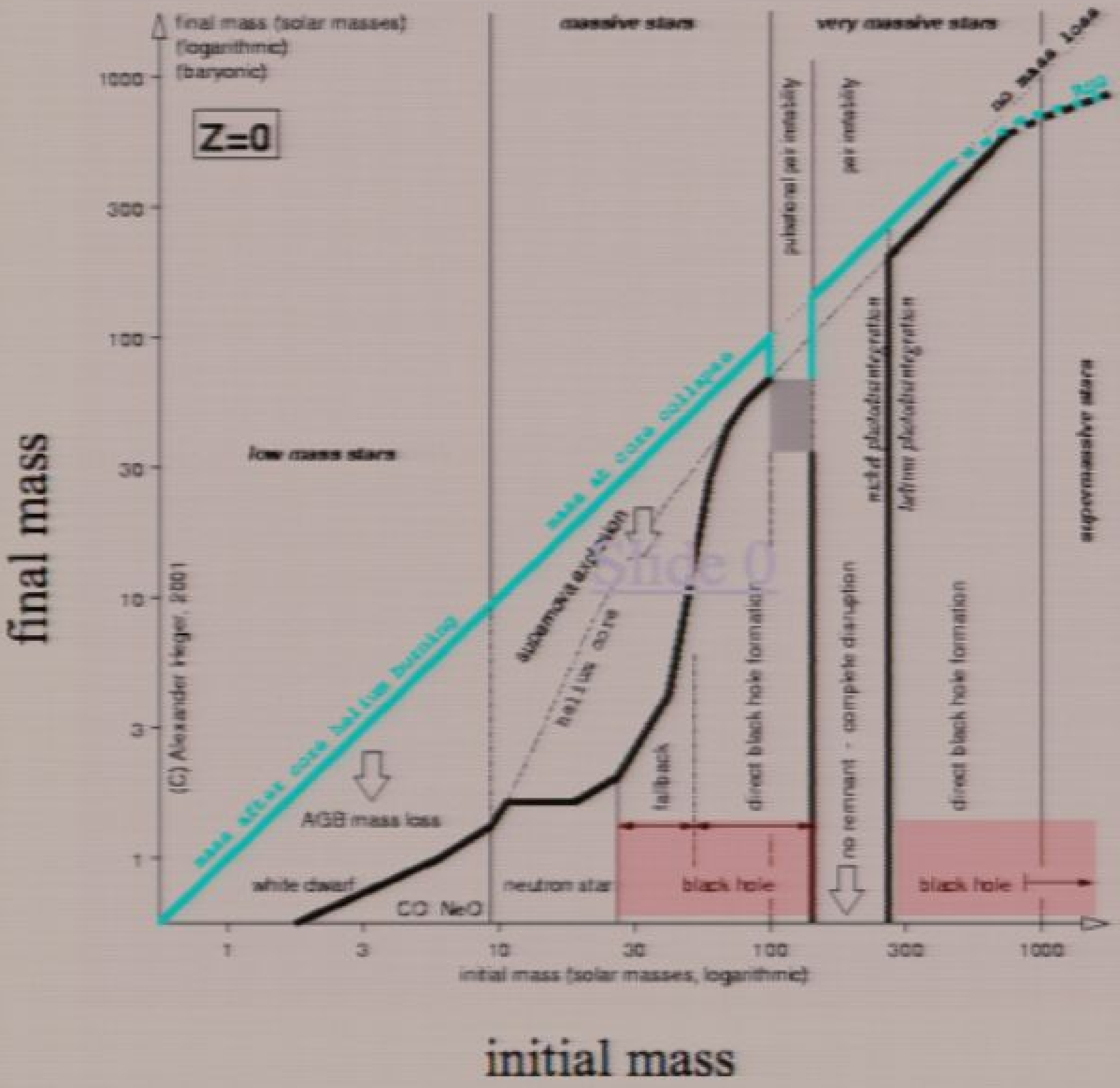
stellar mass black holes

$1\text{-}100\ M_\odot$

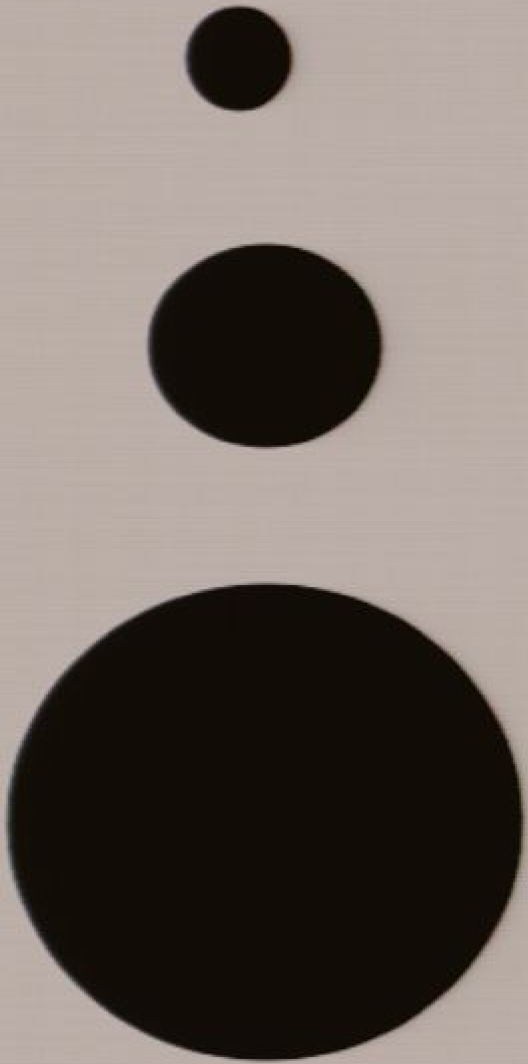
Do intermediate mass bh exist ?

supermassive black holes

$3\text{x}10^5\text{-}\ 3\text{x}10^{10}\ M_\odot$



The end-state of massive stars is a black hole.



stellar mass black holes

1-100 $M_\odot$

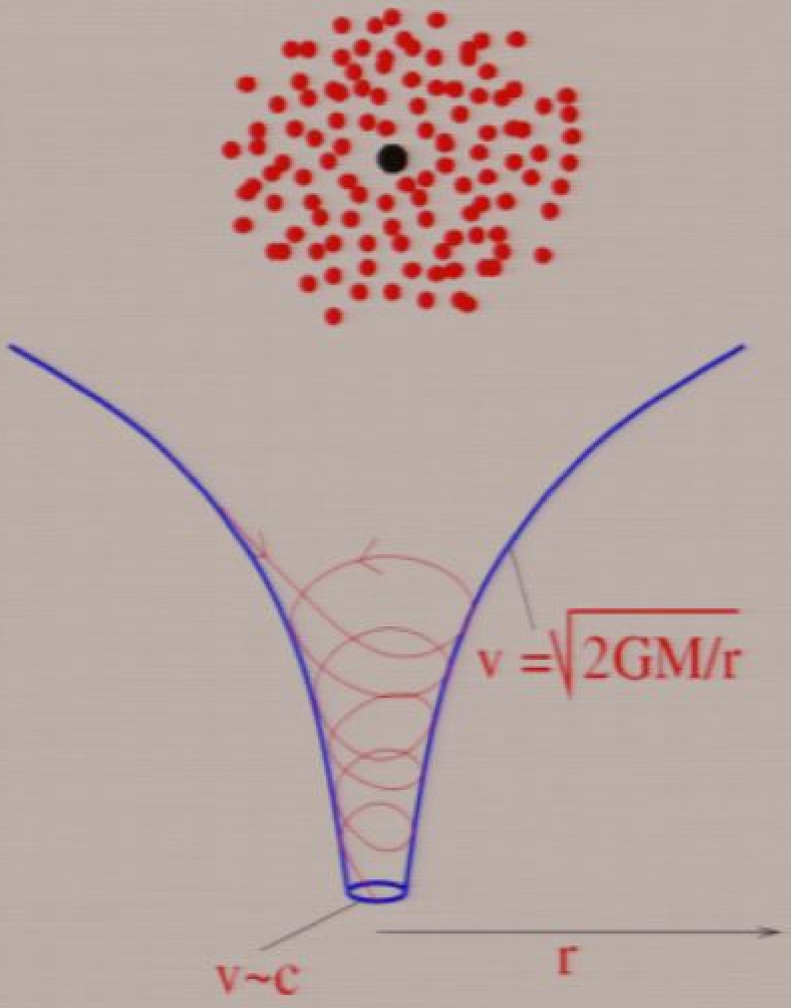
Do intermediate mass bh exist ?

supermassive black holes

$3x10^5$- $3x10^{10}$ $M_\odot$

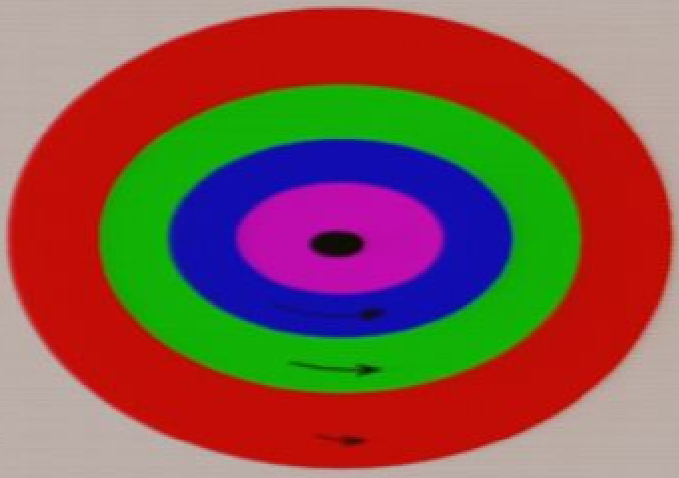
Perimeter, 9th December 2009

Nearby galaxies



QSOs

Accretion disc ↔ **Quasar**

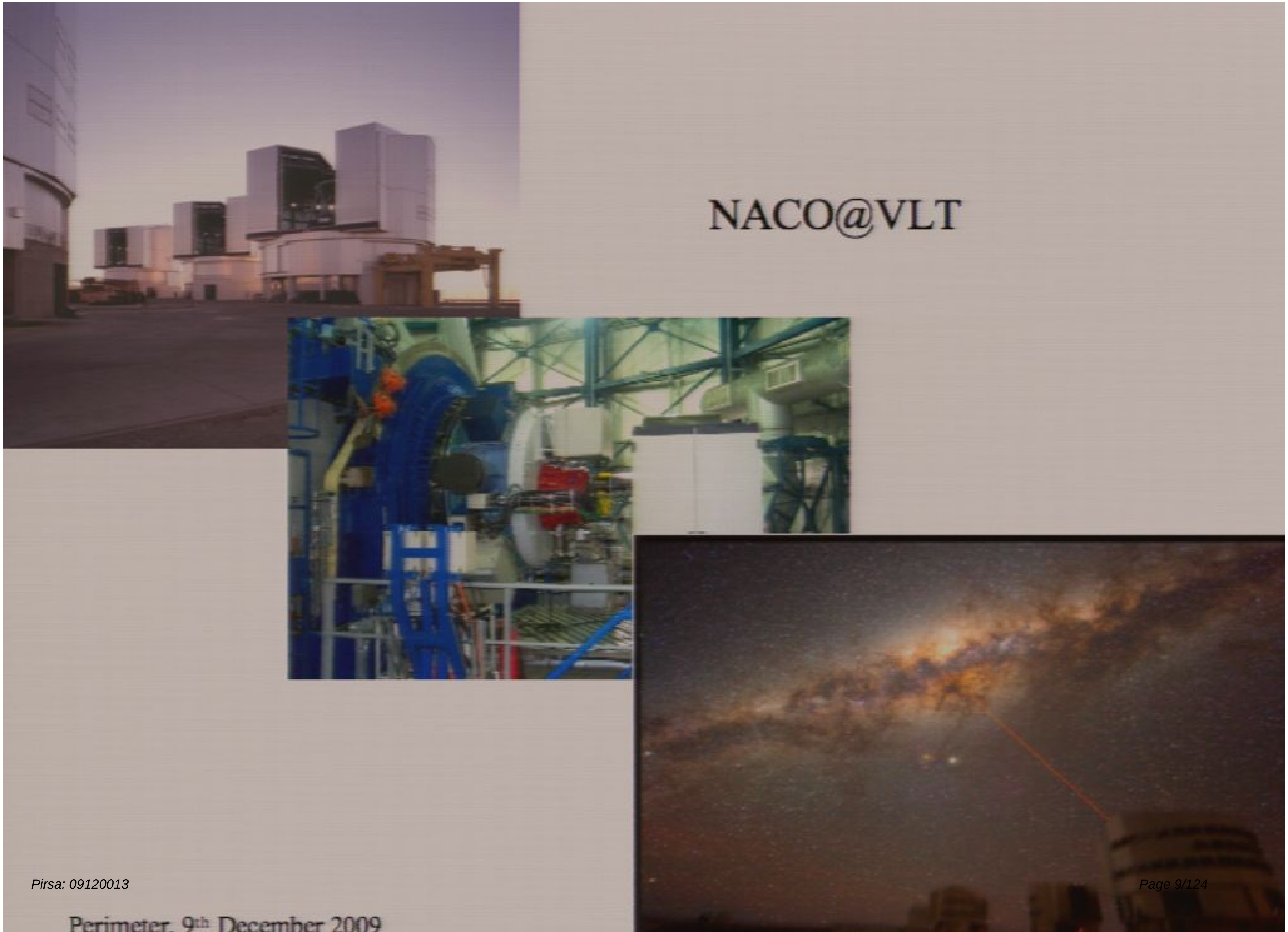


$T \sim 100\,000$ K

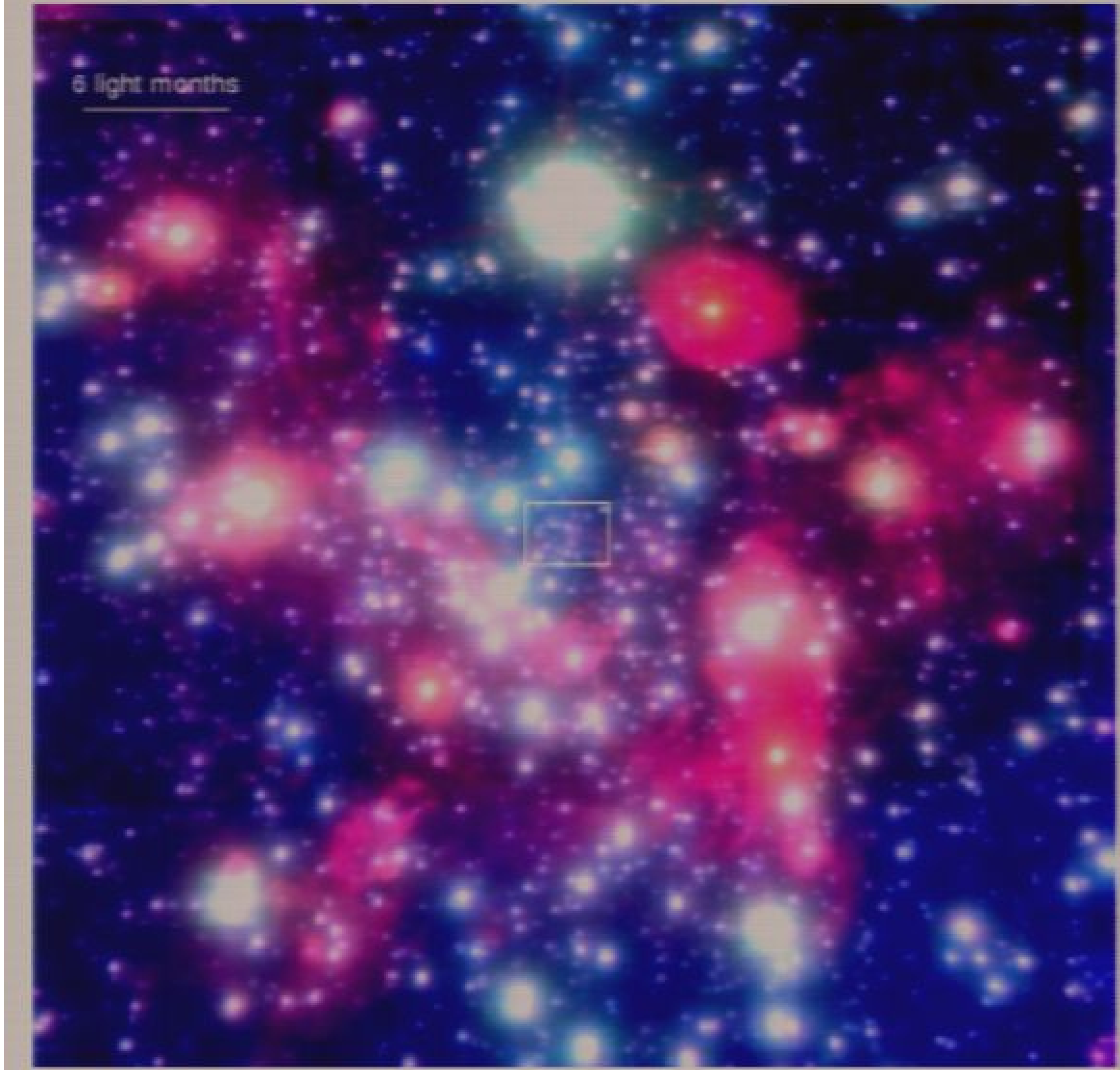
$L \sim 0.1\,\dot{M} c^2$

The supermassive black hole at the galactic centre

NACO@VLT



Perimeter, 9th December 2009



Piercing through the dust in the galactic centre at IR wavelengths.

Genzel et al.

Perimeter, 9th December 2009

The black hole at the centre of our galaxy

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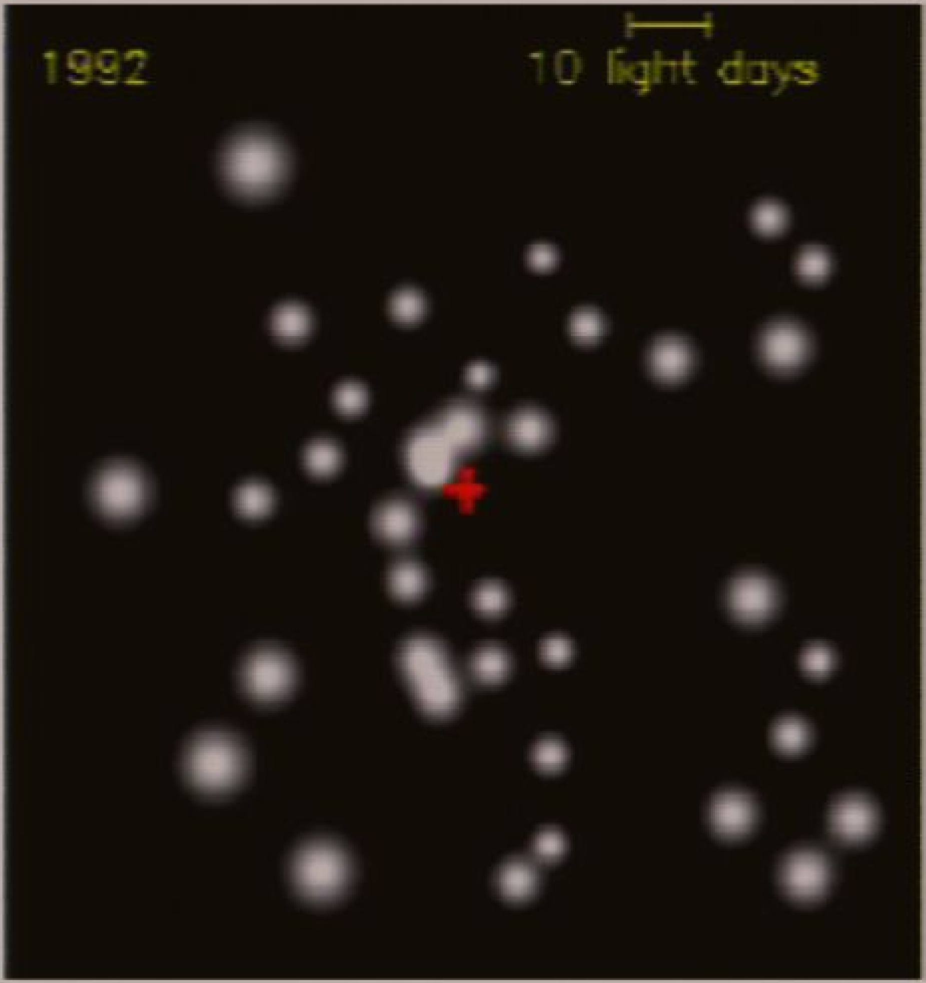
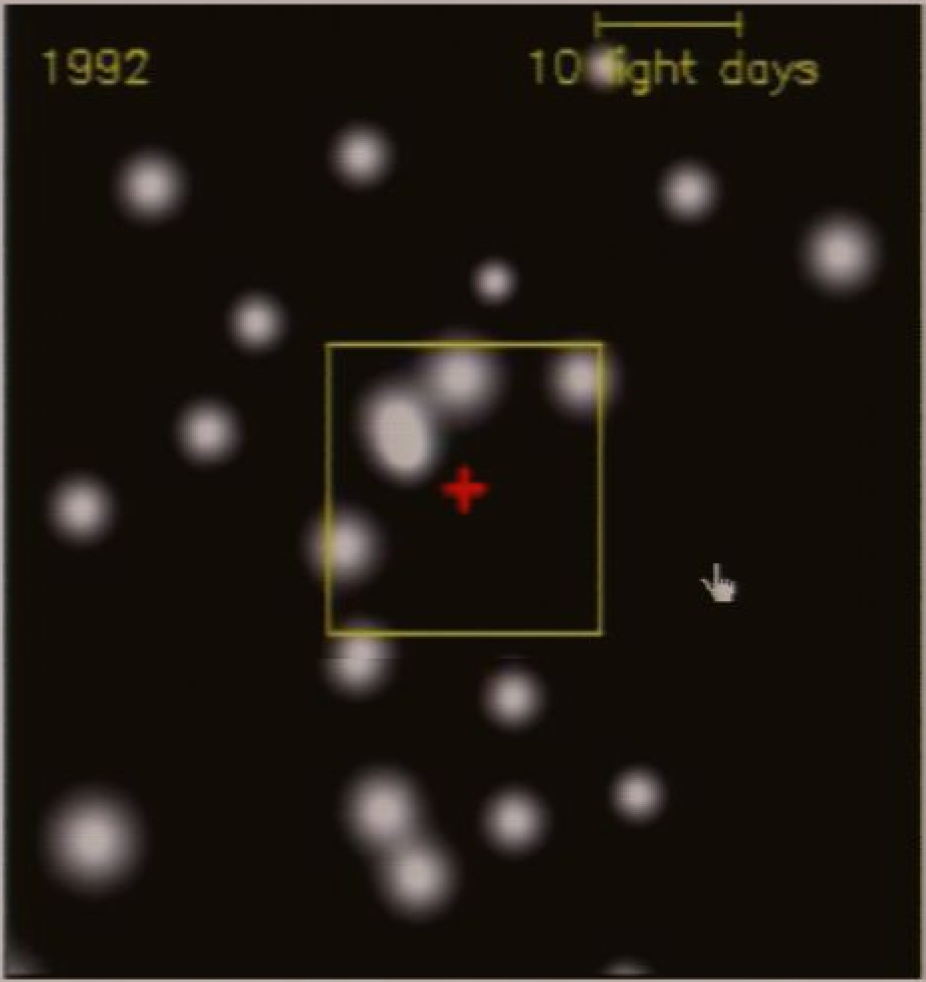
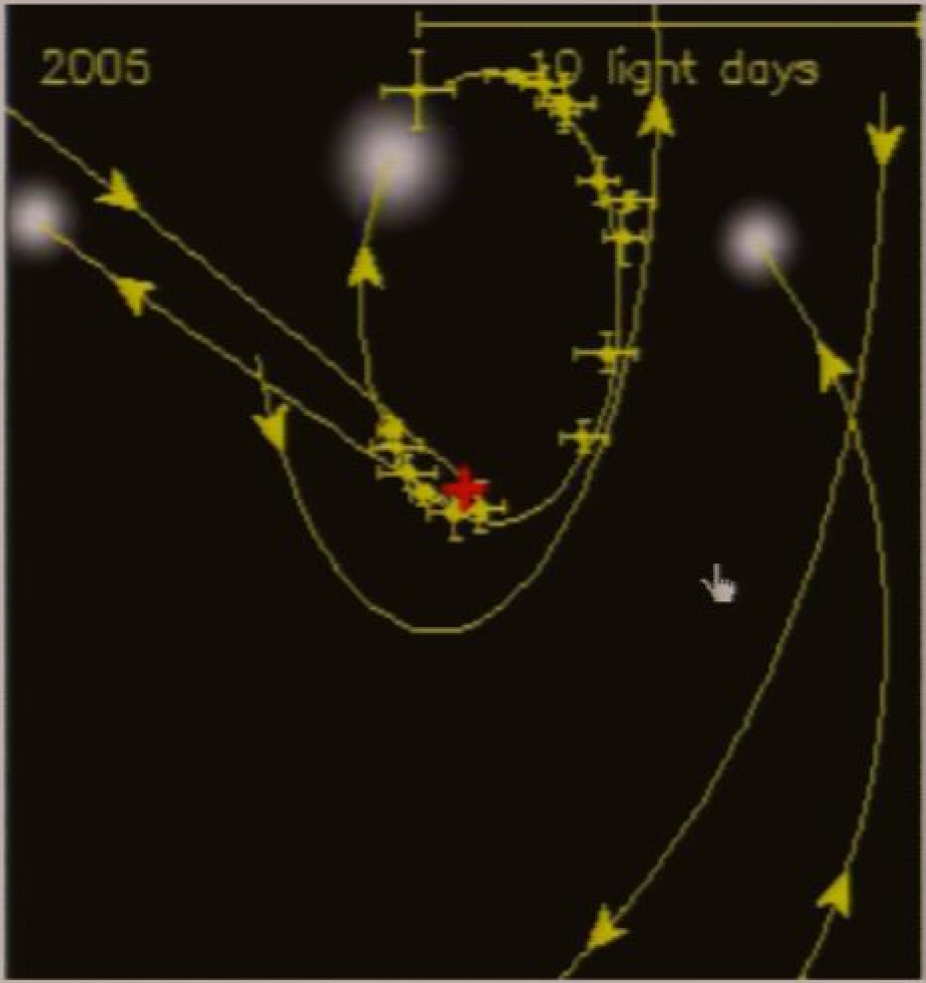


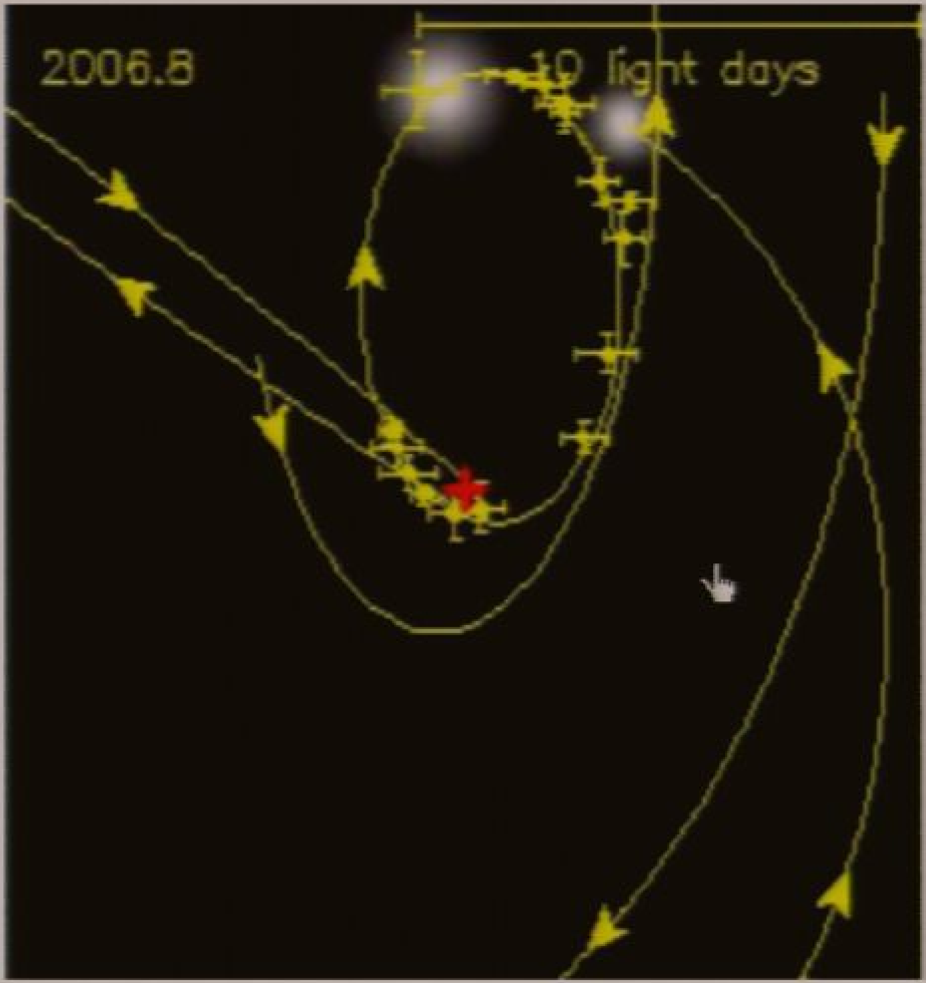
The black hole at the centre of our galaxy

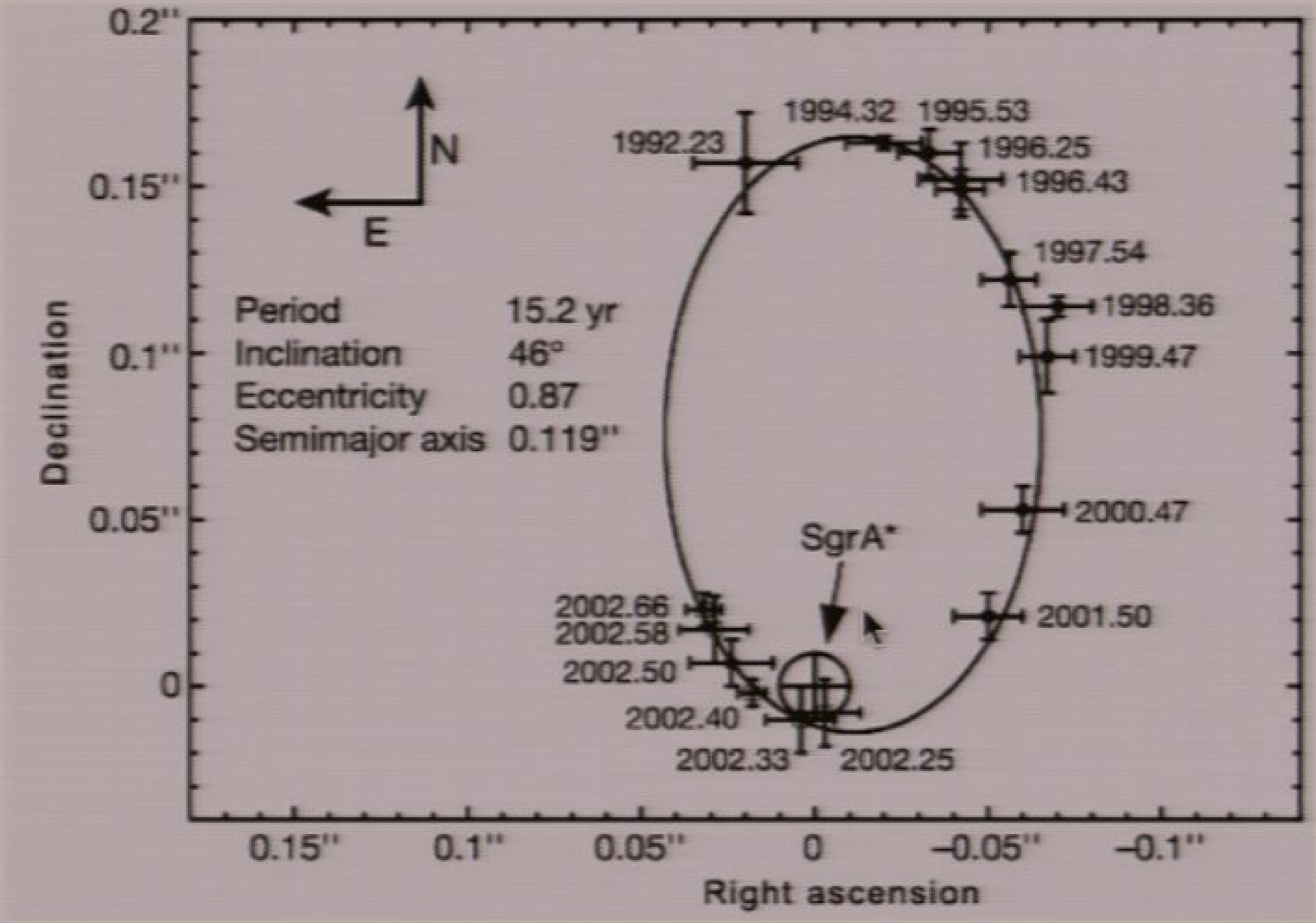


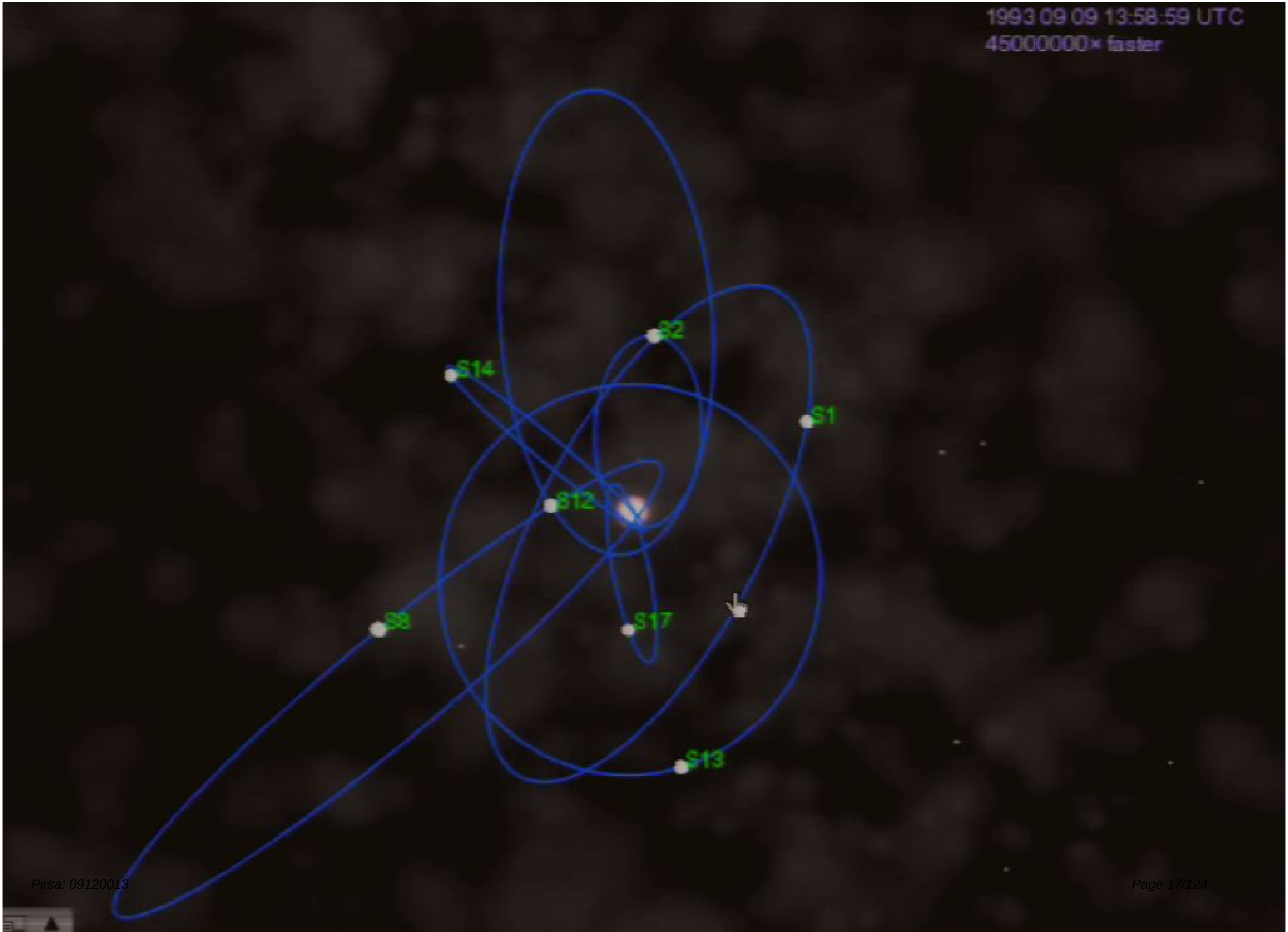
The black hole at the centre of our galaxy



The black hole at the centre of our galaxy




0.2''
0.15''
0.1''
0.05''
0
Declination
N
E
Period 15.2 yr
Inclination 46°
Eccentricity 0.87
Semimajor axis 0.119''
1992.23
1994.32
1995.53
1996.25
1996.43
1997.54
1998.36
1999.47
2000.47
2001.50
SgrA*
2002.66
2002.58
2002.50
2002.40
2002.33
2002.25
0.15''
0.1''
0.05''
0
–0.05''
–0.1''
Right ascension


1993 09 09 13:58:59 UTC
45000000× faster
S2
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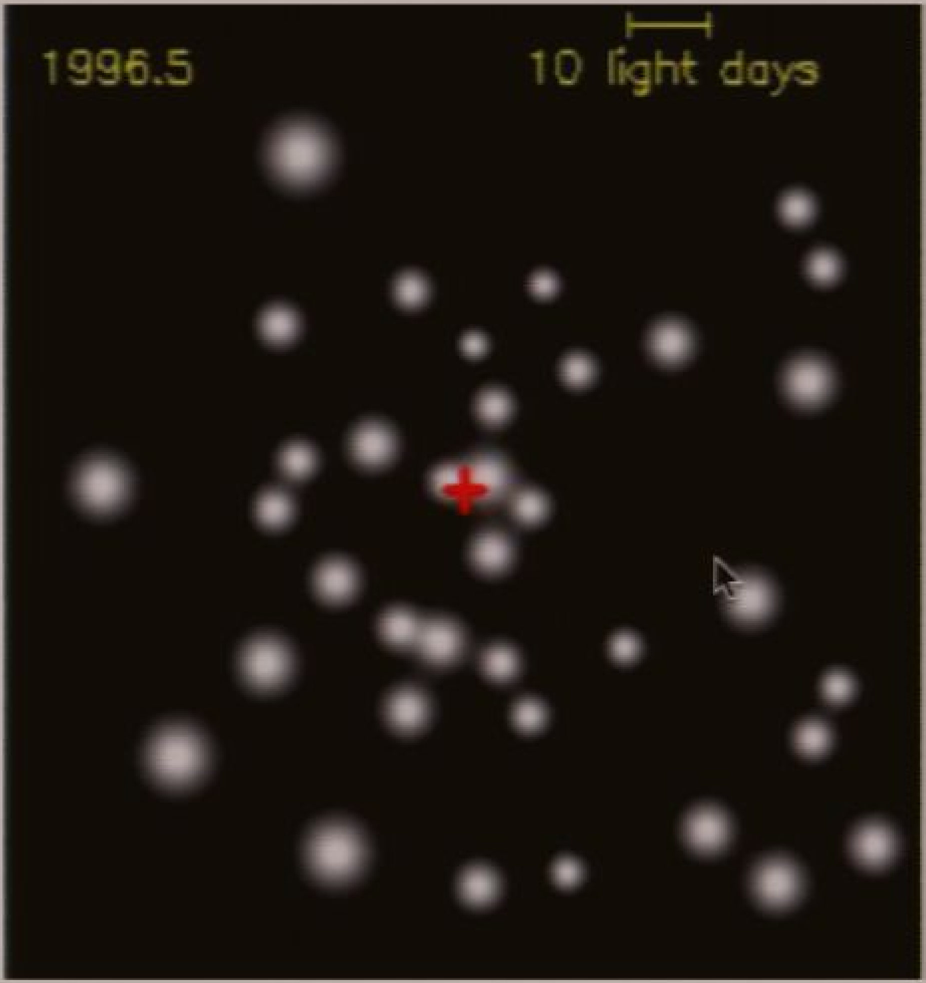
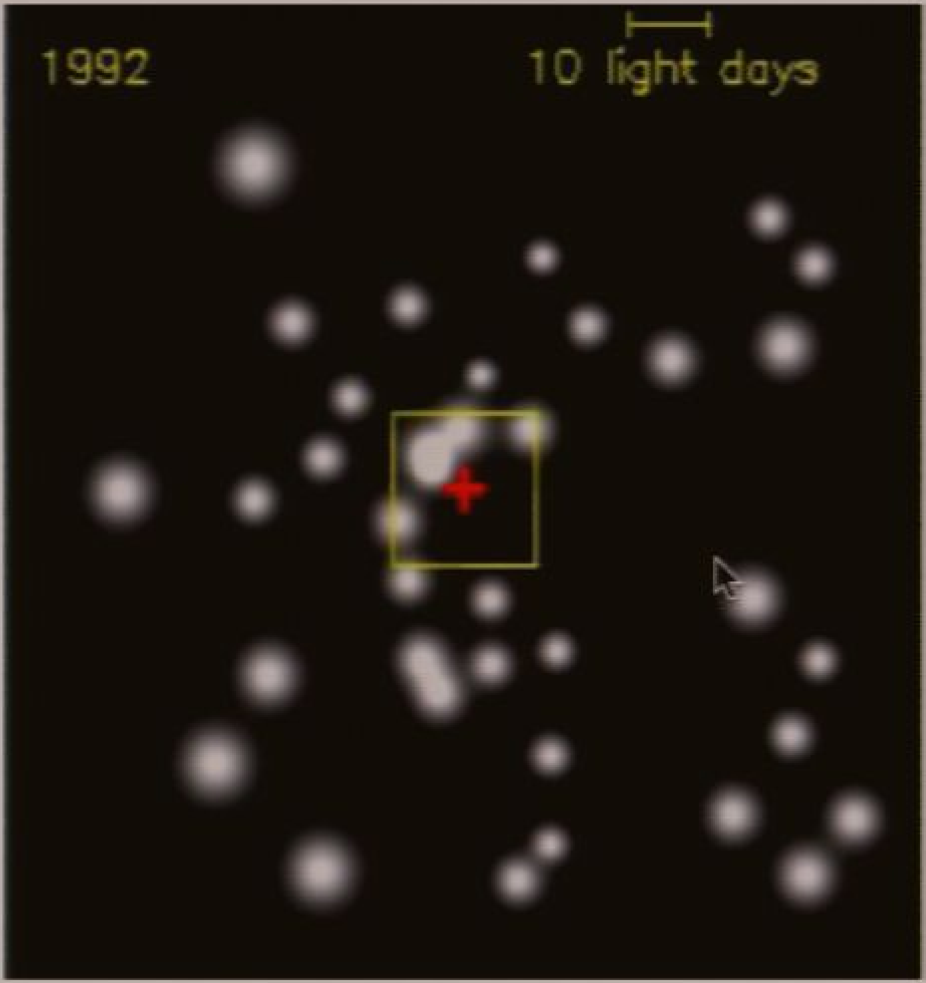
S17
S13

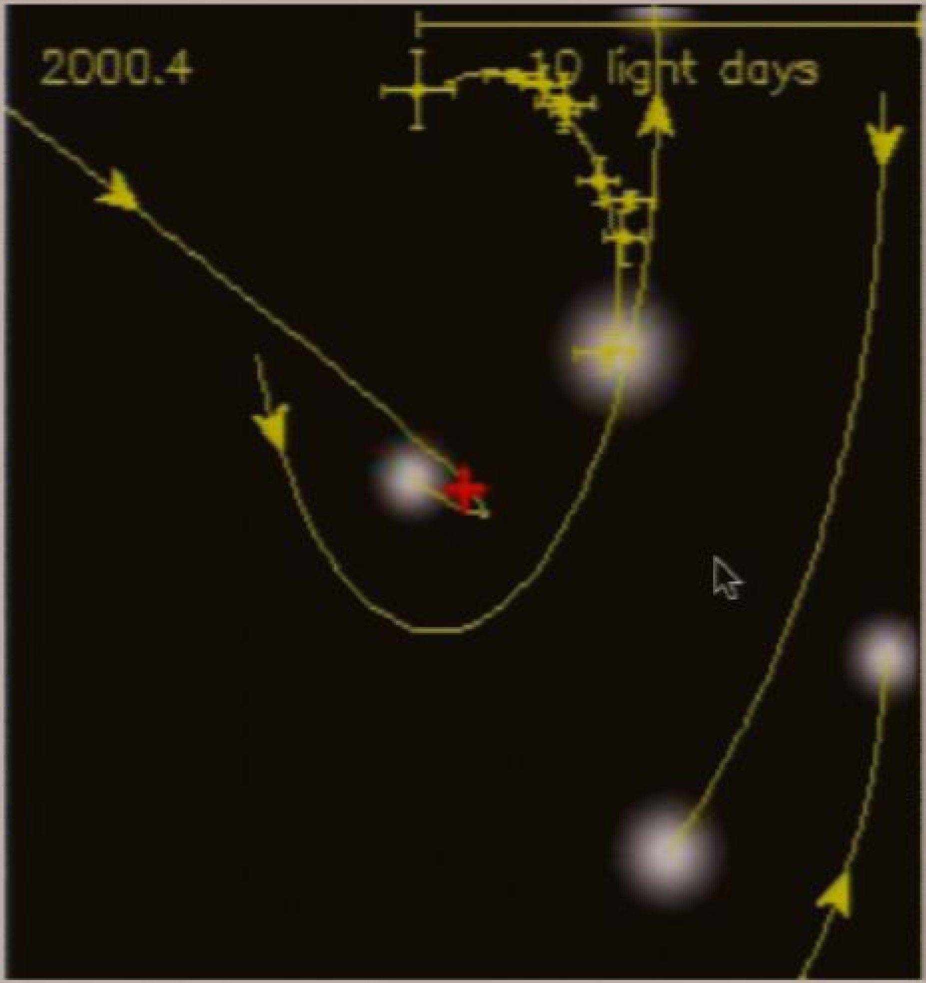
The black hole at the centre of our galaxy

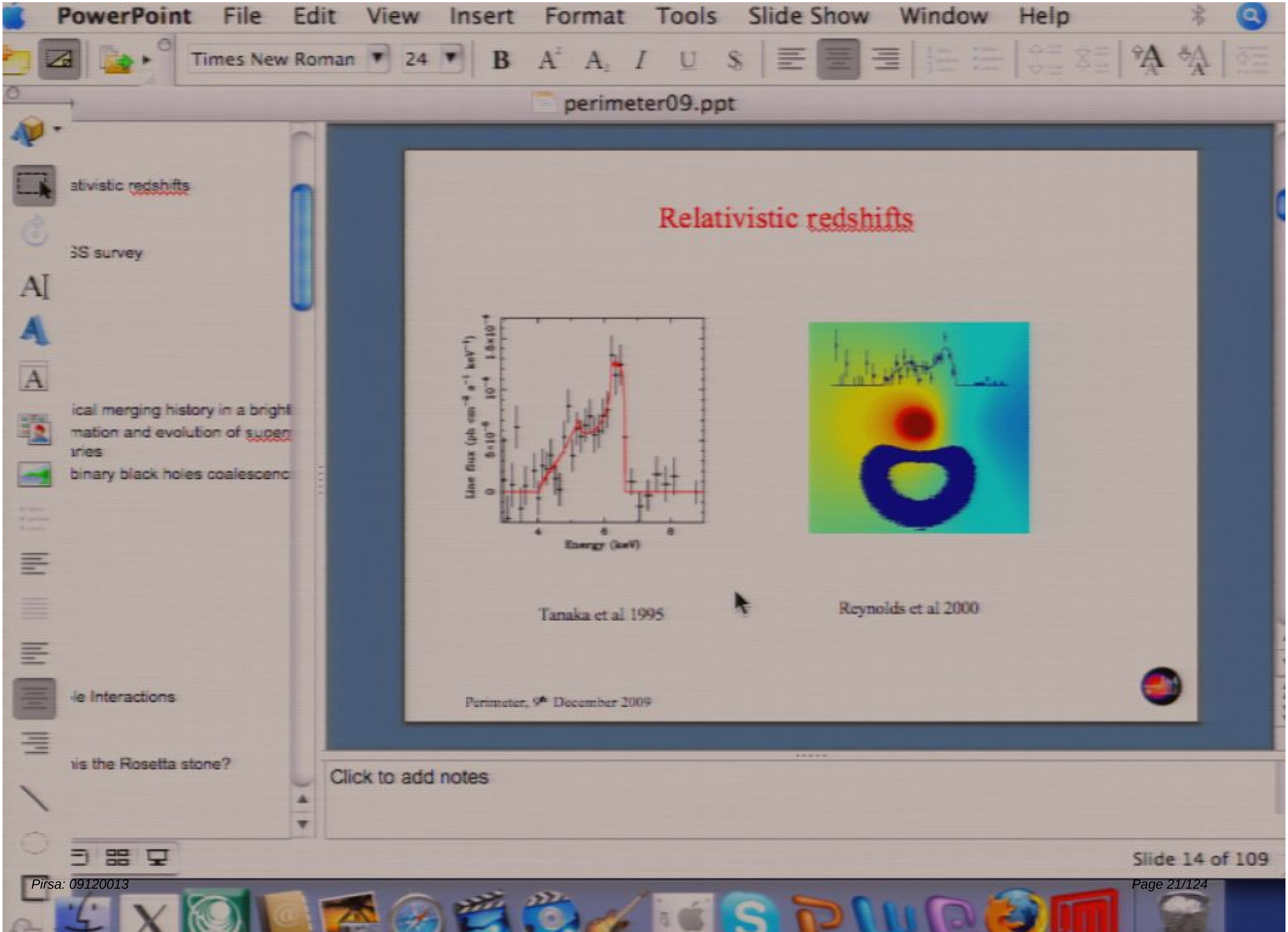


The black hole at the centre of our galaxy



The black hole at the centre of our galaxy





ativistic redshifts

3S survey

ical merging history in a bright
mation and evolution of super
ries
binary black holes coalescenc

le Interactions

is the Rosetta stone?

