Title: Three Astrophysical Laboratories for Particle Physics

Date: Nov 14, 2007 02:00 PM

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Abstract: The Universe offers environments with extreme physical conditions that cannot be realized in laboratories on Earth. These environments provide unprecedented tests for extensions of the Standard Model. I will describe three such \"astrophysical laboratories\", which are likely to represent new frontiers in cosmology and astrophysics over the next decade. One provides a novel probe of the initial conditions from inflation and the nature of the dark matter, based on 3D mapping of the distribution of cosmic hydrogen through its resonant 21cm line. The second allows to constrain the metric around supermassive black holes based on direct imaging or the detection of gravitational waves. The third involves the acceleration of high-energy particles in cosmological shock waves. I will describe past and future observations of these environments and some related theoretical work.

No, I will not discuss the "dark energy"...

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$$w = p/\rho = -1 \pm 0.1$$

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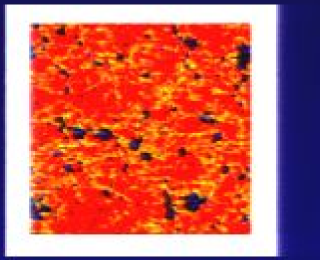
The fact that I nevertheless have something to discuss demonstrates how broad is the contact between astrophysics and fundamental physics!

Three Astrophysical Laboratories for Particle Physics

- **21cm Cosmology:**

  inflation, nature of dark matter

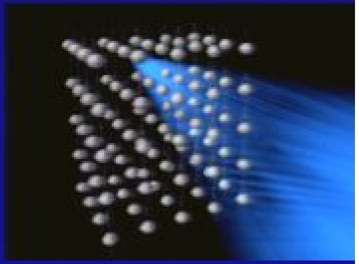


- **Supermassive Black Holes:**

  strong field (but low-curvature) gravity

- **Cosmic Accelerators:**

  high-energy (up to a billion TeV) physics

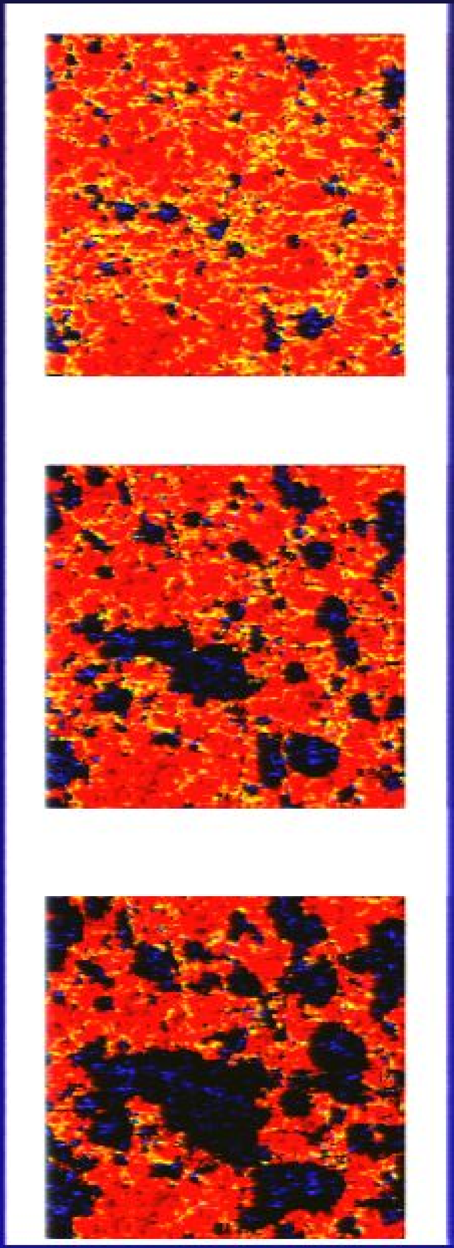


Avi Loeb

Harvard Astronomy Department

21cm Cosmology:

inflation, nature of dark matter



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

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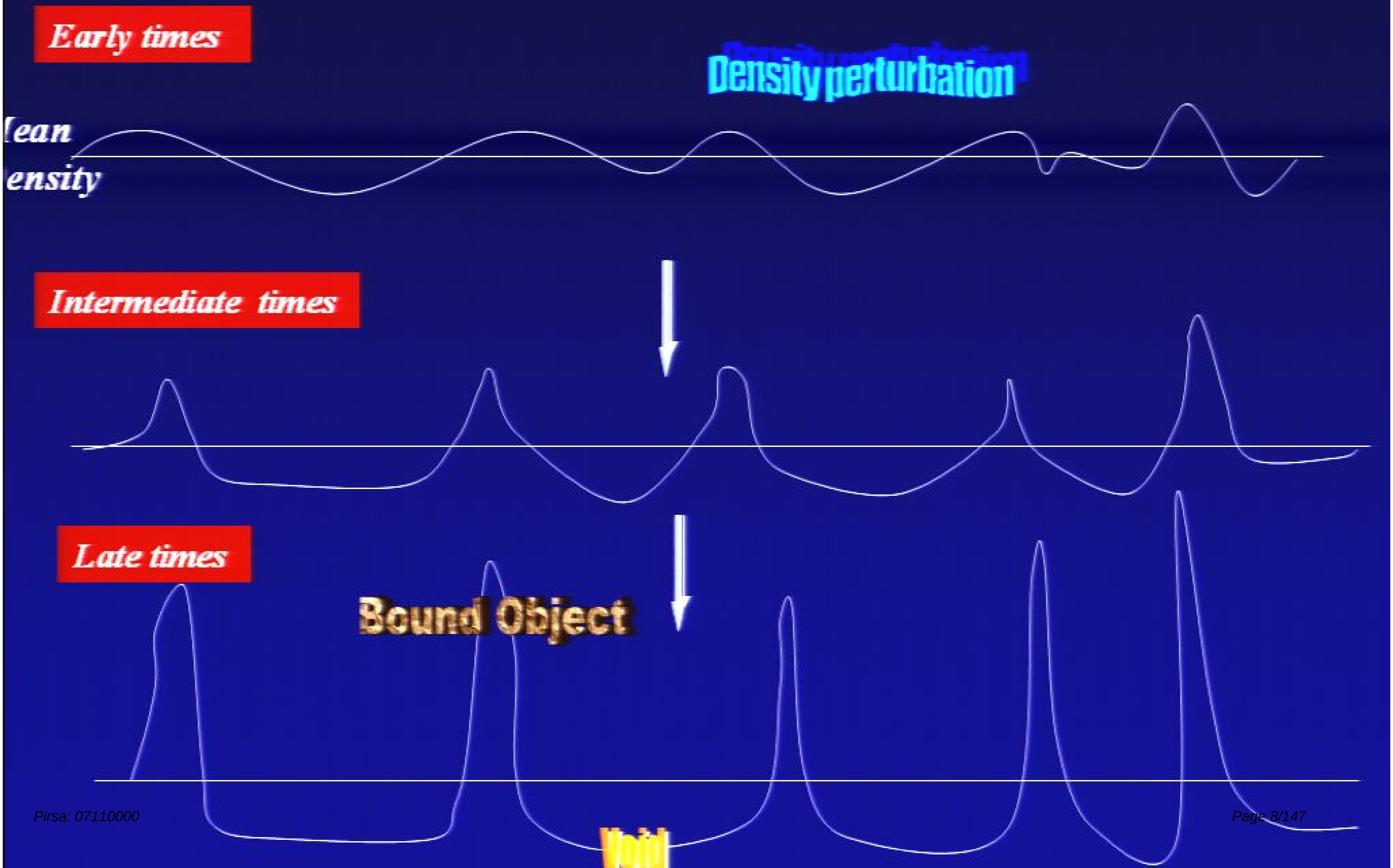
On small scales the universe is clumpy



Early times

Density perturbation

ean
ensity

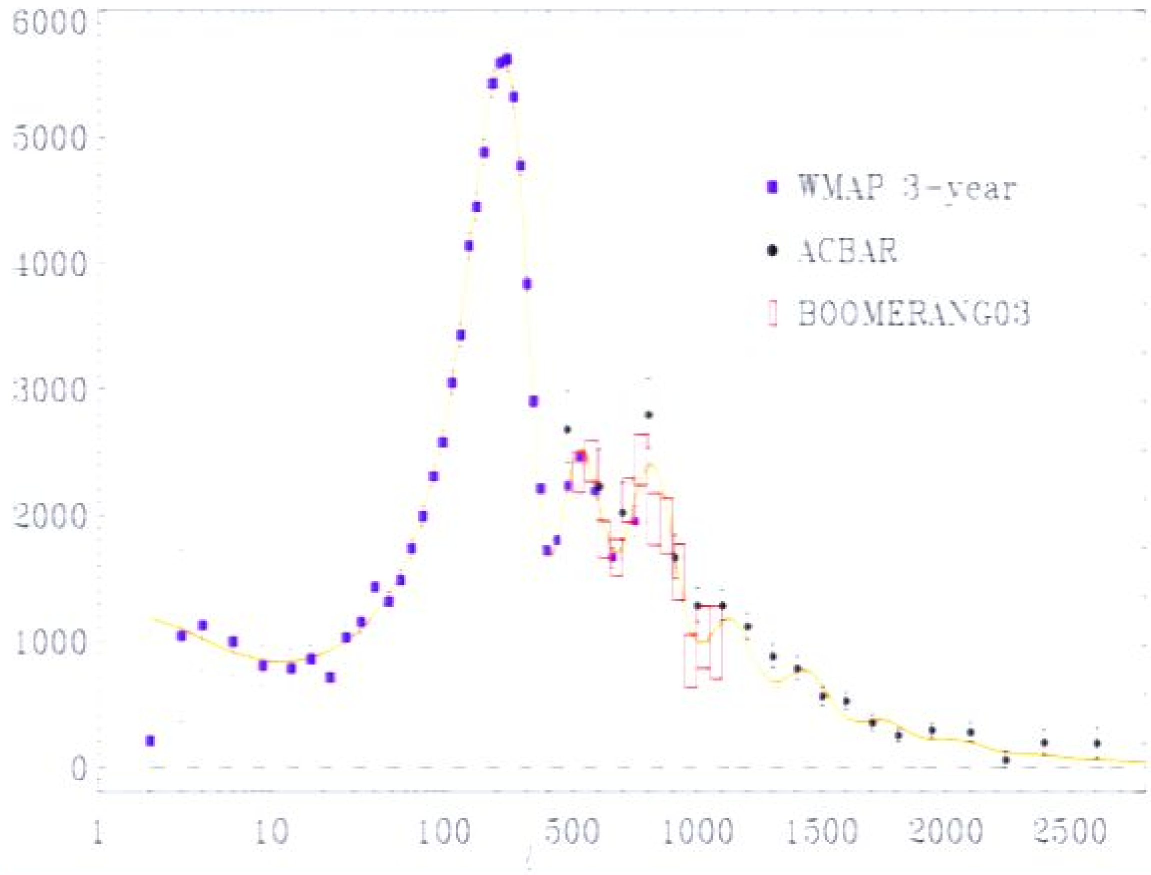
Intermediate times

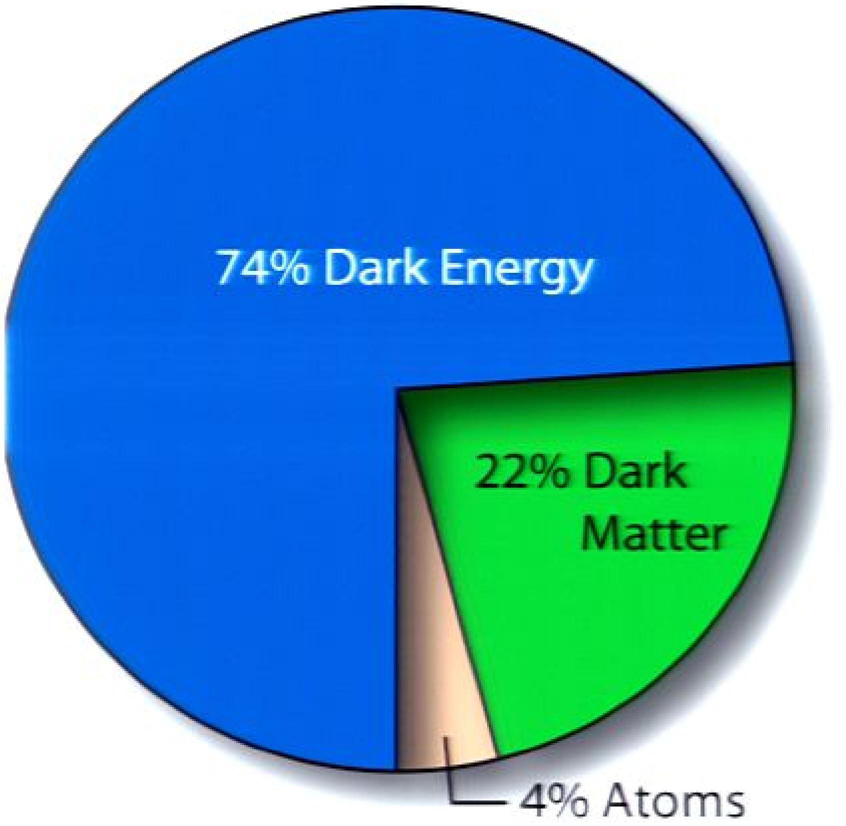
Late times

Bound Object

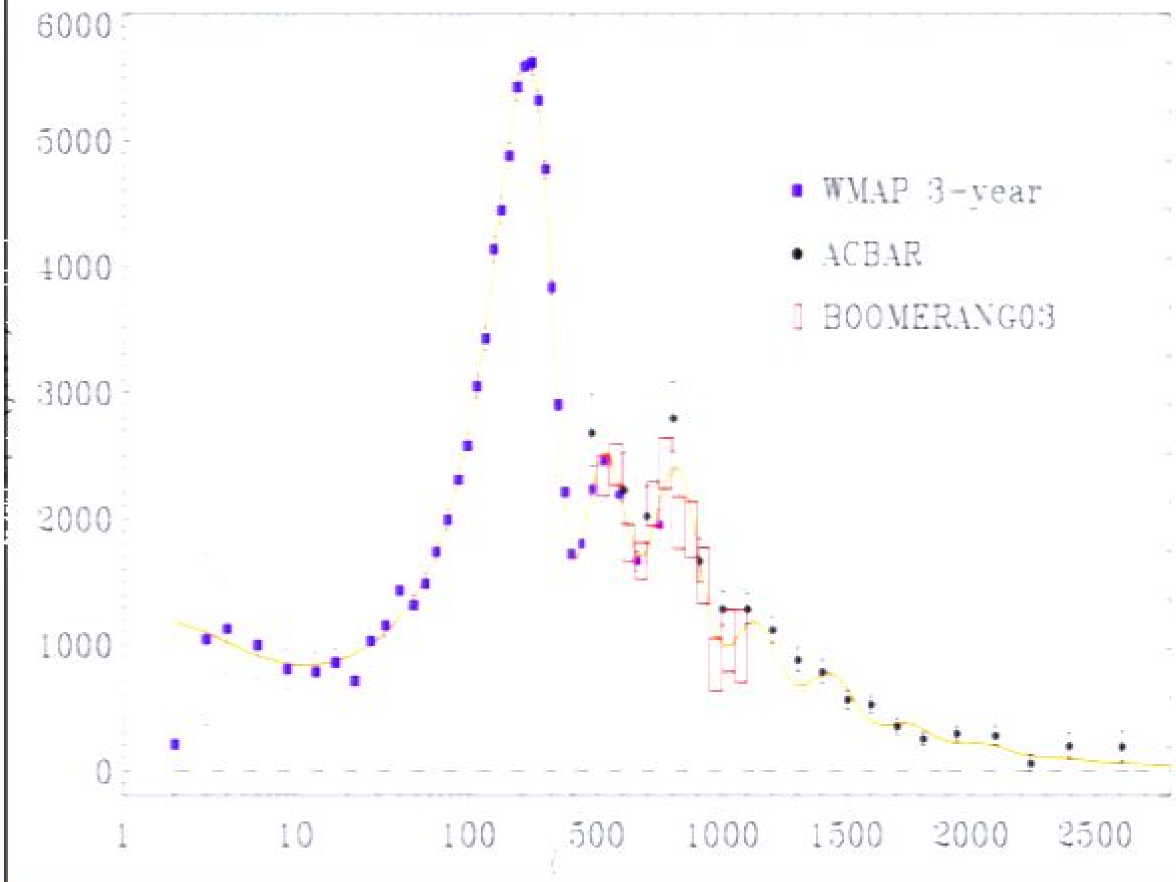
Void

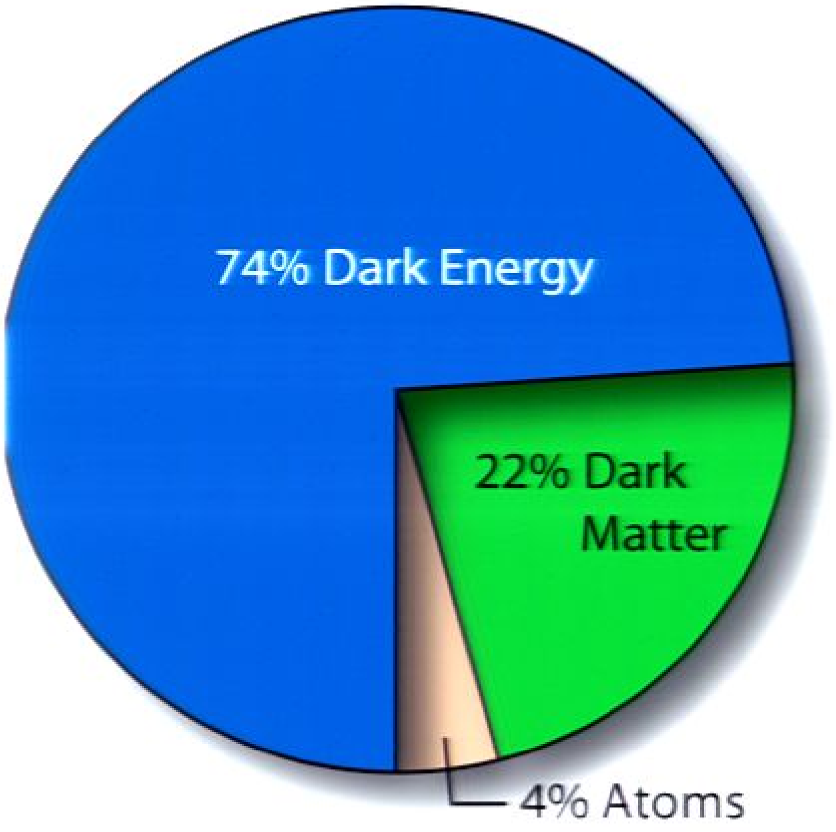
Current Composition of the Universe





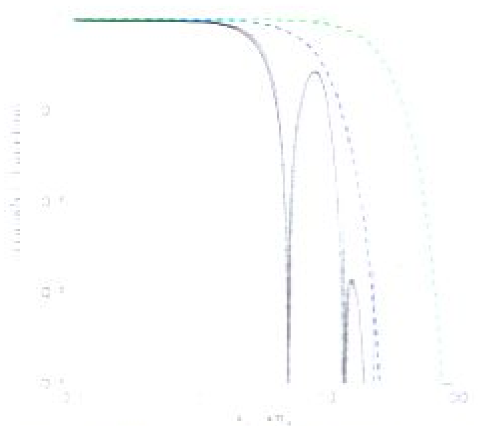
Current Composition of the Universe



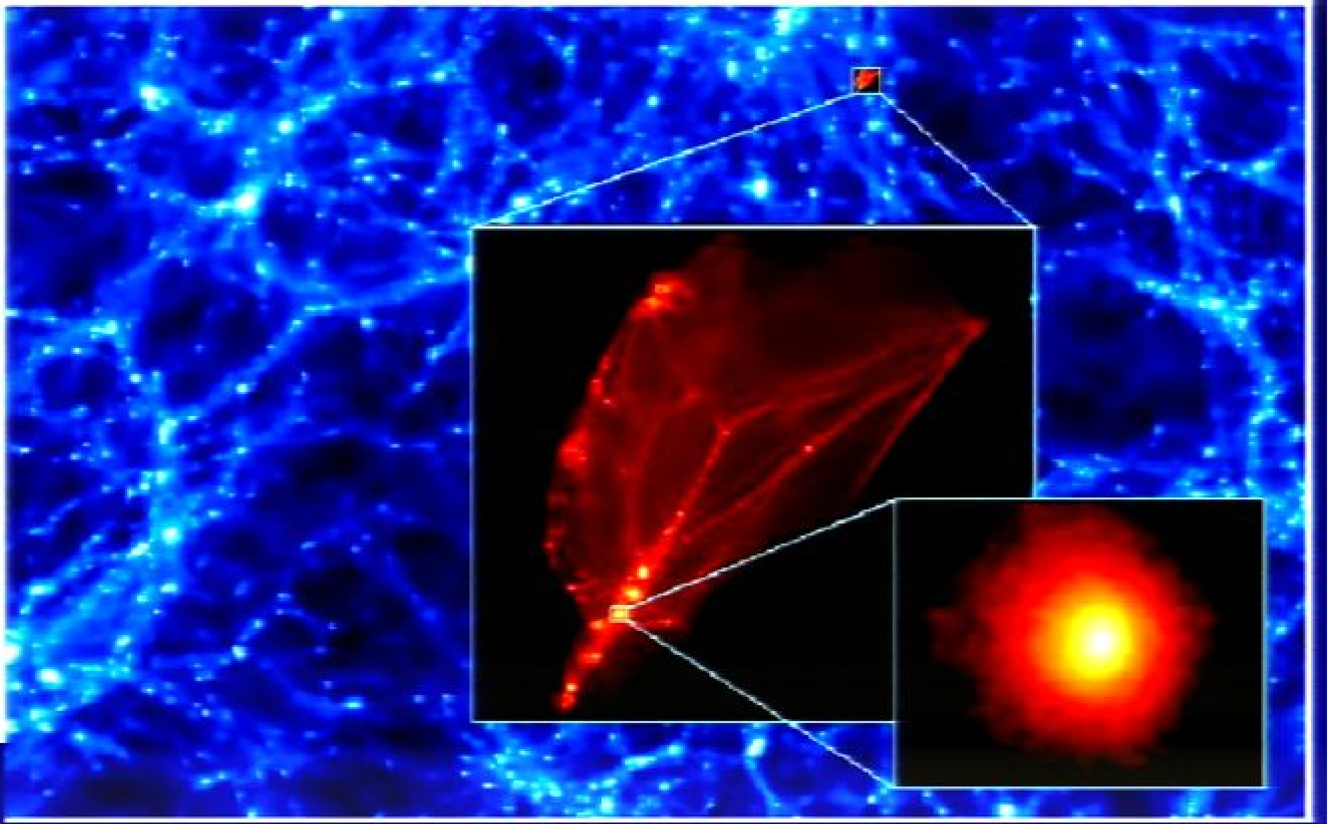


Silk damping of small-scale fluctuatons in the baryon-photon fluid prior to cosmic recombination implies that galaxies could not have formed in our Universe without dark matter!

The First Dark Matter Objects in the Universe



Transfer function of the CDM density perturation amplitude (normalized by the primordial amplitude om inflation). We show two cases: (i) $T_d/M = 10^{-4}$ and $_d/T_{eq} = 10^7$; (ii) $T_d/M = 10^{-5}$ and $T_d/T_{eq} = 10^7$. In each ase the oscillatory curve is our result and the other curve is he free-streaming only result that was derived previously in he literature [4,7,8].



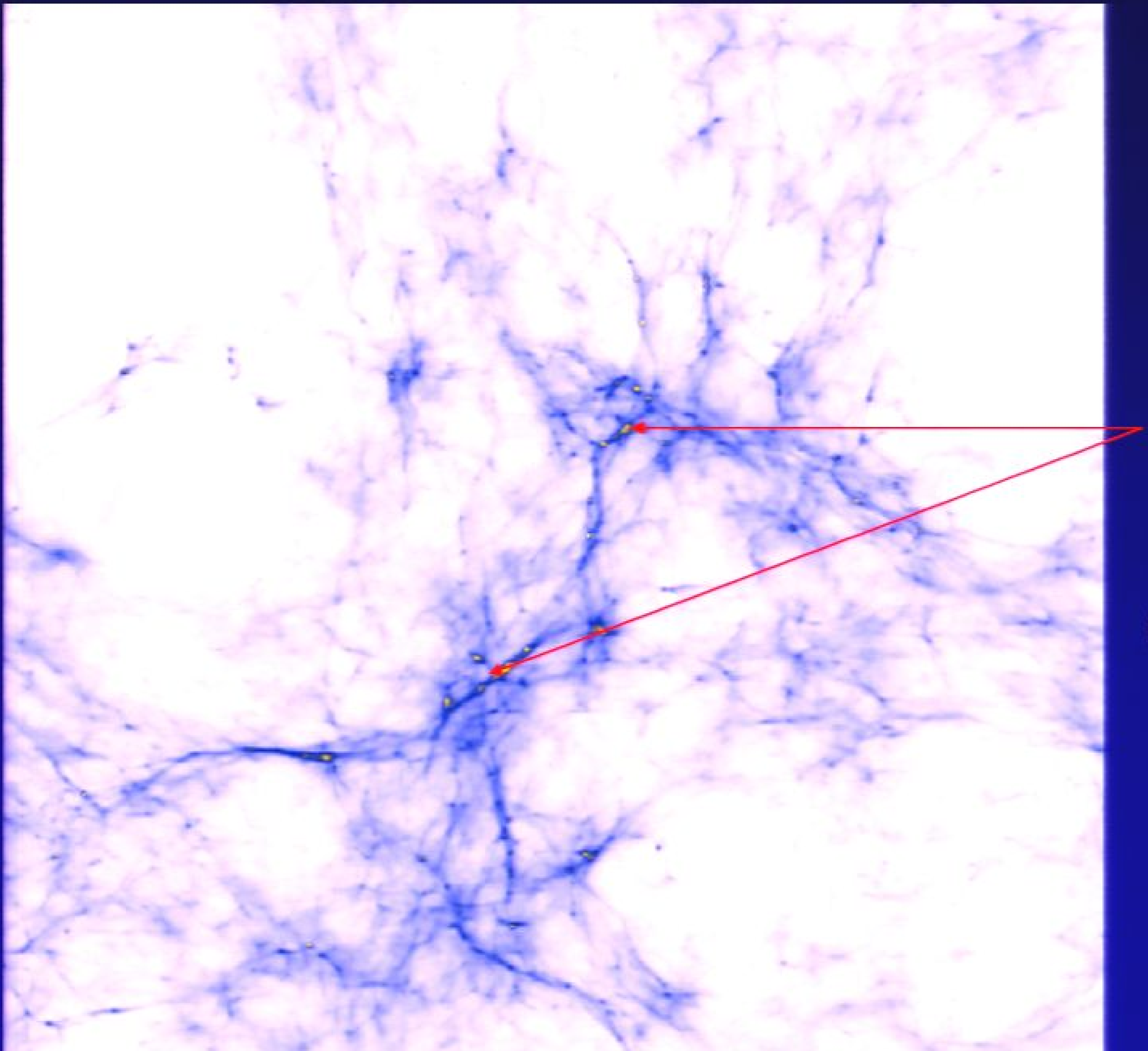
Smallest dark matter clumps: ~0.1 Jupiter mass

$$M_{cut} = \frac{4\pi}{3}\left(\frac{\pi}{k_{cut}}\right)^3 \Omega_M \rho_{crit} \simeq 10^{-4}\left(\frac{T_d}{10\ \mathrm{MeV}}\right)^{-3} M_{\oplus}$$

Loeb & Zaldarriaga, astro-ph/0504112

Diemand, Moore & Stadel astro-ph/0501589

Emergence of the First Star Clusters

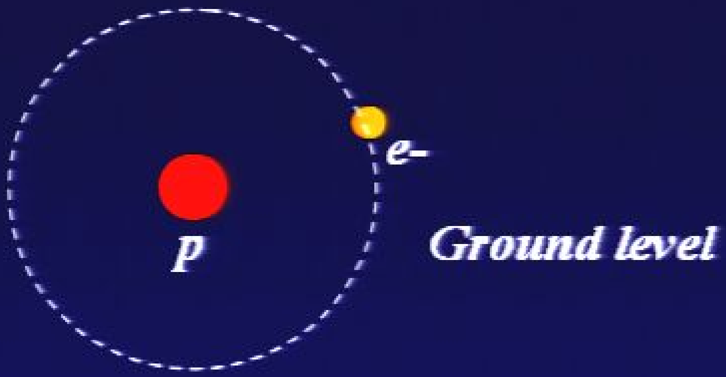


molecular hydrogen in Jeans mass objects

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

Yoshida et al. 2003

Hydrogen



Predicted by Van de Hulst in 1944. Observed by Ewen & Purcell in 1951 at Harvard

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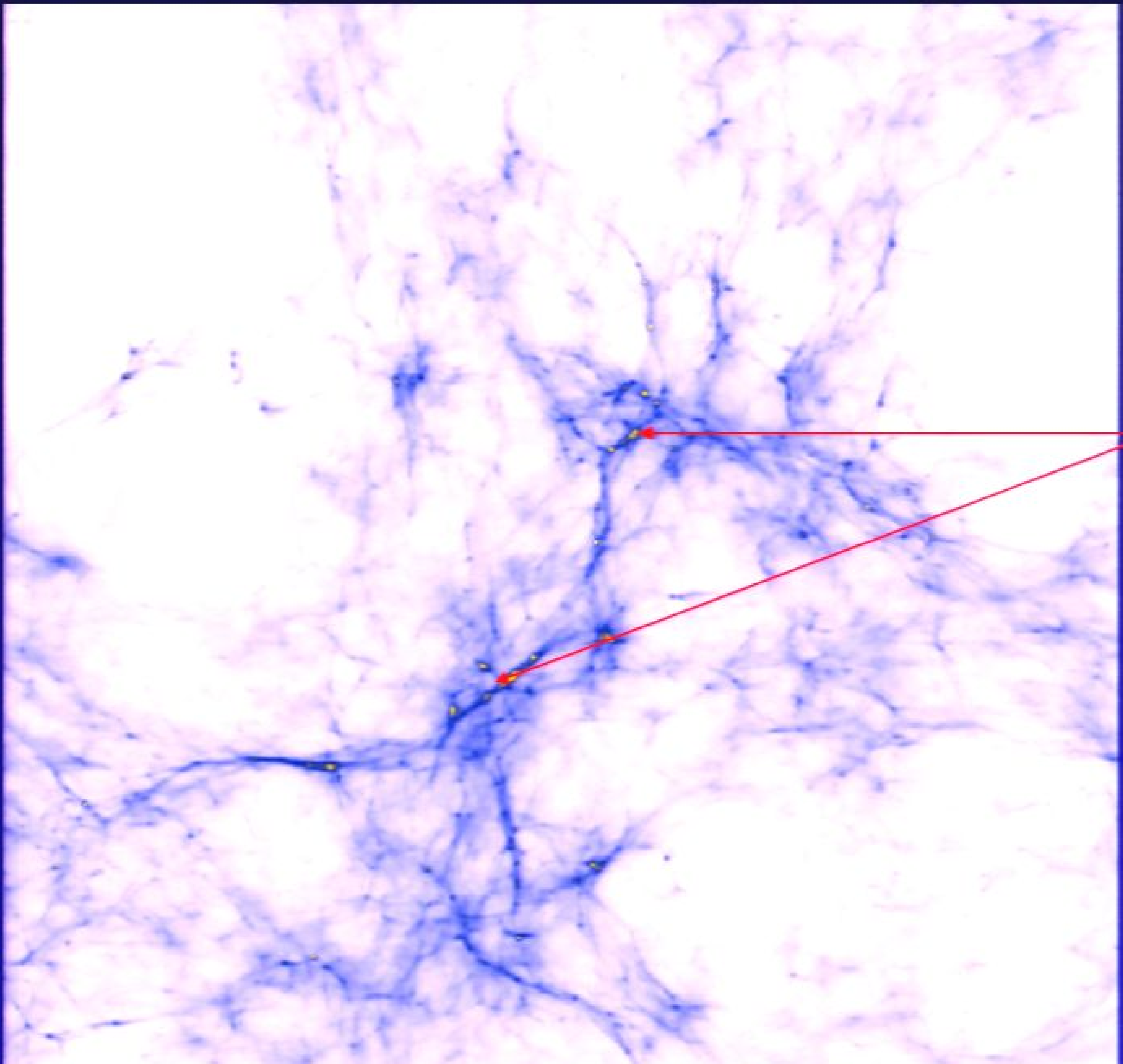

