Title: The Past and Future of the Astrophysical Universe

Date: Jun 26, 2009 02:00 PM

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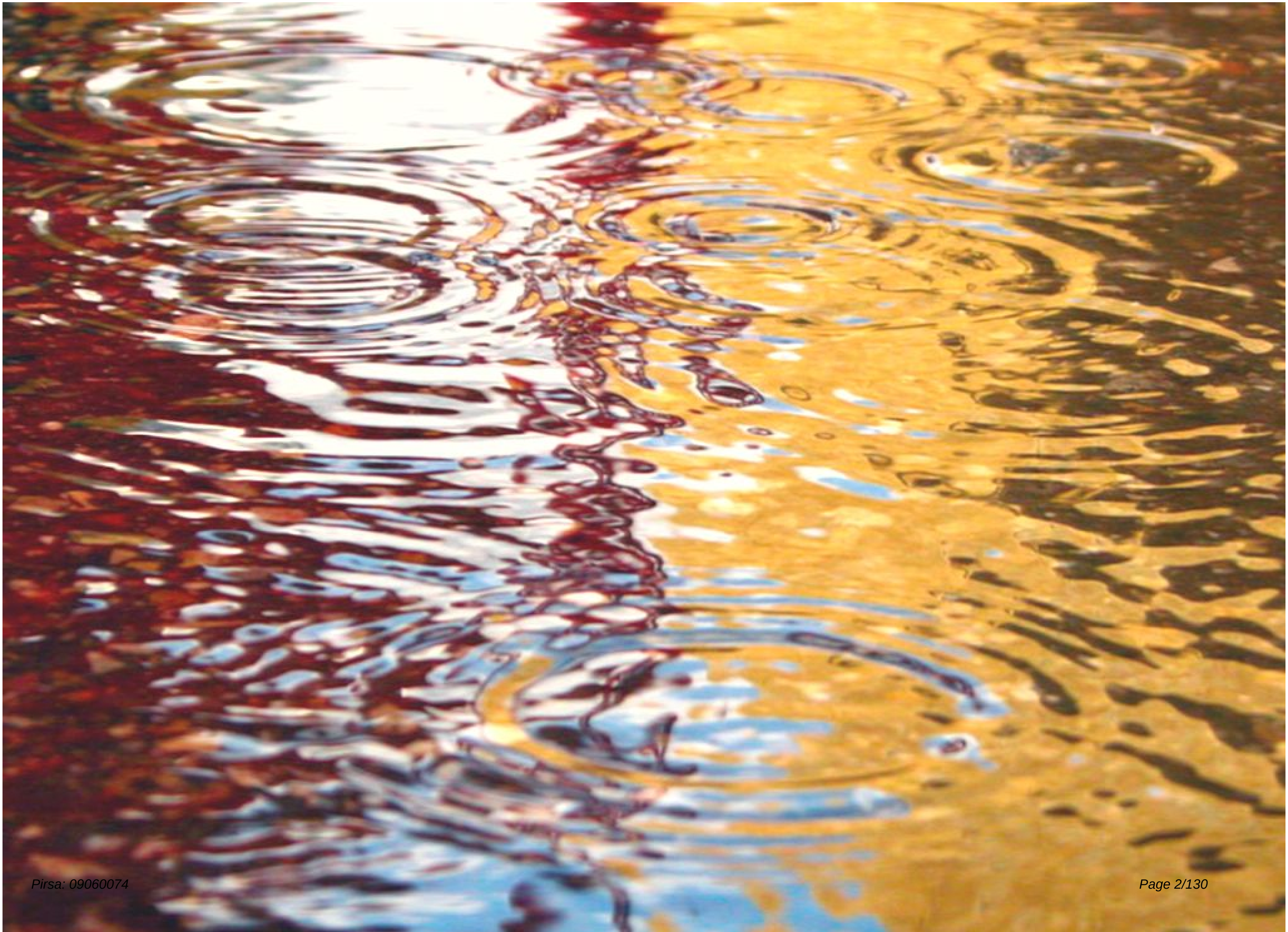
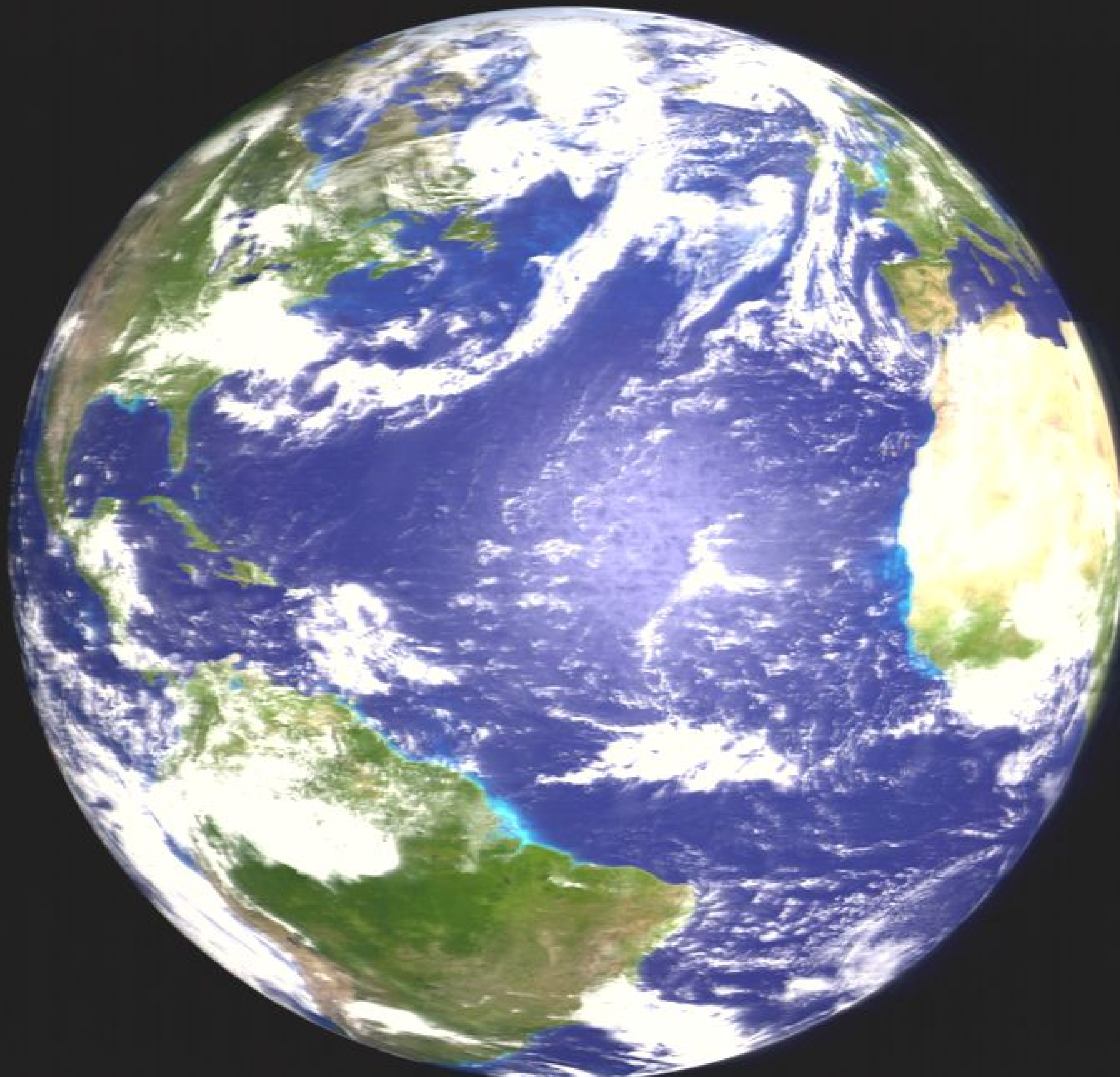
Abstract: The initial conditions of our Universe can be summarized on a single sheet of paper. Yet the Universe is full of complex structures today, such as stars, galaxies and groups of galaxies. I will describe how complexity emerged in the form of the first stars out of the simple initial state of the Universe at early cosmic times. The future of the Universe is even more surprising. Over the past decade it was realized that the cosmic expansion has been accelerating. If this accelerated expansion will continue into the future, then within a hundred billion years there will be no galaxies left for us to observe within the cosmic horizon except one: the merger product between our own Milky Way galaxy and its nearest neighbor, the Andromeda galaxy.






we are here

The Past and Future of Our Universe

Avi Loeb

Harvard University

The biblical order:

The biblical order:

- *Creation of the universe*

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- *Creation of the universe*
- *Light (separation of light from darkness)*

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- *Water (separation of sky from liquid water)*

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- *Stars*
- *Life*
- *People*

The ~~biblical~~ scientific order:

- *Creation of the universe*
- *Light (separation of light from darkness)*
- *Water (separation of sky from liquid water)*
- *Separation of continents out of the water and the spontaneous appearance of vegitation*
- *Stars*
- *Life*
- *People*

The ~~biblical~~ order:
scientific

1 • Creation of the universe

2 • Light (separation of light from darkness)

4 • Water (separation of sky from liquid water)

5 • Separation of continents out of the water and the spontaneous appearance of vegitation

3 • Stars

6 • Life

7 • People

Grade: B+

Impressive insight about 1, but apparent ignorance about the rest

WMAP Cosmological Parameters

Model: lcdm

Data: all

$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
A	=	$0.67^{+0.04}_{-0.05}$
$A_{0.002}$	=	$0.81^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \times 10^{-10} \pm 1 \times 10^{-10}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	=	$(24 \times 10^{-10}{}^{+1\times10^{-10}}_{-2\times10^{-10}}) \times 10^{-10}$
h	=	$0.71^{+0.01}_{-0.02}$
H_0	=	71^{+1}_{-2} km/s/Mpc
ℓ_A	=	$303.0^{+0.9}_{-1.3}$
n_s	=	$0.938^{+0.013}_{-0.018}$
$n_s(0.002)$	=	$0.938^{+0.012}_{-0.023}$
Ω_b	=	$0.044^{+0.002}_{-0.003}$
$\Omega_b h^2$	=	$0.0220^{+0.0006}_{-0.0008}$
Ω_c	=	$0.22^{+0.01}_{-0.02}$
Ω_Λ	=	0.74 ± 0.02
Ω_m	=	$0.26^{+0.01}_{-0.03}$
$\Omega_m h^2$	=	$0.131^{+0.004}_{-0.010}$
r_s	=	148^{+1}_{-2} Mpc
b_{SDSS}	=	$0.95^{+0.05}_{-0.06}$
σ_8	=	$0.75^{+0.03}_{-0.04}$
$\sigma_8 \Omega_m^{0.6}$	=	$0.34^{+0.02}_{-0.03}$
A_{SZ}	=	$0.78^{+0.23}_{-0.78}$
t_0	=	$13.8^{+0.1}_{-0.2}$ Gyr
τ	=	$0.069^{+0.026}_{-0.029}$
θ_A	=	0.594 ± 0.002 °
z_{eq}	=	3135^{+85}_{-159}
z_r	=	$9.3^{+2.8}_{-2.0}$

The initial conditions of the Universe can be summarized on a single sheet of paper, yet thousands of books cannot fully describe the complex structures we see today…

The evolution of the universe is characterized by a persistent transition from ***simplicity to complexity***

The evolution of the universe is characterized by a persistent transition from simplicity to complexity

Why?

The evolution of the universe is characterized by a persistent transition from <u>simplicity to complexity</u>

Why?

Gravitational Instability

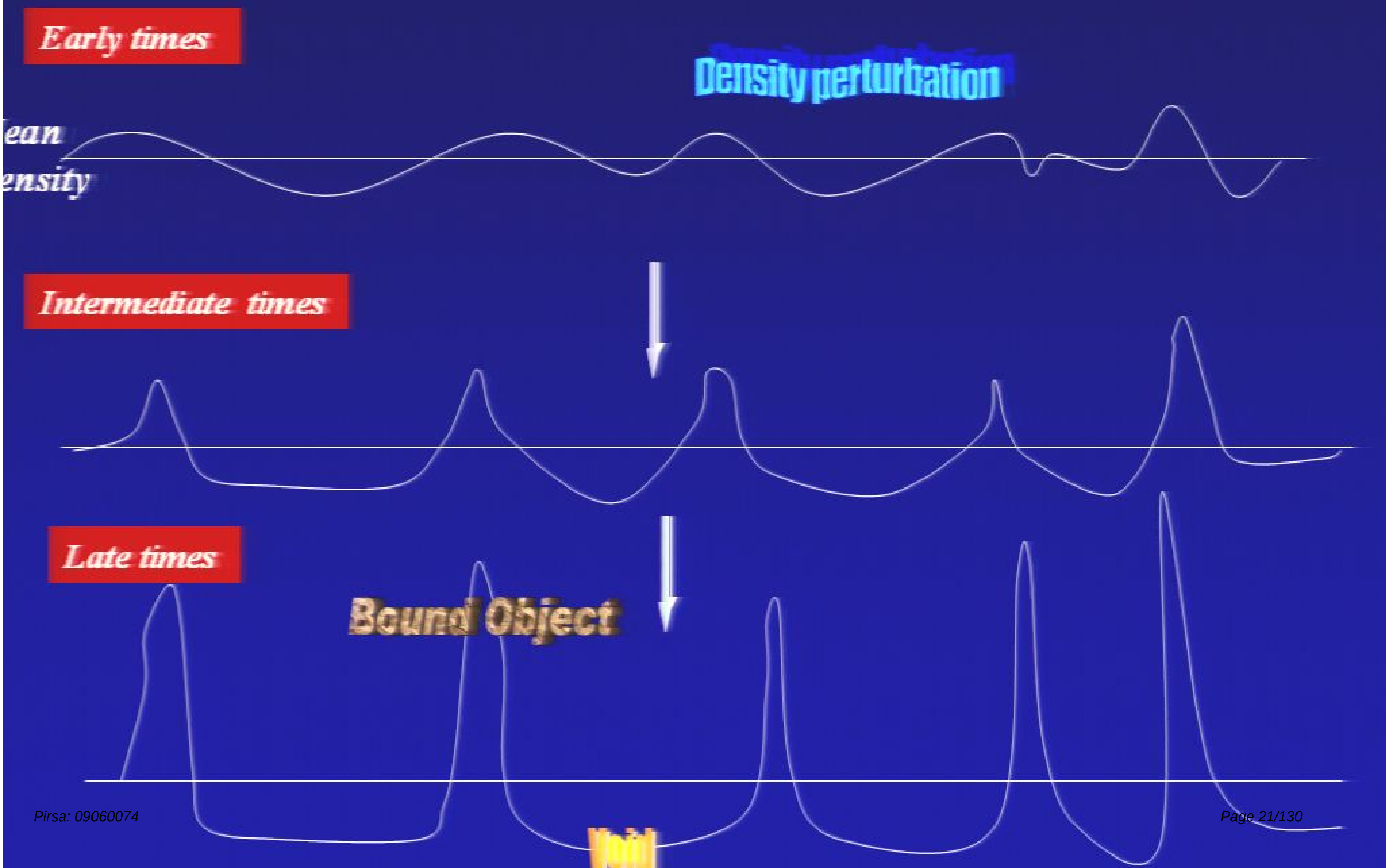
The evolution of the universe is characterized by a persistent transition from *<u>simplicity to complexity</u>*

Why?

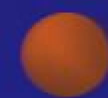
Gravitational Instability

We can feed the initial conditions to a computer and solve for the evolution of cosmic structure. Does it mean that the fate of everthing else (including our own daily actions as human beings) was already encoded, in these initial conditions?

On small scales the universe is clumpy



The building blocks of life were not available in the Big Bang…



Rocky planet:

iron (Fe) core

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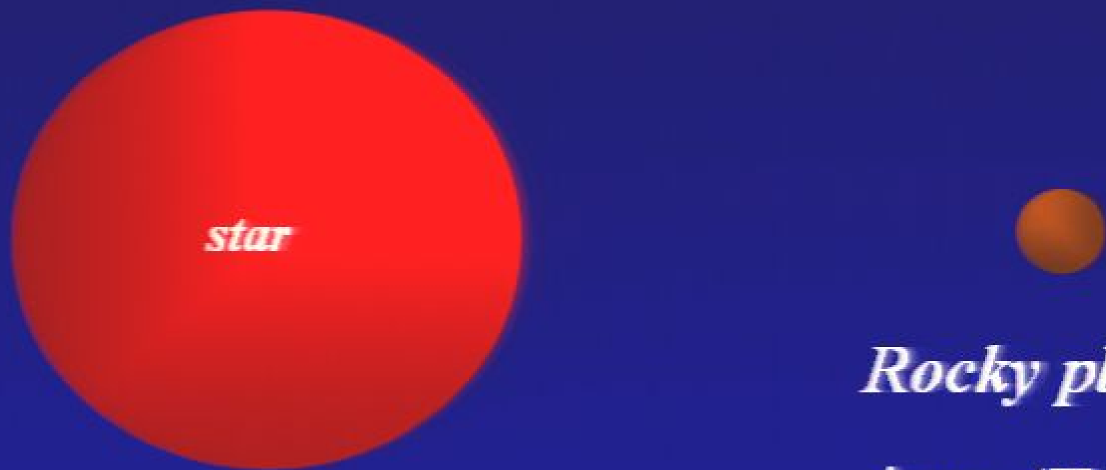

Rocky planet:

iron (Fe) core

Life: H_2O

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Big Bang

The building blocks of life were not available in the Big Bang…

Rocky planet:

iron (Fe) core

Life: H_2O

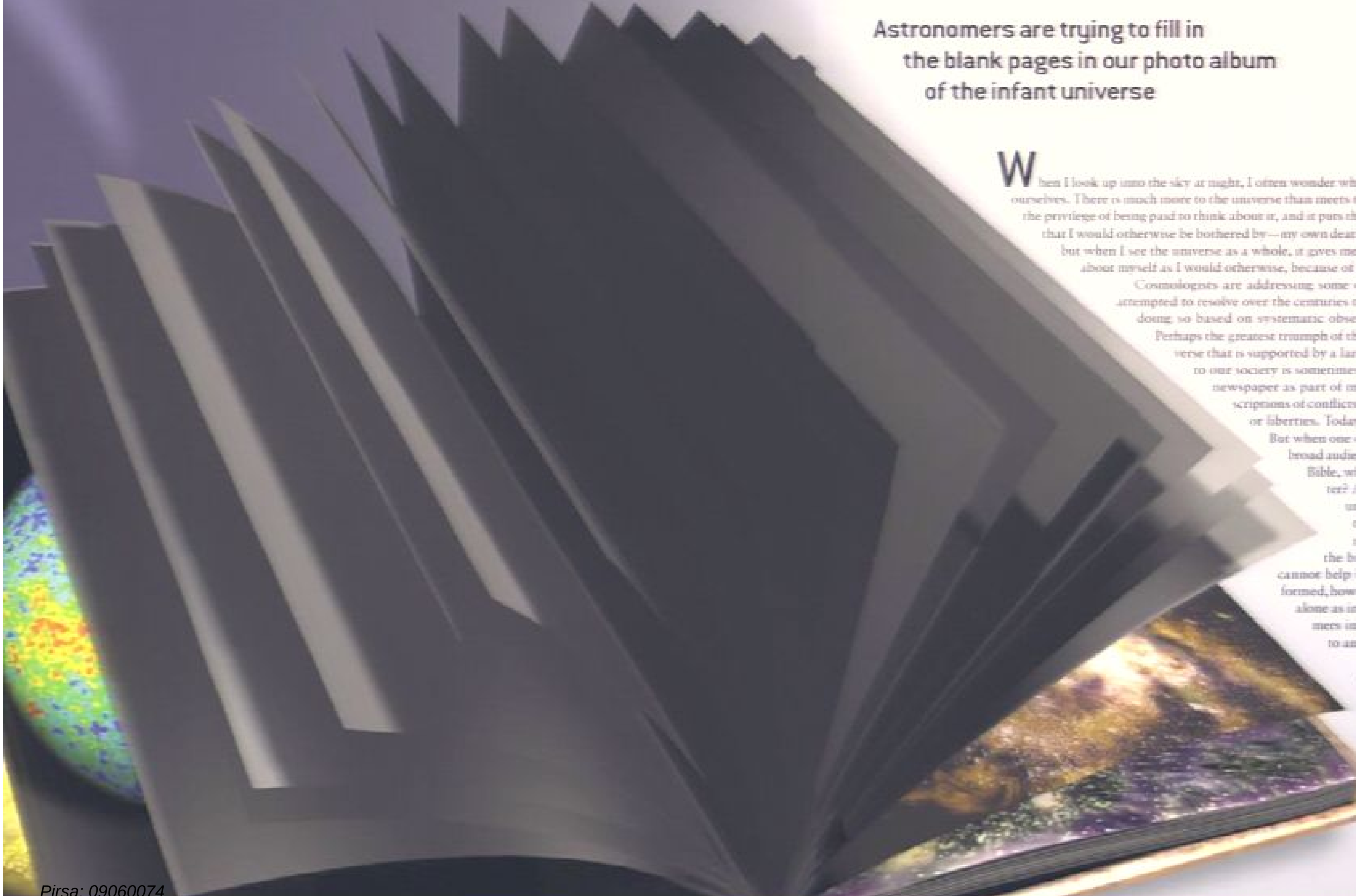
Big Bang → H ; *stars* → O

and they will not be available in the distant future…

THE DARK AGES of the Universe

Astronomers are trying to fill in the blank pages in our photo album of the infant universe

By Abraham Loeb



When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and it puts things in perspective for me. There are things that I would otherwise be bothered by—my own death, for example. Everyone will die sometime, but when I see the universe as a whole, it gives me a sense of longevity. I do not care so much about myself as I would otherwise, because of the big picture.

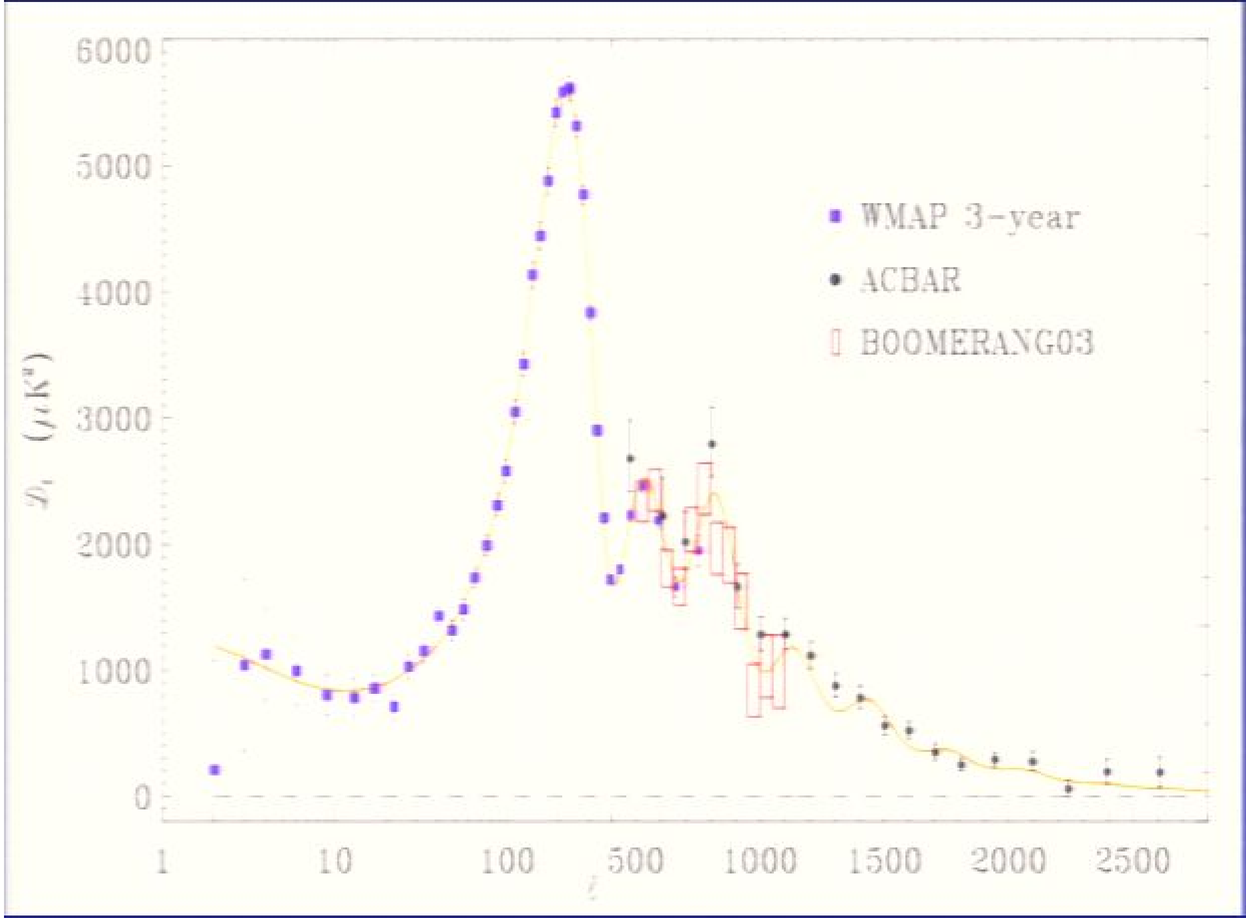
Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the universe that is supported by a large body of data. The value of such a model to our society is sometimes underappreciated. When I open the daily newspaper as part of my morning routine, I often see lengthy descriptions of conflicts between people about borders, possessions or liberties. Today's news is often forgotten a few days later. But when one opens ancient texts that have appealed to a broad audience over a longer period of time, such as the Bible, what does one often find in the opening chapter? A discussion of how the constituents of the universe—light, stars, life—were created. Although humans are often caught up with mundane problems, they are curious about the big picture. As citizens of the universe we cannot help but wonder how the first sources of light formed, how life came into existence and whether we are alone as intelligent beings in this vast space. Astronomers in the 21st century are uniquely positioned to answer these big questions.

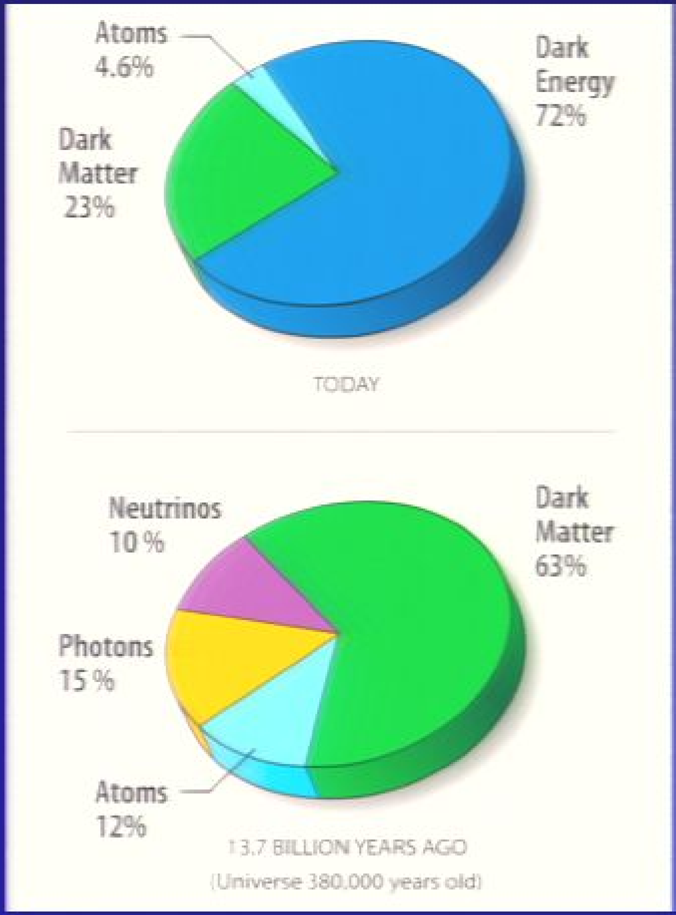
What makes modern cosmology an empirical science is that we are literally able to peer into the past. When you look at your image reflected off a mirror one meter

Cosmic-Archeology

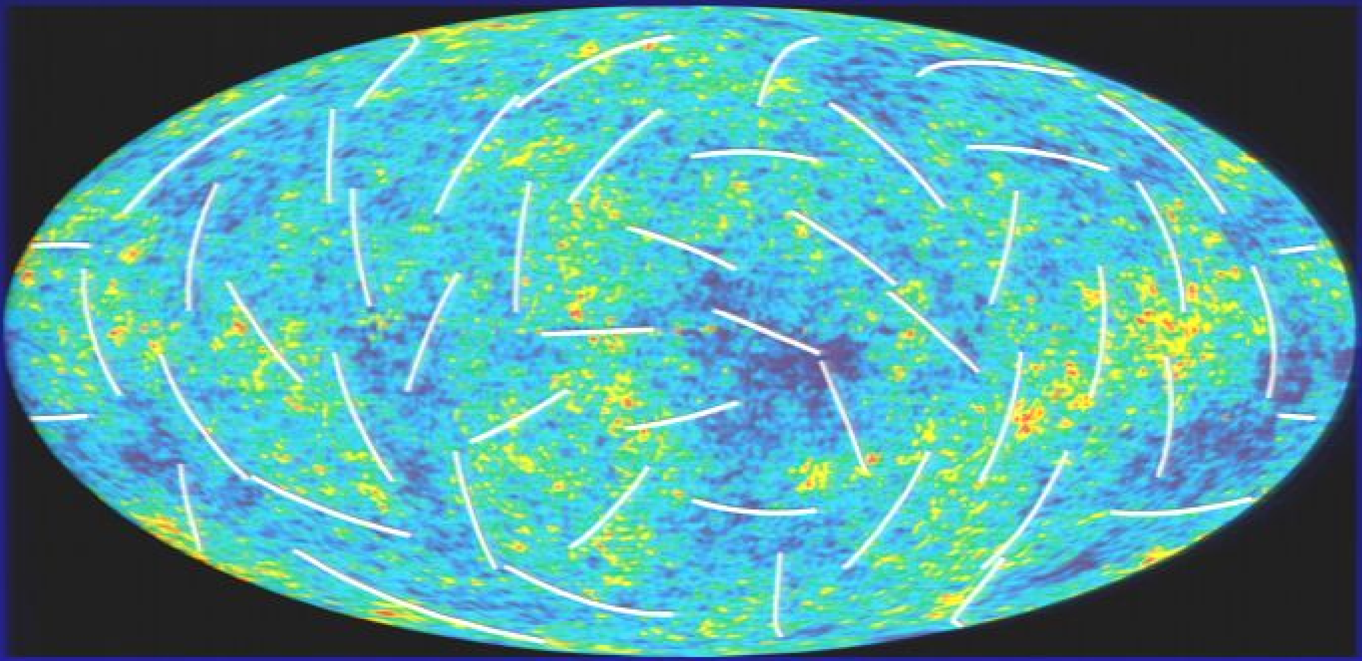
The more distant a source is, the more time it takes for its light to reach us. Hence the light must have been emitted when the universe was younger. By looking at distant sources we can trace the history of the universe.

Evidence that Most Matter is EM Dark





Cosmic Microwave Background (*WMAP5*)

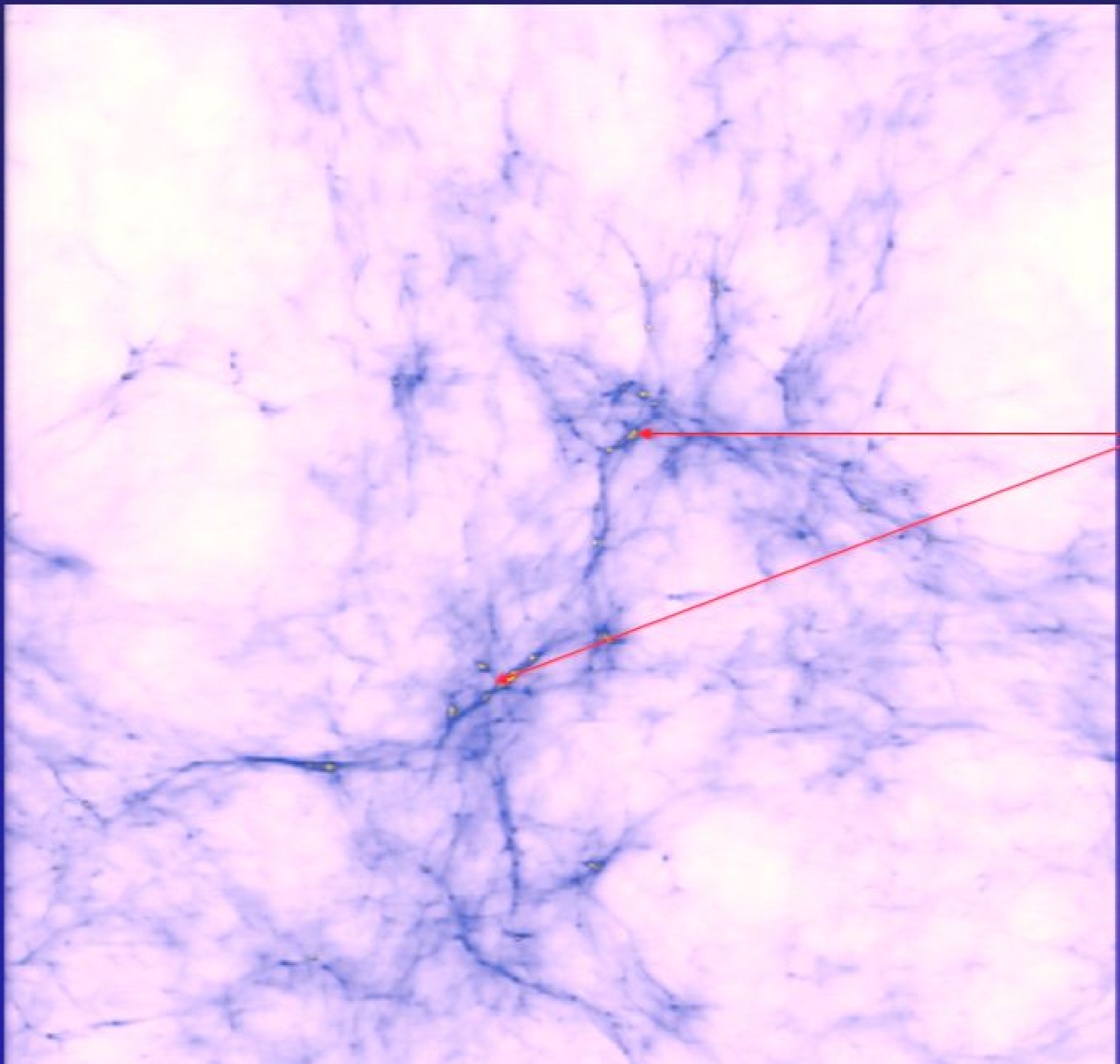


$$\tau = 0.09 \pm 0.02$$

The polarization data indicates that the first stars must have formed 400 million years after the big bang, when the universe was only a few percent of its current age!