Relativistic redshifts

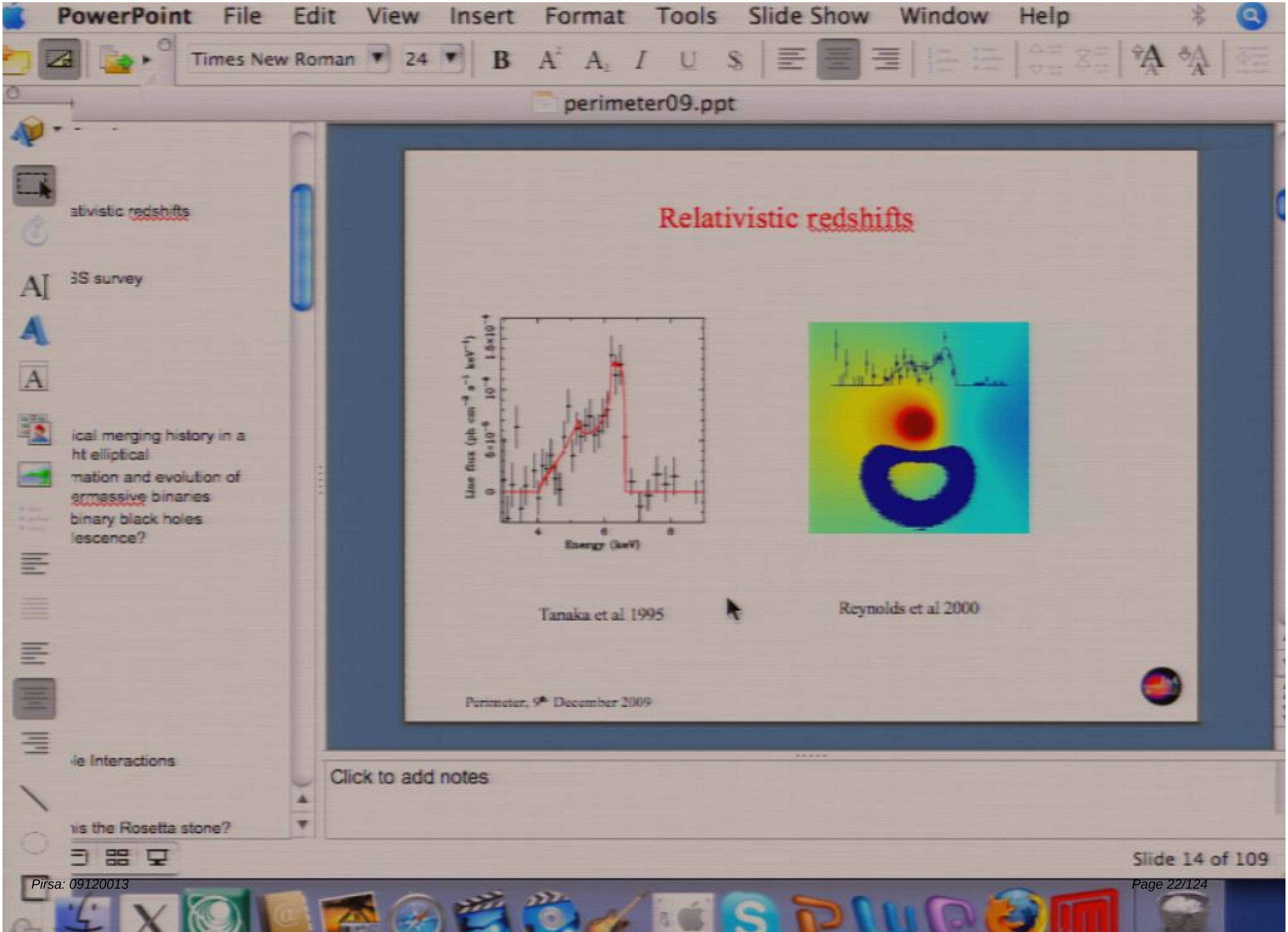
Tanaka et al 1995

Reynolds et al 2000

Perimeter, 9th December 2009

Click to add notes

Slide 14 of 109



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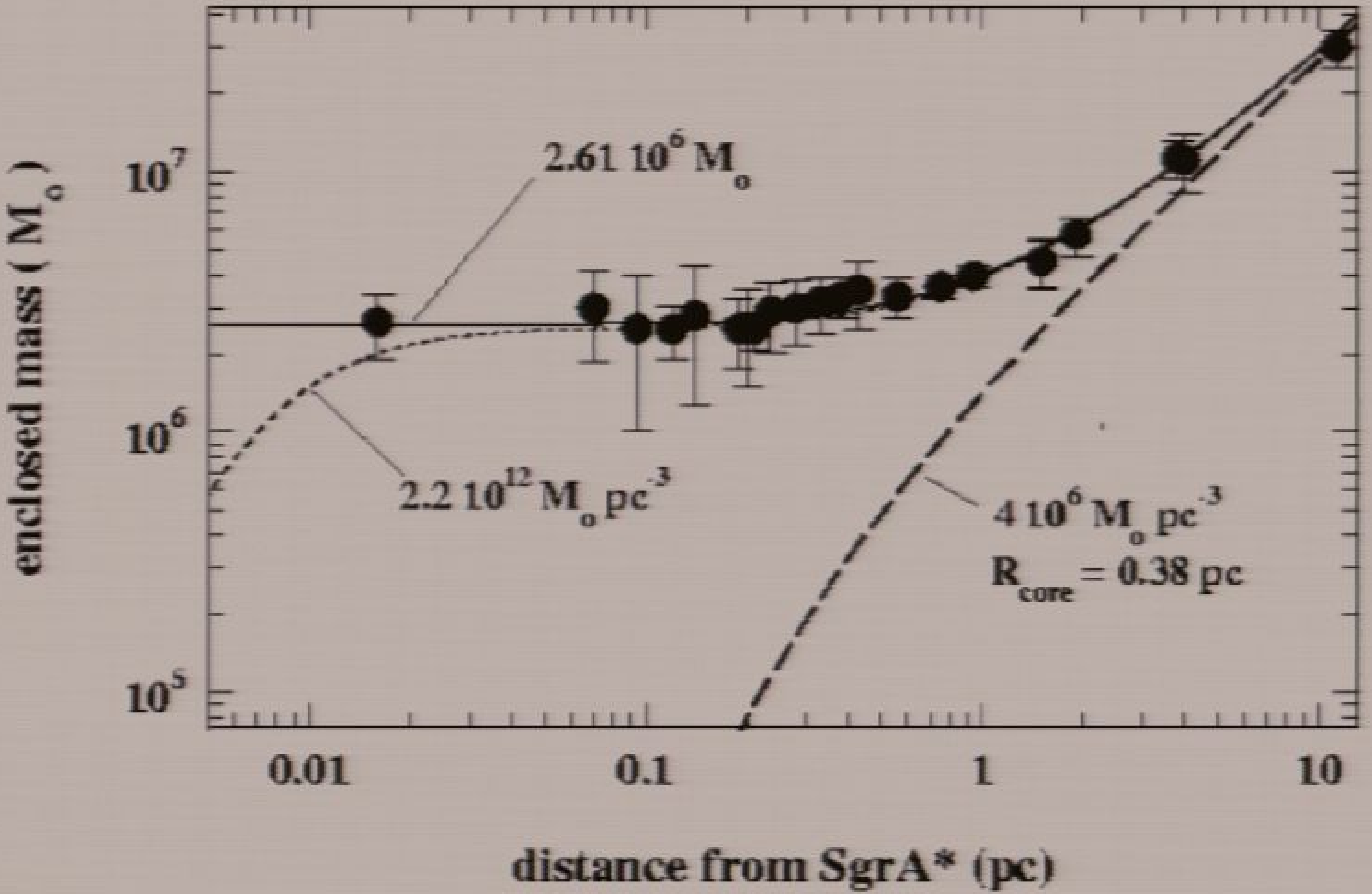
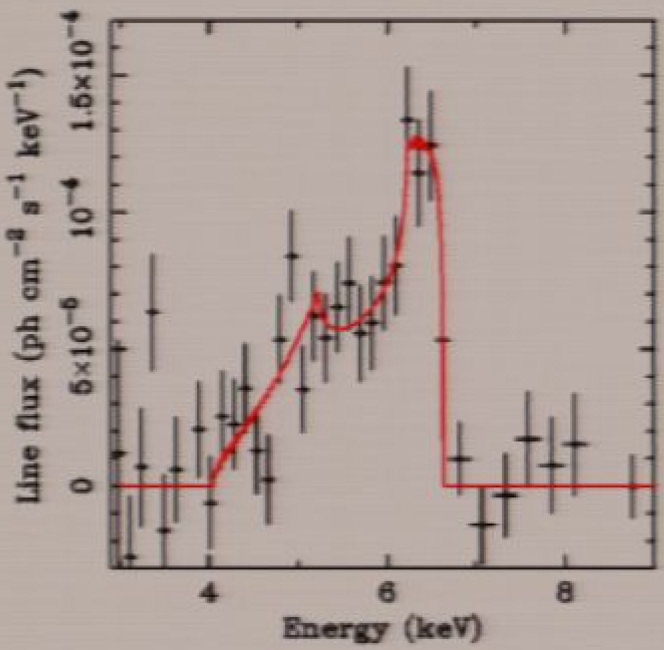
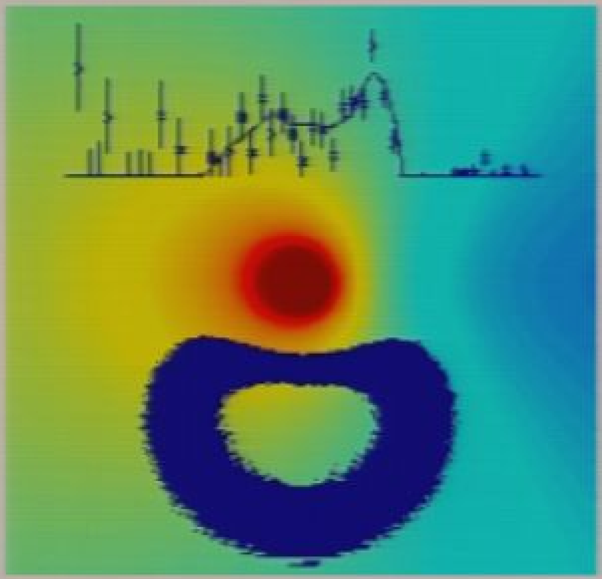


For astrophysicists the presence of a black hole with mass several million that of the sun has been established beyond reasonable doubt.

Relativistic redshifts

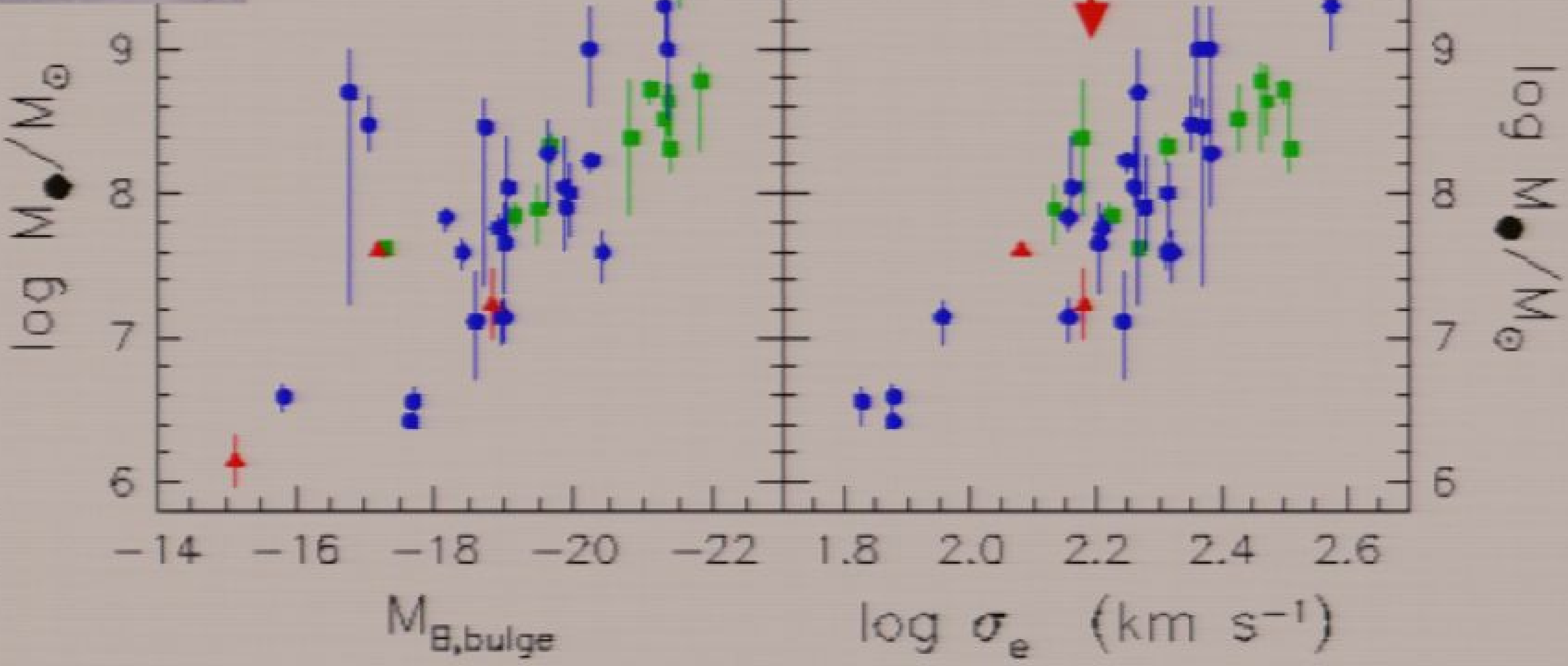


Tanaka et al 1995



Reynolds et al 2000

Is this really tighter?



Kormendy 2003

black hole mass scales with

- bulge mass
- stellar velocity dispersion of the bulge

Massive black holes?

Giant Ellipticals/S0s

Yes

Spirals

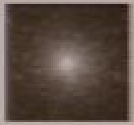
Yes but black hole mass scales with bulge mass not total mass

Dwarfs

~~Possibly~~

A few

Globular Clusters



Maybe

SDSS survey

SDSS survey

1 million galaxy spectra

100 000 QSOs

http://www.sdss.org

A very large,

homogeneous

high-quality

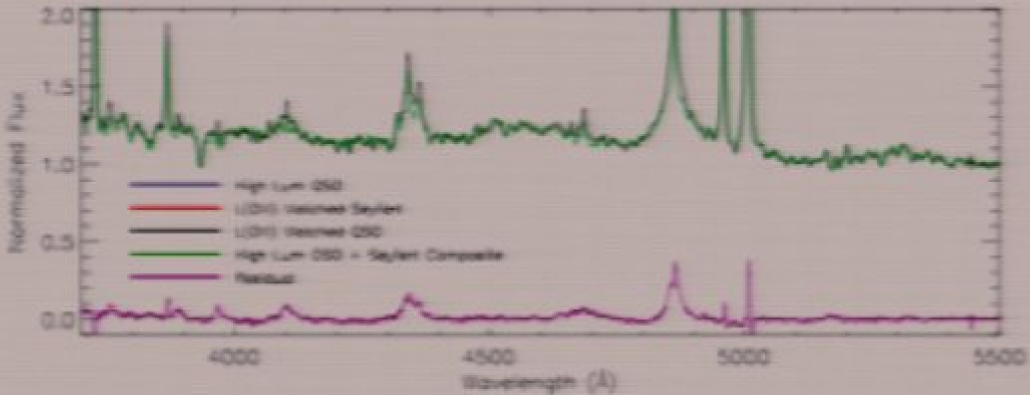
data set.

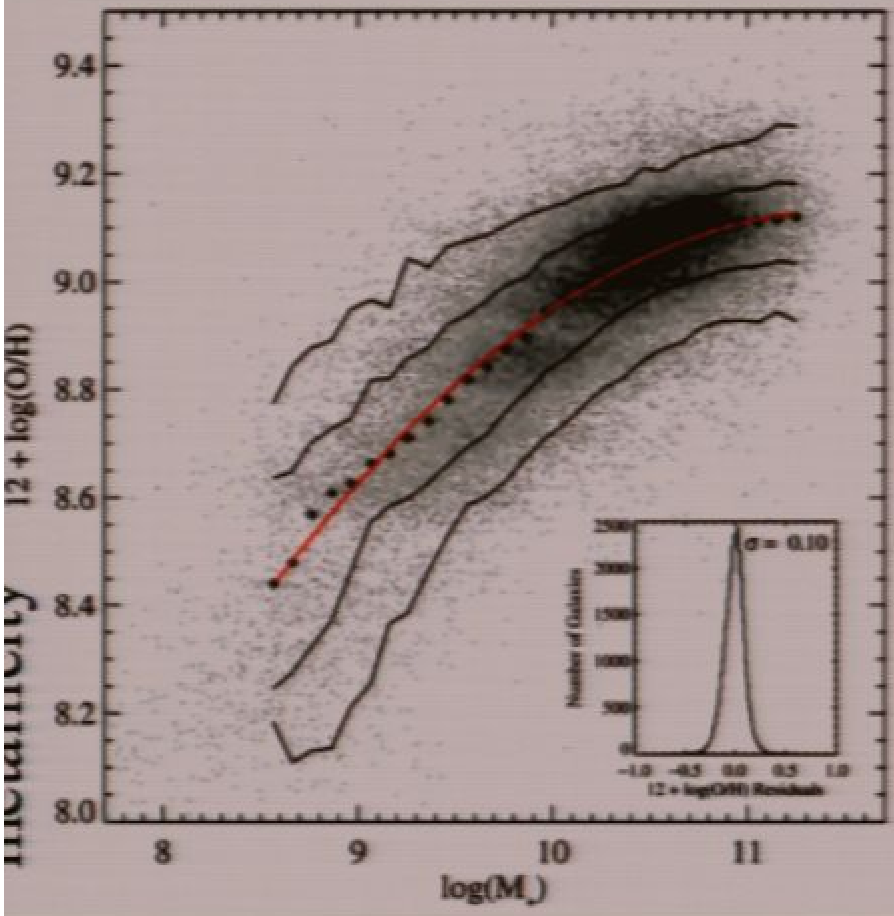

early–type


late–type


early–type with massive companion

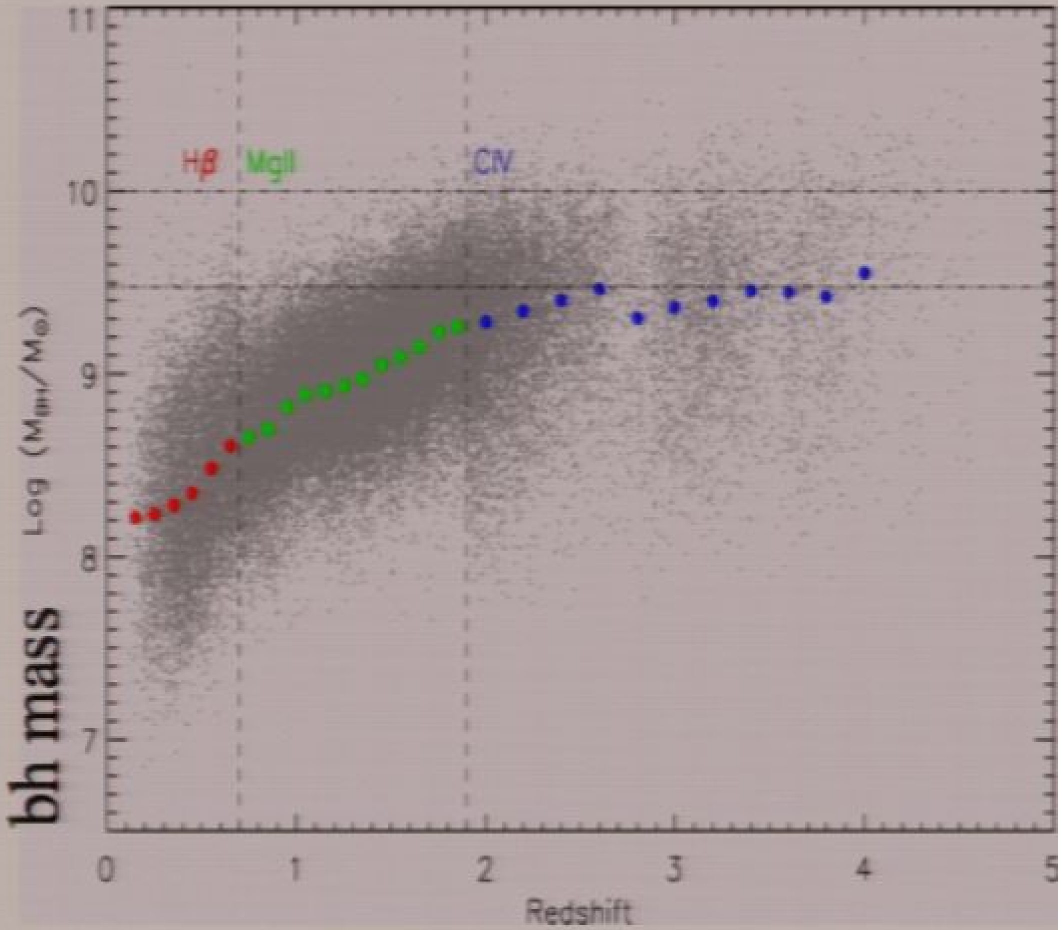

late–type with low mass companion





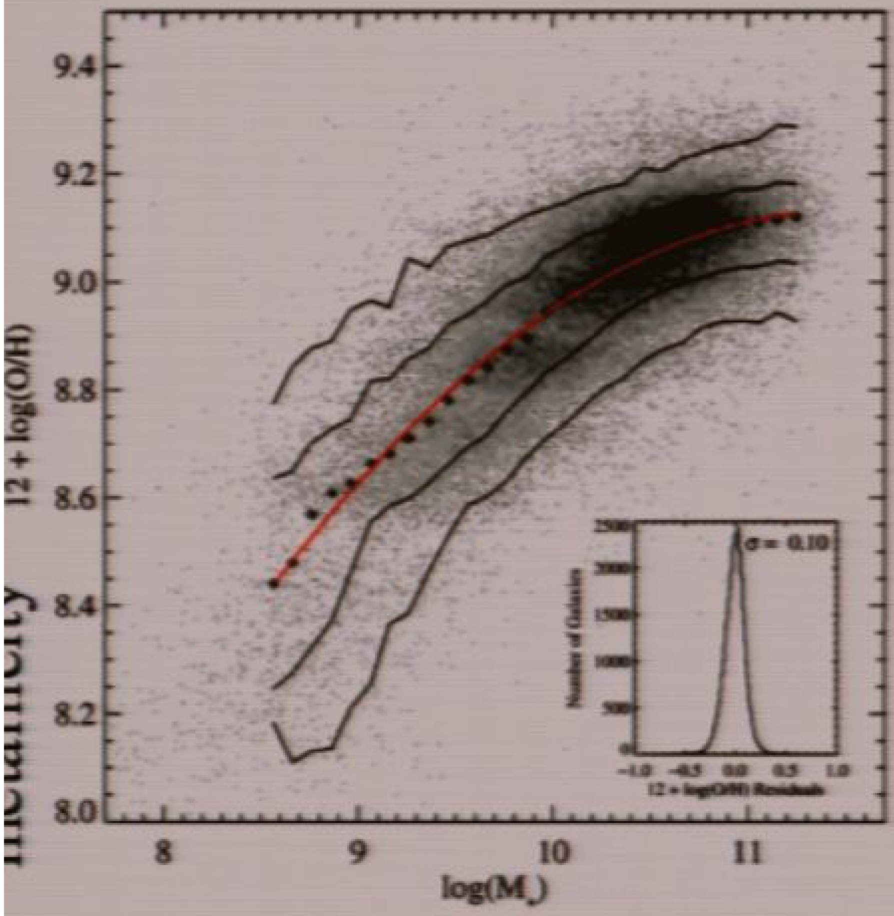
stellar mass

Tremonti et al.



Shen et al.

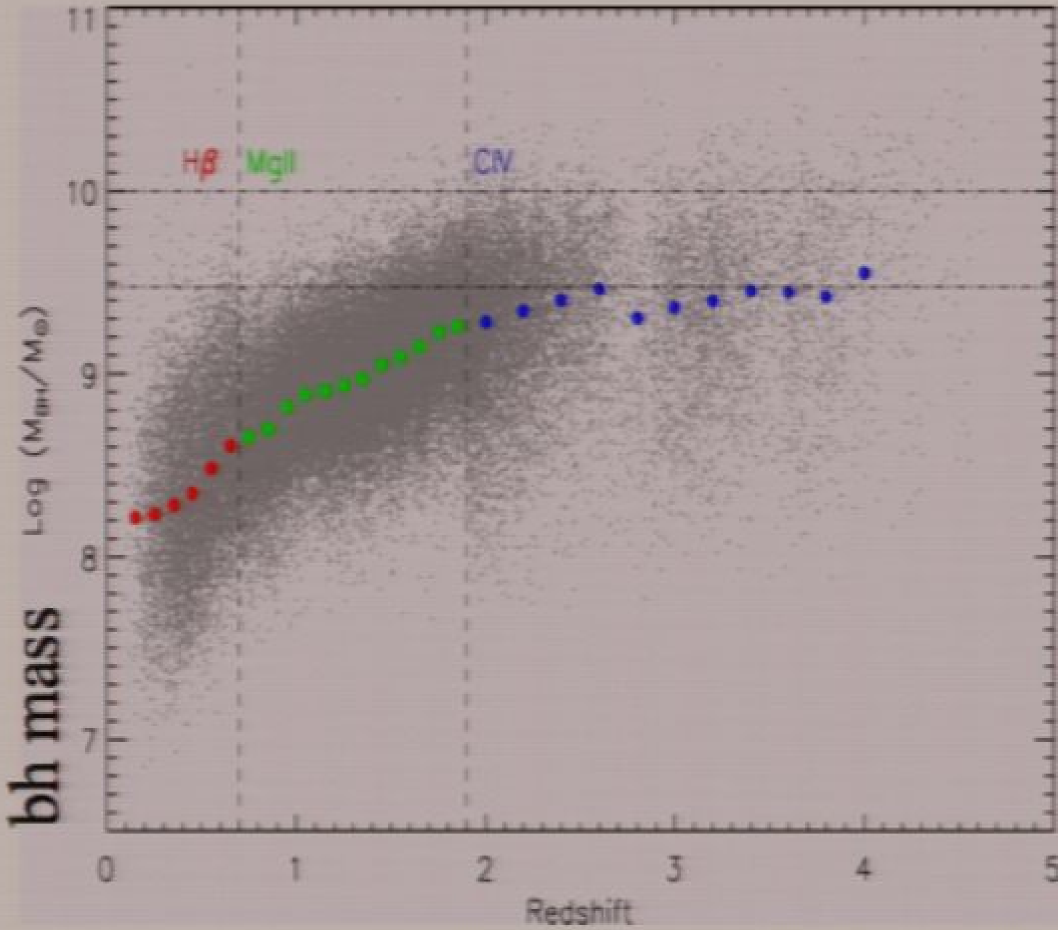
Co-evolution of galaxies and black holes



metallicity

stellar mass

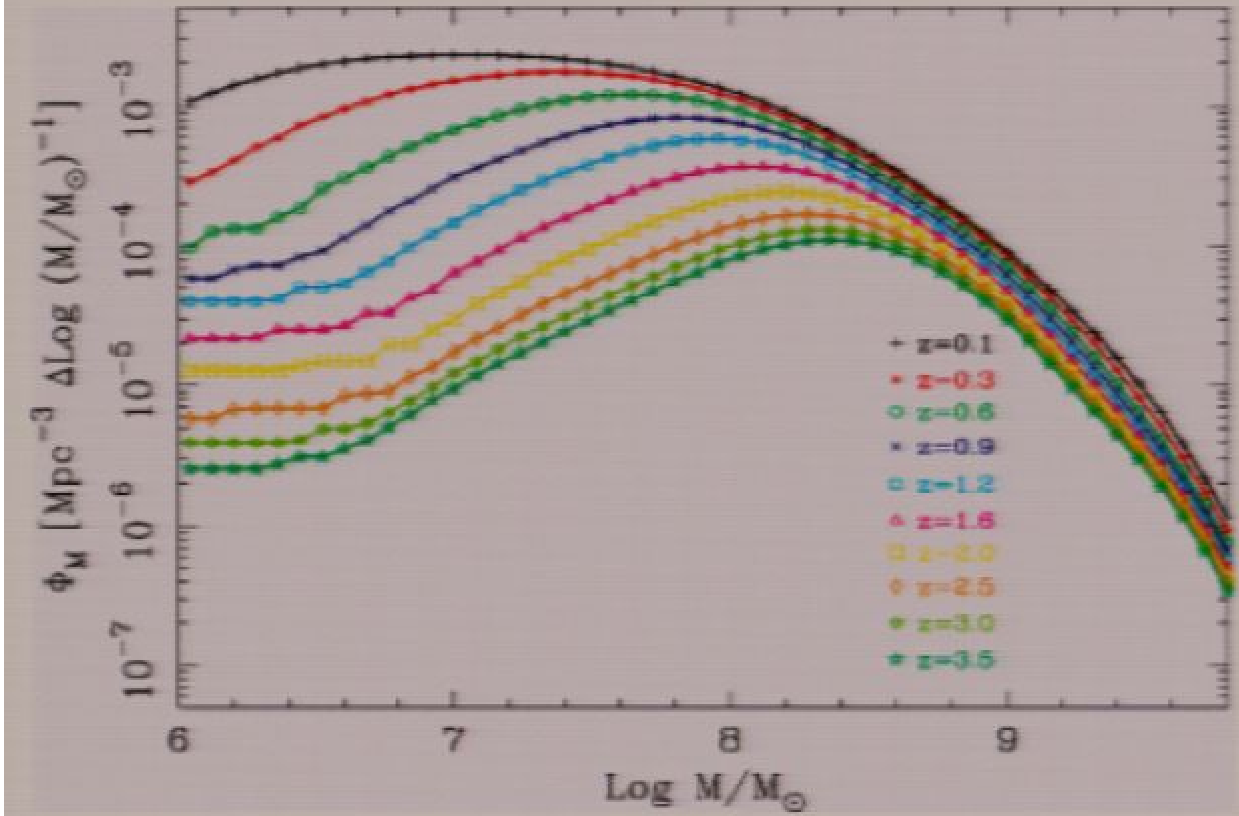
Tremonti et al.



bh mass

Shen et al.

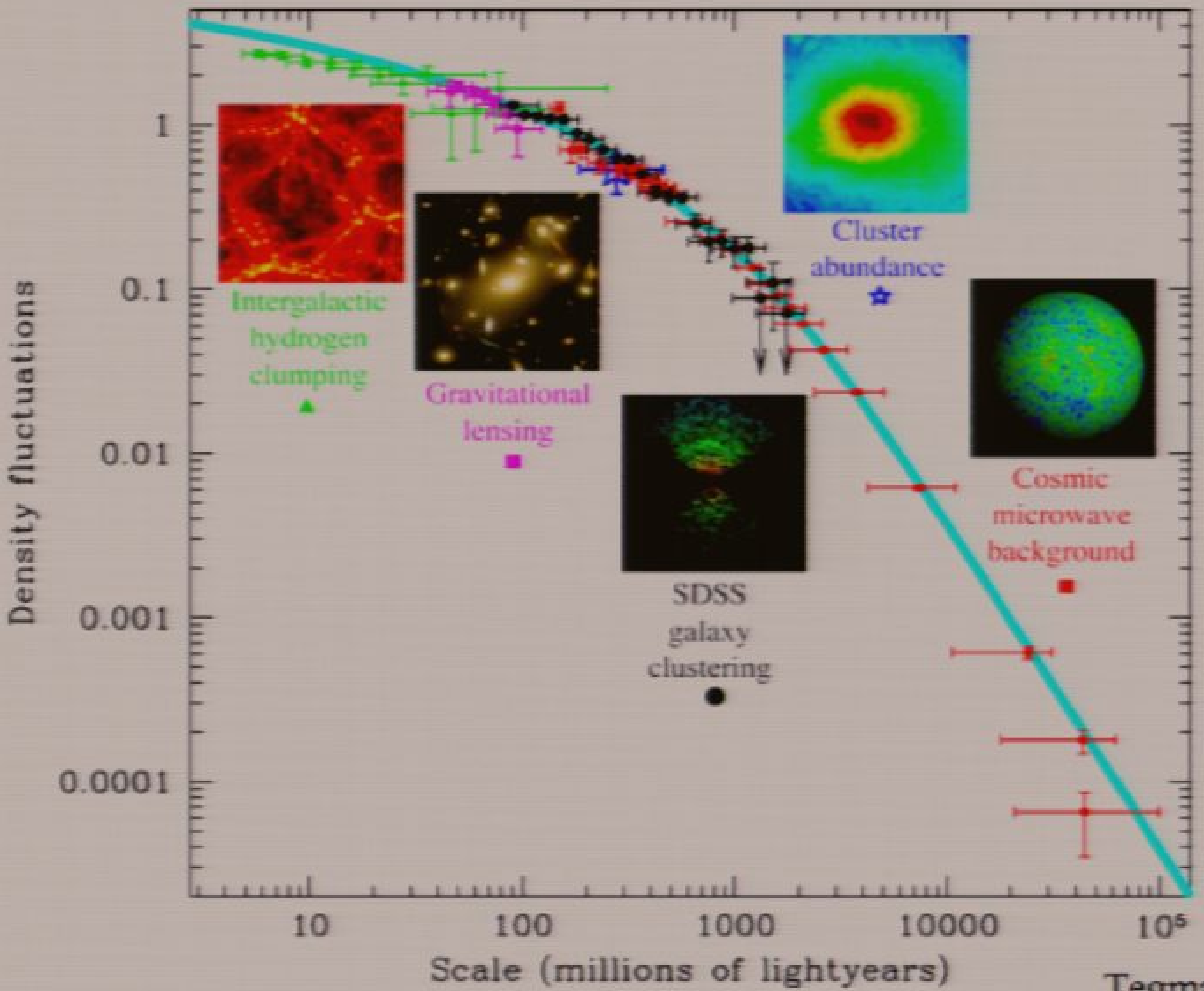
Evolution of the black hole mass function as reconstructed from accretion history



Cosmic Downsizing

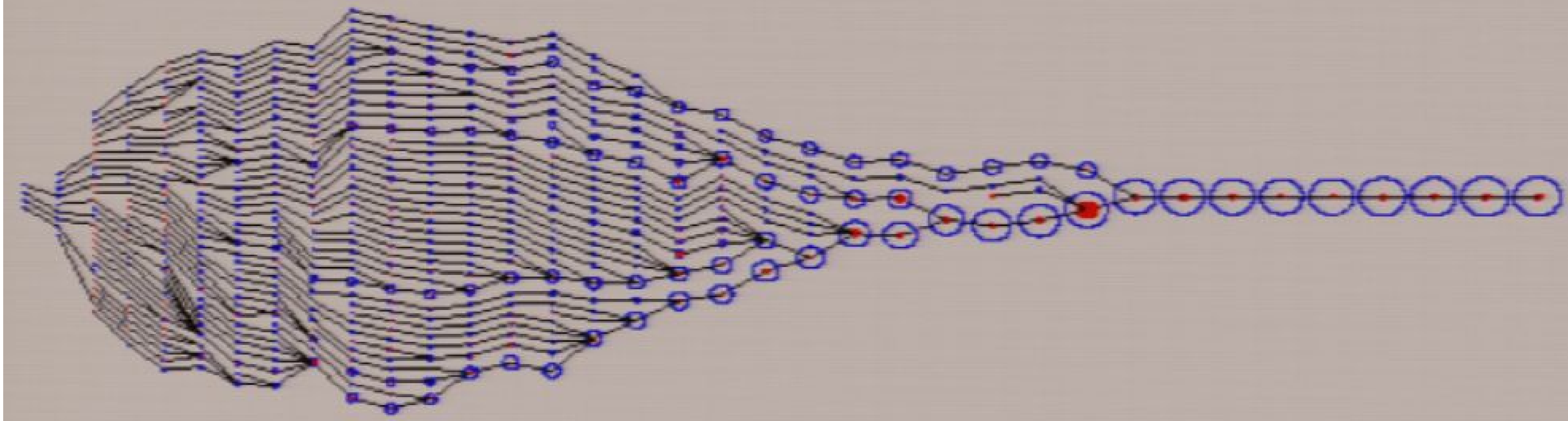
Most of the big black holes form at high redshift. Most of the black holes still growing at the present day are small. These small black holes have gained most of their mass recently.