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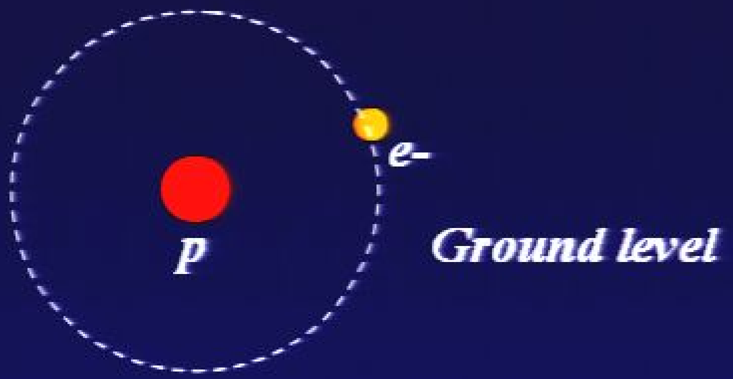

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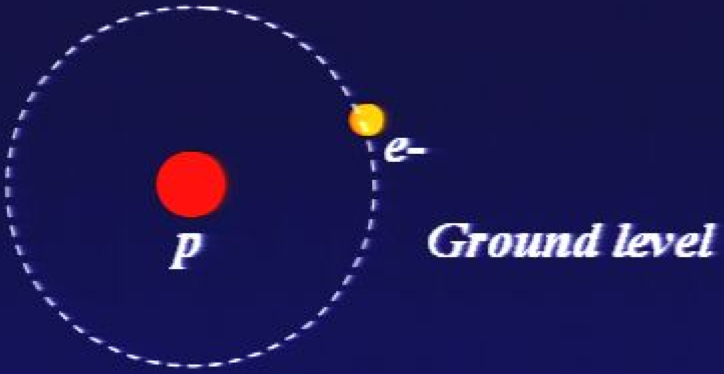
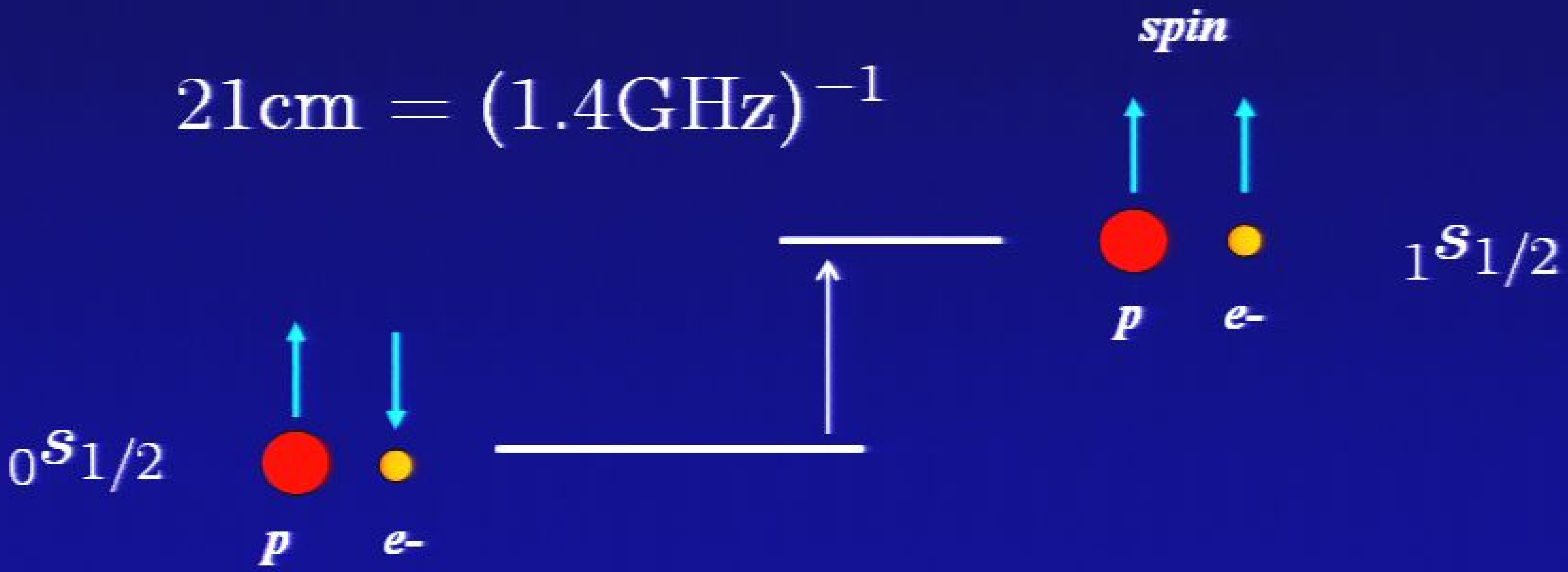


$$21\text{cm} = (1.4\text{GHz})^{-1}$$



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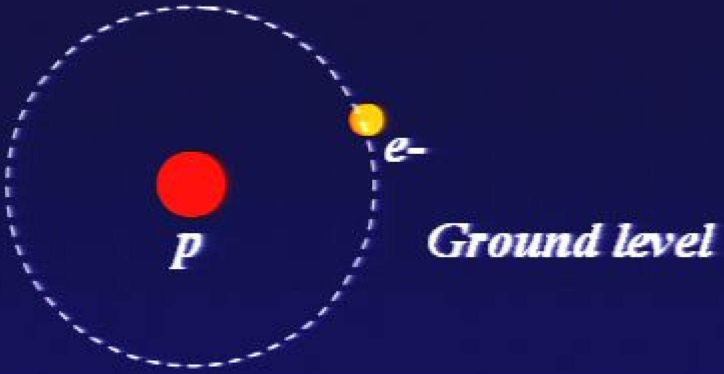

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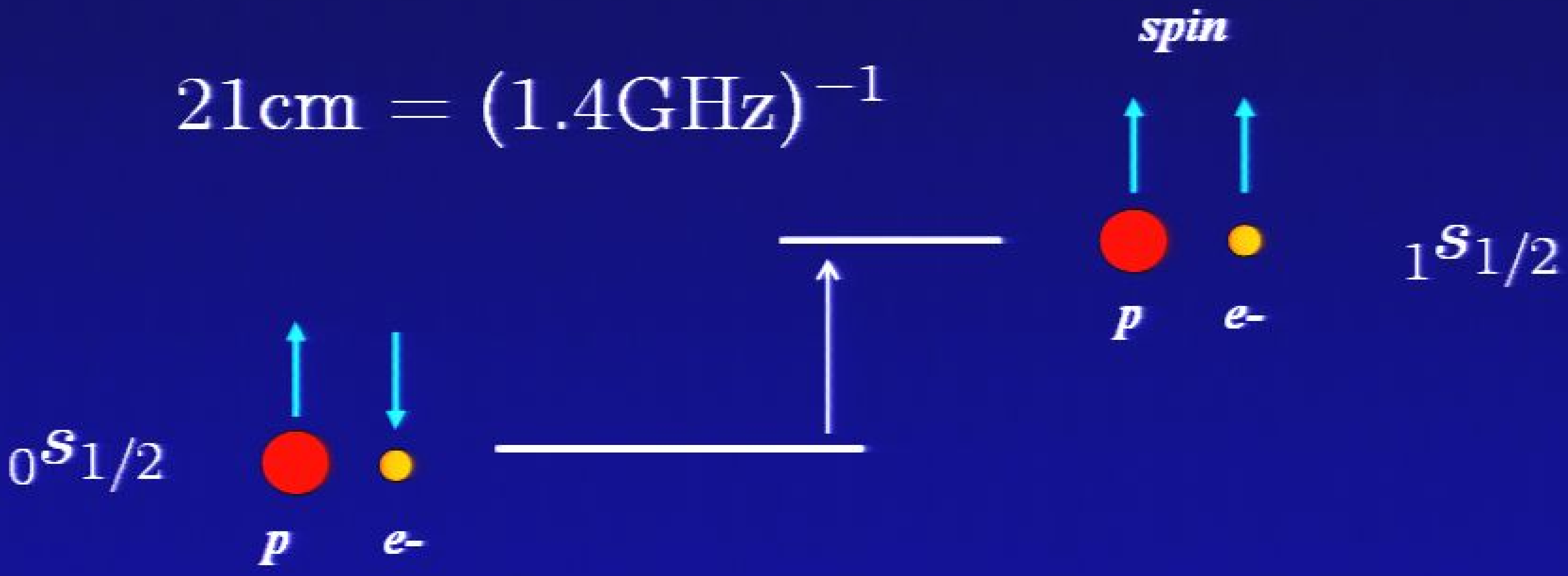
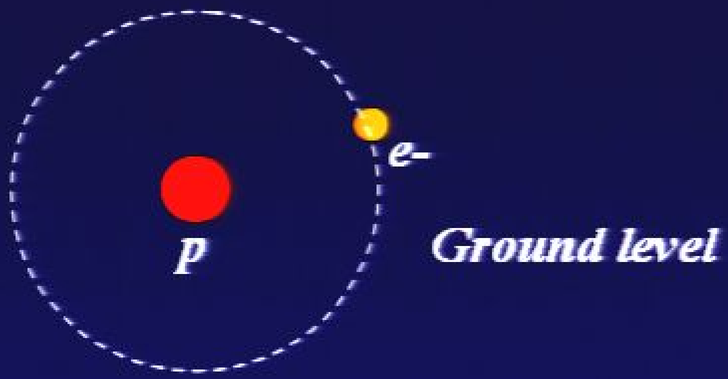


Spin Temperature

Predicted by Van de Hulst in 1944. Observed by Ewen & Purcell in 1951 at Harvard

Hydrogen



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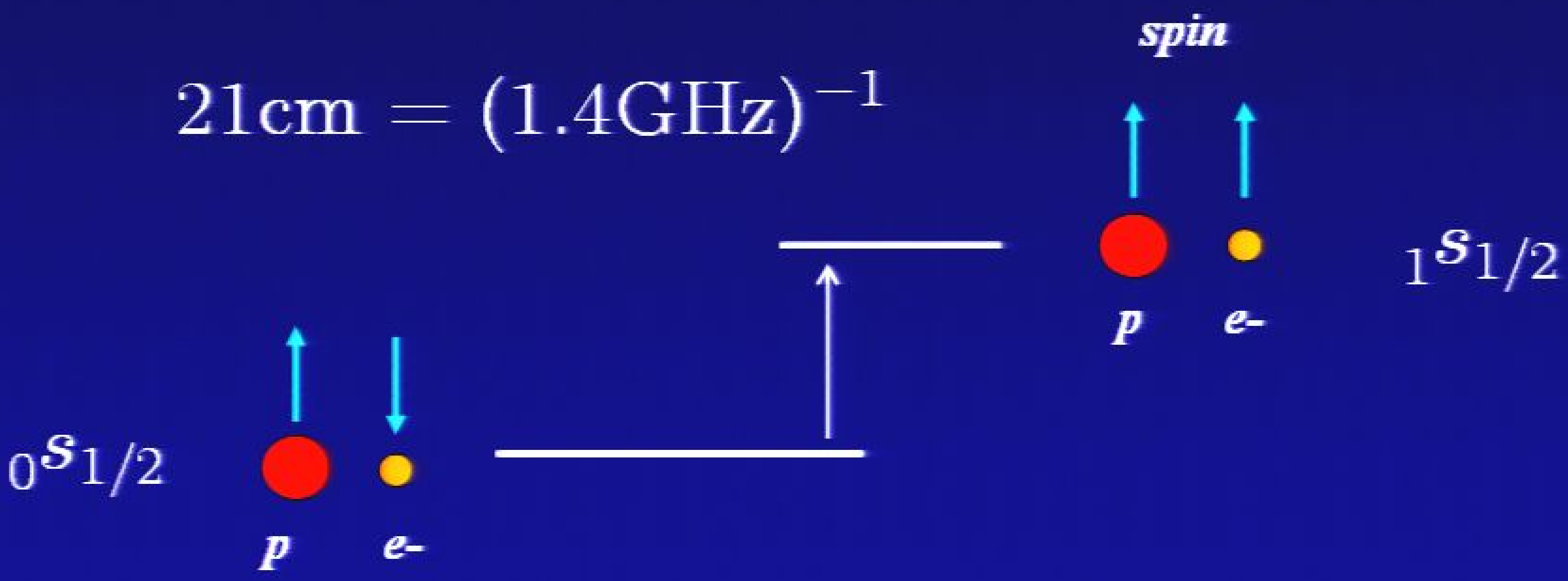

Spin Temperature $$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\{-\frac{0.068\mathrm{K}}{T_s}\}$$

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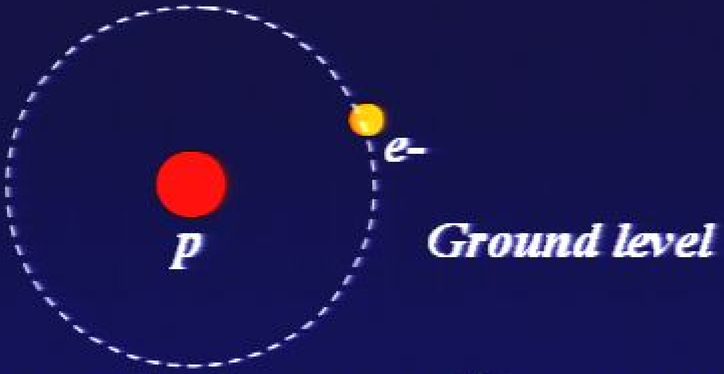
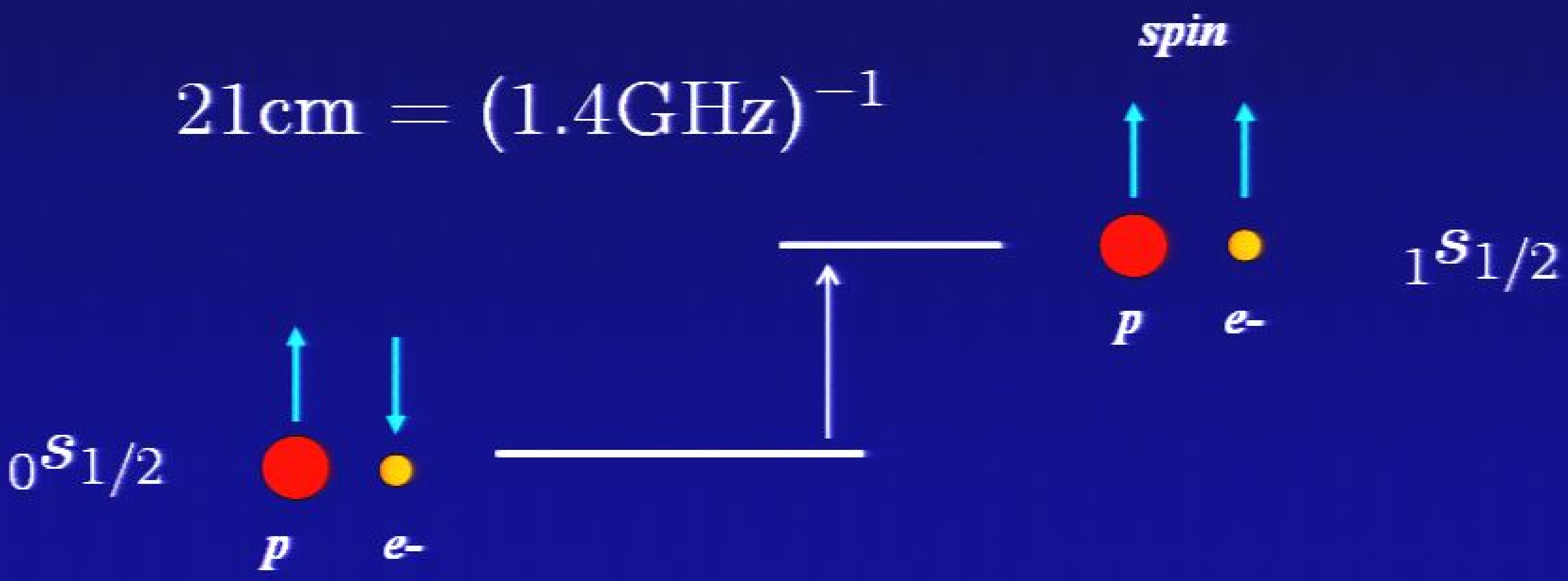
Hydrogen



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

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

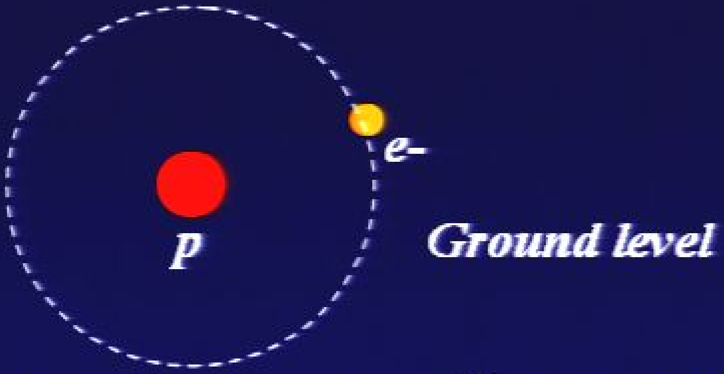


Spin Temperature

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

Predicted by Van de Hulst in 1944, Observed by Ewen & Purcell in 1951 at Harvard

Hydrogen



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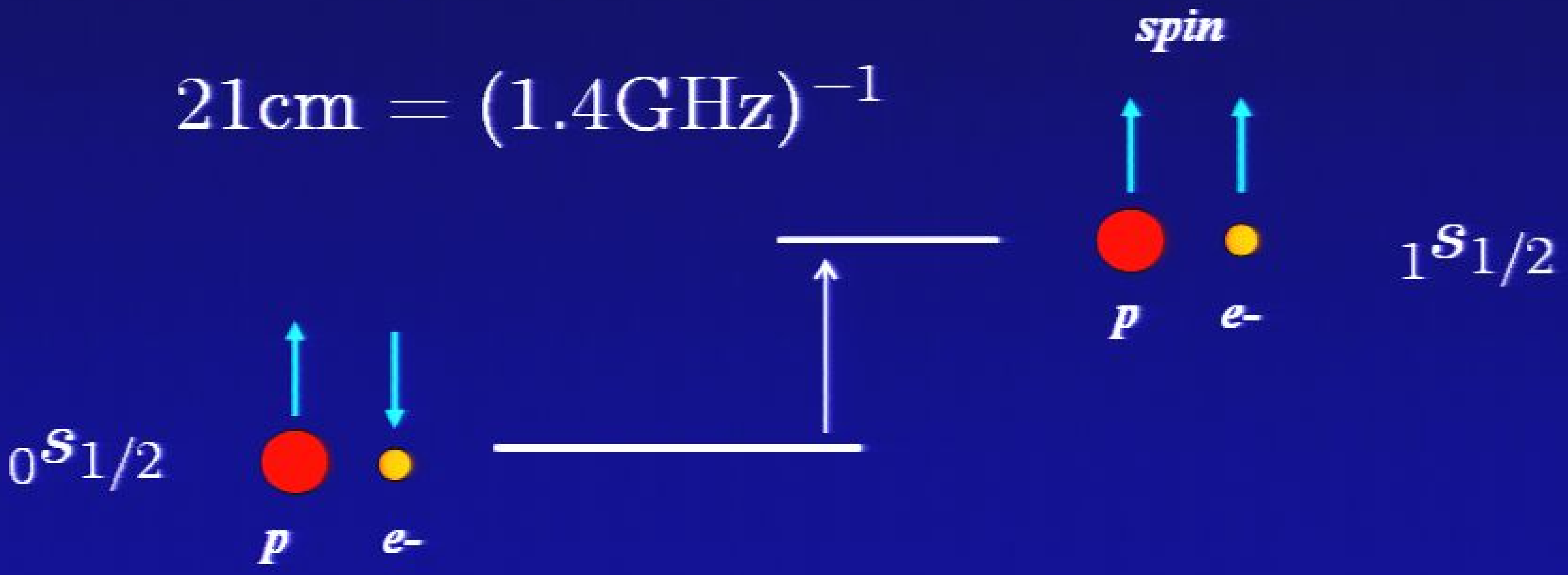
Couple T_s ***to***

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



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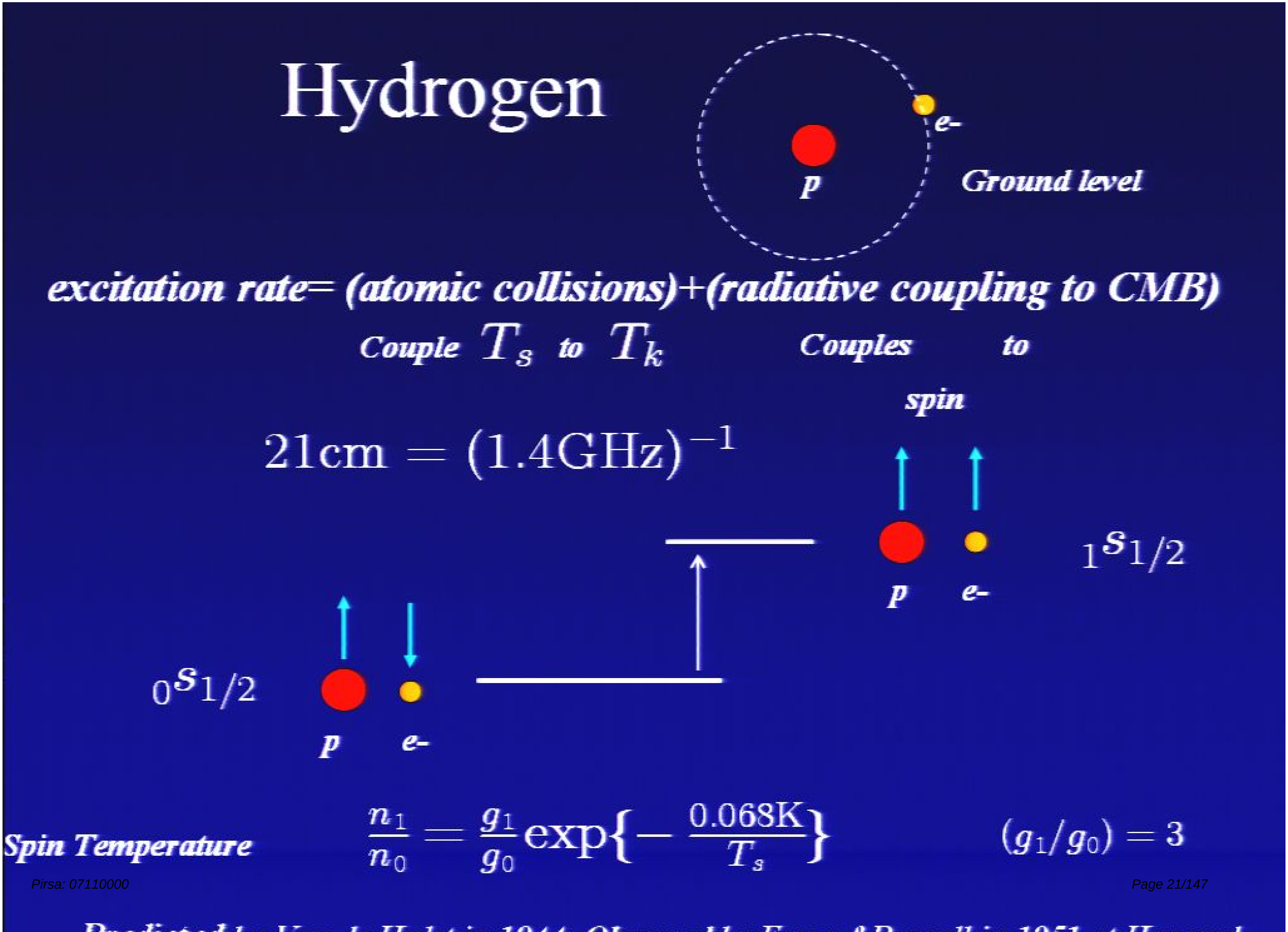


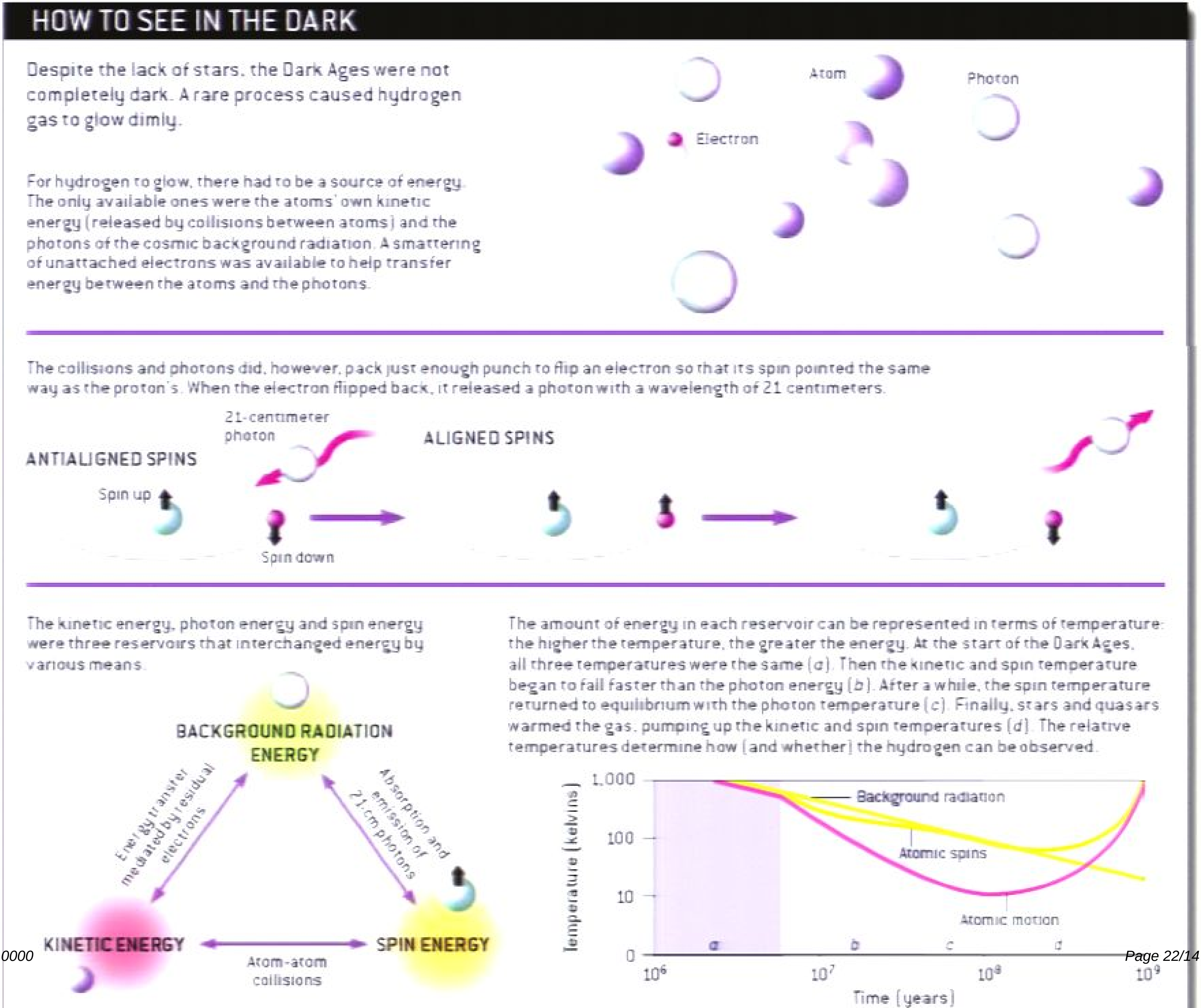
Hydrogen

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

Couple T_s *to* T_k *Couples to spin*

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

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



HOW TO SEE IN THE DARK

Despite the lack of stars, the Dark Ages were not completely dark. A rare process caused hydrogen gas to glow dimly.

For hydrogen to glow, there had to be a source of energy. The only available ones were the atoms' own kinetic energy (released by collisions between atoms) and the photons of the cosmic background radiation. A smattering of unattached electrons was available to help transfer energy between the atoms and the photons.

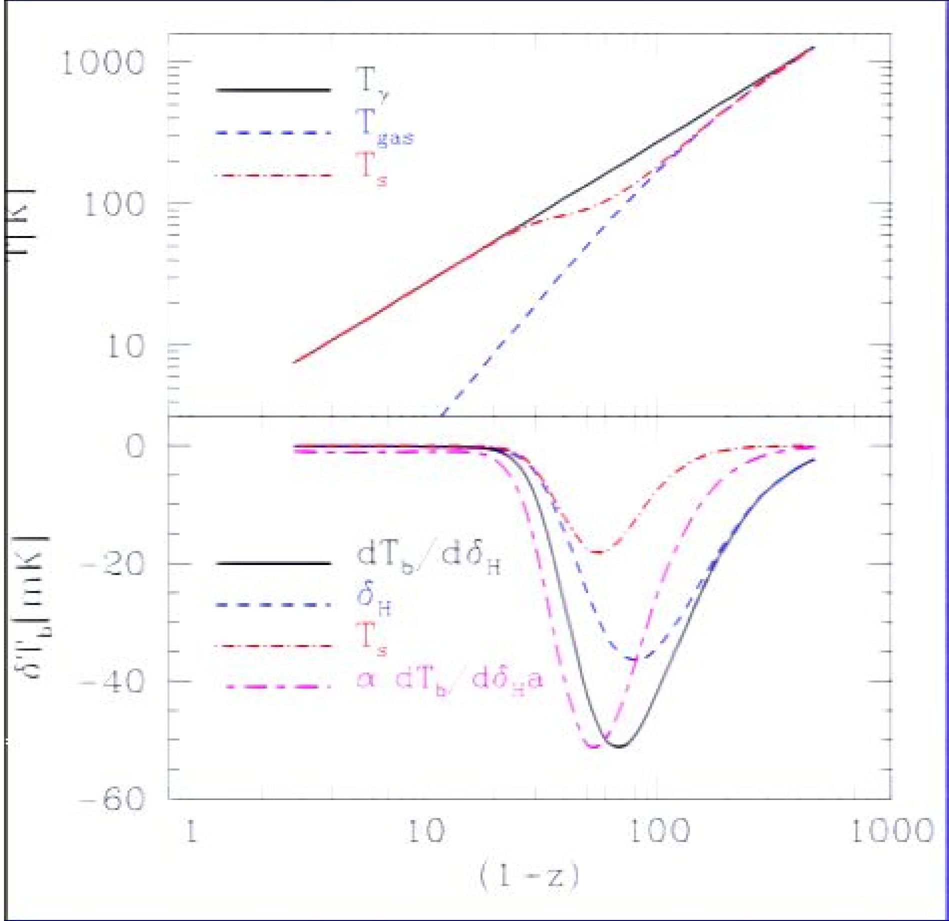
The collisions and photons did, however, pack just enough punch to flip an electron so that its spin pointed the same way as the proton's. When the electron flipped back, it released a photon with a wavelength of 21 centimeters.