Dunkley et al. 2008

The First Dwarf Galaxies Form at z~30

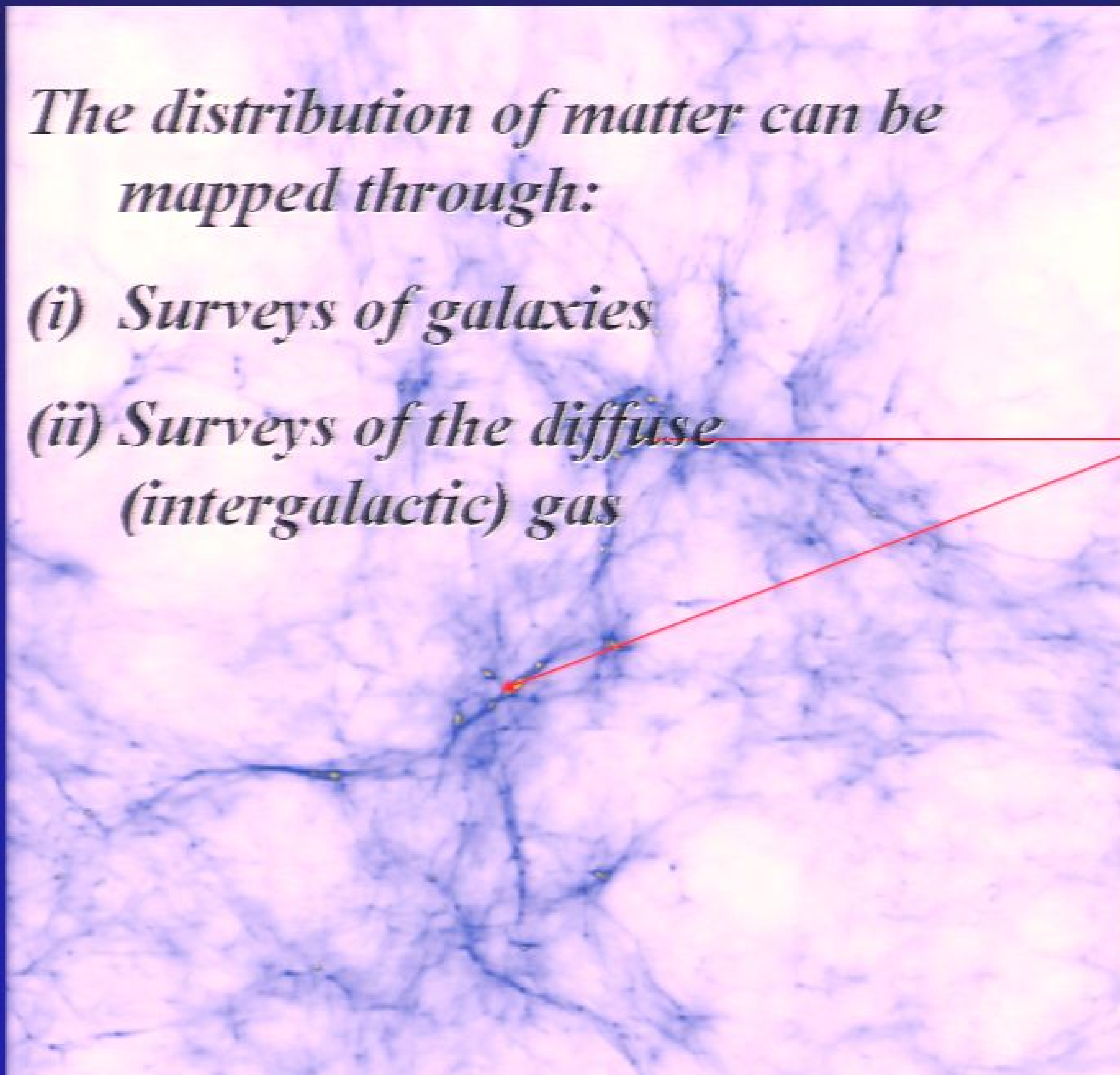


molecular hydrogen in Jeans mass objects

$(\sim 10^5 M_\odot)$

Yoshida et al. 2003

The First Dwarf Galaxies Form at z~30



The distribution of matter can be mapped through:

(i) Surveys of galaxies

(ii) Surveys of the diffuse (intergalactic) gas

molecular hydrogen in Jeans mass objects

$(\sim 10^5 M_{\odot})$

Yoshida et al. 2003

Observing the Stars

Hubble Ultra Deep Field (HUDF)

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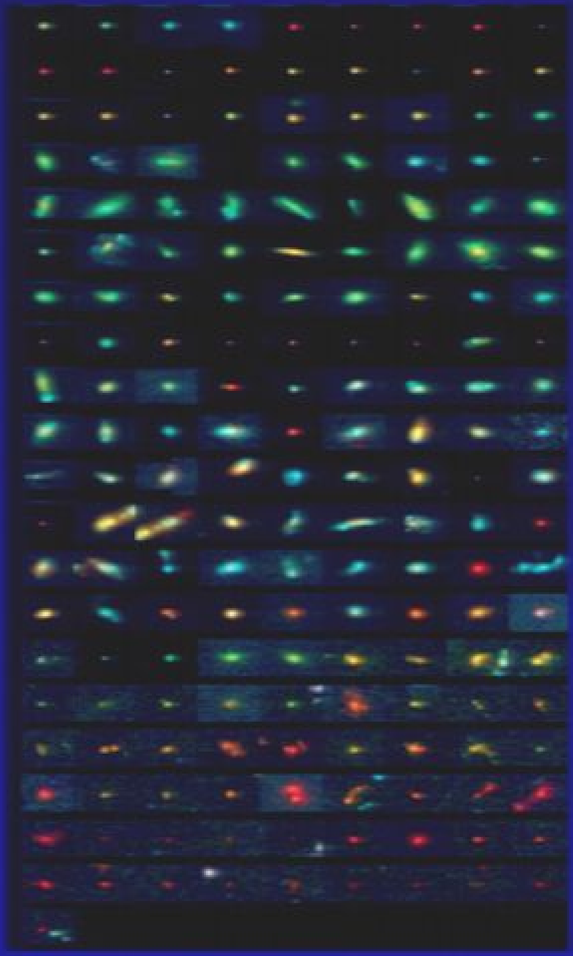
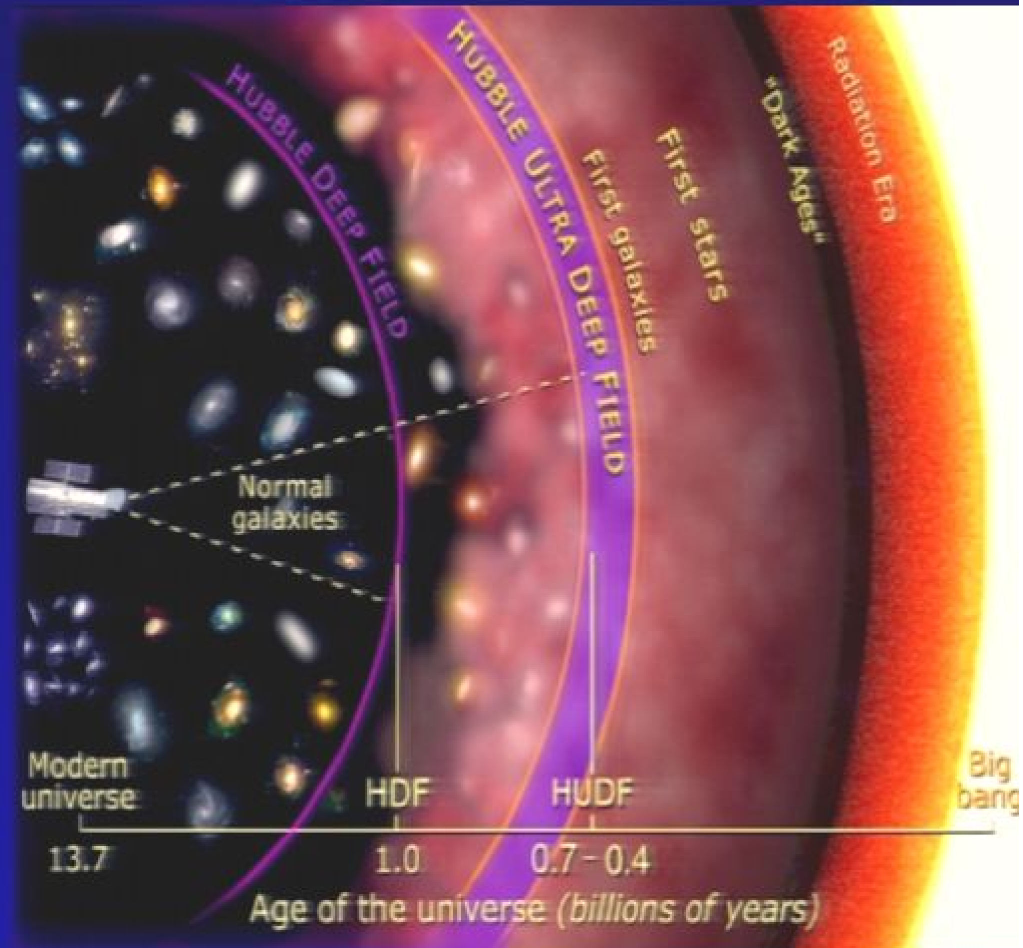
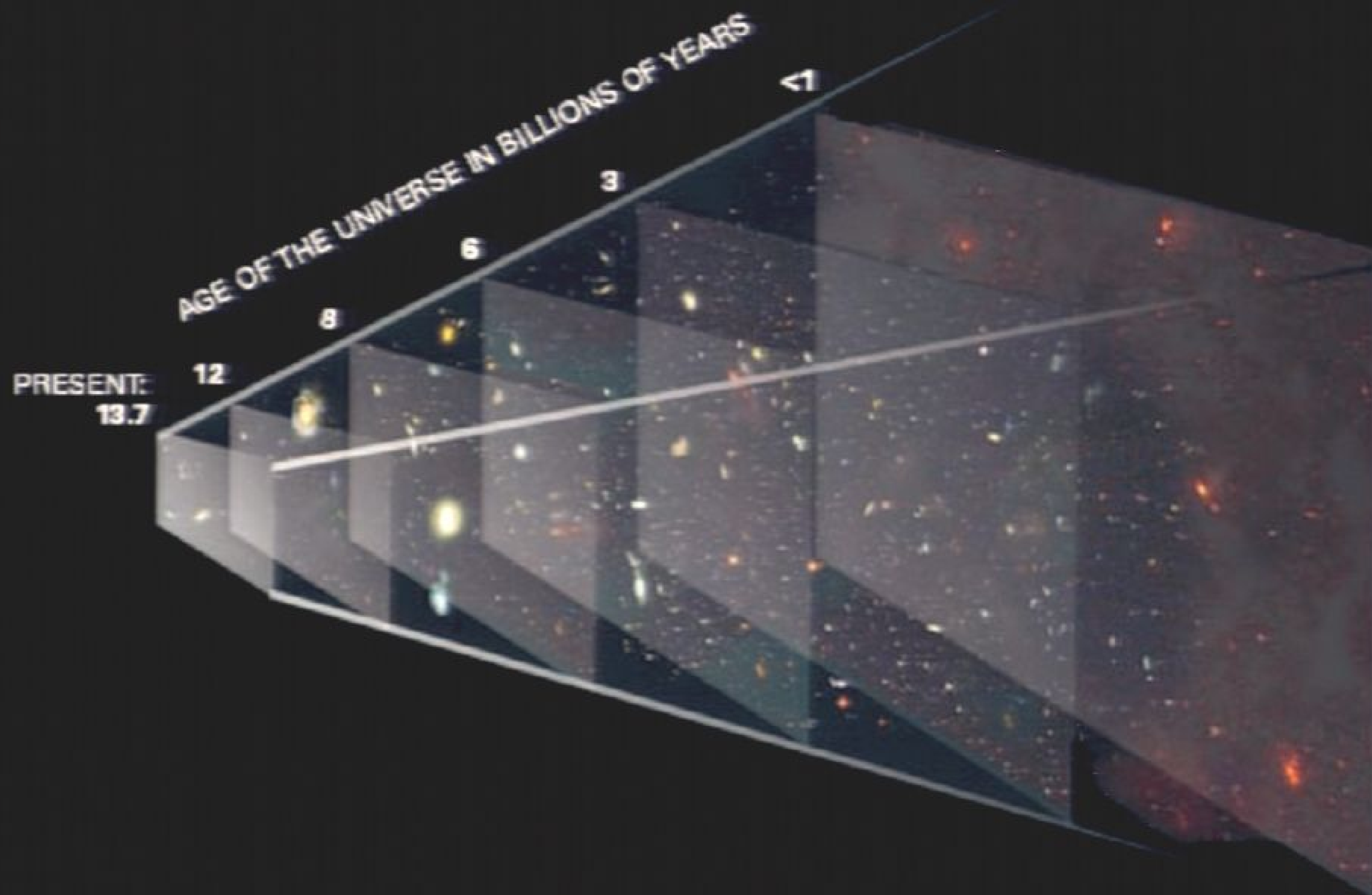


Hubble Ultra Deep Field (HUDF)



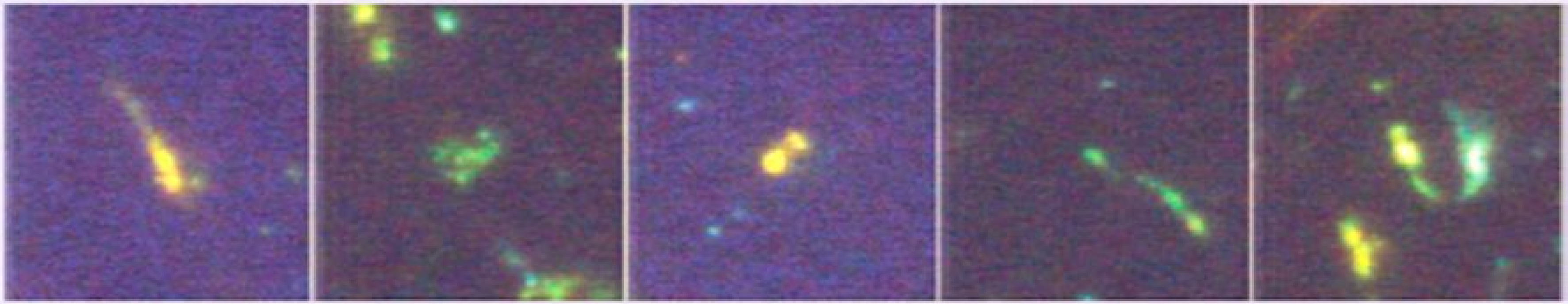


A three-dimensional view of the Hubble Ultra Deep Field. Each plane is labeled with the age of the universe at the time when the light we now see left the galaxies.

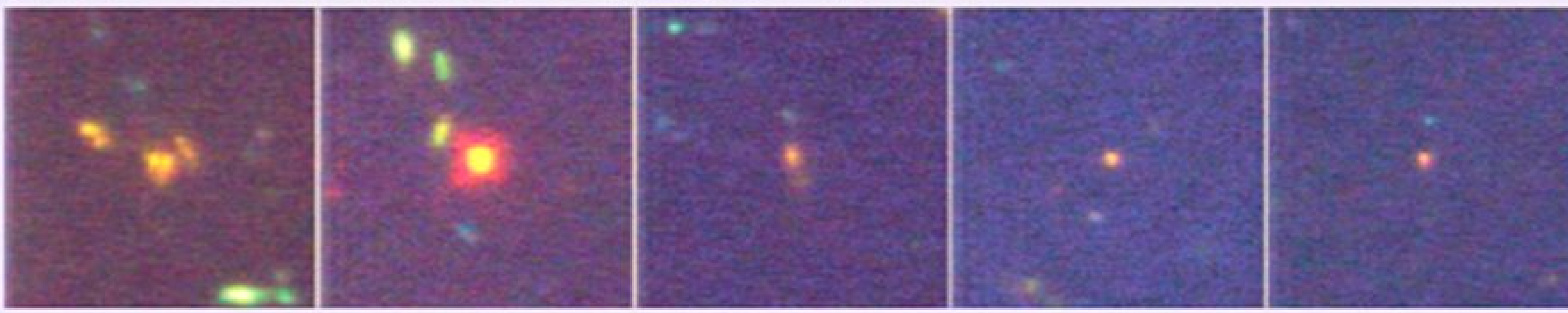
Close-up images of some of the most distant galaxies in the Hubble Ultra Deep Field

Galaxies at very early times tend to be very small and often show signs of interactions. The HUDF contains nearly 50 galaxies at redshifts 5–6, compared to a few tentative identifications in earlier, shallower observations.

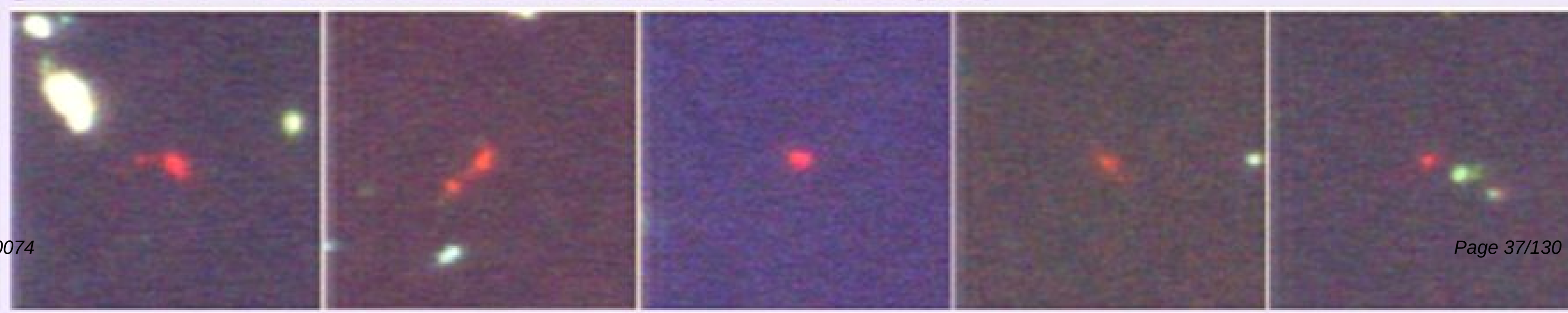
galaxies $z \sim 3$–4 Lookback time 11.4–12 billion years (312 objects)



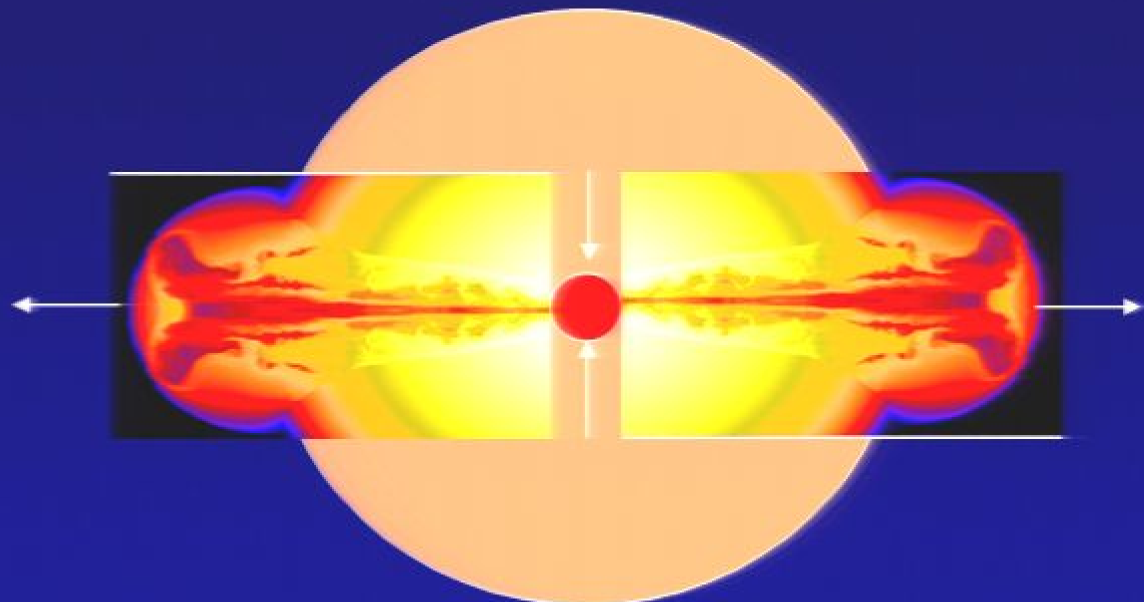
galaxies $z \sim 4$–5 Lookback time 12–12.3 billion years (79 objects)



galaxies $z > 5$ Lookback time 12.3–12.6 billion years (45 objects)



Long Gamma-Ray Bursts: *Observing One Star at a Time*

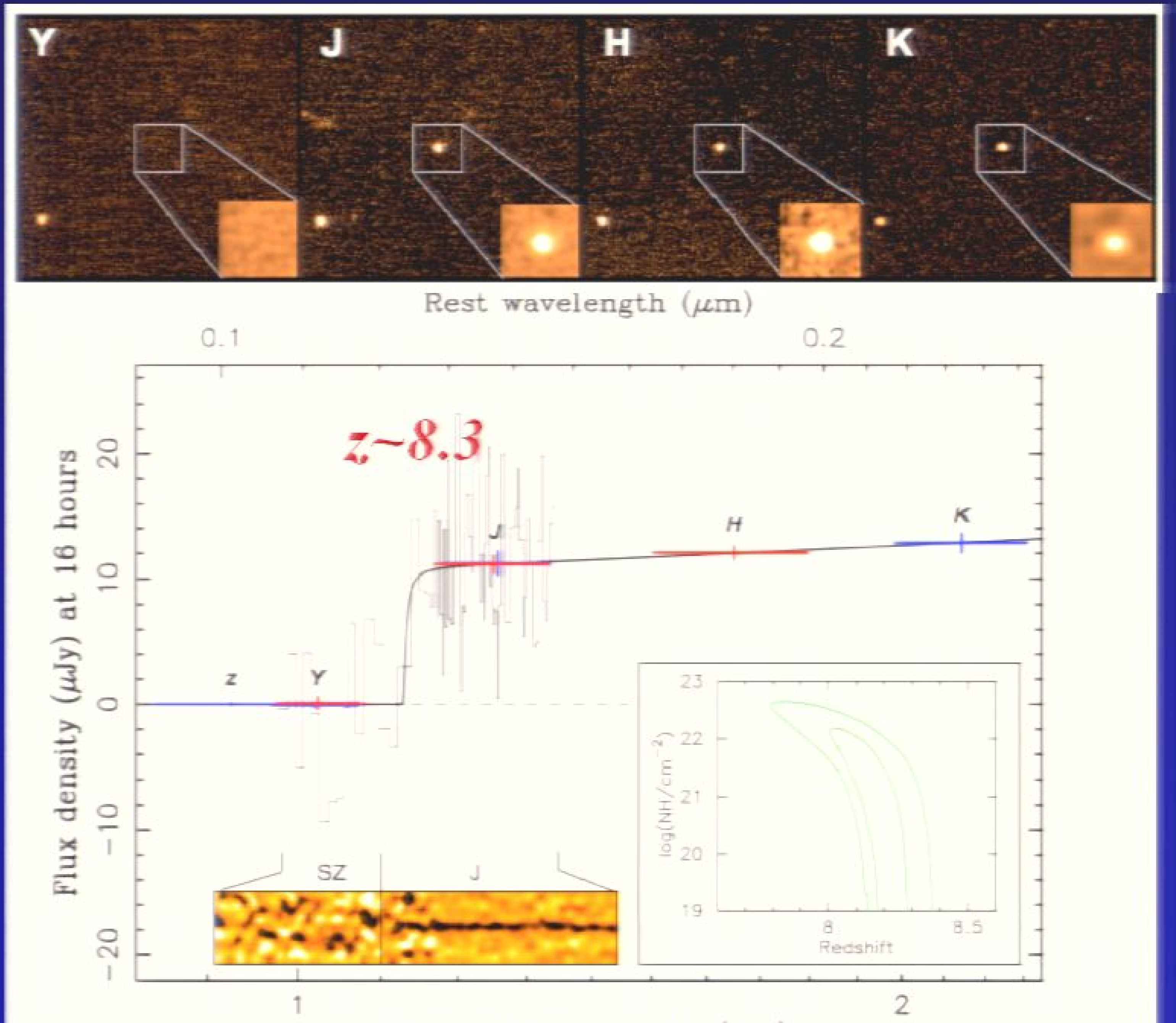


Collapse of a Massive Star

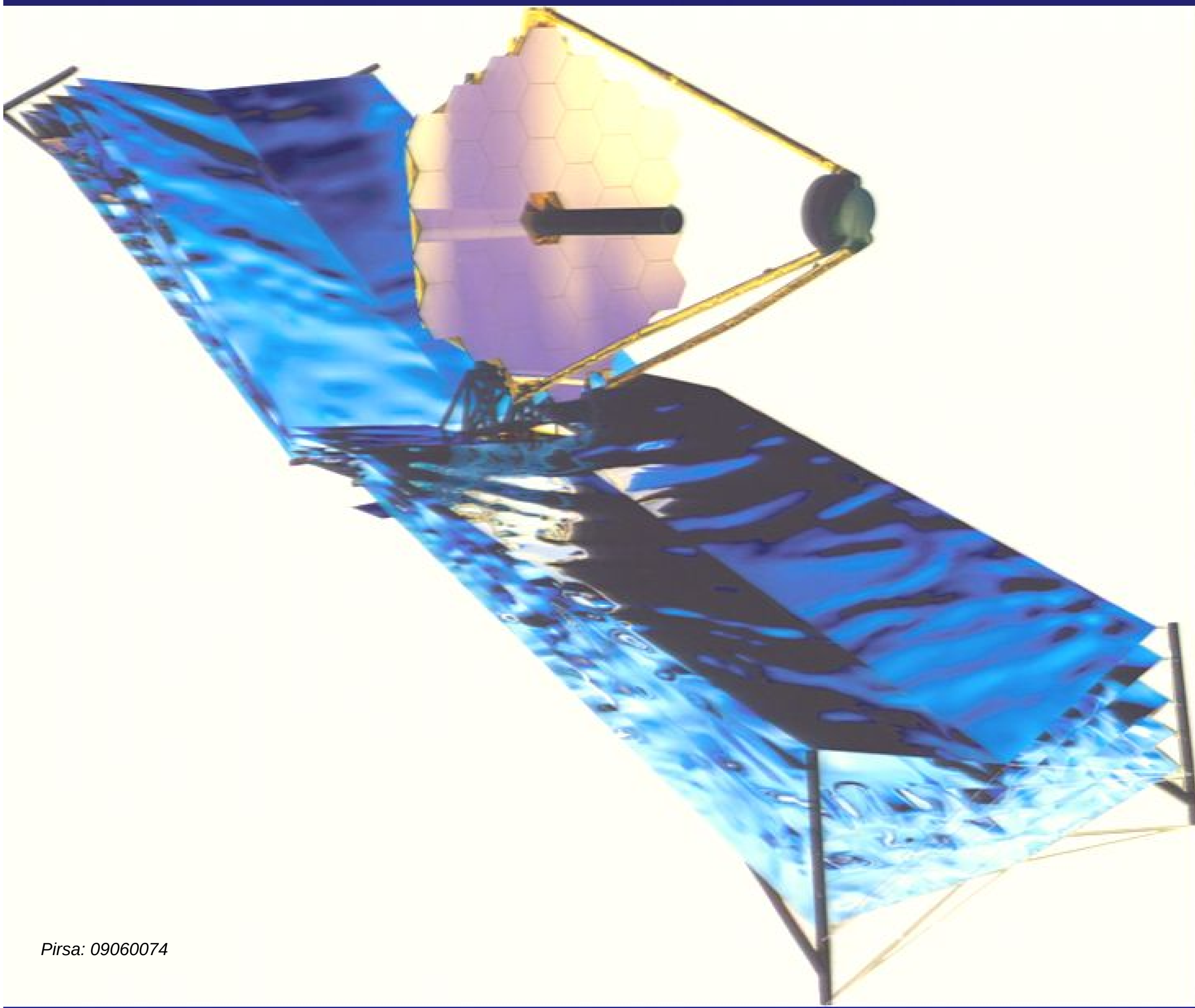
(accompanied by a supernova)

Existing finder: *Swift;* **Proposed:** *JANUS, EXIST (high–z GRBs)*

A Bright Explosion 600 Million Years after the Big Bang



***James Webb Space Telescope** (successor to **Hubble Space Telescope**): Searching for the First Light*



Mirror diameter: 6.5 meter

Material: beryllium

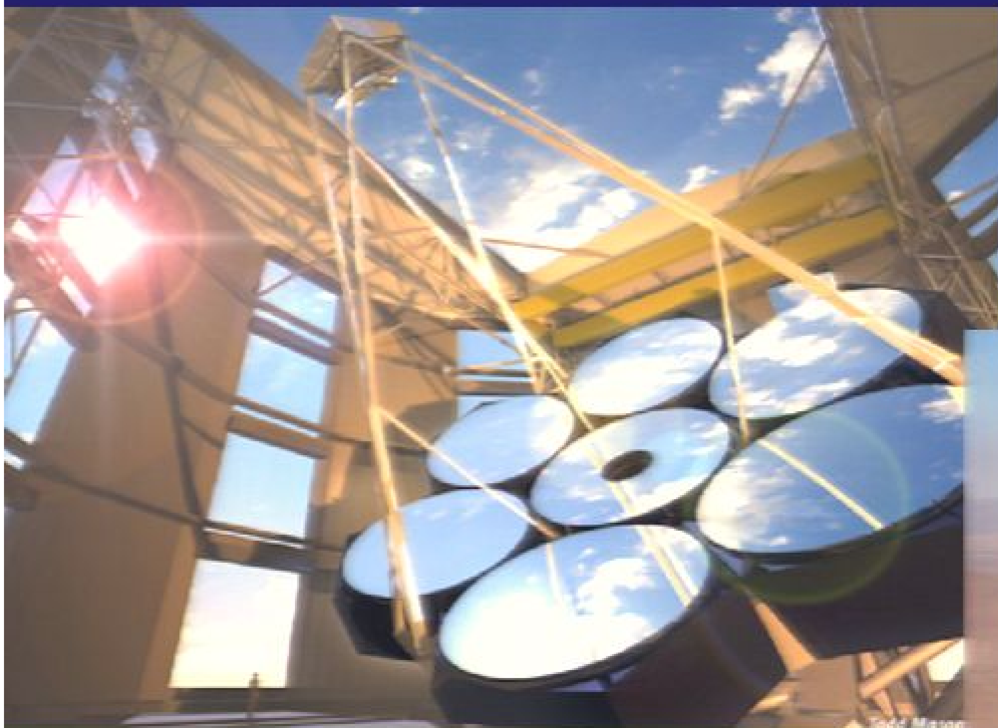
18 segments

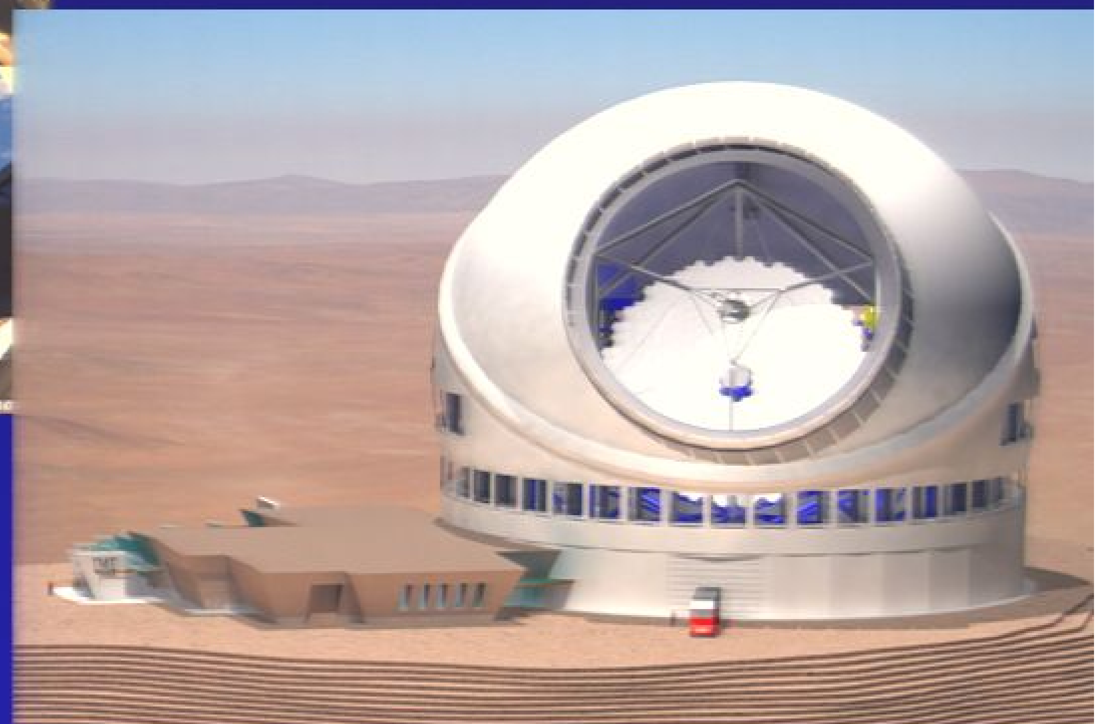
Wavelength coverage: 0.6-28 micron

L2 orbit

Launch date: 2013

Extremely Large Telescopes (20-40 meters)



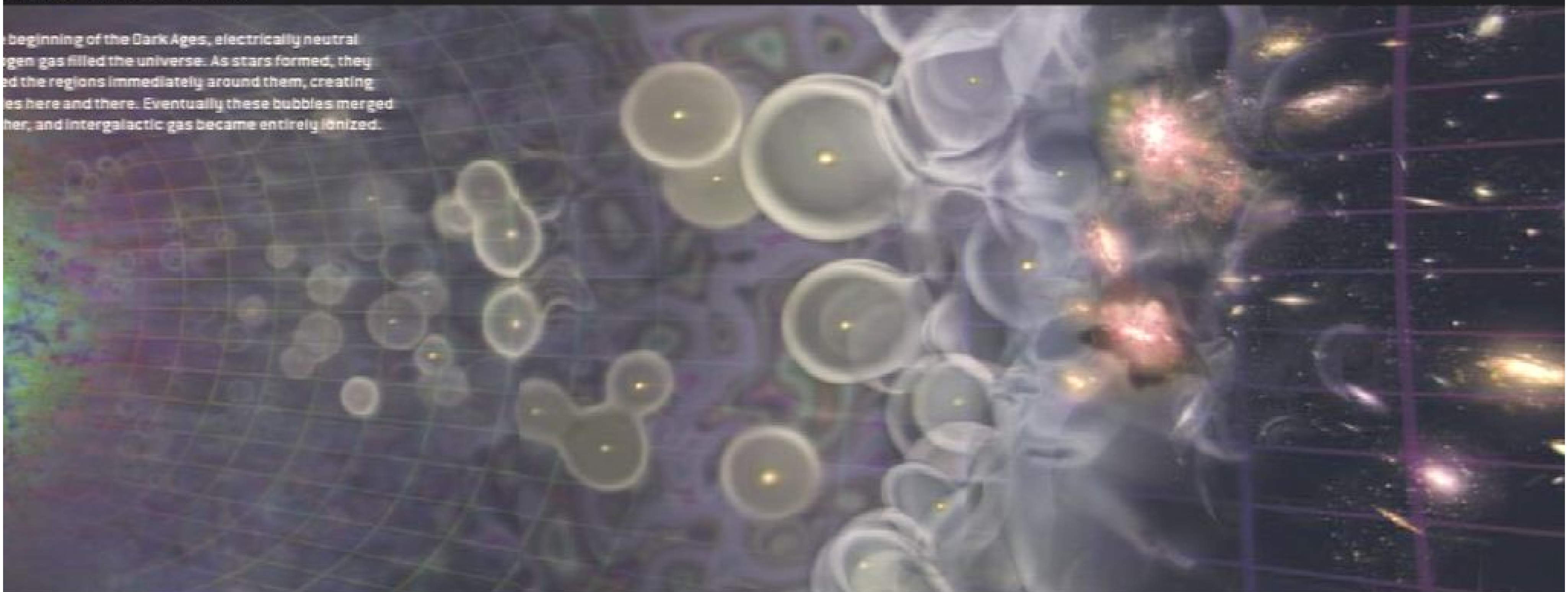


- GMT=Seven mirrors, each 8.4m in diameter
- TMT, EELT – segmented 20-40m aperture

Observing the Cosmic Hydrogen

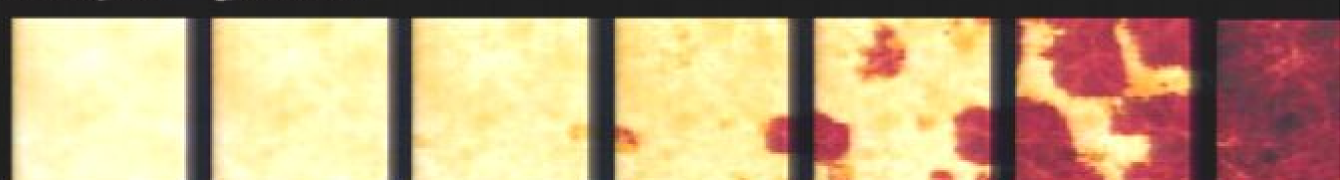
HTING UP THE COSMOS

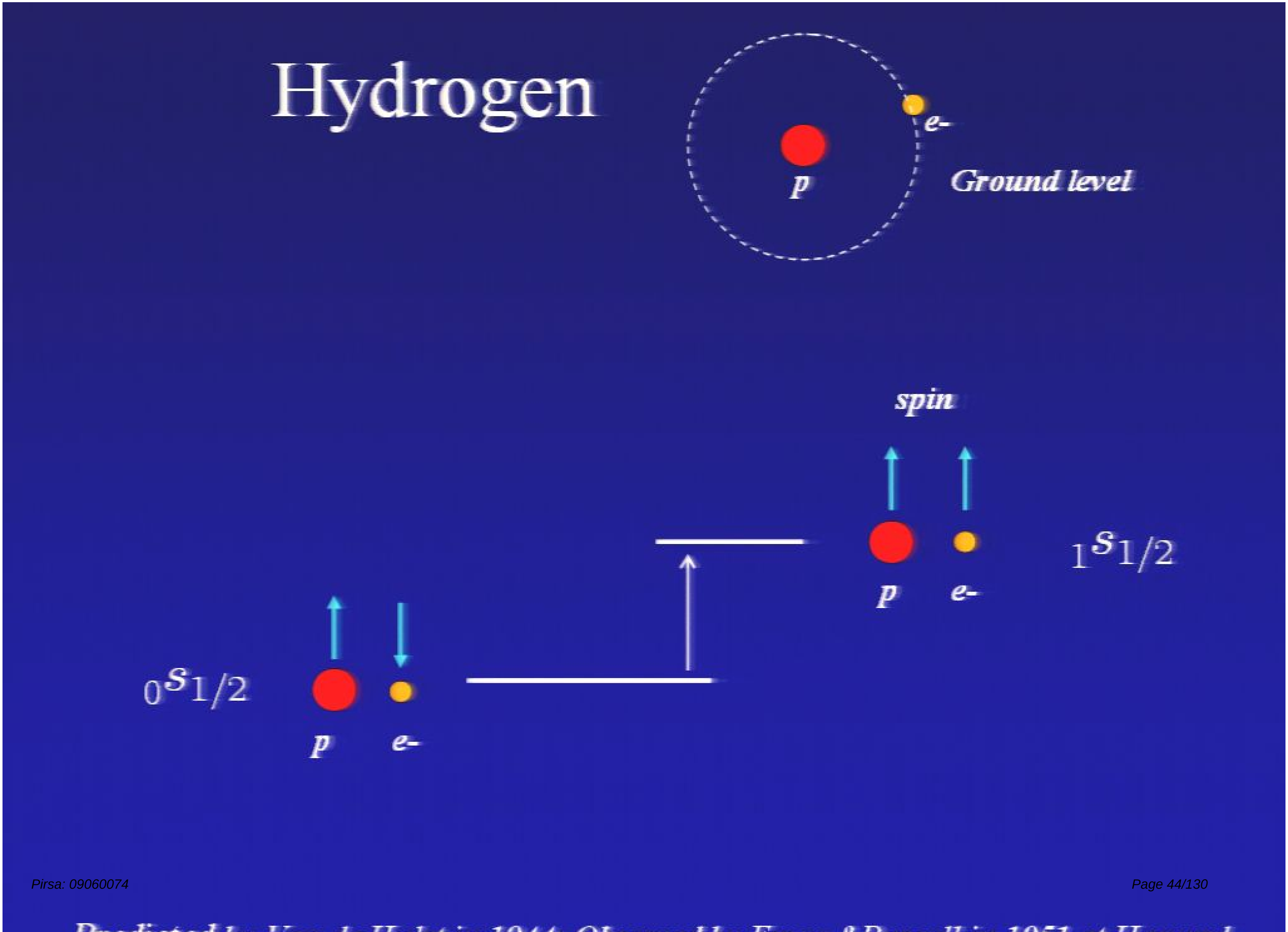
e beginning of the Dark Ages, electrically neutral
gen gas filled the universe. As stars formed, they
ed the regions immediately around them, creating
es here and there. Eventually these bubbles merged
her, and intergalactic gas became entirely ionized.