Merloni 2004



Tegmark

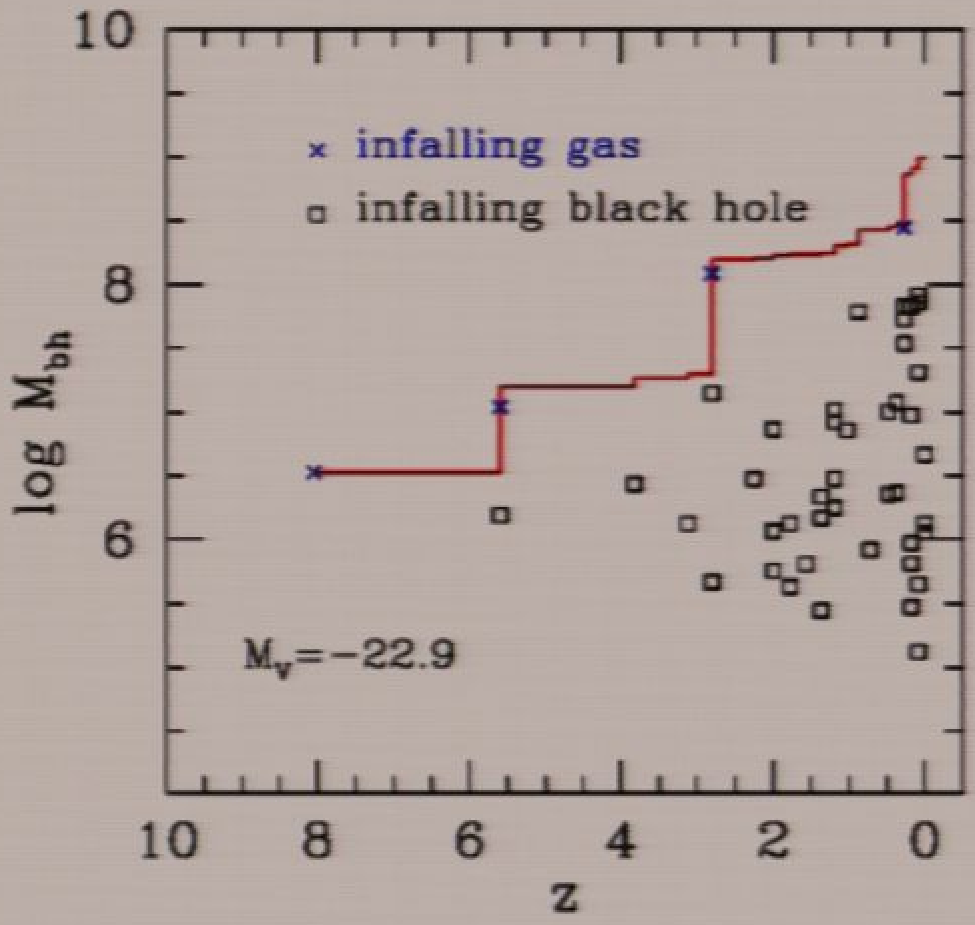
We know the DM power spectrum very well!



Bullock et al.

DM haloes grow by merging

Typical merging history in a bright elliptical



Kauffmann & Haehnelt 2002

Growth of black holes dominated by accretion of gas and feedback regulated

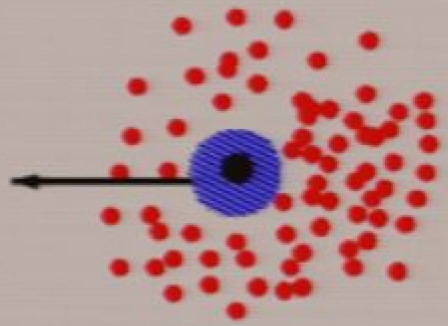
At late time also growth by infall and merging of black holes

How do 10^6 Msol black holes form?

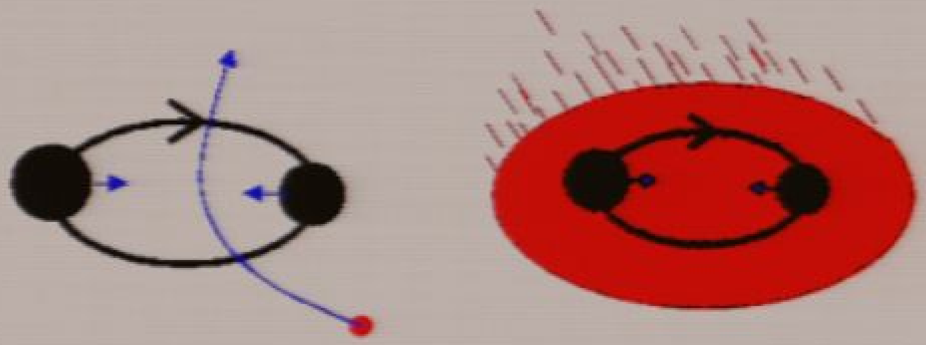
Formation and evolution of supermassive binaries

1. Dynamical friction

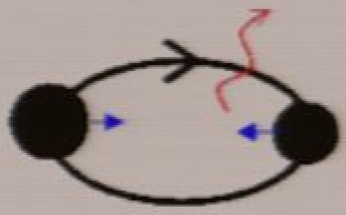
$t \propto a$



2. Binary hardening
due to stars
or
accretion of gas

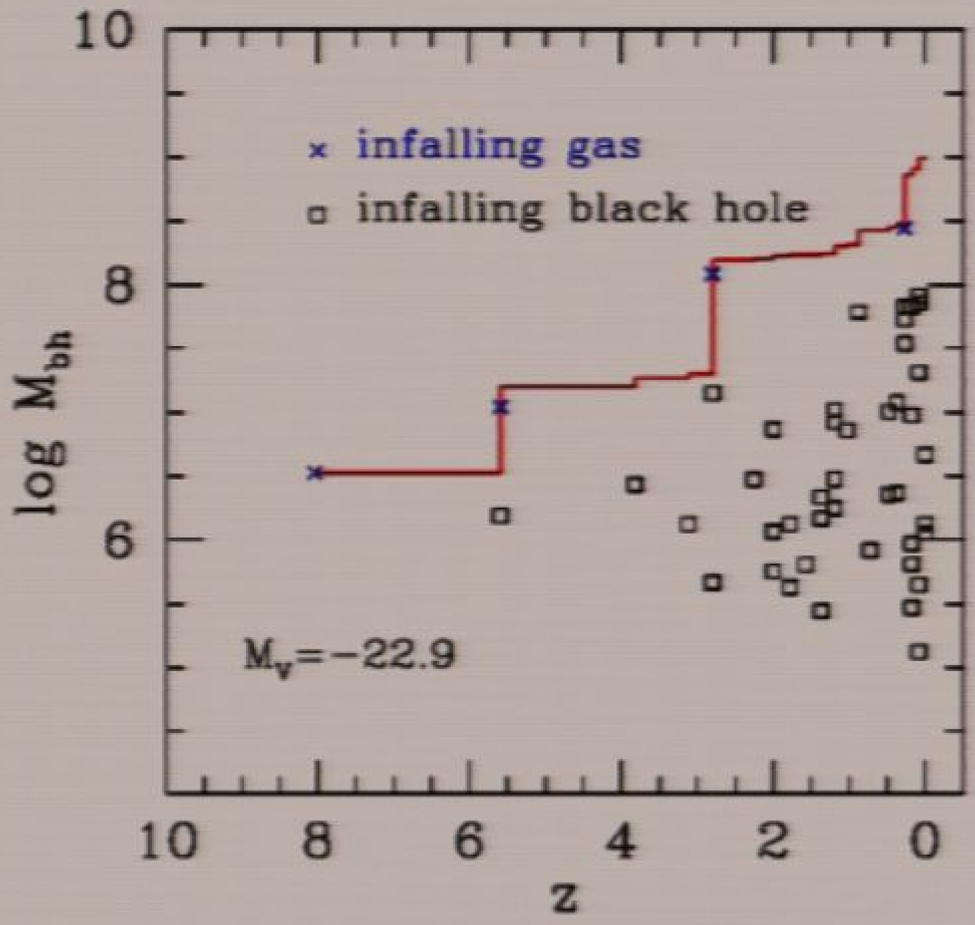


3. Gravitational radiation



$t \propto a^4$

Typical merging history in a bright elliptical



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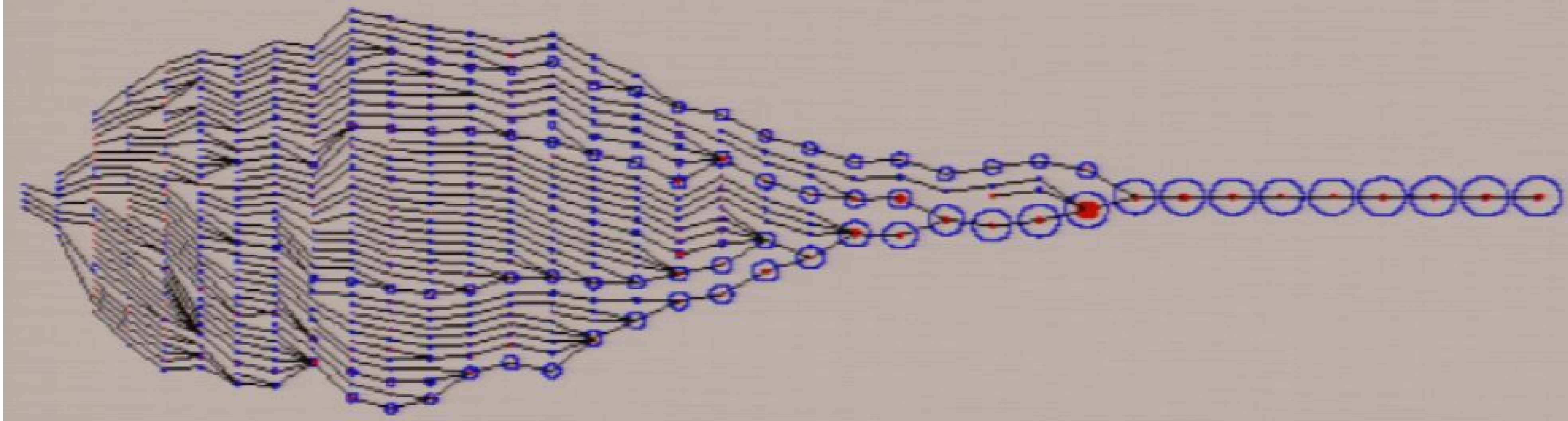

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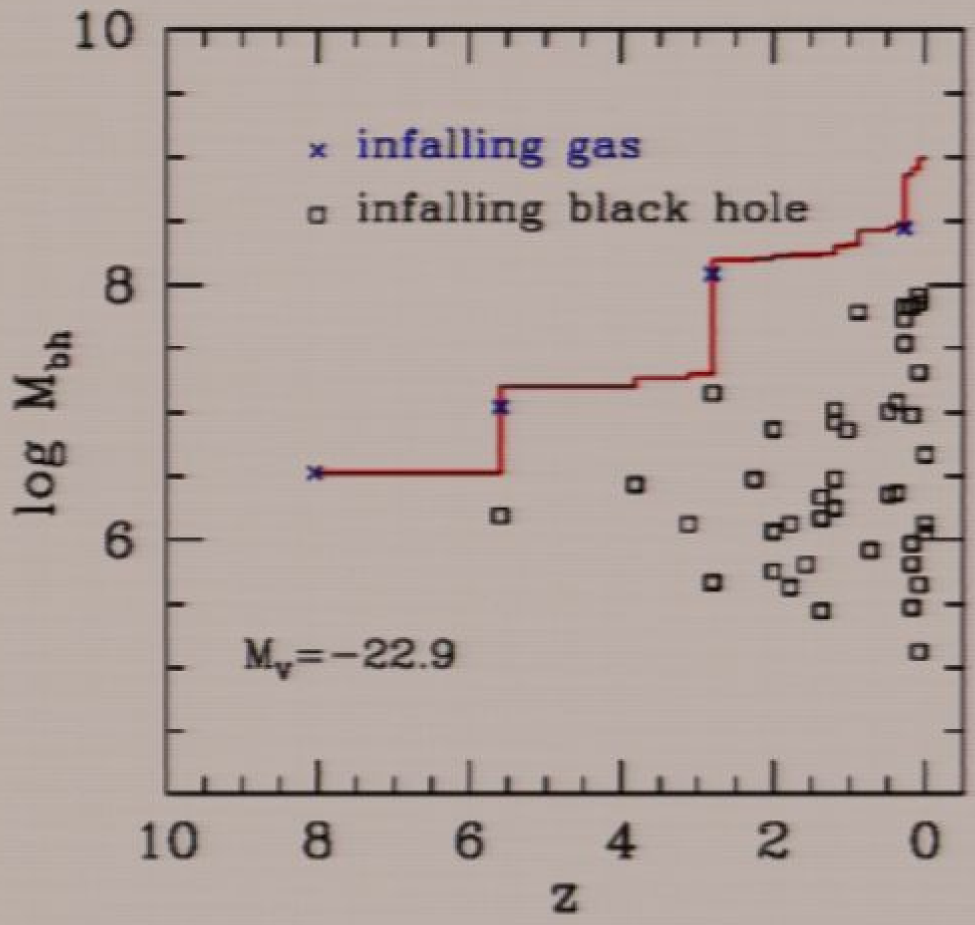

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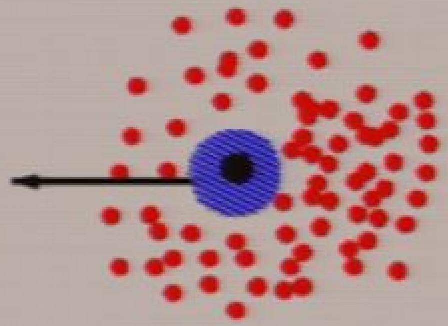

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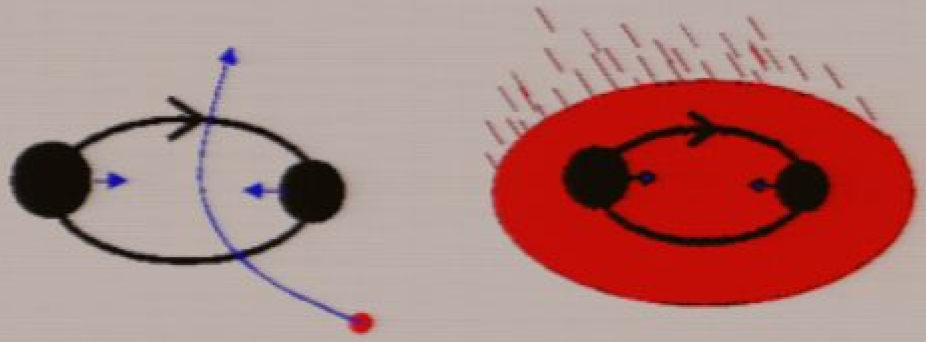

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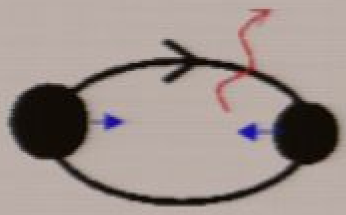
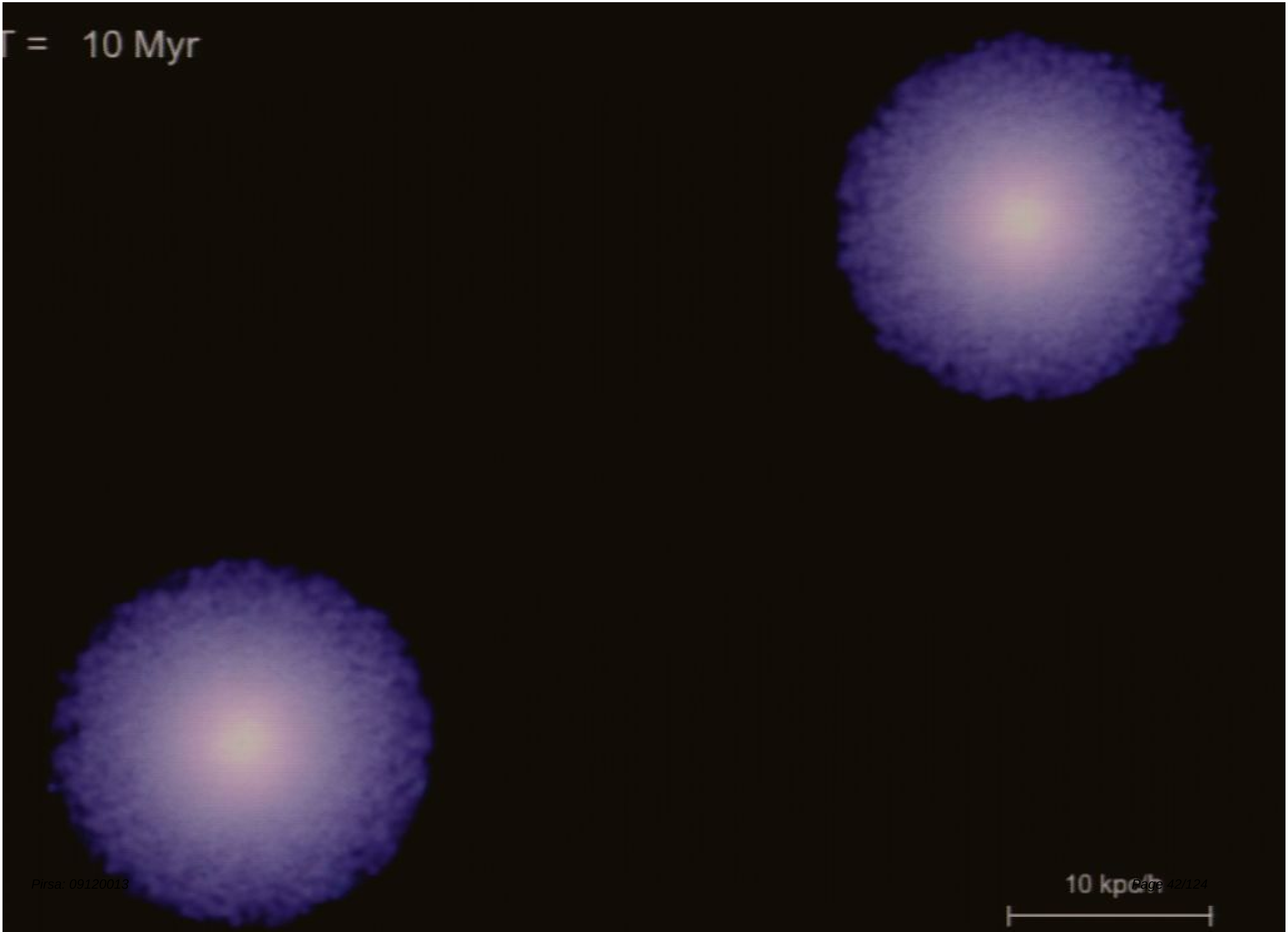
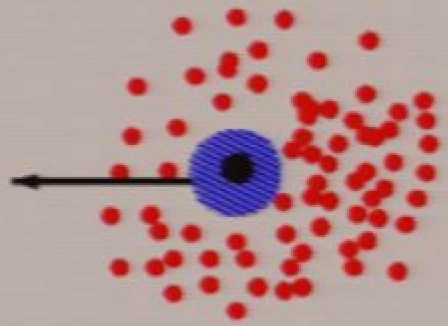



T = 10 Myr
10 kpc/h

Formation and evolution of supermassive binaries

1. Dynamical friction

$t \propto a$



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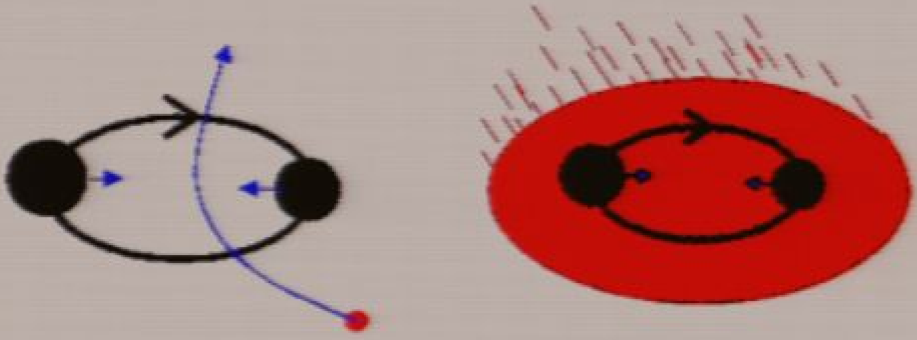

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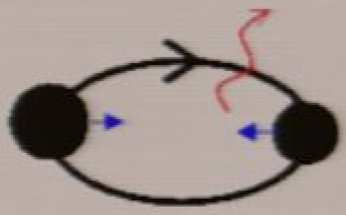
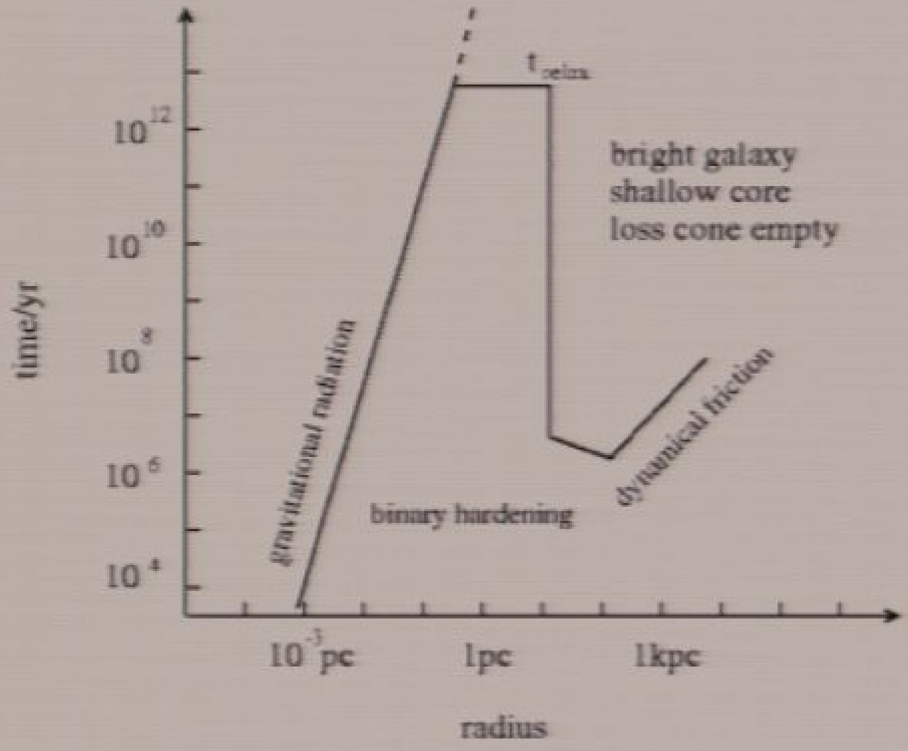


Perimeter, 9th December 2009

Do binary black holes coalescence?



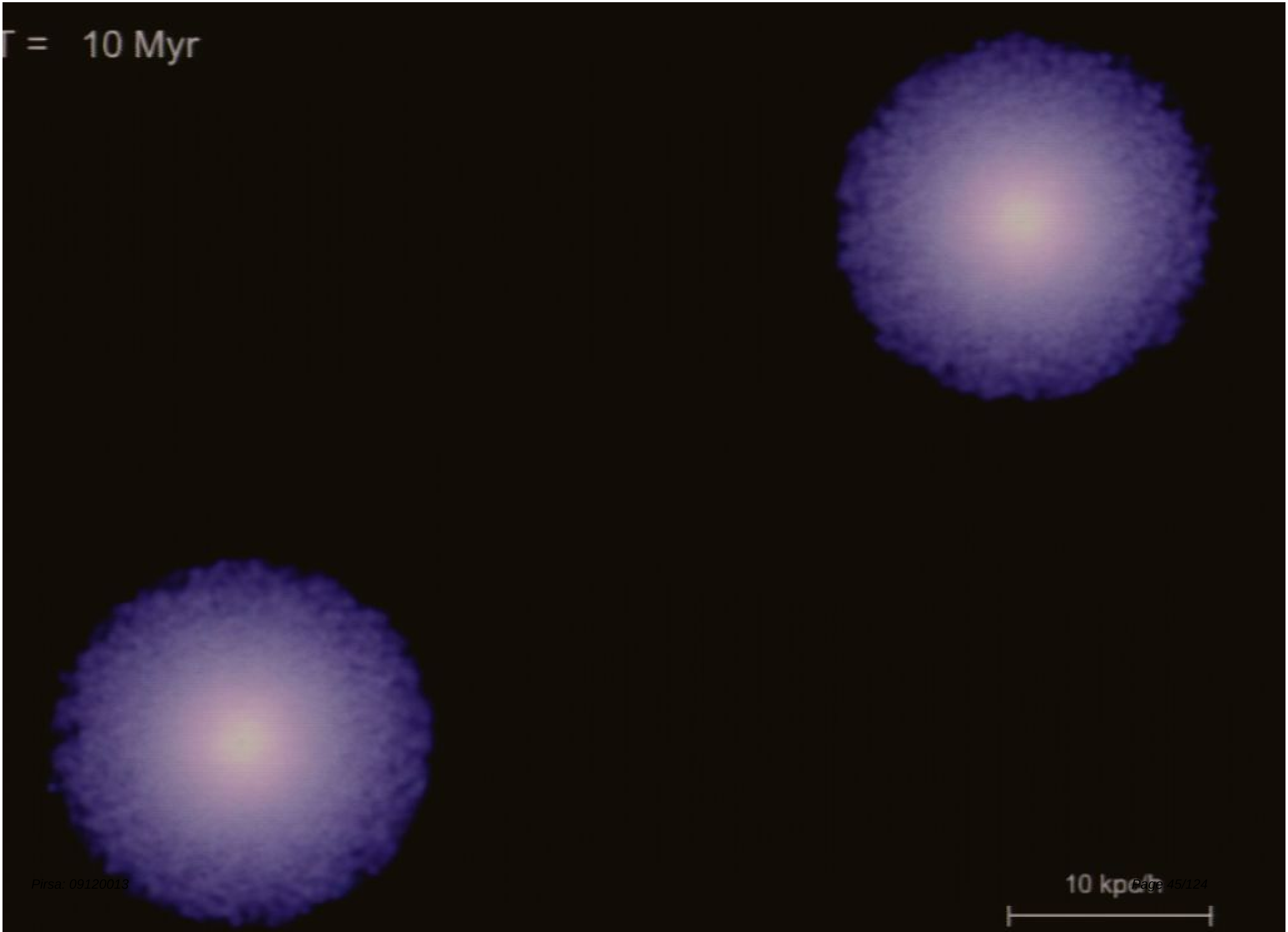
Begelman Blandford & Rees 1980
Yu 2002

Need either:

accretion of gas

or

efficient refilling of loss cone (only in small galaxies and maybe at high redshift)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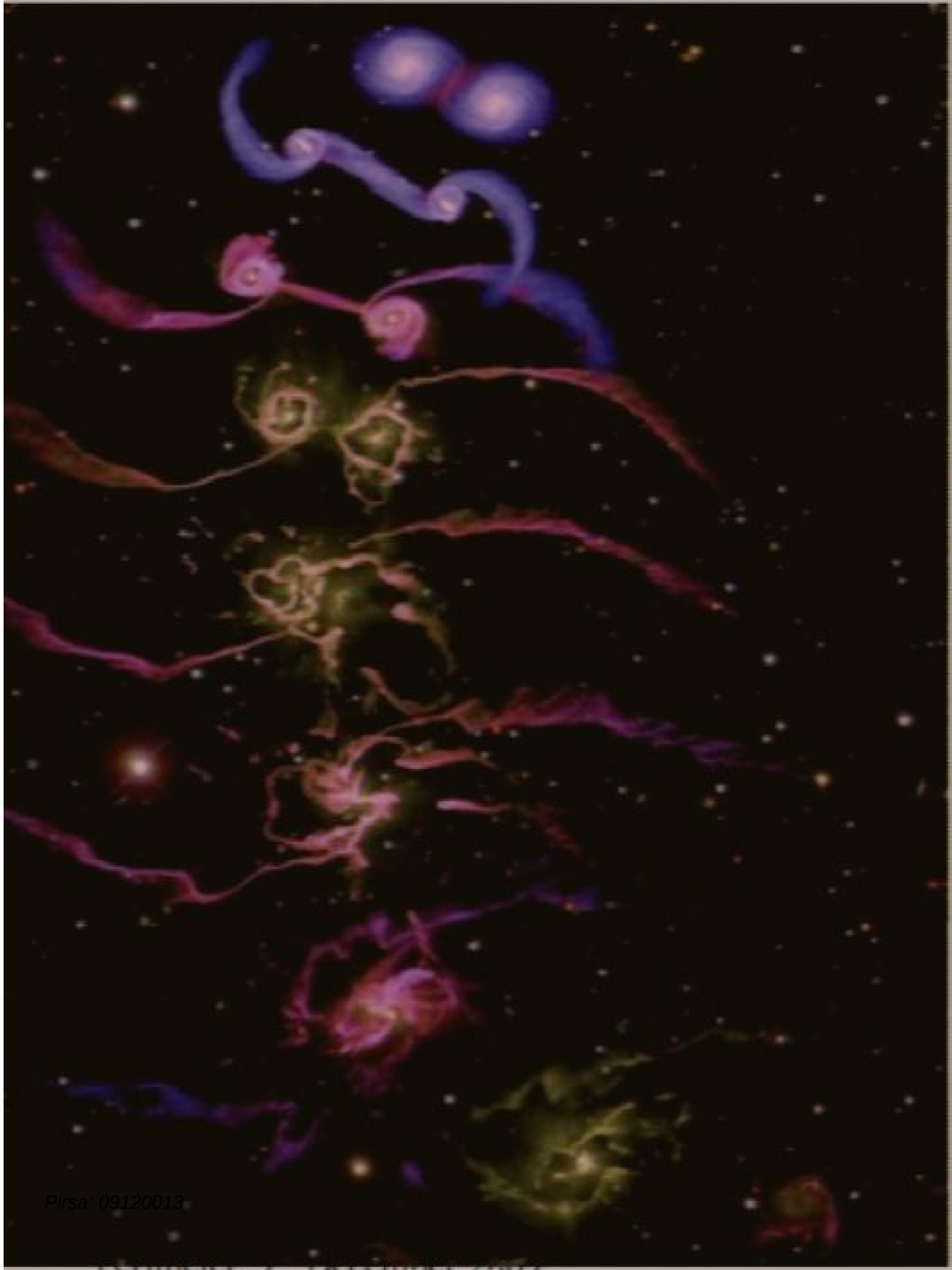
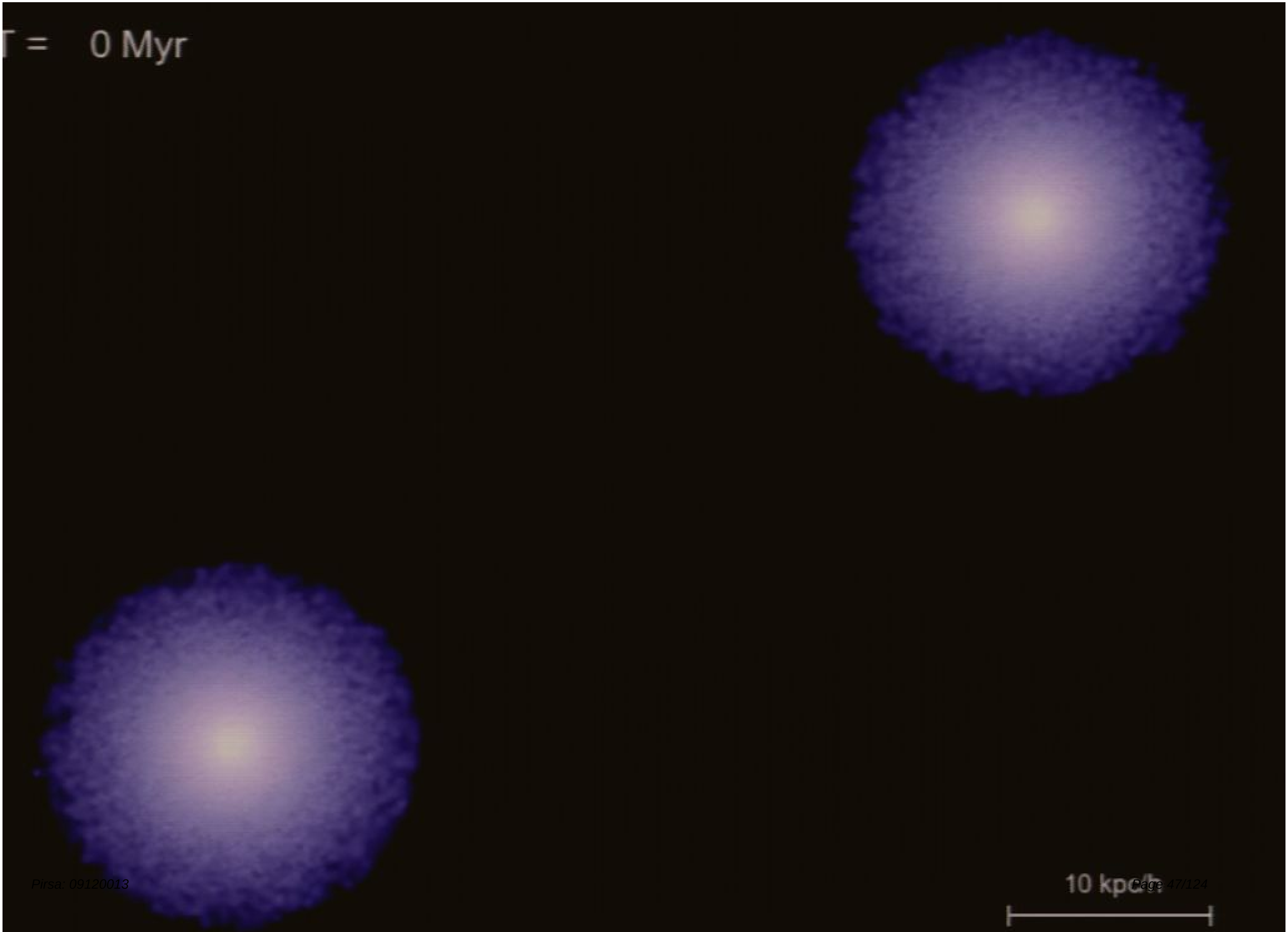
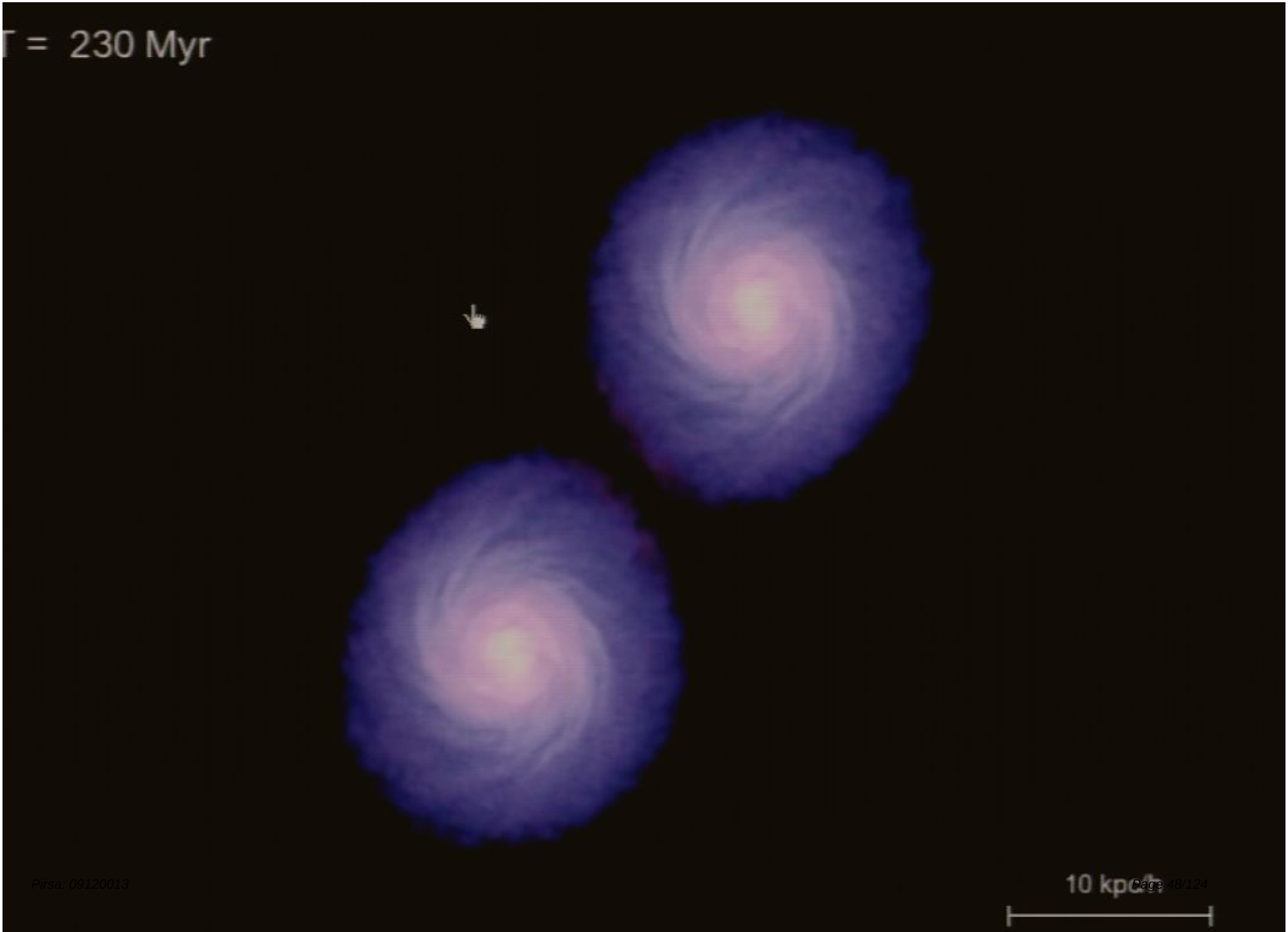
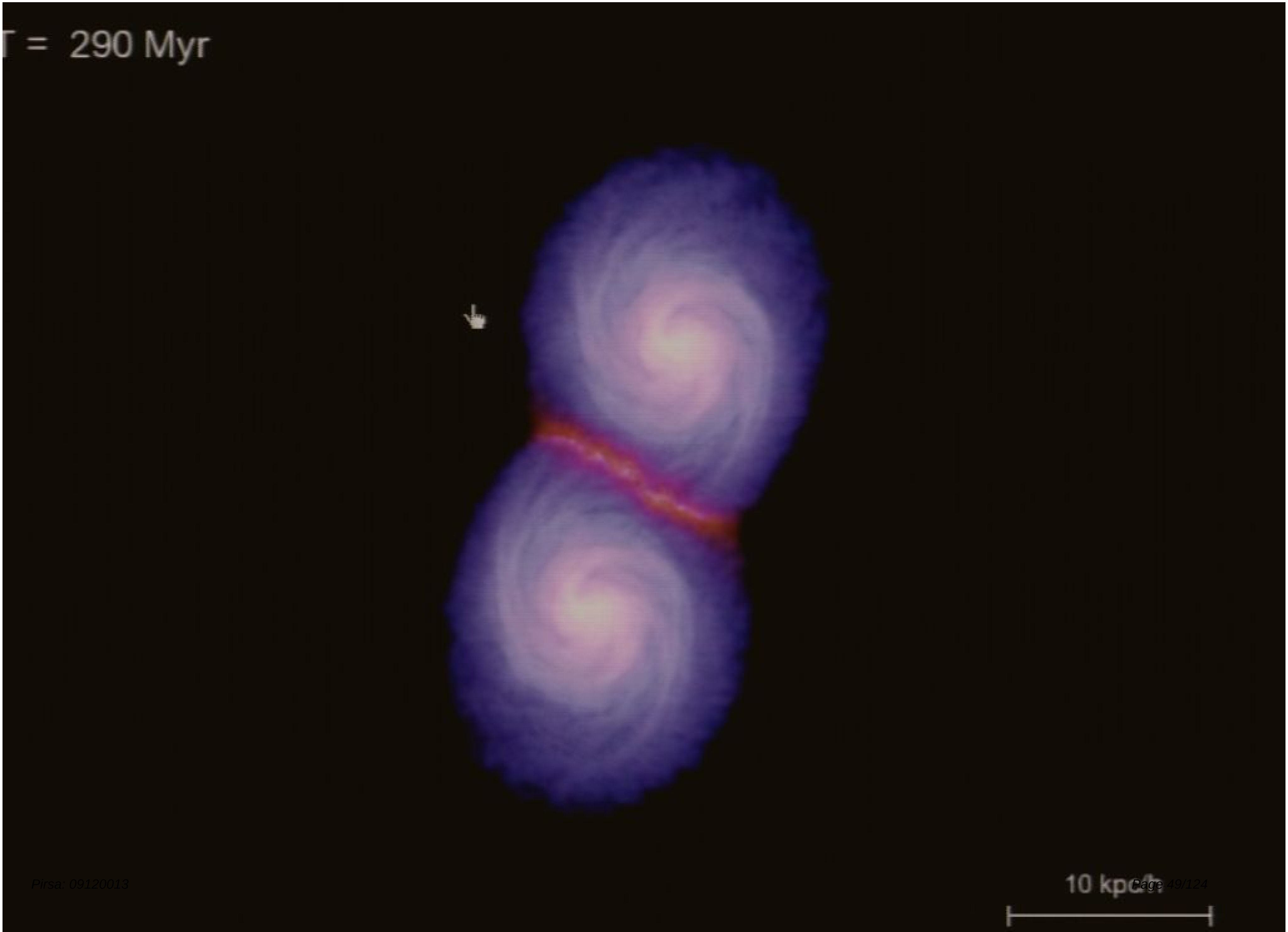
10 kpc/h