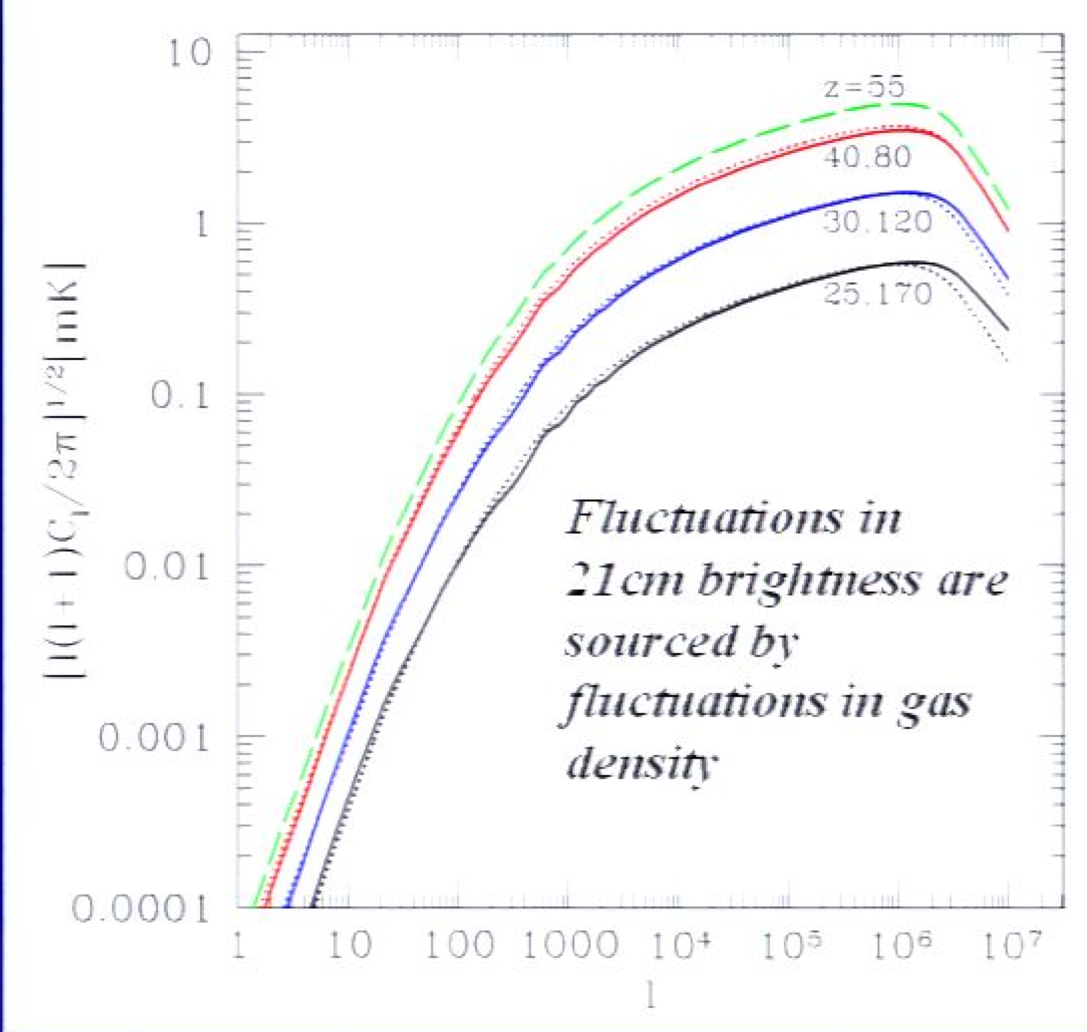
The kinetic energy, photon energy and spin energy were three reservoirs that interchanged energy by various means.

The amount of energy in each reservoir can be represented in terms of temperature: the higher the temperature, the greater the energy. At the start of the Dark Ages, all three temperatures were the same (*a*). Then the kinetic and spin temperature began to fall faster than the photon energy (*b*). After a while, the spin temperature returned to equilibrium with the photon temperature (*c*). Finally, stars and quasars warmed the gas, pumping up the kinetic and spin temperatures (*d*). The relative temperatures determine how (and whether) the hydrogen can be observed.

21 cm Absorption by Hydrogen Prior to Structure Formation

$$T_b = \tau \left(\frac{T_s - T_\gamma}{1+z} \right) \qquad T_b = 28\mathrm{mK} \left(\frac{1+z}{10} \right)^{1/2} \left(\frac{T_s - T_\gamma}{T_s} \right)$$



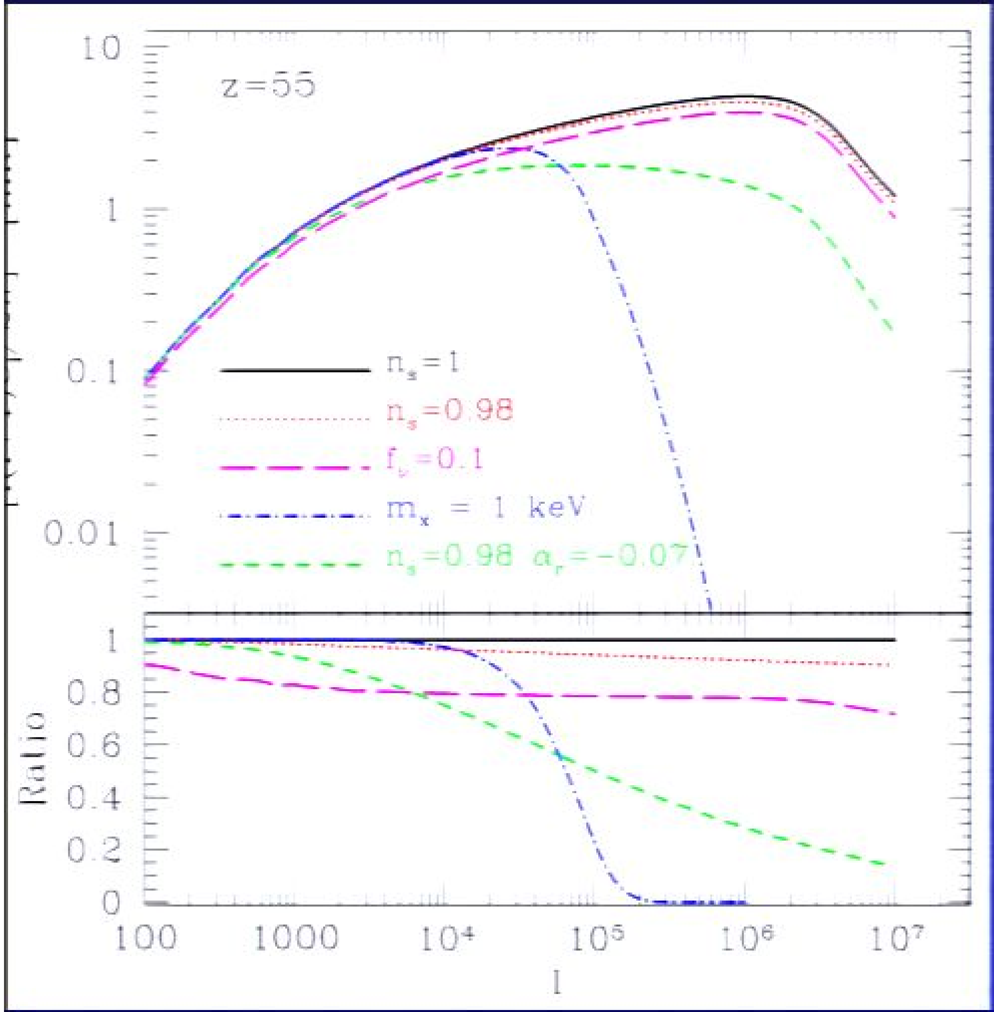


Fluctuations in 21cm brightness are sourced by fluctuations in gas density

Loeb & Zaldarriaga, Phys. Rev. Lett., 2004;
Scott & Rees, MNRAS, 1990

Observed wavelength=21cm (1+z) → 3D tomography (slicing the universe in redshift)

Largest Data Set on the Sky



Number of independent patches:

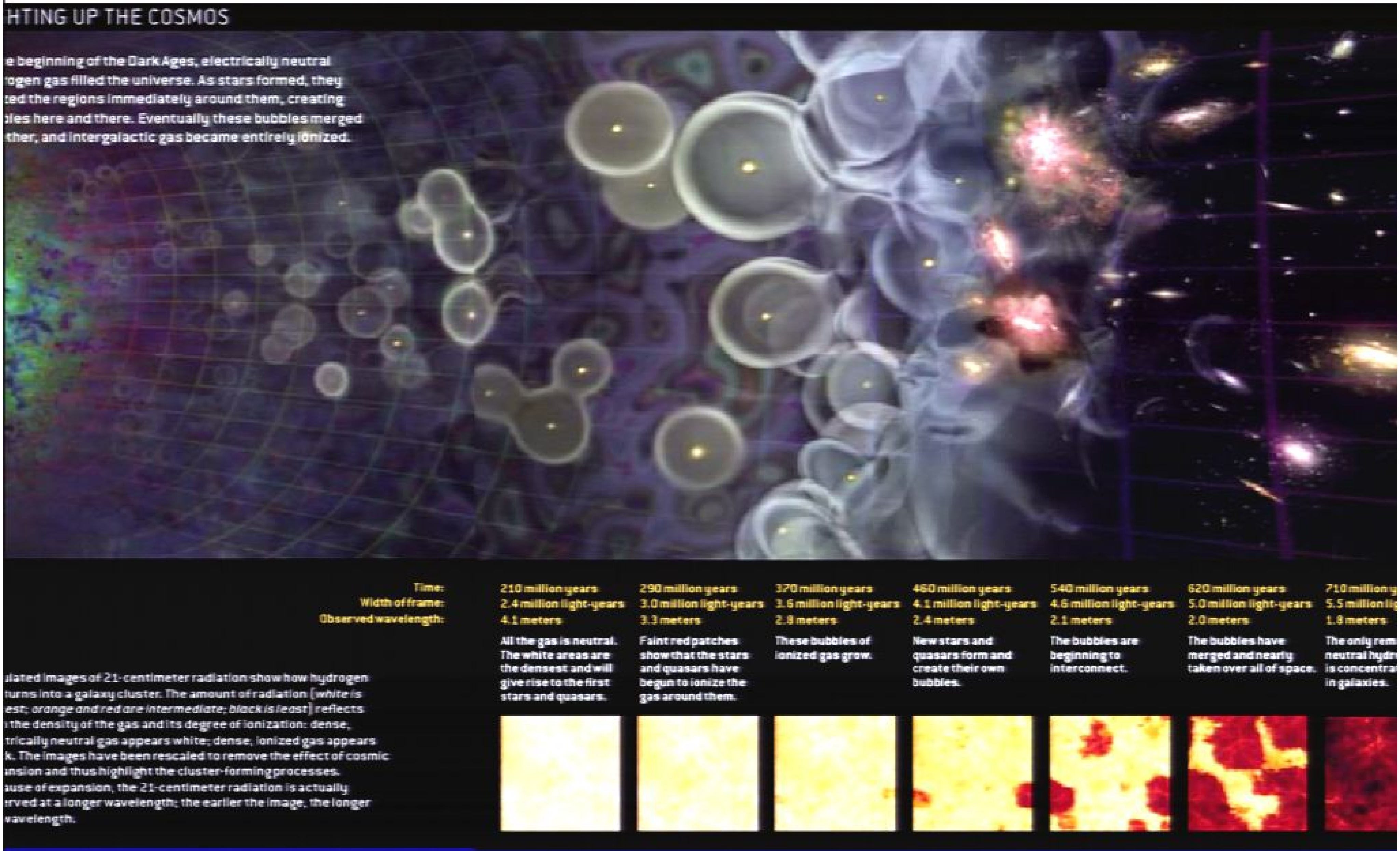
$$\sim 10^{16} \left(\frac{l_{\rm max}}{10^6}\right)^3 \left(\frac{\Delta\nu}{\nu}\right)$$

while Silk damping limits the primary CMB anisotropies to only $\sim 10^7$

Noise due to foreground sky brightness:

$$N_\nu \sim 0.4\ {\rm mK} \left(\frac{I_\nu}{5\times10^5\ {\rm Jy\ sr^{-1}}}\right)\left(\frac{l_{\rm min}}{35}\right)\left(\frac{5000}{l_{\rm max}}\right)\left(\frac{0.016}{f_{\rm cover}}\right) \times \left(\frac{1\ {\rm year}}{t_0}\right)^{1/2}\left(\frac{\Delta\nu}{\nu}\right)^{-1/2}\left(\frac{50\ {\rm MHz}}{\nu}\right)^{5/2}.$$

Loeb & Zaldarriaga, Phys. Rev. Lett., 2004; astro-ph/0312134



HTING UP THE COSMOS

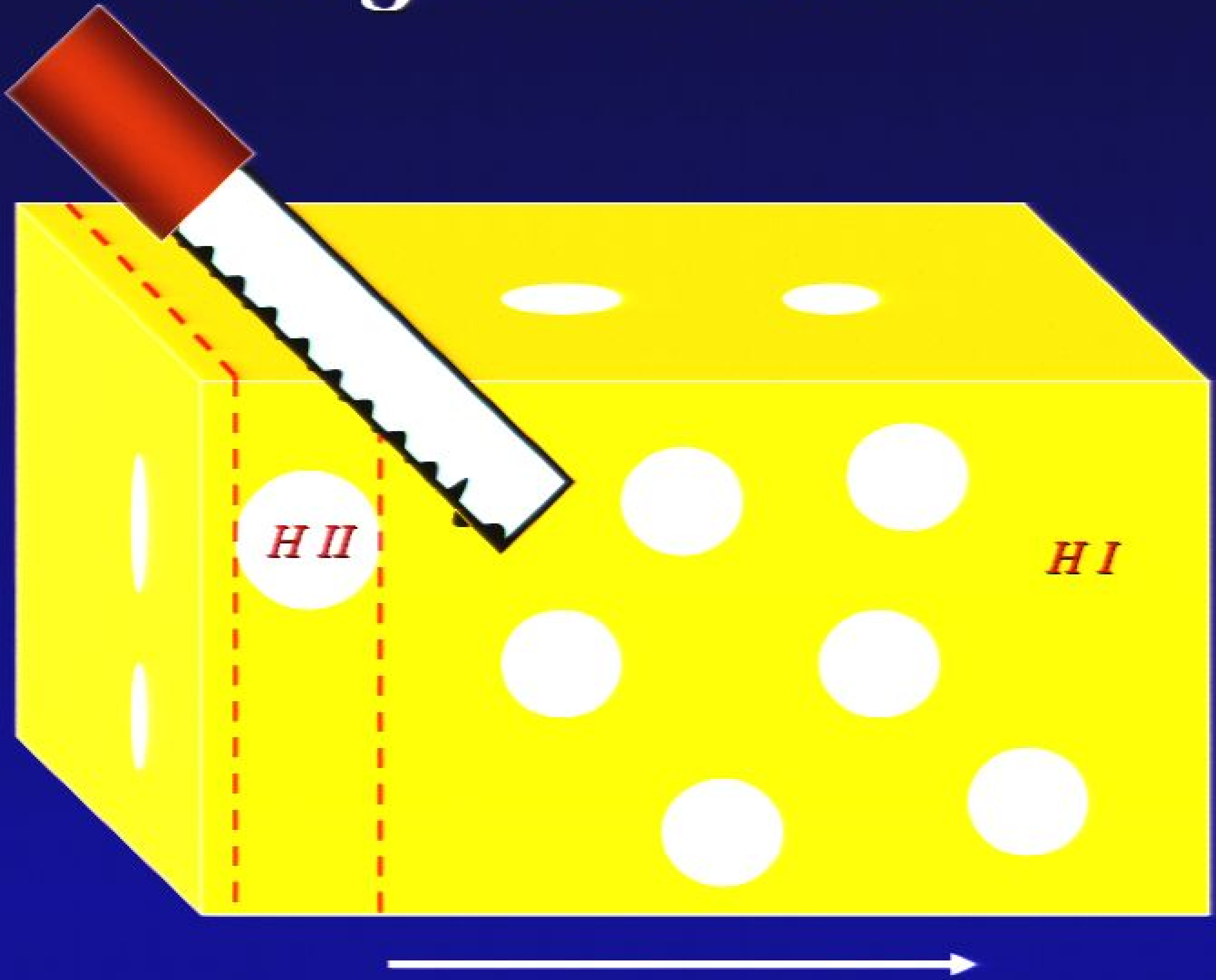
e beginning of the Dark Ages, electrically neutral rogen gas filled the universe. As stars formed, they zed the regions immediately around them, creating bles here and there. Eventually these bubbles merged ther, and intergalactic gas became entirely ionized.

Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million y
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 li
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 rem neutral hydr is concentra in galaxies.

ulated images of 21-centimeter radiation show how hydrogen turns into a galaxy cluster. The amount of radiation [*white is est; orange and red are intermediate; black is least*] reflects the density of the gas and its degree of ionization: dense, trically neutral gas appears white; dense, ionized gas appears k. The images have been rescaled to remove the effect of cosmic ansion and thus highlight the cluster-forming processes. ause of expansion, the 21-centimeter radiation is actually rved at a longer wavelength; the earlier the image, the longer wavelength.

21cm Tomography of Ionized Bubbles During Reionization is like

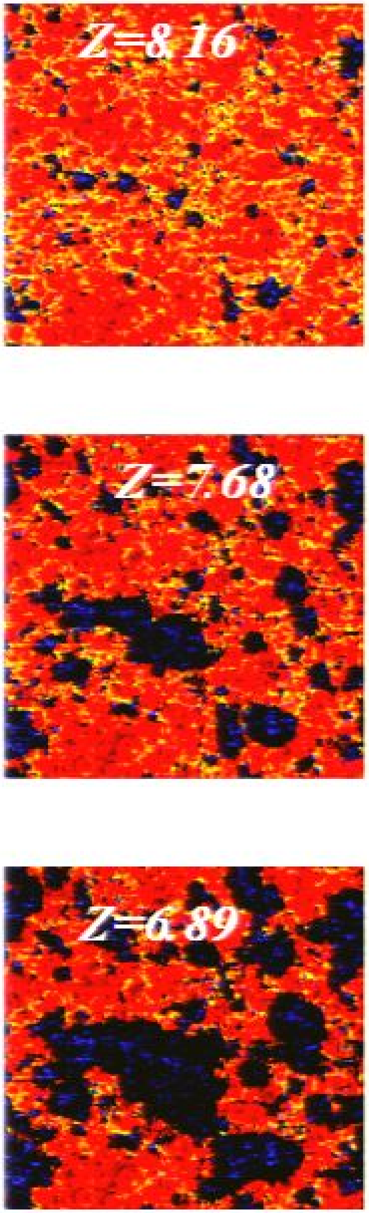
Slicing Swiss Cheese



Observed wavelength ⇔ distance

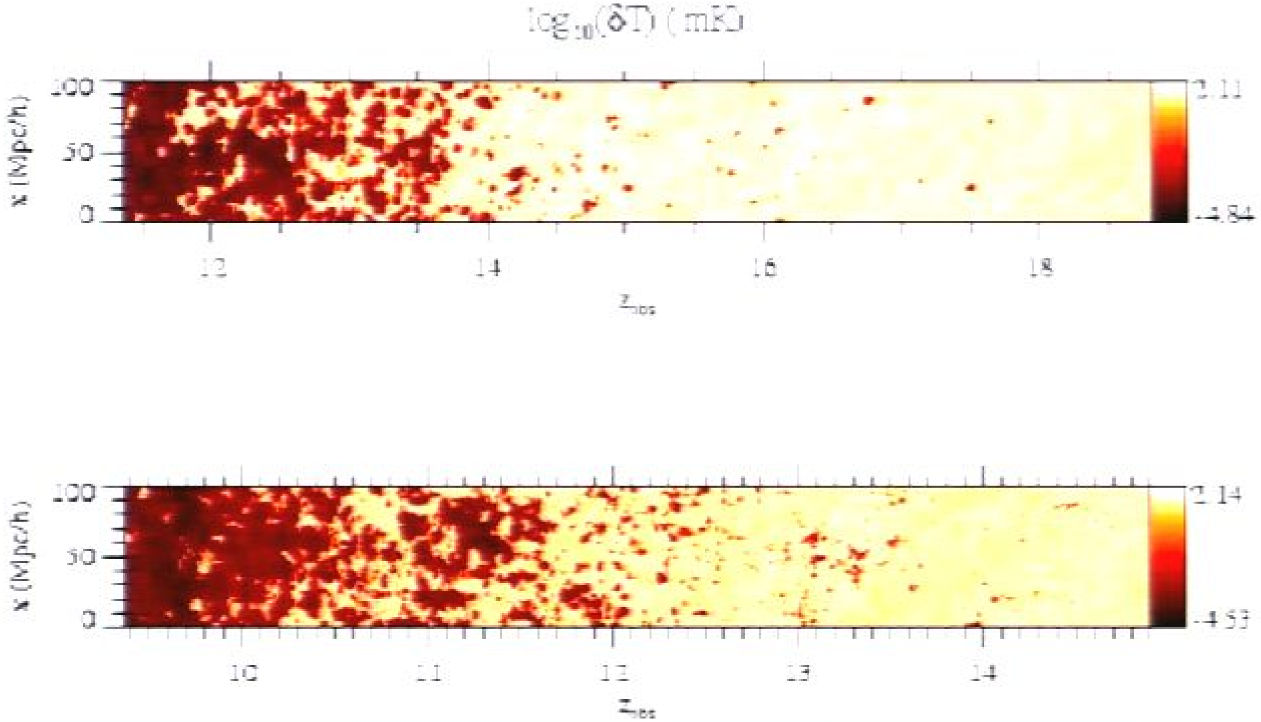
$$21\text{cm} \times (1+z)$$

HI Density



Zahn et al 2006

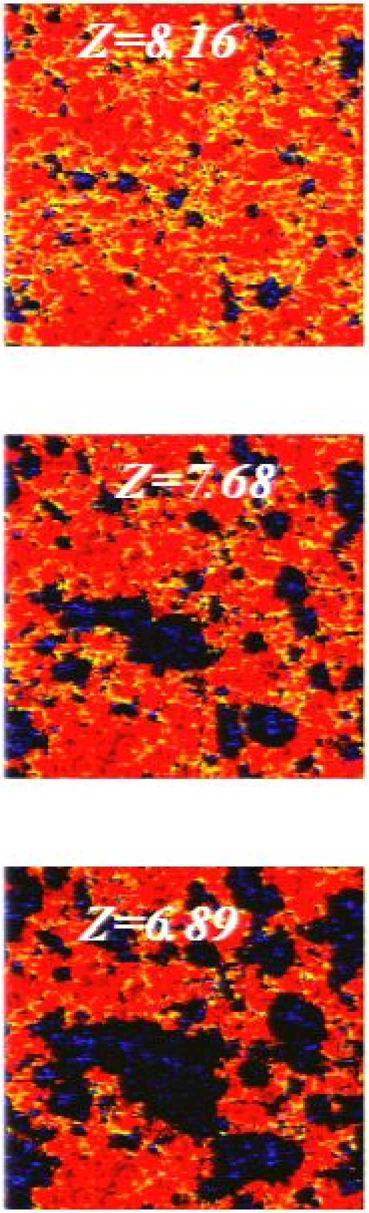
21cm Brightness



Mellema et al 2006

Shin, Trac, & Cen 2007

HI Density



Zahn et al 2006

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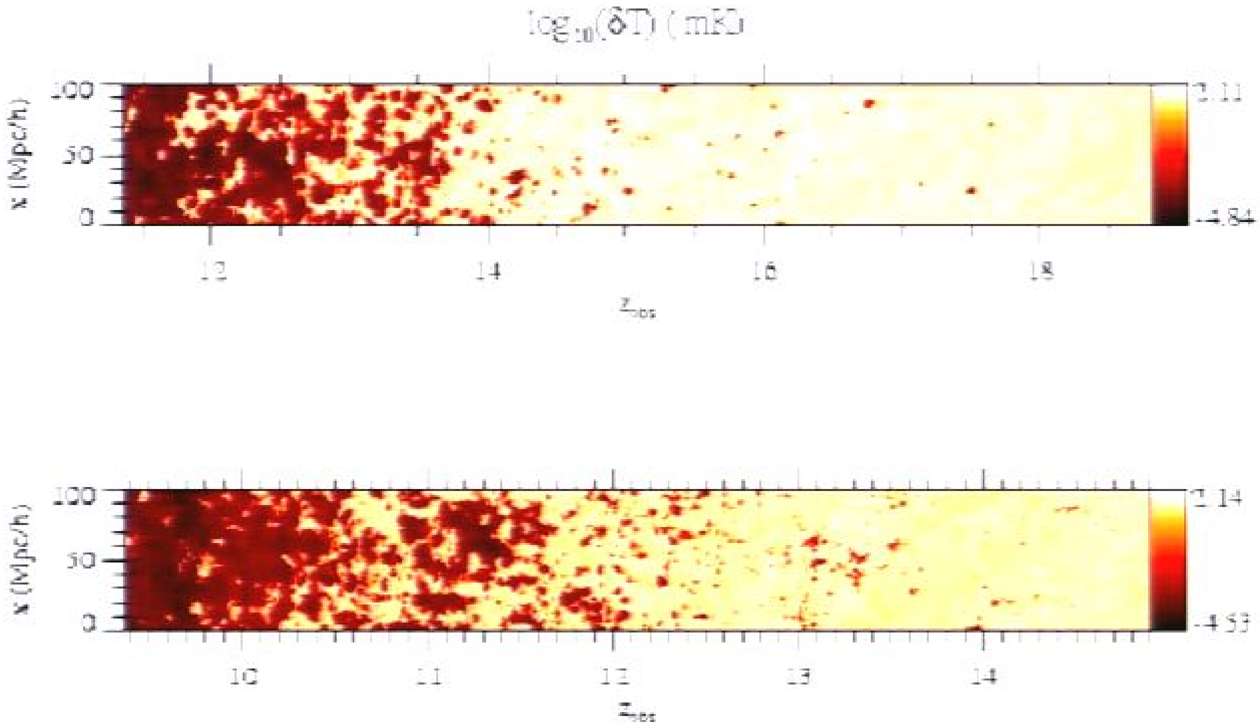

Mellema et al 2006

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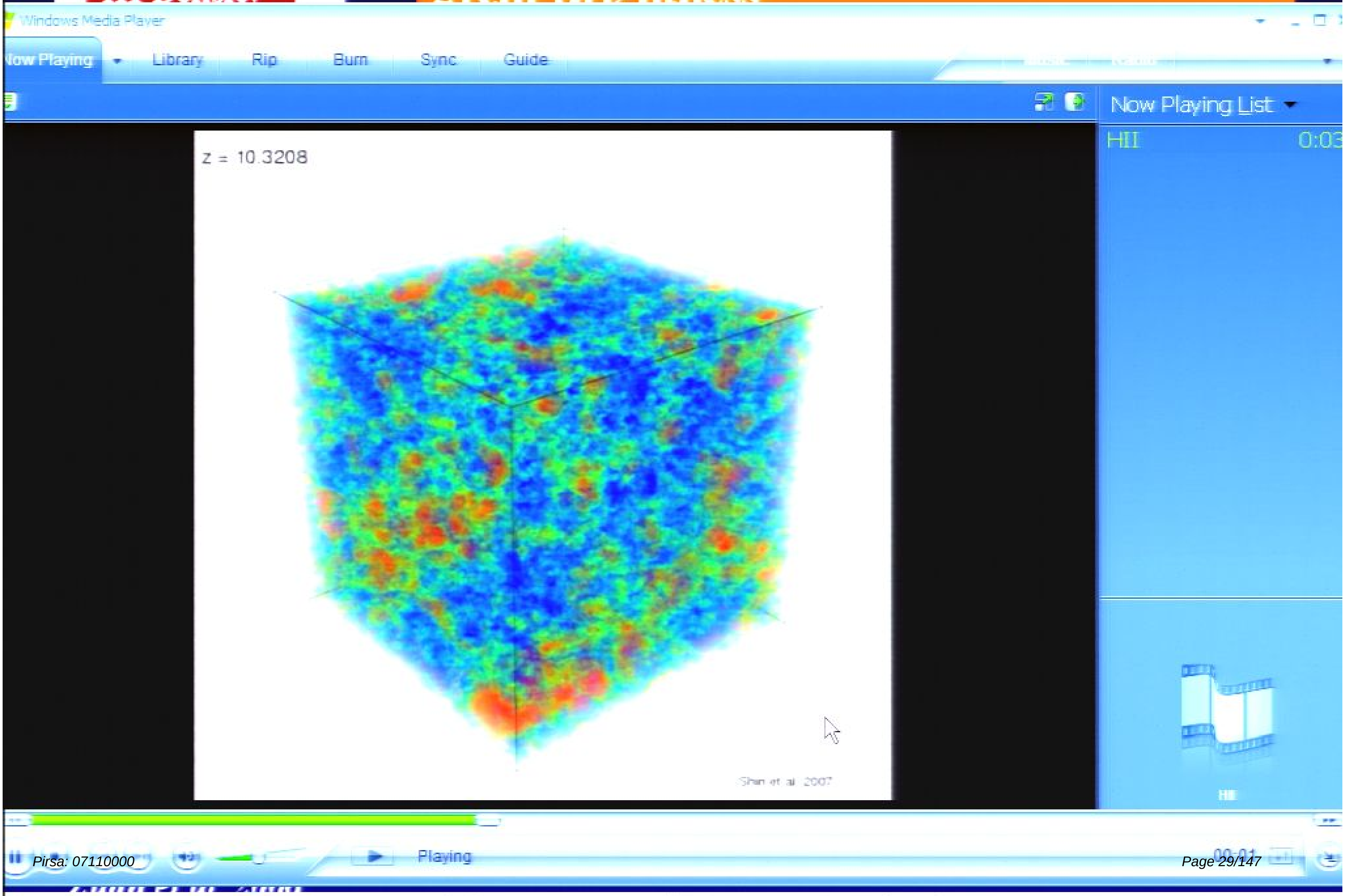
Shin, Trac, & Cen 2007