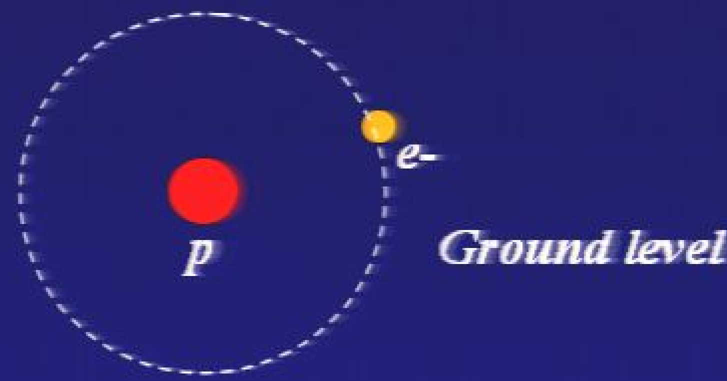
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million yea
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million ligh
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters
	All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.	Faint red patches show that the stars and quasars have begun to ionize the gas around them.	These bubbles of ionized gas grow.	New stars and quasars form and create their own bubbles.	The bubbles are beginning to interconnect.	The bubbles have merged and nearly taken over all of space.	The only remai neutral hydrog is concentrate in galaxies.

ated images of 21-centimeter radiation show how hydrogen
urns into a galaxy cluster. The amount of radiation (*white is*
st; orange and red are intermediate; black is least) reflects
the density of the gas and its degree of ionization: dense,
ically neutral gas appears white; dense, ionized gas appears
. The images have been rescaled to remove the effect of cosmic
nsion and thus highlight the cluster-forming processes.
use of expansion, the 21-centimeter radiation is actually
rved at a longer wavelength; the earlier the image, the longer
avelength.

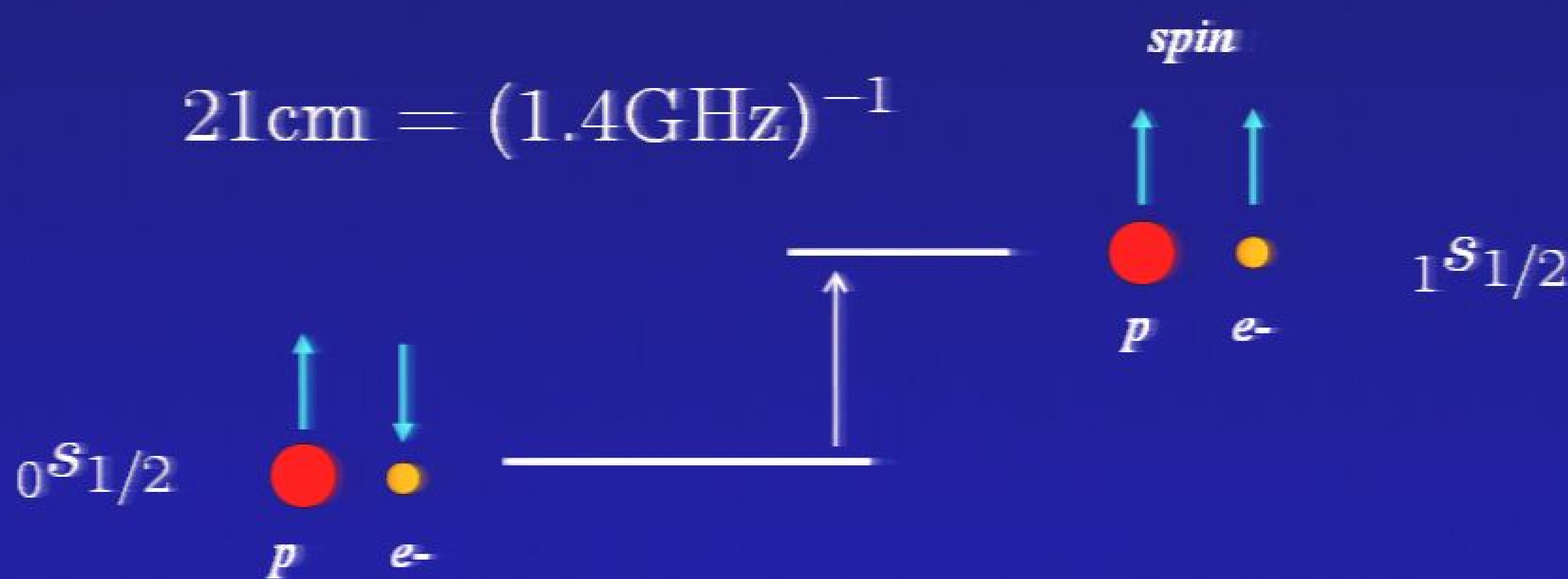



Hydrogen
e-
p
Ground level
spin
$_1S_{1/2}$
p
e-
$_0S_{1/2}$
p
e-

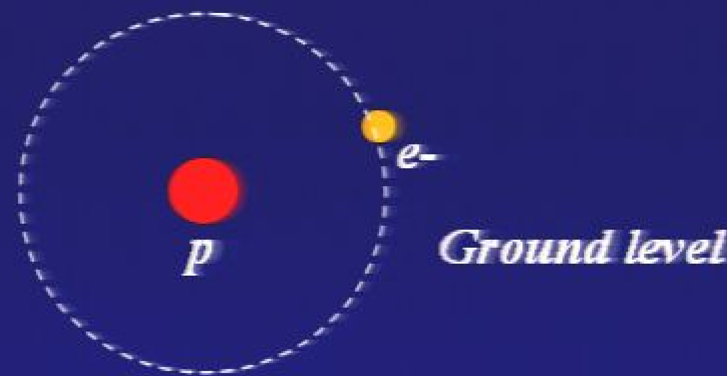
Hydrogen



$$21\text{cm} = (1.4\text{GHz})^{-1}$$



Hydrogen



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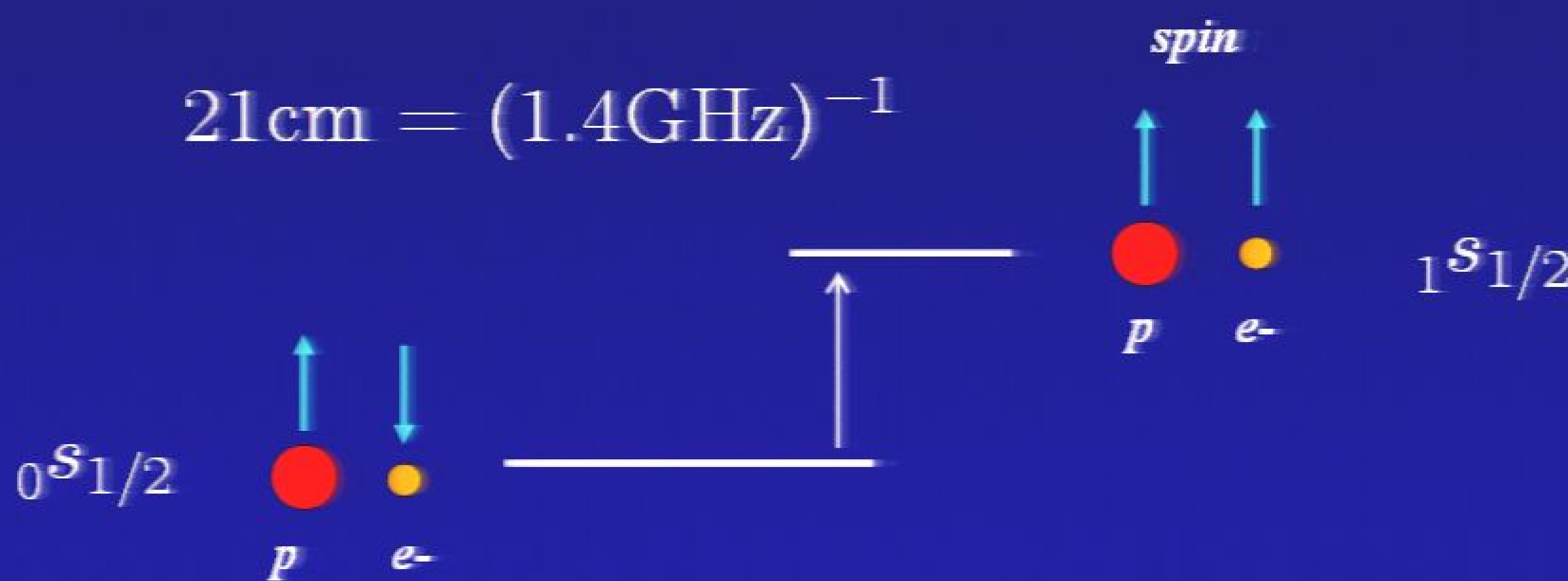
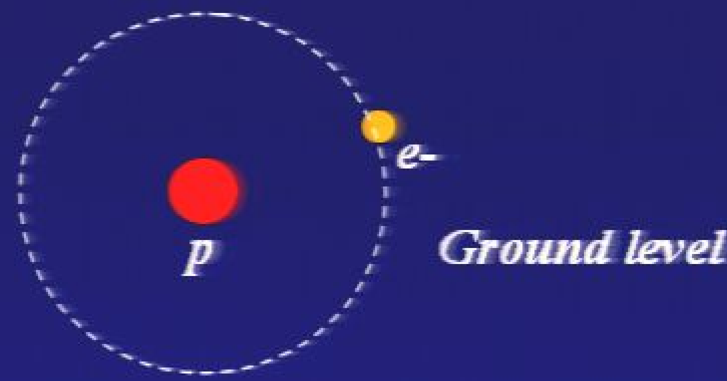


Spin Temperature

Hydrogen



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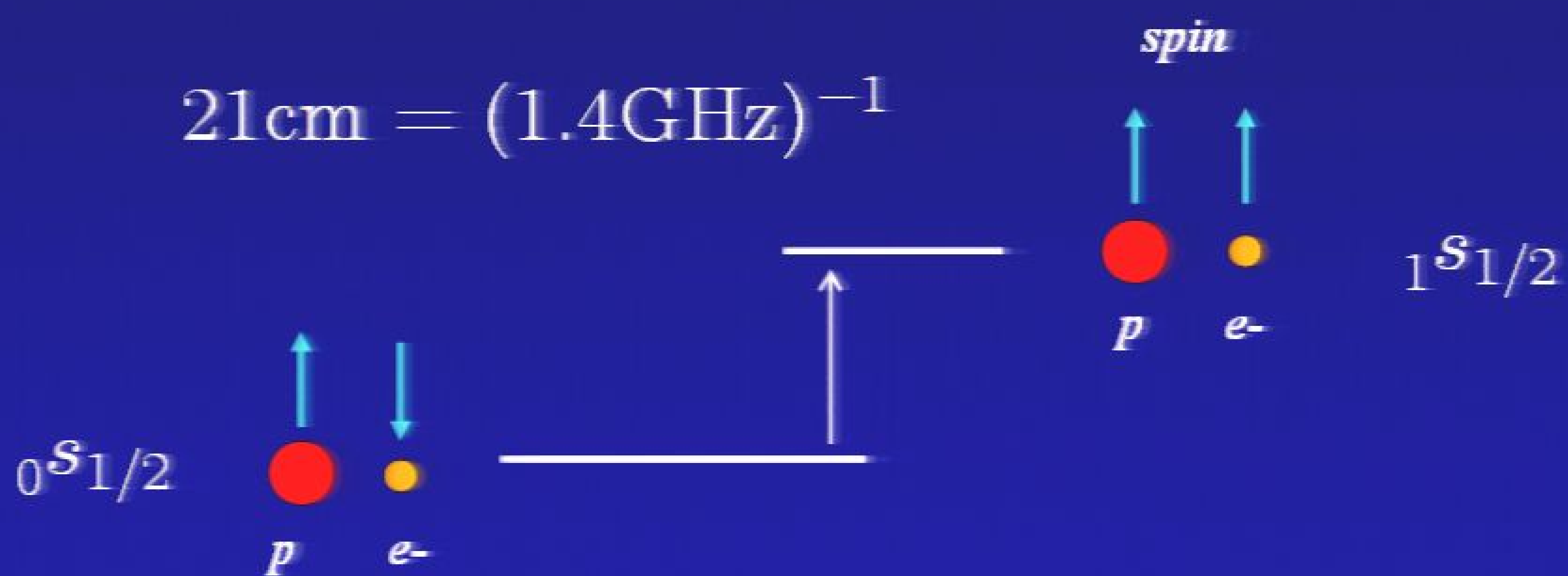
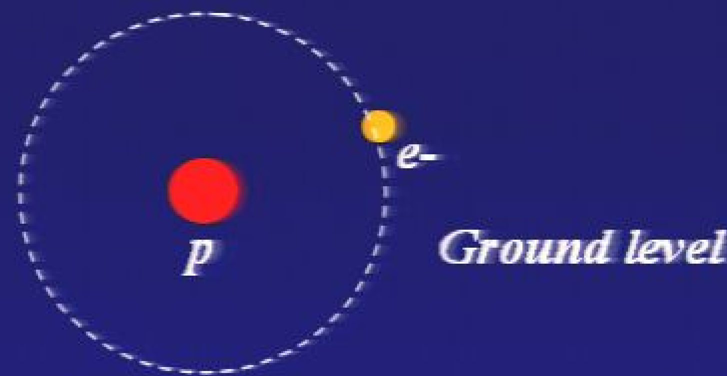


Spin Temperature

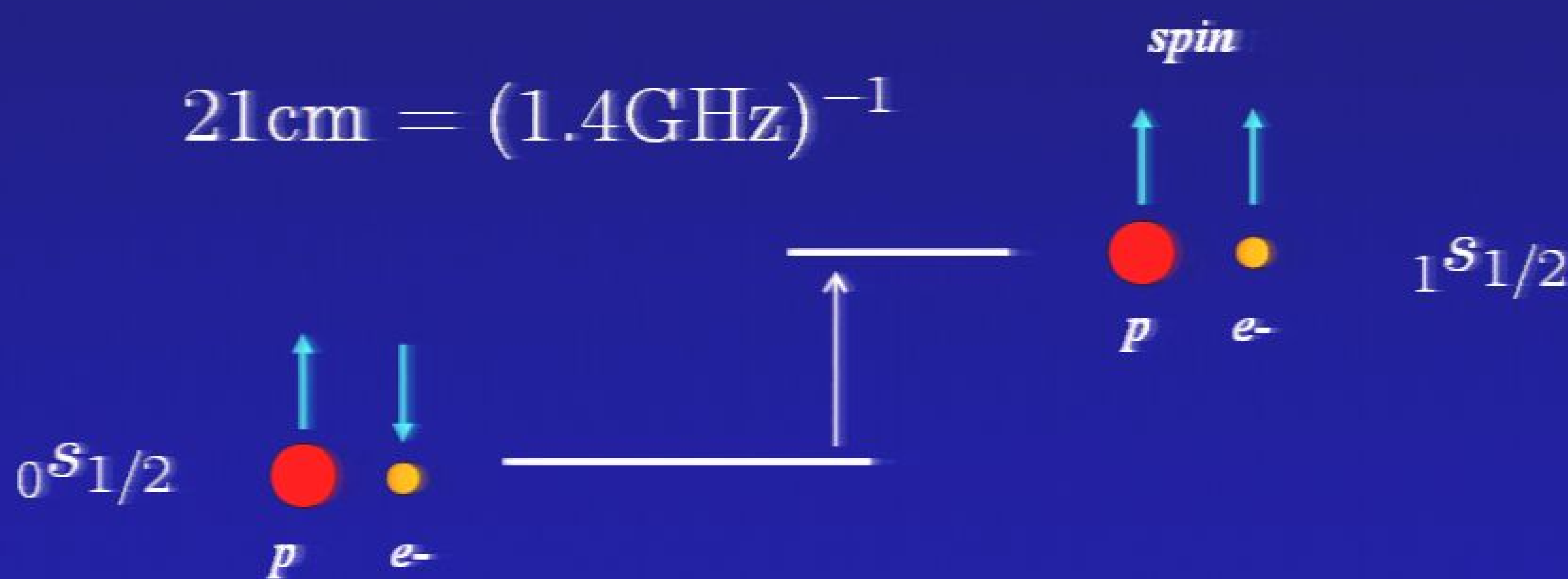
$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\mathrm{K}}{T_s}\}$$

Hydrogen



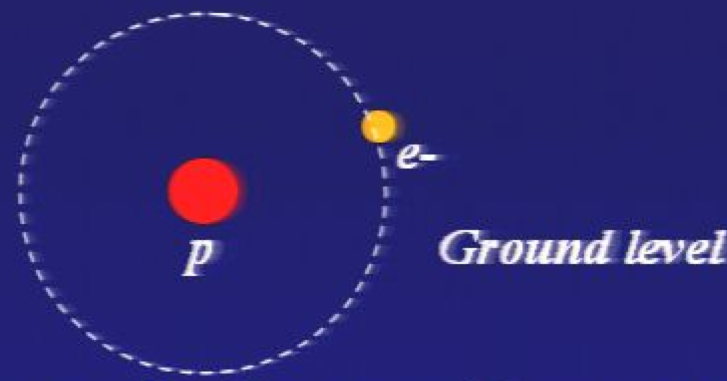
excitation rate= (atomic collisions)+(radiative coupling to CMB)

$$21\text{cm} = (1.4\text{GHz})^{-1}$$



Spin Temperature
$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\text{K}}{T_s}\} \qquad (g_1/g_0) = 3$$

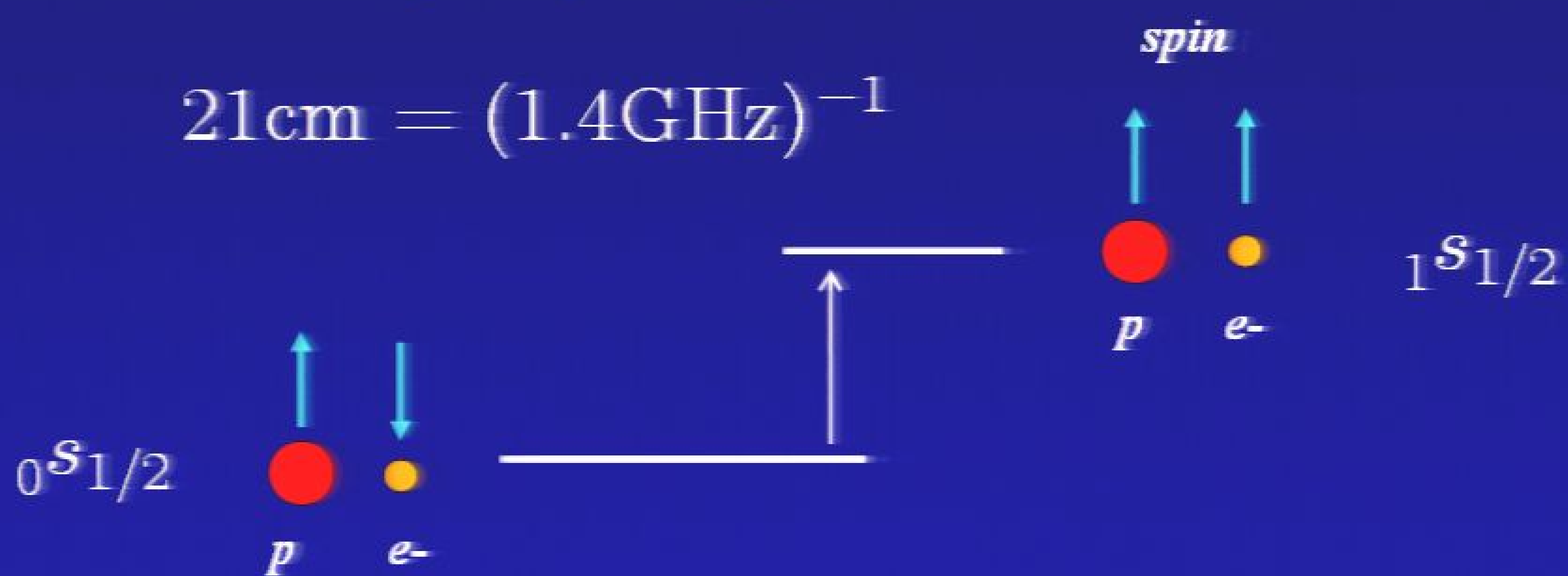
Hydrogen



excitation rate= (atomic collisions)+(radiative coupling to CMB)

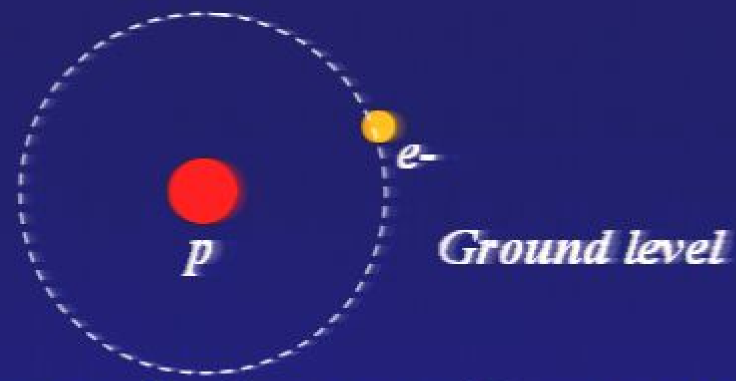
Couple T_s *to* T_k

$$21\text{cm} = (1.4\text{GHz})^{-1}$$



Spin Temperature $$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\text{K}}{T_s}\}$$ $$(g_1/g_0) = 3$$

Hydrogen

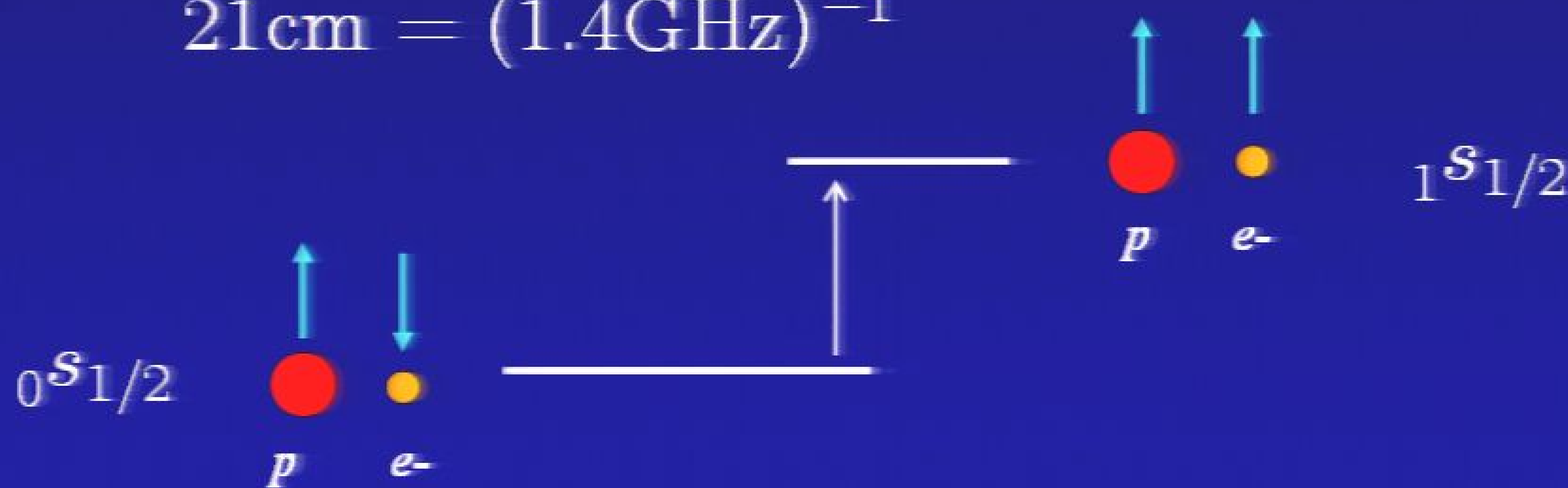


excitation rate= (atomic collisions)+(radiative coupling to CMB)

Couple T_s *to* T_k

Couples T_s *to spin*

$$21\text{cm} = (1.4\text{GHz})^{-1}$$

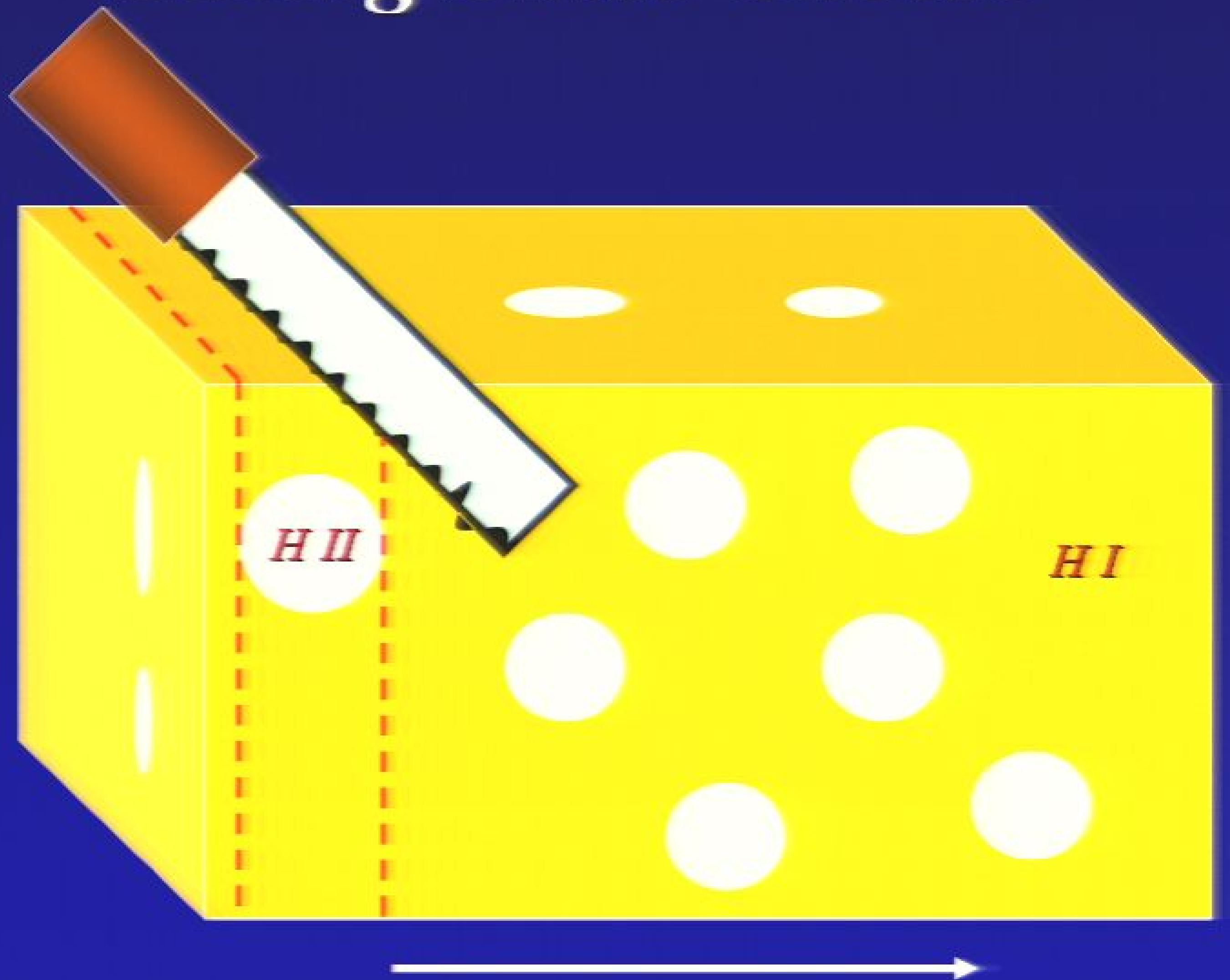


Spin Temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\left\{-\frac{0.068\text{K}}{T_s}\right\} \qquad (g_1/g_0) = 3$$