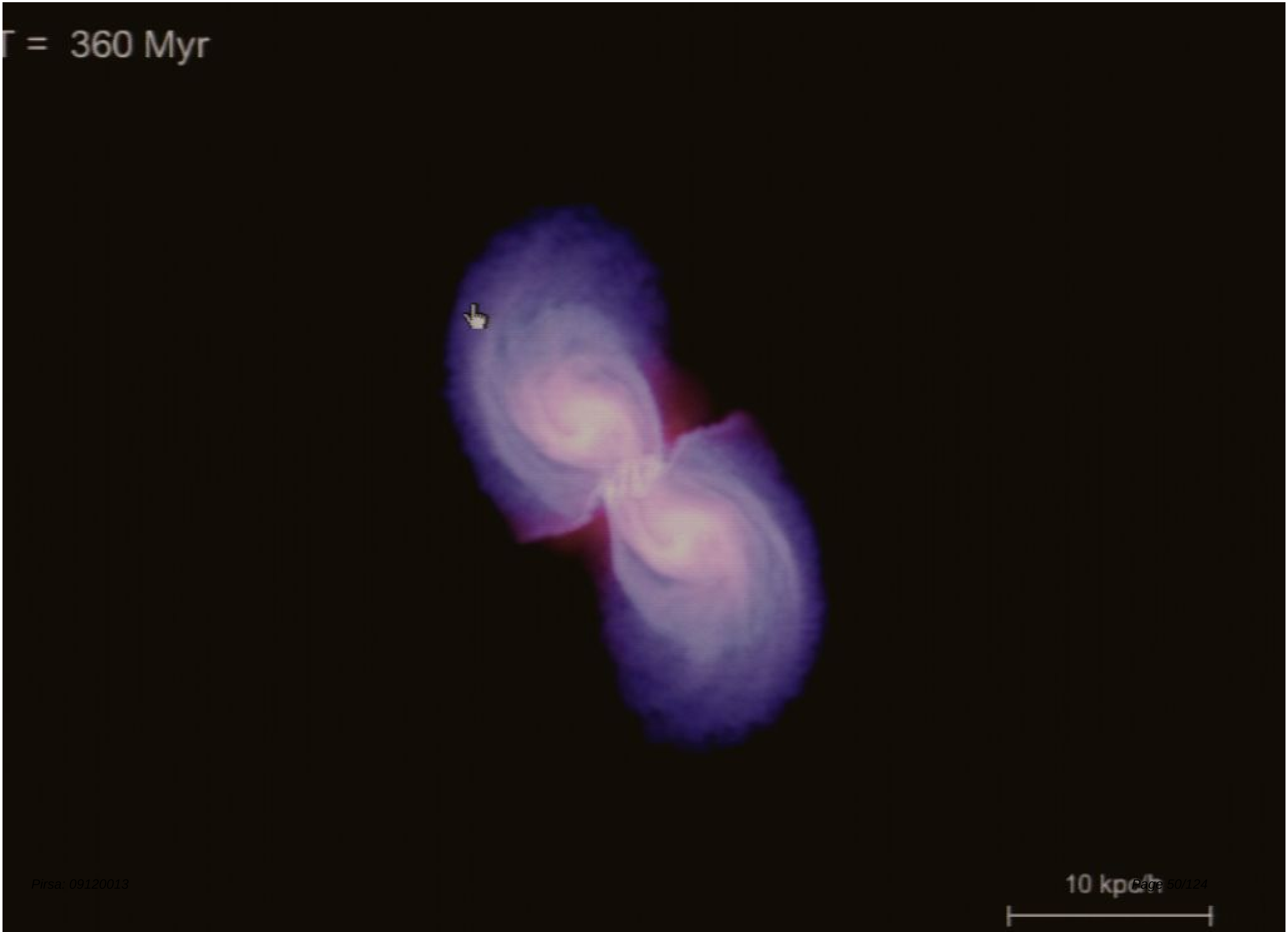


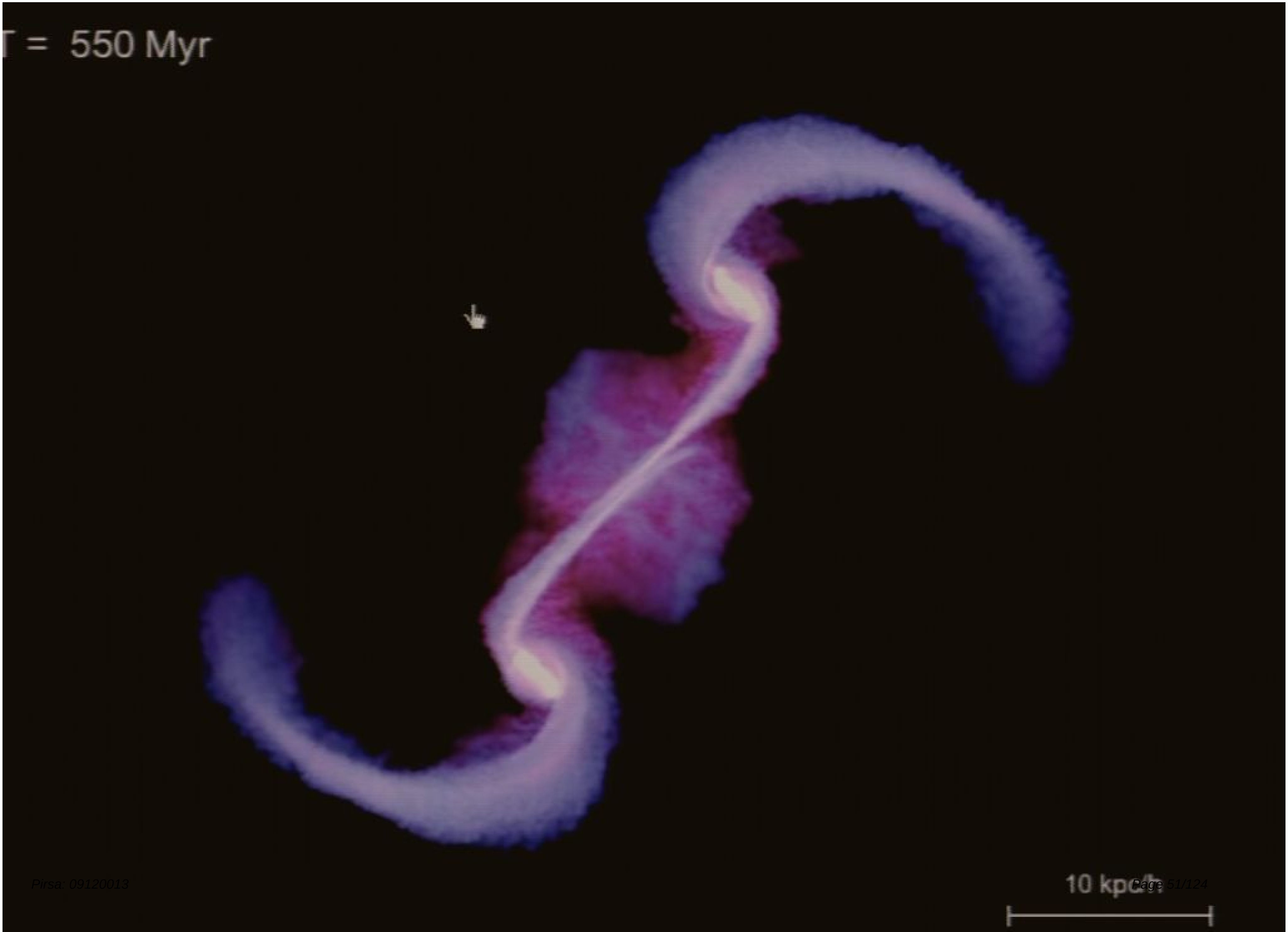
NGC2207

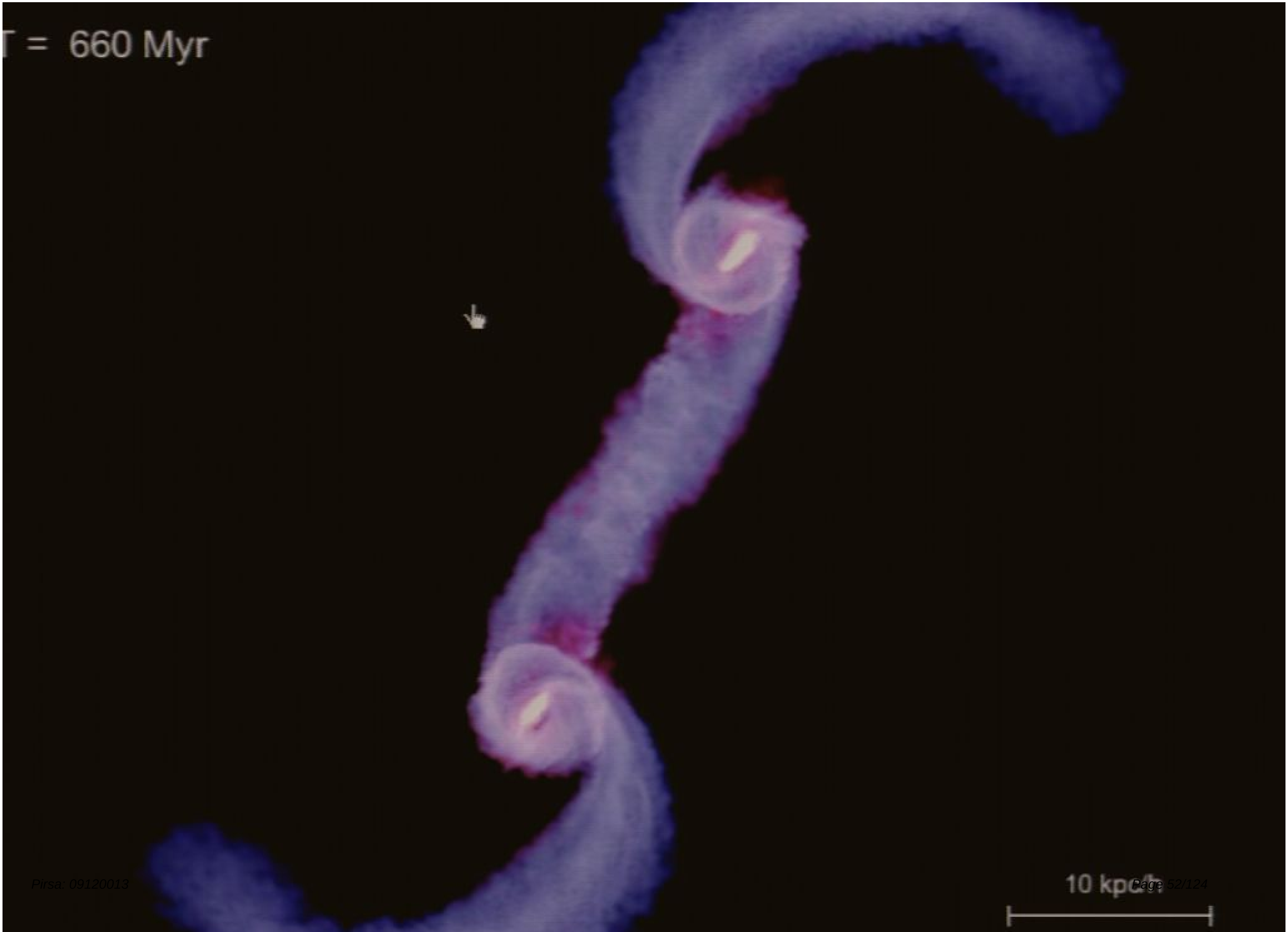

T = 0 Myr
10 kpc/h

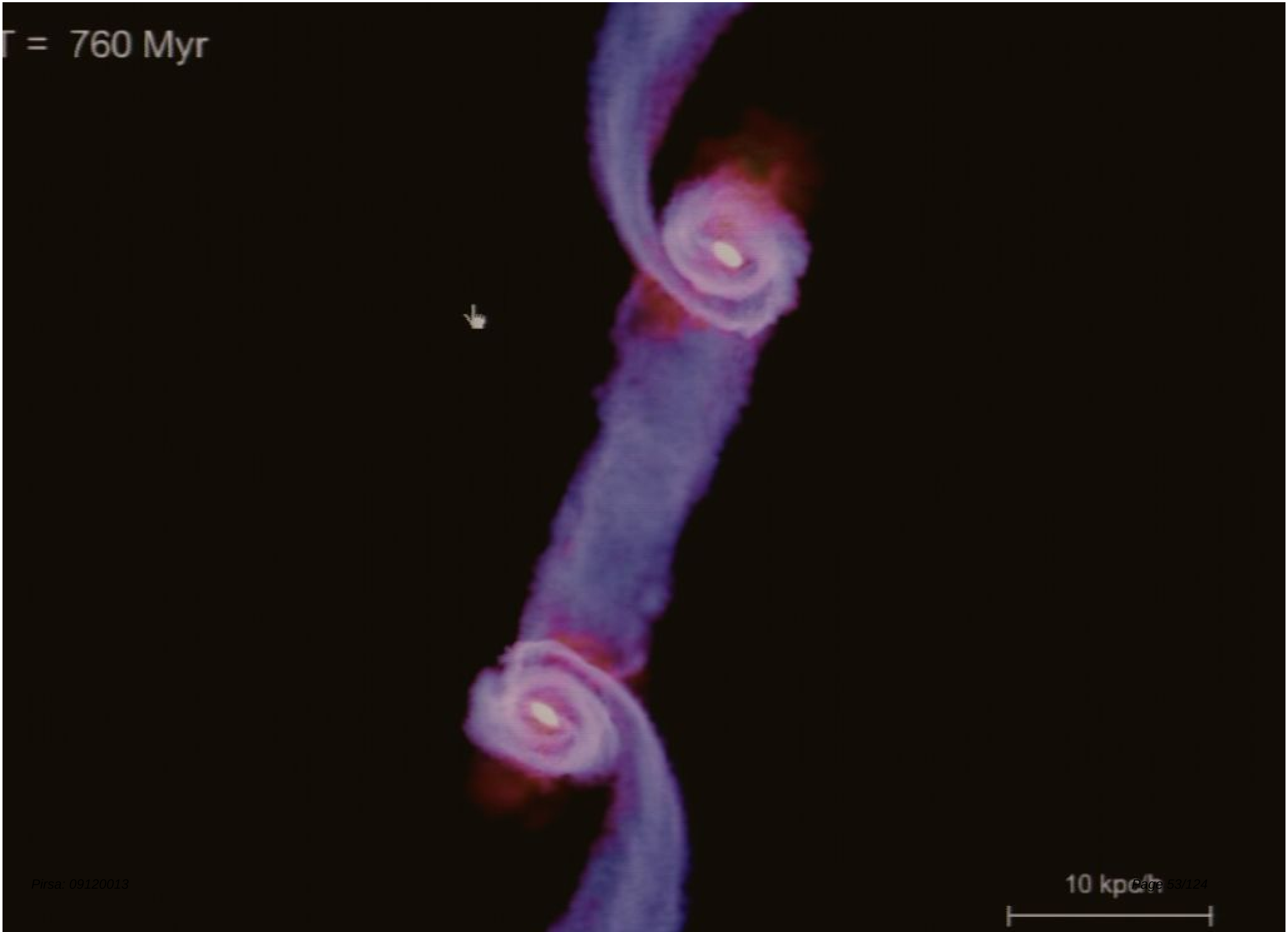

T = 230 Myr
10 kpc/h

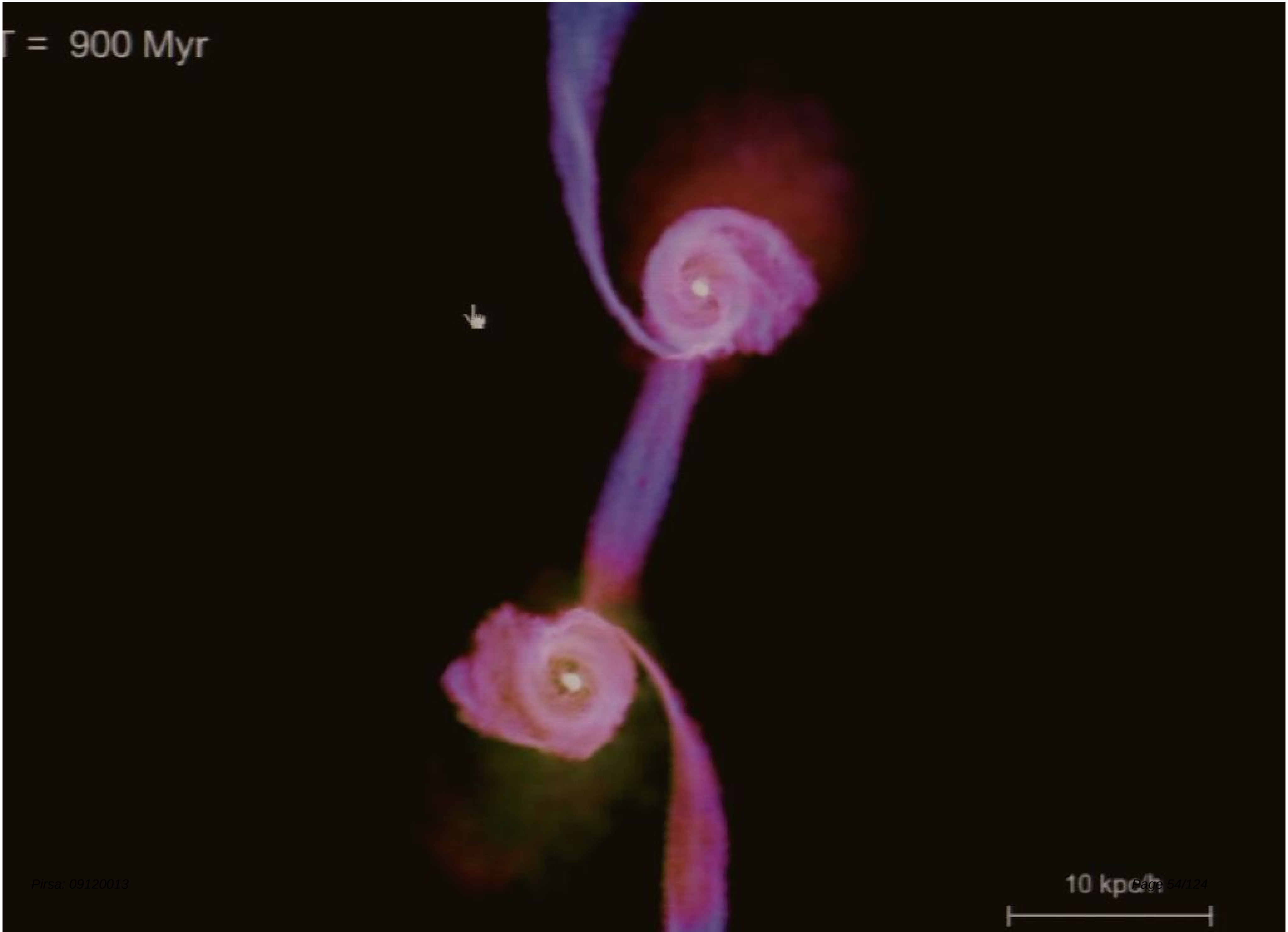

T = 290 Myr
10 kpc/h

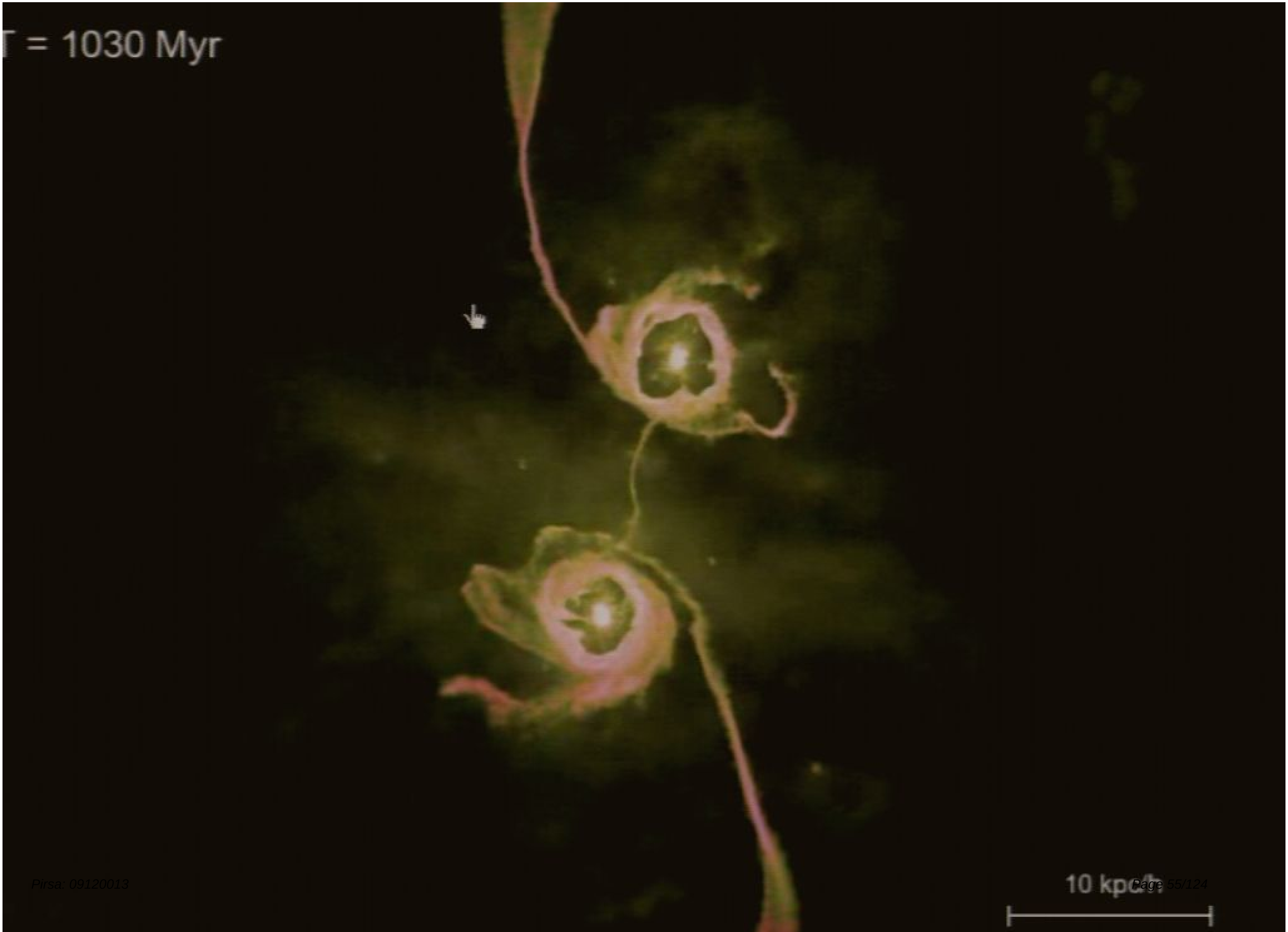

T = 360 Myr
10 kpc/h

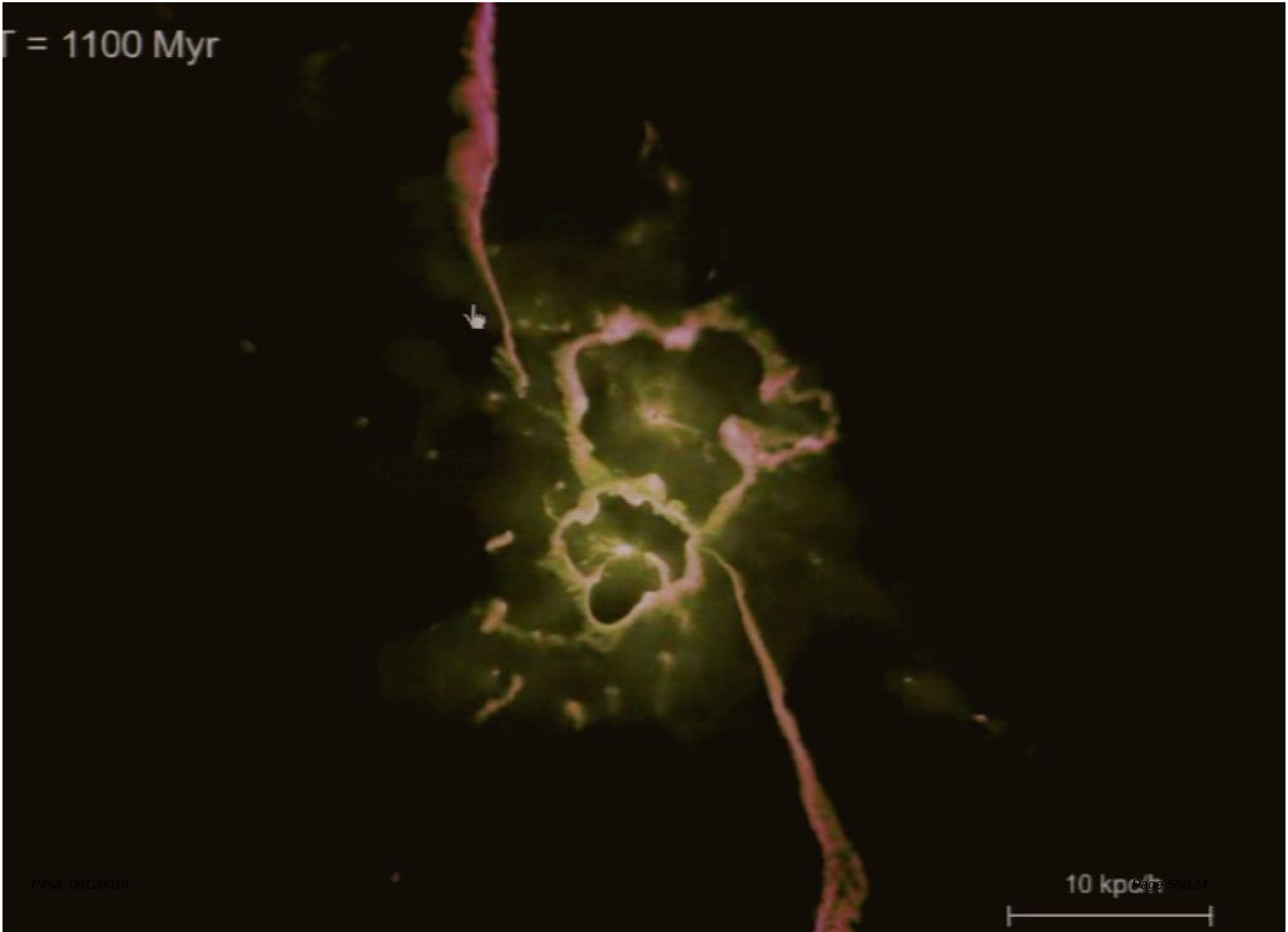

T = 550 Myr
10 kpc/h

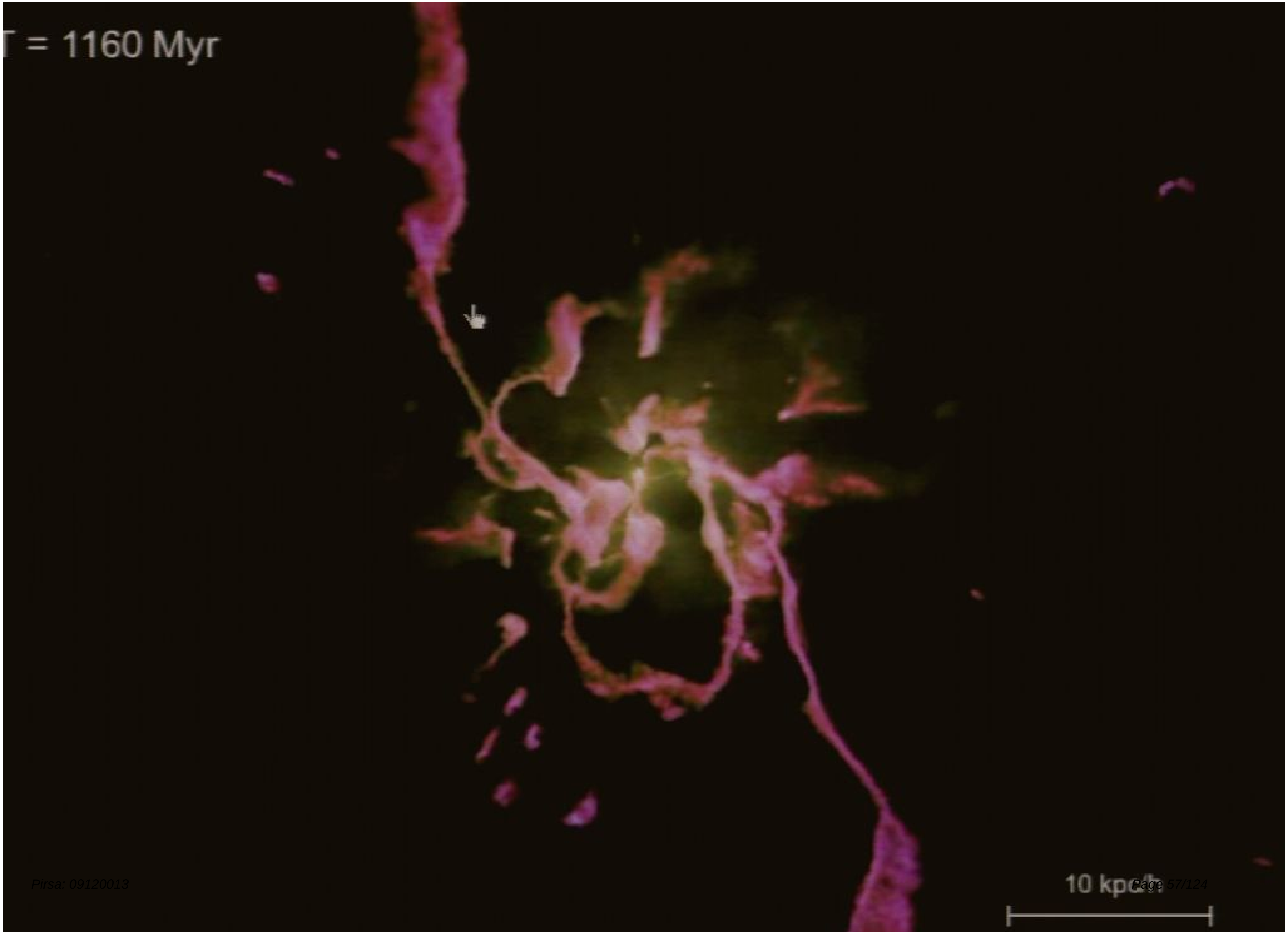

T = 660 Myr
10 kpc/h

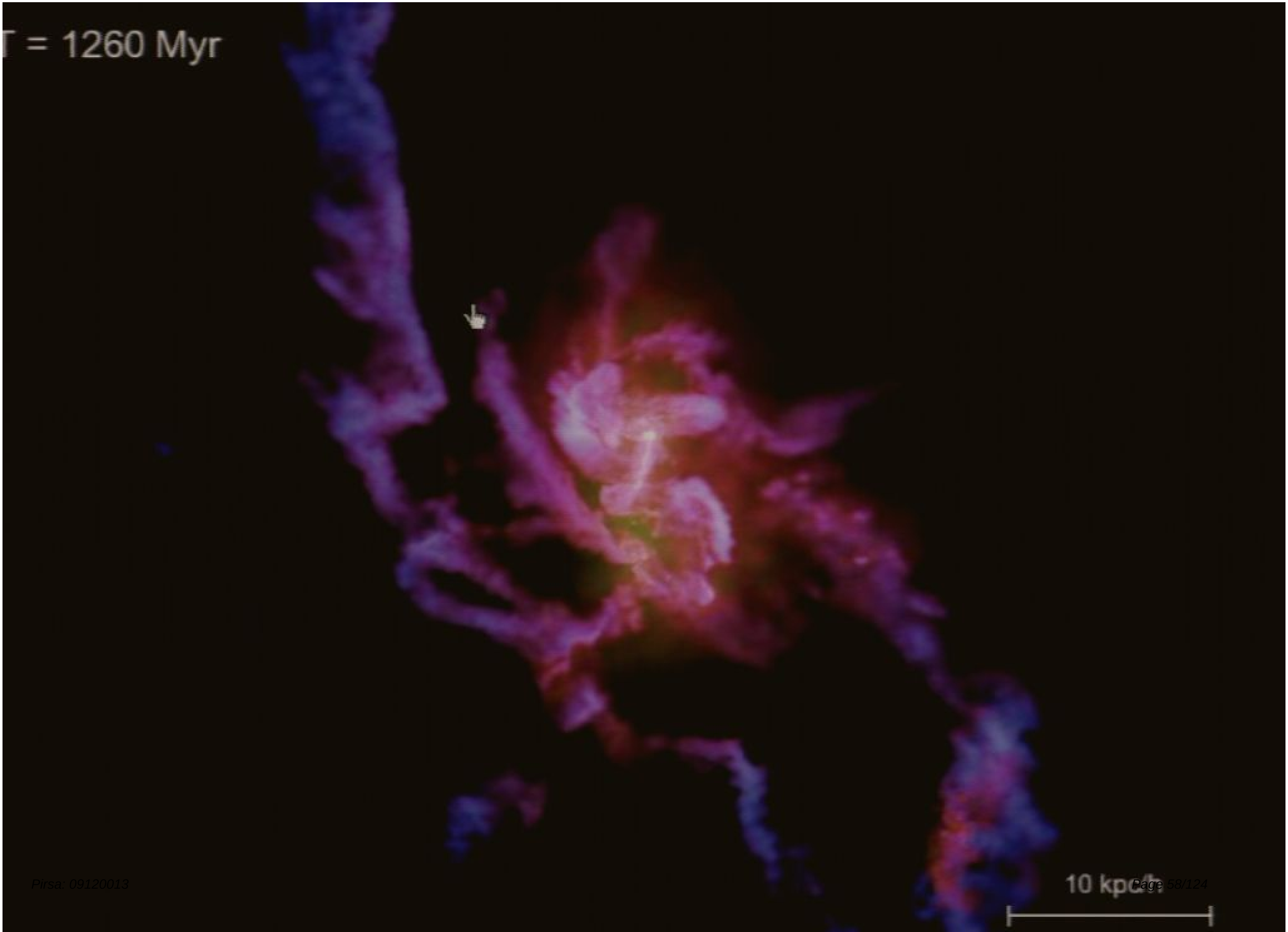

T = 760 Myr
10 kpc/h

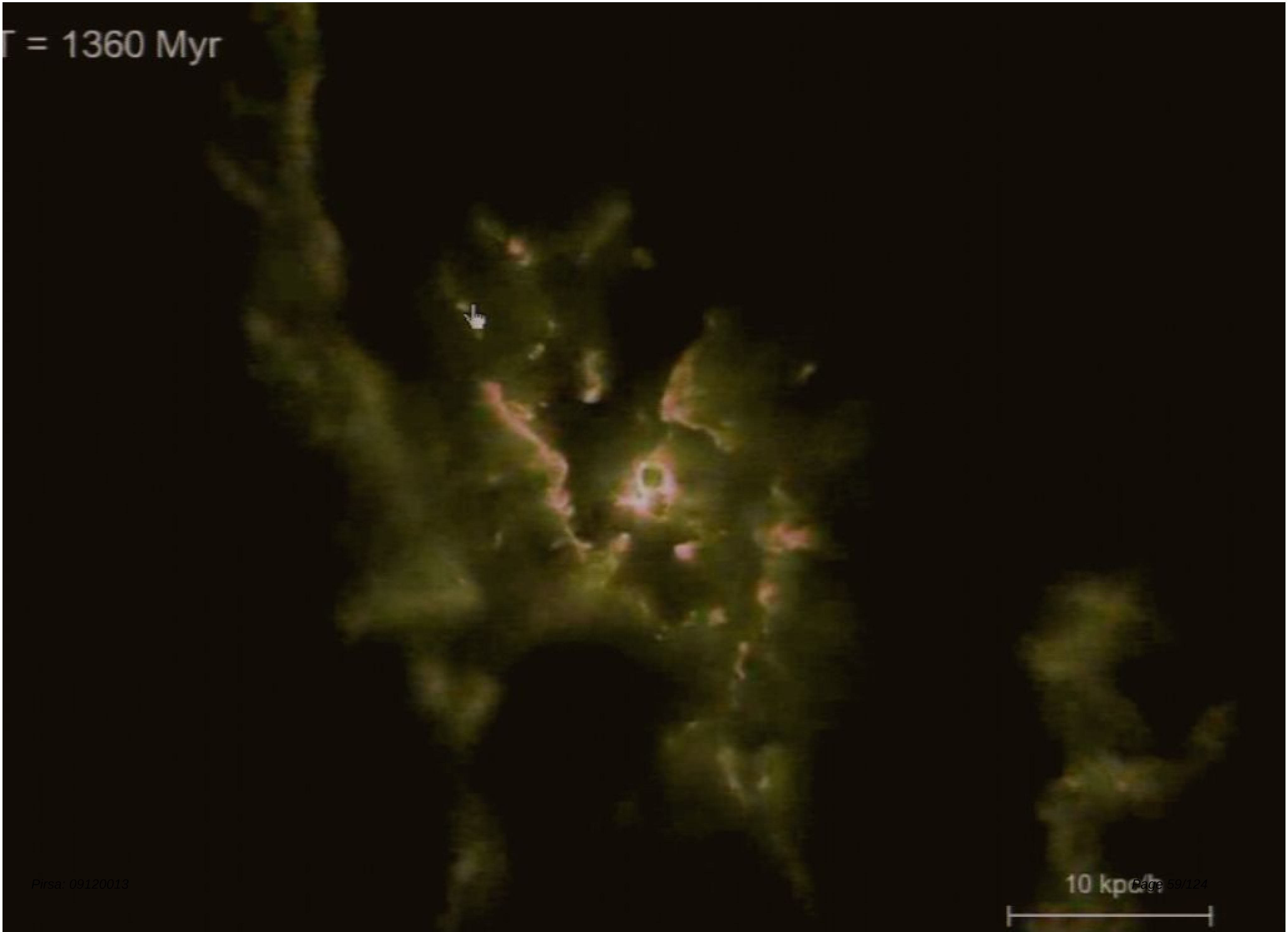

T = 900 Myr
10 kpc/h

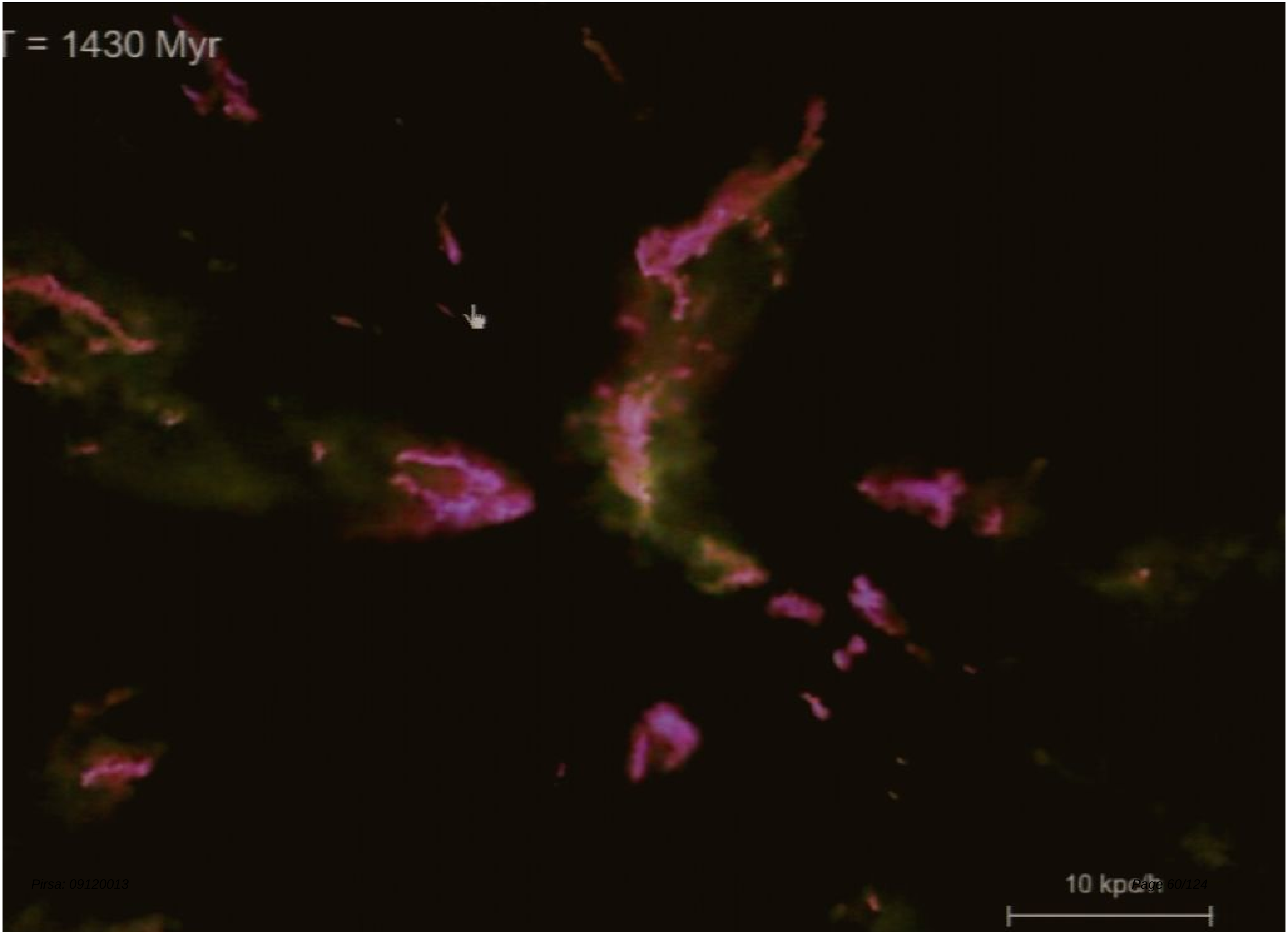

T = 1030 Myr
10 kpc/h

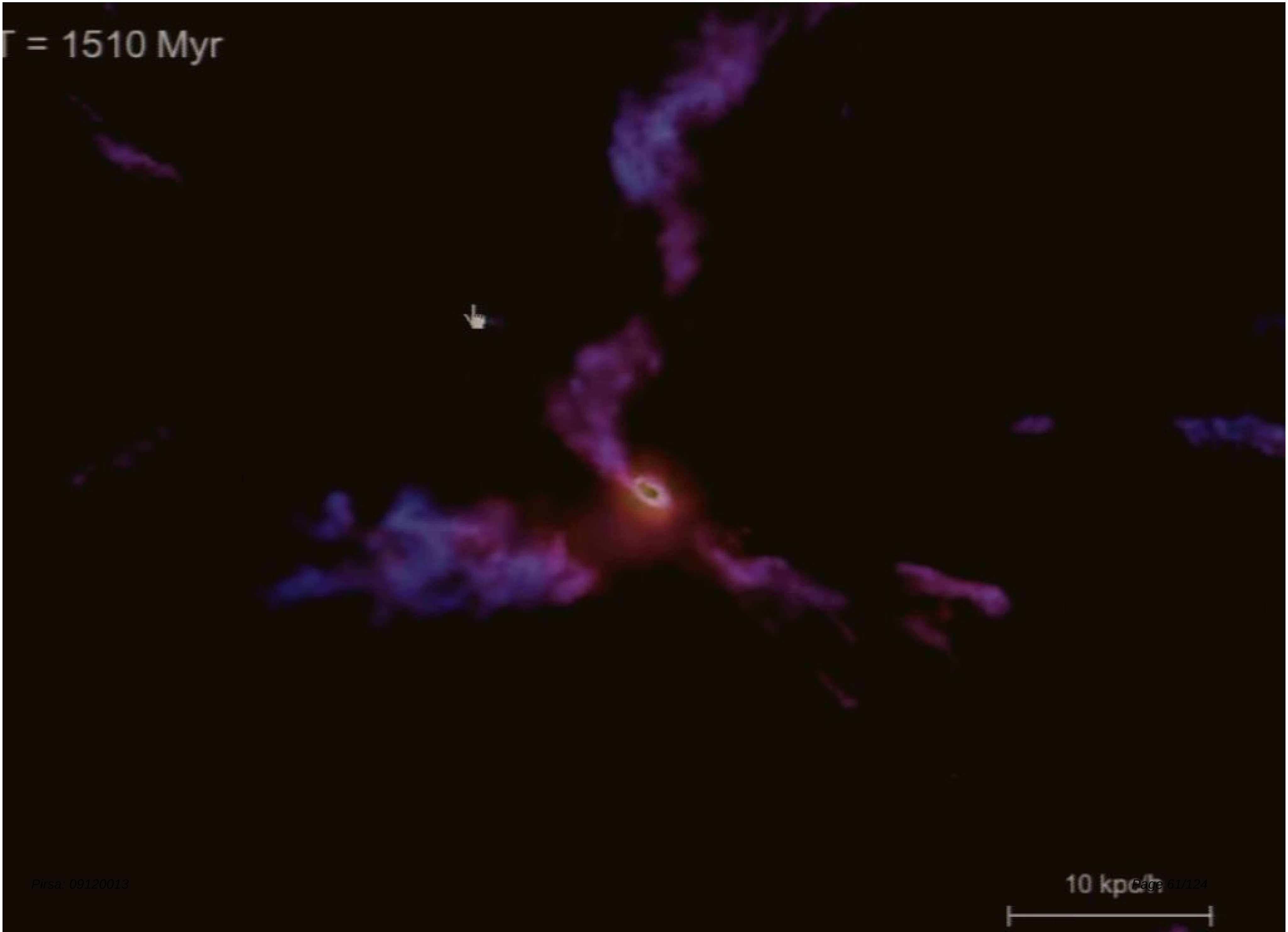

T = 1100 Myr
10 kpc/h

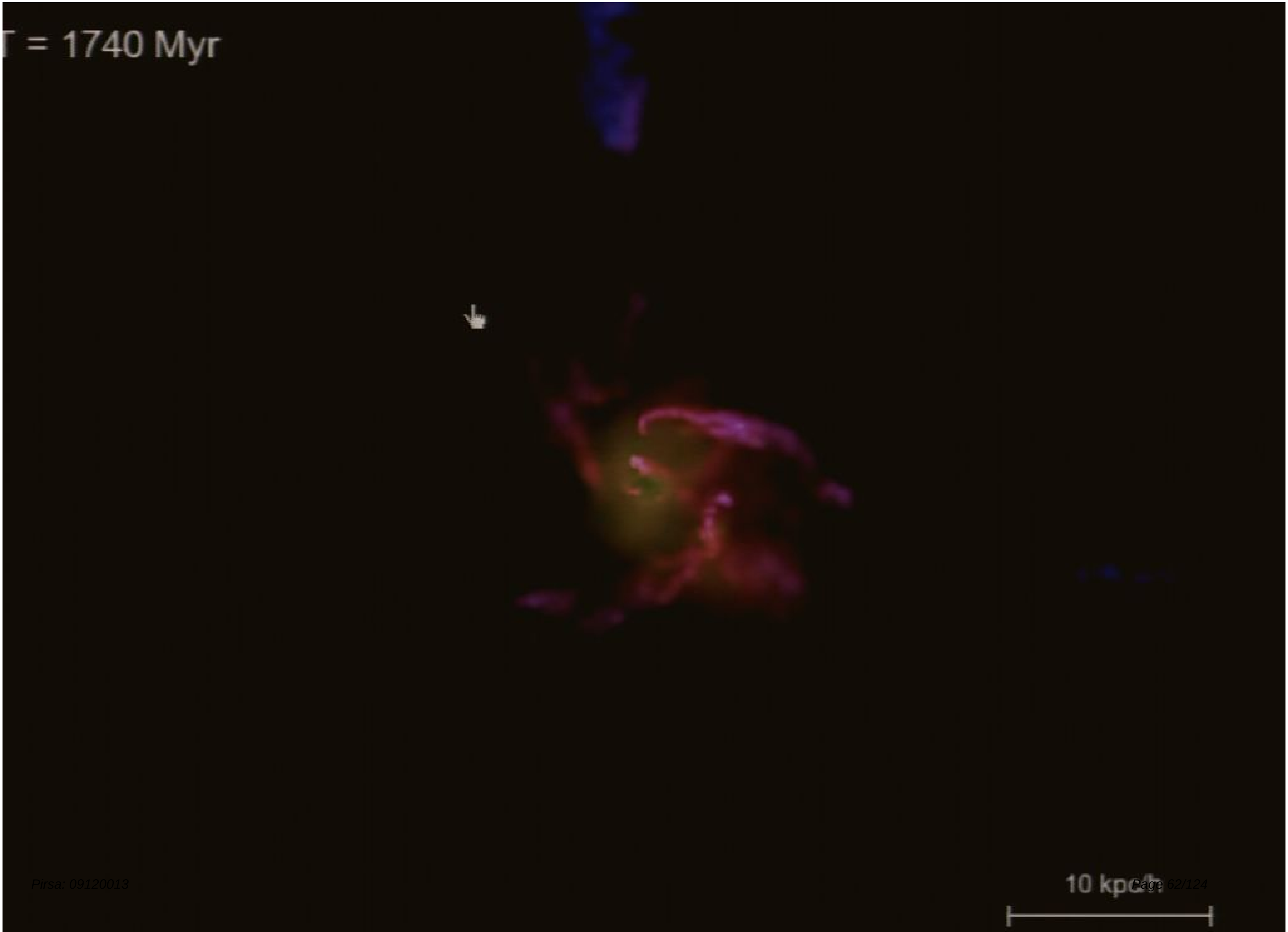

T = 1160 Myr
10 kpc/h

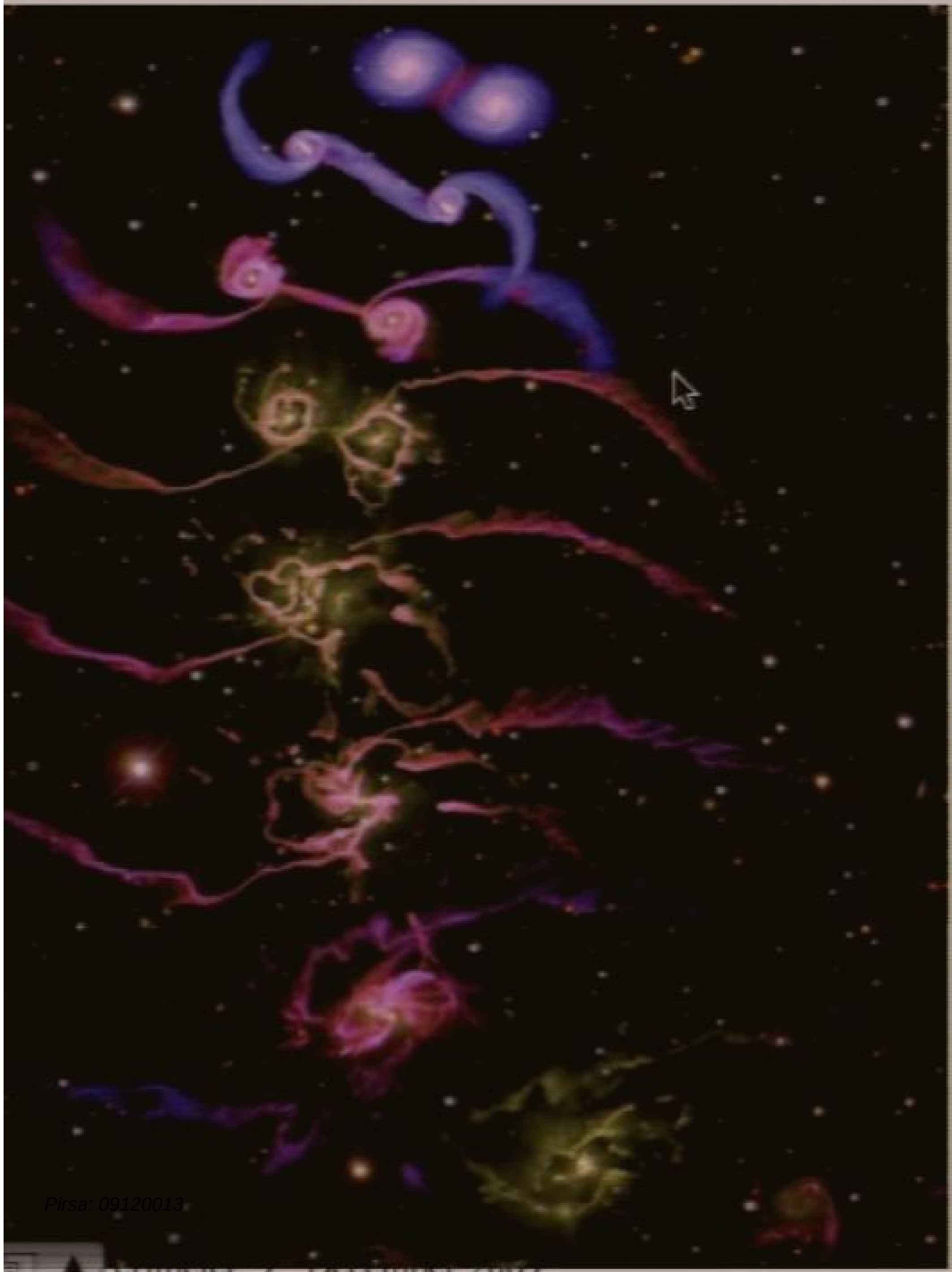

T = 1260 Myr
10 kpc/h


T = 1360 Myr
10 kpc/h


T = 1430 Myr
10 kpc/h

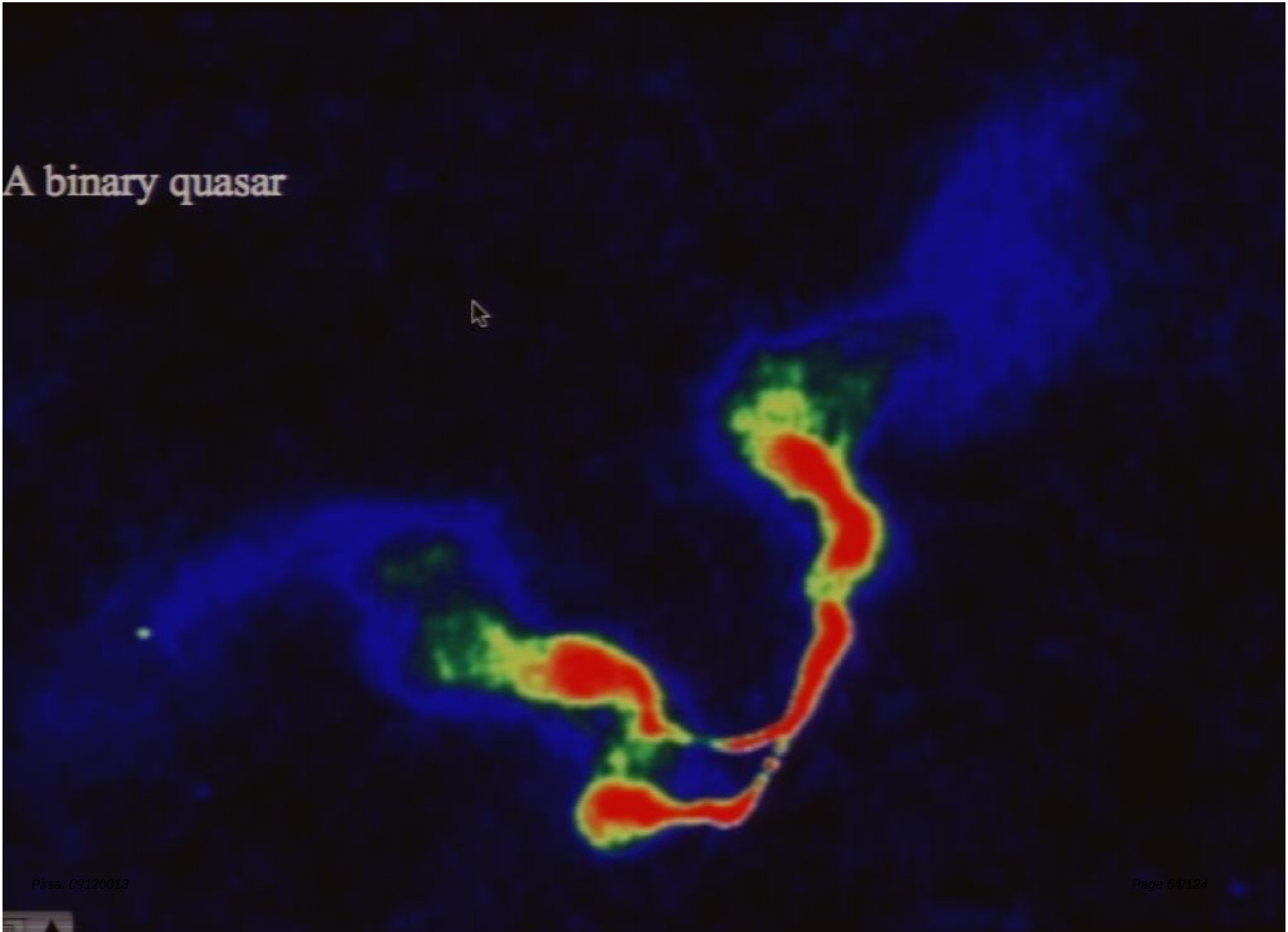

T = 1510 Myr
10 kpc/h

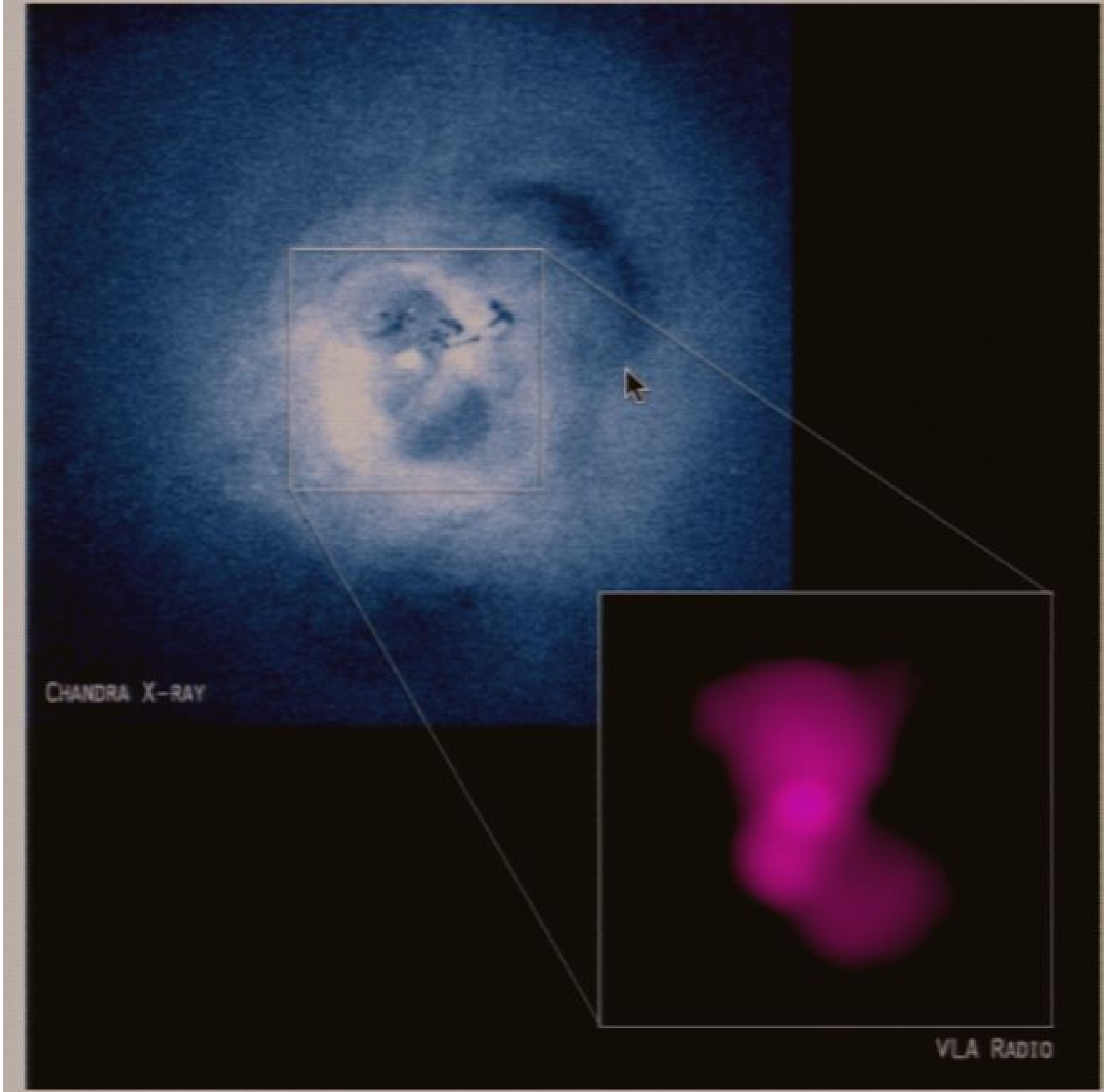

T = 1740 Myr
10 kpc/h



NGC2207

A binary quasar





Supermassive black holes heat the gas in galaxy clusters .

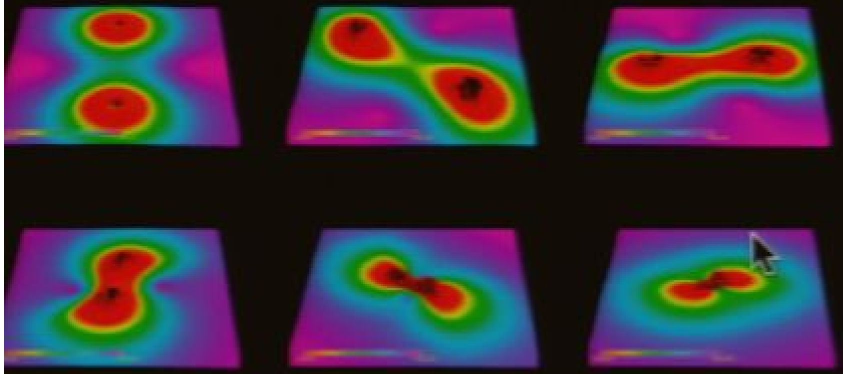
Sanders, Fabian et al.

A Revolution in Numerical Relativity

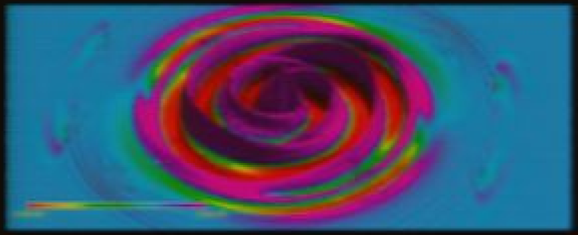
National Aeronautics and Space Administration
www.nasa.gov

SCIENCE MISSION DIRECTORATE

Modeling Gravitational Wave Sources for LISA



Snapshots showing a time sequence of the field representing the dynamics of two merging black holes.



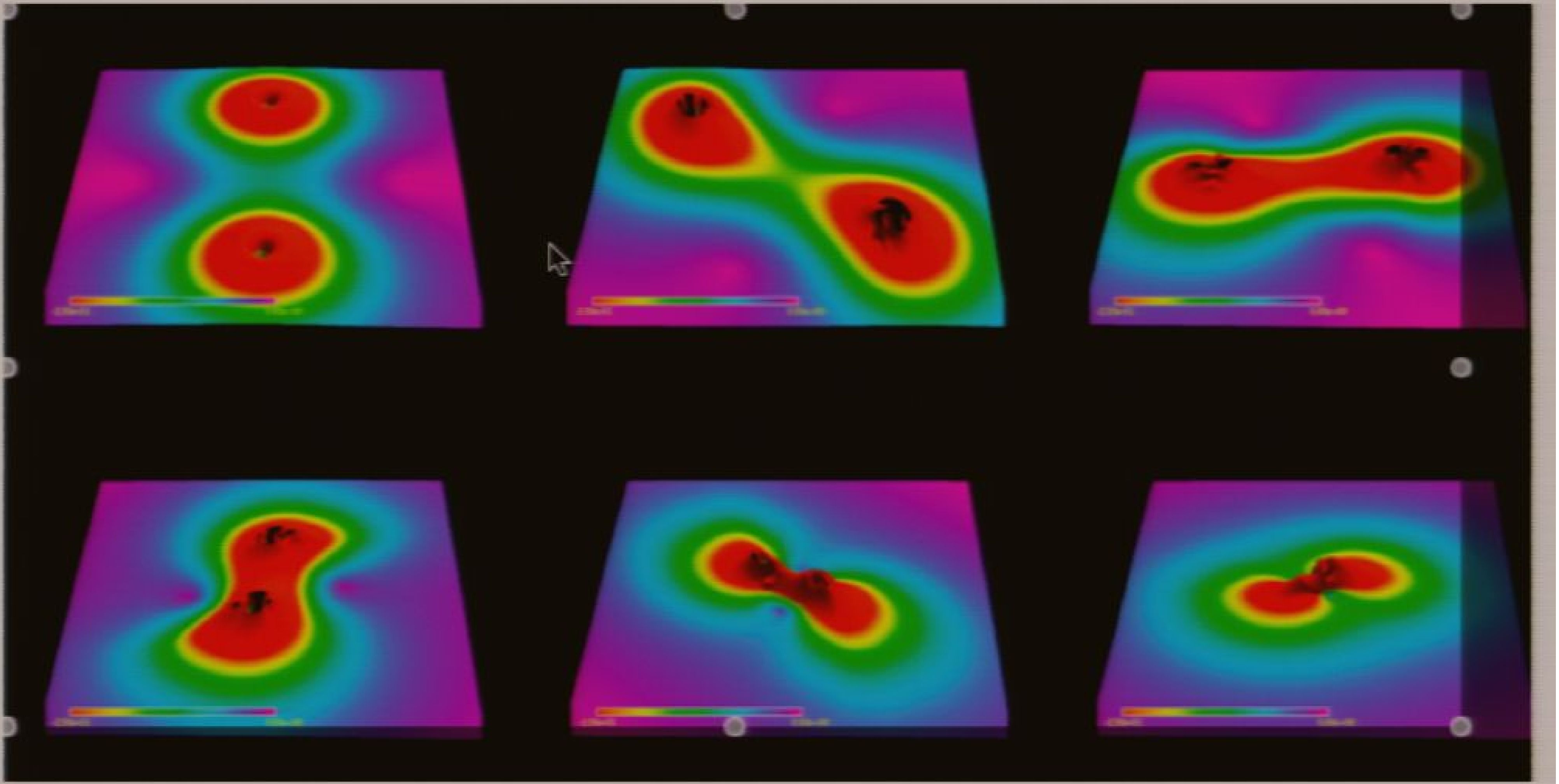
A snapshot showing the field representing gravitational waves generated from two inspiralling black holes.

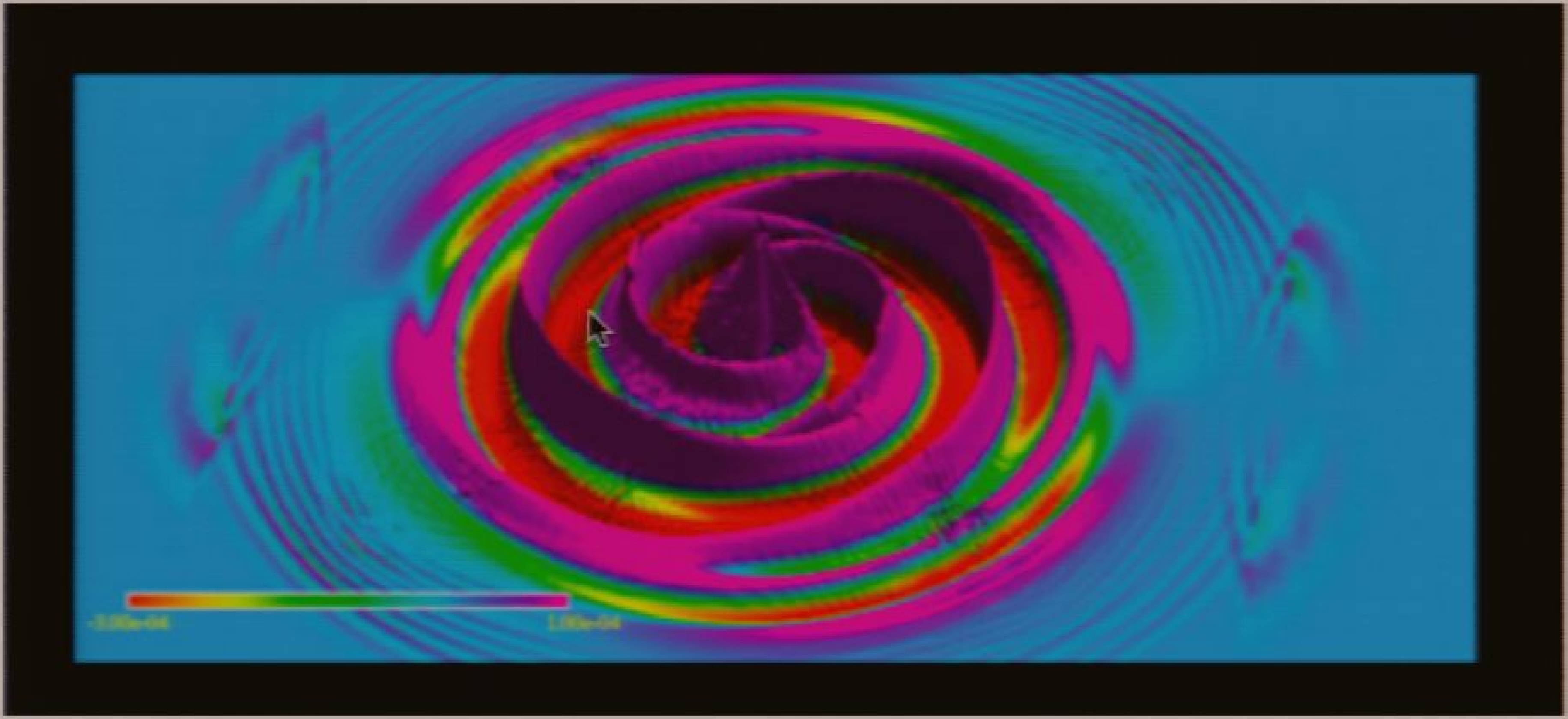
We model the astrophysical coalescence of comparable-mass, massive black hole binaries for different mass ratios and spins and calculate the resulting gravitational wave (GW) signatures. A key feature of our work is the use of mesh refinement techniques to handle the wide range of physical scales involved, from the black holes (~1M) to the gravitational waves (~10-100M), and to enable extraction of gravitational waveforms in the wave-zones.

Our methodology involves solving a closely coupled system of partial differential equations with many variables on a very large computational domain. Moreover, we use highly structured component-grids that are distributed across many processors, with a significant amount of communication between processors. Our simulations typically require hundreds of gigabytes and run on several hundred processors for hundreds of hours.

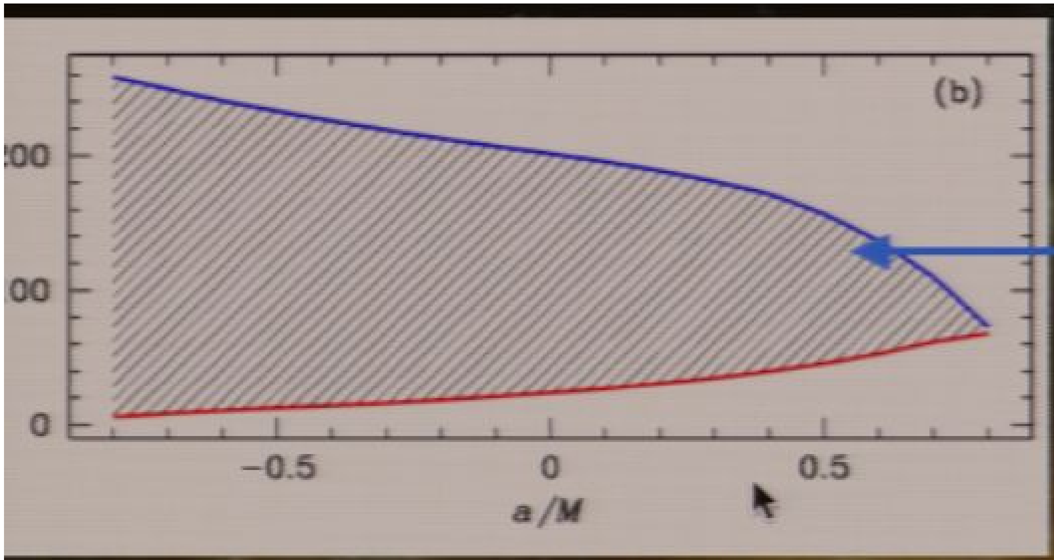