HI Density

21cm Brightness



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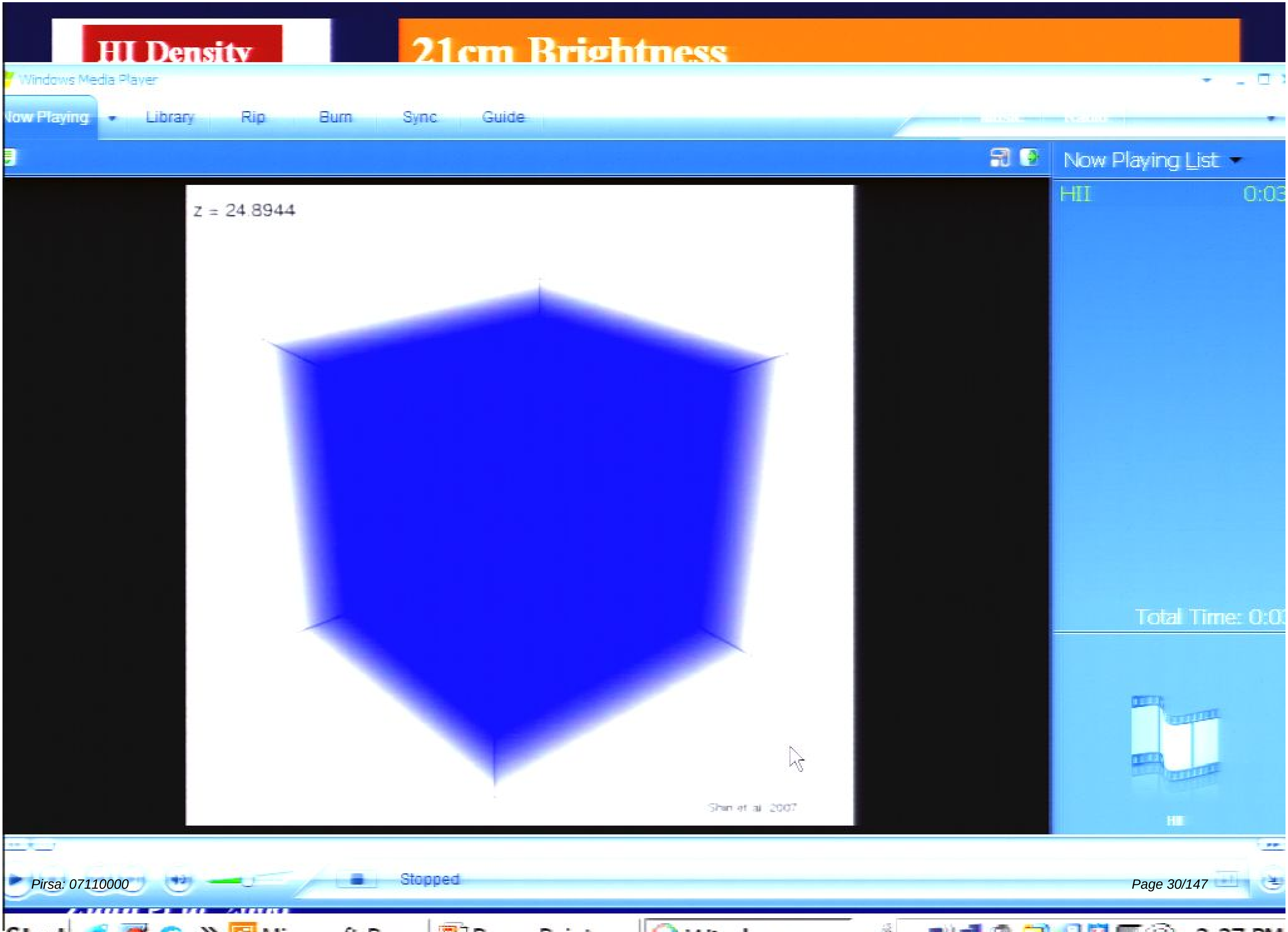
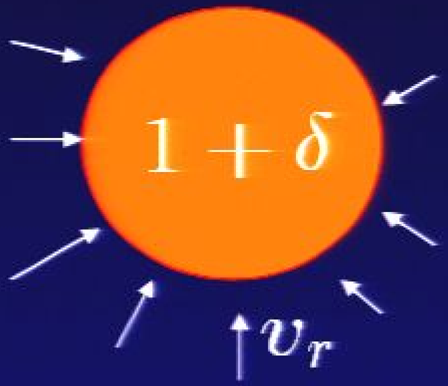


z = 24.8944

Shan et al. 2007

Line-of-Sight Anisotropy of 21cm Flux Fluctuations

$$T_b = \tau \left(\frac{T_s - T_\gamma}{1+z} \right)$$



Barkana & Loeb, astro-ph/0409572; see also Bharadwaj & Ali, astro-ph/0401206

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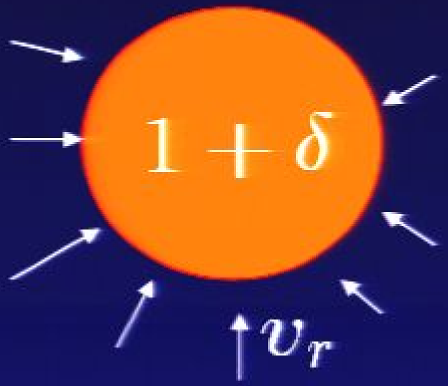

Peculiar velocity changes

Barkana & Loeb, astro-ph/0409572; see also Bharadwaj & Ali, astro-ph/0401206

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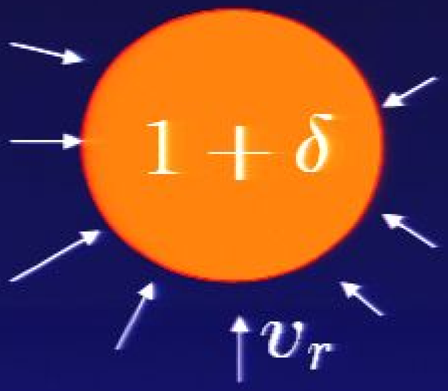

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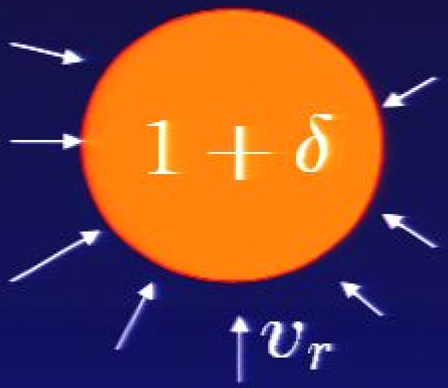

Peculiar velocity changes $\tau \propto \frac{n_{\rm HI}}{dv_r/dr}$

Barkana & Loeb, astro-ph/0409572; see also Bharadwaj & Ali, astro-ph/0401206

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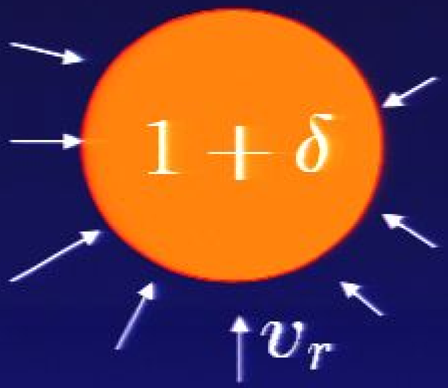


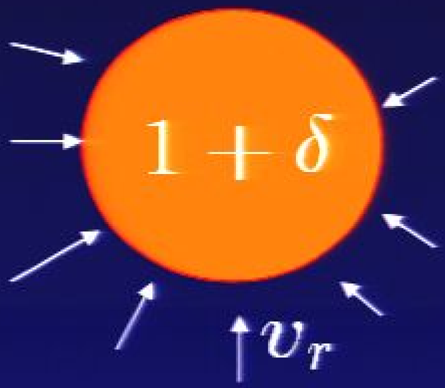
Peculiar velocity changes

$$\tau \propto \frac{n_{\rm HI}}{dv_r/dr} \quad \begin{matrix} = \bar{n}(1+\delta) \\ \sim \bar{H}(1-\frac{1}{3}\delta) \end{matrix}$$

Barkana & Loeb, astro-ph/0409572; see also Bharadwaj & Ali, astro-ph/0401206

Line-of-Sight Anisotropy of 21cm Flux Fluctuations

$$T_b = \tau \left(\frac{T_s - T_\gamma}{1+z}\right)$$



Peculiar velocity changes $\quad \tau \propto \dfrac{n_{\rm HI}}{dv_r/dr} \begin{array}{l} = \bar{n}(1+\delta) \\ \sim \bar{H}(1-\frac{1}{3}\delta) \end{array}$

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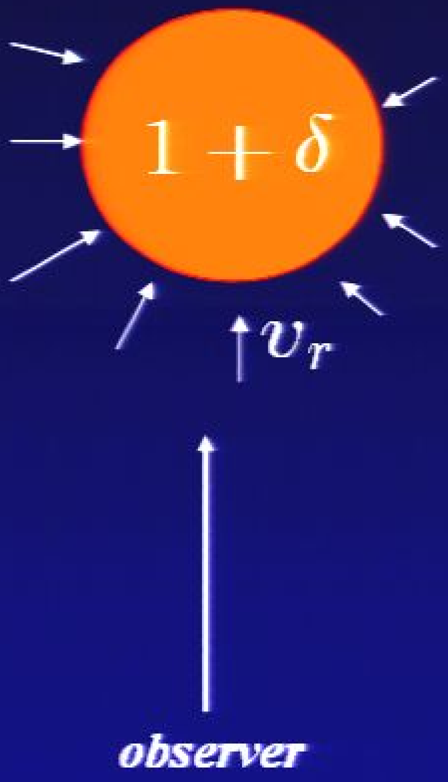

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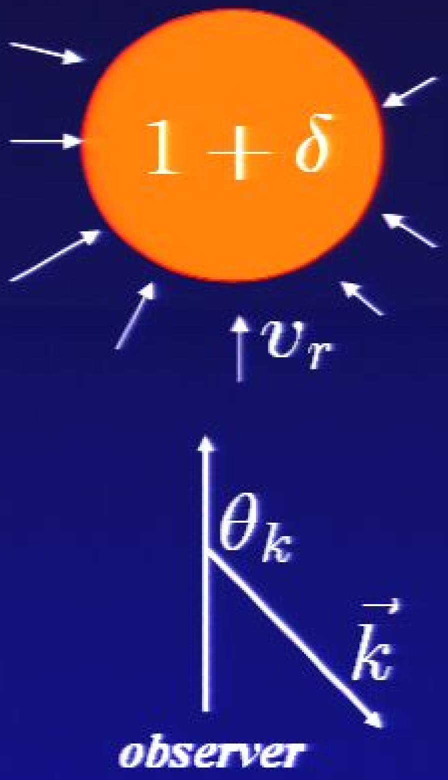

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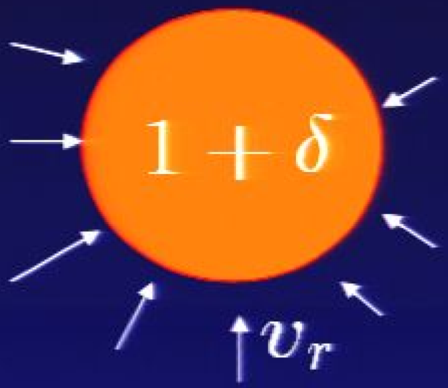

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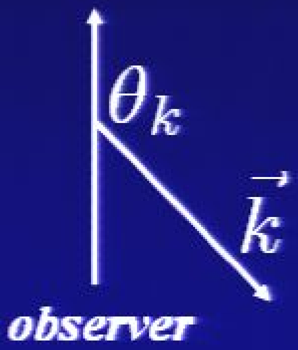

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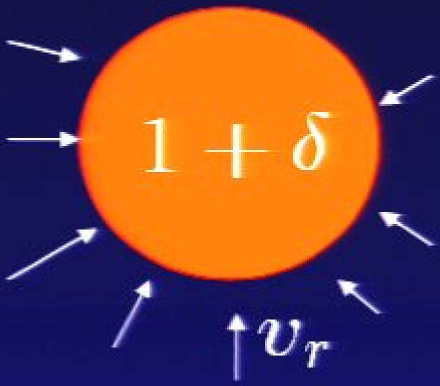

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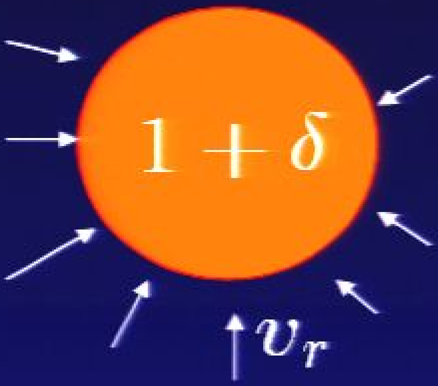

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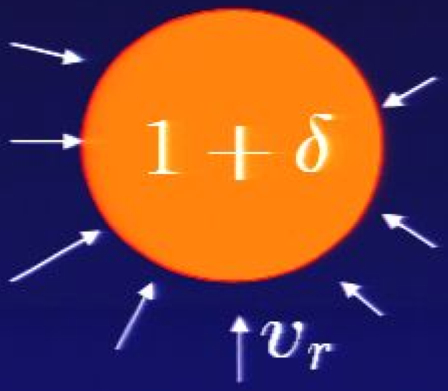

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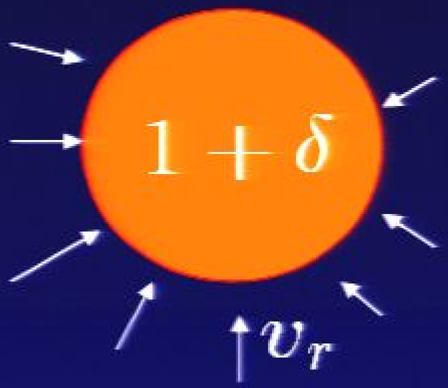

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Barkana & Loeb, astro-ph/0409572; see also Bharadwaj & Ali, astro-ph/0401206

Experiments

**MWA (Murchison Wide-Field Array)*

MIT/CfA/Australia

**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

Primary challenge: foregrounds

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- Terrestrial: radio broadcasting

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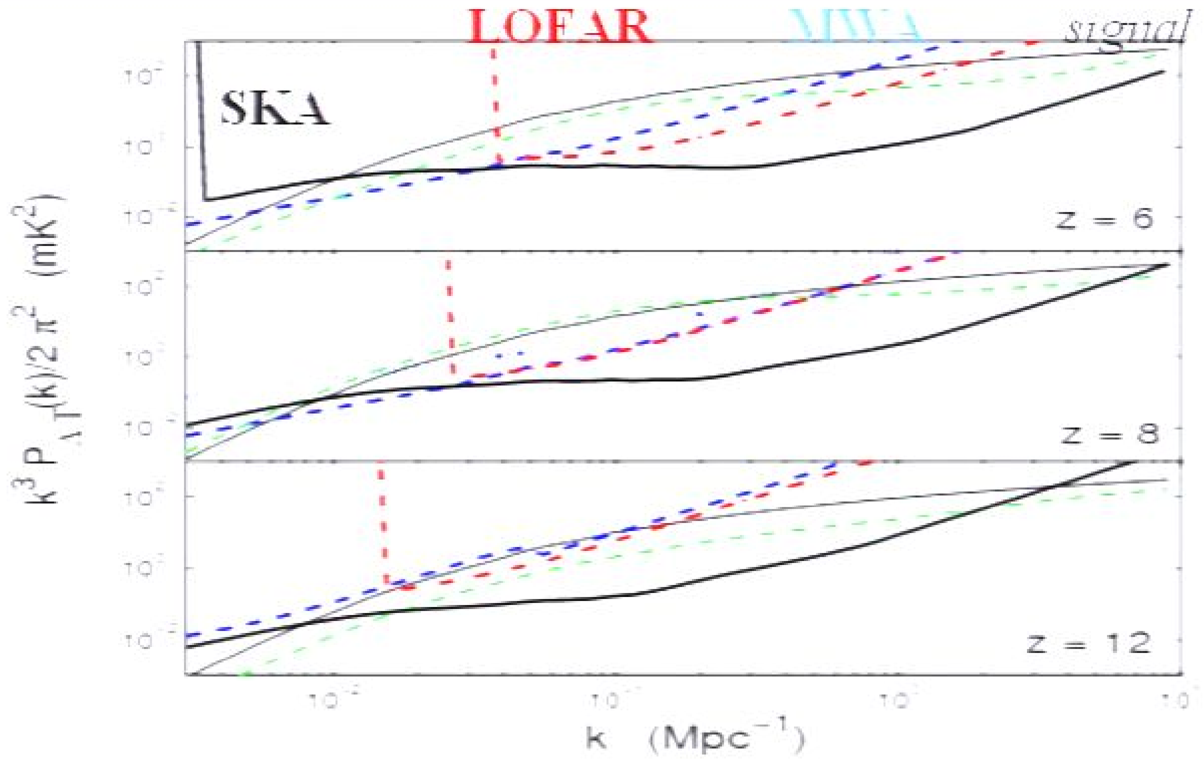
Although the sky brightness (>10K) is much larger than the 21cm signal (<10mK), the foregrounds have a smooth frequency dependence while the signal fluctuates rapidly across small shifts in frequency (=redshift). Theoretical estimates indicate that the 21cm signal is detectable with the forthcoming generation of low-frequency arrays

(Zaldarriaga et al. astro-ph/0311514; Morales & Hewitt astro-ph/0312437)

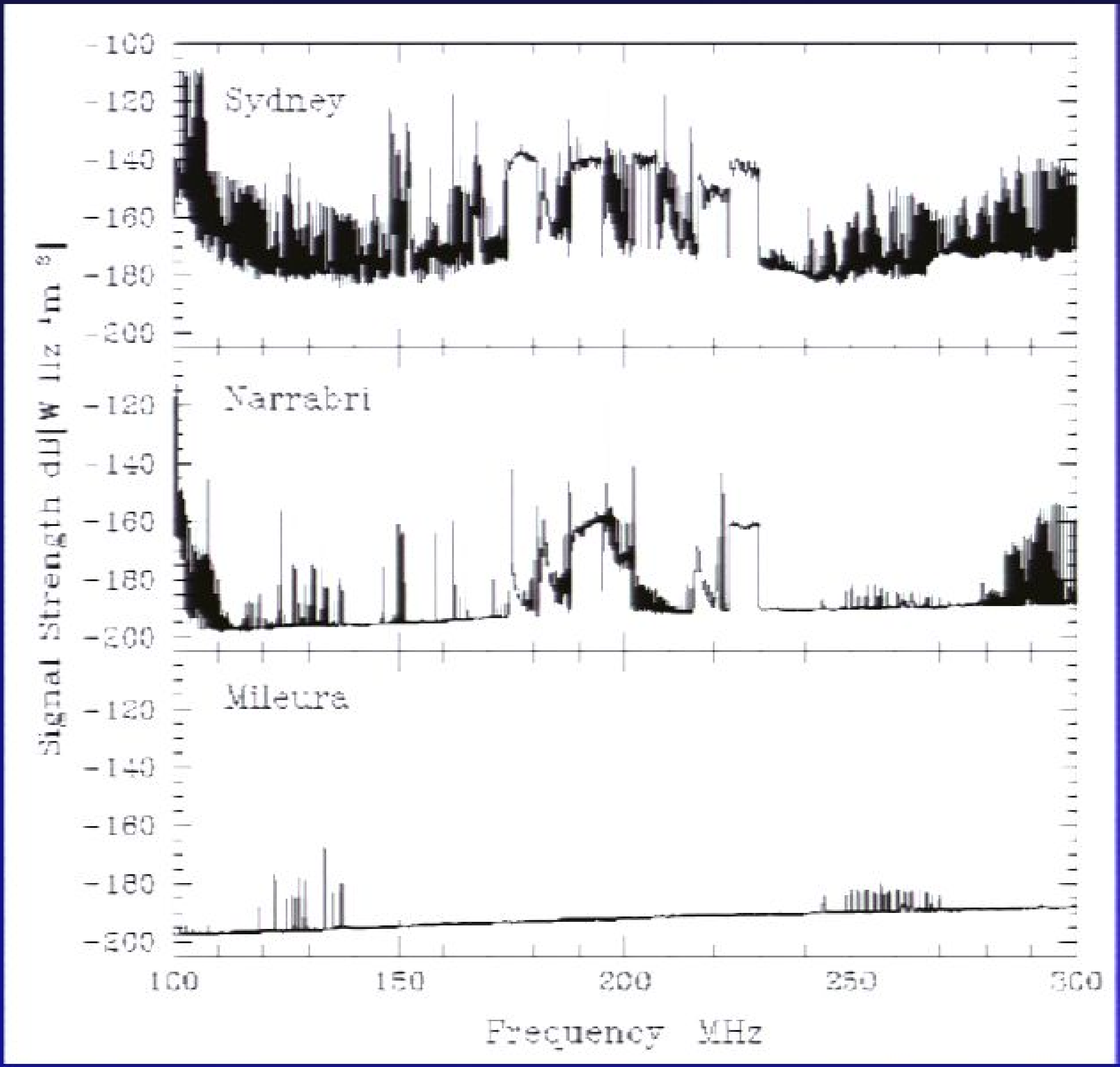
Power-Spectrum Sensitivity



Isotropic power spectrum sensitivity, in logarithmic bins with $\Delta k = k/2$, for several experimental configurations. In each panel, the thin solid and dashed curves show estimates of the signal with and without reionization. The thick solid, dashed, and dot-dashed curves show error estimates for 1000 hour observations over 6 MHz with the SKA, MWA, and LOFAR, respectively. Each assumes perfect foreground removal. The dotted curve in the middle panel assumes a flat antenna distribution for the MWA. From *McQuinn et al. 2006*

$$T_{sky} \sim 180 \left(\frac{\nu}{180\ \mathrm{MHz}}\right)^{-2.6}\ \mathrm{K} \qquad \Delta T^N|_{\mathrm{int}} \sim 2\ \mathrm{mK} \left(\frac{A_{\mathrm{tot}}}{10^5\ \mathrm{m}^2}\right)^{-1} \left(\frac{10'}{\Delta\theta}\right)^2 \left(\frac{1+z}{10}\right)^{4.6} \left(\frac{\mathrm{MHz}}{\Delta\nu}\,\frac{100\ \mathrm{hr}}{t_{\mathrm{int}}}\right)^{1/2}.$$

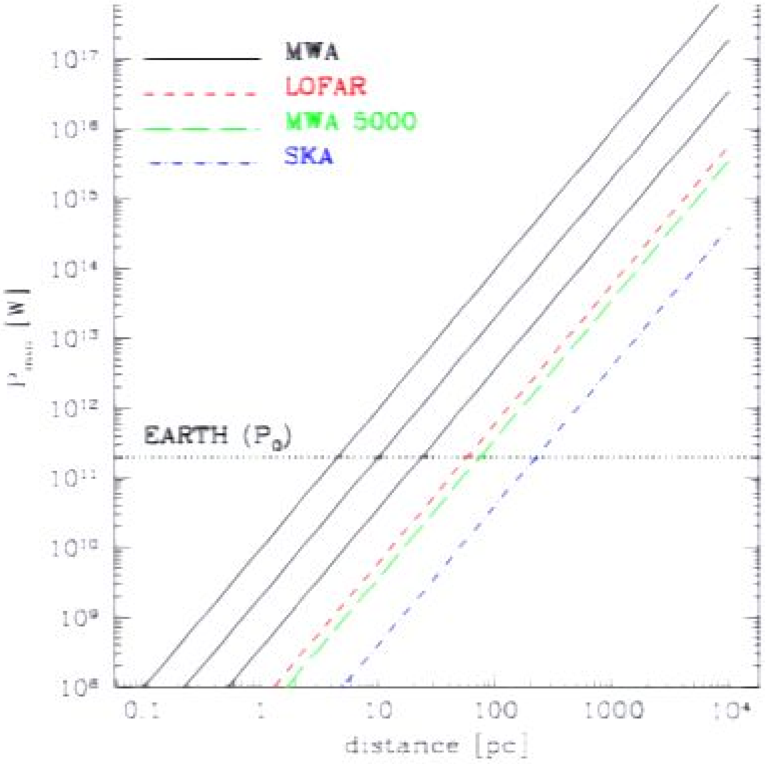
Terrestrial Radio Frequency Interference



$200\text{dB} = 10^6\text{Jy}$; ***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

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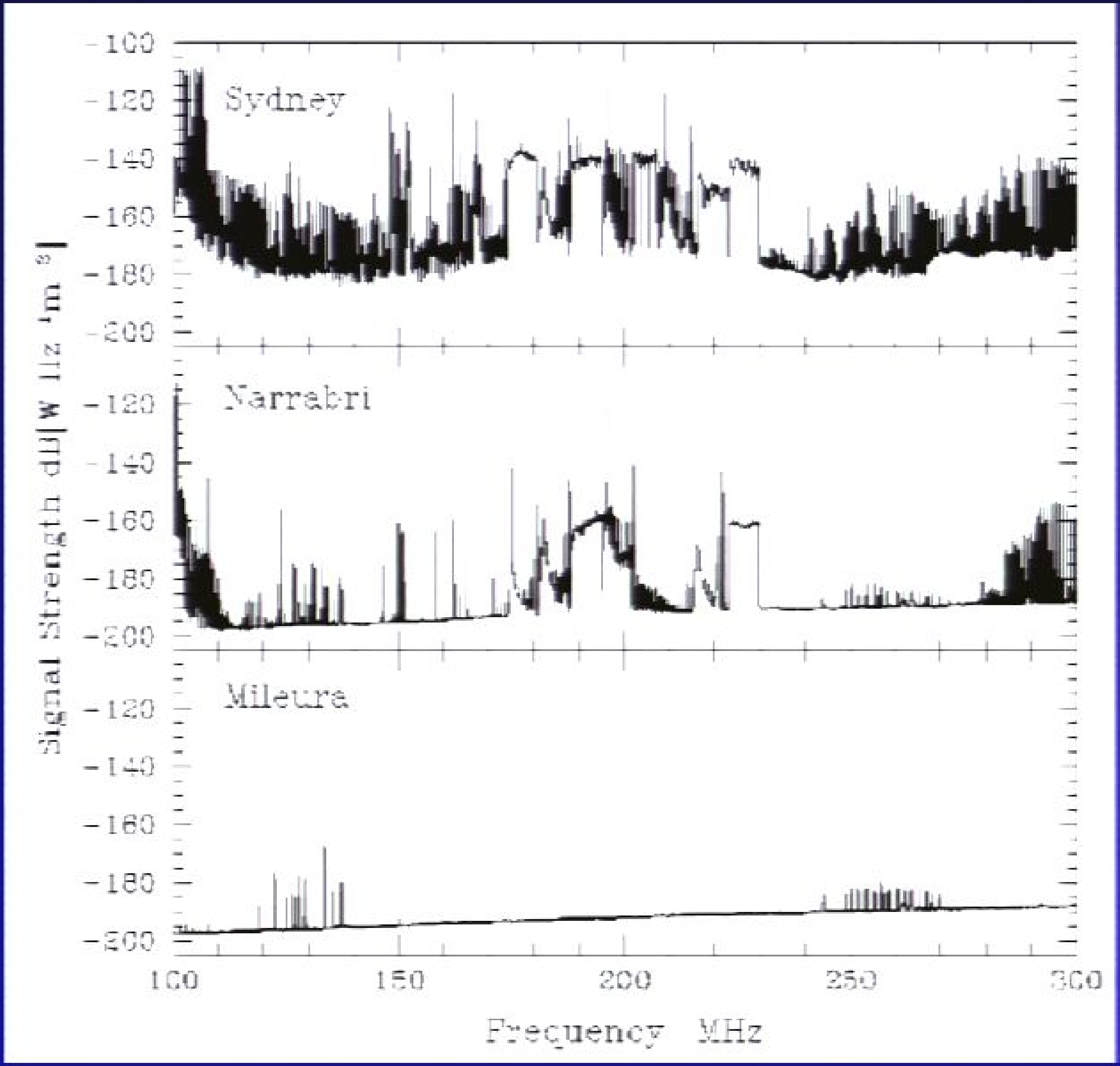

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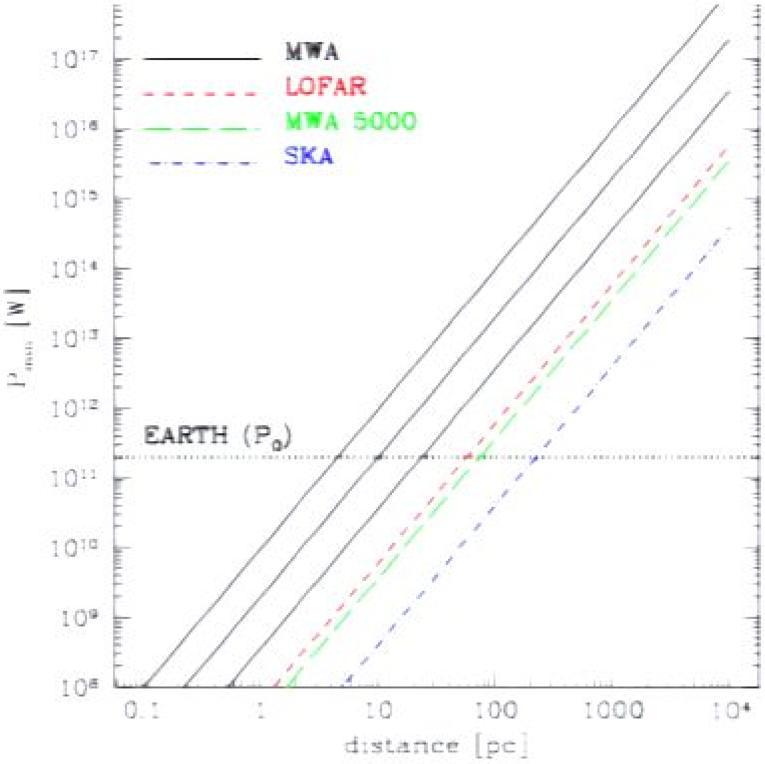

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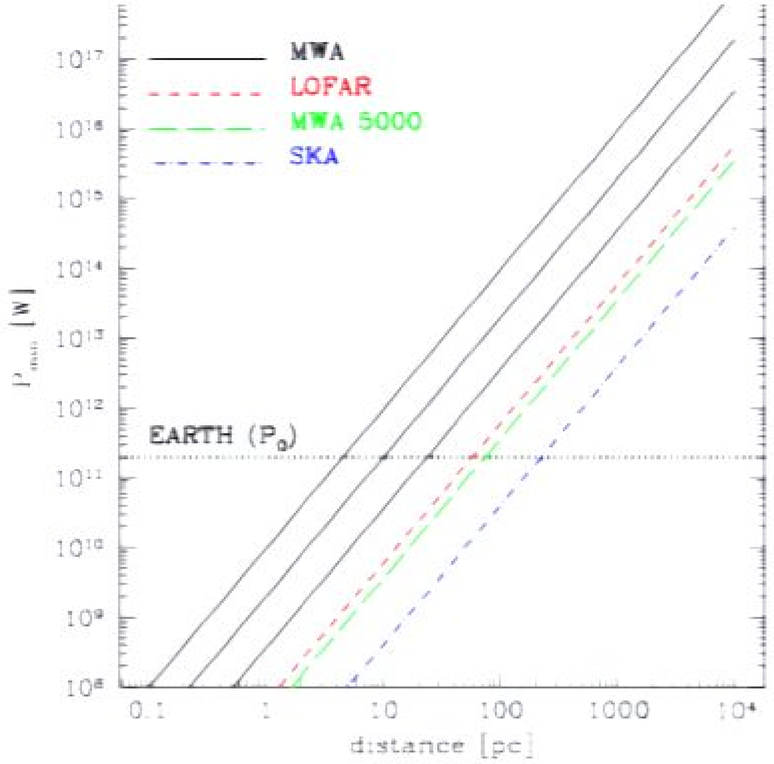

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…and we have been broadcasting for 50 years!

21cm Cosmology After Reionization?