21cm Tomography of Ionized Bubbles During Reionization is like

Slicing Swiss Cheese

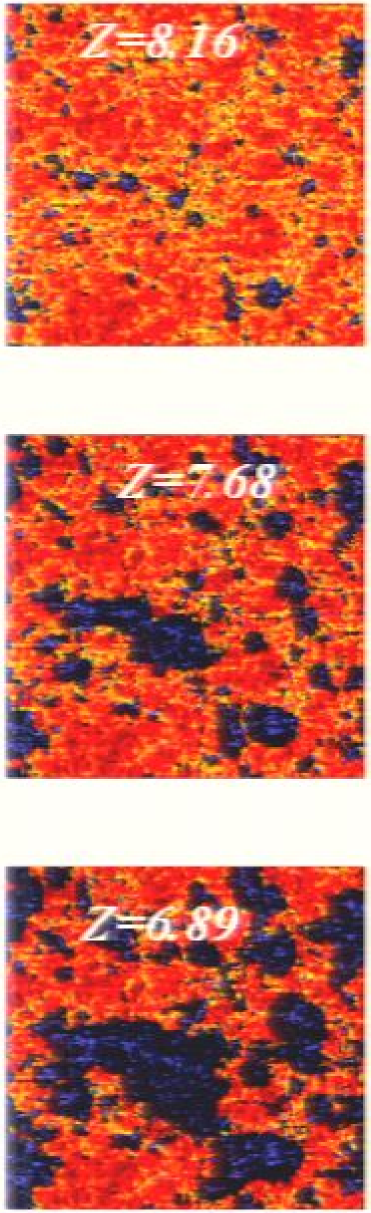


Observed wavelength ⇔ distance

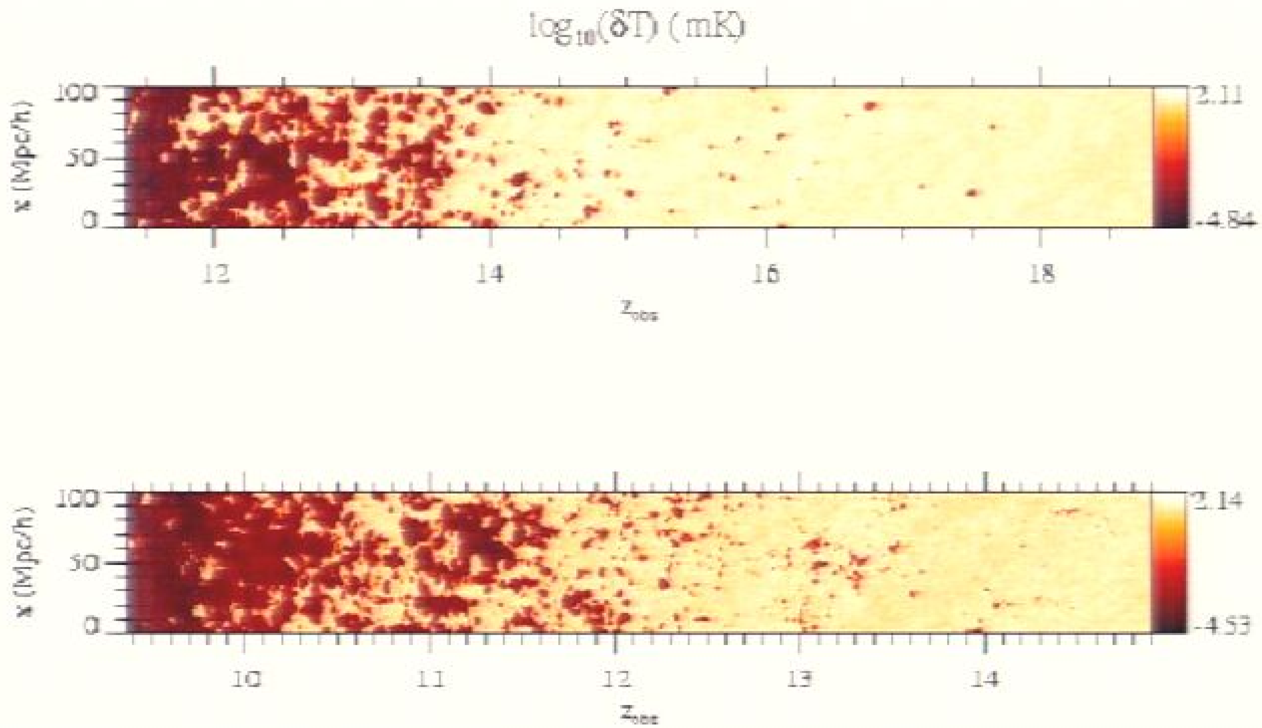
$$21\text{cm} \times (1+z)$$

21cm Mapping of Epoch of Reionization

HI Density



Zahn et al. 2006

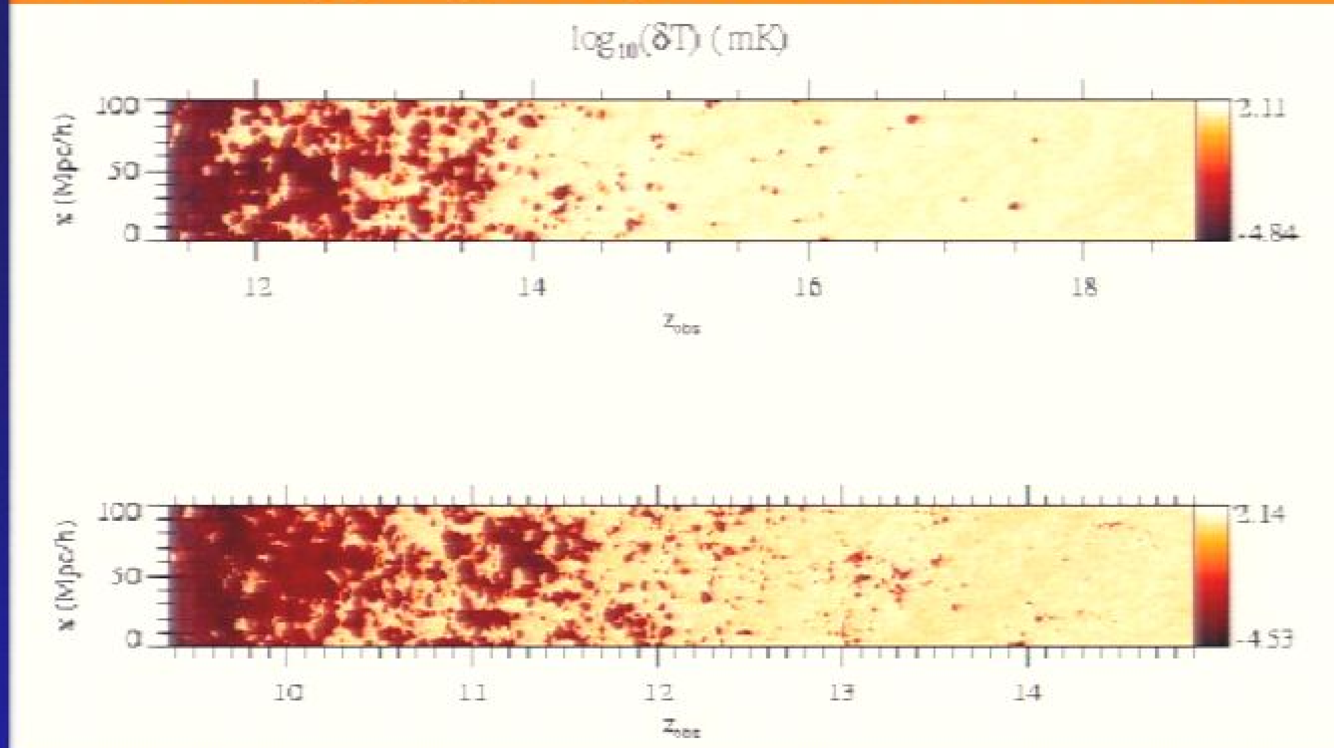


Mellema et al. 2006

Trac, Cen, & Loeb 2008

HI Density

21cm Mapping of Epoch of Reionization



Mellema et al. 2006

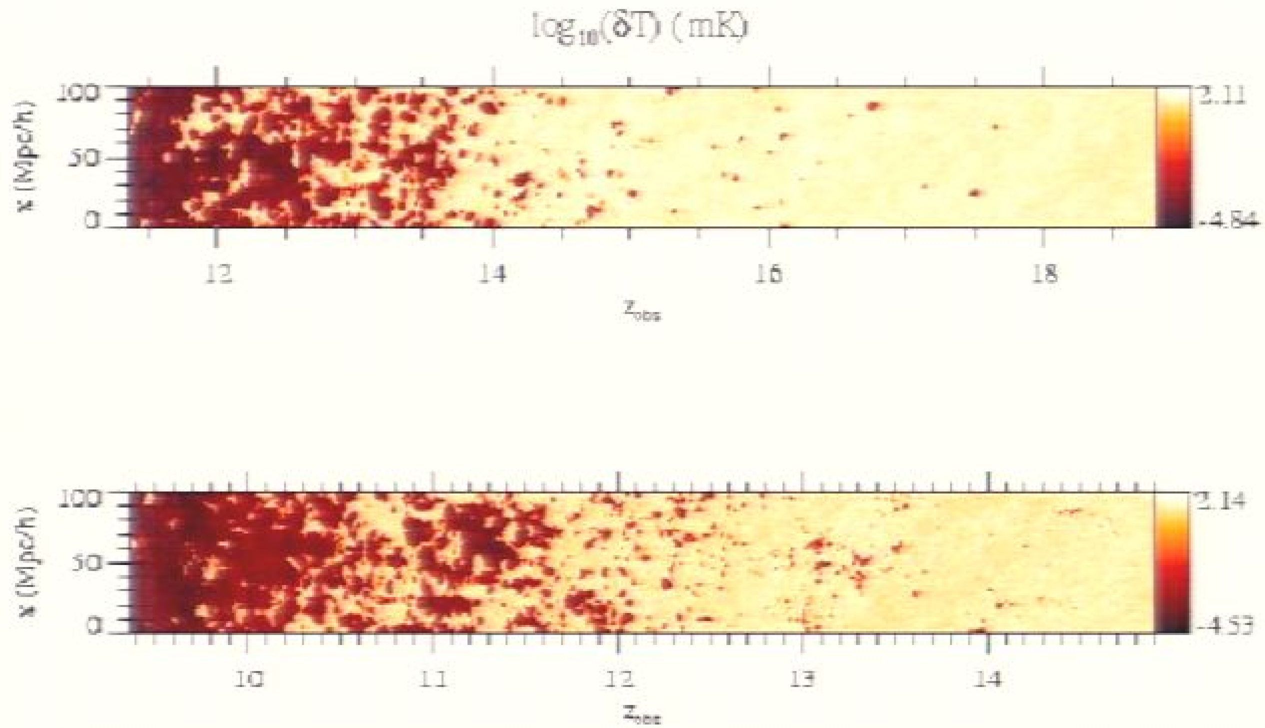
Zahn et al. 2006

Trac, Cen, & Loeb 2008

21cm Mapping of Epoch of Reionization

HI Density

Zahn et al. 2006



Mellema et al. 2006

C:\loeb\Images\New\rhoHII_768.mov

x_HI(z)

T(z)

PopII/Pop III

Trac, Cen, & Loeb 2008

Separating the Physics from the Astrophysics

Physics: *initial conditions from inflation; nature of dark matter and dark energy*

Astrophysics: *consequences of star formation*

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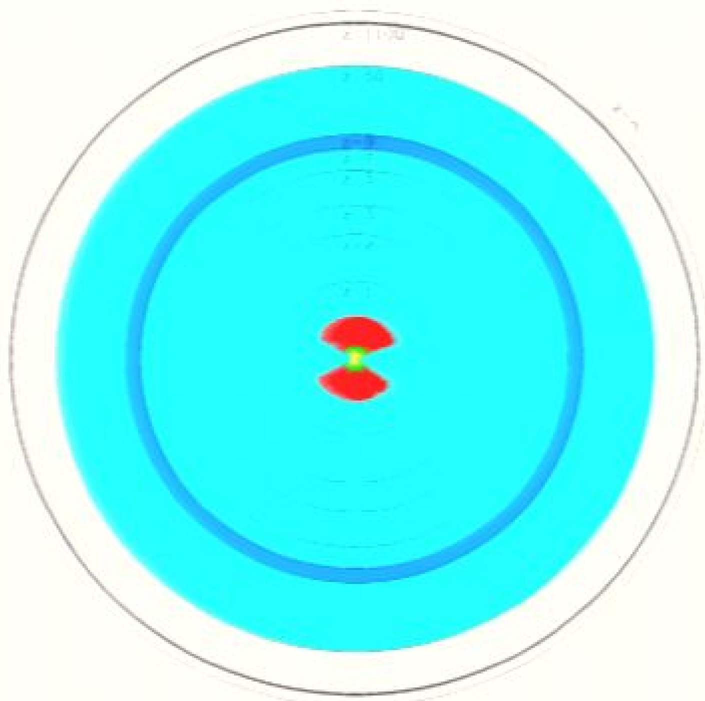
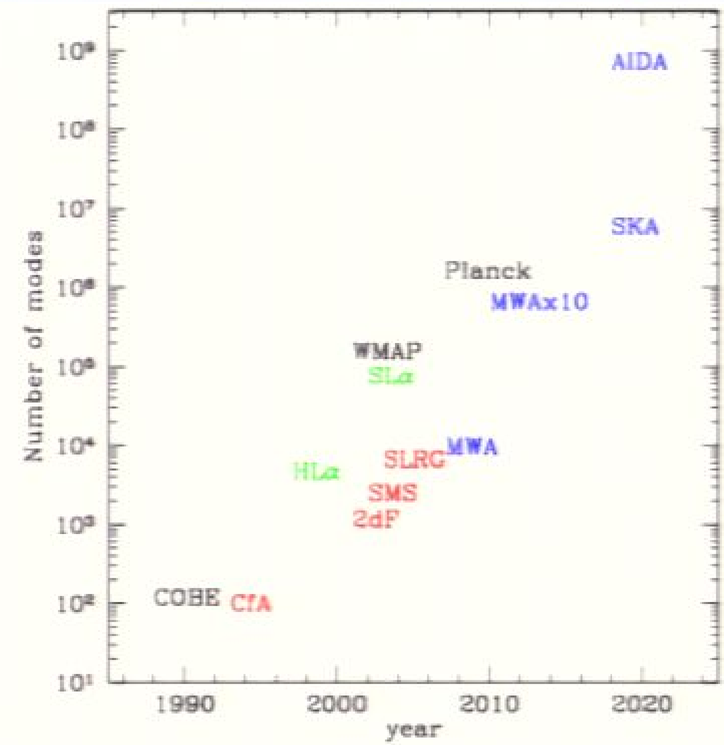
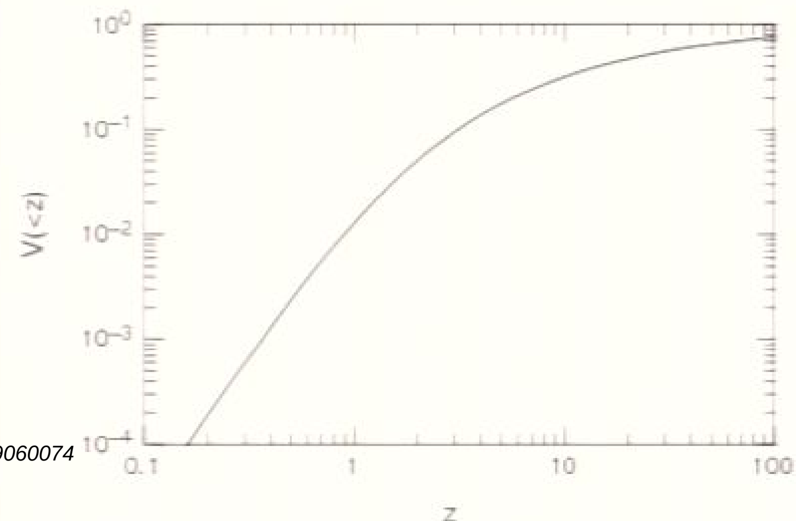
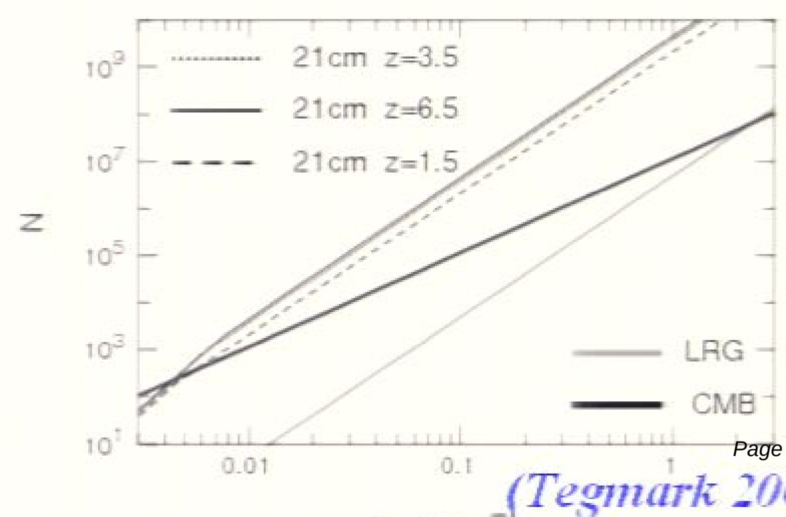
- ***After reionization (z<6):*** dense pockets of residual hydrogen (DLAs) trace large scale structure

Counting Modes in Cosmological Surveys

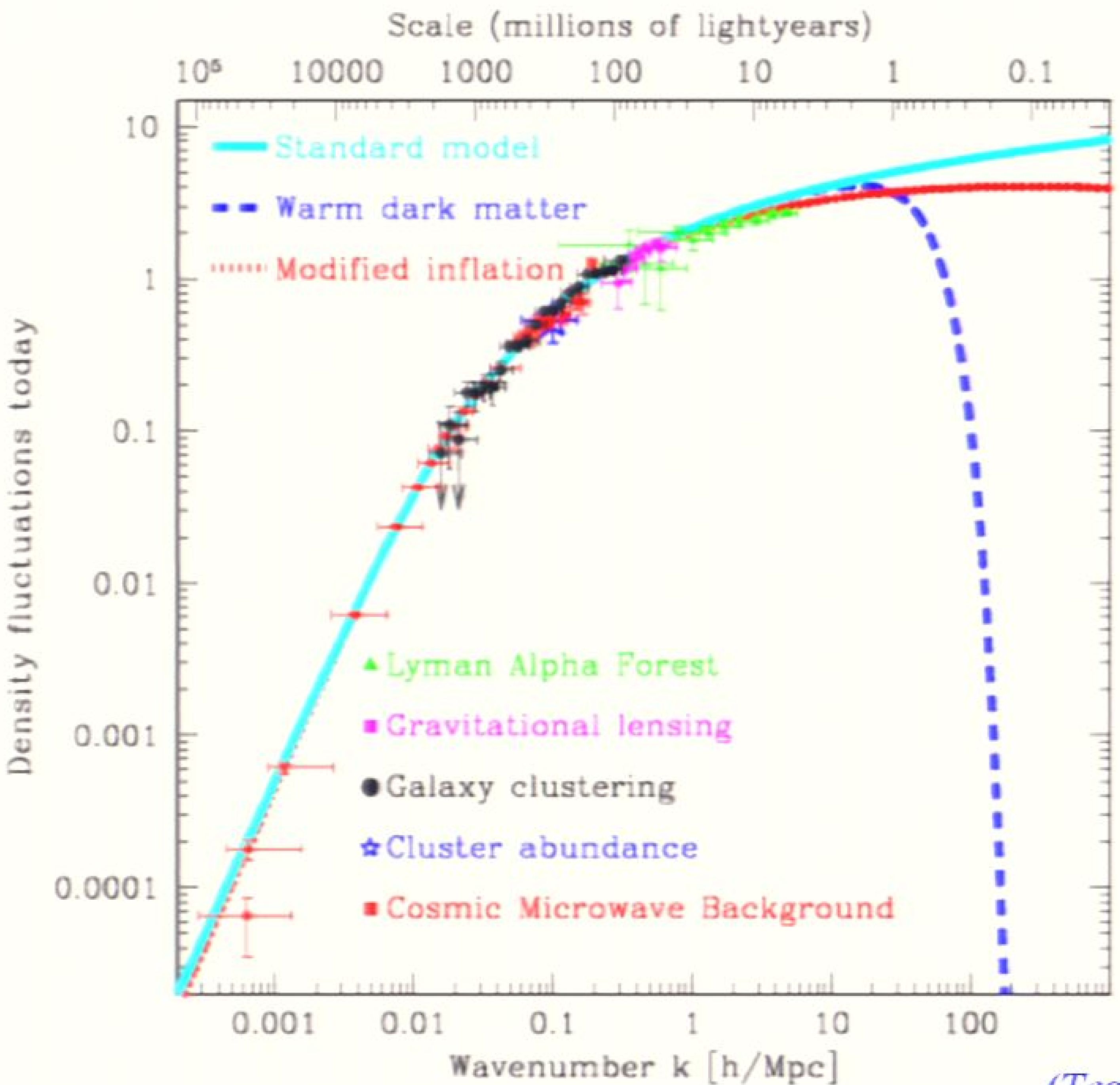








(Tegmark 2008)



(Tegmark 2008)

Experiments

*MWA (Murchison Wide-Field Array)

MIT/U.Melbourne,ATNF,ANU/CfA/Raman I.

*LOFAR (Low-frequency Array)

Netherlands

*21CMA (formerly known as PAST)

China

*PAPER

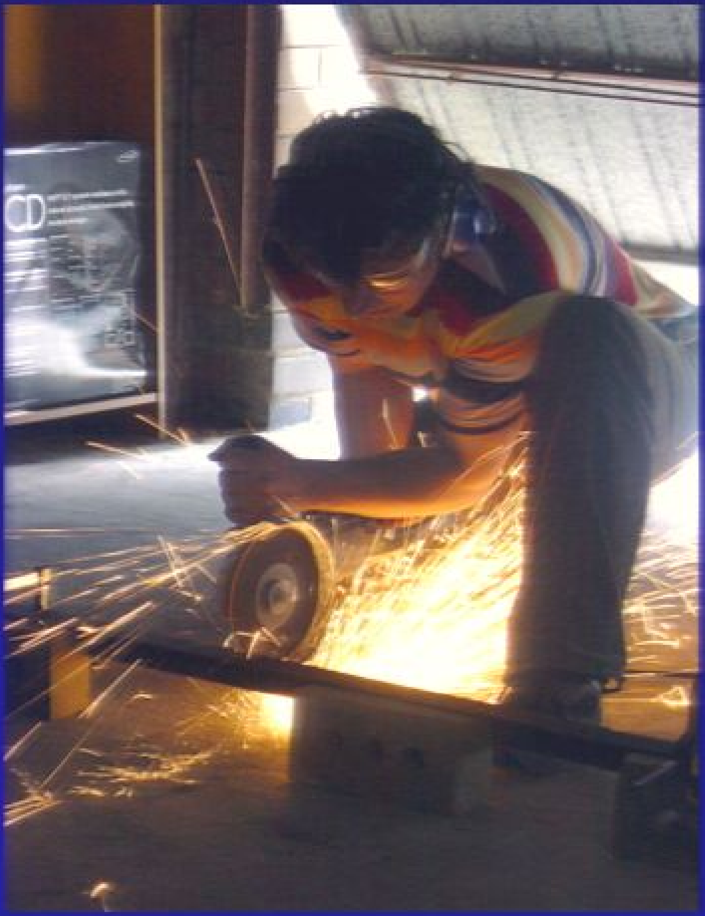
UCB/NRAO

*GMRT (Giant Meterwave Radio Telescope)

India/CITA/Pittsburg

*SKA (Square Kilometer Array)

International



Murchison Wide-Field Array: *mapping cosmic hydrogen through its 21cm emission*

- 4mx4m tiles of 16 dipole antennae, 80-300MHz
- 500 antenna tiles with total collecting area 8000 sq.m. at 150MHz across a 1.5km area; few arcmin resolution

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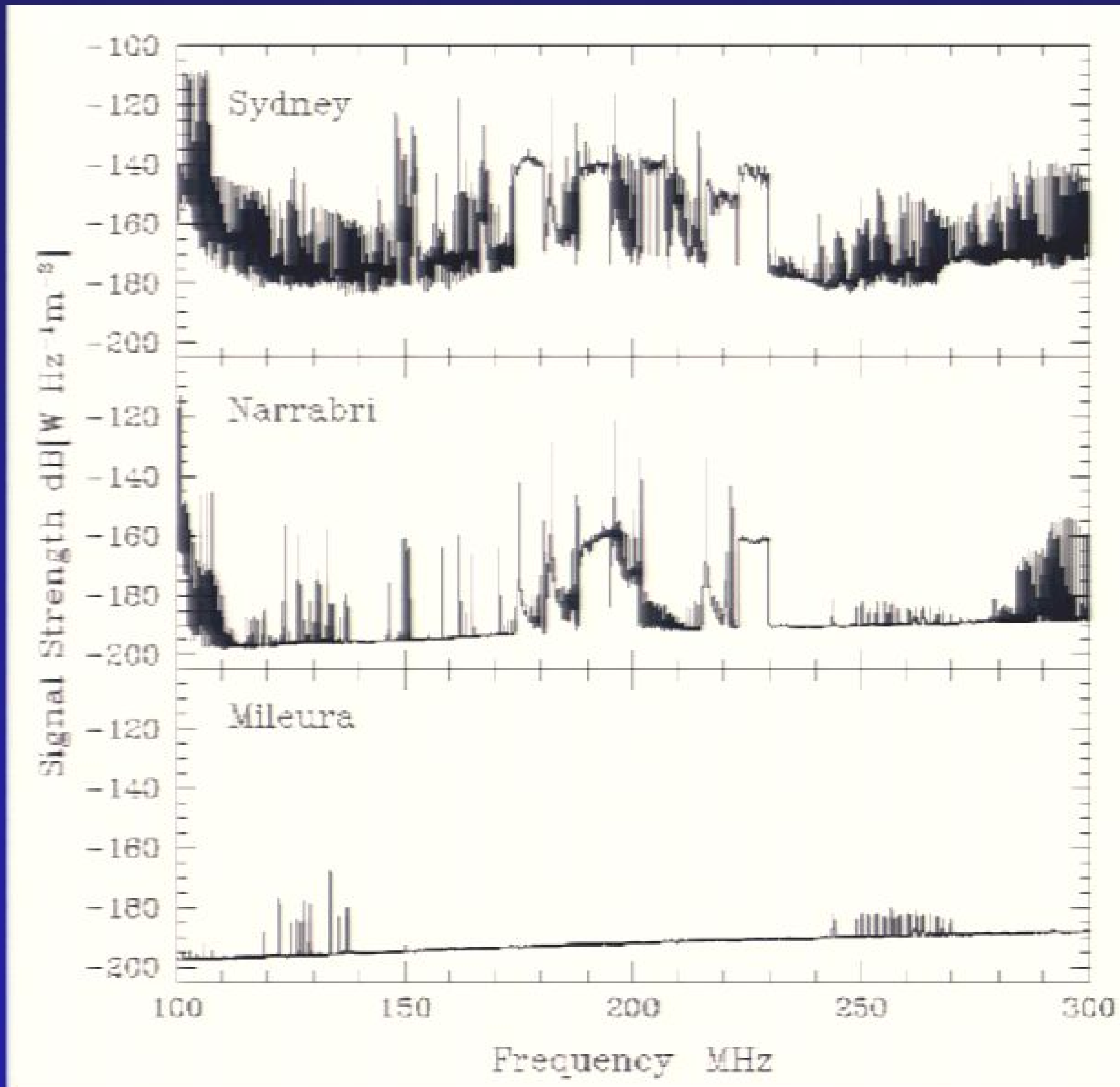
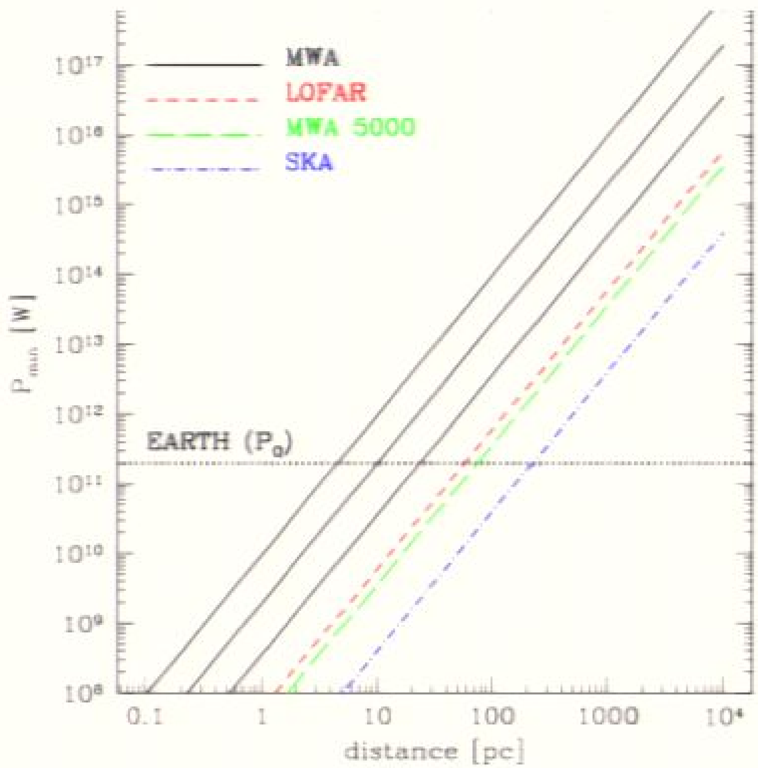
Terrestrial Radio Frequency Interference



$200\text{dB} = 10^6\text{Jy}$; ***Required:*** $\sim 10\mu\text{Jy}$

Extra-terrestrials can see us with an MWA-like observatory out to 50 light years!

Service	Freq. (MHz)	Transmitters (No.)	Max. Power per Tr. (W)	Bandwidth (Hz)	Power (W)	Power/Hz (W/Hz)
Military	~ 400	10	2×10^8	10^3	2×10^9	2×10^6
TV	40-850	2000	5×10^5	0.1	10^9	10^{10}
FM	88-108	9000	4×10^3	0.1	4×10^7	4×10^8



P_m for various high redshift 21 cm surveys and observing times as a function of the distance to the source. The power assumes the source emits isotropically. for the MWA we we assume a bandwidth of $\Delta\nu = 8$ kHz and observing times of 1 hour. 1 day and one month (from top to bottom). We assumed the same bandwidth for LOFAR . MWA 5000

If a more advanced civilization is discovered, it would be tempting to ask them if they know more about the Universe... but

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Ballistic Missile Early Warning Systems

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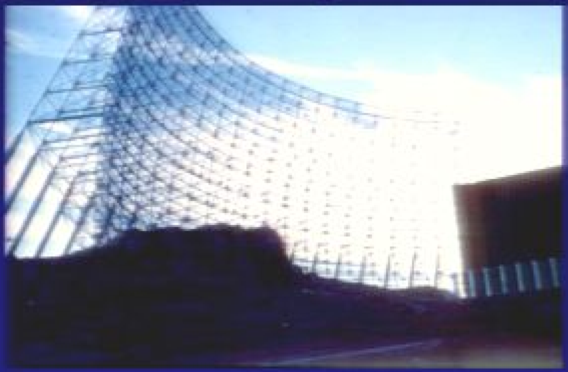
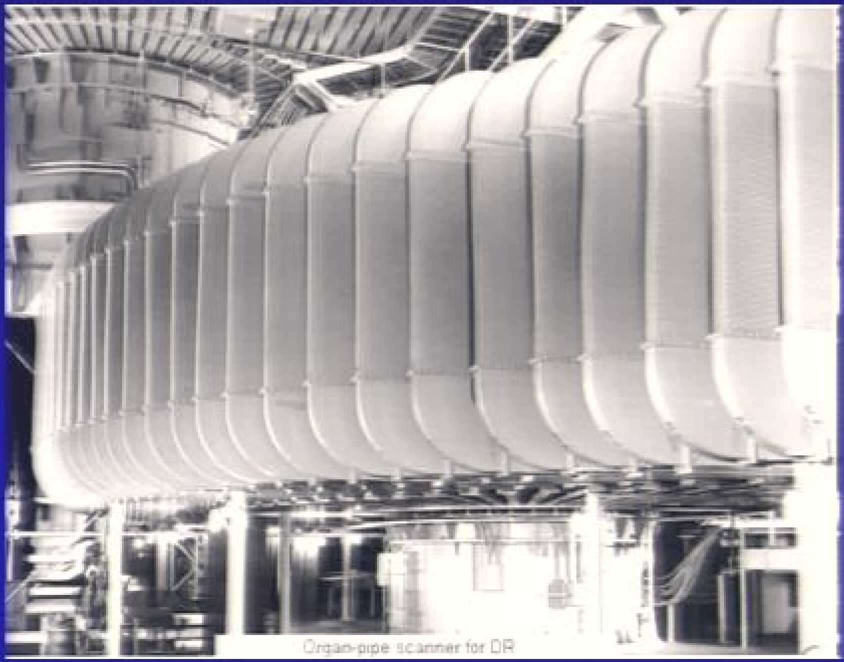


Detection Radar transmitter area. Note waveguide size

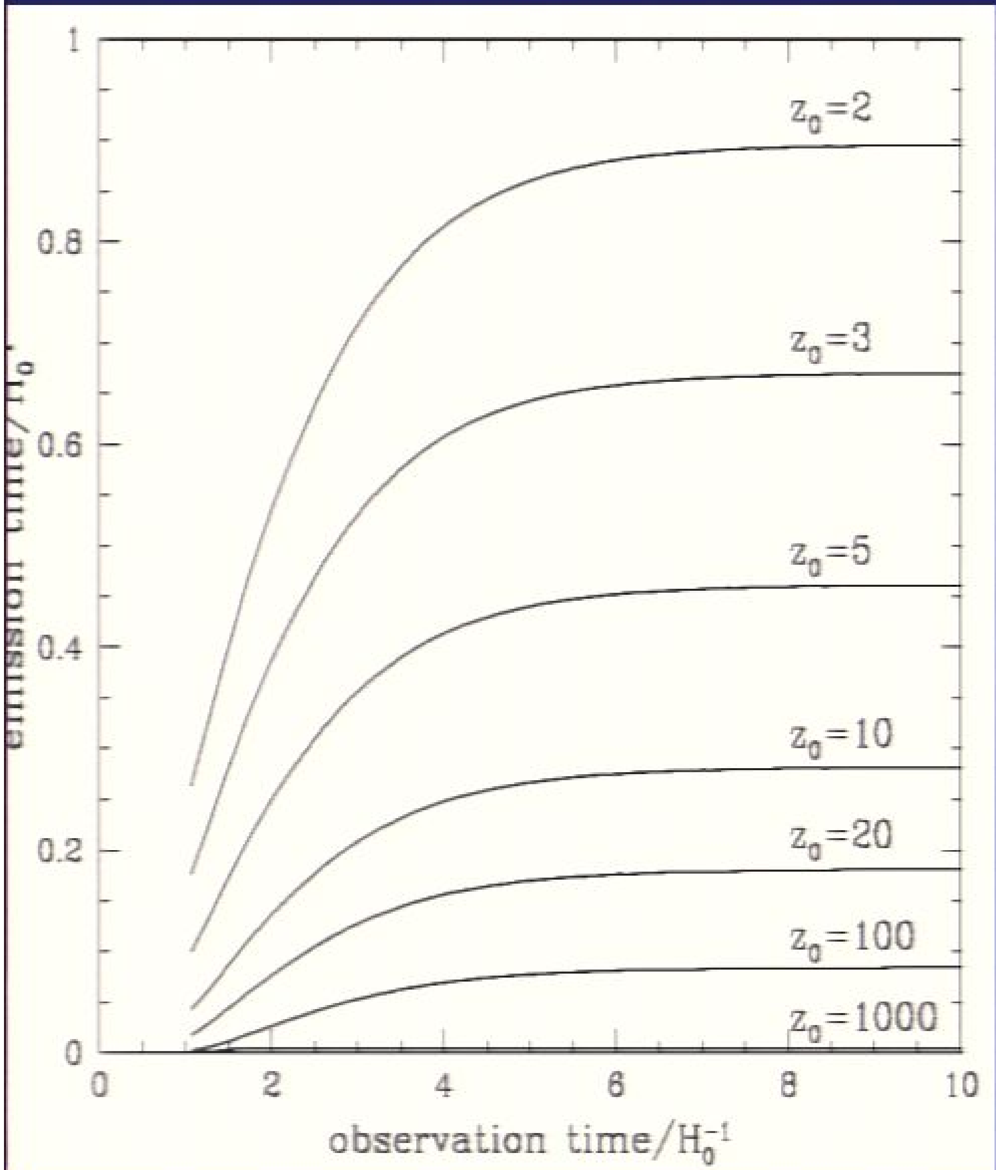


Organ-pipe scanner for DR

Since most of the radio power on Earth was transmitted for military purposes, we better not communicate with the brightest extra-terrestrial civilization

Enough about the past…
what does the future hold?