Astrophysical motivation guides our simulations. The waveforms determined by these simulations will be applied to analyzing and interpreting observed GW data from the Laser Interferometer Space Antenna (LISA) mission. Linear momentum loss due to asymmetrical radiation of GW in the unequal mass mergers imparts "kicks" to the merger remnant. High kick velocities from such mergers have the potential to strongly impact our understanding of how massive black holes have developed over cosmological time-scales.

http://universe.gsfc.nasa.gov/gravity/research/numrel.html





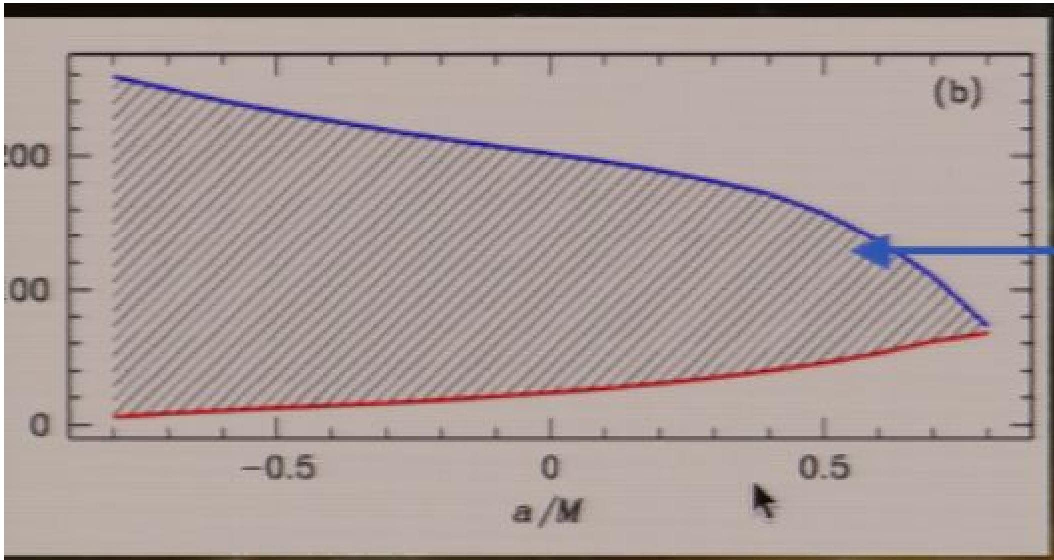
The merged black hole receives a recoil “kick” due to asymmetric gravitational wave emission.



Favata et al. 2004

estimated kick velocity after binary merger

can be > 2000 kms^{-1} for anti-aligned spins!

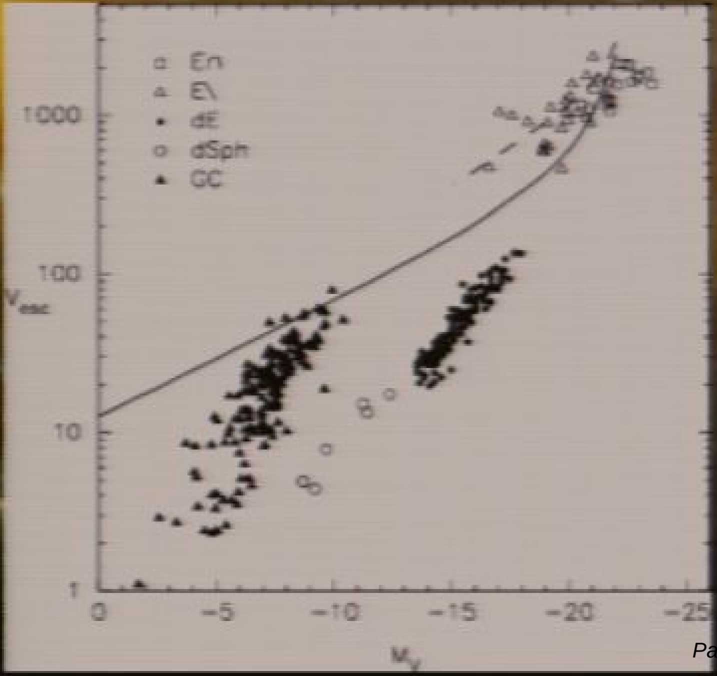


Favata et al. 2004

estimated kick velocity after binary merger

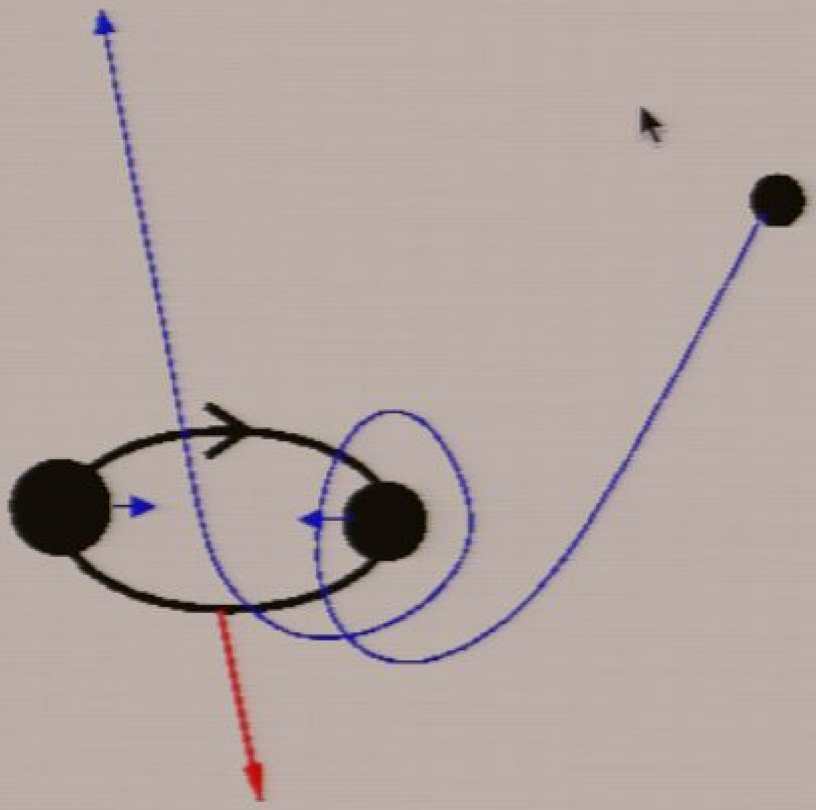
can be > 2000 kms^{-1} for anti-aligned spins!

escape velocity from galaxies



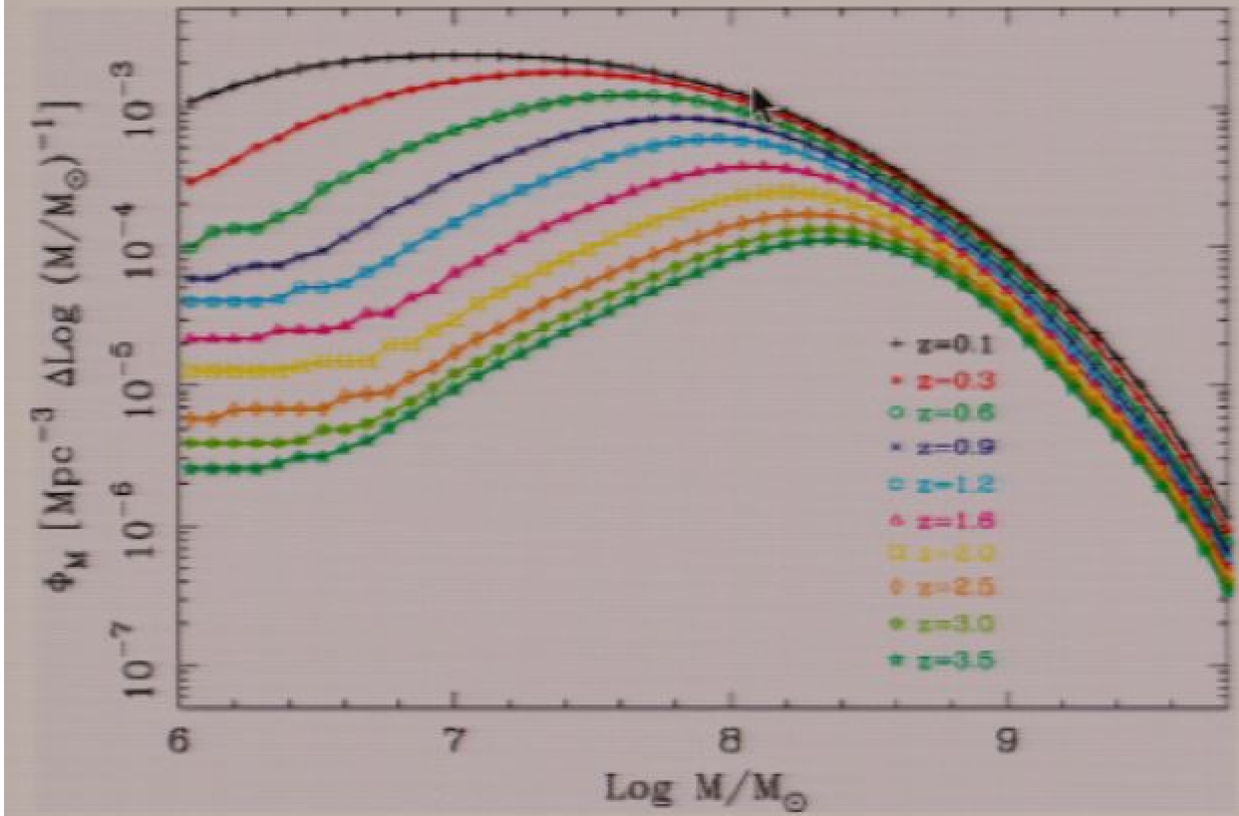
Merritt et al. 2004

Triple Interactions



If the binary does not coalesce before a third black hole falls in sling shot ejection of the lightest or in some cases all three black holes will occur

Saslaw, Valtonen & Aarseth 1974

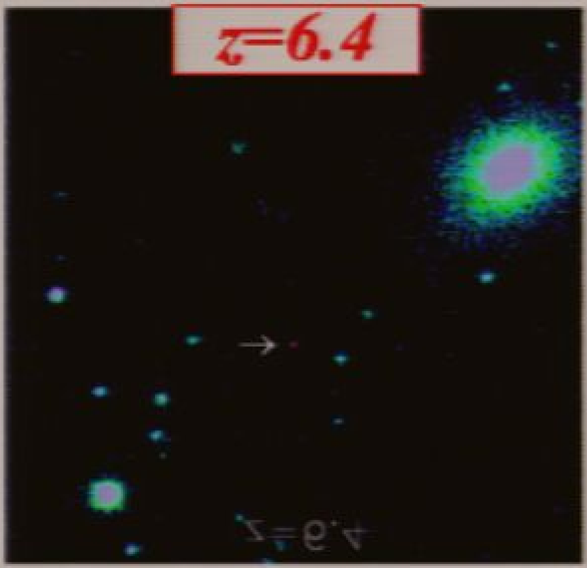


The co-evolution of galaxies and their central supermassive galaxies is now reasonably well Understood.

Merloni 2004

But how do supermassive black holes form in the first place?

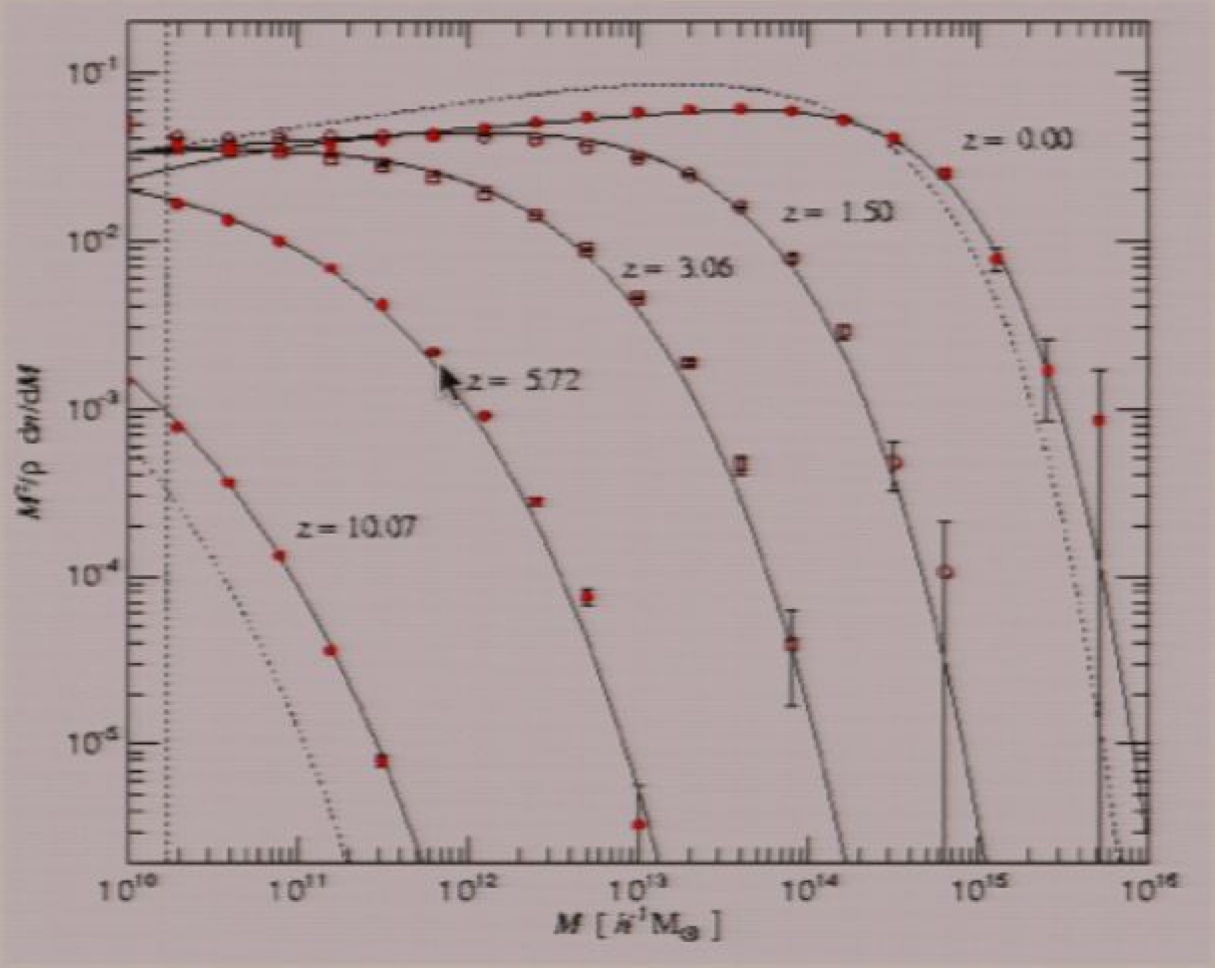
Is this the Rosetta stone?



Black holes as massive as the most massive black holes today have already formed at z=6.4.

Estimated mass: 3 x 10^9 Msol

Fan et al.



Springel et al 2005

Sufficiently massive haloes do exist at z=6.

Eddington-limited accretion

Radiation pressure due to Thomson scatteing on electrons equals gravitational attraction if

$$\frac{GMm_{\mathrm{p}}}{r^2} = \frac{L_{\mathrm{Edd}}\ \sigma_{\mathrm{T}}}{c\ 4\pi\ r^2}$$

The luminosity due to accretion can be written as

$$L_{\mathrm{acc}} = \varepsilon\ \dot{M}\ c^2$$

The Eddington limit for (spherical) accretion is

$$\dot{M}_{\mathrm{Edd}} = \varepsilon^{-1}\ \frac{Gm_{\mathrm{p}}}{c\sigma_{\mathrm{T}}}\ M$$

The characteristic timescale for Eddington limited exponential growth is

$$t_{\mathrm{Salp}} = \varepsilon\ \frac{c\sigma_{\mathrm{T}}}{4\pi\ Gm_{\mathrm{p}}} \approx 4.5\ \varepsilon_{0.1}\ 10^7\ \mathrm{yr}$$

Age of Universe at z=6.4: 0.8-0.9 Gyr

↓

For Eddington limited accretion only 20 $\varepsilon_{0.1}^{-1}$ e-foldings possible since Big Bang!