Wyithe & Loeb 2007

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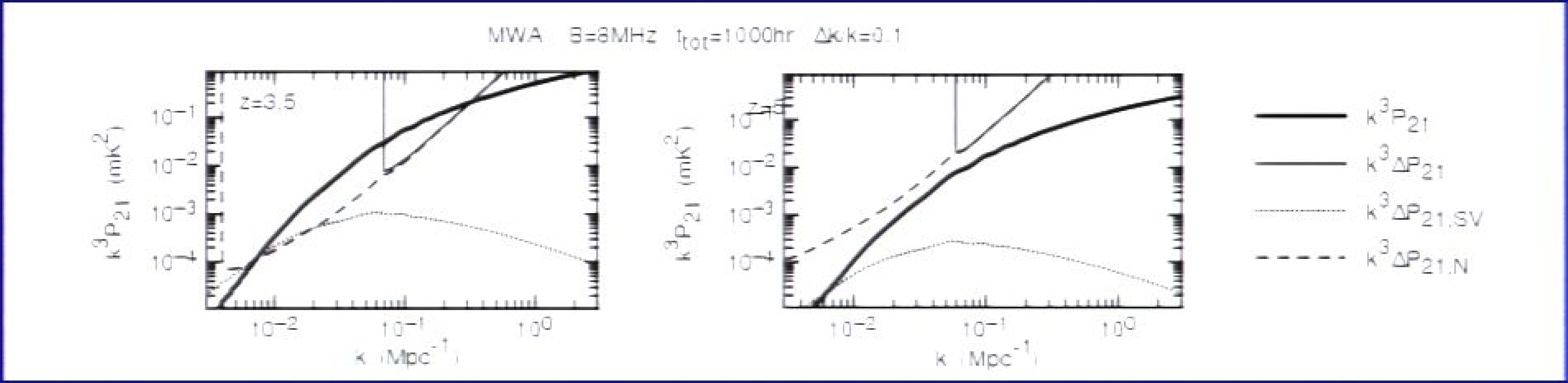

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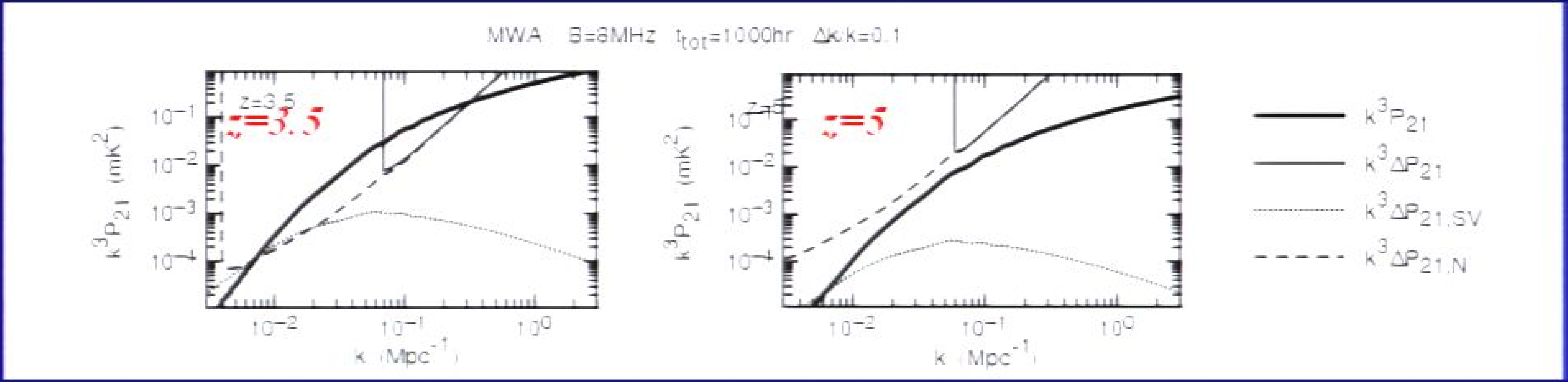


Acoustic peak: constrain dark energy at 2<z<15

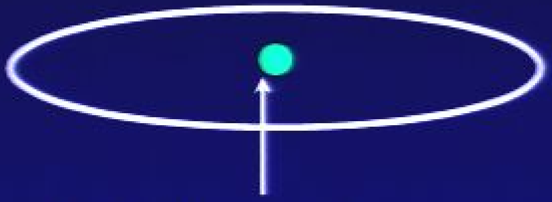
Wyithe & Loeb 2007

Acoustic Oscillations

Acoustic Oscillations

Inflation: t=0

Acoustic Oscillations



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Gas is freed to fall into dark matter potential fluctuations at z~1000

Acoustic Oscillations

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Correlation across the radiation sound horizon, left over from coupling of gas to CMB at z>1000.

Acoustic Oscillations

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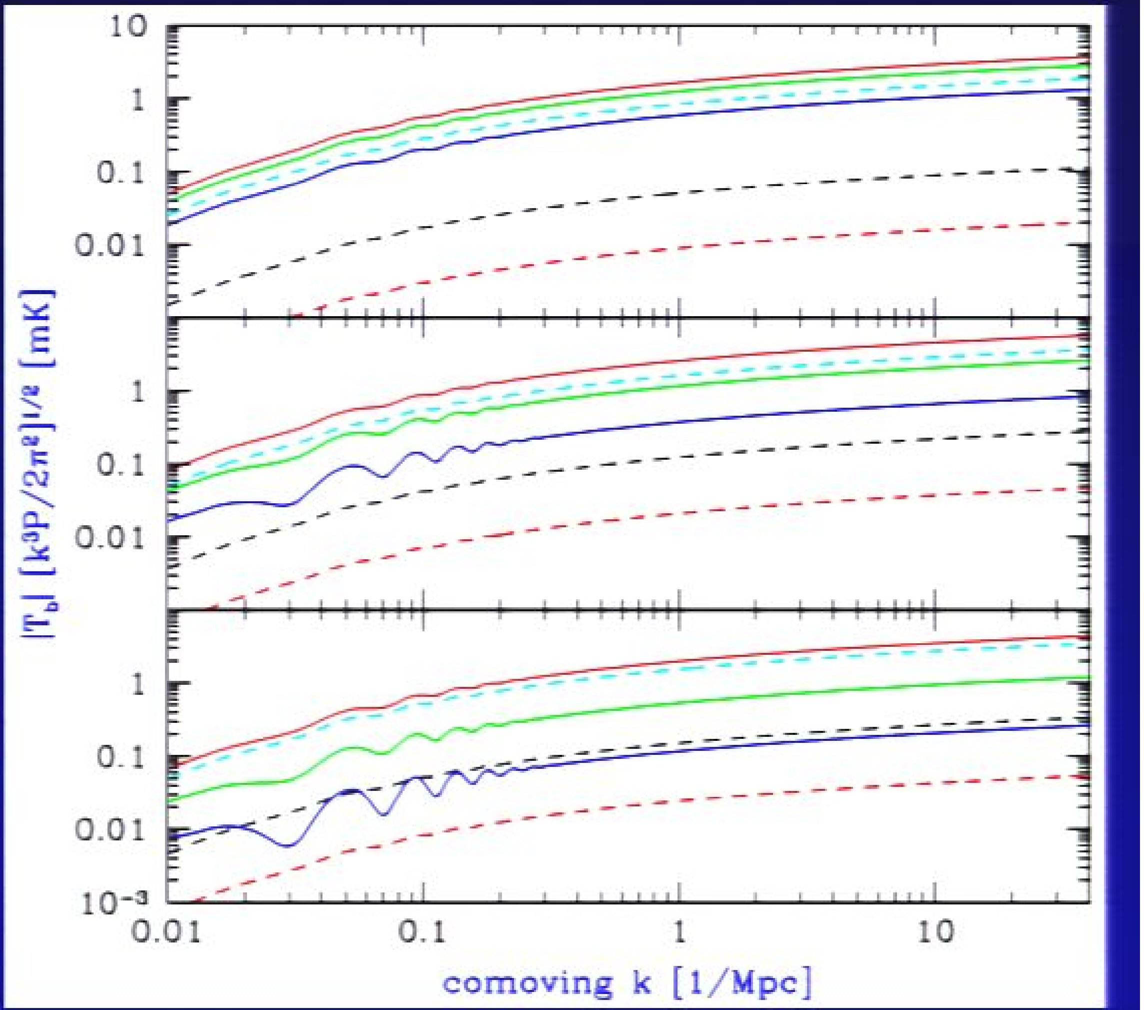
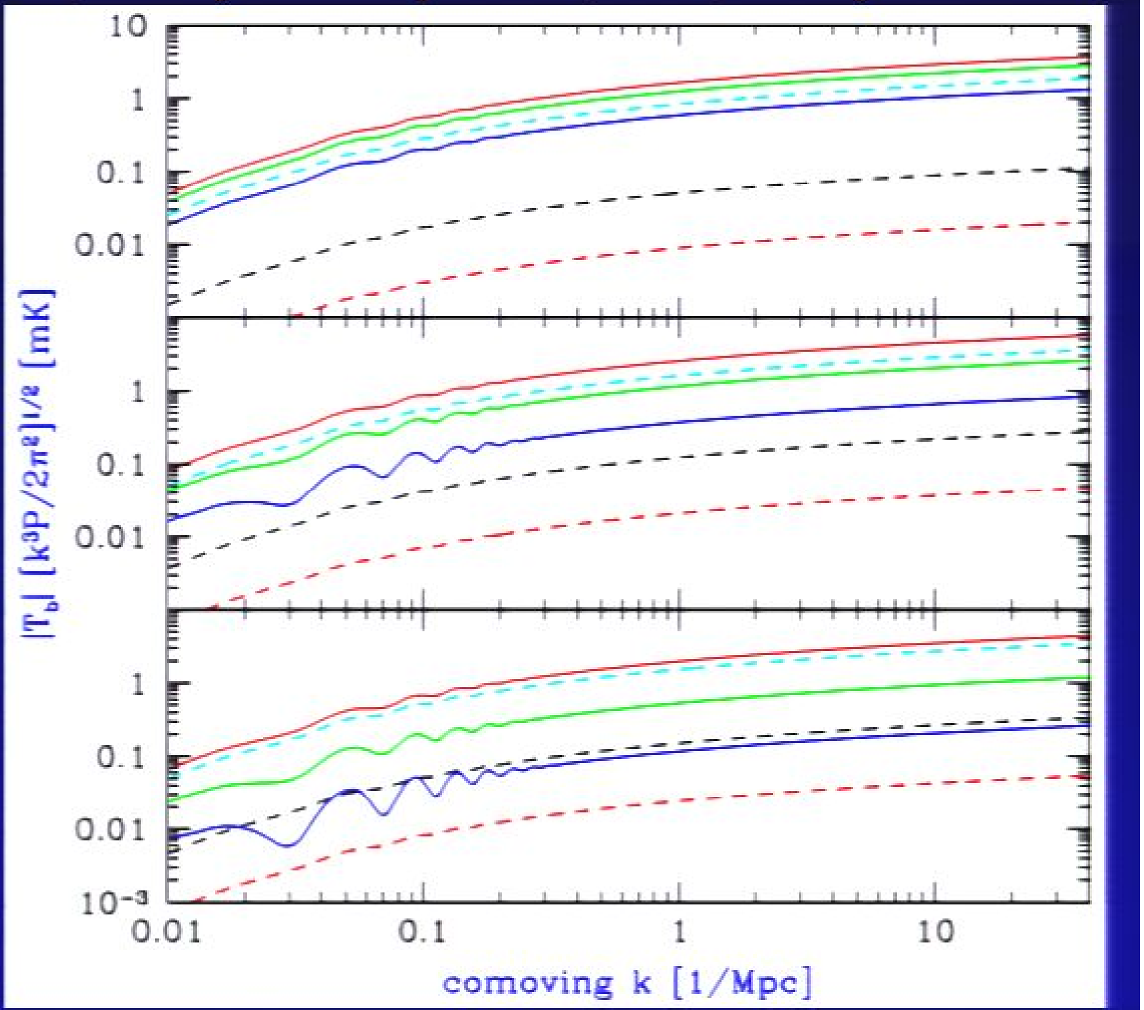


- *Correlation across the radiation sound horizon, left over from coupling of gas to CMB at z>1000.*
- *Standard ruler- sensitive probe to contribution from dark energy at redshifts 0-200*

Acoustic Oscillations

$z = 150, 100, 30(solid); 35, 20, 15(dashed$



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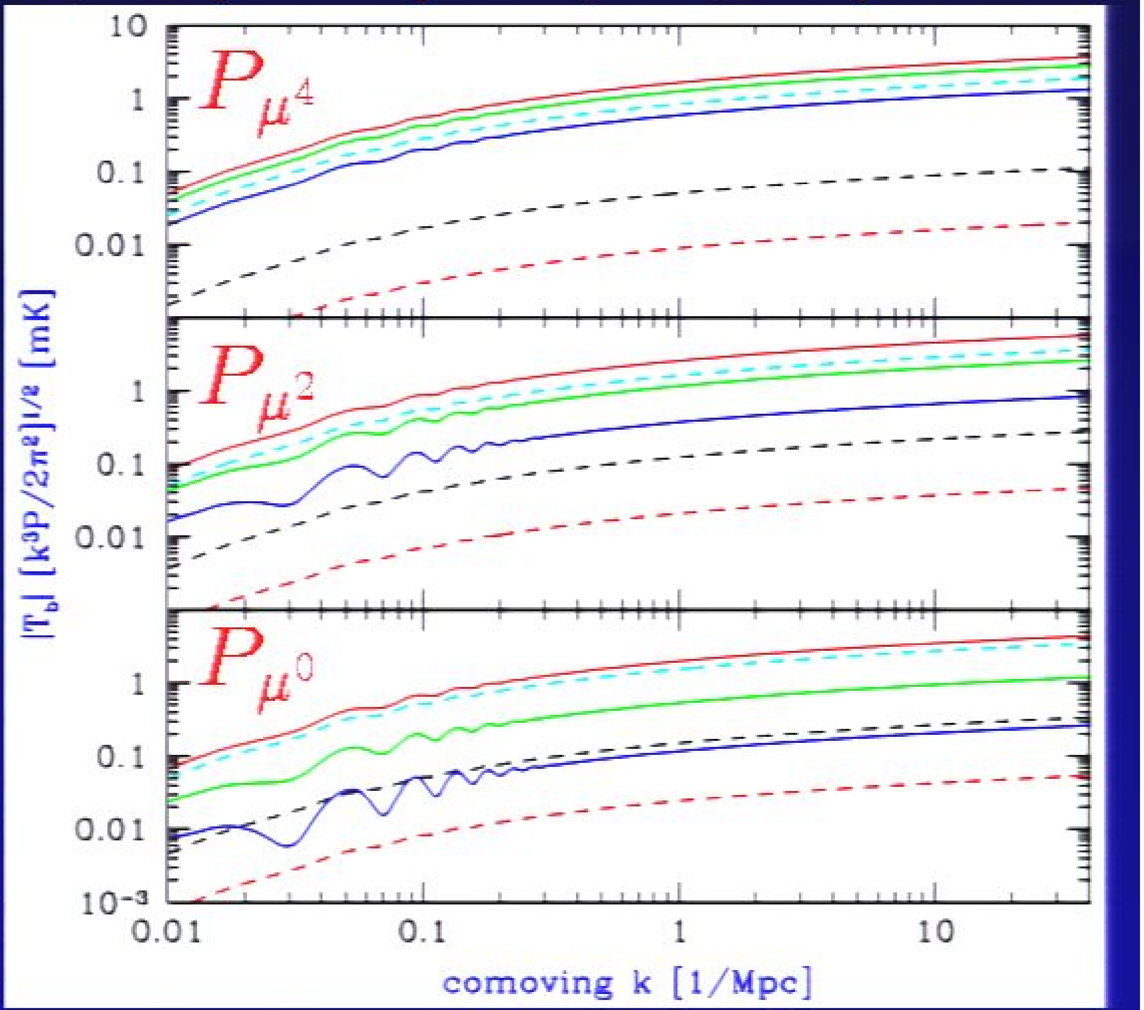

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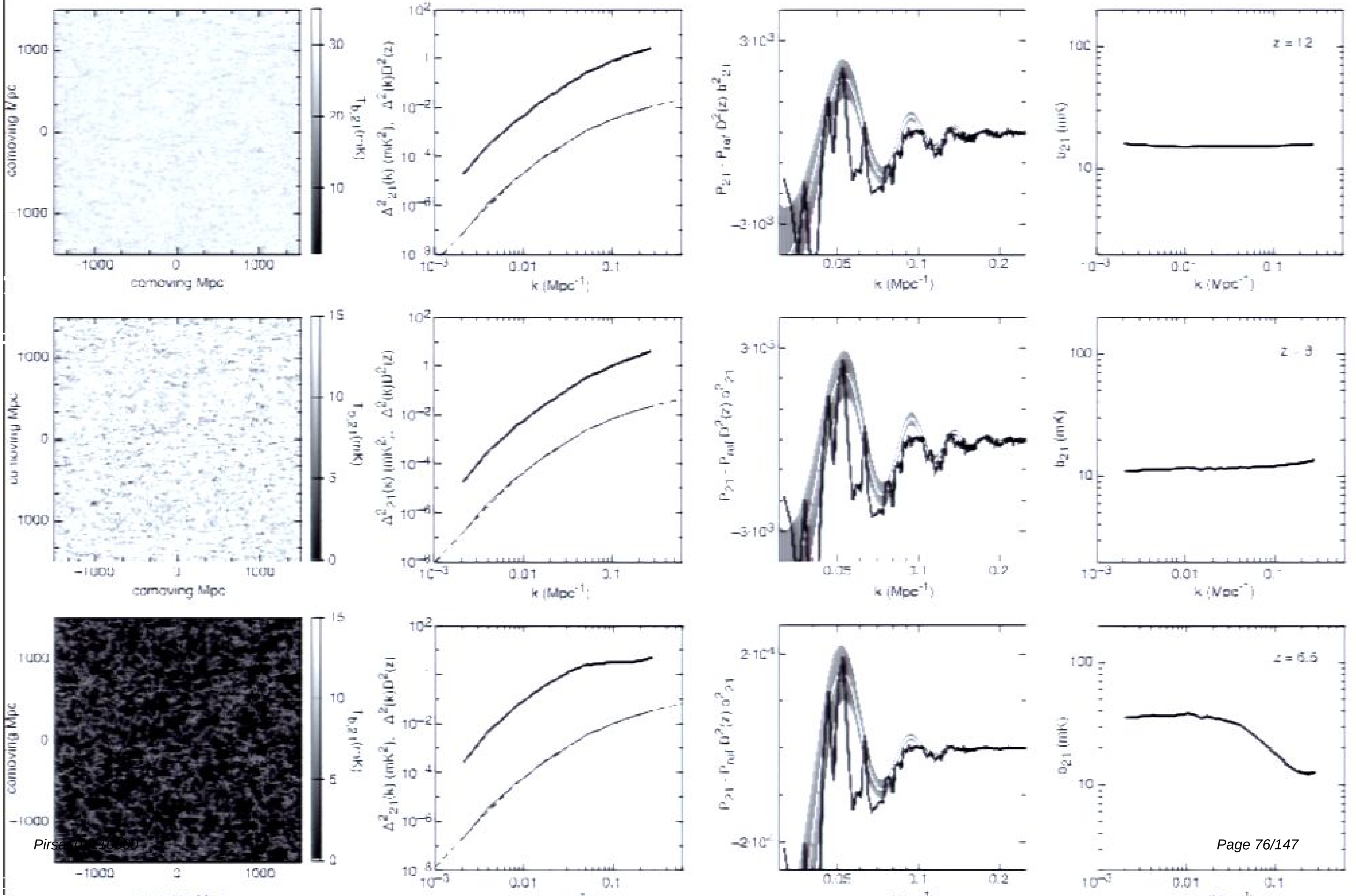

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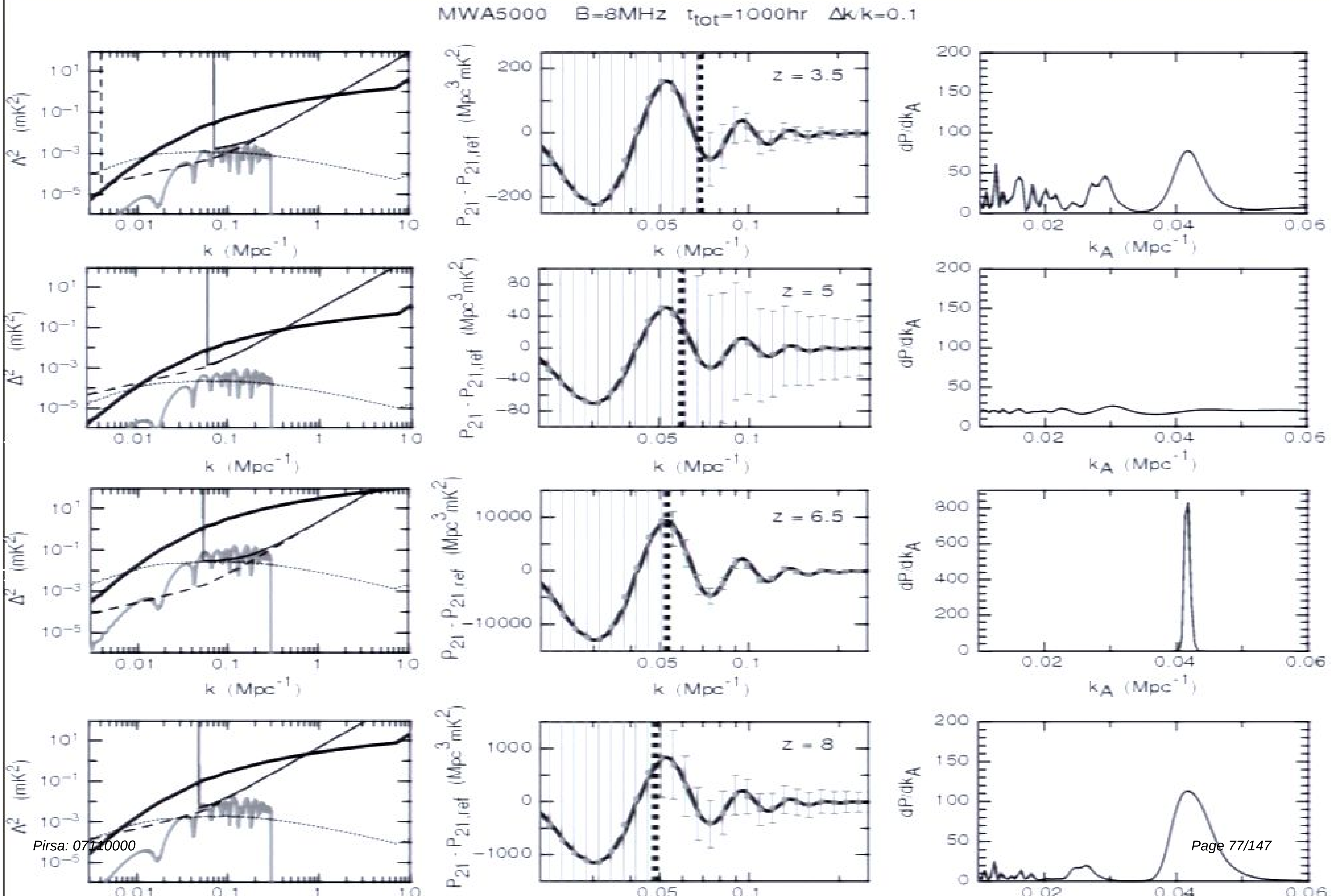
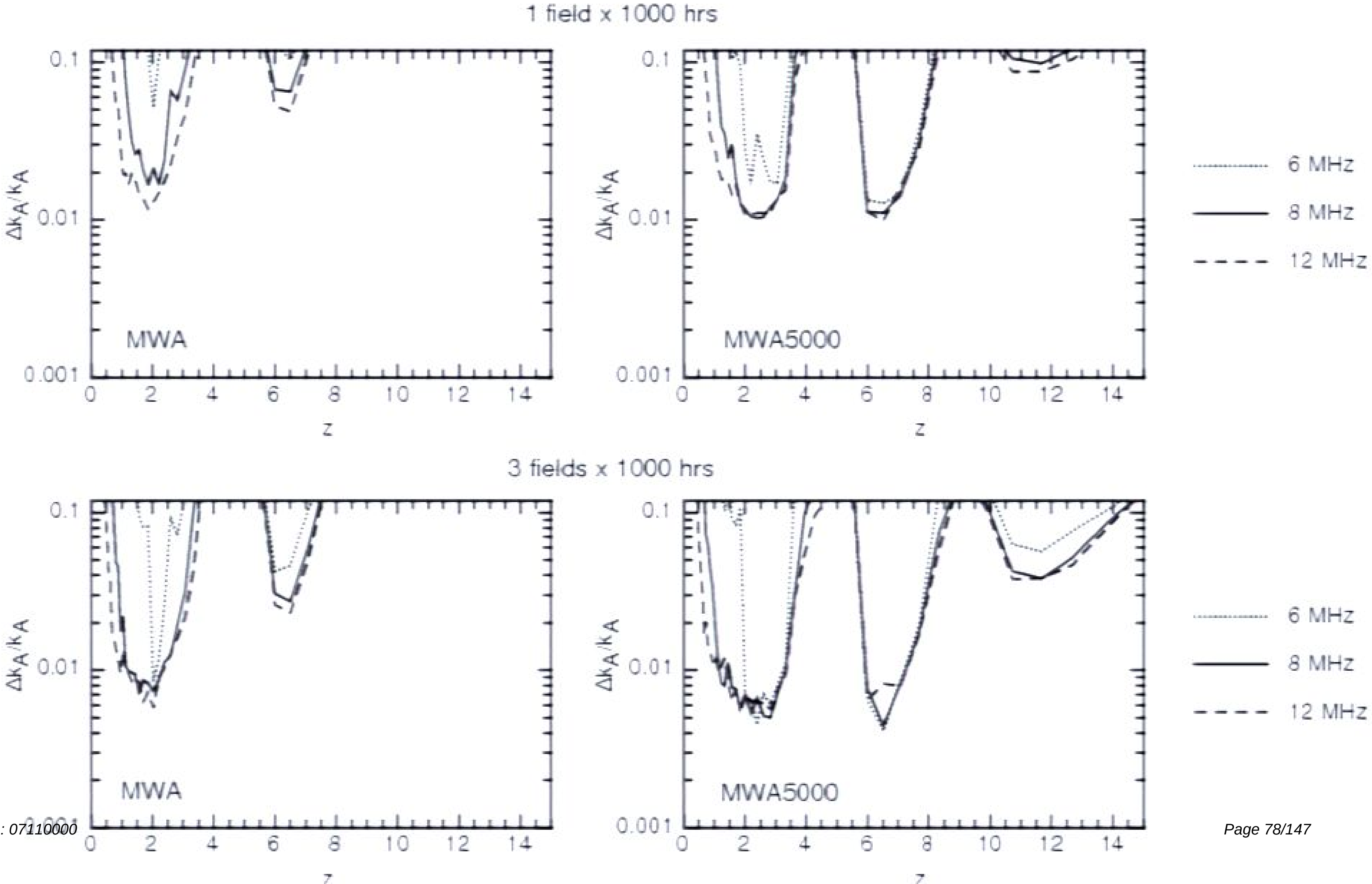
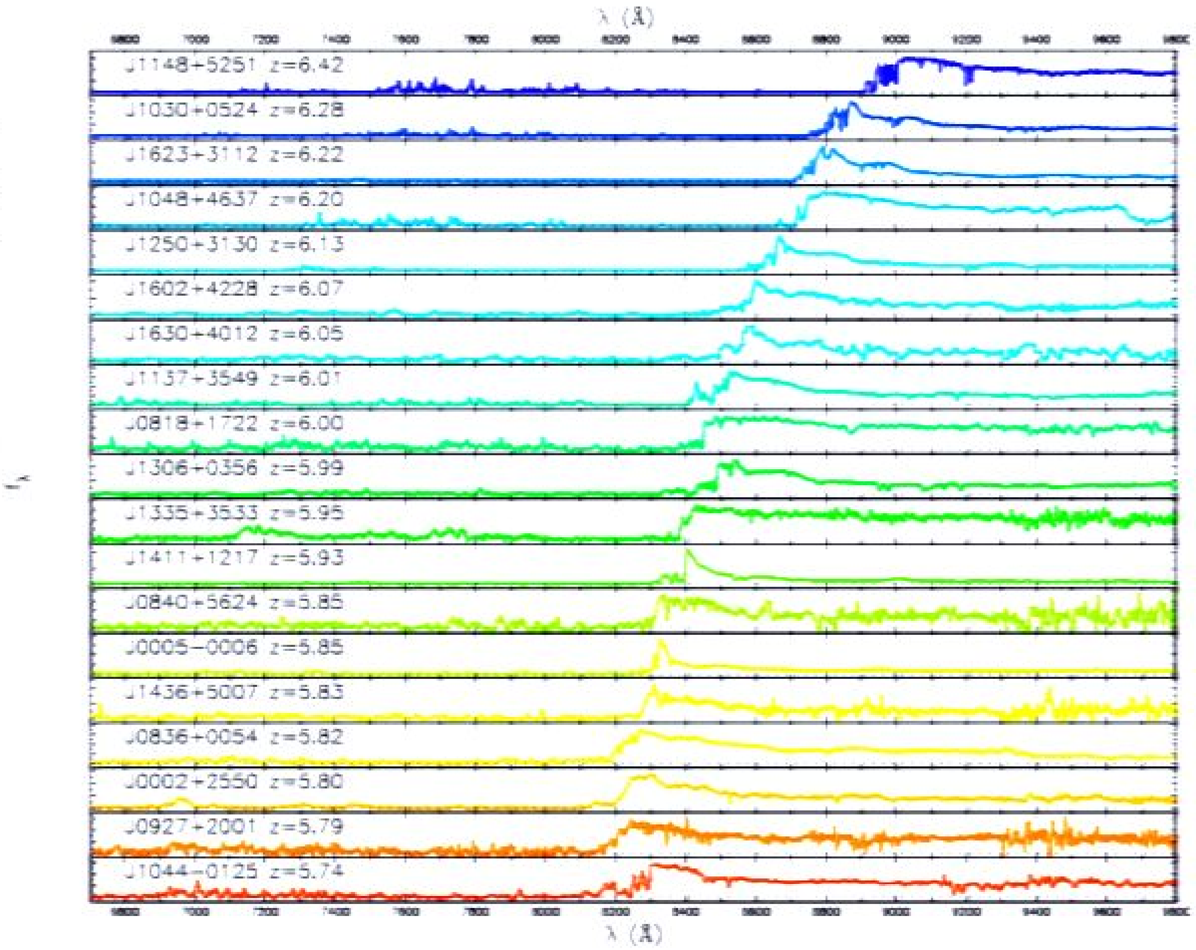


Acoustic Oscillations

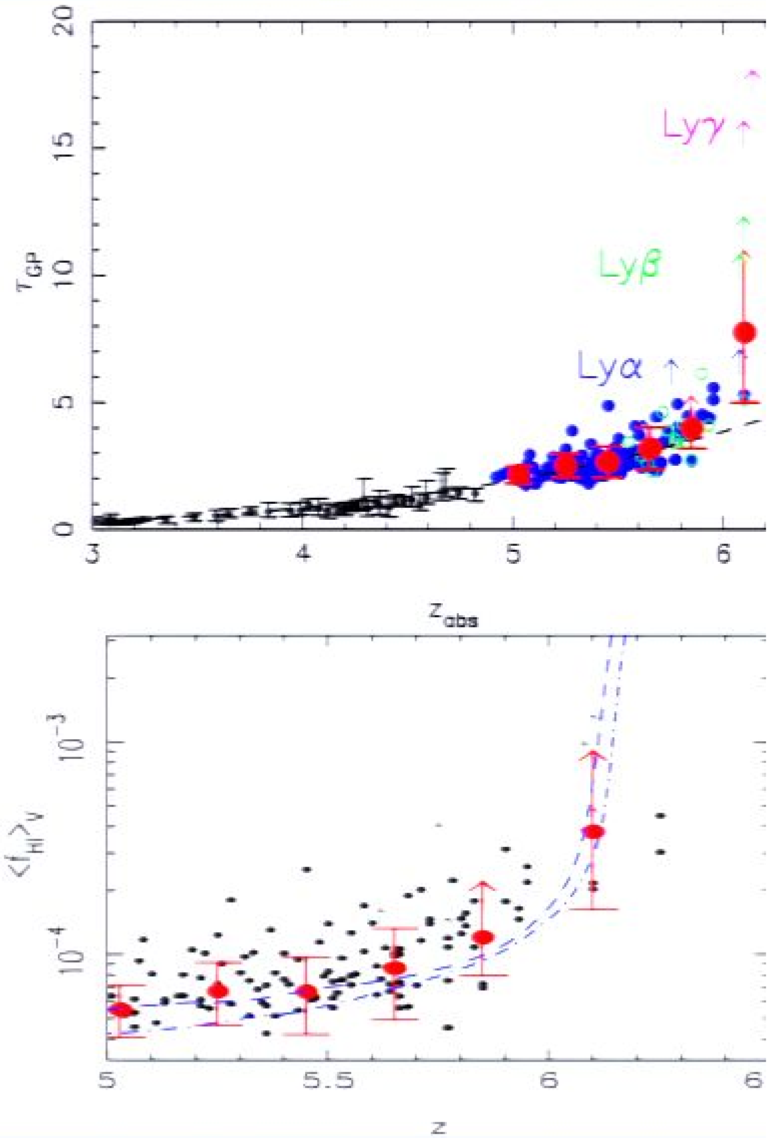
yithe. Loeb & Geil



So far, the hydrogen was only probed by quasars



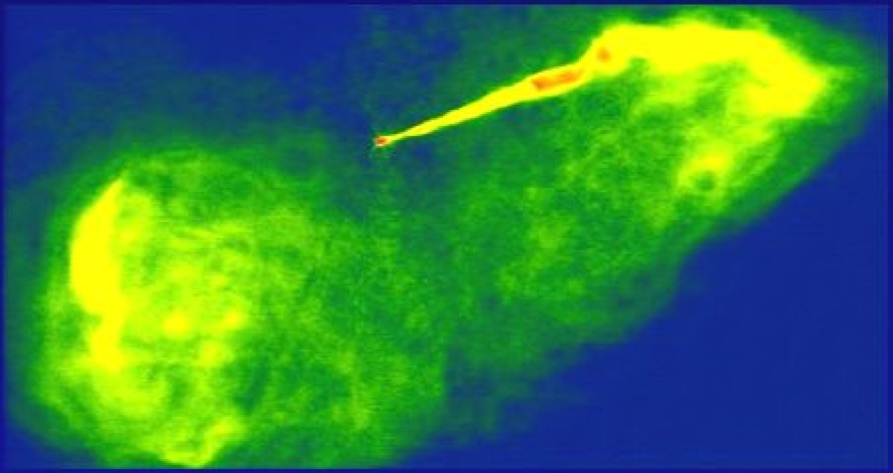
Spectra of our sample of nineteen SDSS quasars at $5.74 < z < 6.42$. Twelve of the spectra e taken with Keck ESI, while the others were observed with the MMT Red Channel and Kitt k 4-meter MARS spectrographs. See Table 1 for detailed information.