The Long Term Future of Extragalactic Astronomy



All galaxies beyond a redshift of z=1.8 are already outside our horizon (no cell phone communication to z>1.8!) (Loeb 2001)

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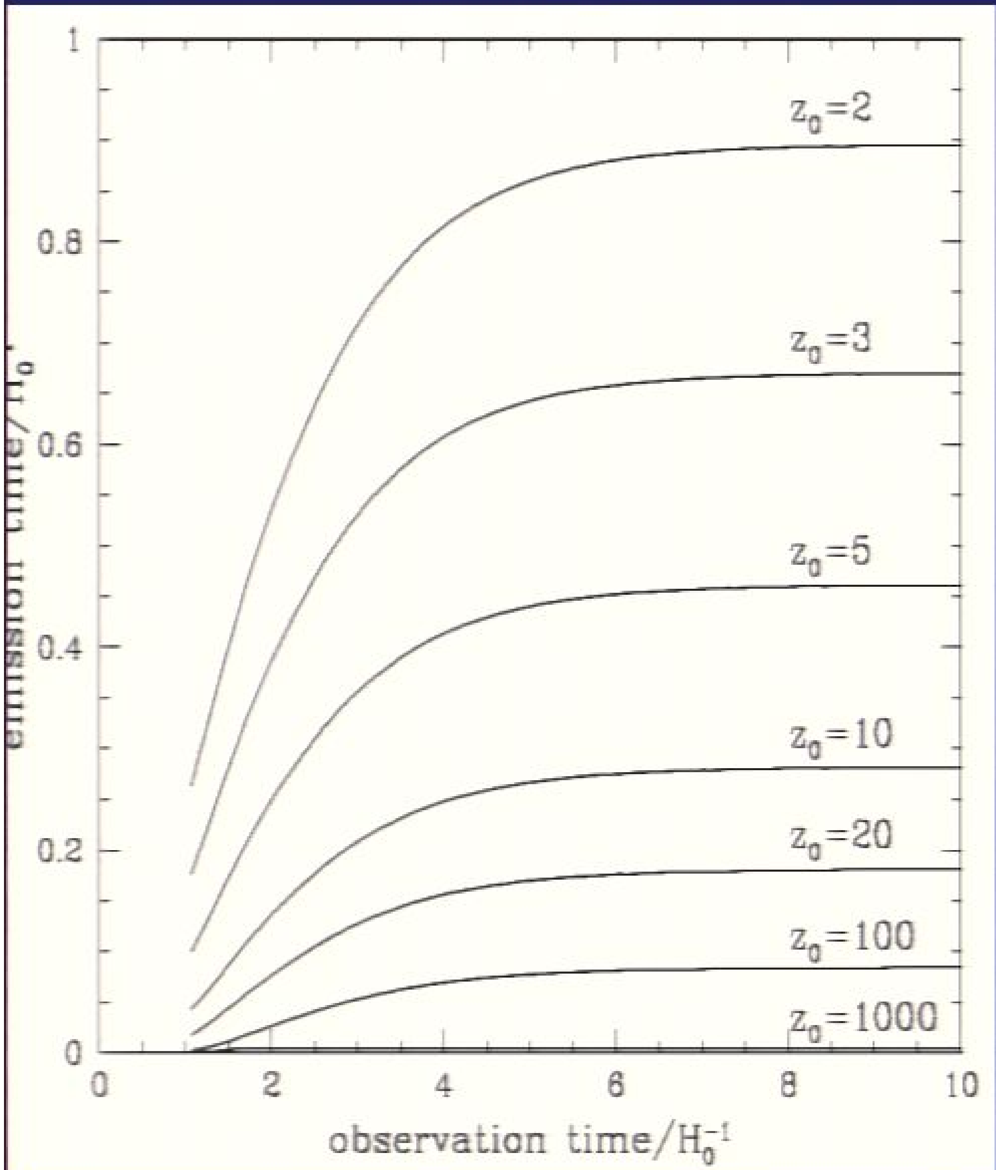

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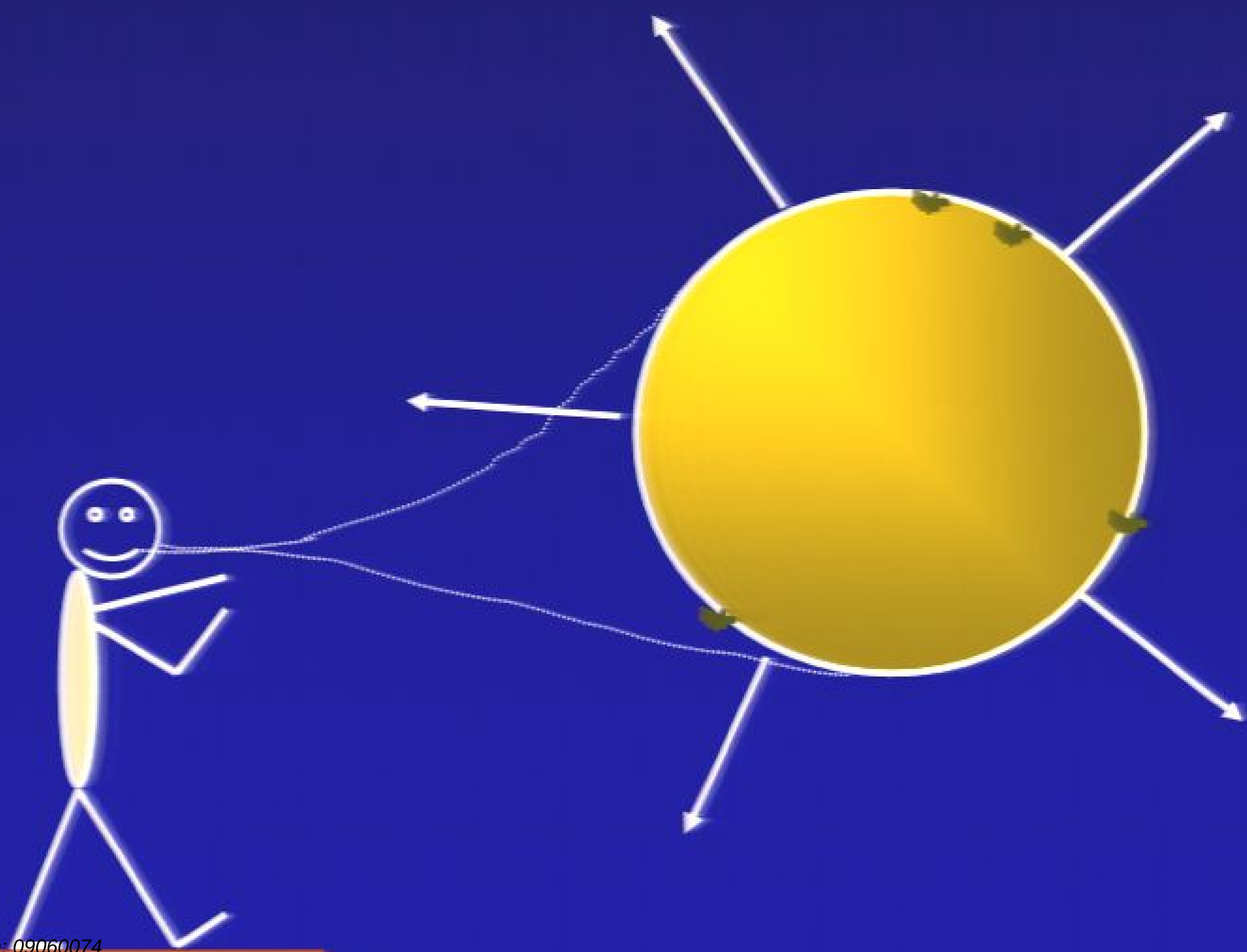
Analogy

Ants = Photons

Balloon=Expanding Space



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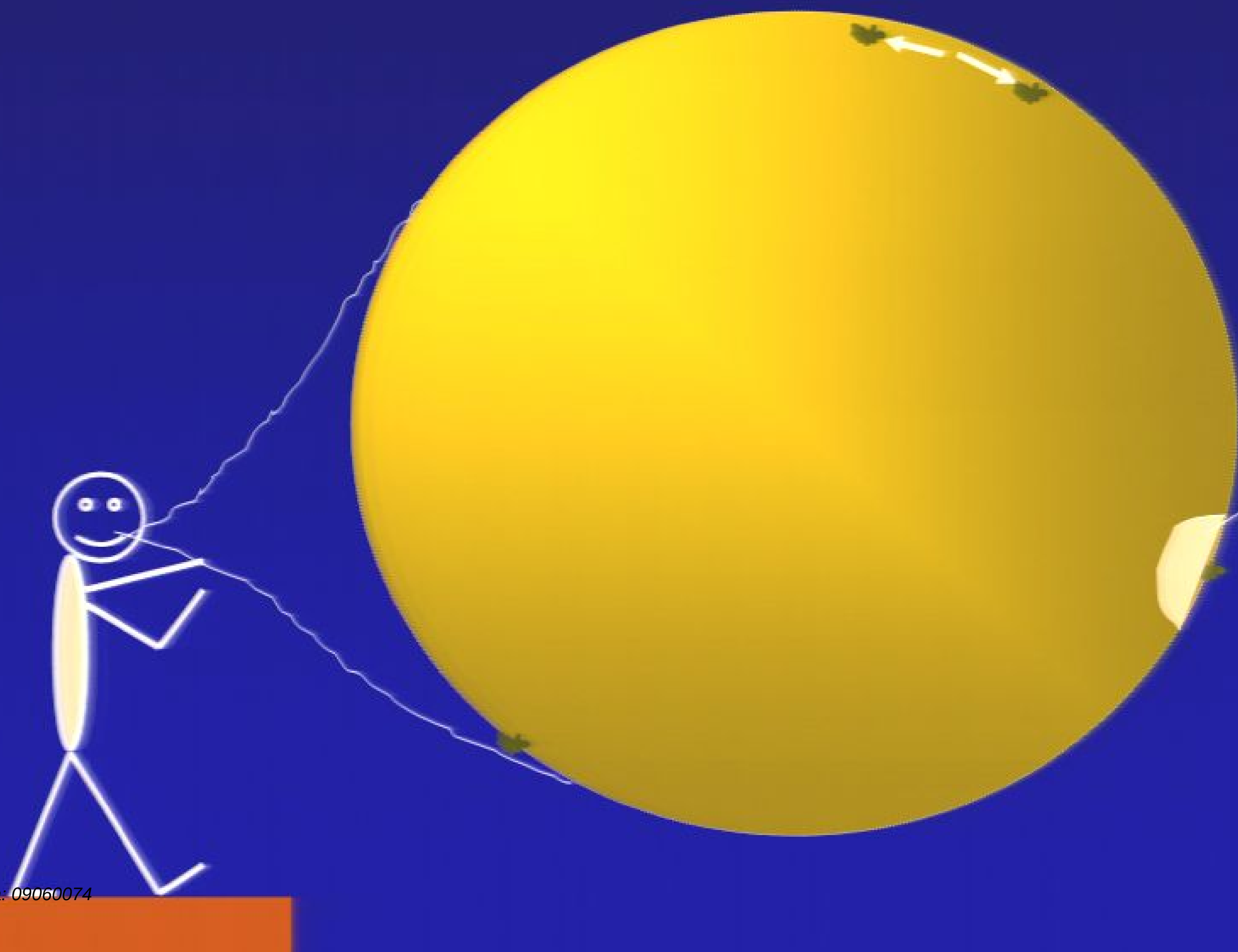
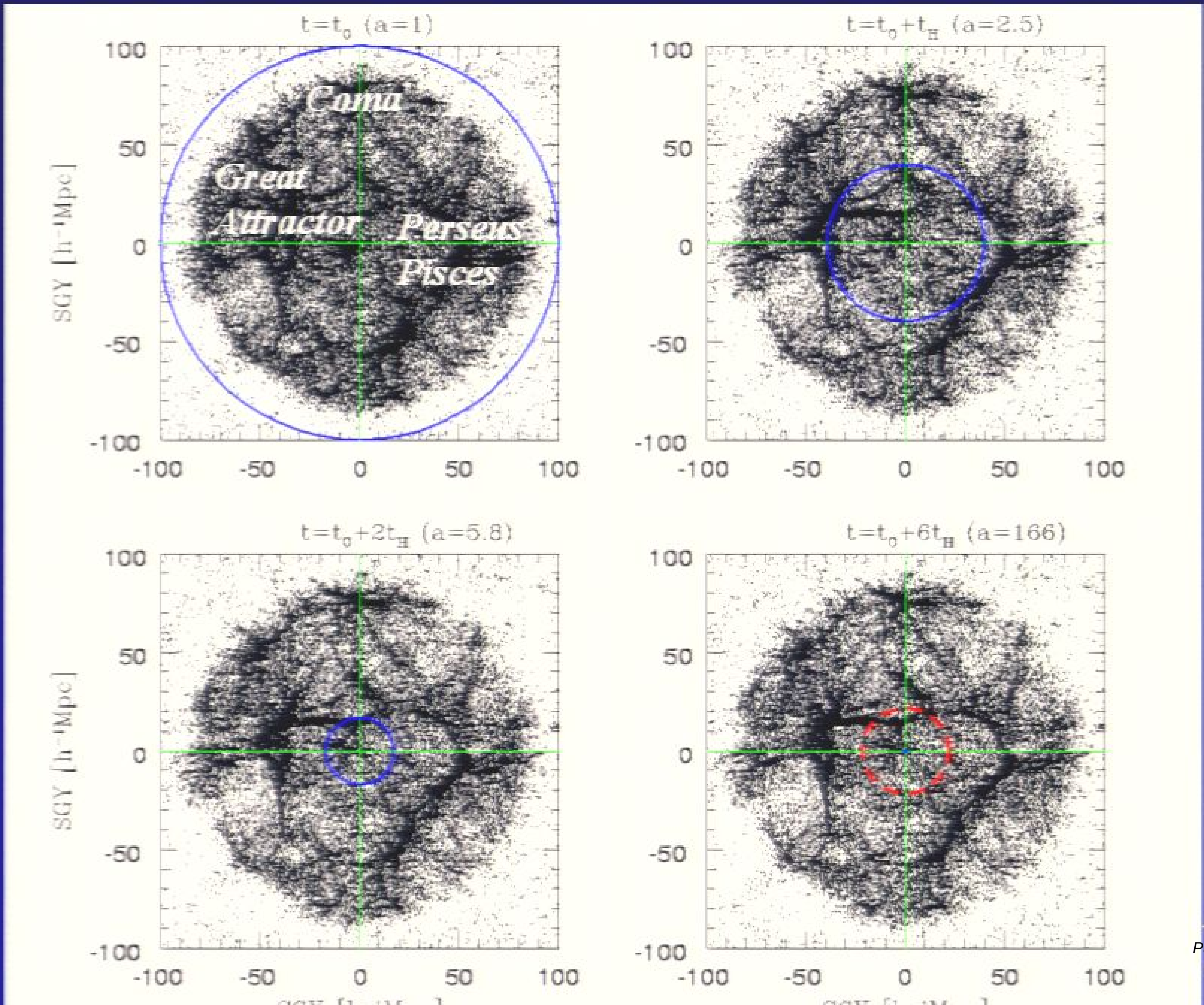


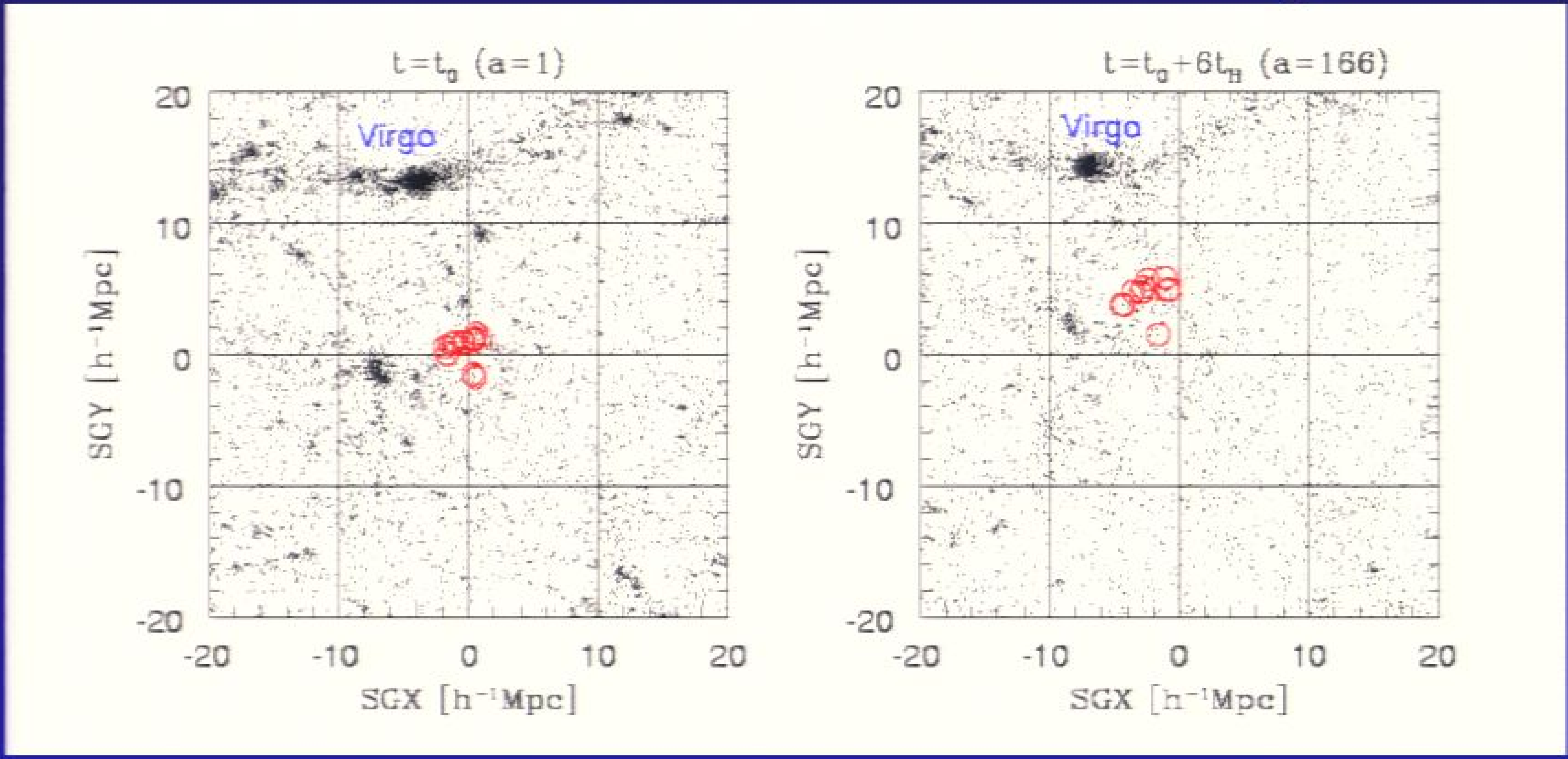
visited area (horizon) since blowing started (Big Bang)

Future Evolution of Nearby Large-Scale Structure



Nagamine & Loeb 2002,2003

How many galaxies will reside within our event horizon in 100 billion years?



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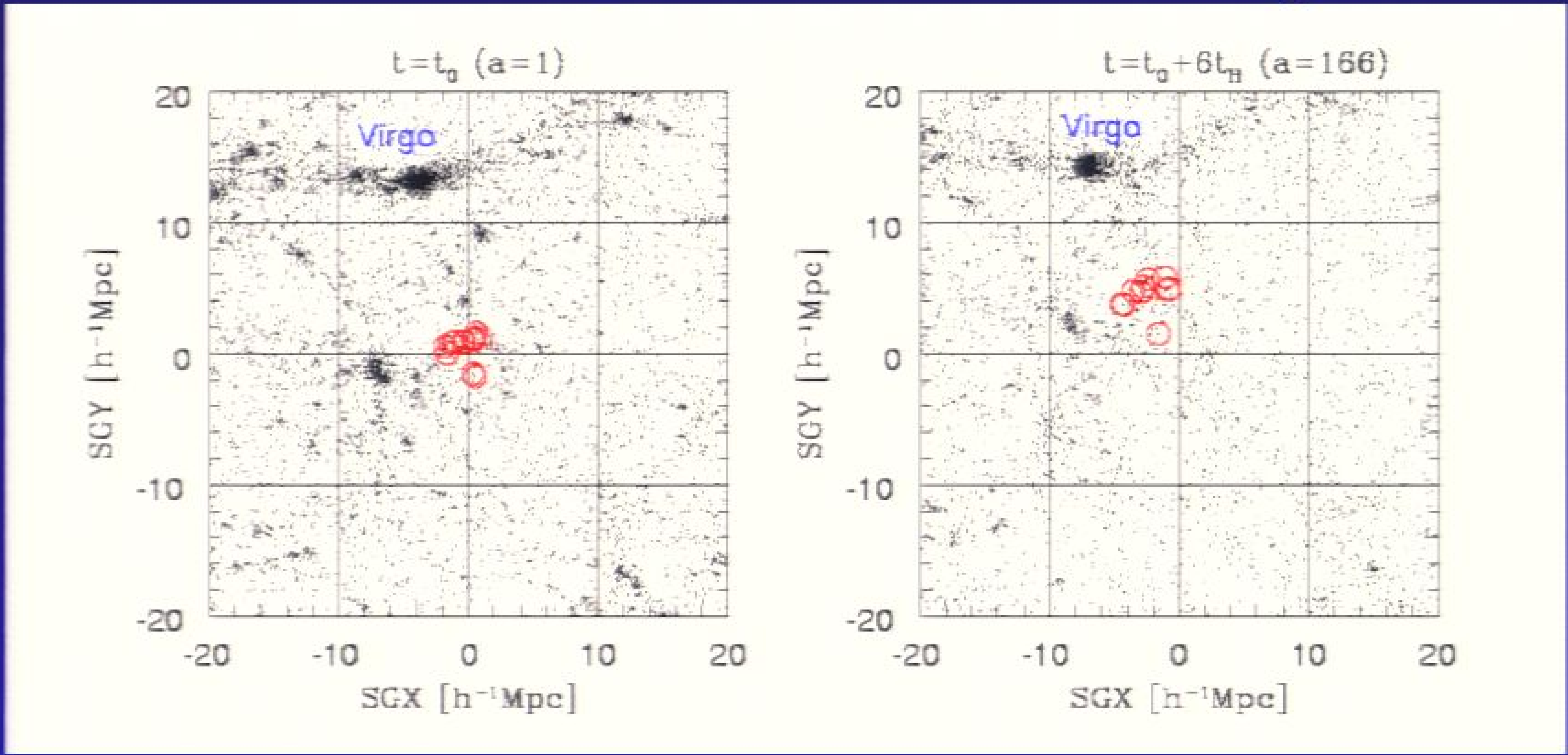

Answer: ***one surrounded by vacuum***

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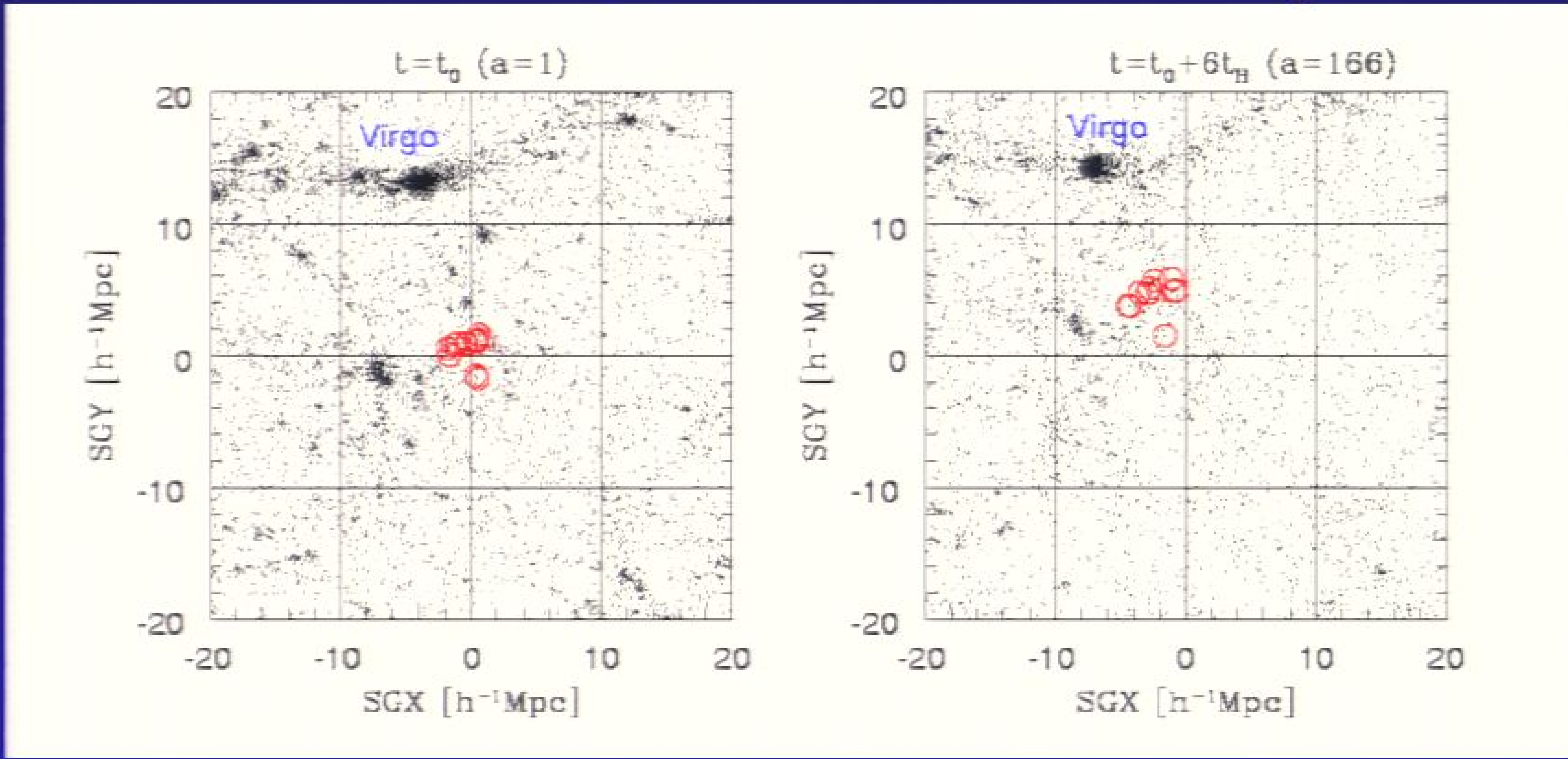
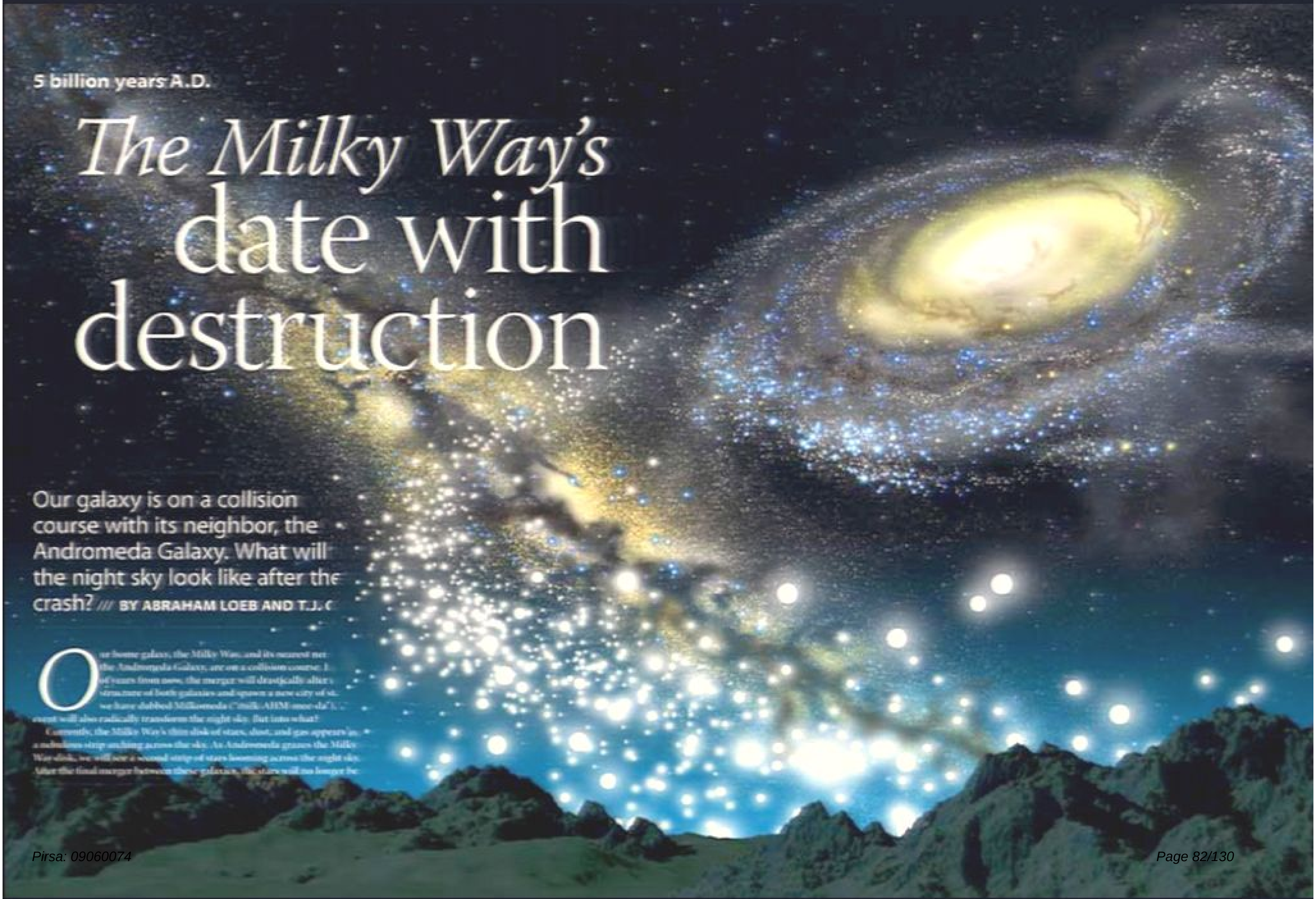


Answer: *one surrounded by vacuum*

The merger product of the Andromeda and Milky-Way galaxies!


5 billion years A.D.
The Milky Way's date with destruction
Our galaxy is on a collision course with its neighbor, the Andromeda Galaxy. What will the night sky look like after the crash? /// BY ABRAHAM LOEB AND T.J. C

The Forthcoming Collision Between the Milky-Way and Andromeda

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- The merger product is the only cosmological object that will be observable to future astronomers in 100 billion years

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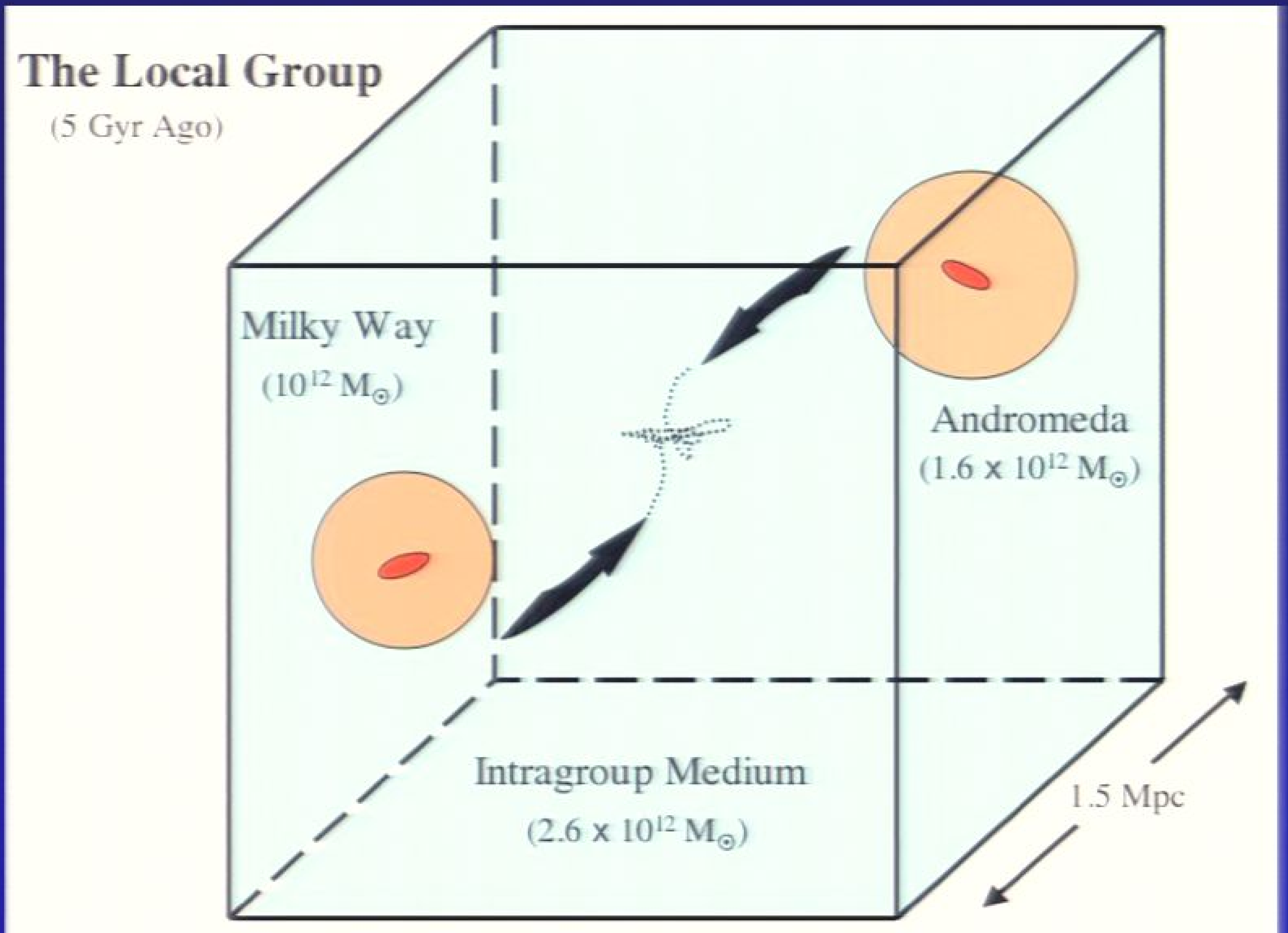
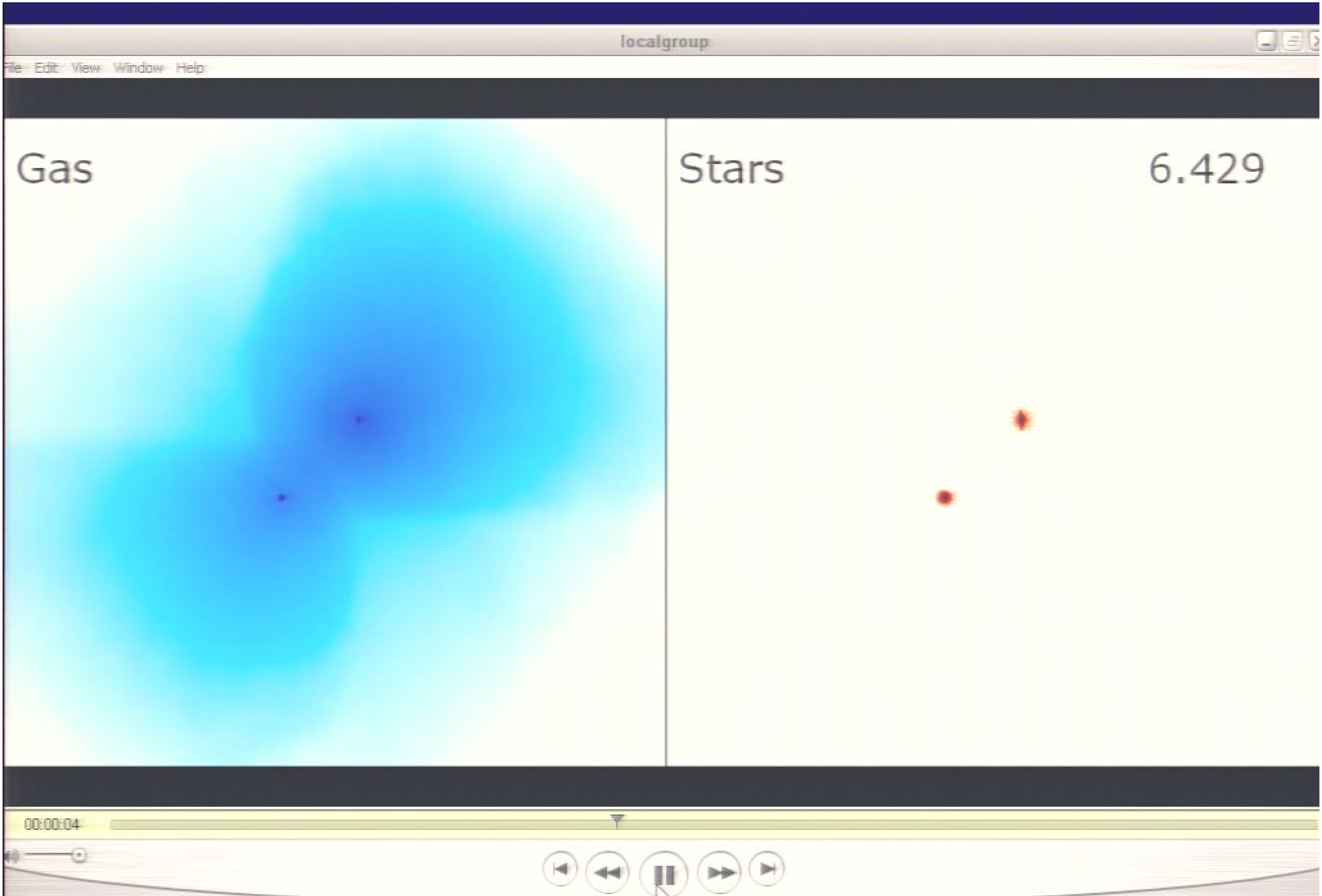
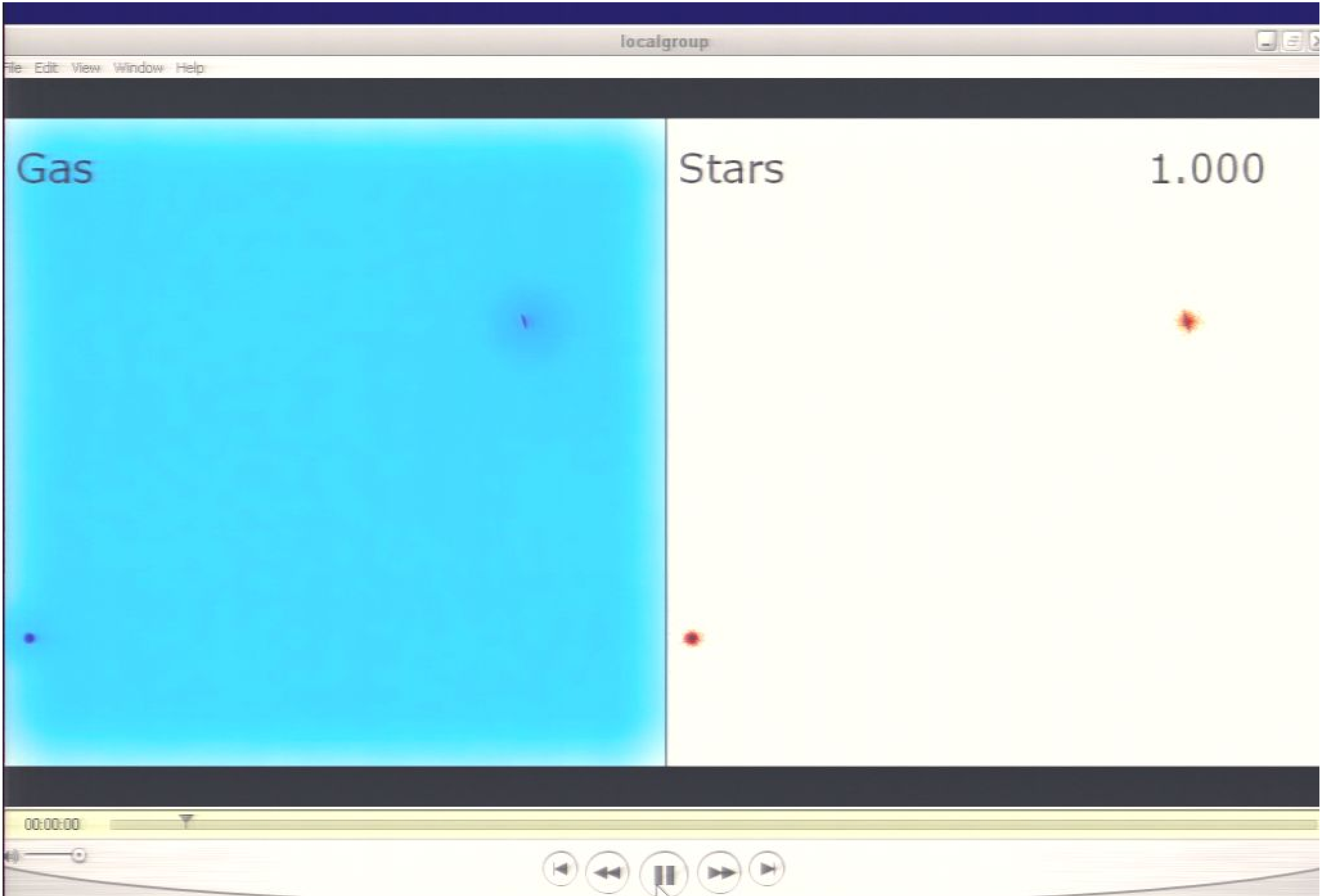
- *The only paper of mine that has a chance of being cited in five billion years…*