Growth from stellar mass seeds requires

Eddington-limited accretion with duty cycle close to one

and

efficient growth in shallow potential wells

and

("fine tuning" of space density of stellar mass black hole seeds to avoid excessive ejection by black hole recoils in hierarchically merging proto-galaxies)

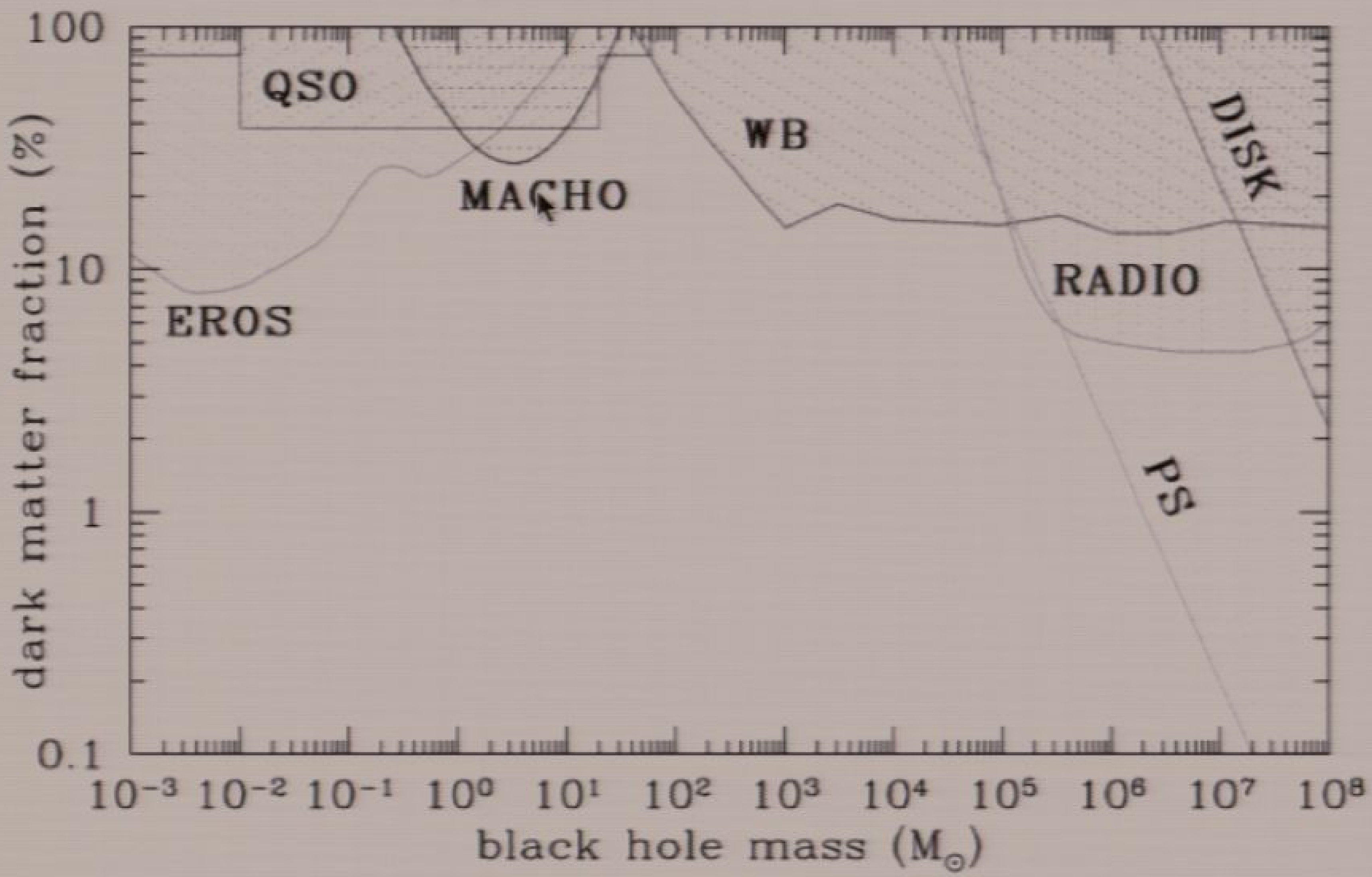
or

super-Eddington accretion

A): Primordial Black Holes

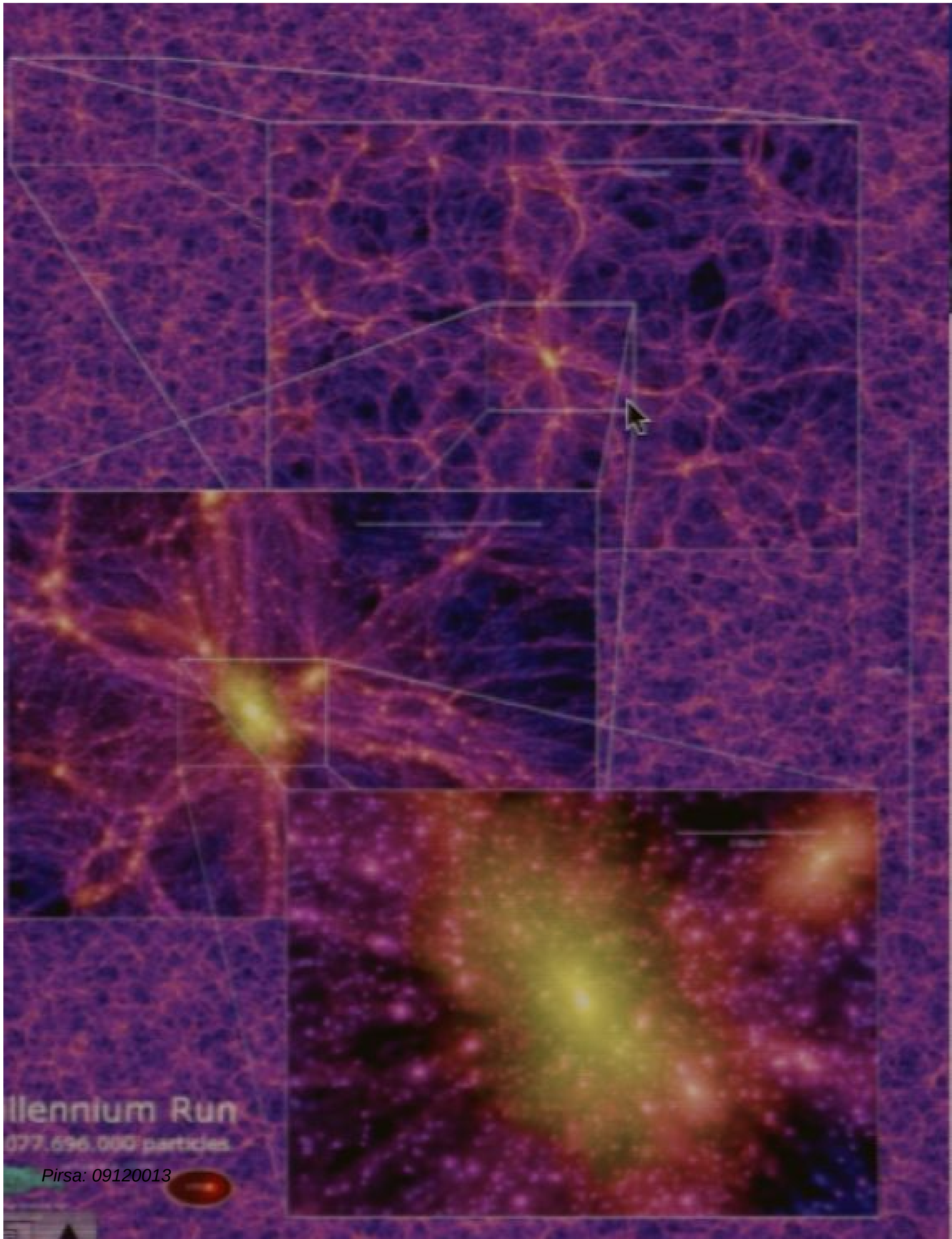
- Proposed by many authors as artifacts of phase changes at, for example, quark-hadron transition. No consensus.
- Fractional mass is small fraction of DM.
- At origin, some fraction of horizon mass.
- “Compensated” at birth but soon un-compensated.
- Distribution Poisson like.

Limits on primordial black holes



Mack, Ricotti & Ostriker

The early growth of supermassive black holes

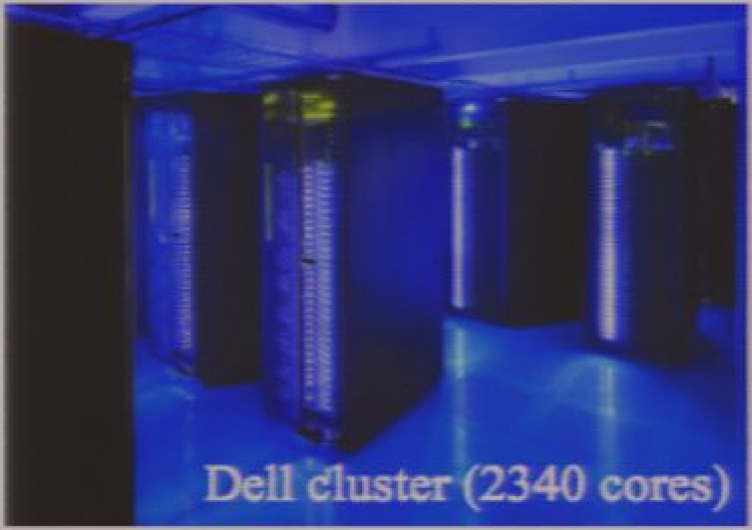


Volker Springel Deborah Sijacki

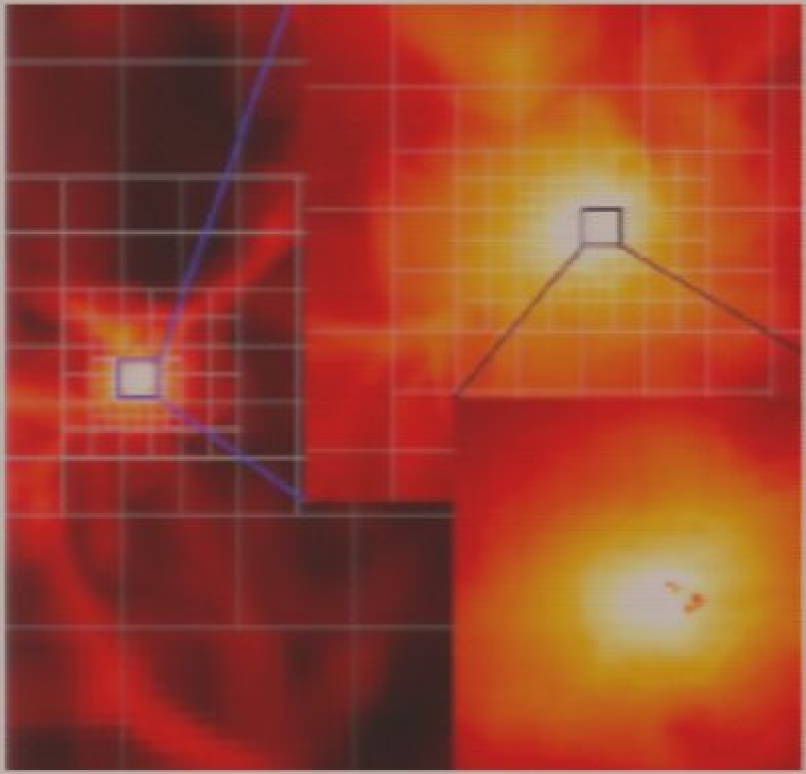
Resimulating the build-up of galaxies and black holes (including spin history and kicks due to gravitational wave re-coil) in the most massive halo at z=6 with higher resolution.

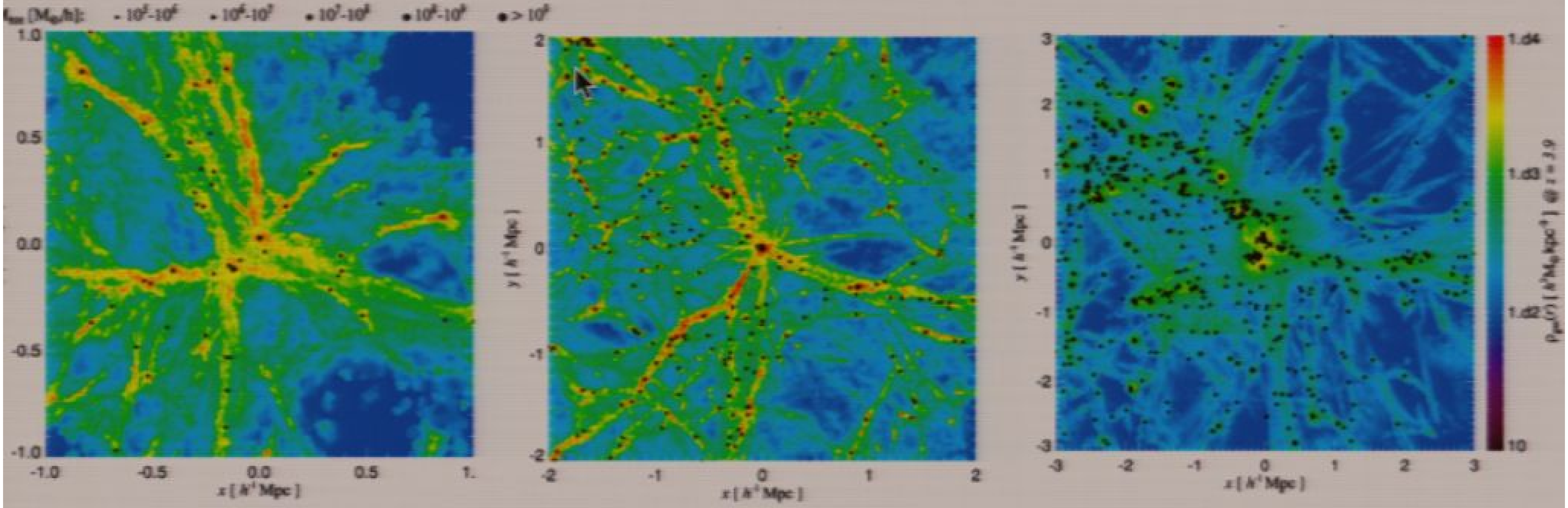
Cosmos

Darwin



ENZO AMR

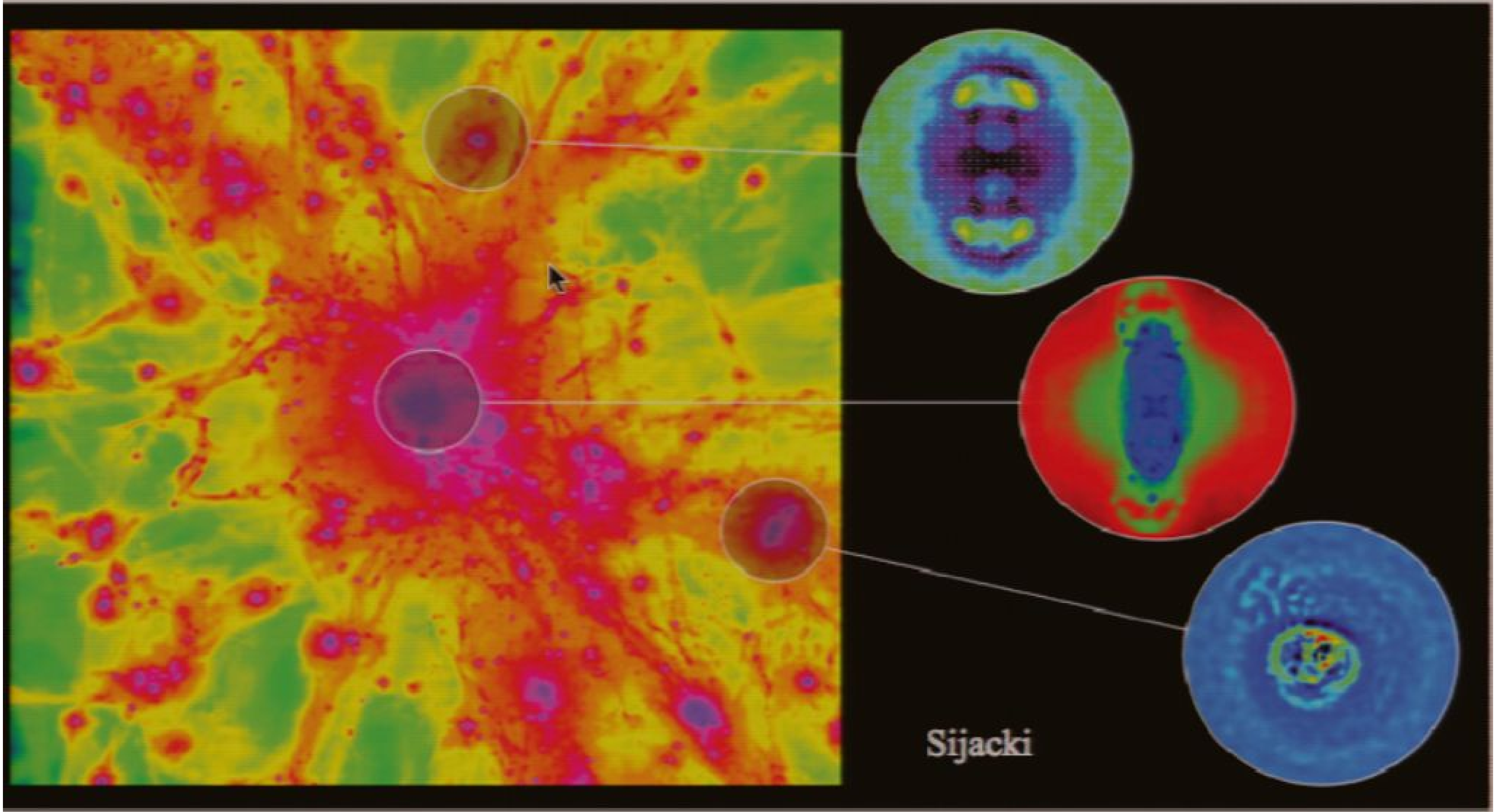



1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.
x [h⁻¹ Mpc]
2
1
0
-1
-2
-2
-1
0
1
2
y [h⁻¹ Mpc]
x [h⁻¹ Mpc]
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3
y [h⁻¹ Mpc]
x [h⁻¹ Mpc]
1.d4
1.d3
1.d2
10

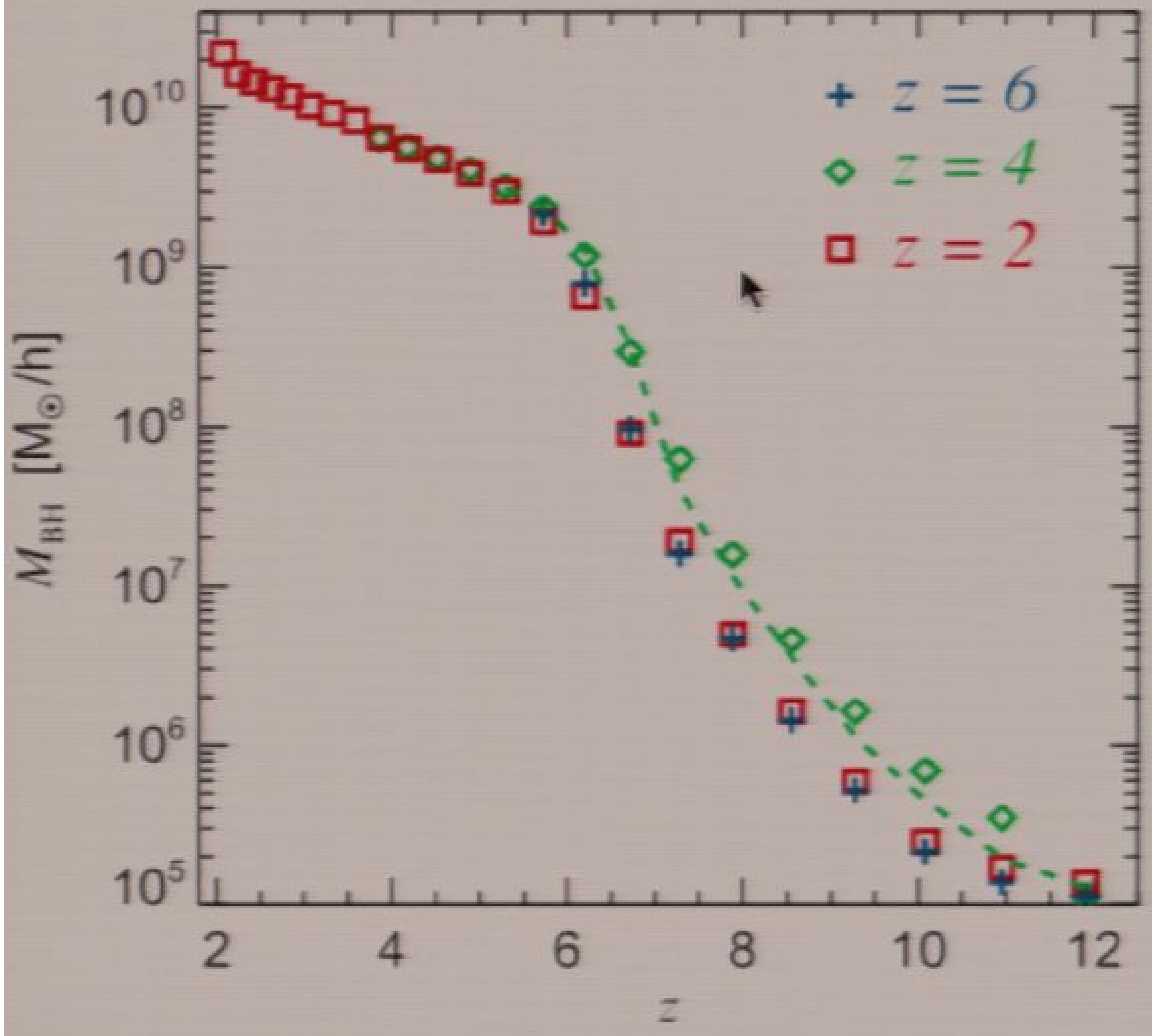
z=7.9

z=6.2

z=3.9

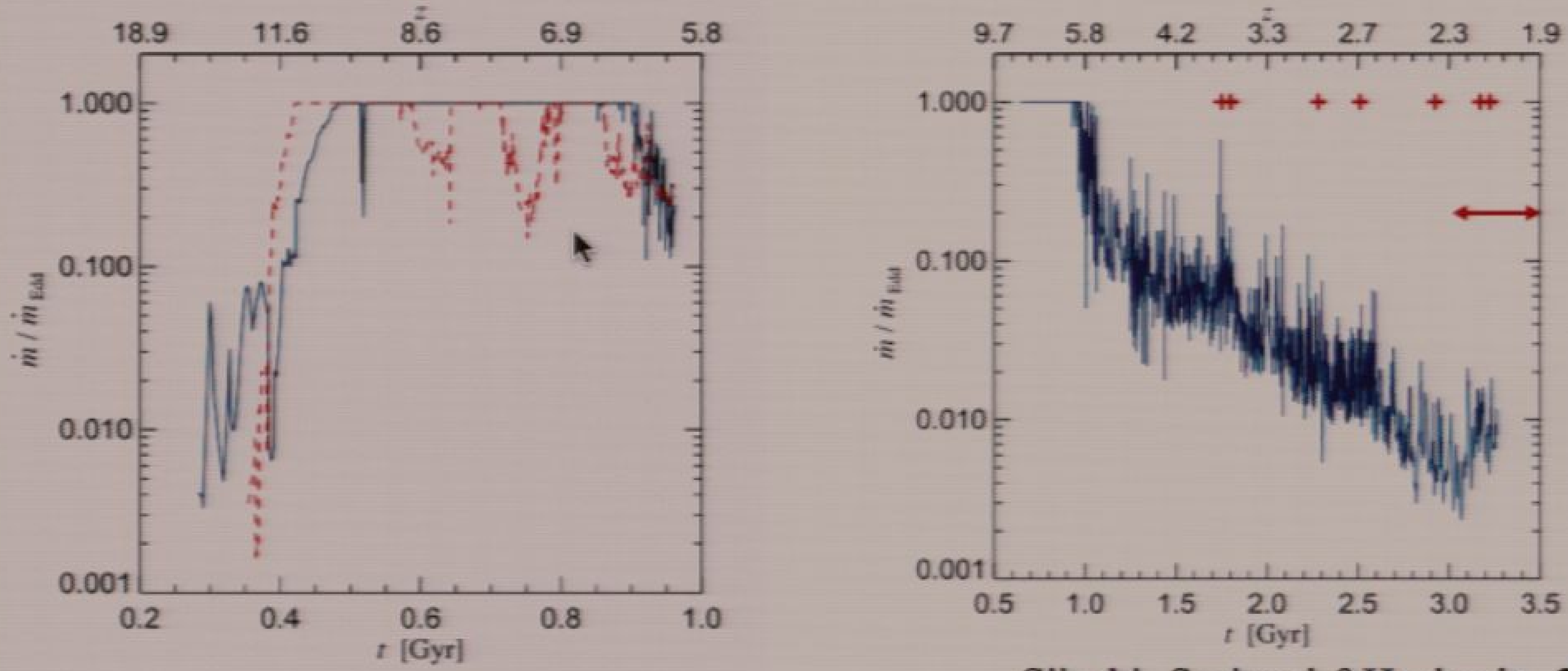


It is now possible to include most of the relevant physics.



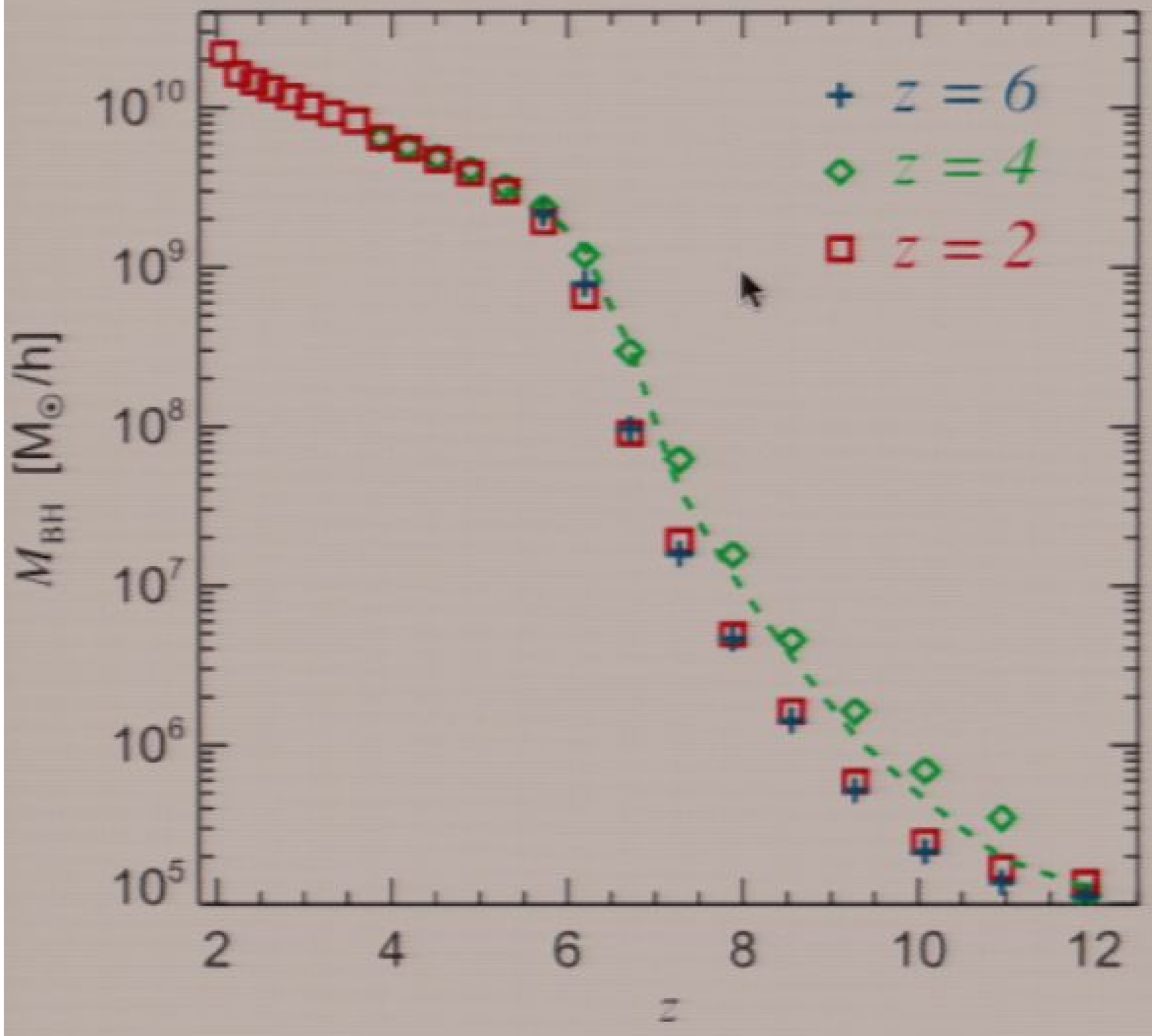
Sijacki, Springel &Haehnelt 2009

By z=6 the 10^5 $M_\odot$ seed black hole has grown into a supermassive black hole with mass several billion times that of the sun.



Sijacki, Springel &Haehnelt 2009

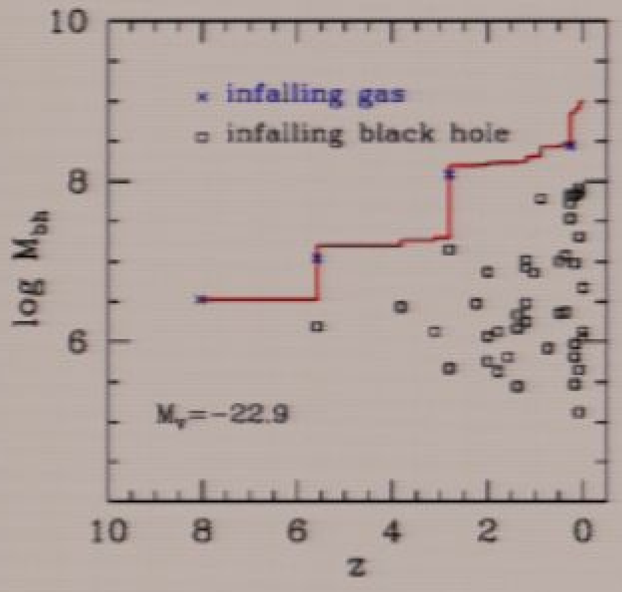
Early on the accretion rate is at the Eddington limit for more than 50% of the time.



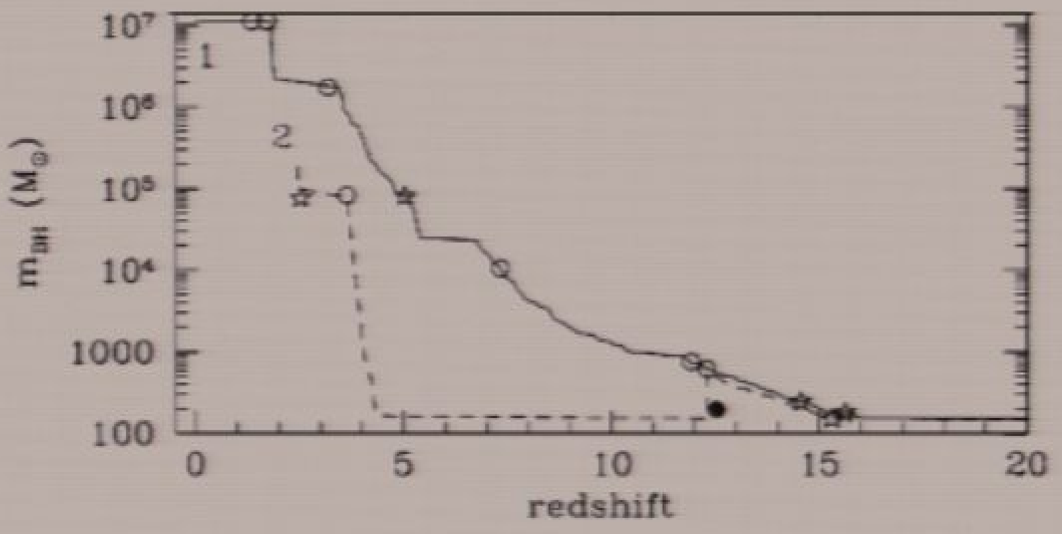
Sijacki, Springel &Haehnelt 2009

By z=6 the 10^5 $M_\odot$ seed black hole has grown into a supermassive black hole with mass several billion times that of the sun.

Perimeter, 9th December 2009



Kauffmann & Haehnelt



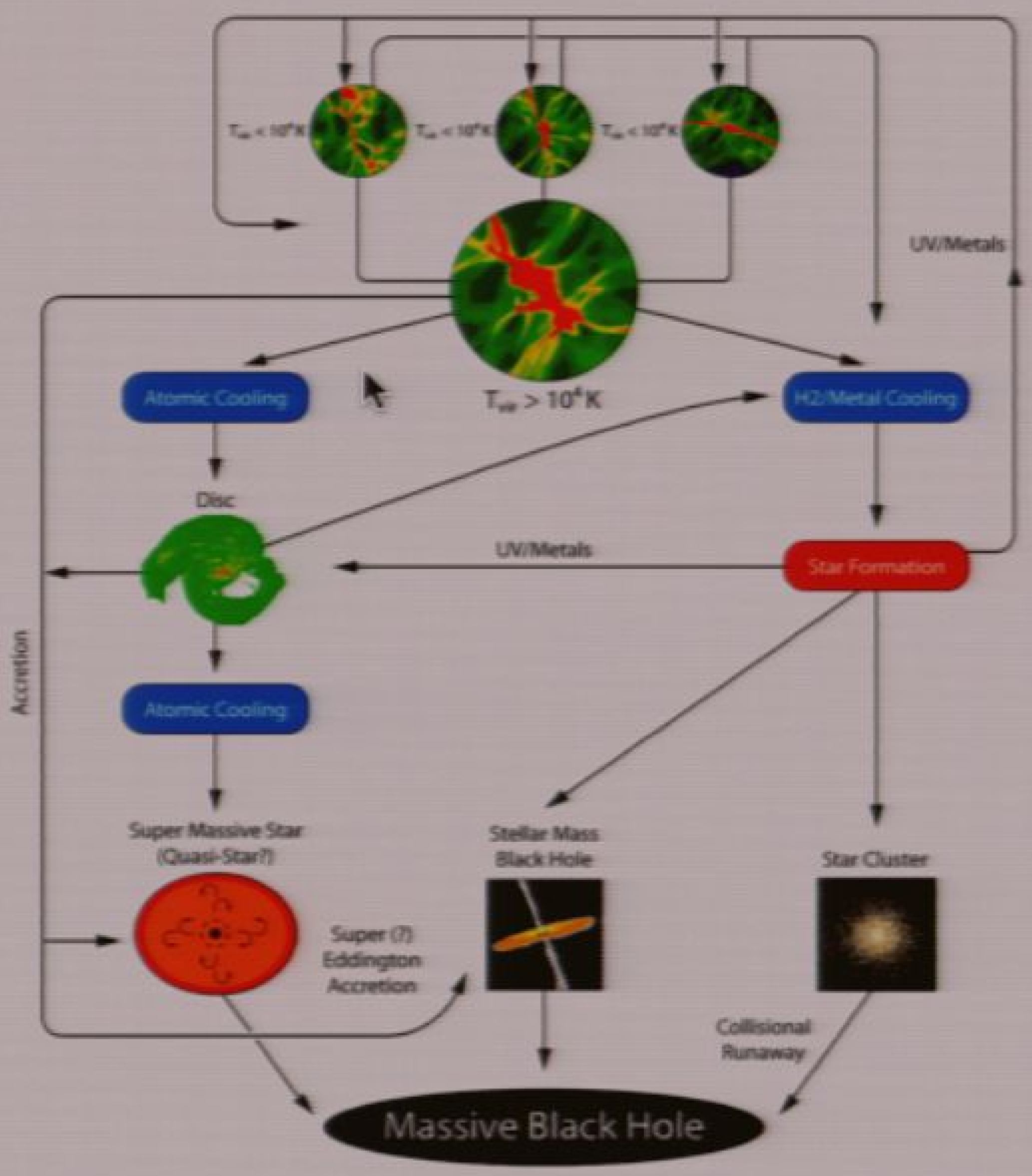
Volonteri et al.

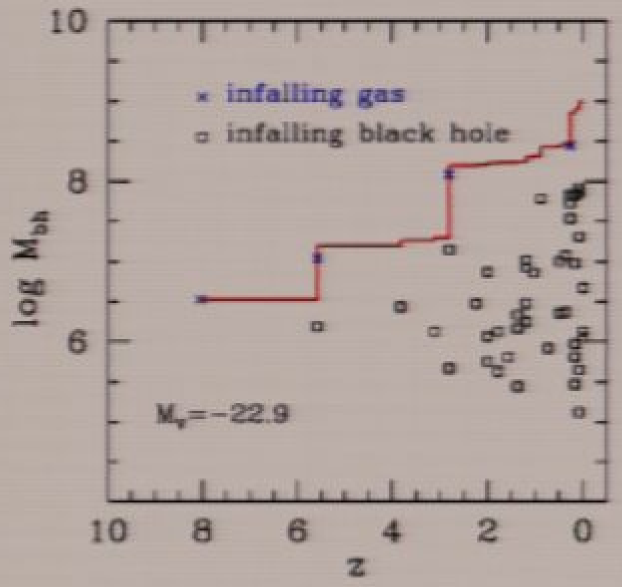
Does the hierarchical growth start with a minimum seed mass?

or

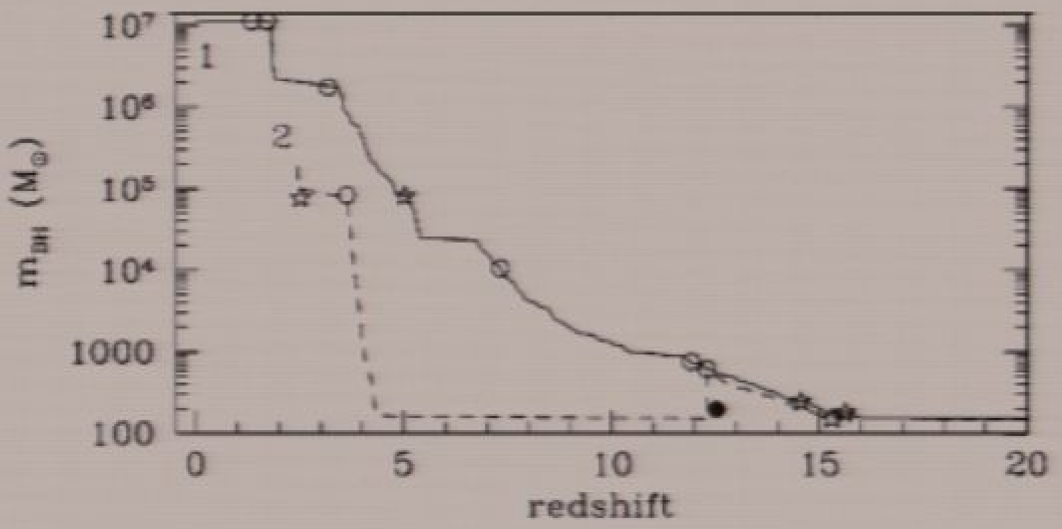
Does the hierarchical assembly extend all the way to stellar mass black holes?

We most probably need massive seed black holes.
How do massive seed black holes form?


$T_{vir} < 10^4$ K
$T_{vir} < 10^4$ K
$T_{vir} < 10^4$ K
UV/Metals
$T_{vir} > 10^4$ K
Atomic Cooling
H2/Metal Cooling
Disc
UV/Metals
Star Formation
Accretion
Atomic Cooling
Super Massive Star
(Quasi-Star?)
Stellar Mass
Black Hole
Star Cluster
Super (?)
Eddington
Accretion
Collisional
Runaway
Massive Black Hole



Kauffmann & Haehnelt



Volonteri et al.

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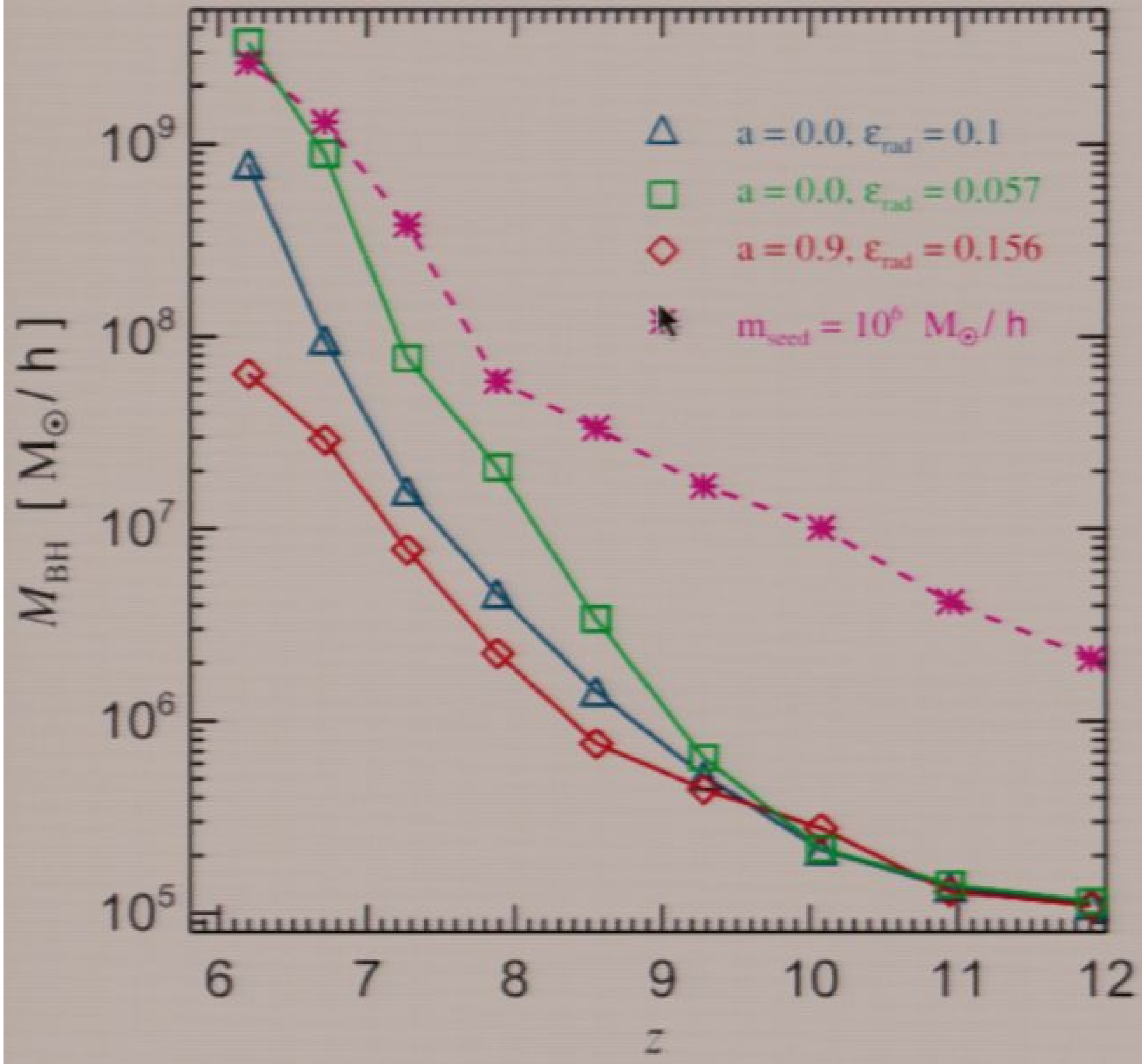
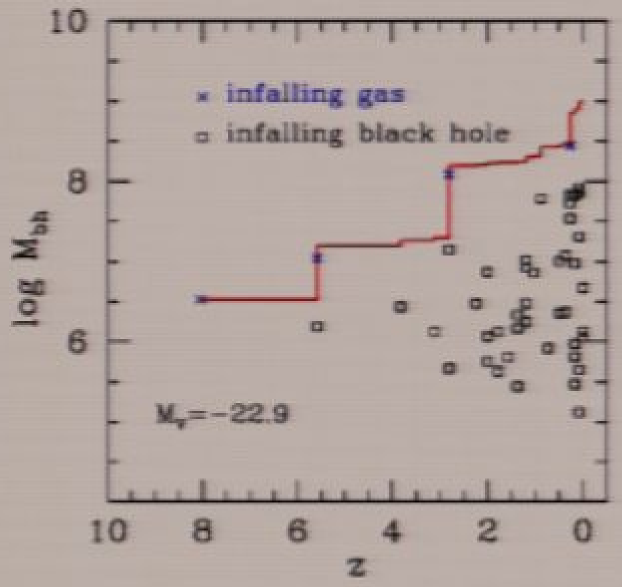
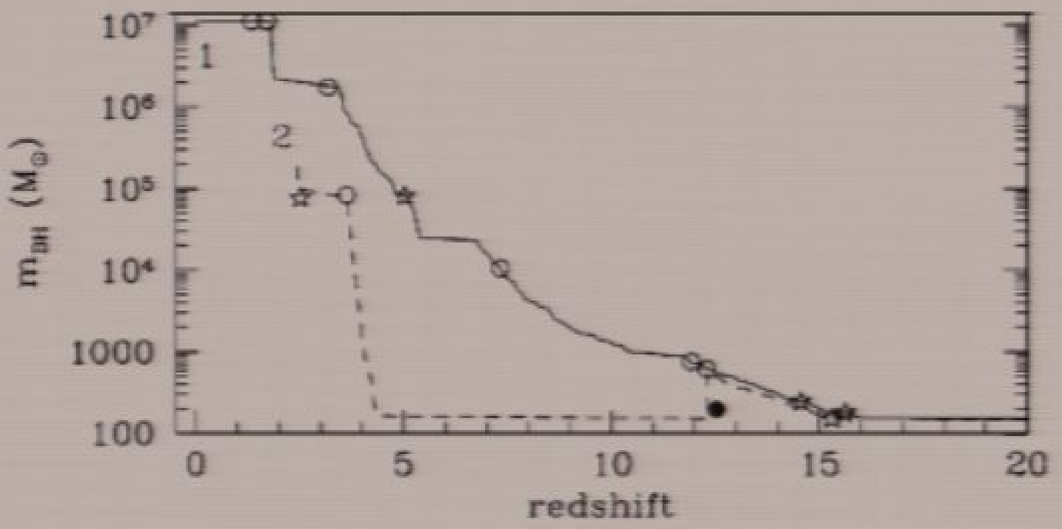


The mass at z=6 depends strongly on the radiative efficiency of the accretion and therefore on the spin of the black hole.