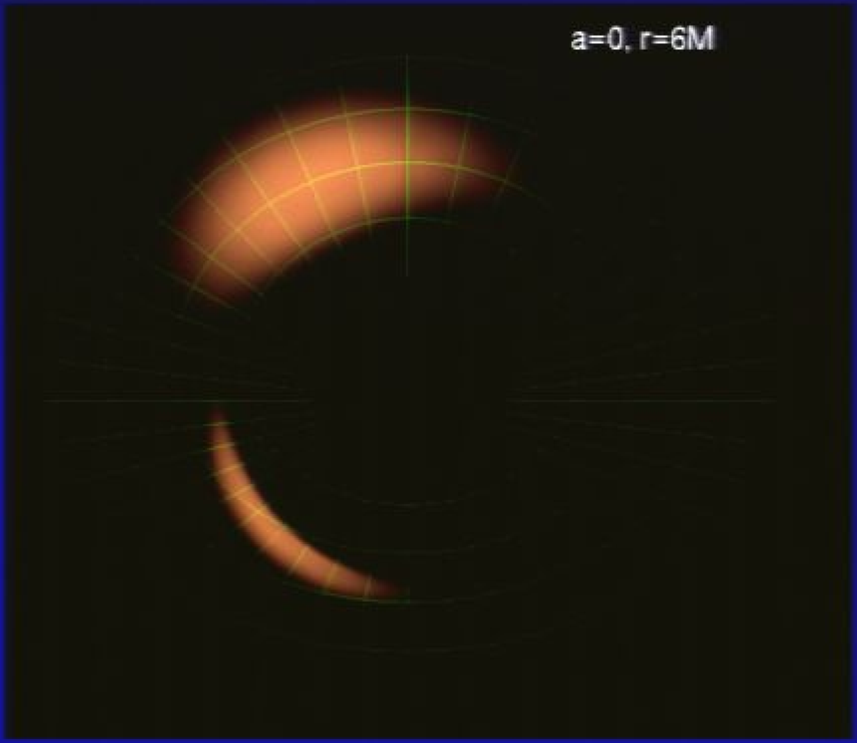


Fan et al. 2005

Supermassive Black Holes:

Probing strong field gravity





The Black Hole in the Galactic Center:

SgrA*

VLT with Adaptive Optics

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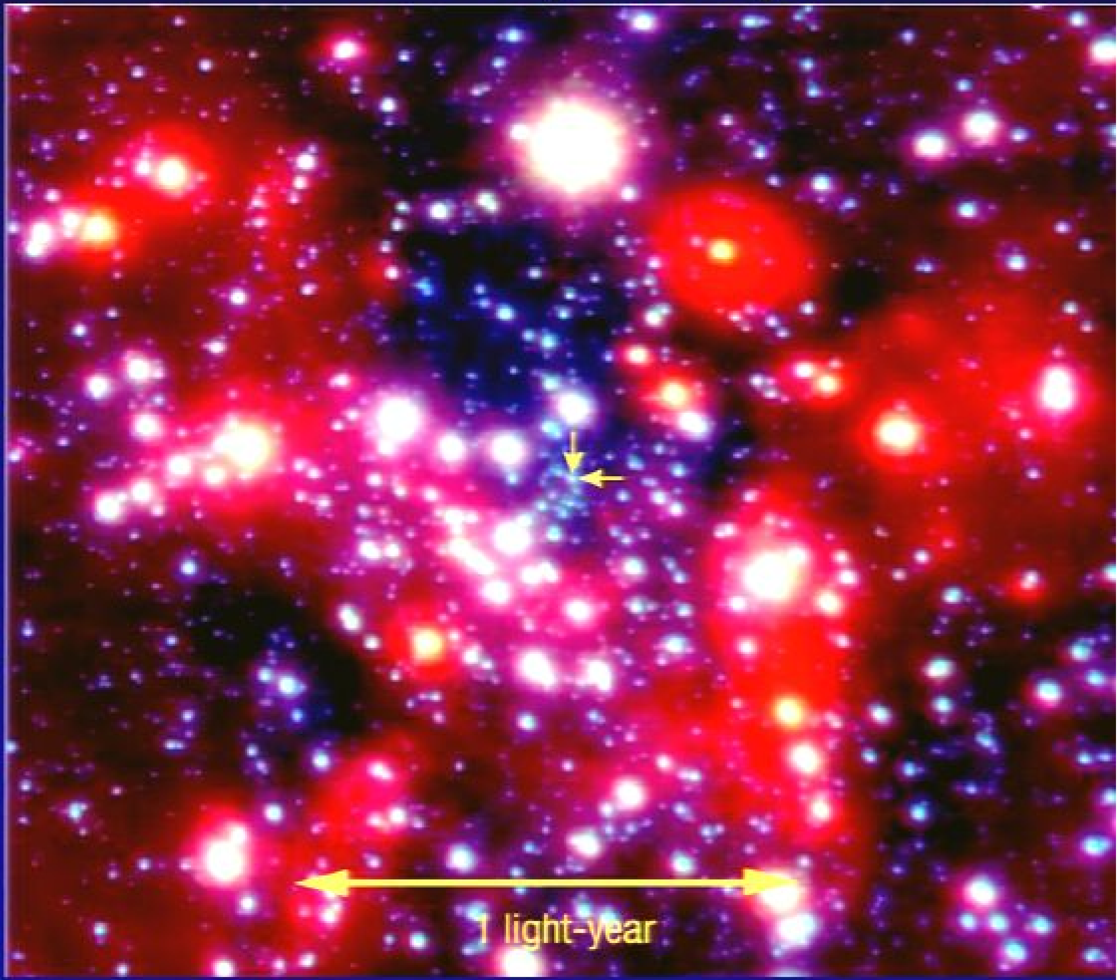
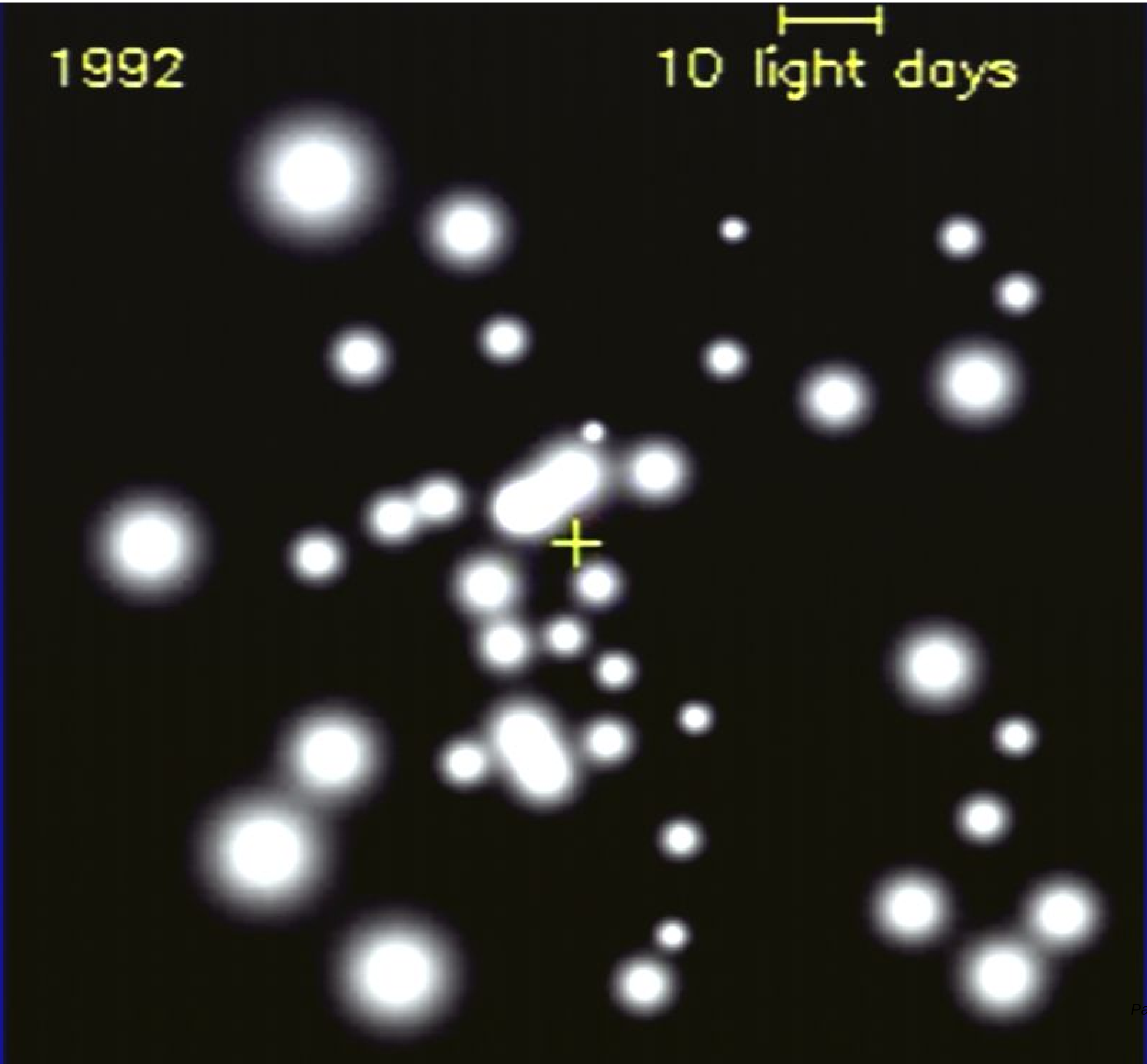
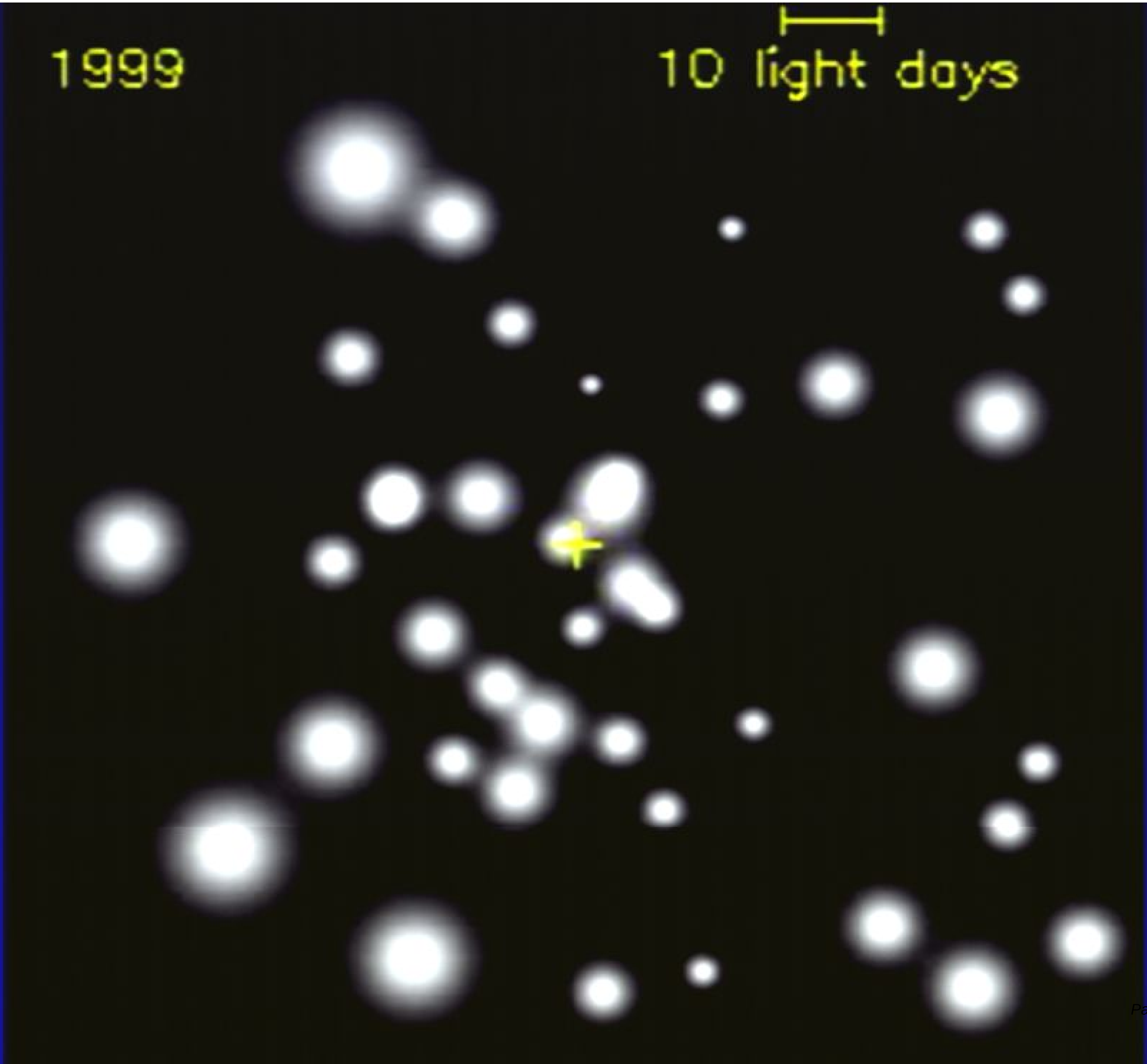
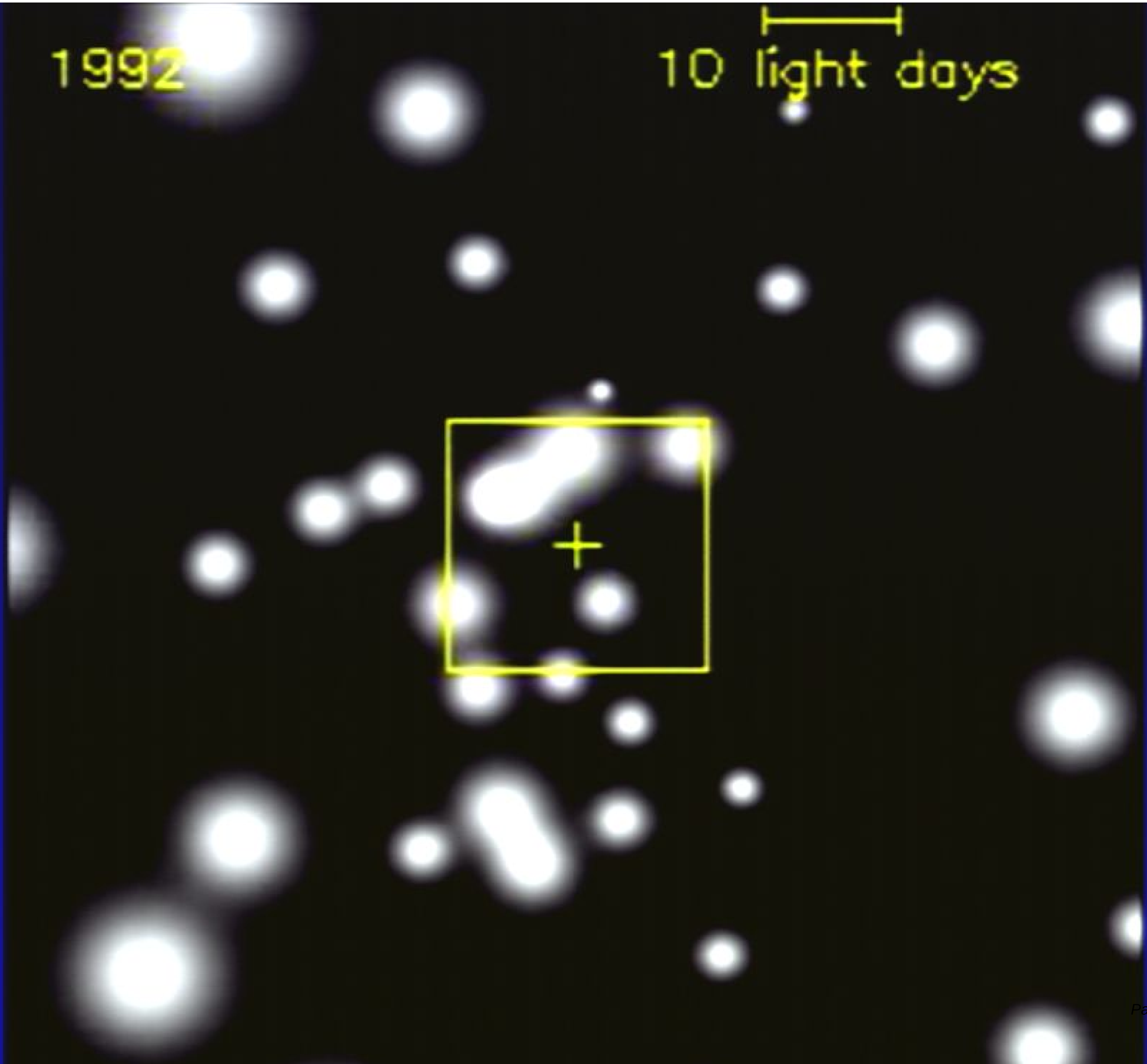
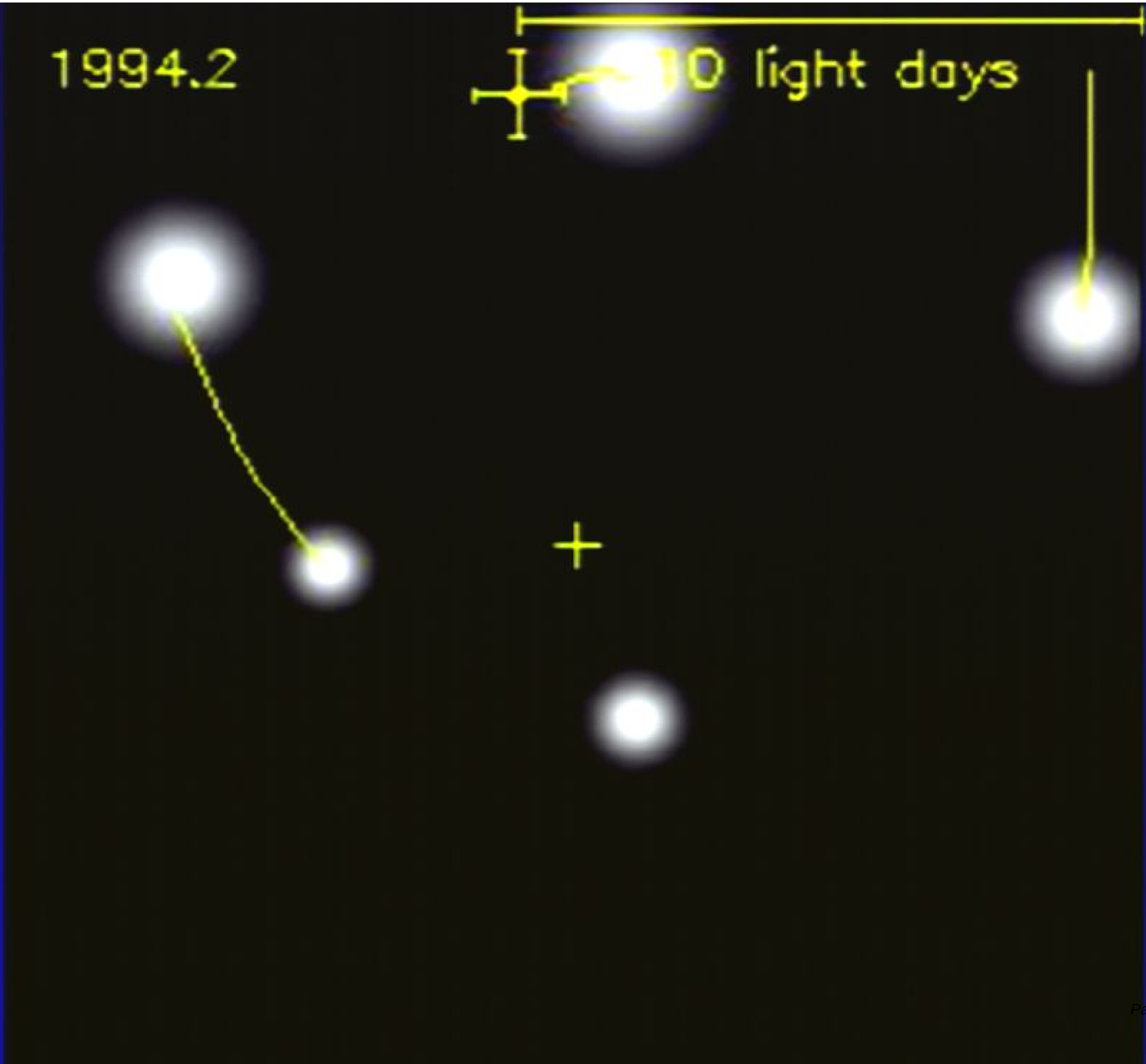
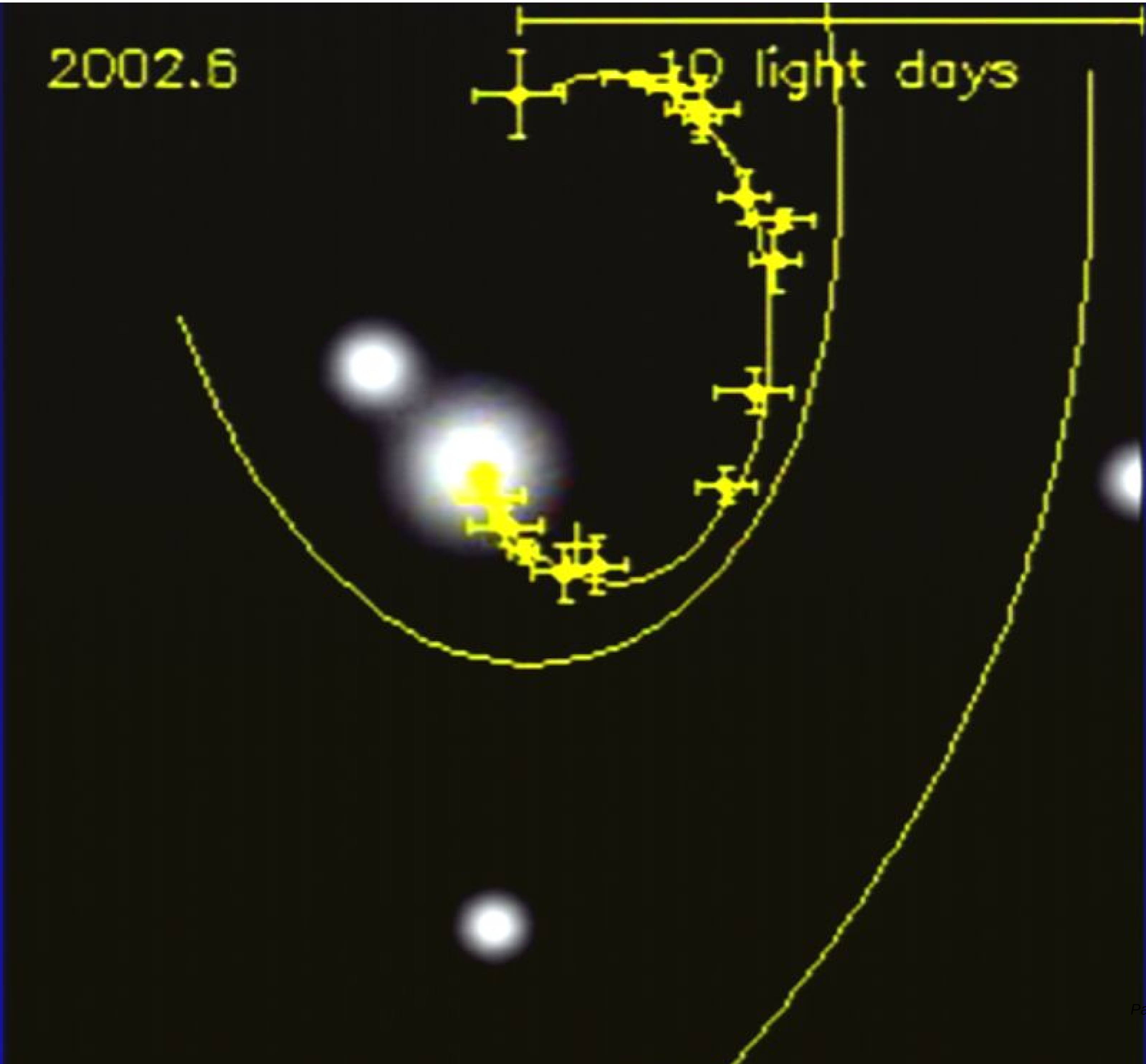