The Local Group
(5 Gyr Ago)
Milky Way
(10^{12} $M_{\odot}$)
Andromeda
(1.6×10^{12} $M_{\odot}$)
Intragroup Medium
(2.6×10^{12} $M_{\odot}$)
1.5 Mpc

The Future Collision between the Milky Way and Andromeda Galaxies


localgroup
File Edit View Window Help
Gas
Stars
6.429
00:00:04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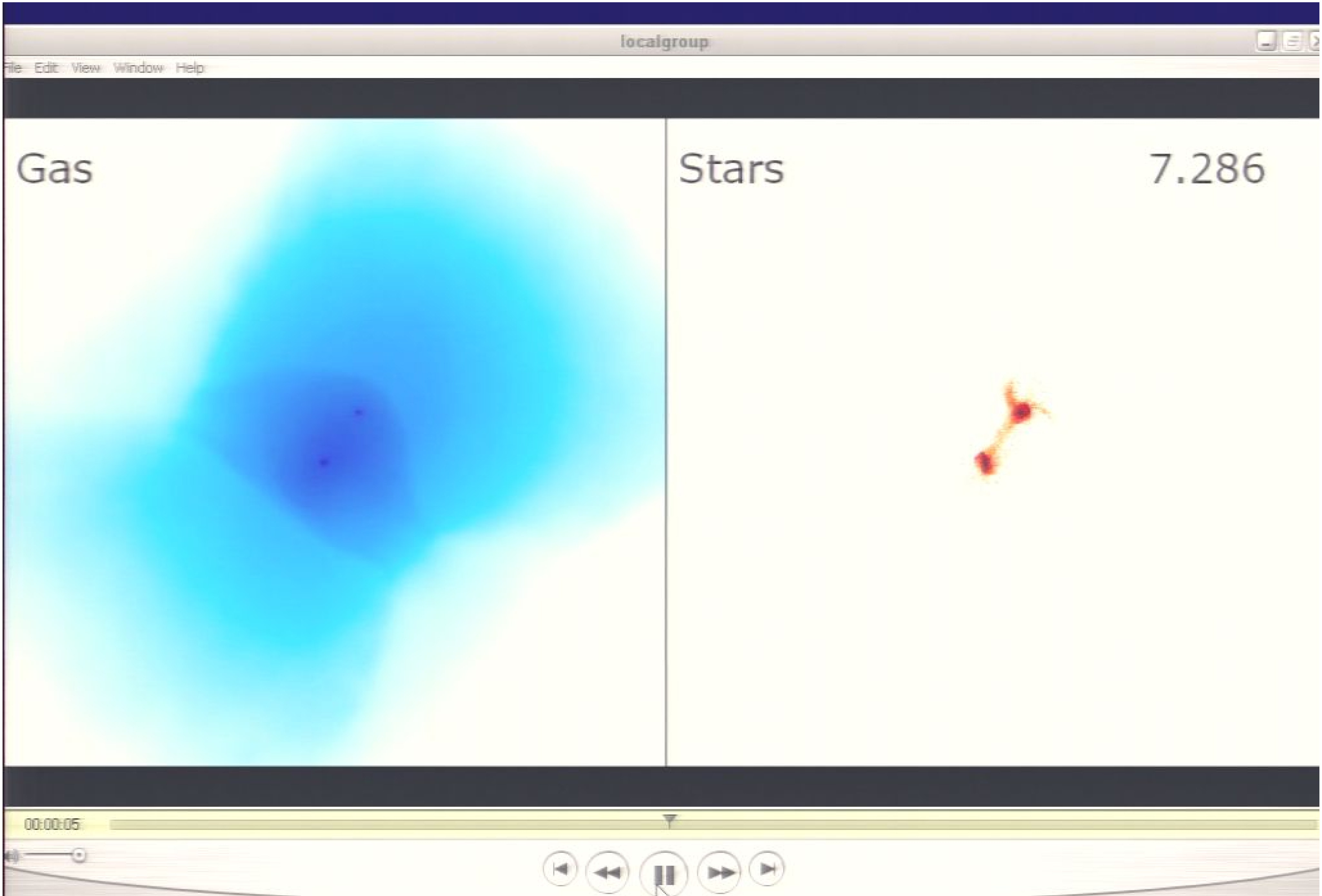
1.000
00:00:00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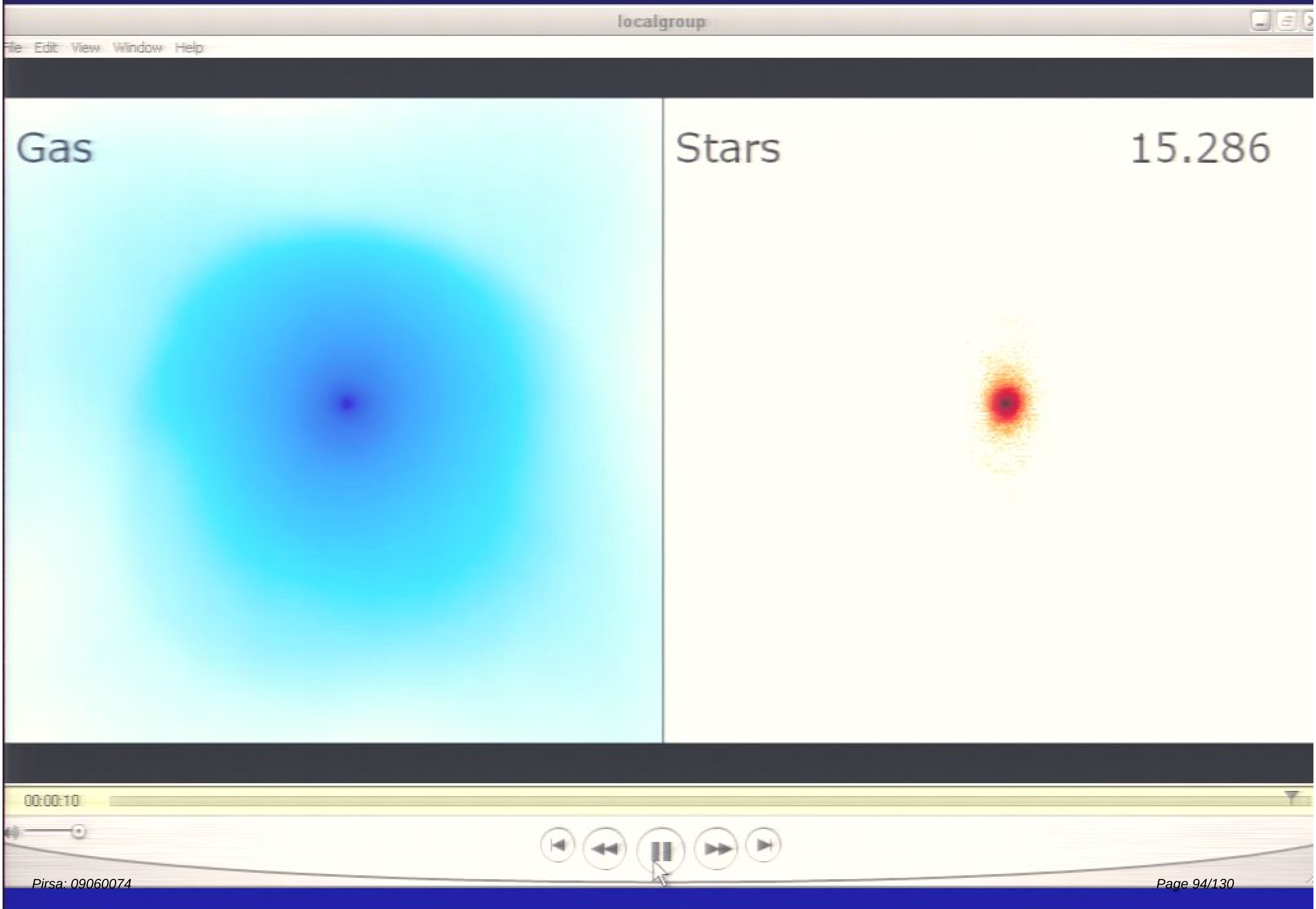
00:00:05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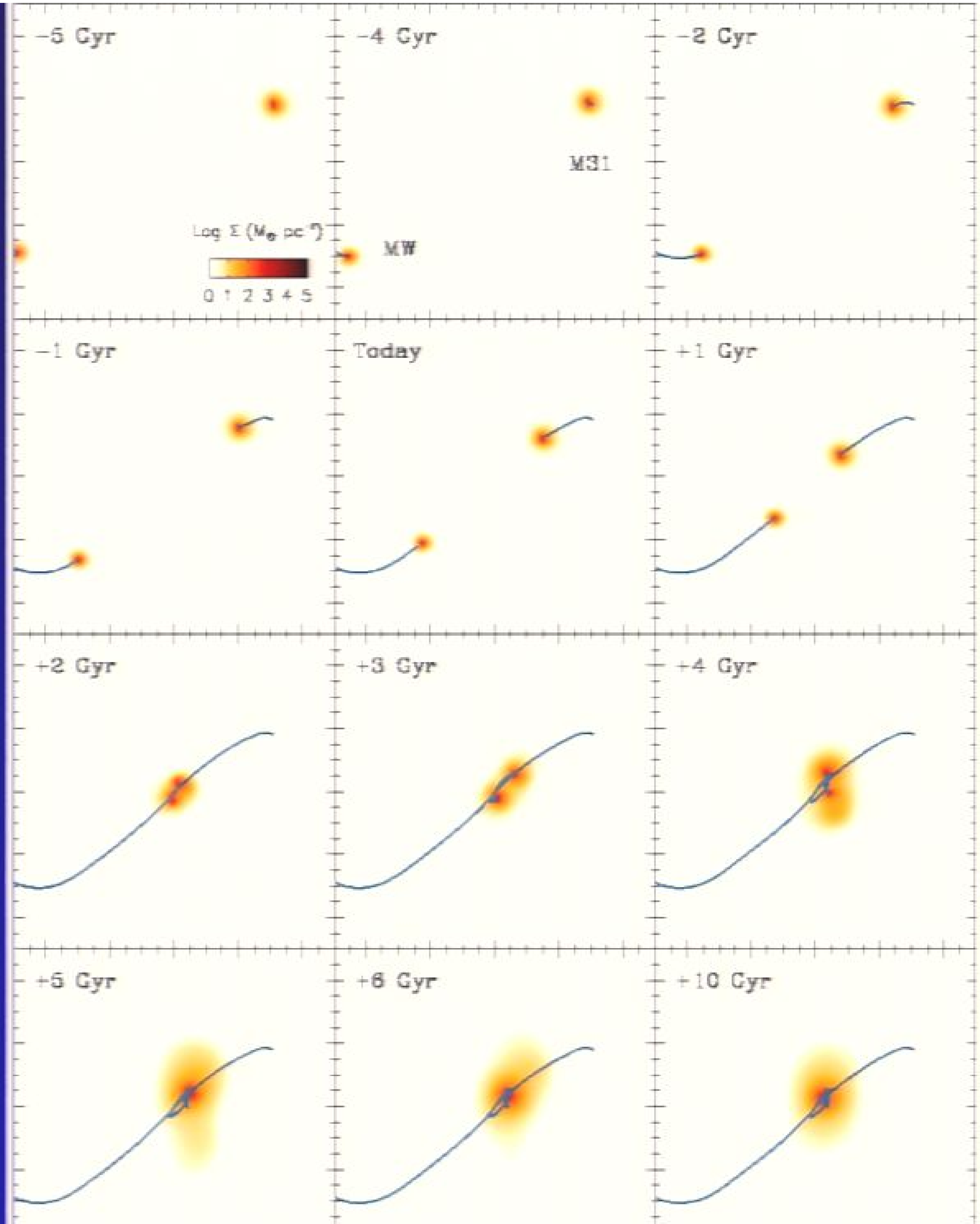
Gas
Stars
15.286
00:00:10



−5 Gyr
−4 Gyr
−2 Gyr
M31
MW
0 1 2 3 4 5
−1 Gyr
Today
+1 Gyr
+2 Gyr
+3 Gyr
+4 Gyr
+5 Gyr
+6 Gyr
+10 Gyr

Fate of the Sun

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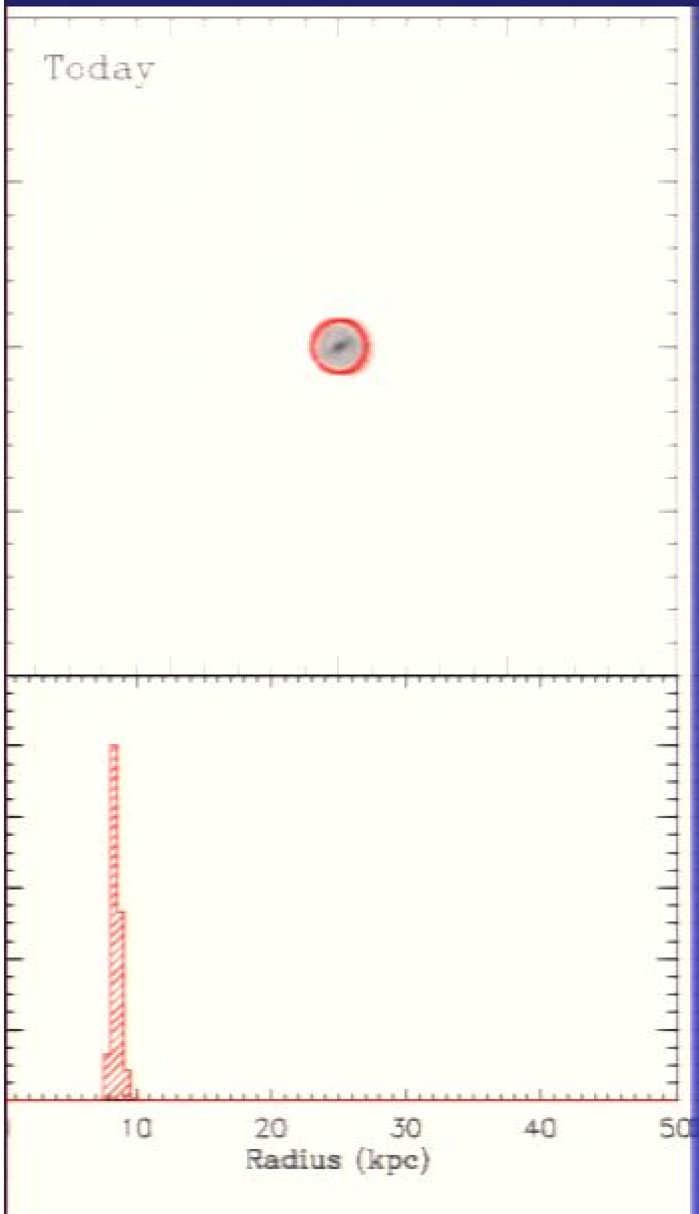

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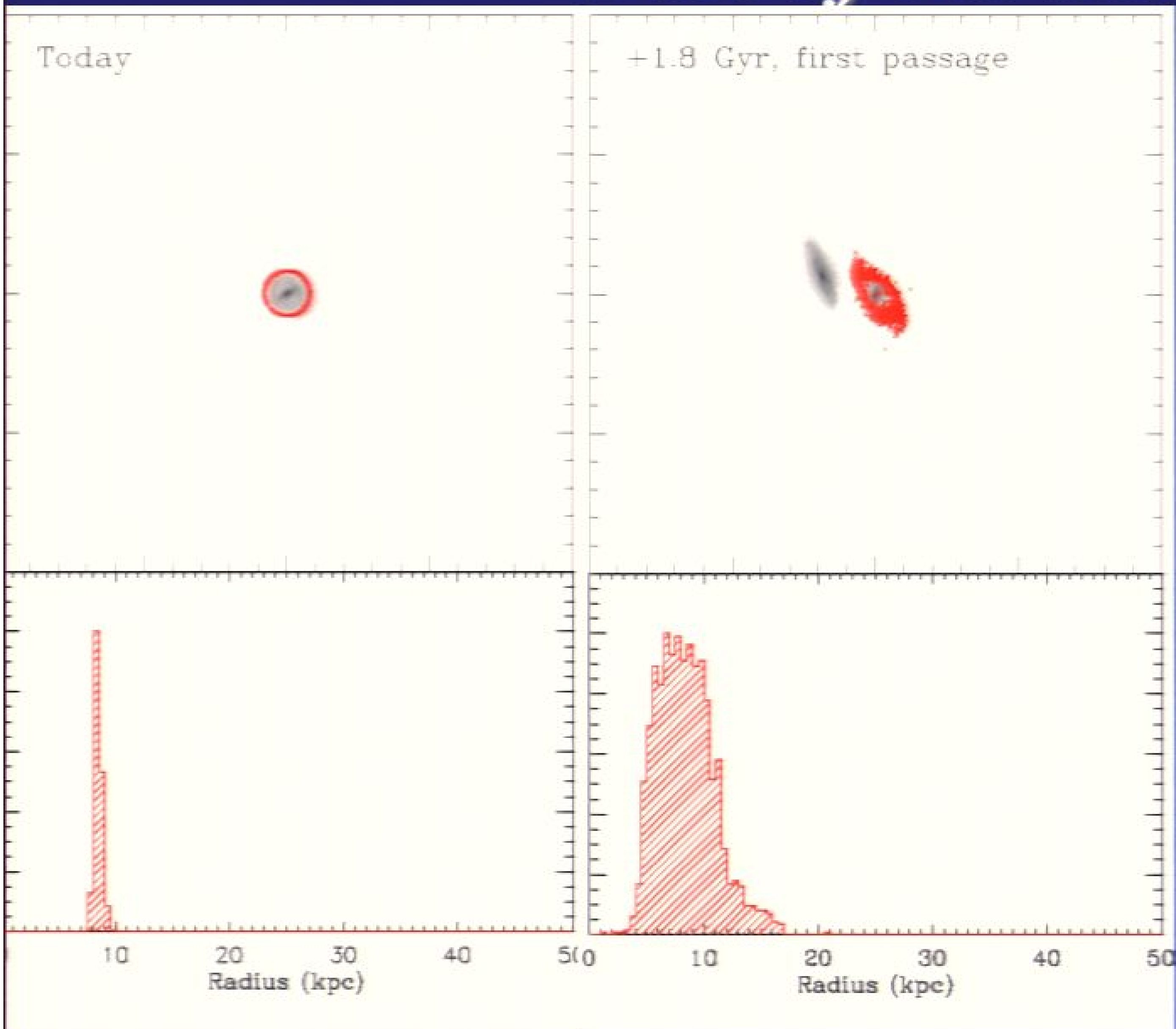

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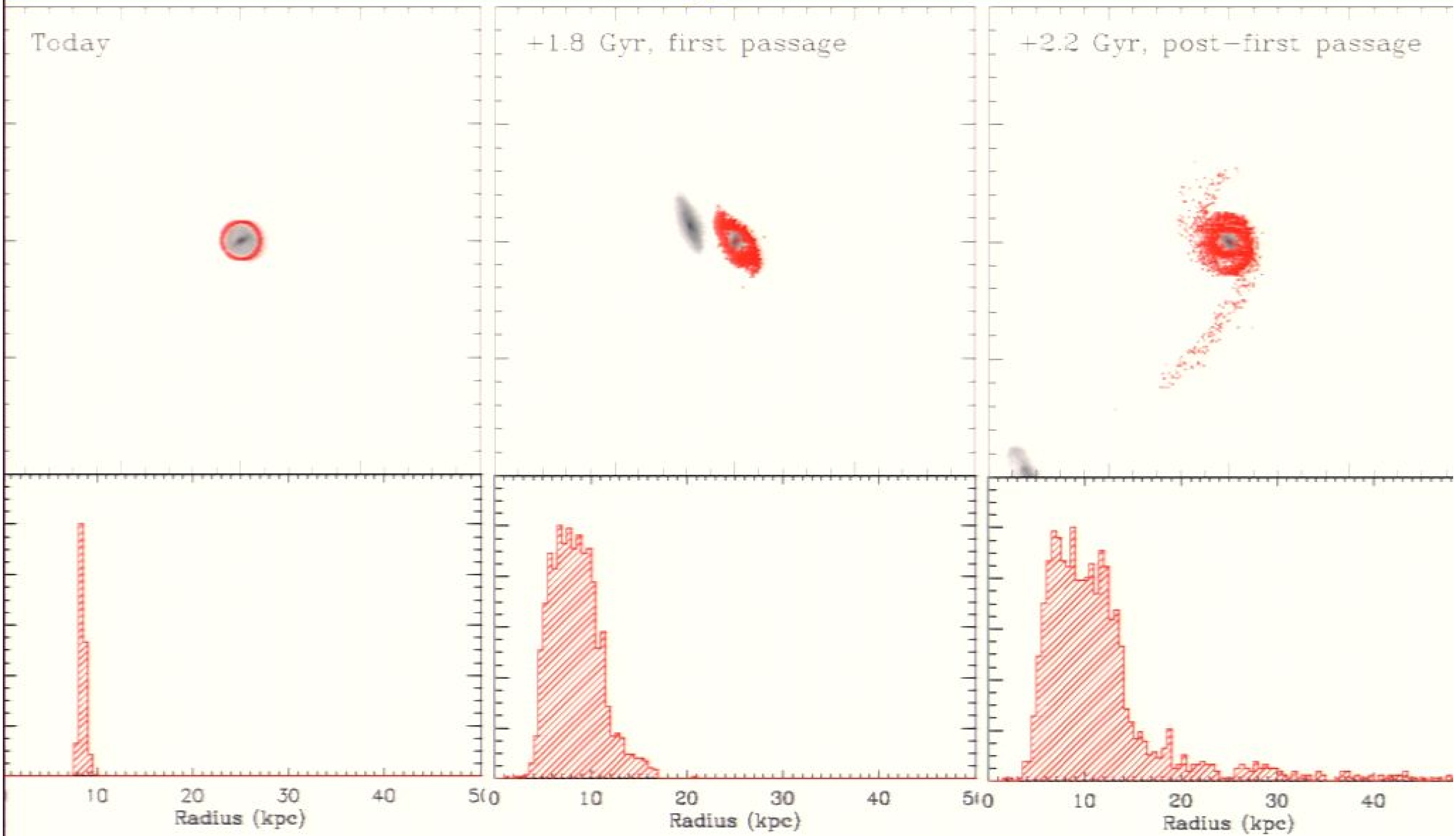

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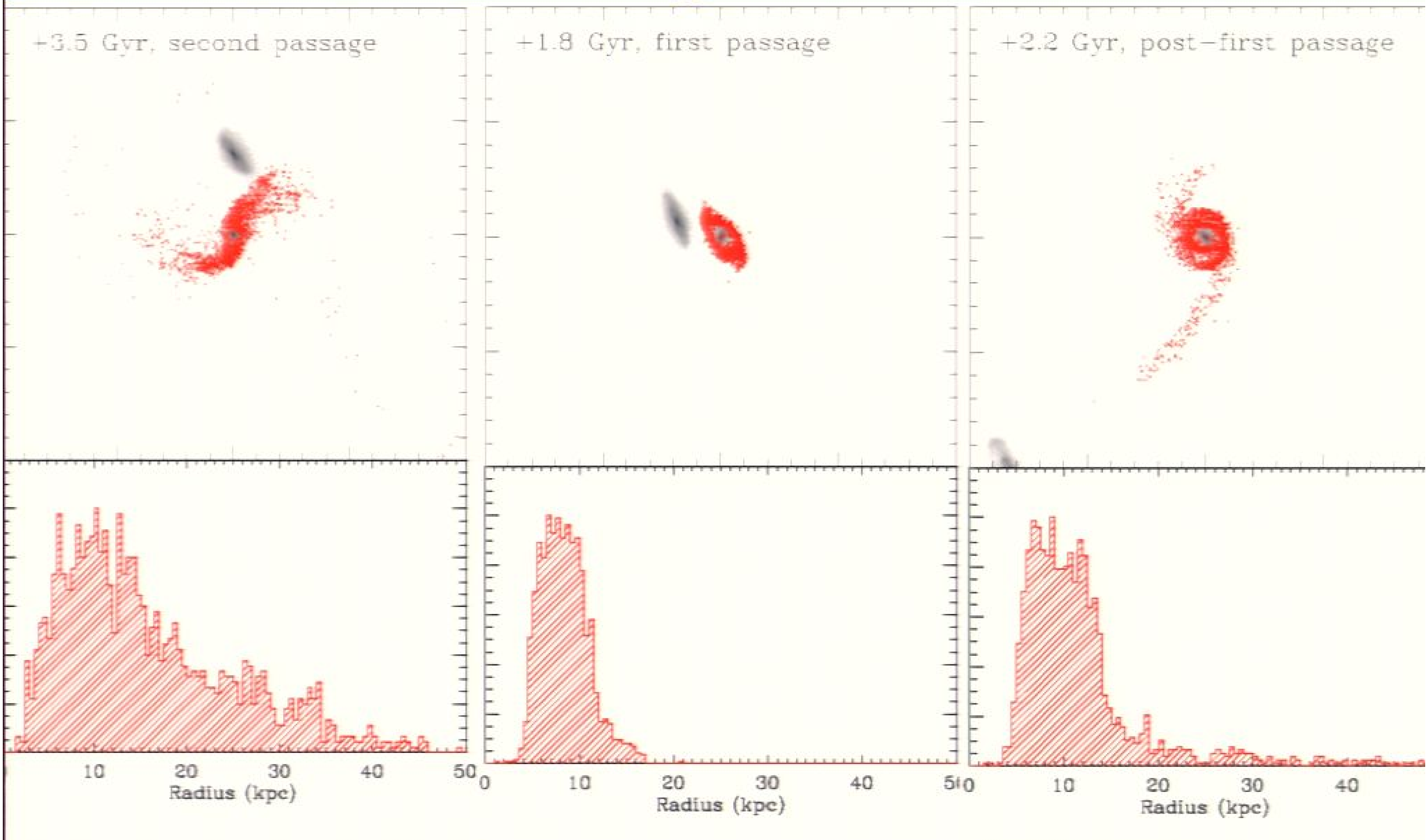

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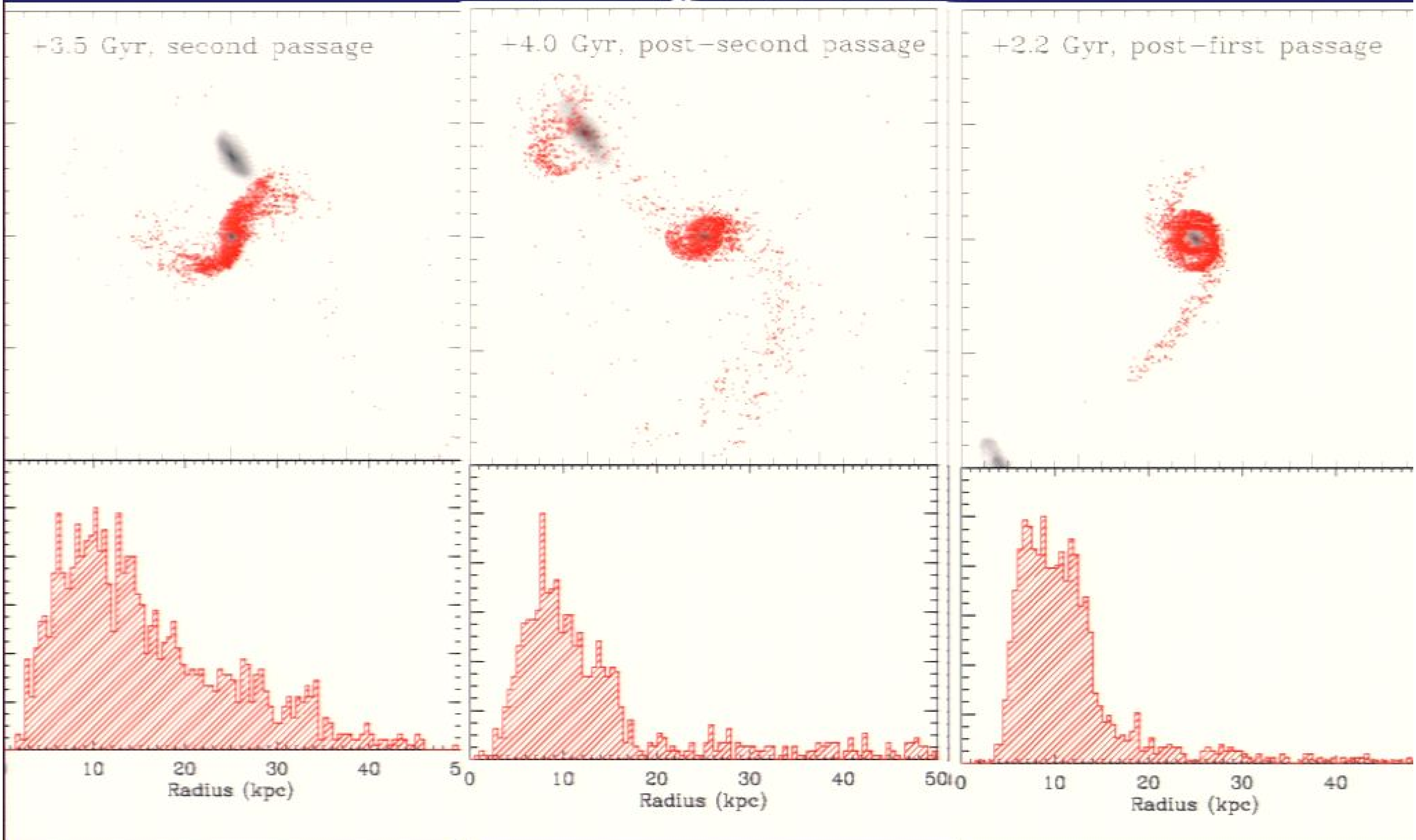