Kauffmann & Haehnelt



Volonteri et al.

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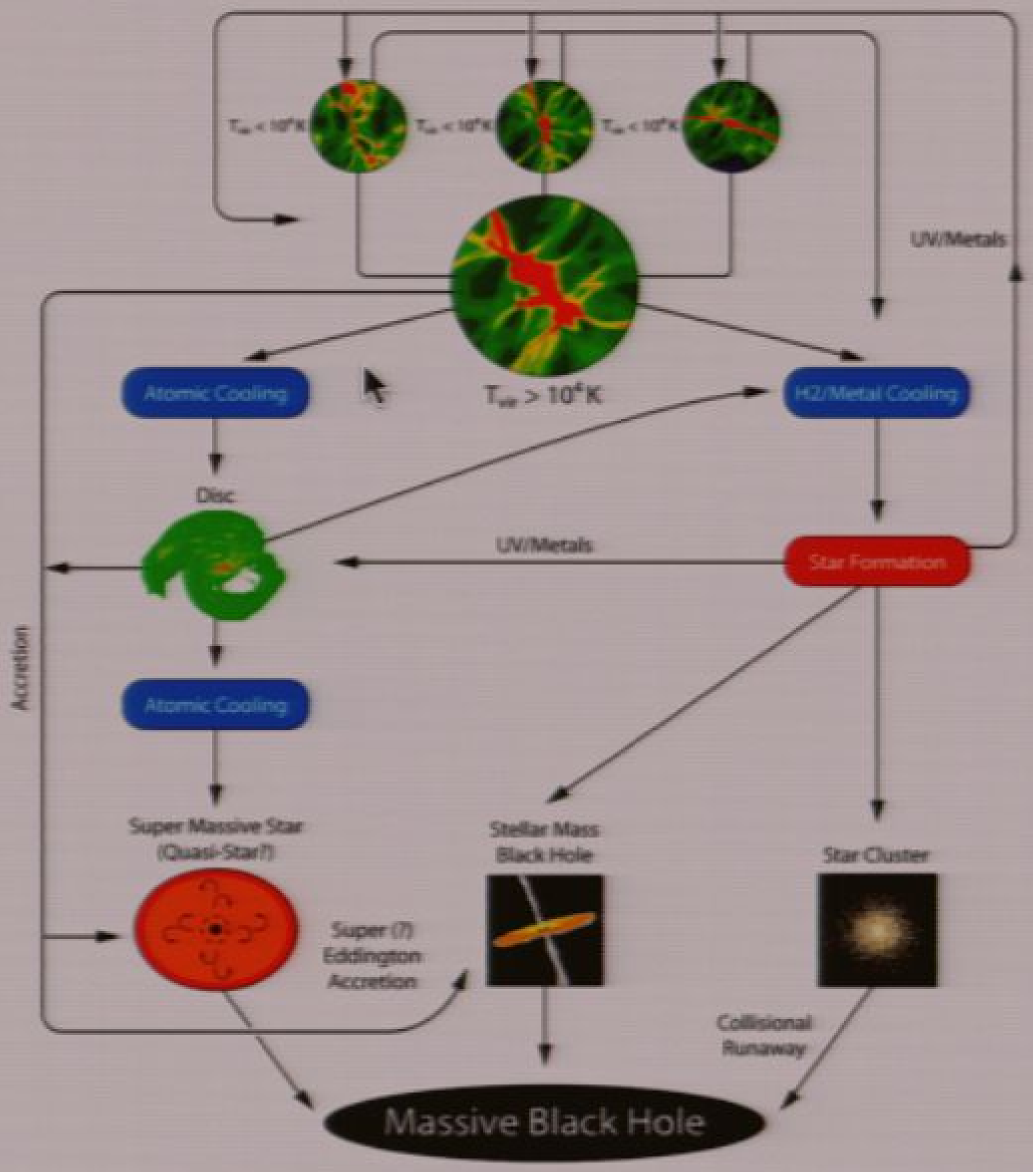
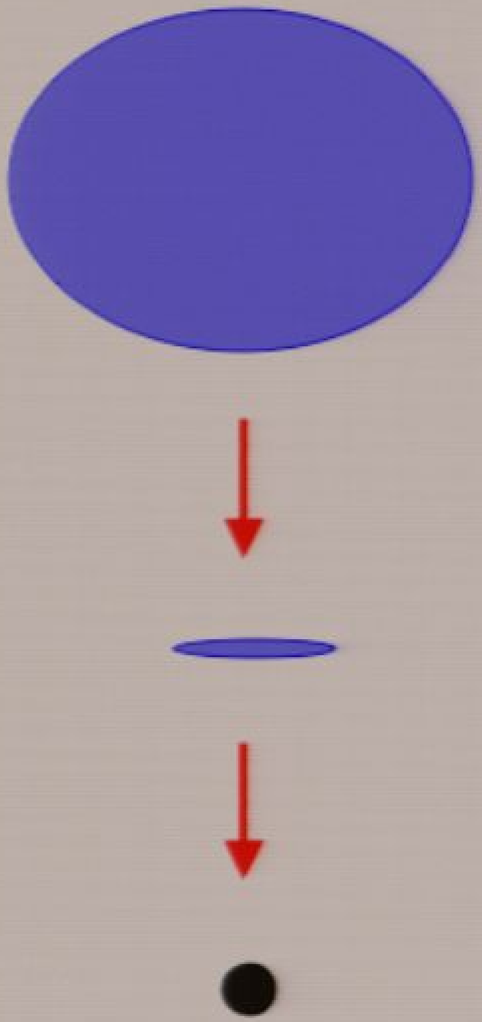


Perimeter, 9th December 2009

Direct collapse into a compact massive self-gravitating disc

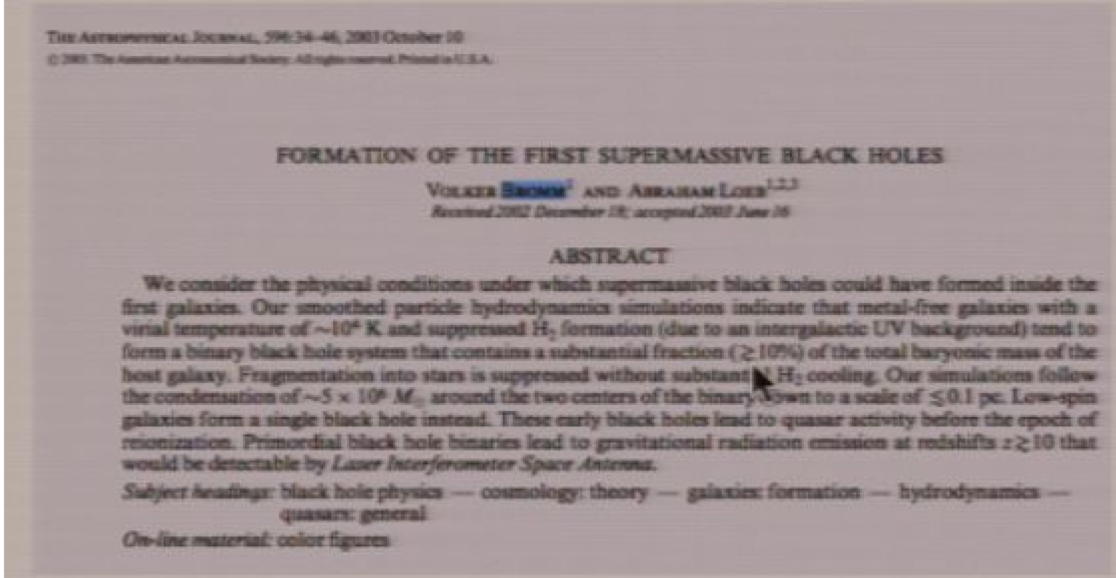


H_2 cooling
metal cooling

↔

fragmentation

haloes with $T_{vir} \geq$ 10000K
with no metals (and H_2 supression)
are least prone to fragmentation



The Astrophysical Journal, 596:34–46, 2003 October 10

FORMATION OF THE FIRST SUPERMASSIVE BLACK HOLES

Volker Bromm[1] and Abraham Loeb[1,2,3]

Received 2002 December 19; accepted 2003 June 16

ABSTRACT

We consider the physical conditions under which supermassive black holes could have formed inside the first galaxies. Our smoothed particle hydrodynamics simulations indicate that metal-free galaxies with a virial temperature of $\sim 10^4$ K and suppressed H_2 formation (due to an intergalactic UV background) tend to form a binary black hole system that contains a substantial fraction ($\gtrsim 10\%$) of the total baryonic mass of the host galaxy. Fragmentation into stars is suppressed without substantial H_2 cooling. Our simulations follow the condensation of $\sim 5 \times 10^6\, M_\odot$ around the two centers of the binary down to a scale of $\lesssim 0.1$ pc. Low-spin galaxies form a single black hole instead. These early black holes lead to quasar activity before the epoch of reionization. Primordial black hole binaries lead to gravitational radiation emission at redshifts $z \gtrsim 10$ that would be detectable by *Laser Interferometer Space Antenna.*

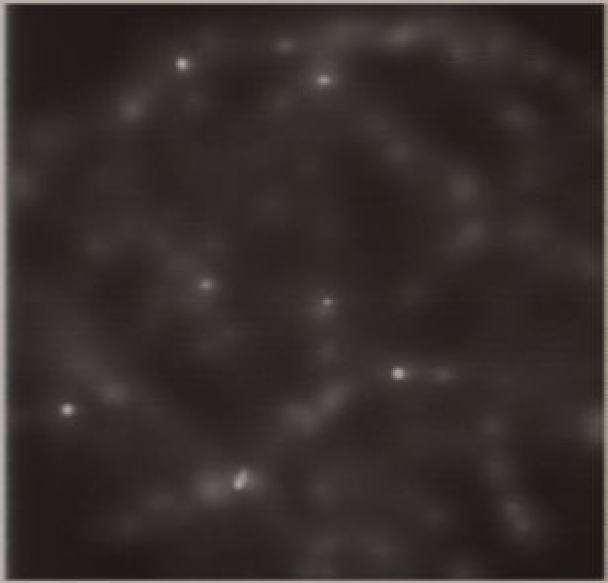
Subject headings: black hole physics — cosmology: theory — galaxies: formation — hydrodynamics — quasars: general

On-line material: color figures

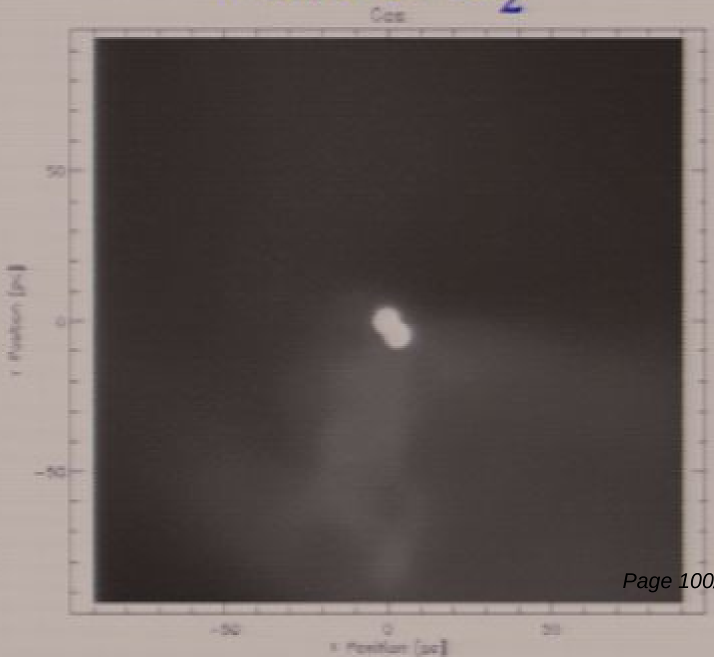
collapsing 10^4K halo:

strongly suppressed fragmentation without H_2 cooling

with H_2



without H_2



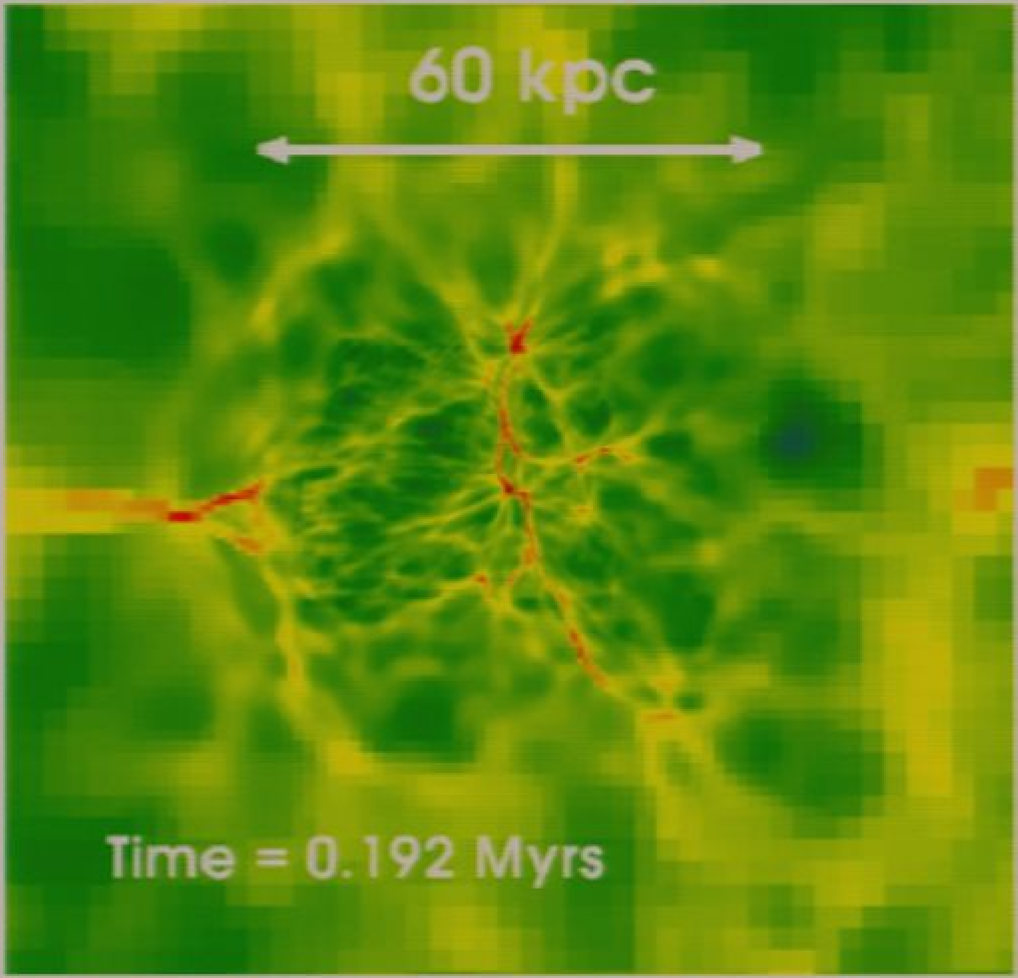
$T_{vir} \sim 35000K$

$V_{vir} \sim 30kms^{-1}$

$M_{tot} \sim 3.3 \times 10^8 M_\odot$

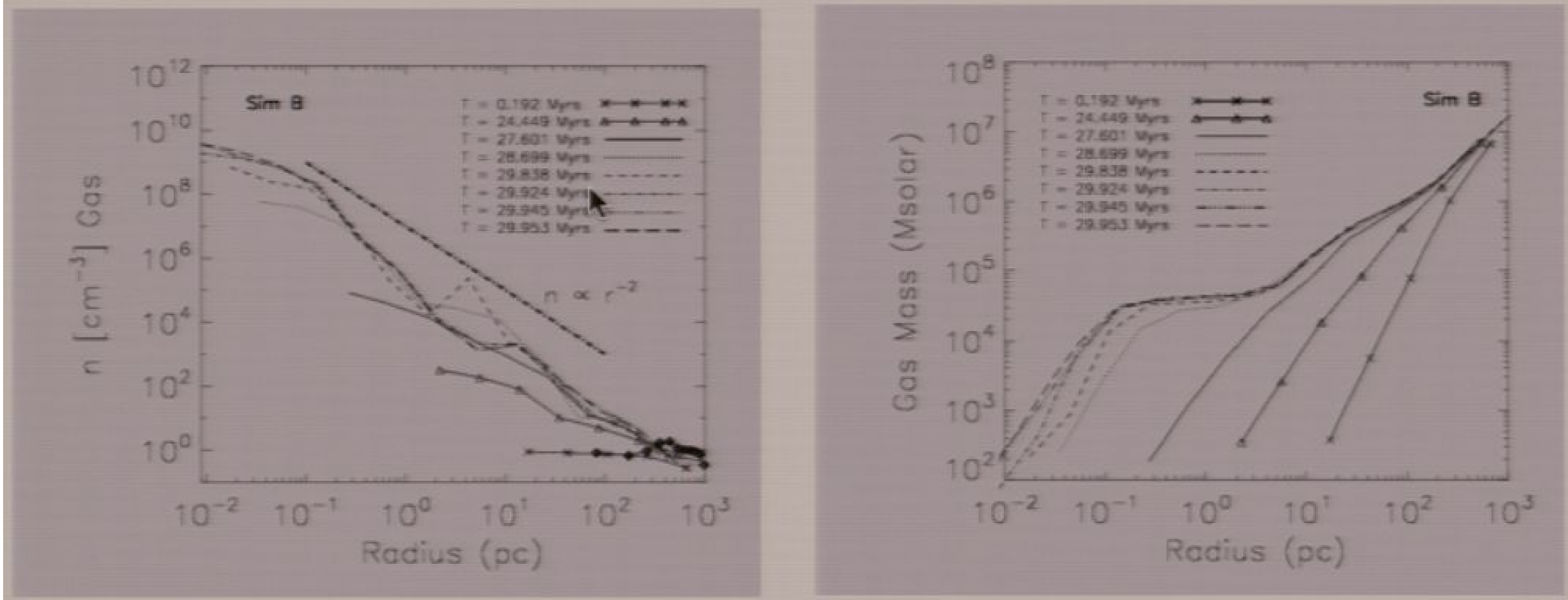
$z \sim 15$

no H_2 cooling



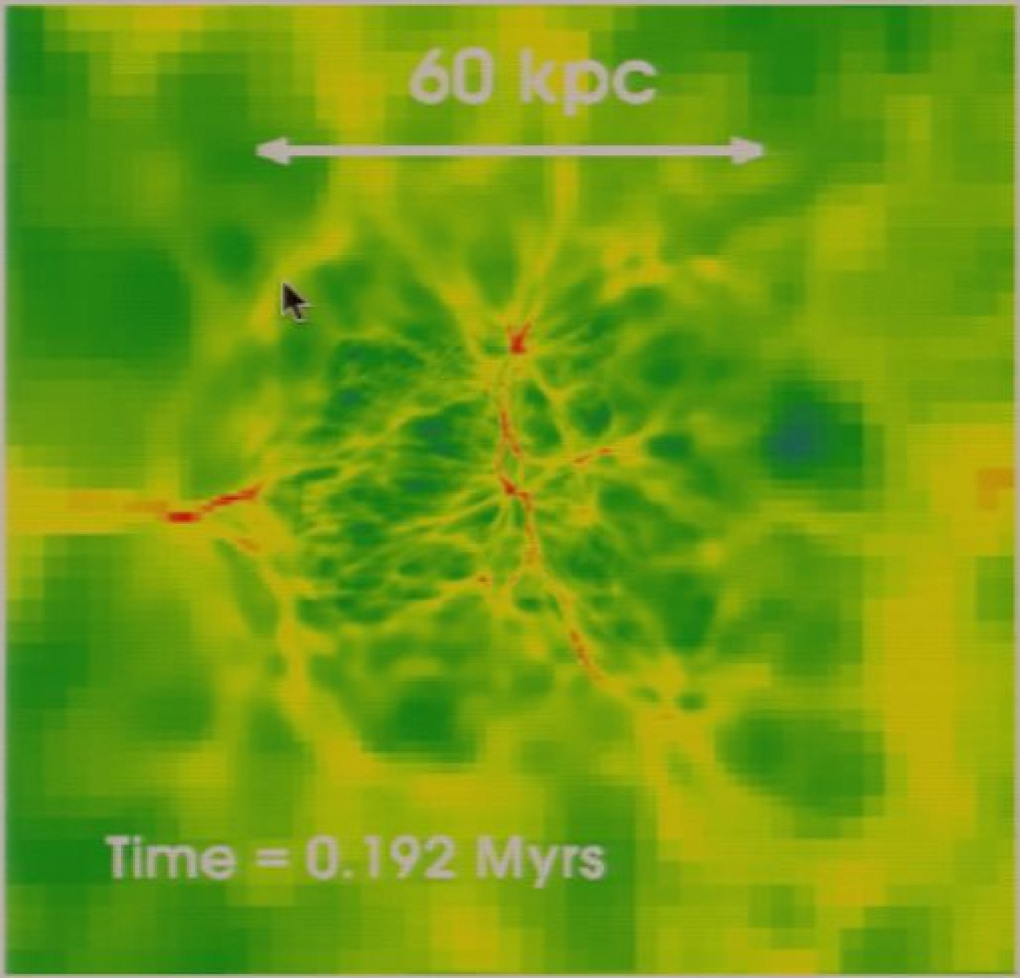
Regan & Haehnelt 2009

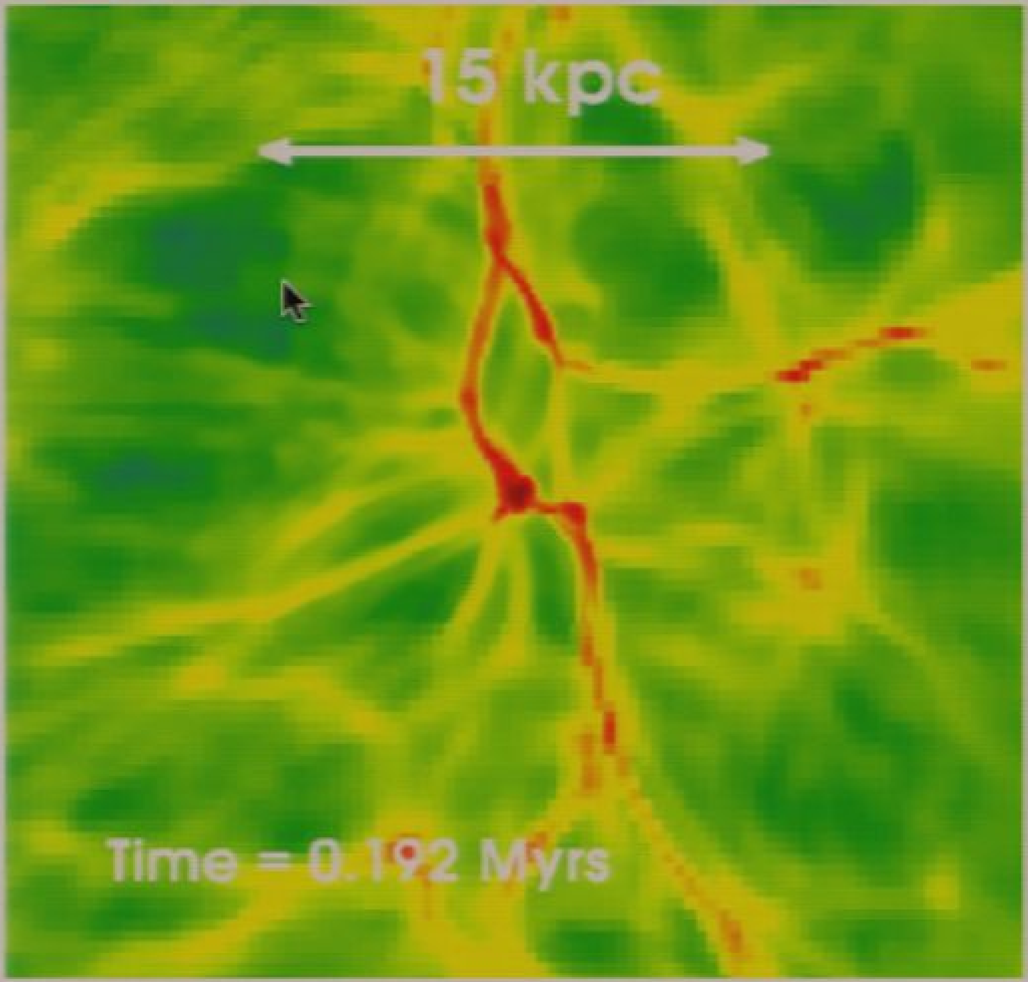
Isothermal collapse at T~7000-8000K

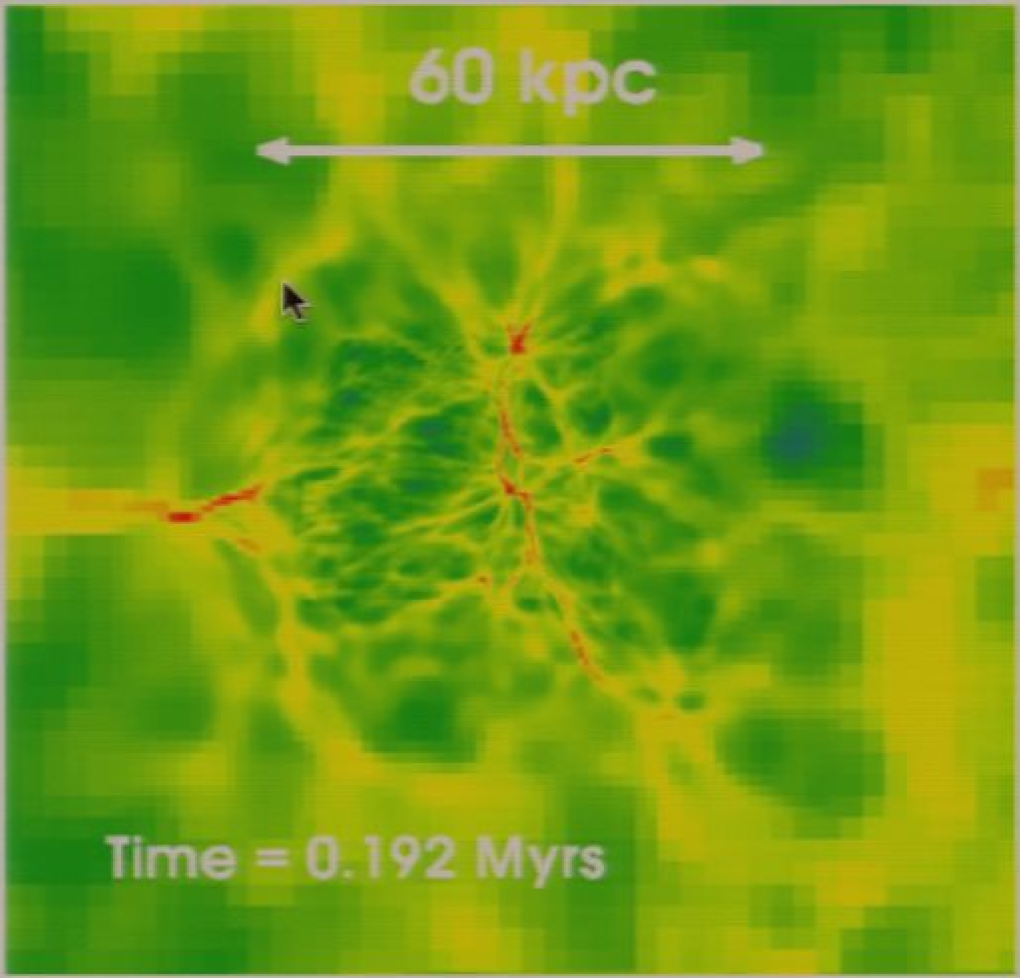


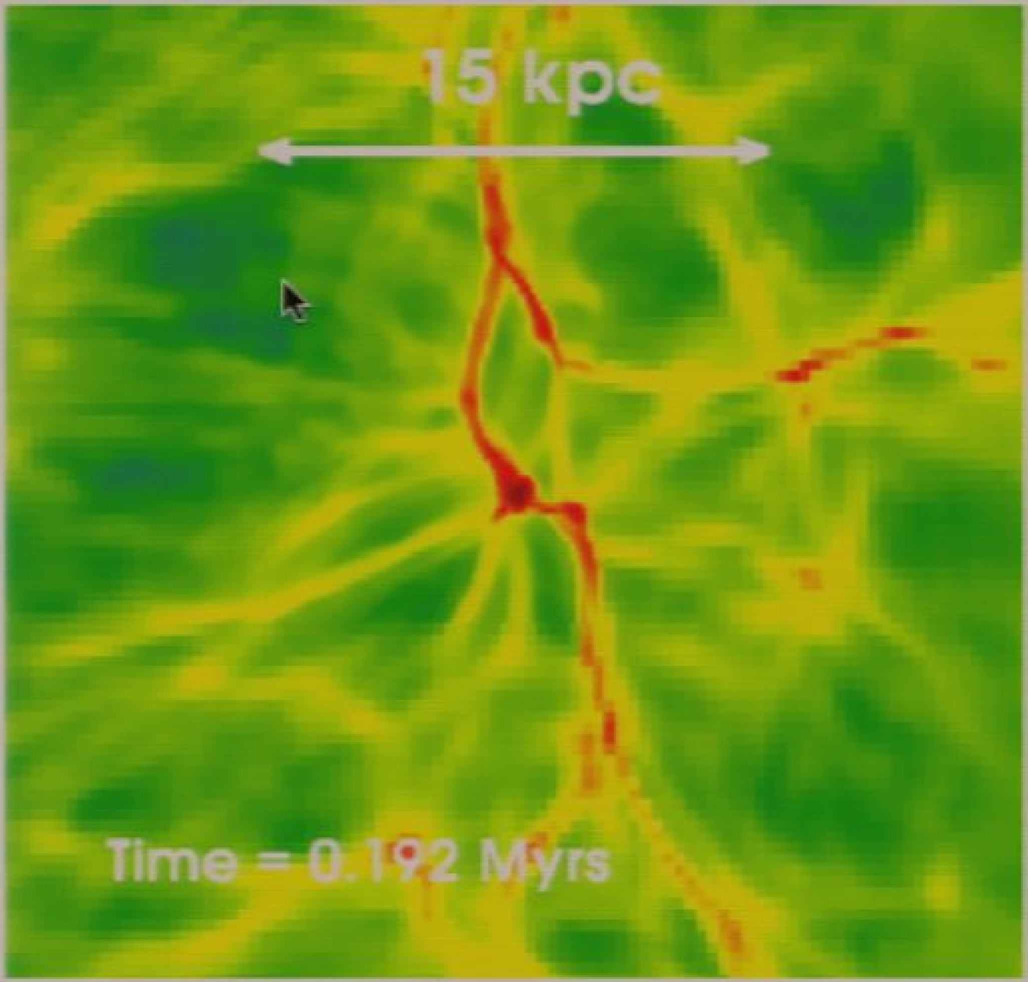
Regan & Haehnelt 2008

The inner $2\text{x}10^4\,M_\odot$ collapse by a factor 1000 in radius before they settle into rotational support!


60 kpc
Time = 0.192 Myrs


15 kpc
Time = 0.192 Myrs


60 kpc
Time = 0.192 Myrs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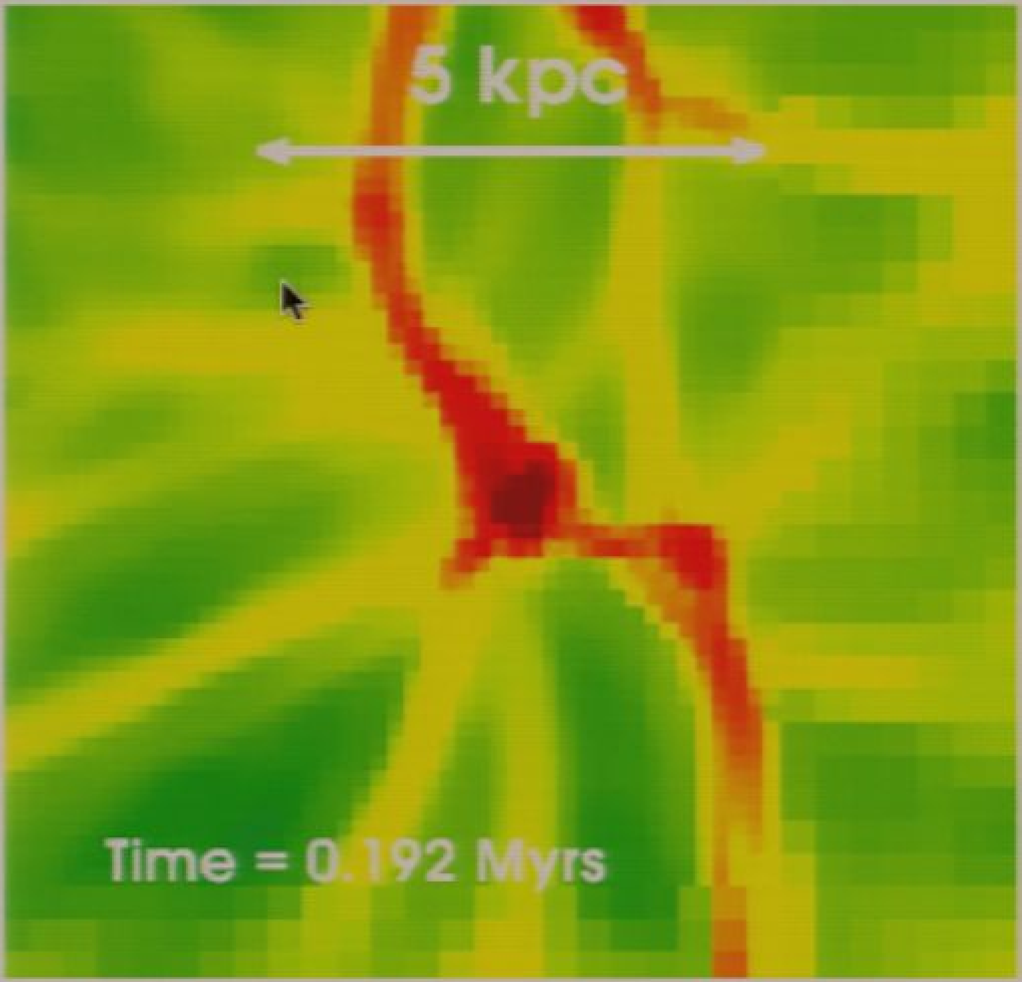
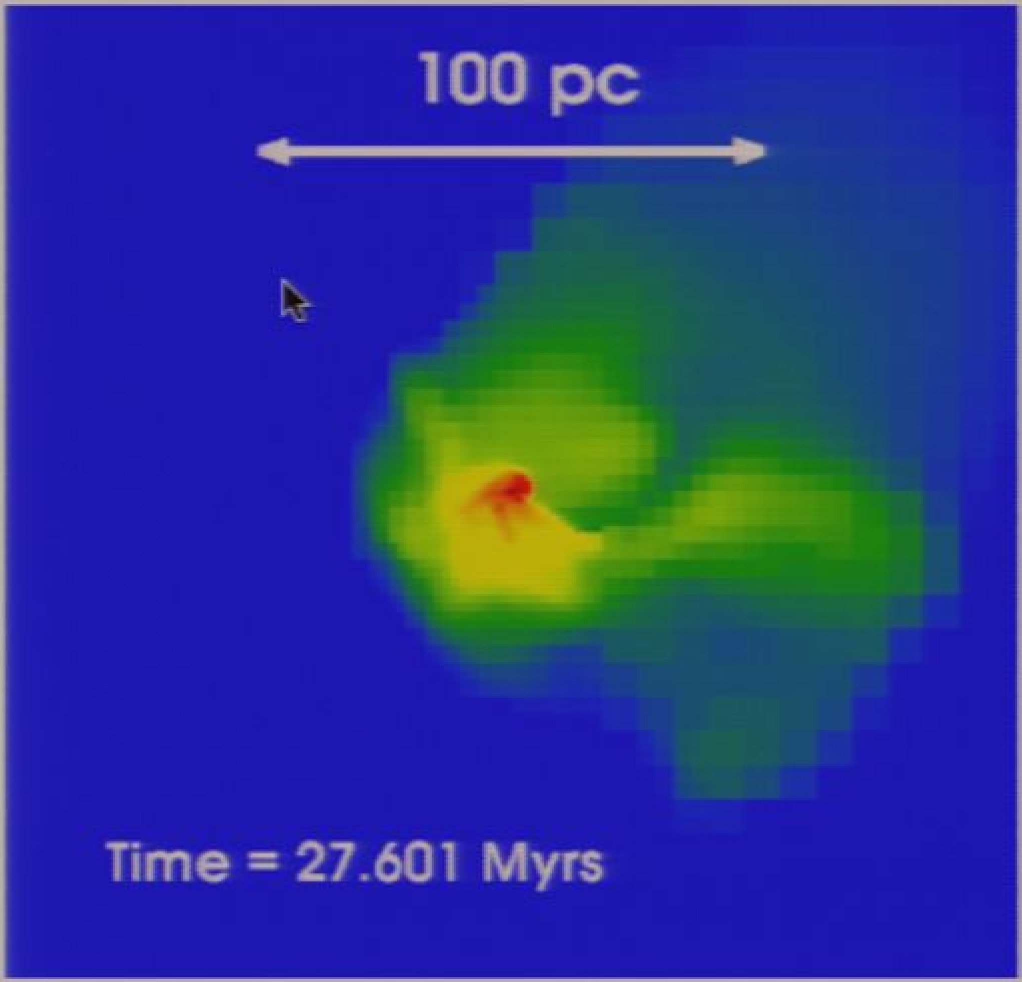
Time = 0.192 Myrs