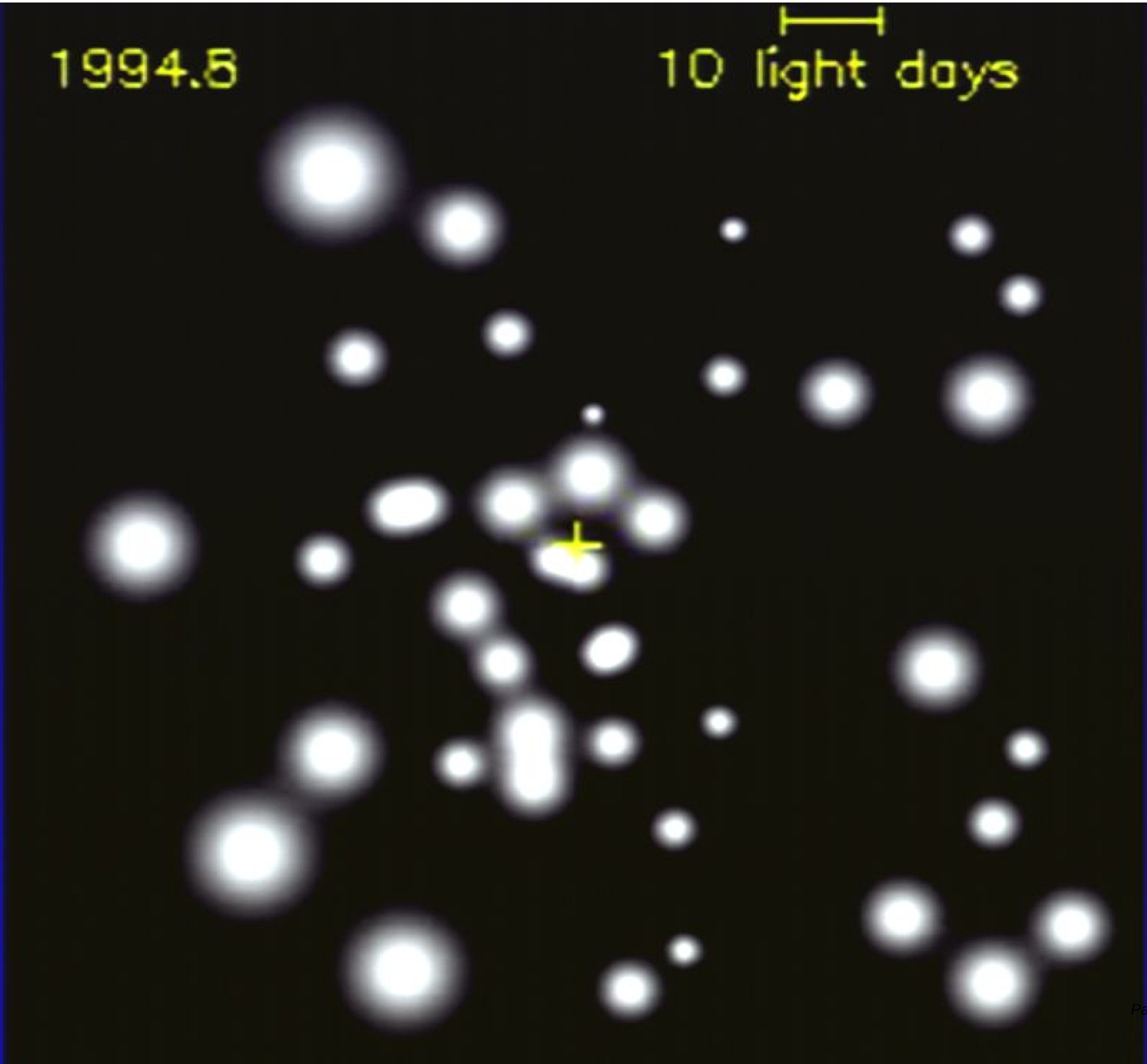

1992
10 light days

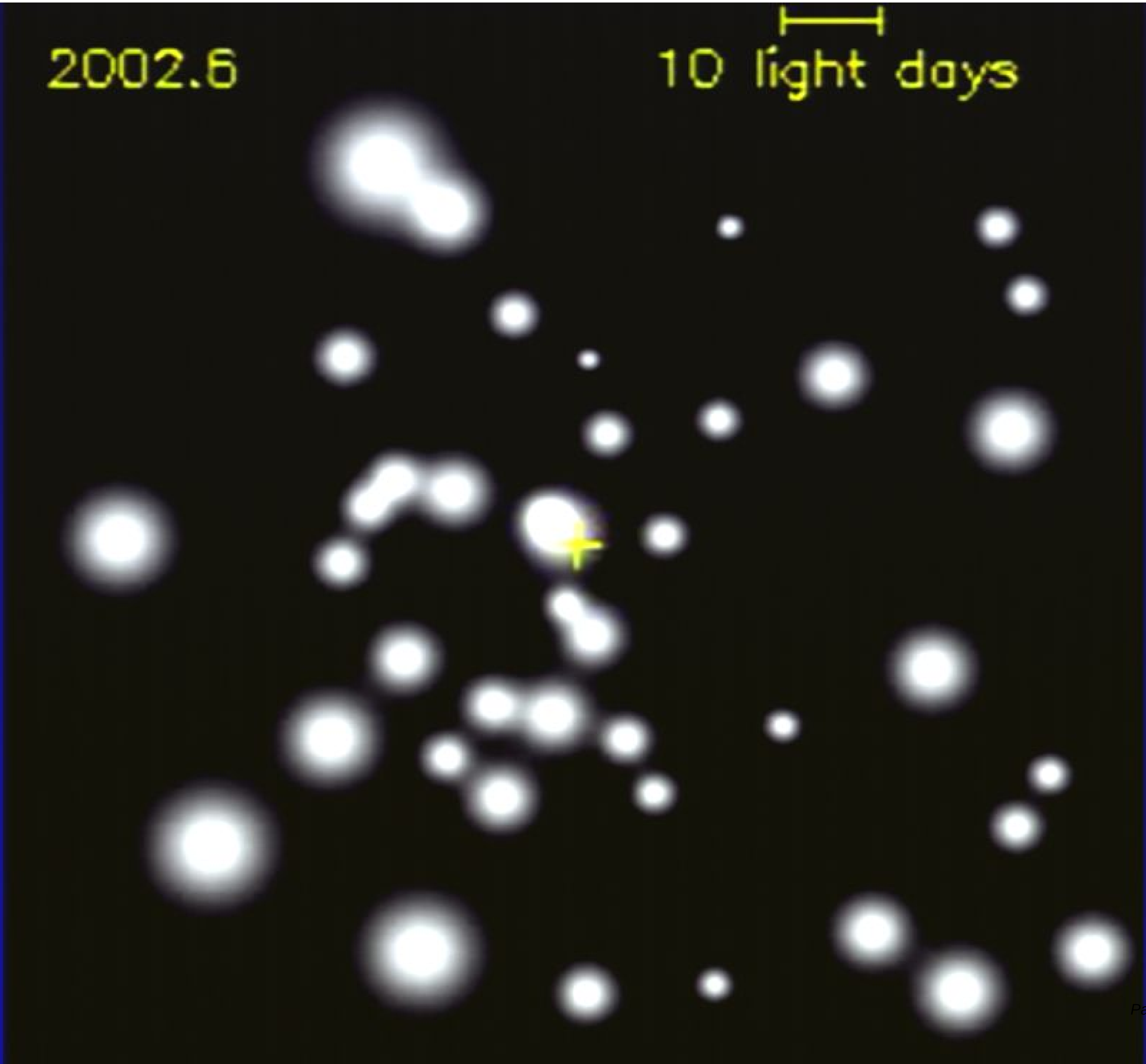

1999
10 light days


1992
10 light days


1994.2
10 light days


2002.6
10 light days


1994.5
10 light days


2002.6
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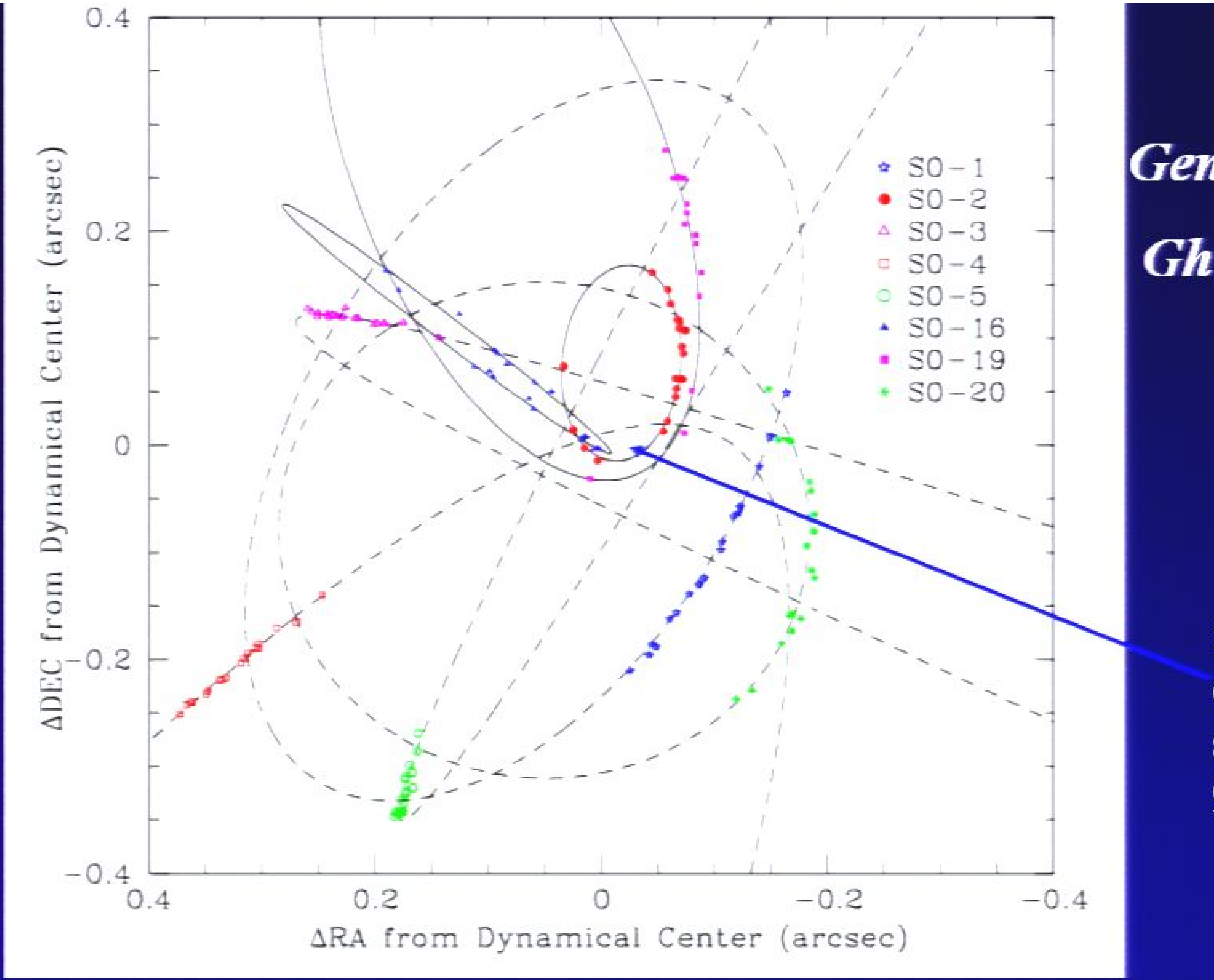

Genzel et al 200

Ghez et al. 200

SO-16
closest
approach at
90 AU

Simultaneous fit of orbits implies:

1. BH mass: $M_{\rm bh} = (3.7 \pm 0.2) \times 10^6 M_\odot; d = 7.4 \pm 0.2{\rm kpc}$

2. BH proper motion: $< 0.8 \pm 0.7$ mas/yr

Hypervelocity Stars

Hypervelocity Stars

- Ten unbound stars in MW halo with (Brown et al. 05-07; Edelmann et al. 05; Hirsch et al. 05)

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- Ten unbound stars in MW halo with $v \sim 10^3 \ \mathrm{km/s}$ (Brown et al. 05-07; Edelmann et al. 05; Hirsch et al. 05)

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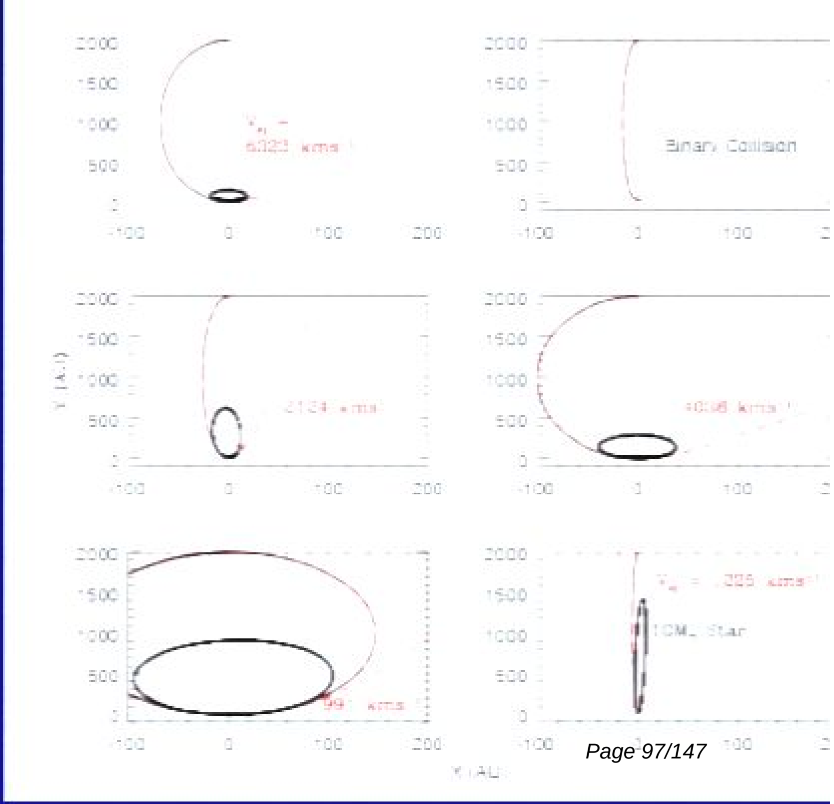

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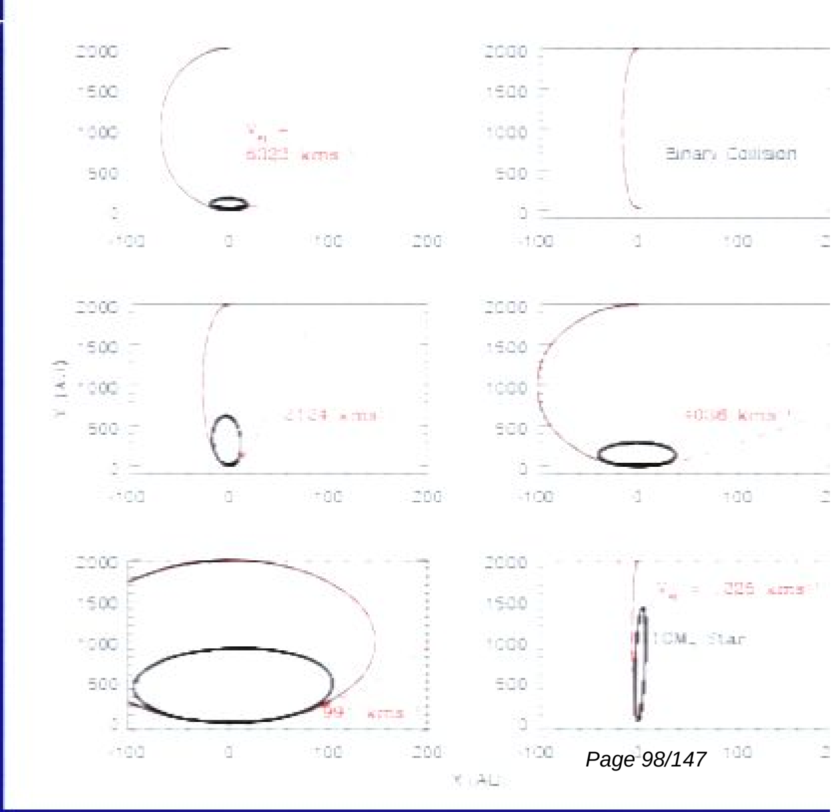

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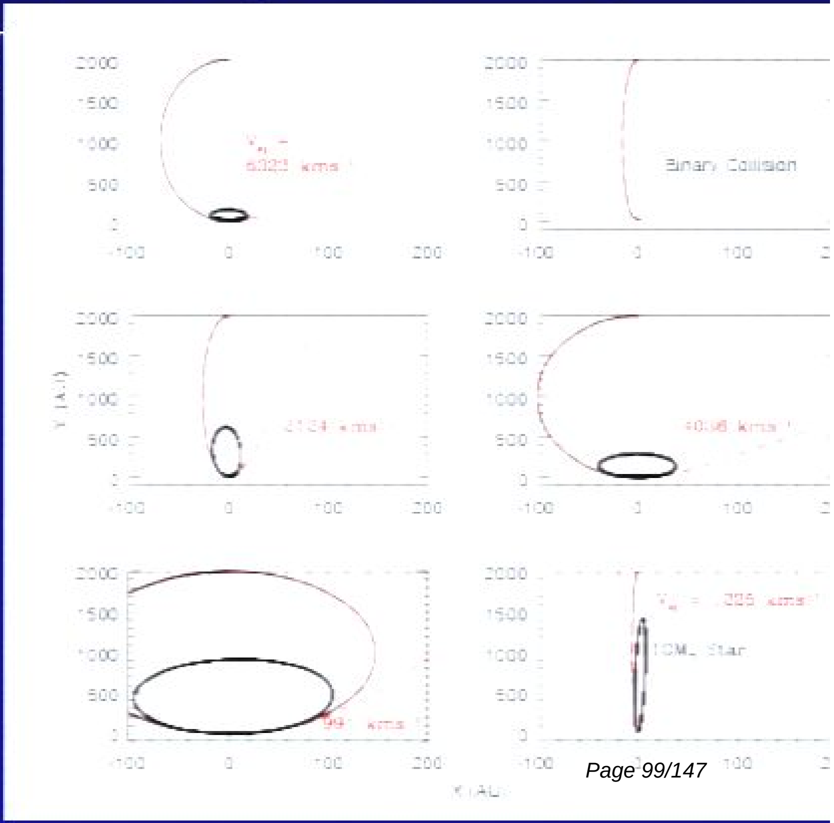
iii) Scattering stars off stellar BH



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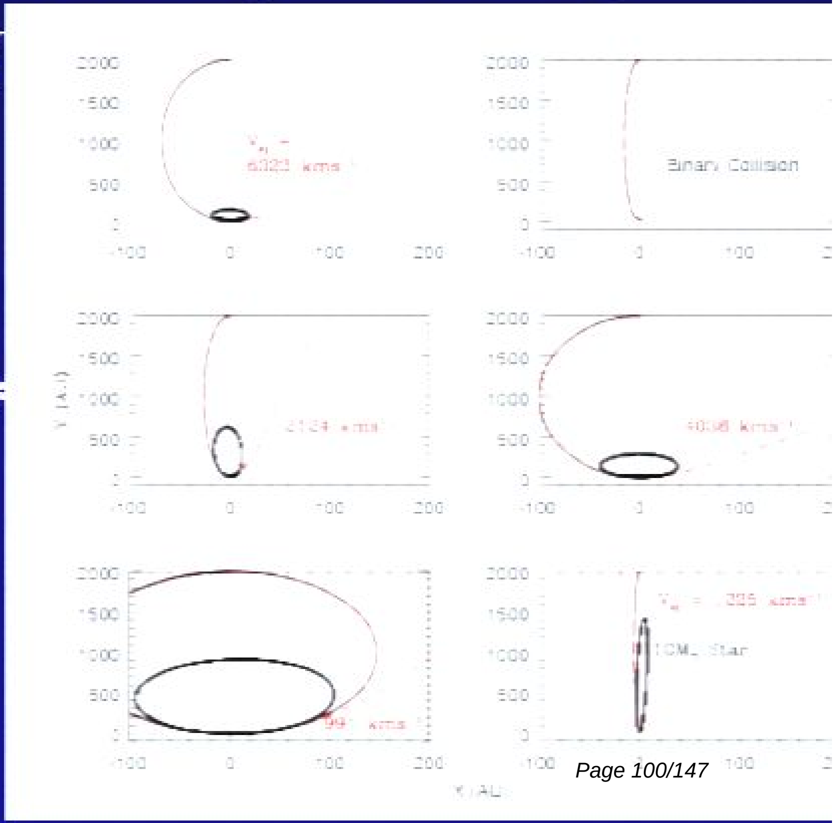

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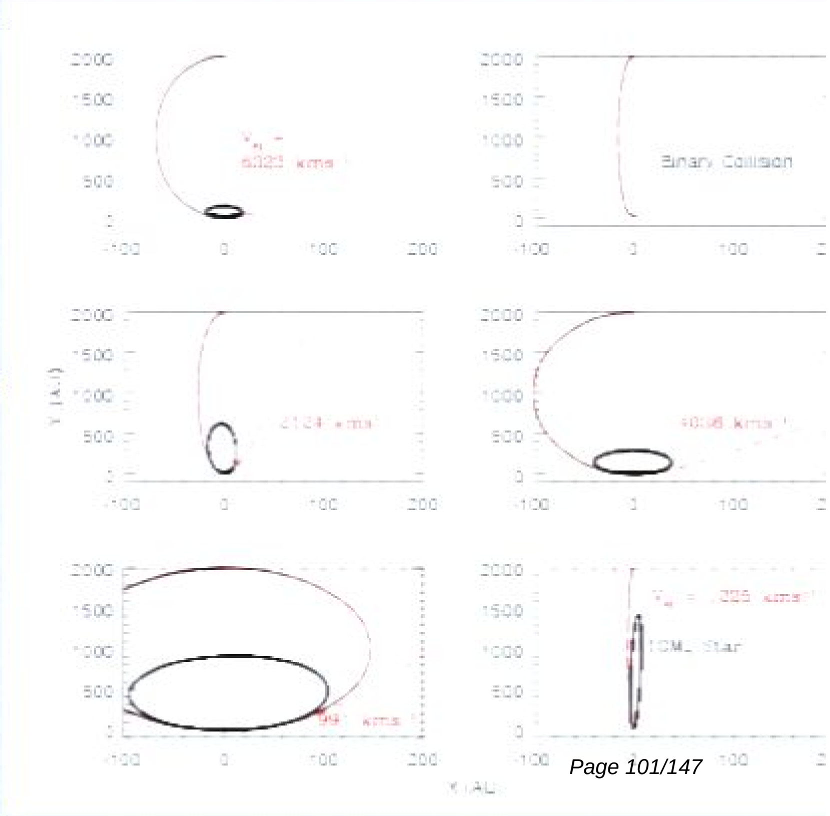

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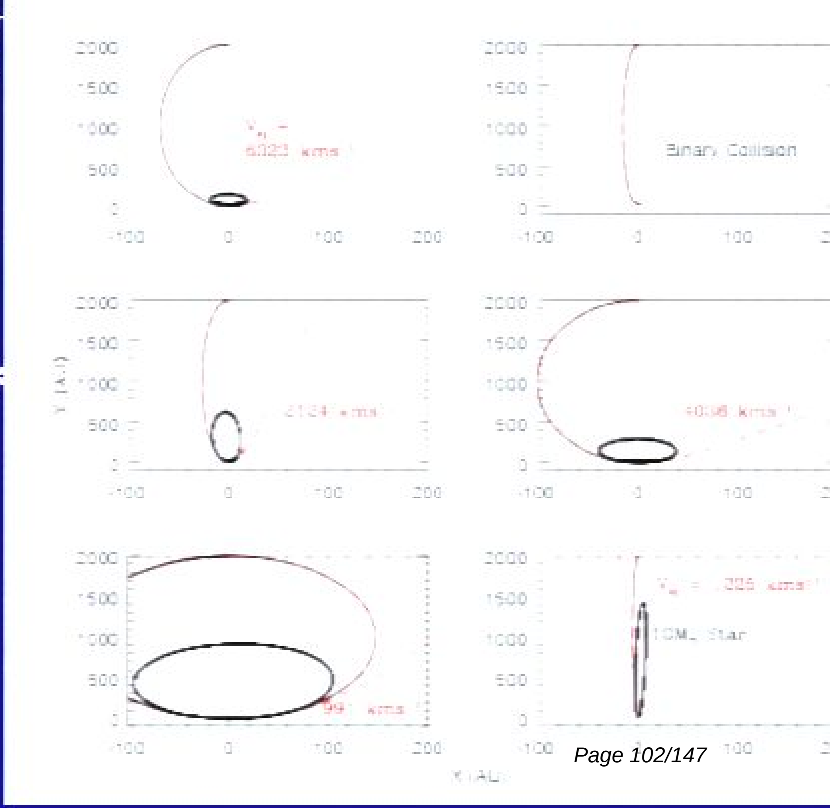
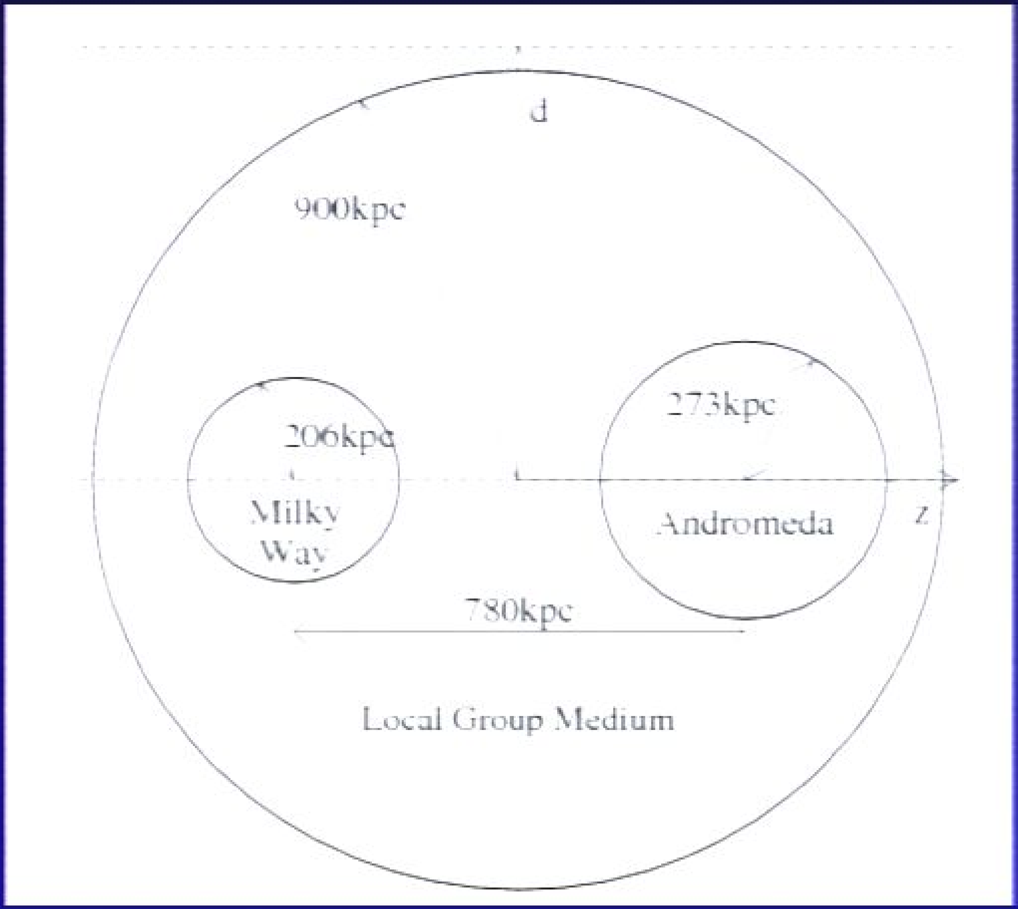
$\sim 10^{-6}$ yr^{-1}

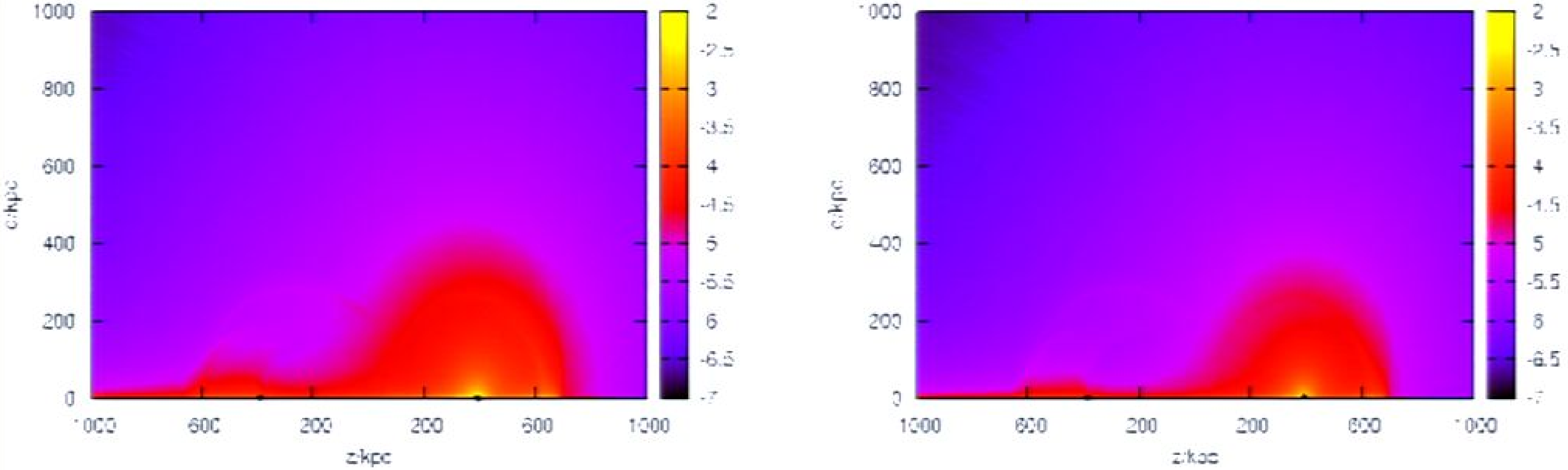


Hypervelocity Stars from Andromeda



Sherwin, Loeb, & O'Leary 2007

Hypervelocity Stars from Andromeda

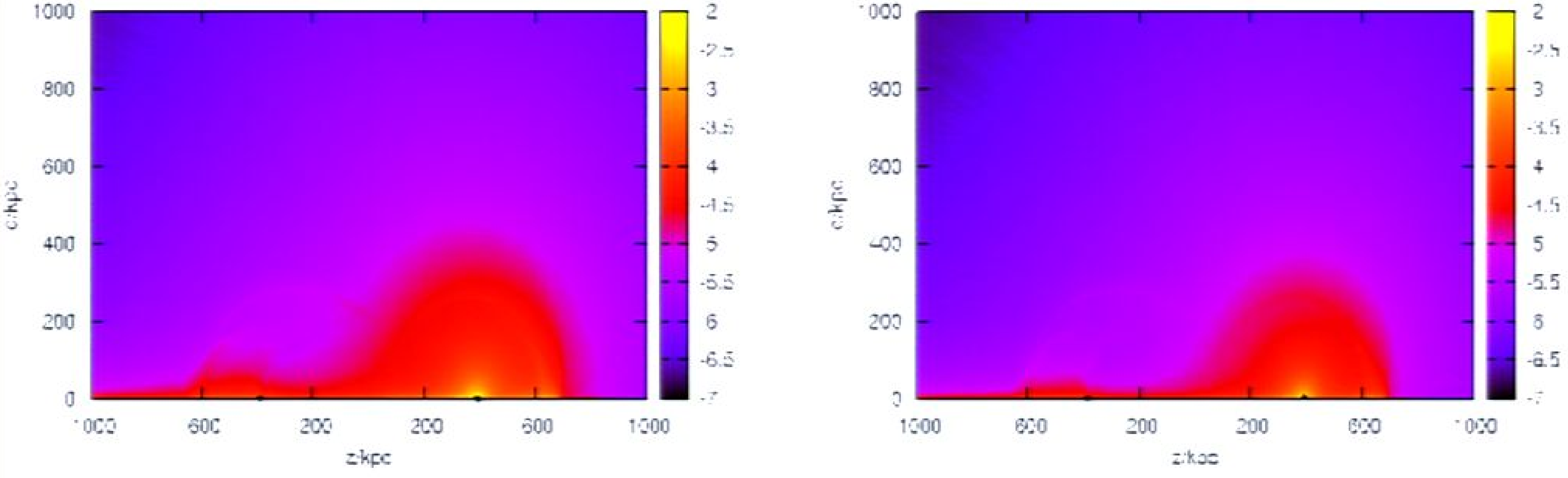


(a) $\log_{10}$ of the number of stars per cubic kpc (TB)

(b) $\log_{10}$ of the number of stars per cubic kpc (IBH)

Sherwin, Loeb, & O'Leary 2007

Hypervelocity Stars from Andromeda



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Sherwin, Loeb, & O'Leary 2007

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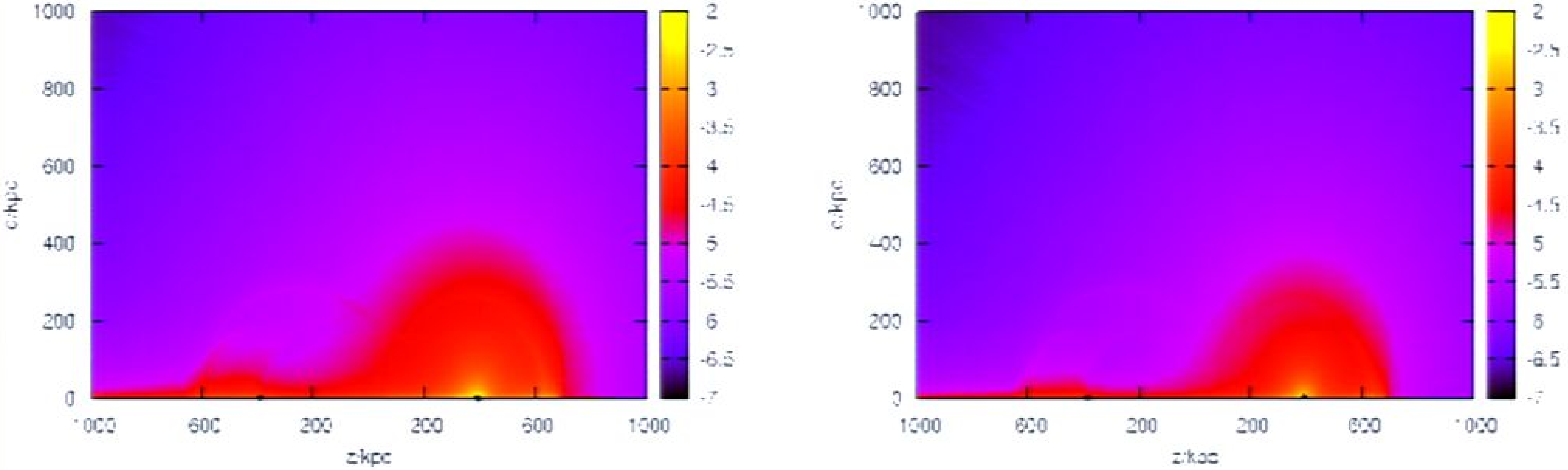

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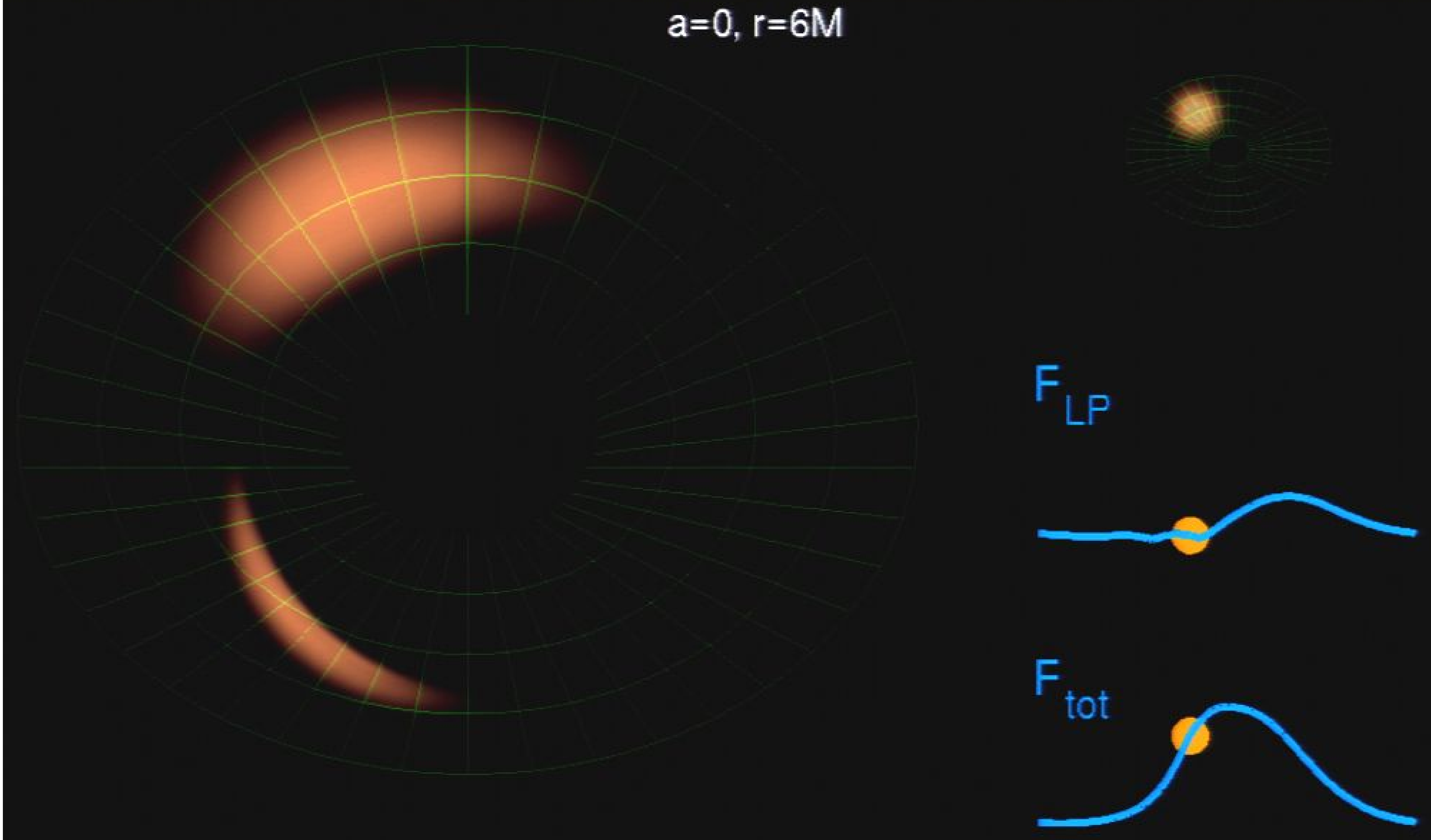
- Expect ~1000 HVS in MW halo
- Tens of giant HVS visible out to ~100kpc in M31

Sherwin, Loeb, & O'Leary 2007

SgrA* is the largest black hole on the sky

Is general relativity a valid description of strong gravity?