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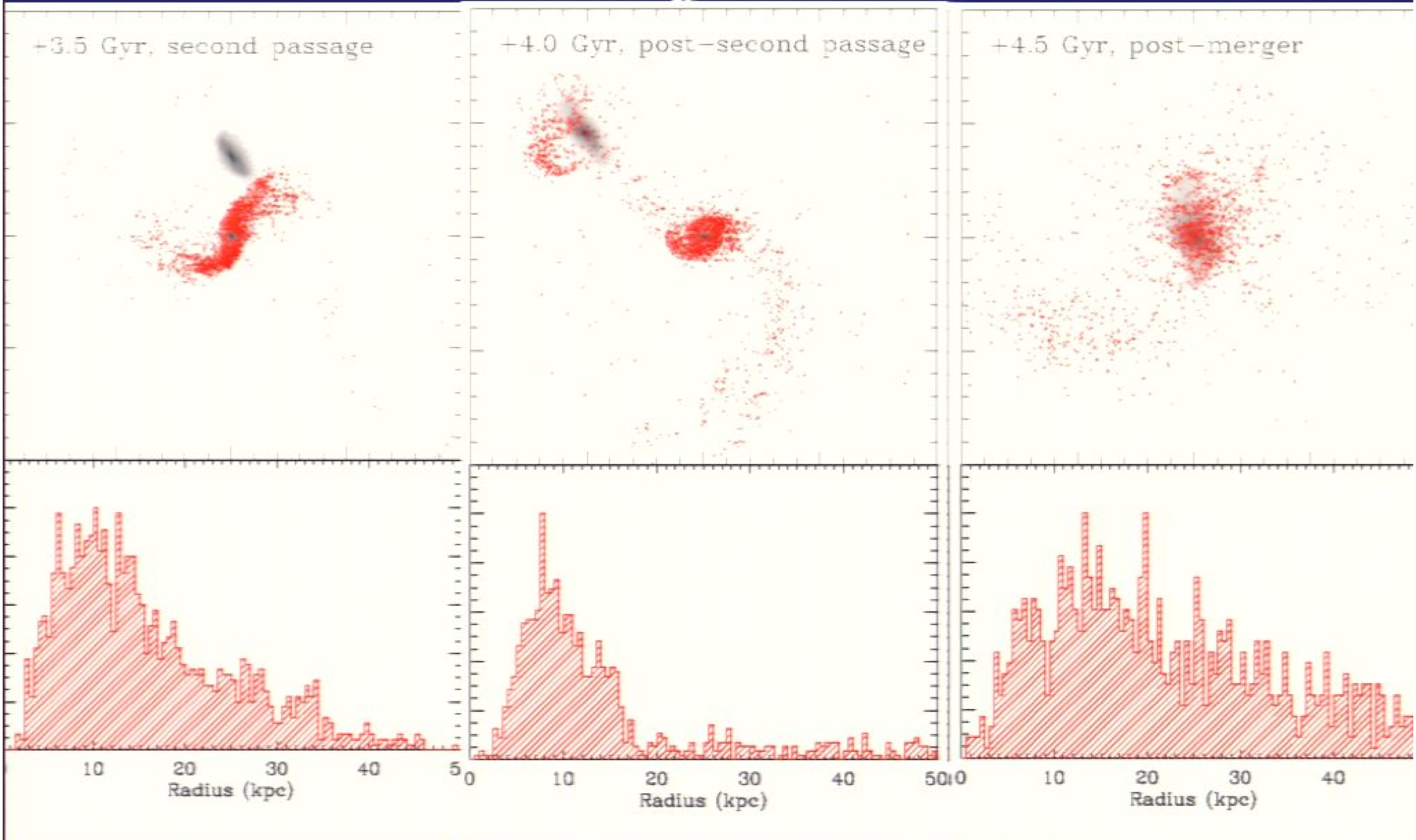


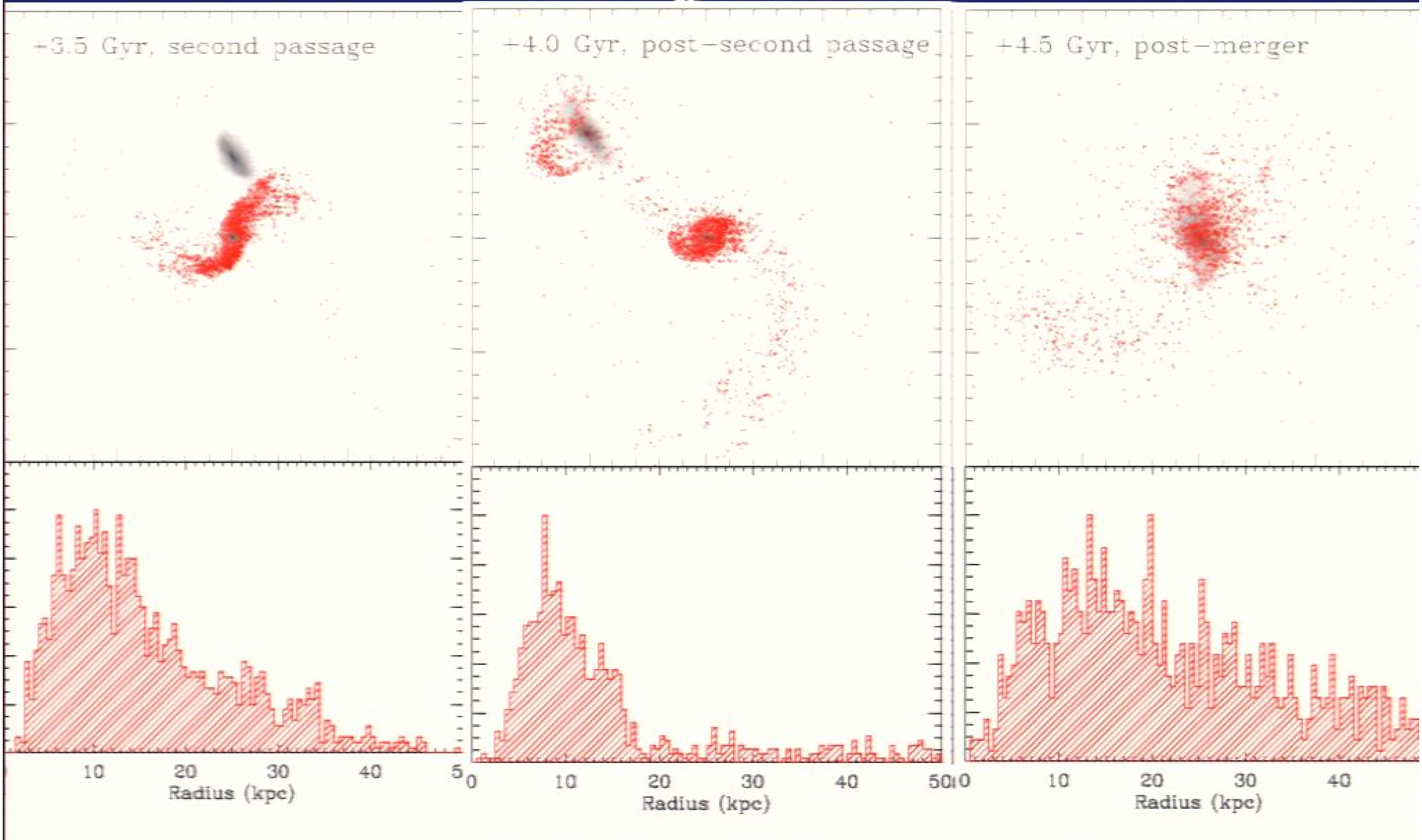
S-Stars Orbits Around SgrA*

$$M_{\rm BH} = (4.5 \pm 0.4) \times 10^6 M_\odot$$

$$d_{\rm GC} = 8.4 \pm 0.4 {\rm kpc}$$ *(BH at rest in GC)*

Ghez et al. 2008; Genzel et al. 2008

Fate of the Sun



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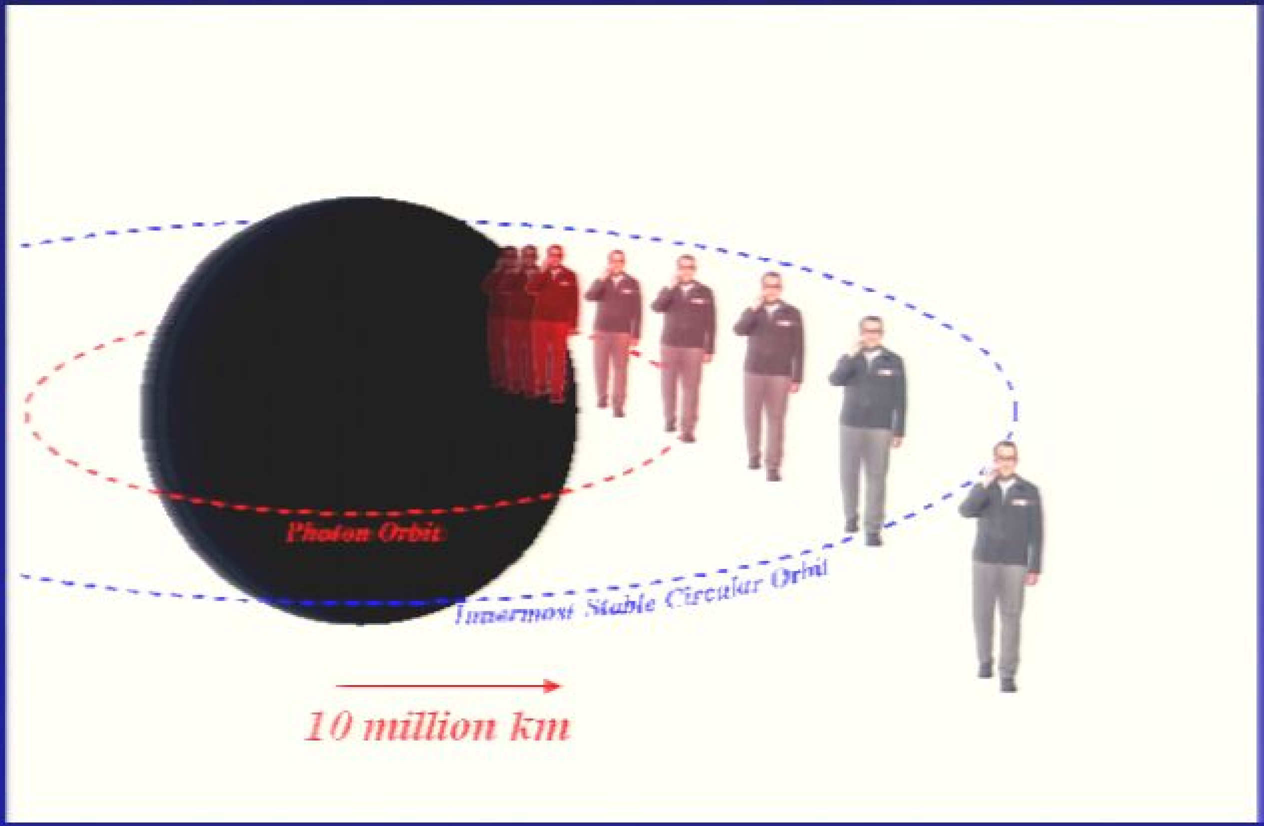
Can you hear me now?



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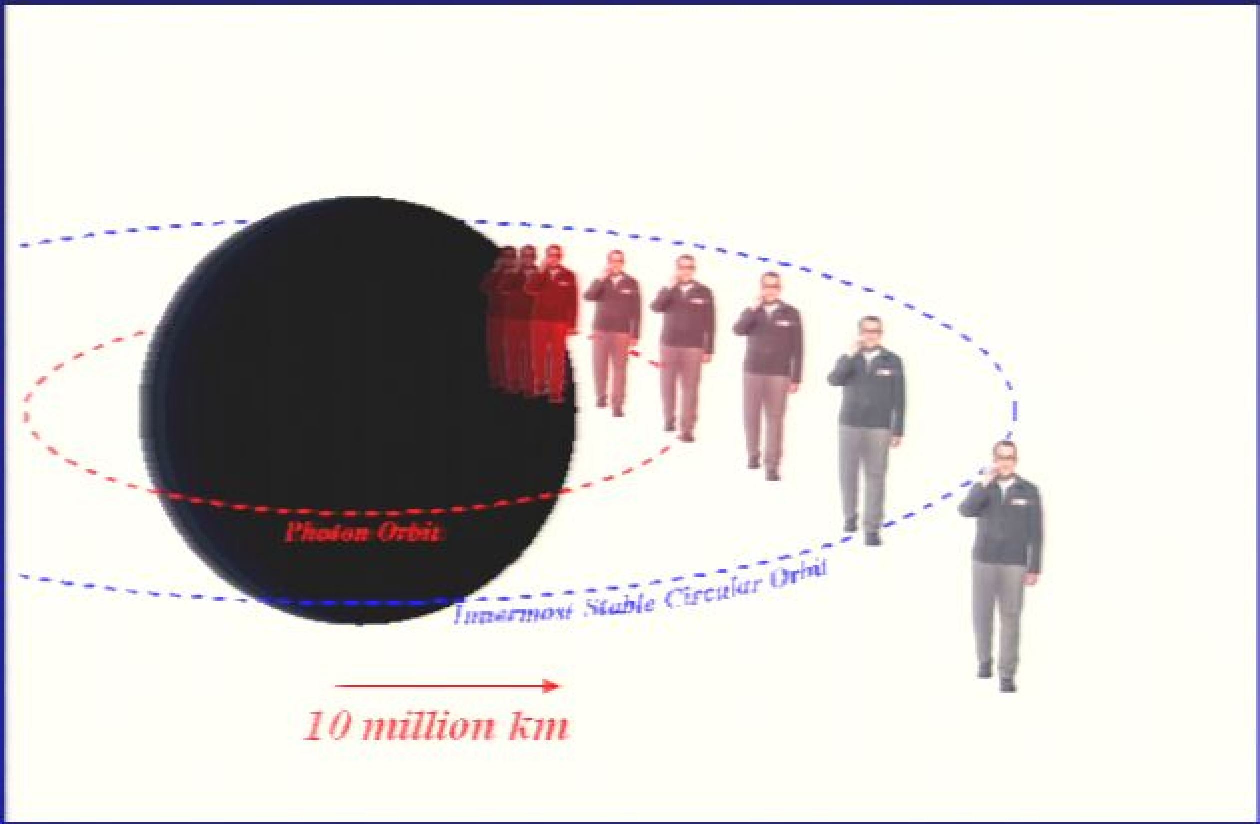
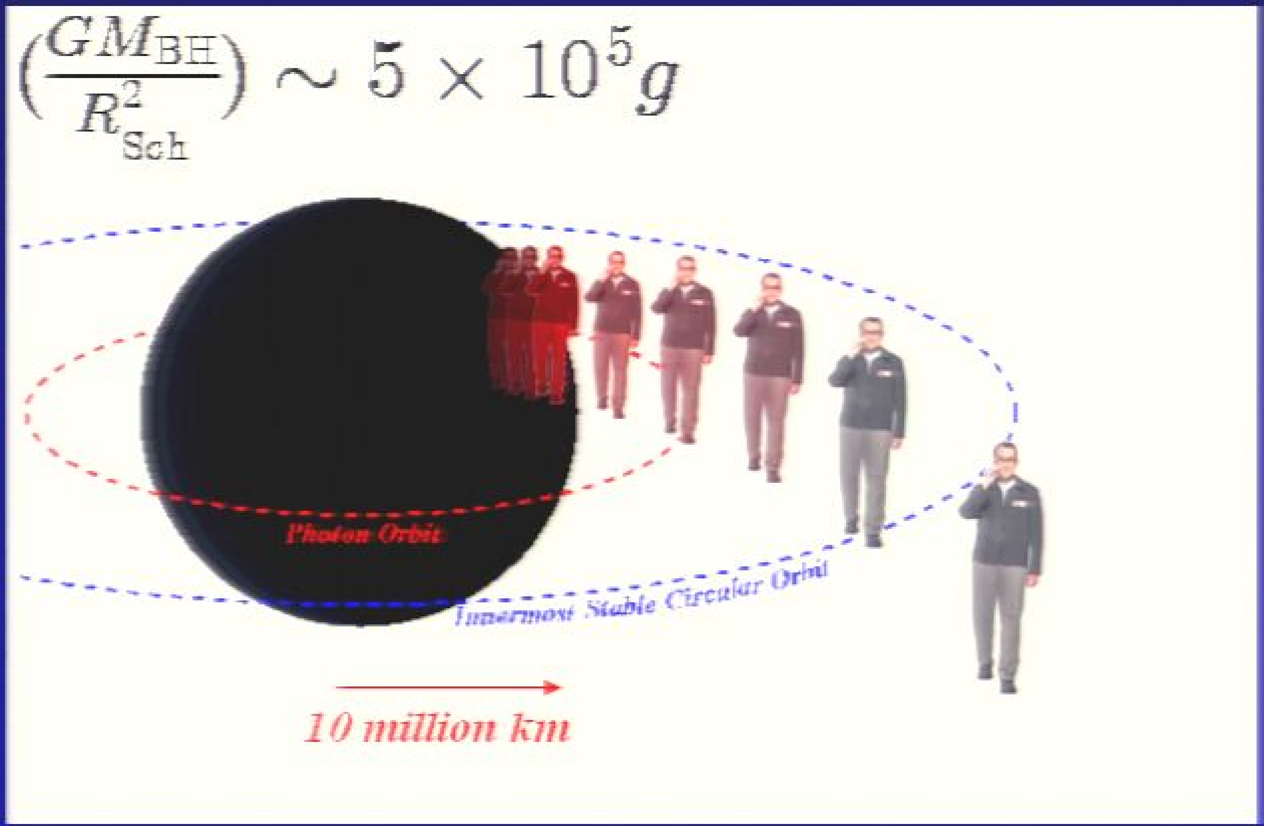


No, but no worries - you will be able to hear us for ~10 minutes until you reach the singularity…

Can you hear me now?



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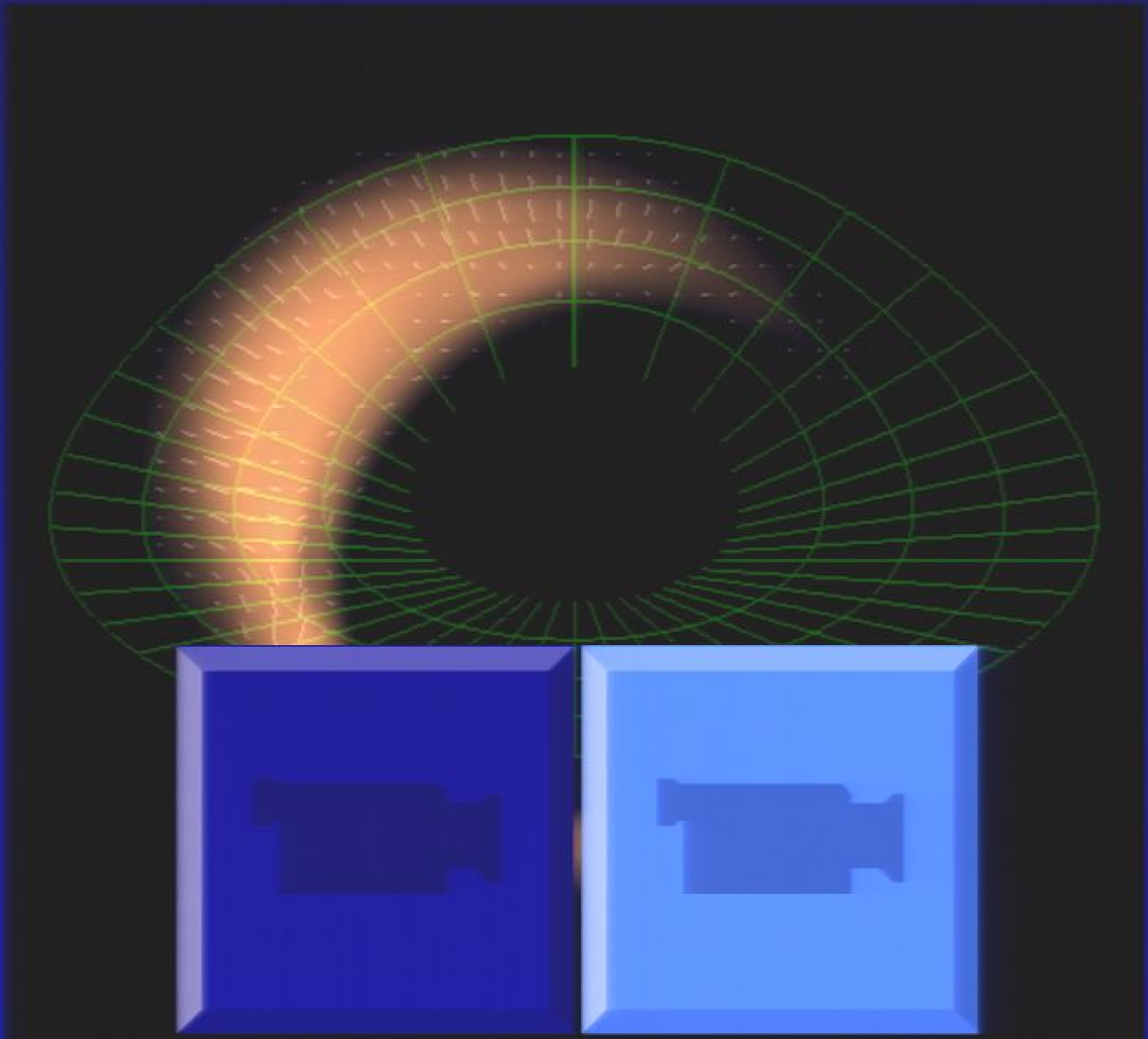
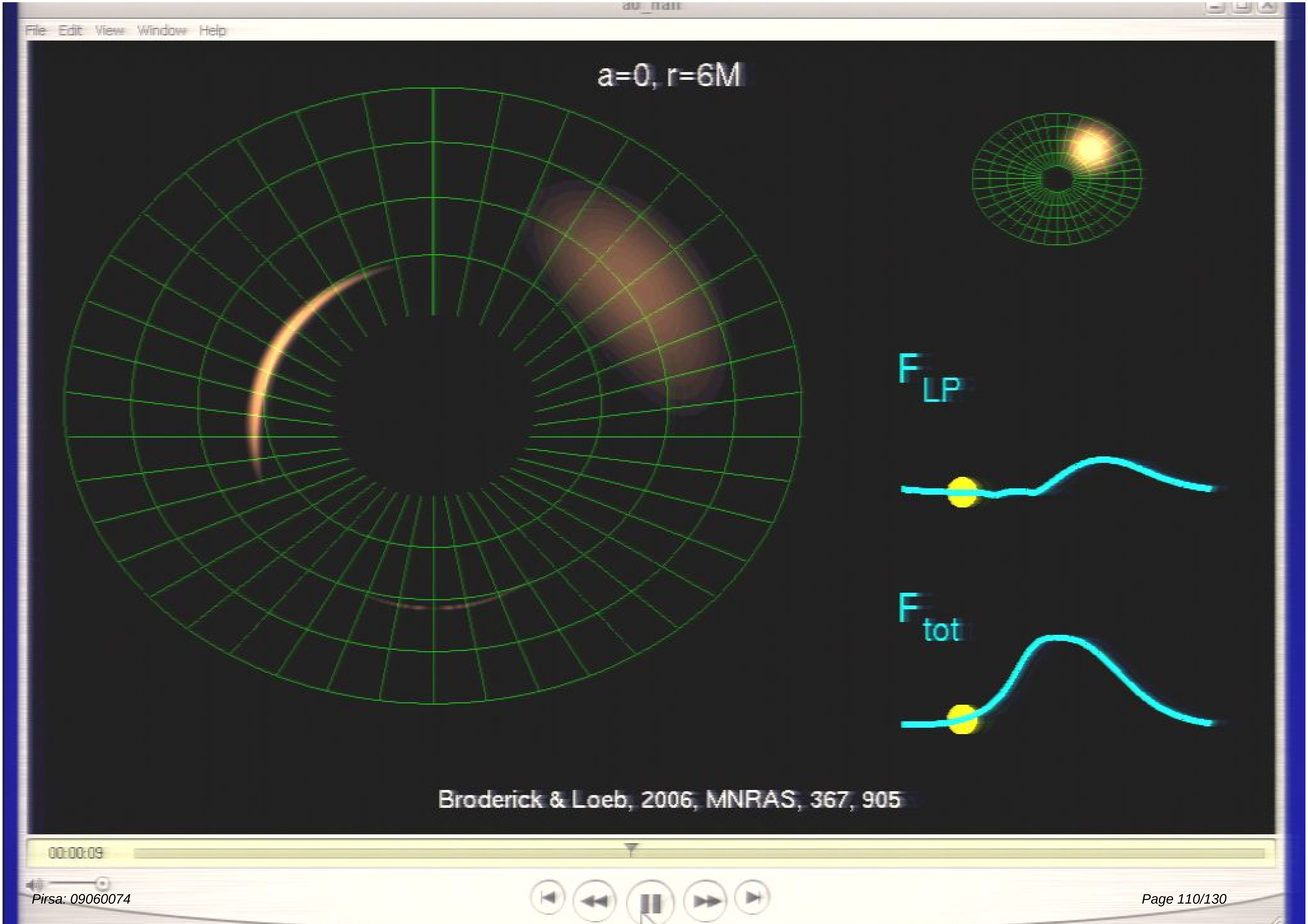
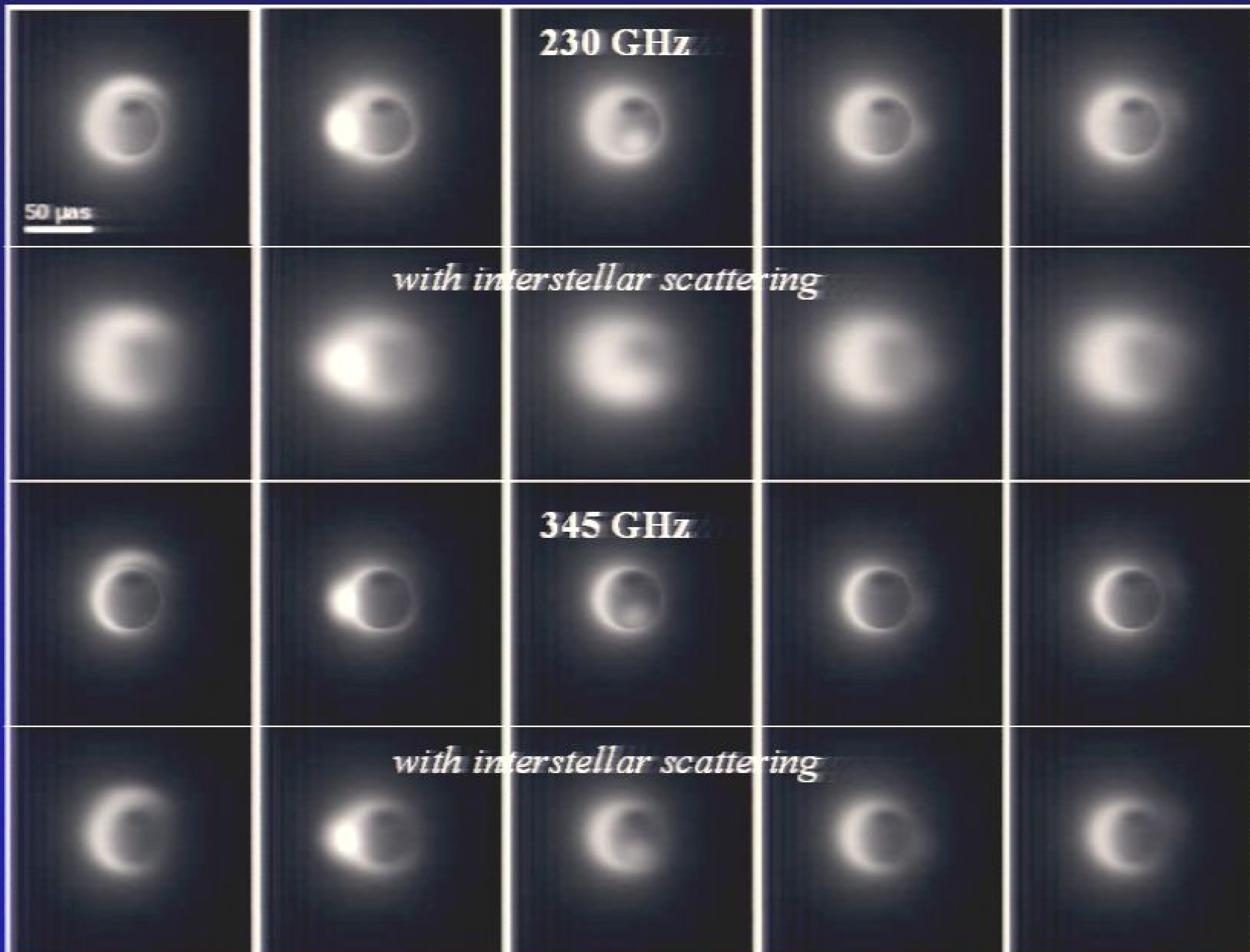
Is general relativity a valid description of strong gravity?



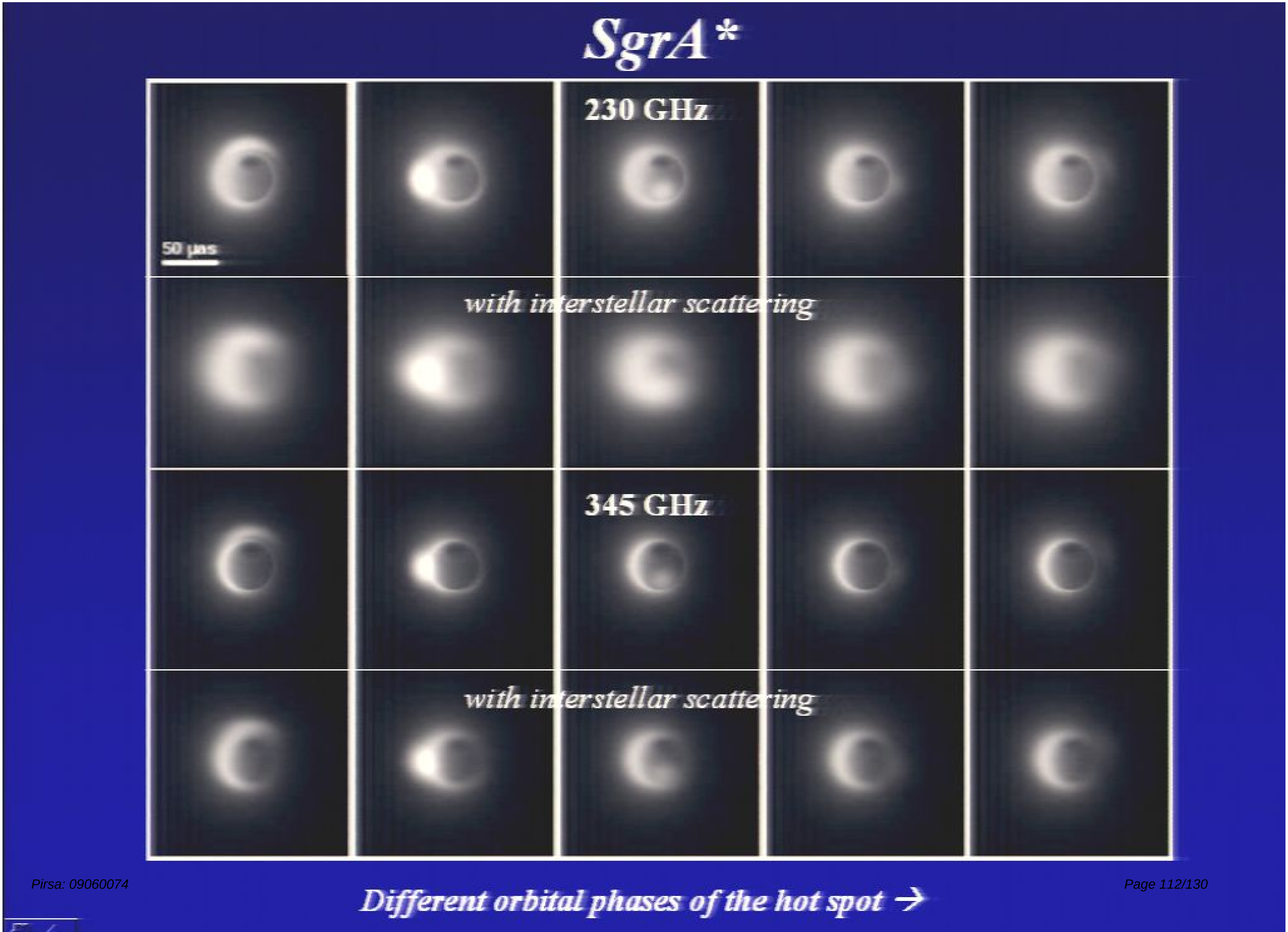
Broderick & Loeb 2005


a=0, r=6M
F LP
F tot
Broderick & Loeb, 2006, MNRAS, 367, 905
00:00:09

SgrA*

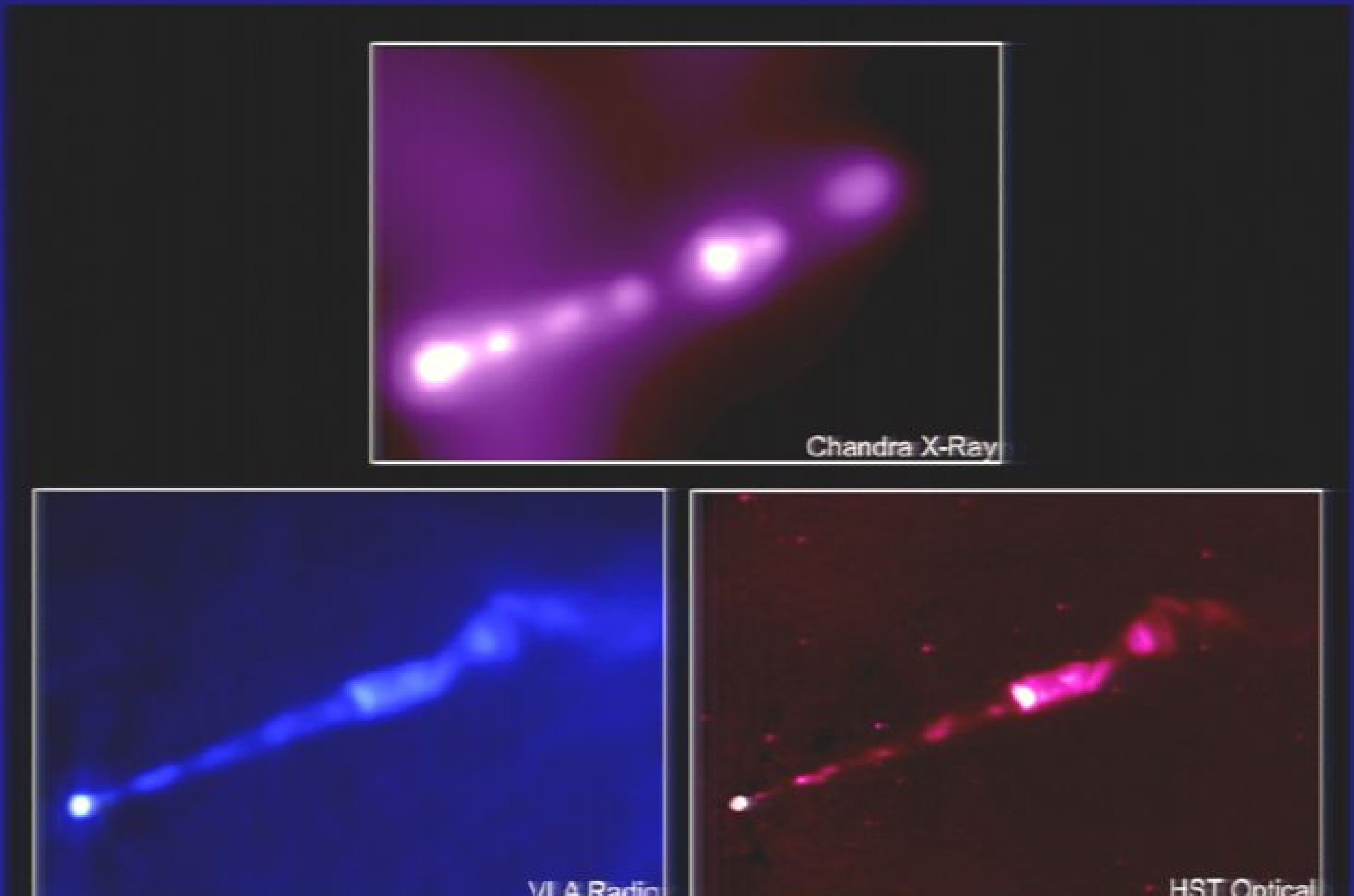


Different orbital phases of the hot spot →



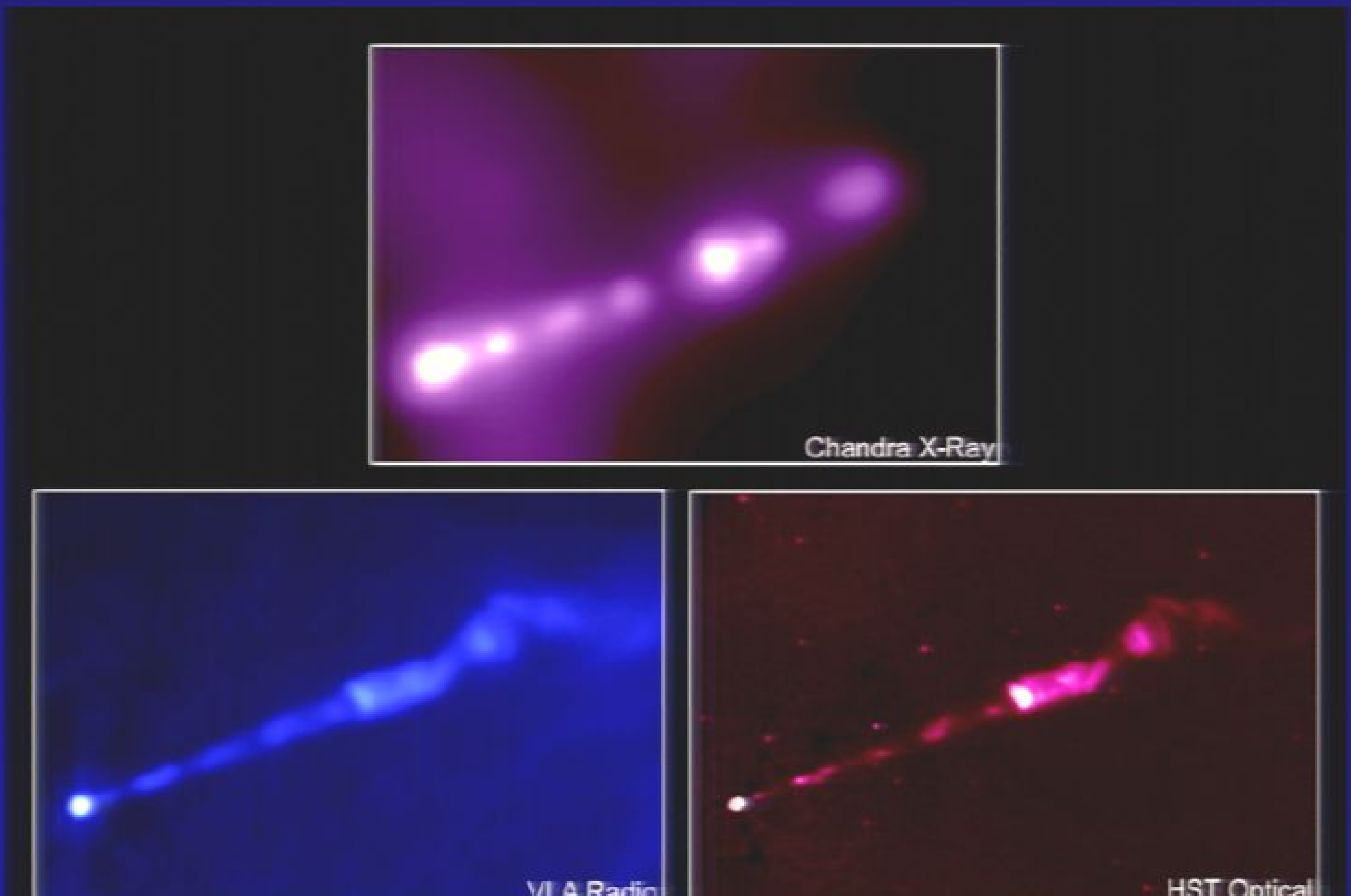
SgrA*
230 GHz
50 μas
with interstellar scattering
345 GHz
with interstellar scattering
Different orbital phases of the hot spot →