5 kpc
Time = 0.192 Myrs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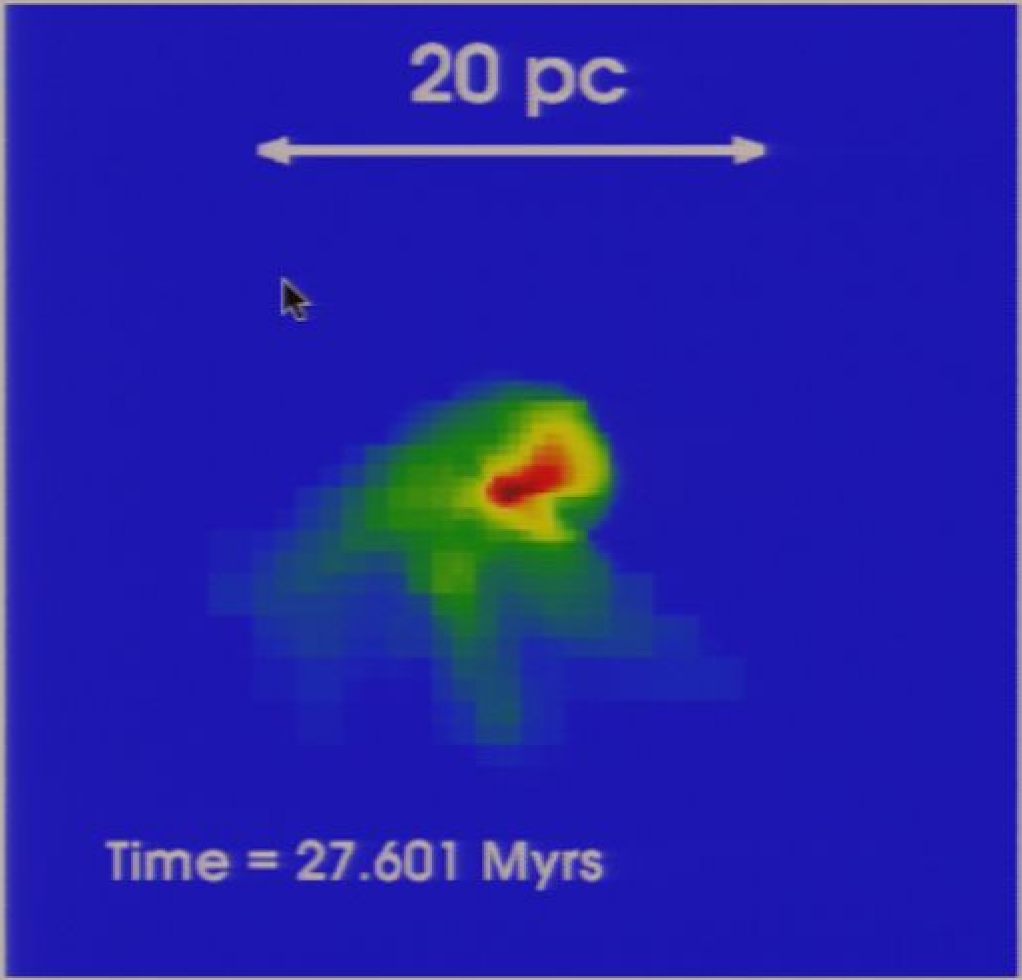
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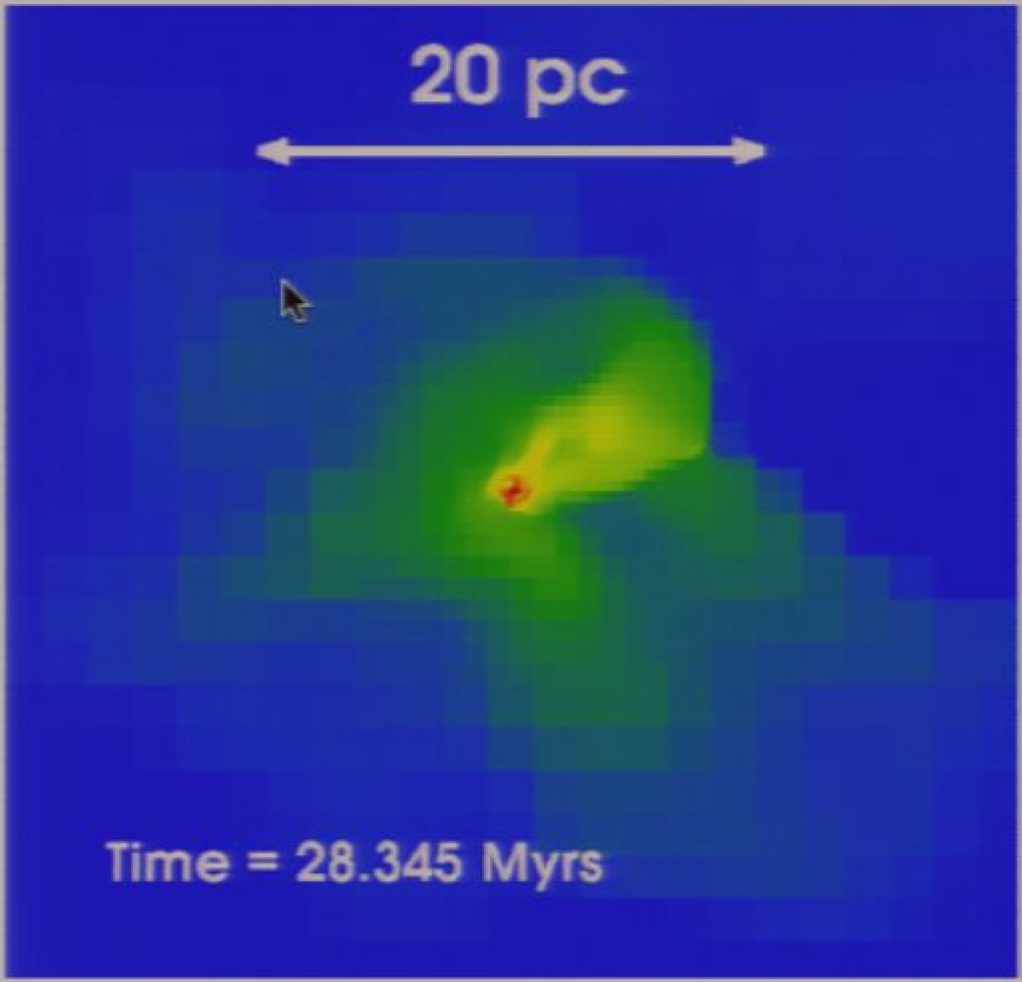
20 pc
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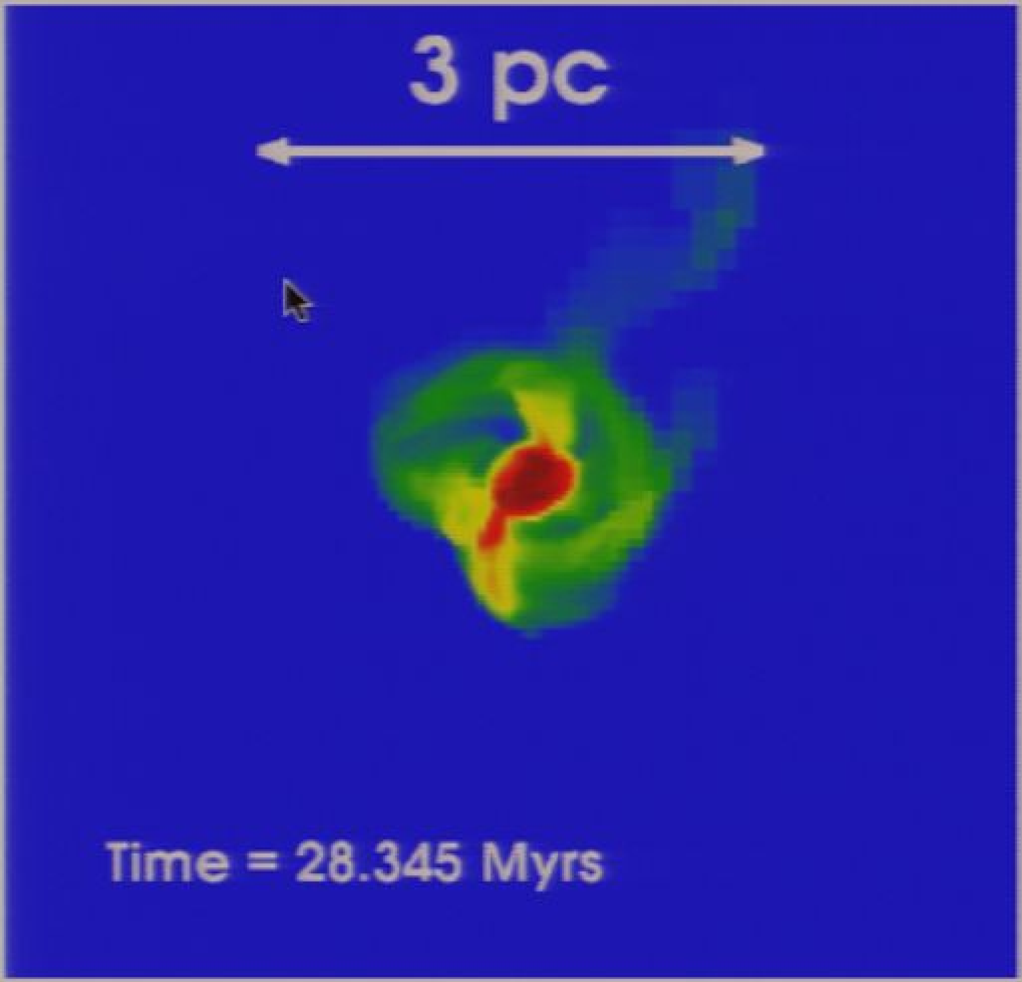
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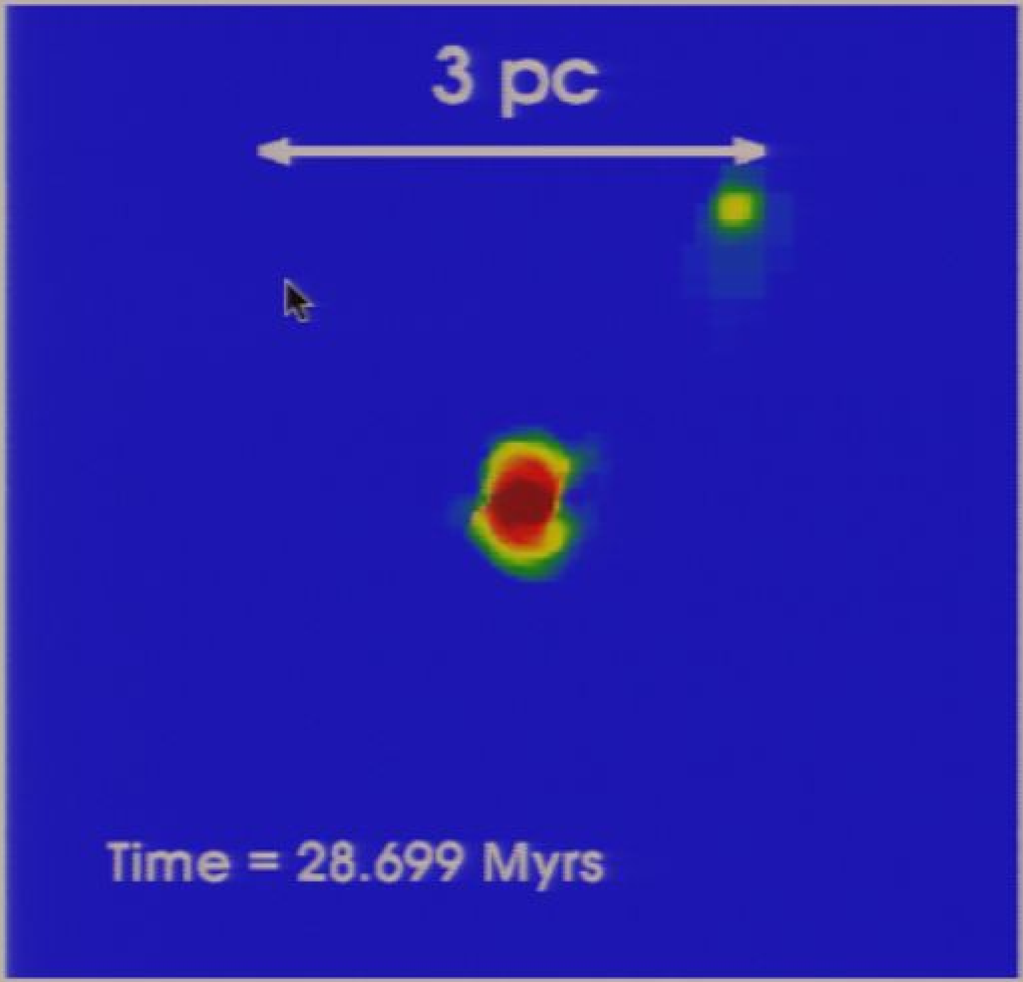
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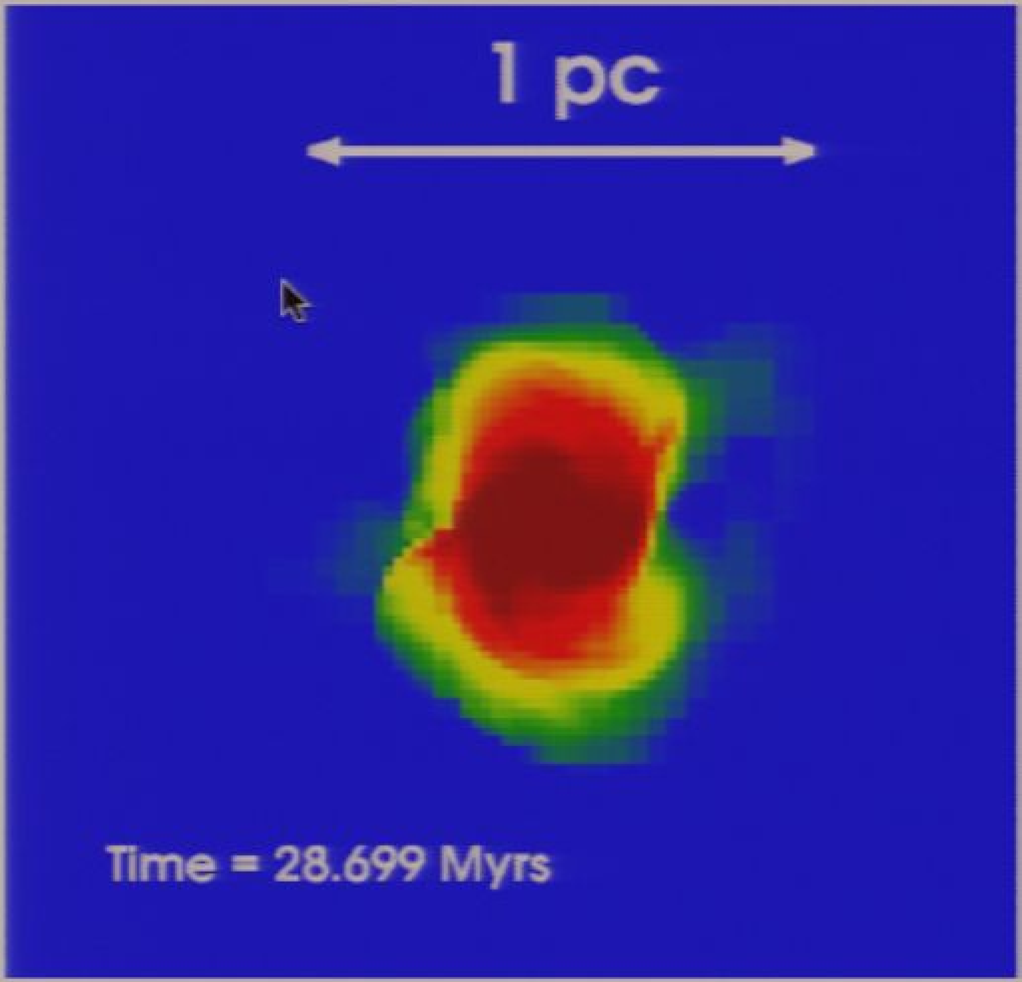
1 pc
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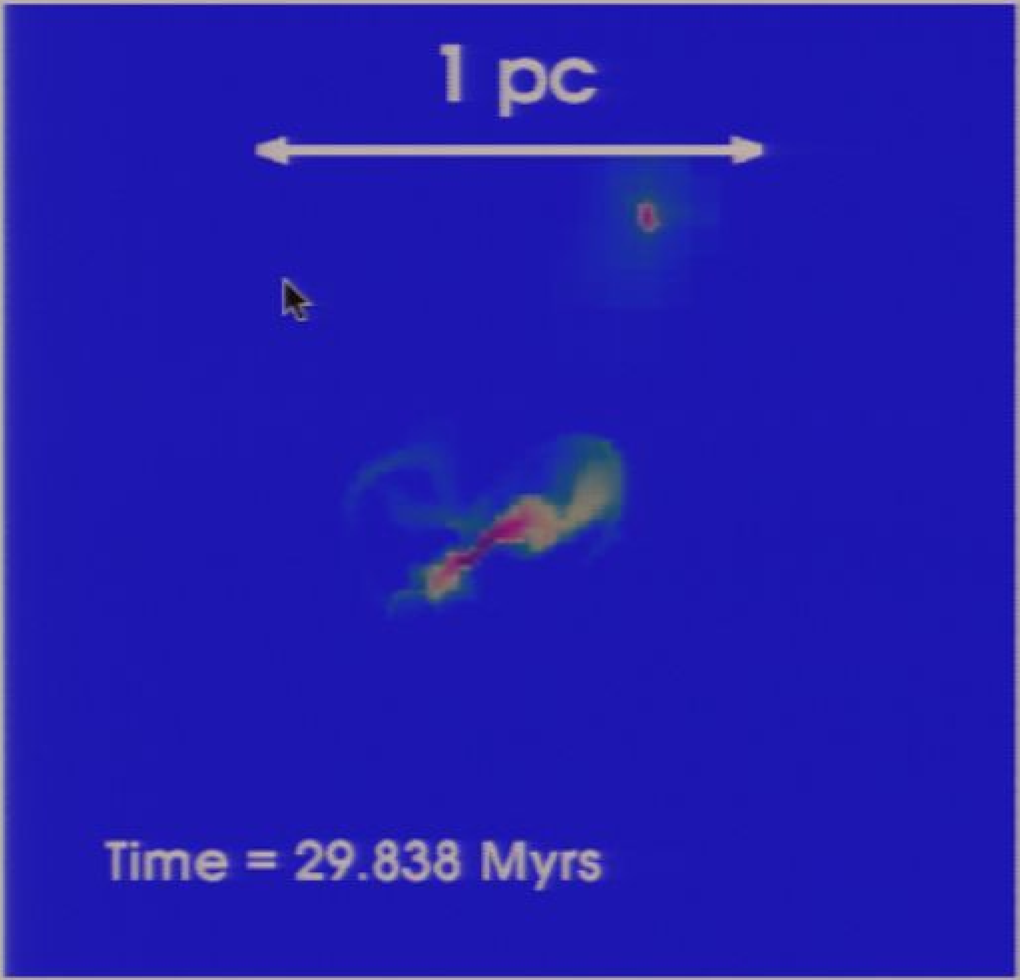
1 pc
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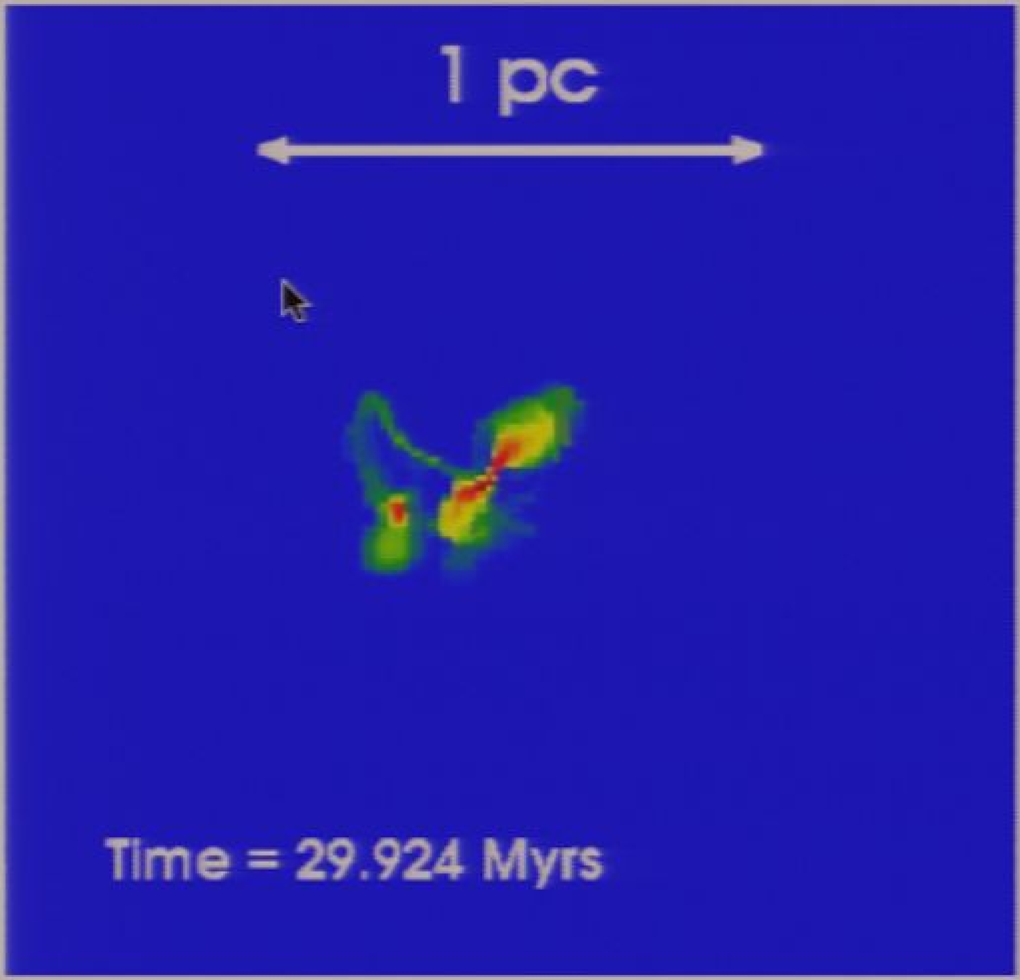
1 pc
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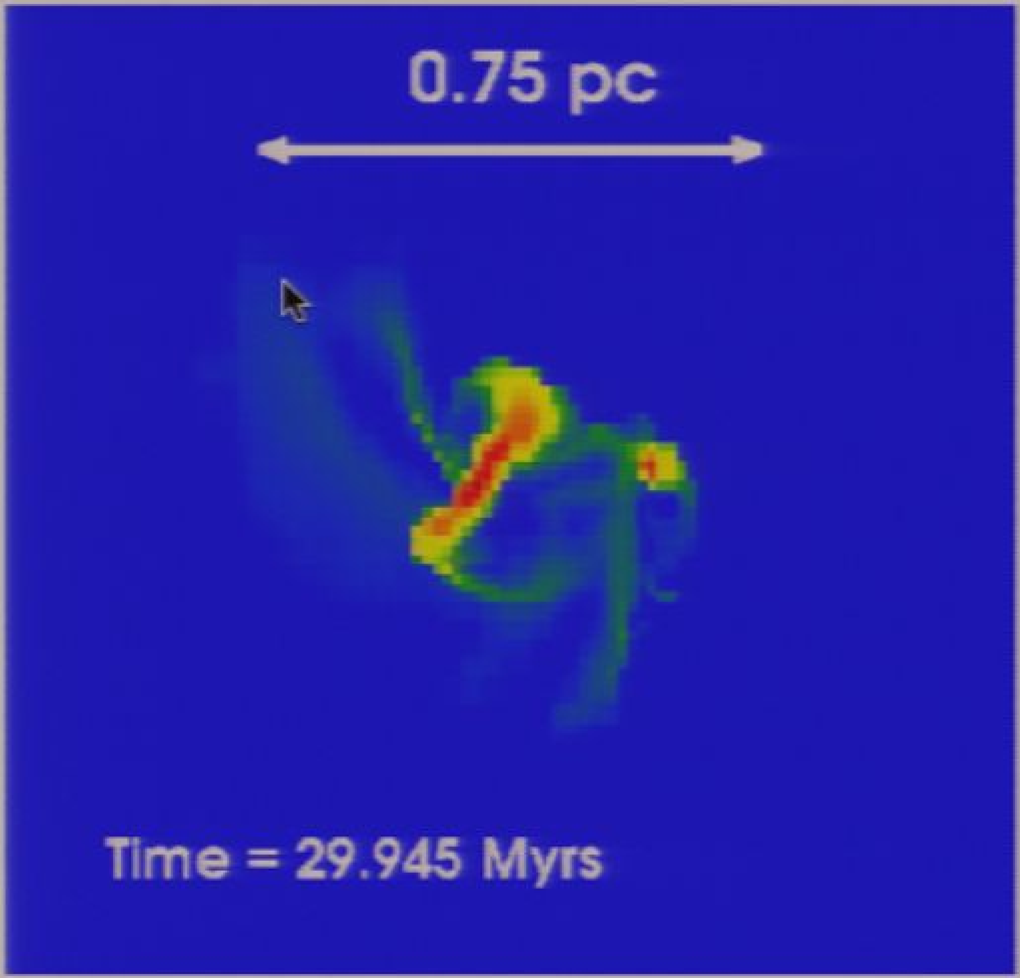
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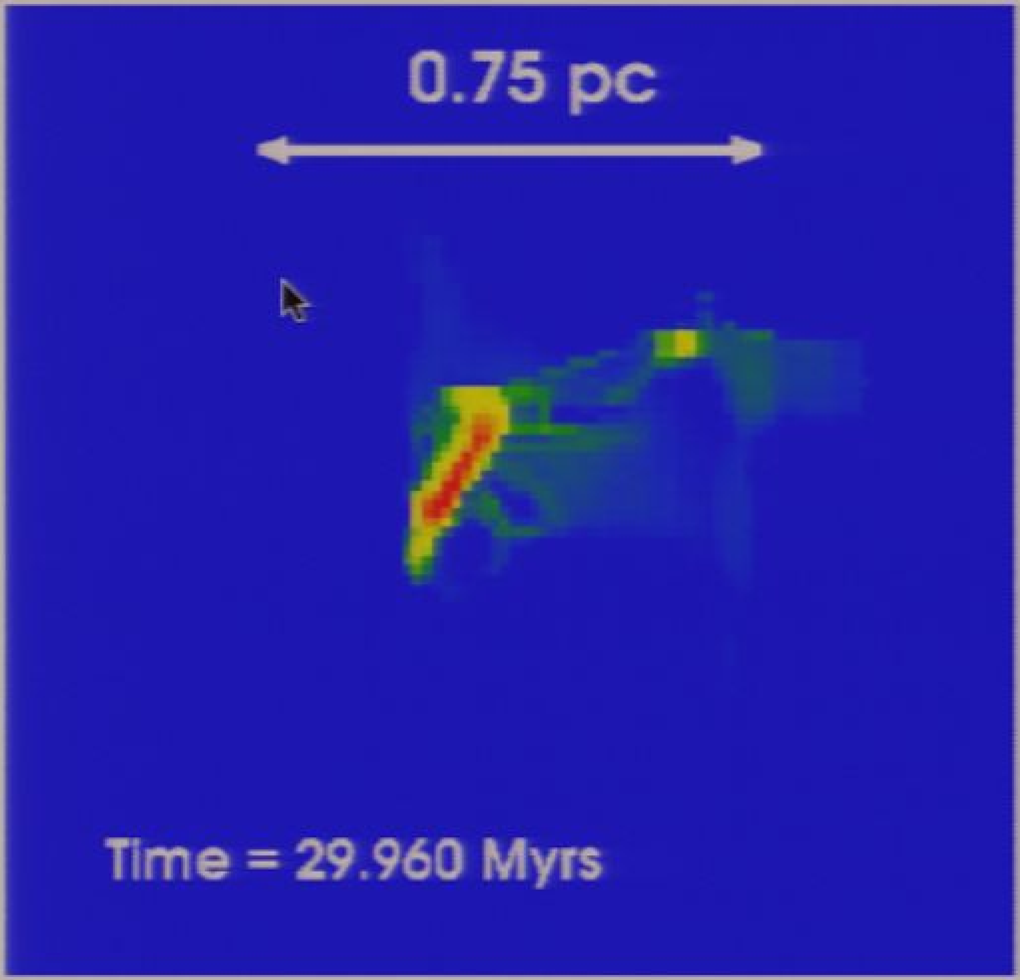
0.75 pc
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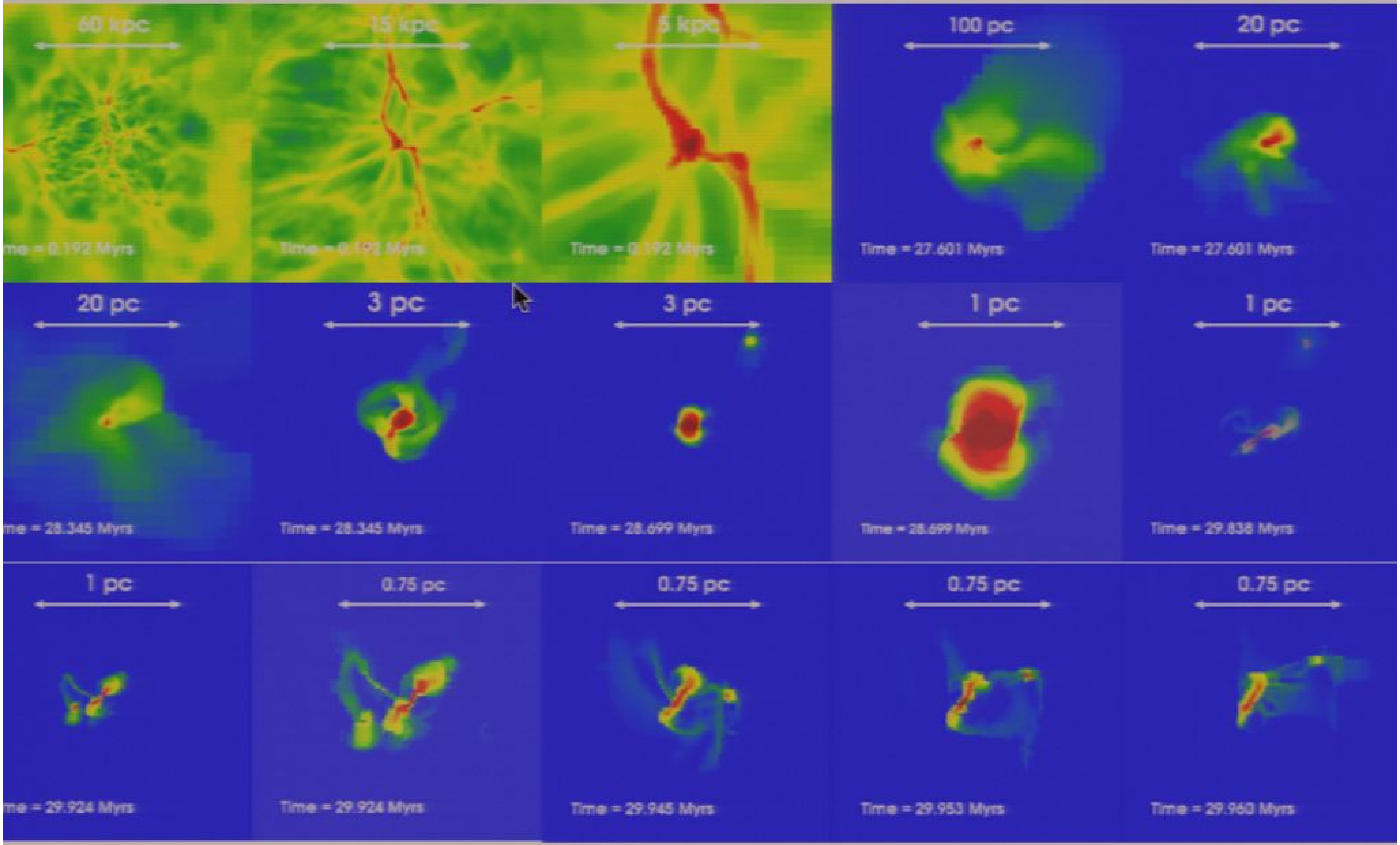
60 kpc
me = 0.192 Myrs
15 kpc
Time = 0.192 Myrs
5 kpc
Time = 0.192 Myrs
100 pc
Time = 27.601 Myrs
20 pc
Time = 27.601 Myrs
20 pc
me = 28.345 Myrs
3 pc
Time = 28.345 Myrs
3 pc
Time = 28.699 Myrs
1 pc
Time = 28.699 Myrs
1 pc
Time = 29.838 Myrs
1 pc
me = 29.924 Myrs
0.75 pc
Time = 29.924 Myrs
0.75 pc
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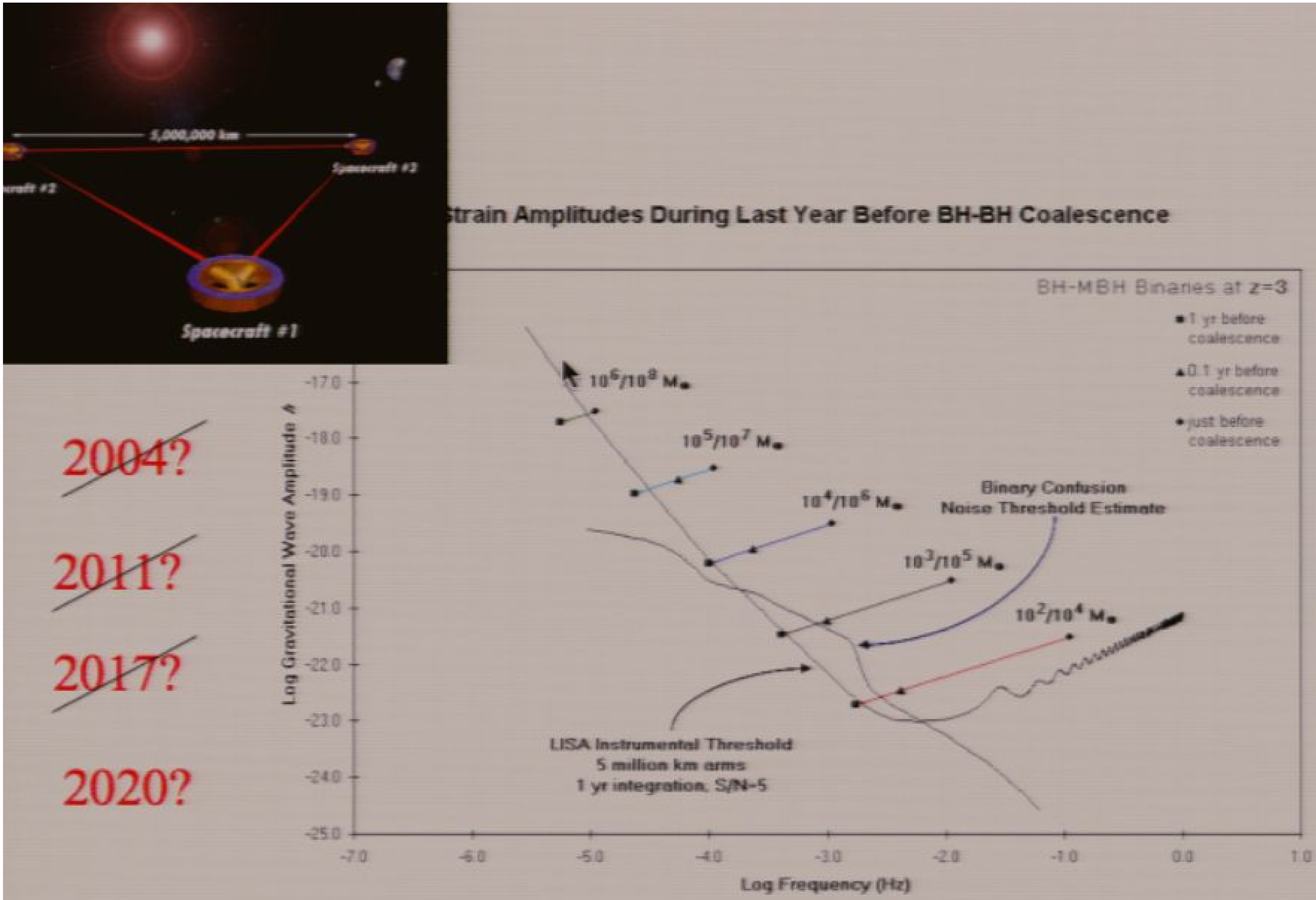
0.75 pc
Time = 29.953 Myrs
0.75 pc
Time = 29.960 Myrs



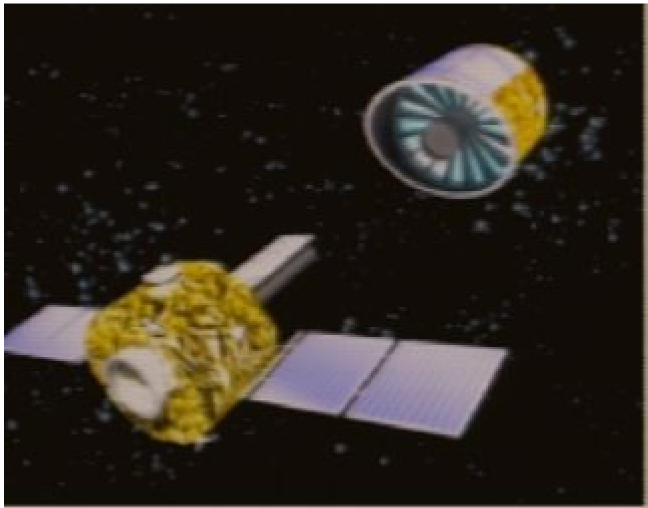
~~2004?~~

~~2011?~~

~~2017?~~

2020?

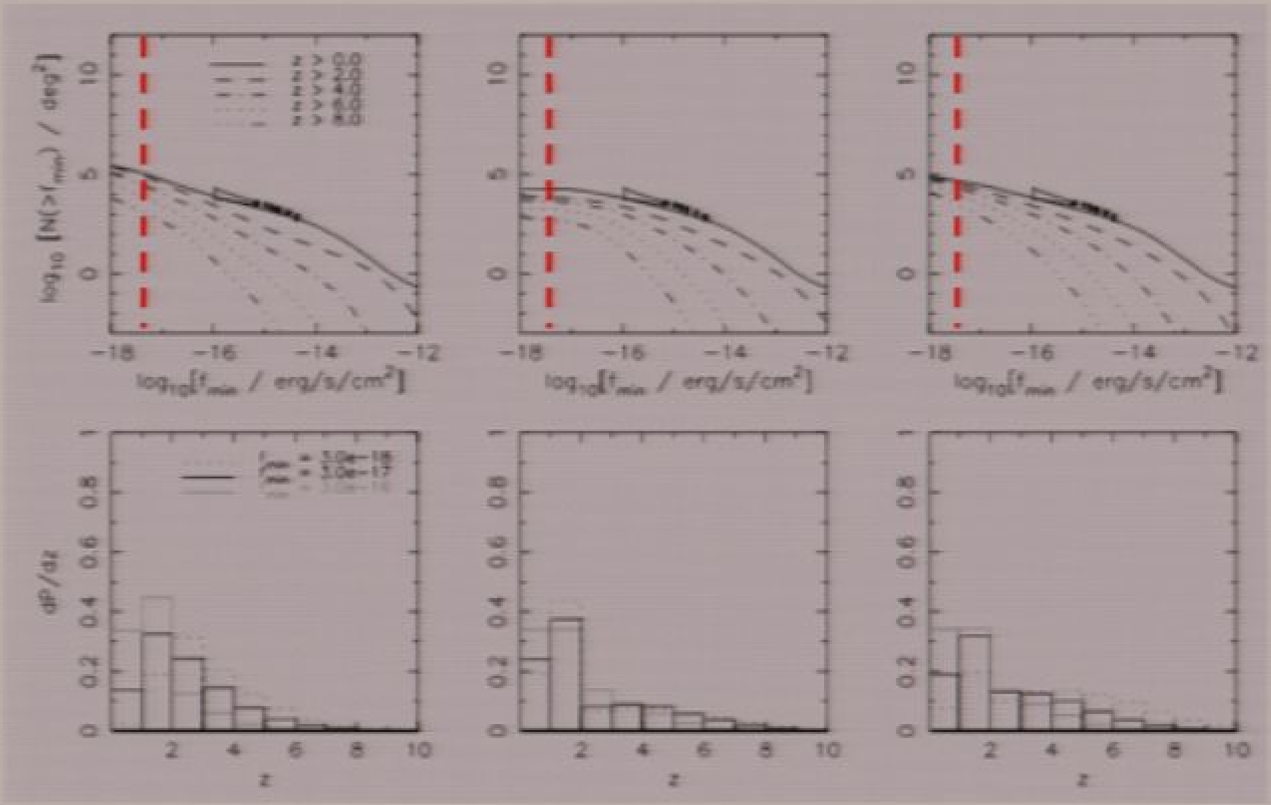
LISA will see mergers of $10^5 - 10^7 M_\odot$ binary black holes with high S/N

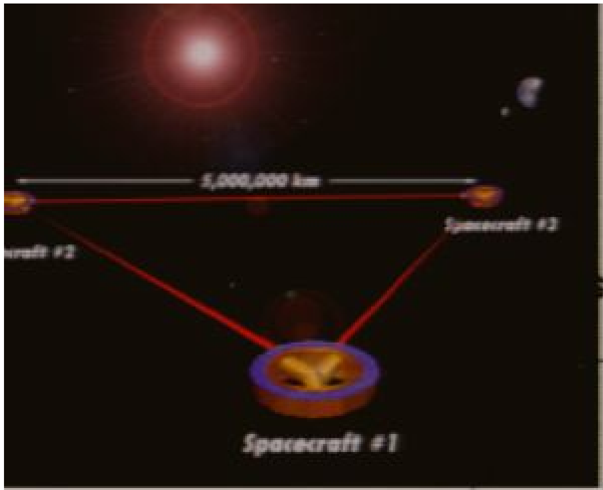


Detecting quasars at very high redshift with next generation X-ray telescopes

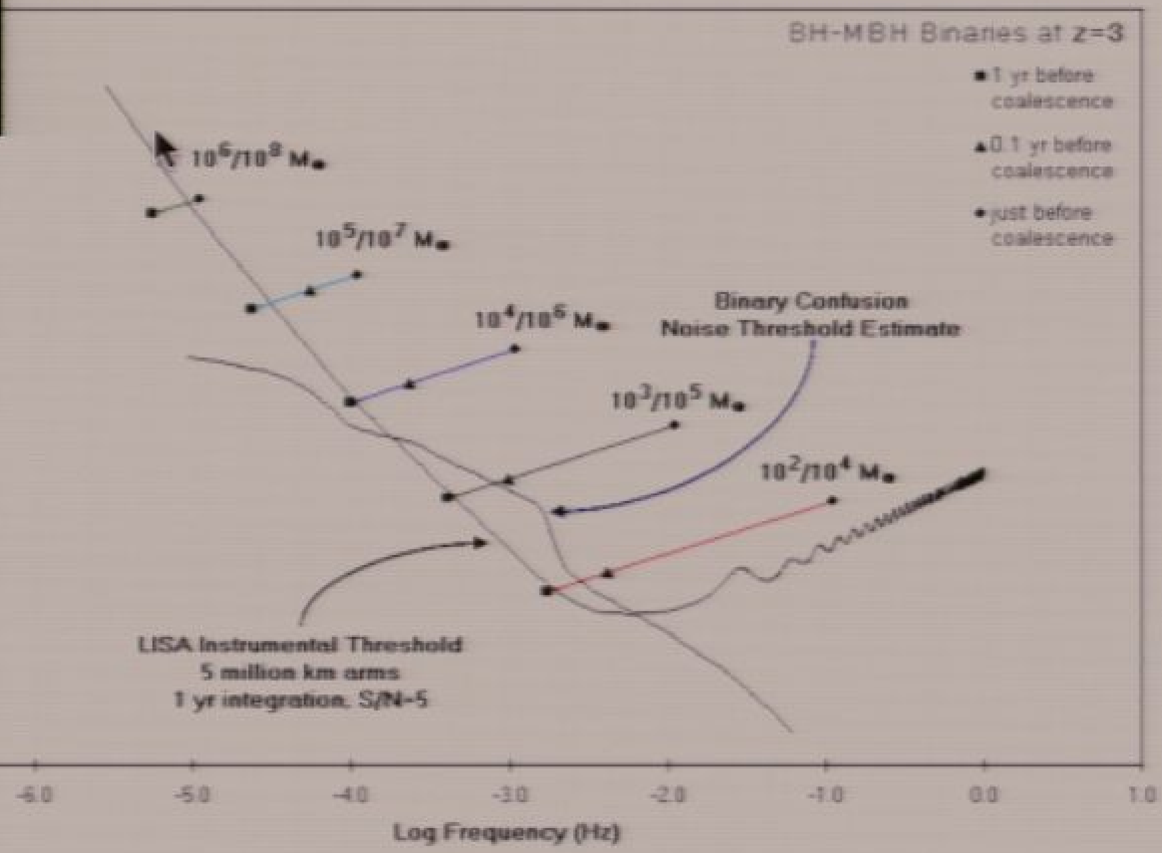
Kirsty J. Rhook* & Martin G. Haehnelt†
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

A significant fraction of the X-ray sources detected by XEUS should be at z>6. Should be able to see black holes with masses as small as $10^5\,M_\odot$.





train Amplitudes During Last Year Before BH-BH Coalescence



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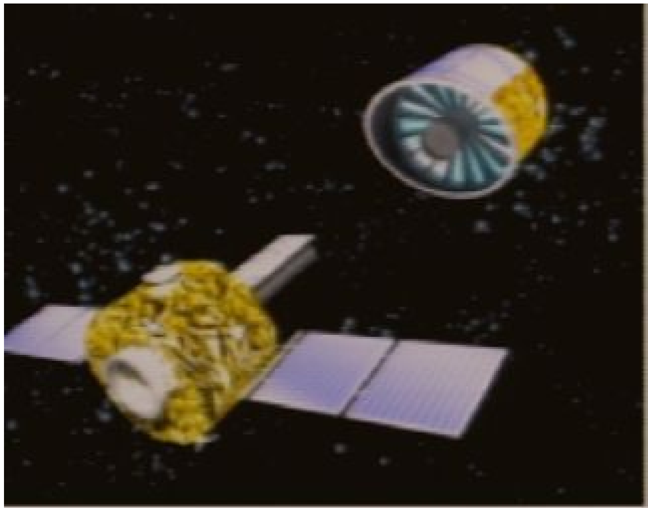
2020?

LISA will see mergers of $10^5 - 10^7 M_\odot$ binary black holes with high S/N

Perimeter, 9th December 2009



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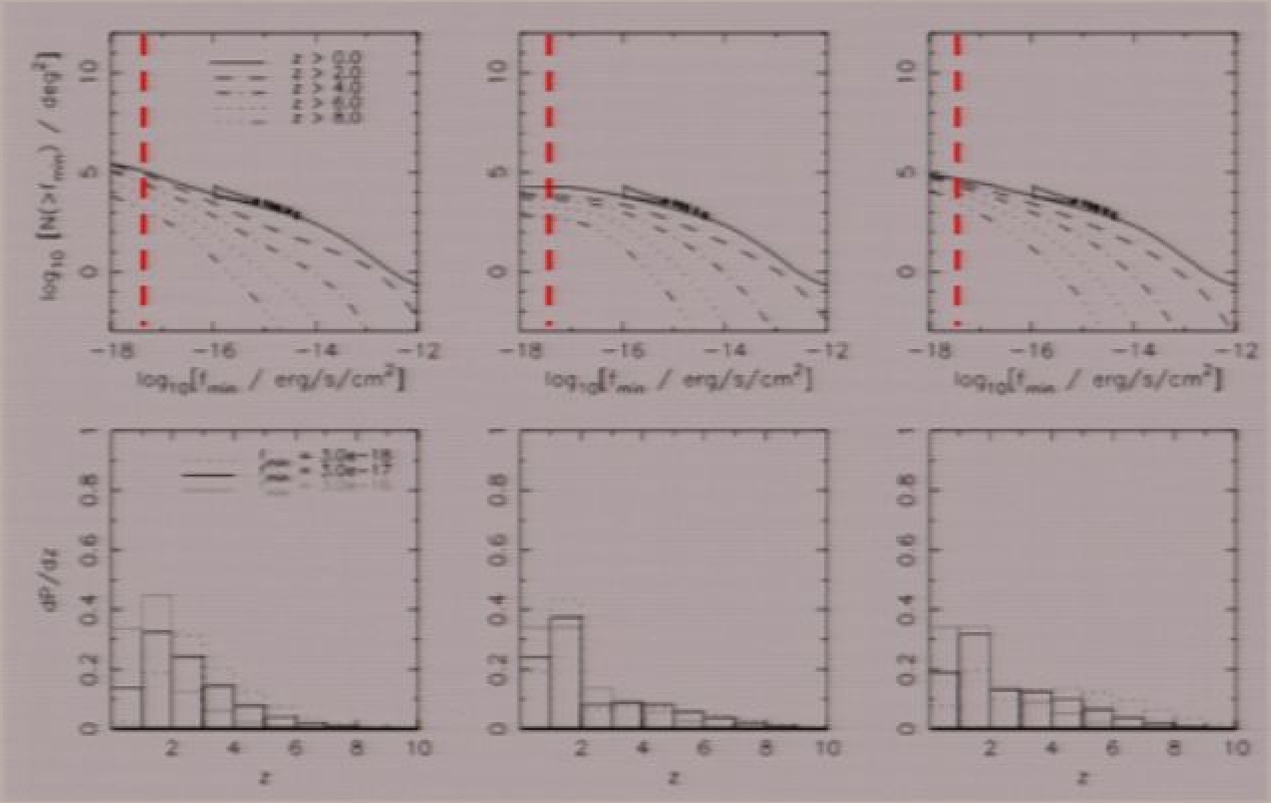

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Summary

- Substantial progress on the observation and modelling of feedback regulated co-evolution of galaxies and their central black holes has been made which is now reasonably well understood.
- We still don’t know how and when supermassive black holes form in the first place!
- Most probably require massive seed black holes. Direct collapse of gas in haloes with $T_{vir} \geq 10000K$ with no metals (and H_2 supression) is least prone to fragmentation into stars. Further evolution via a massive Quasi-Star?
- Primordial massive black holes probably not required.
- LISA and future X-ray missions offer excellent prospects for unravelling the early build-up of supermassive black holes.

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