M87



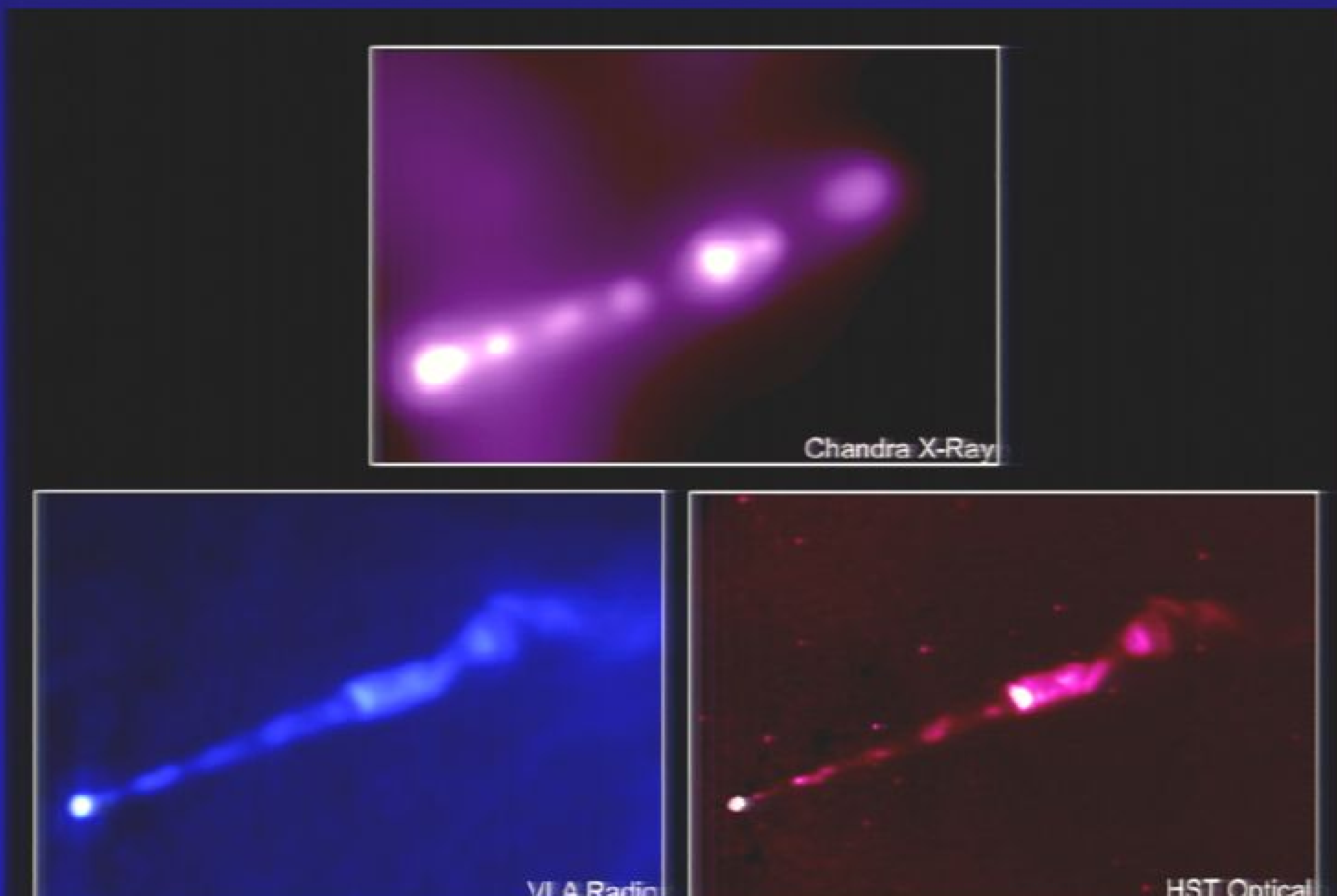
M87

$$M_{\rm BH} = 3 \times 10^9 M_\odot$$



M87

$M_{\mathrm{BH}} = 3 \times 10^9 M_\odot$ *(~700 times more massive than SgrA*)*



M87

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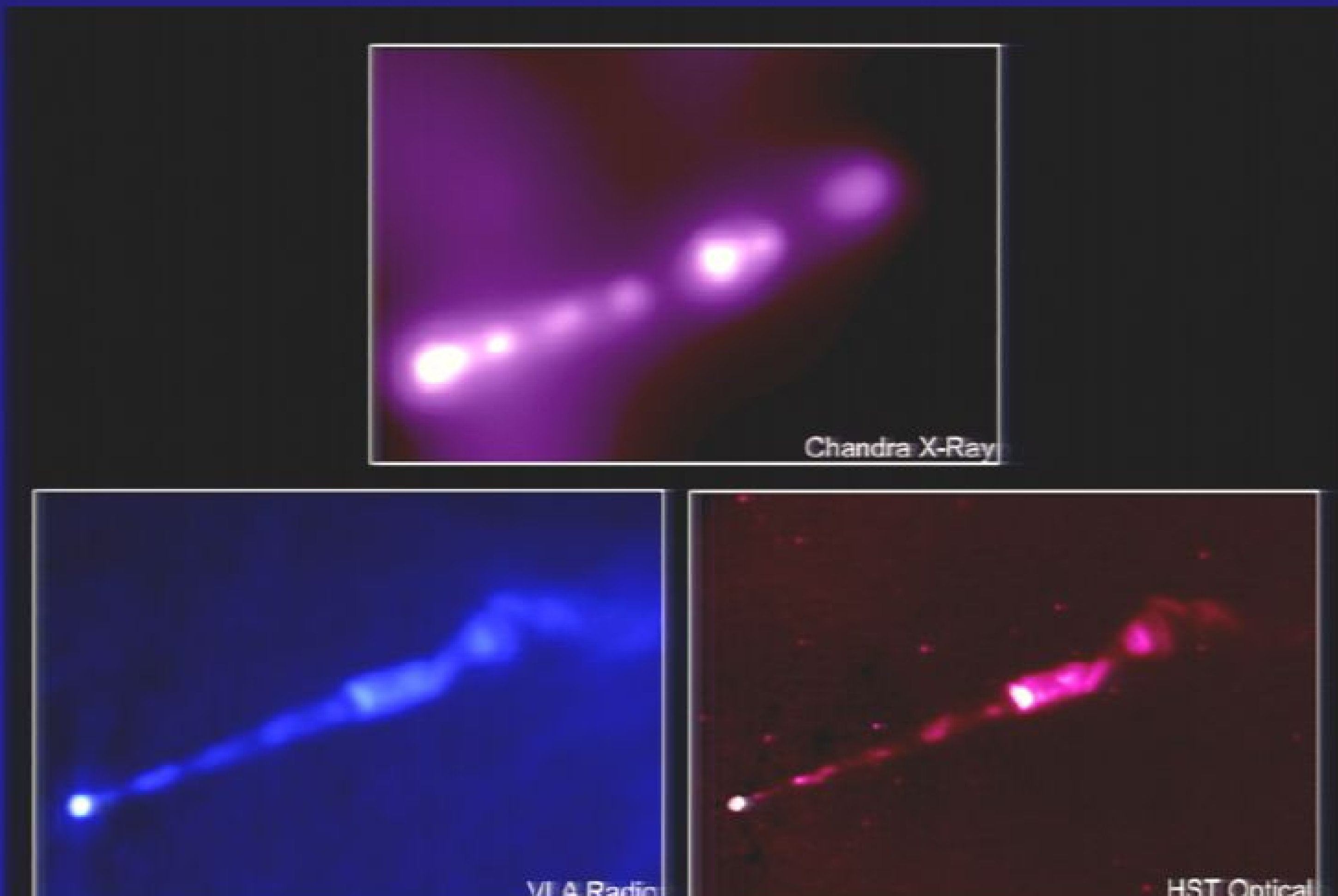
$d_{\rm M87} = 16 \pm 1.2 {\rm Mpc}$



M87

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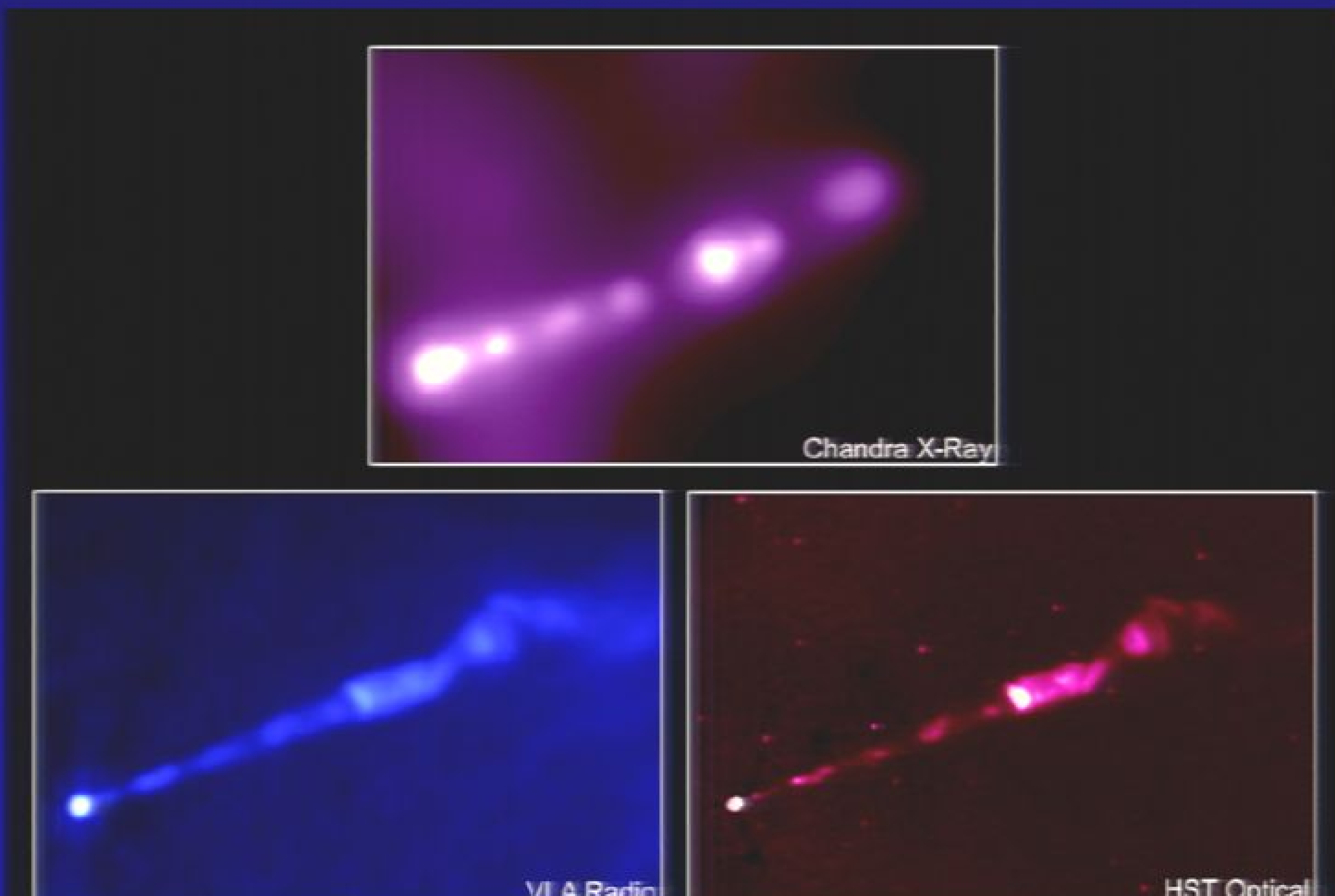
$d_{\rm M87} = 16 \pm 1.2 {\rm Mpc}$ *(~2000 times farther than SgrA*)*



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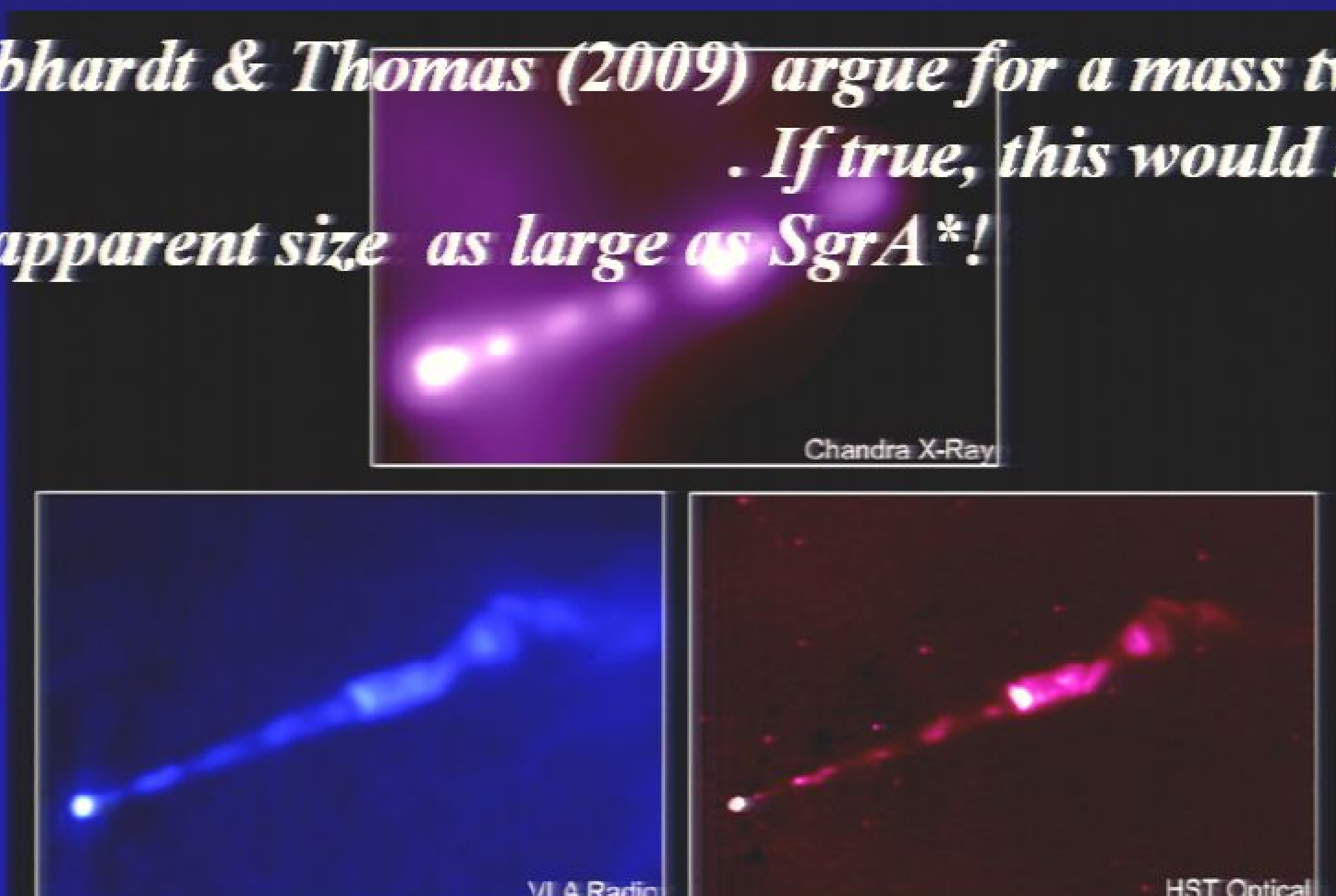
But Gebhardt & Thomas (2009) argue for a mass twice as large, . If true, this would make M87's apparent size as large as SgrA*!



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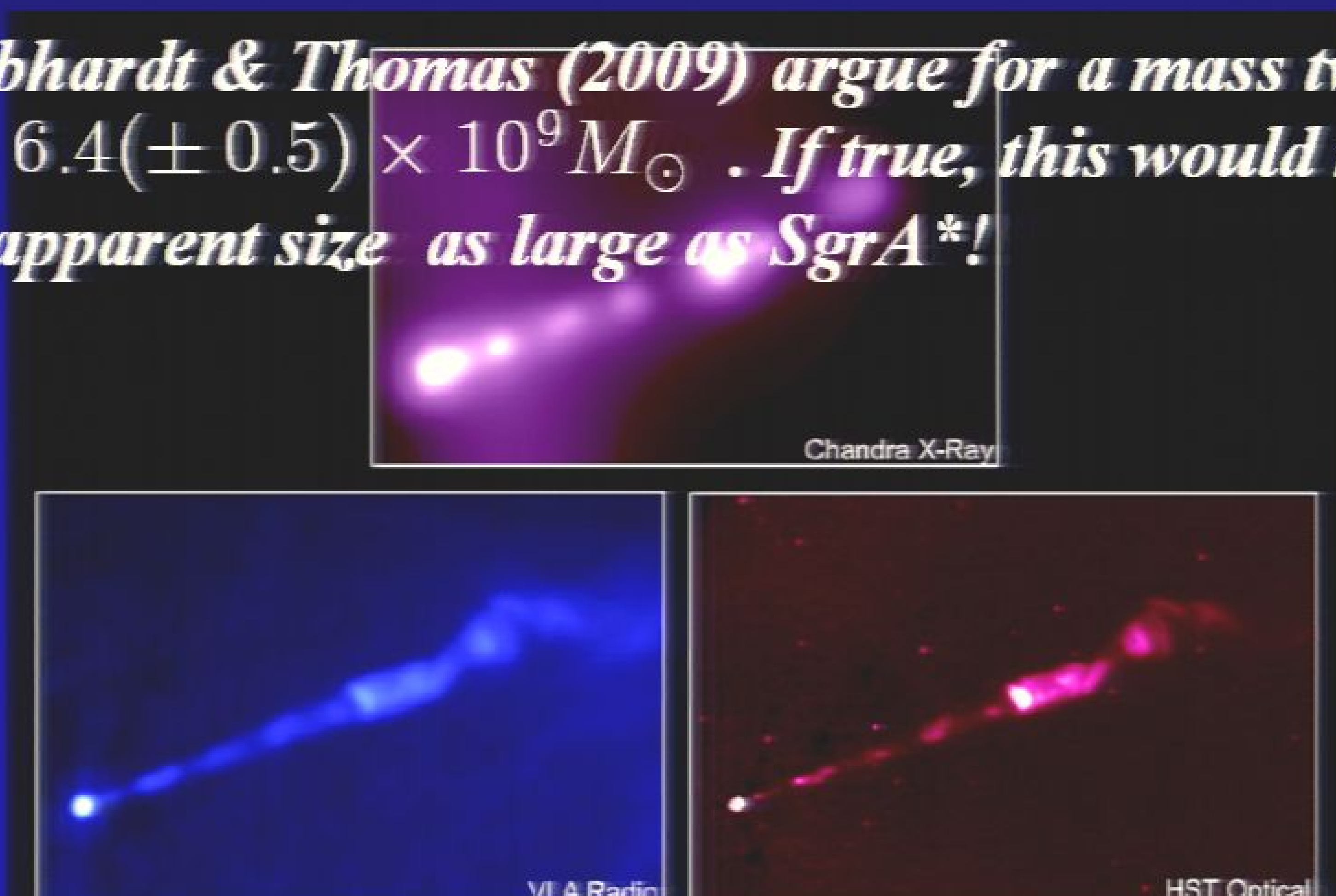
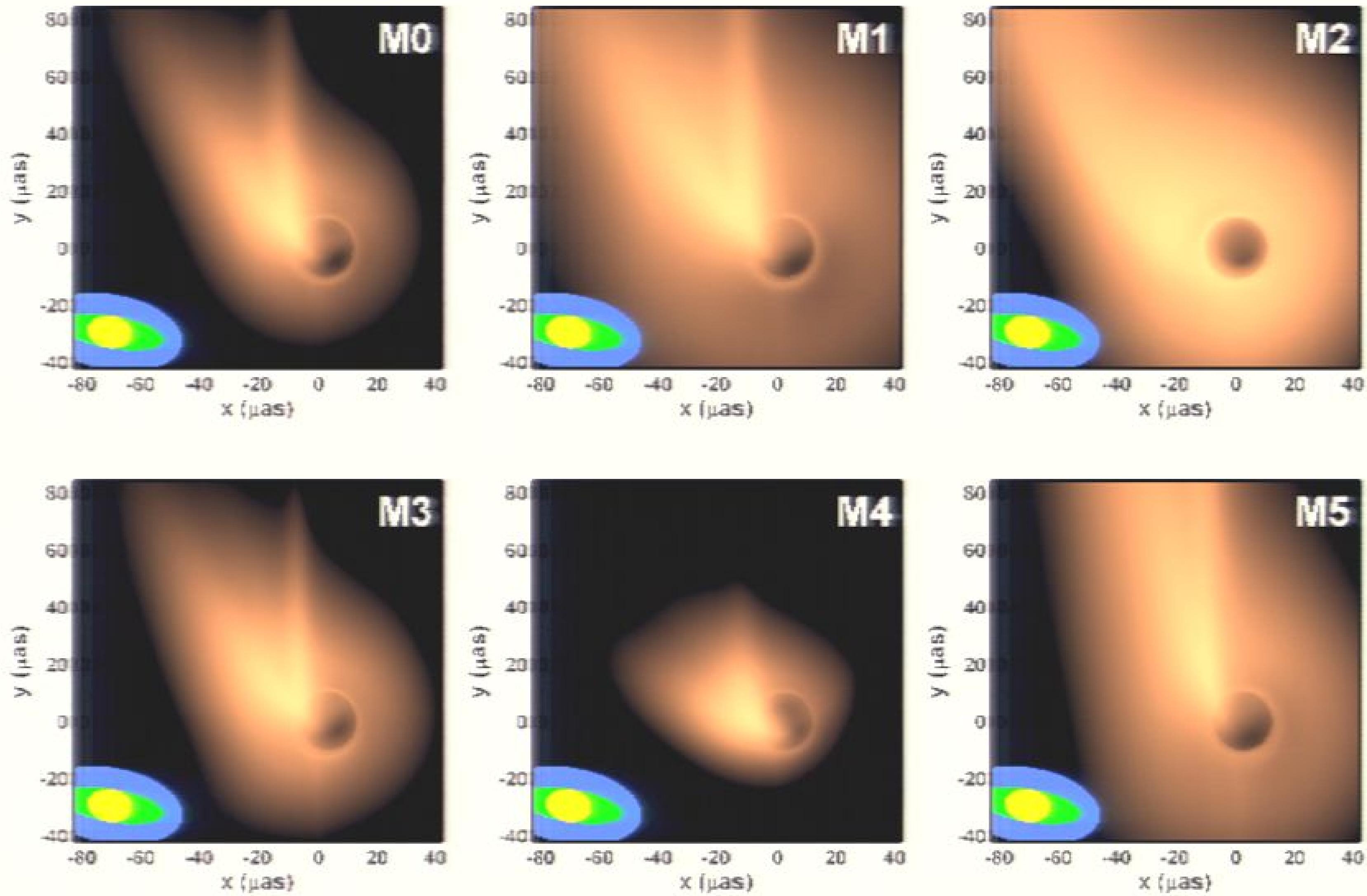


0.87 mm Images

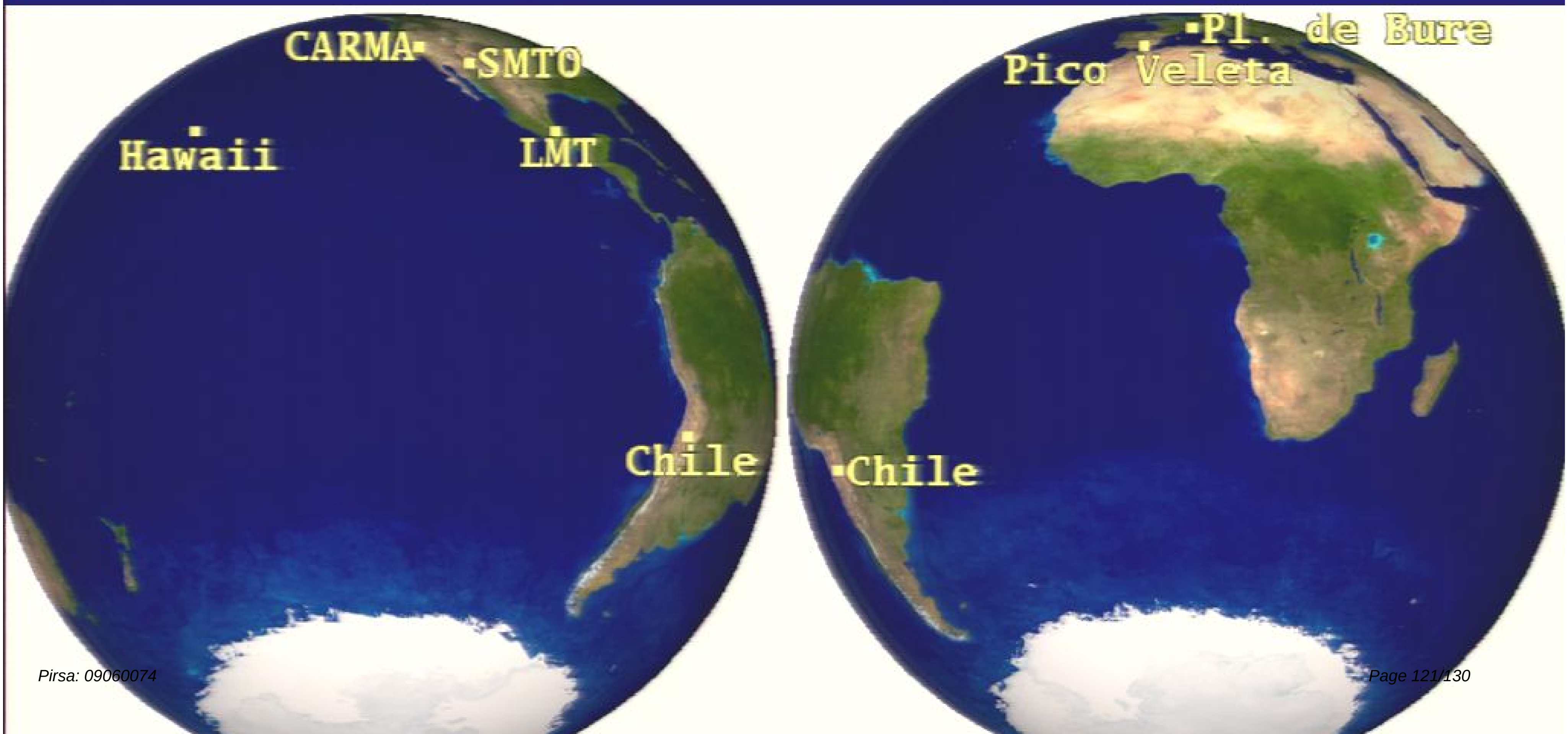


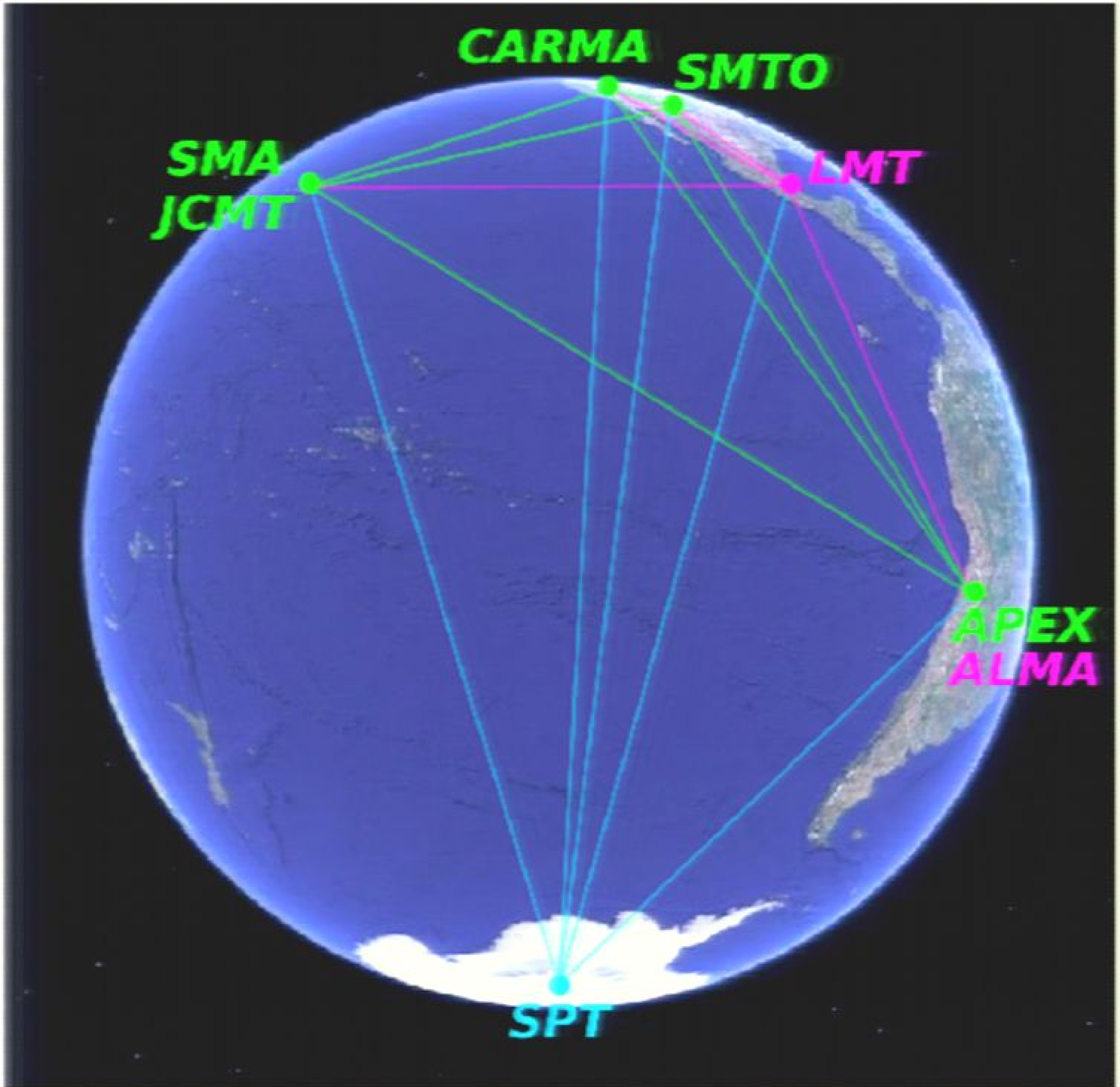
US

+EU

+LMT

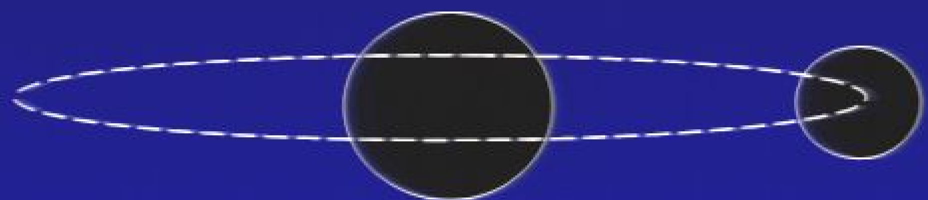
Very Large Baseline Interferometry (VLBI) at sub-millimeter wavelengths




CARMA
SMTO
SMA
JCMT
LMT
APEX
ALMA
SPT

Hydrodynamic Simulations of Quasar Feedback

Gravitational Wave Recoil

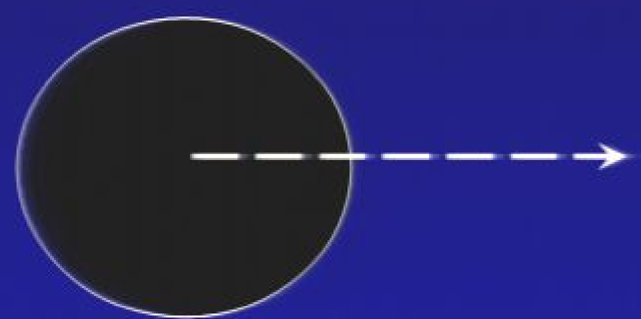


Gravitational Wave Recoil

Gravitational Wave Recoil

Anisotropic emission of gravitational waves → momentum recoil

Gravitational Wave Recoil



Highlights

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- *The merger product of the Milky-Way and Andromeda (Milkomeda) is the only object that will remain visible to us as the Universe ages by a factor of ten (a hundred billion years from now). Subsequent generations of observers will not be able to find direct evidence for the big bang.*