Broderick & Loeb, 2006, MNRAS, 367, 905

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*****_Infrared variability of flux (Genzel et al.) and polarization (Eckart et al.) of SgrA*: hot spots._

*****_Innermost Stable Circular Orbit: radius of 30 (10) micro-arcsecond and orbital time of 30 (8) minutes for a non-rotating (maximally-rotating) black hole at the Galactic center_

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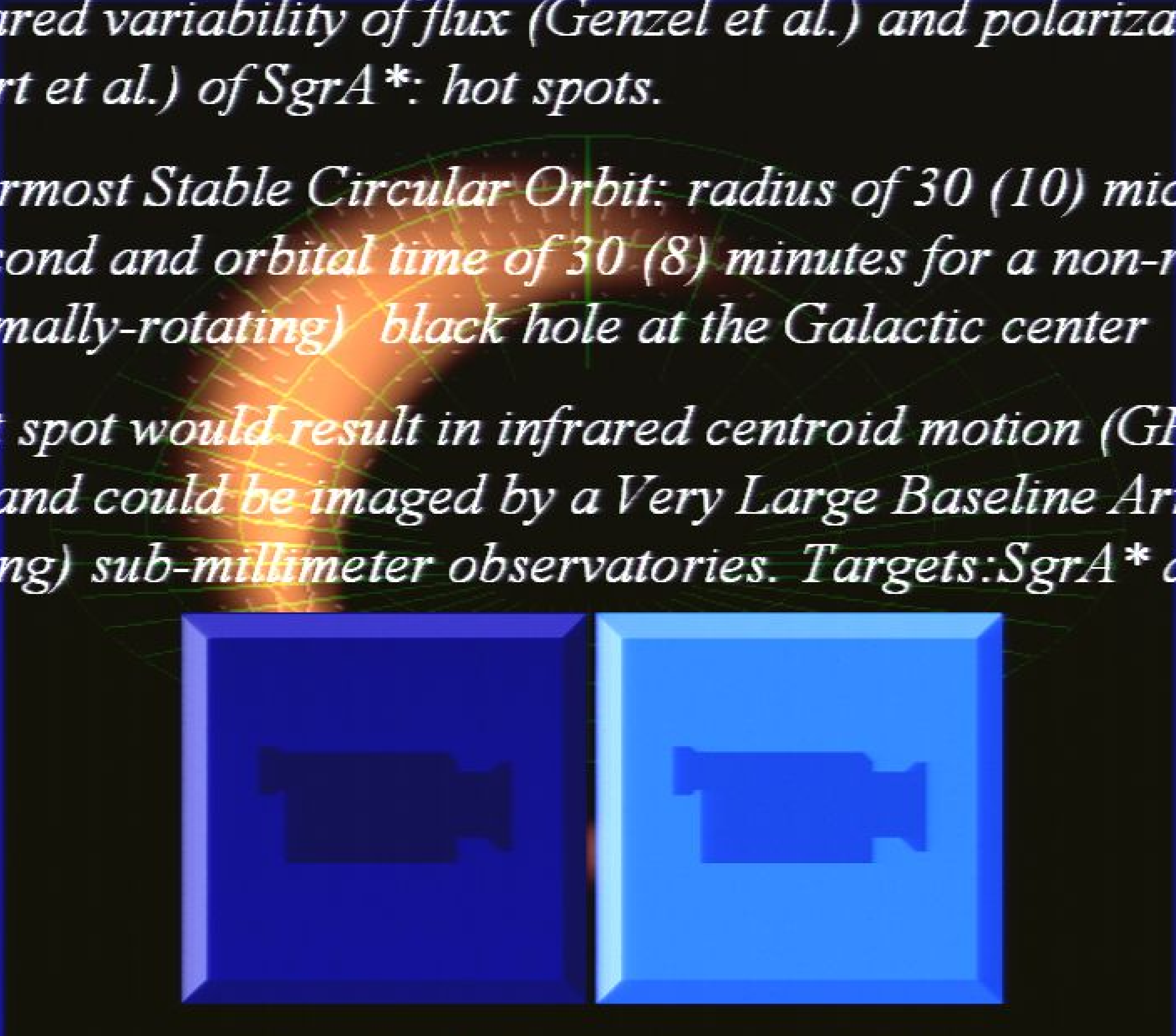

Broderick & Loeb 2005

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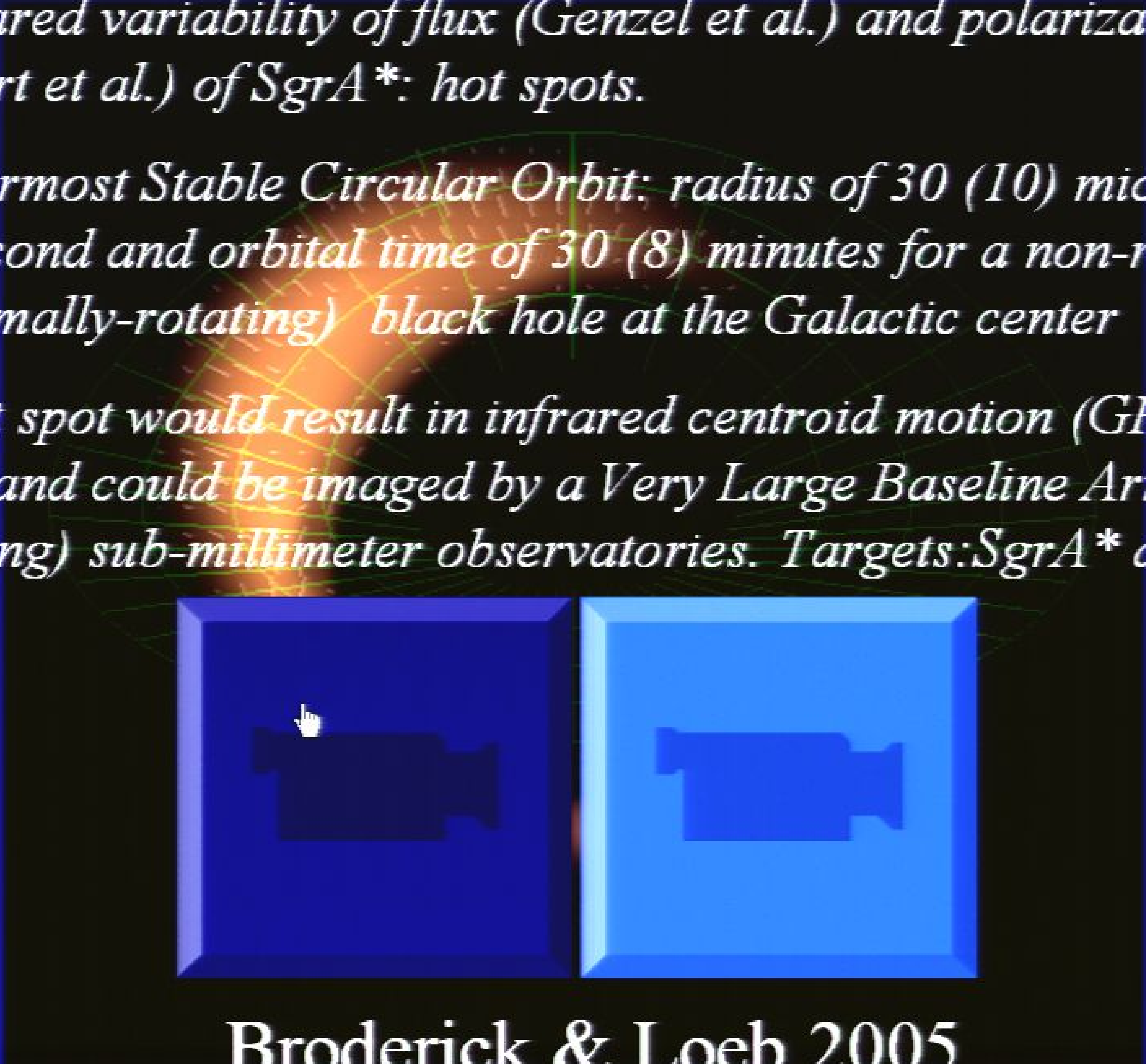

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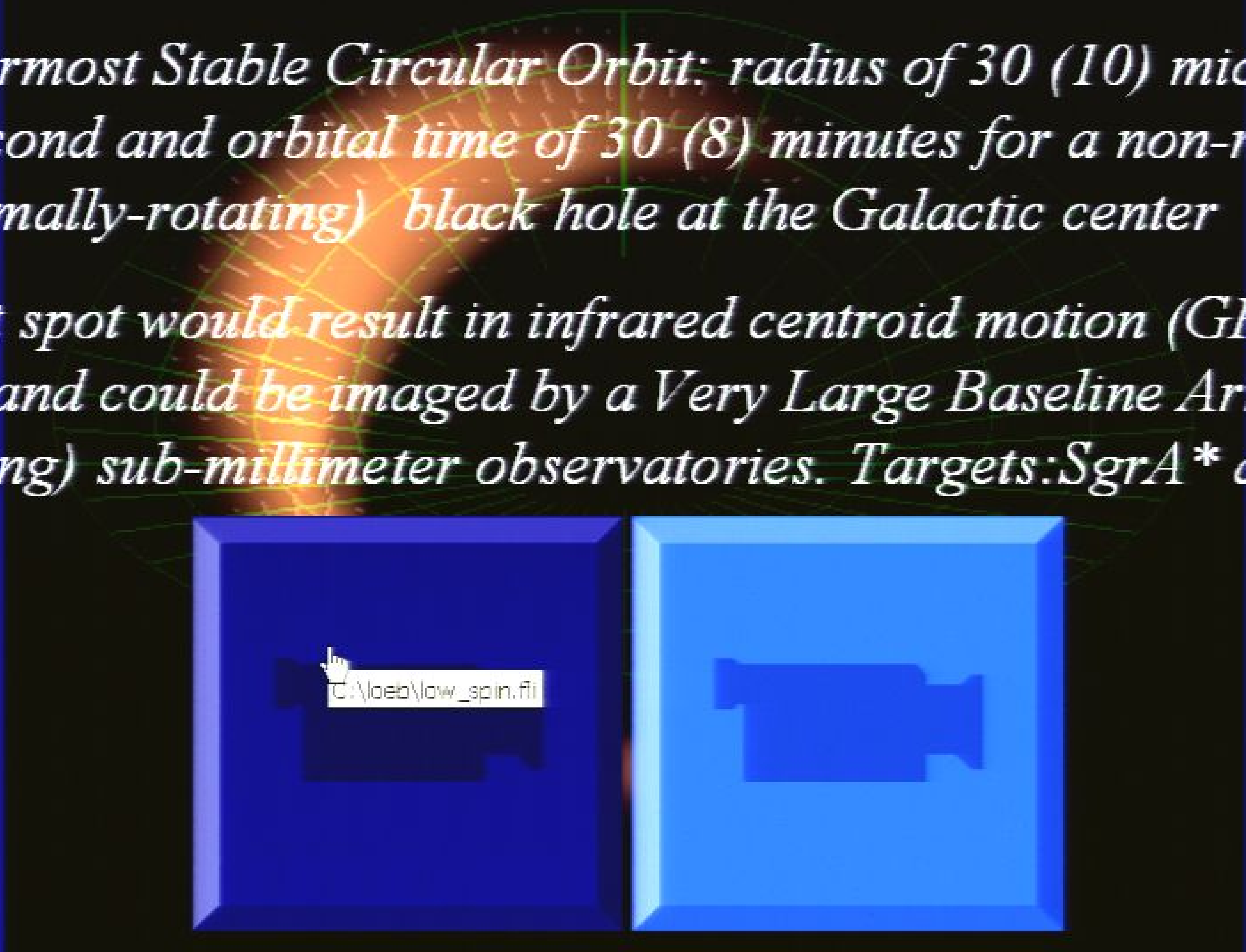
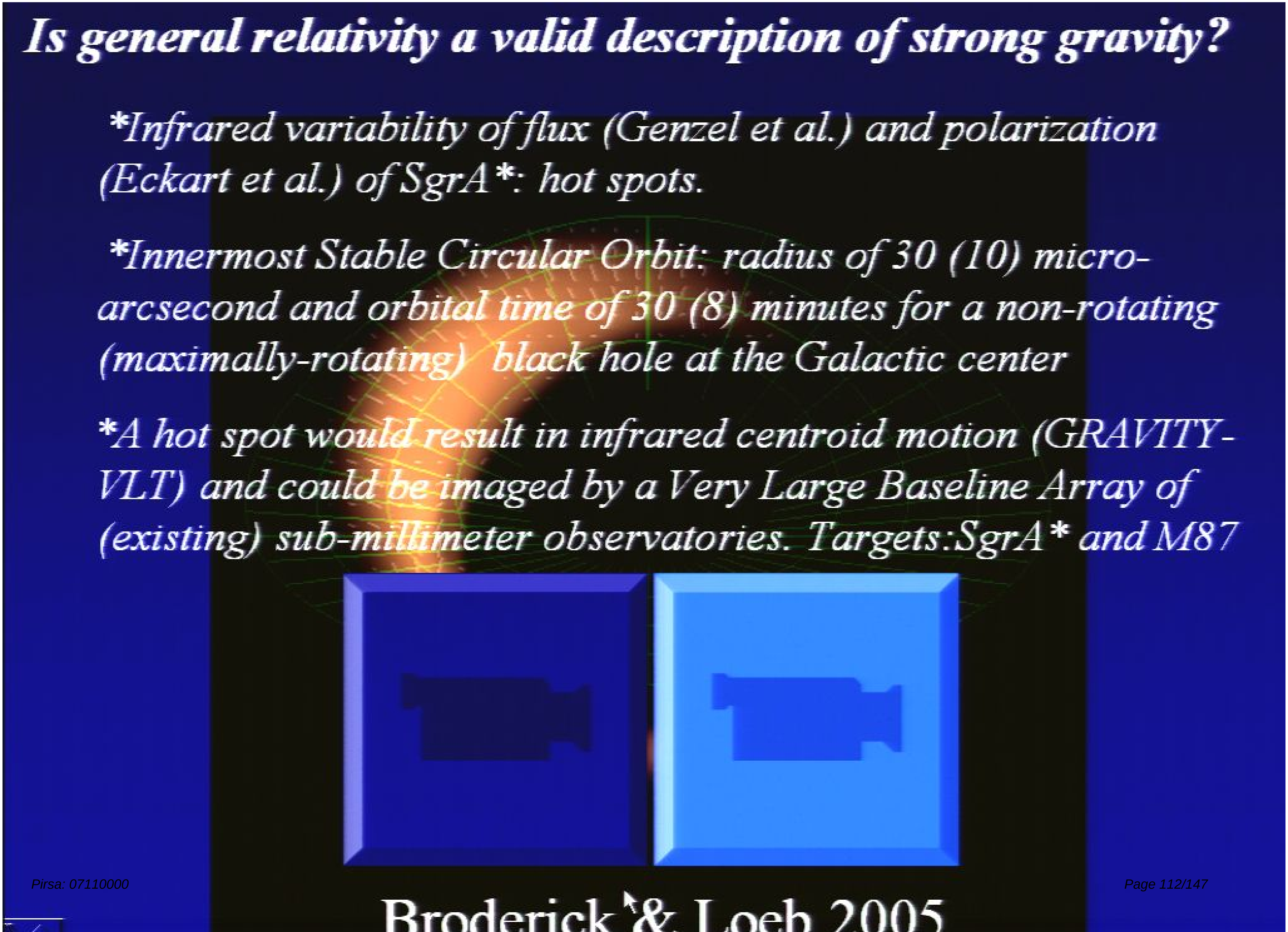


Broderick & Loeb 2005



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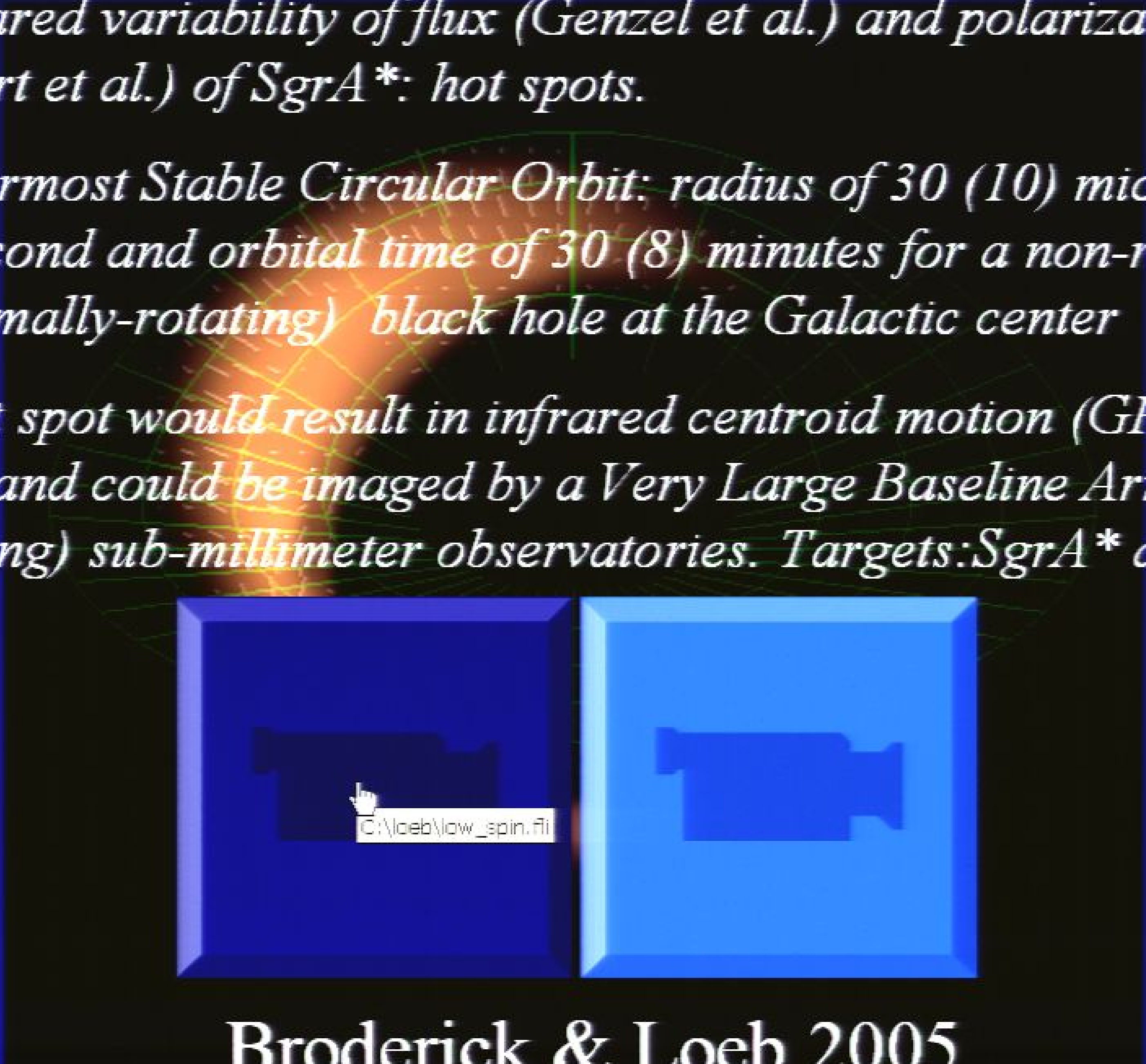

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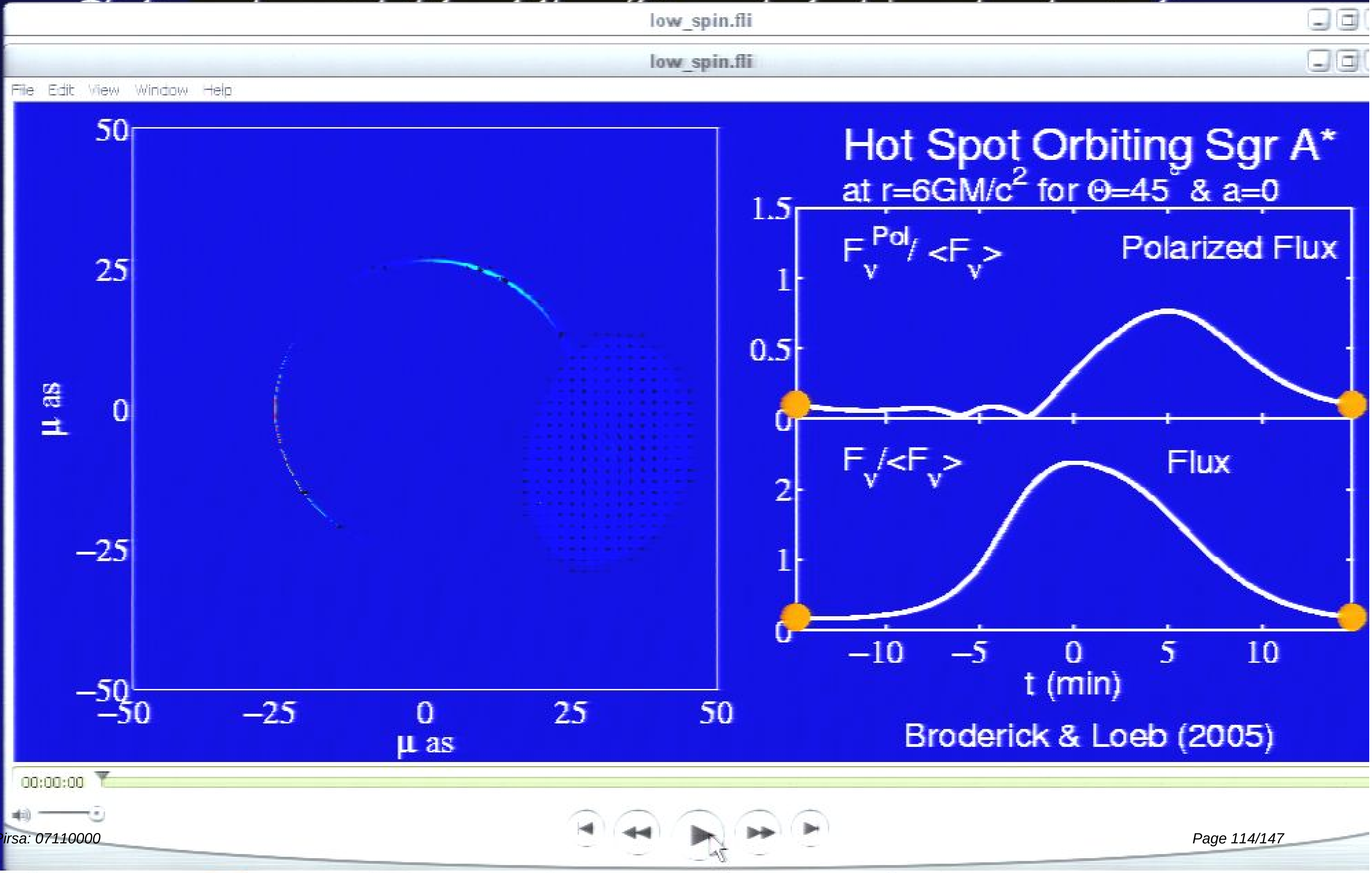

Broderick & Loeb (2005)

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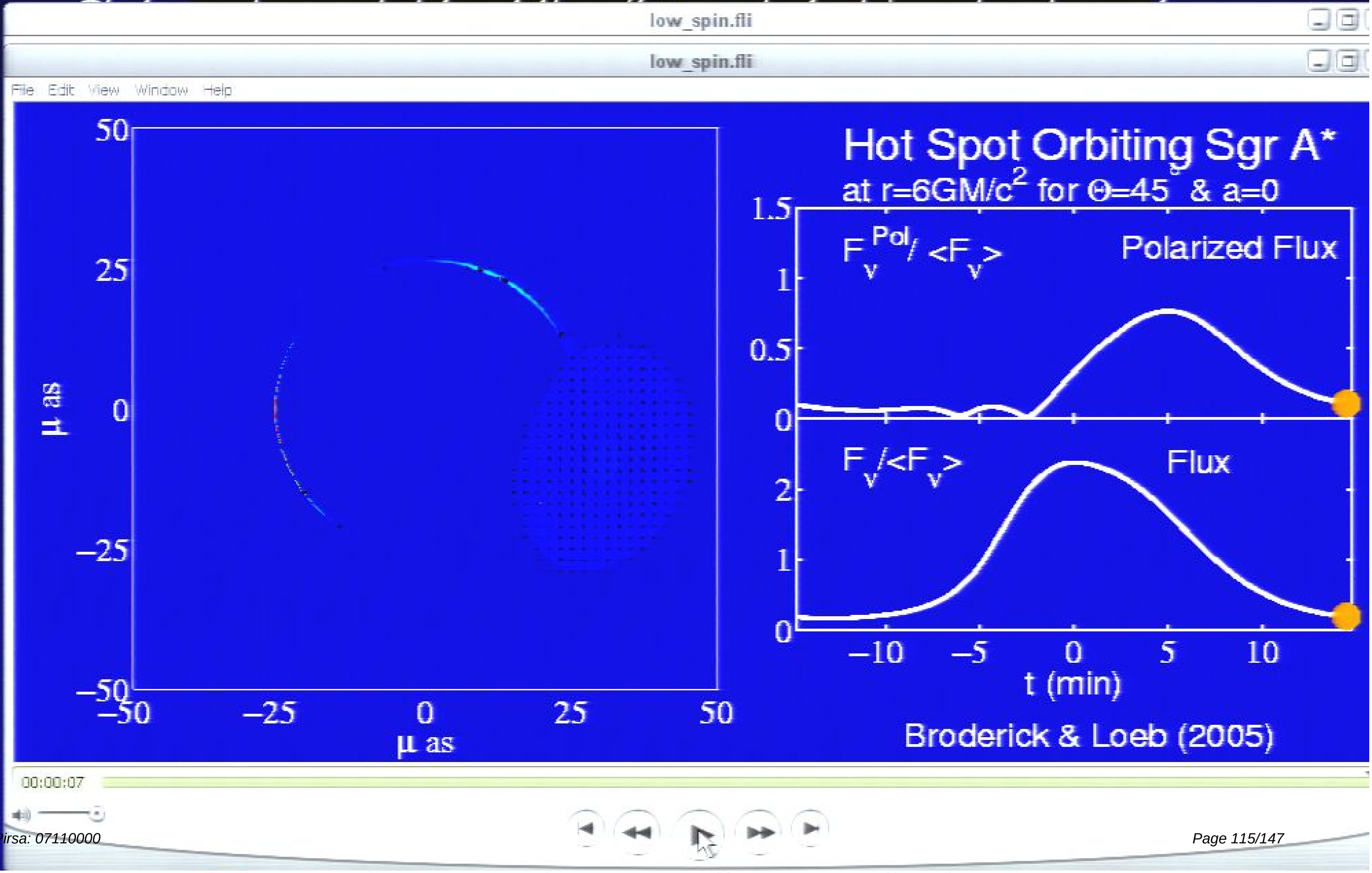

Hot Spot Orbiting Sgr A*

at $r=6GM/c^2$ for $\Theta=45^\circ$ & $a=0$

Broderick & Loeb (2005)

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 Future Collision between the Milky Way and Andromeda Galaxies

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The Future Collision between the Milky Way and Andromeda Galaxies

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Window Help

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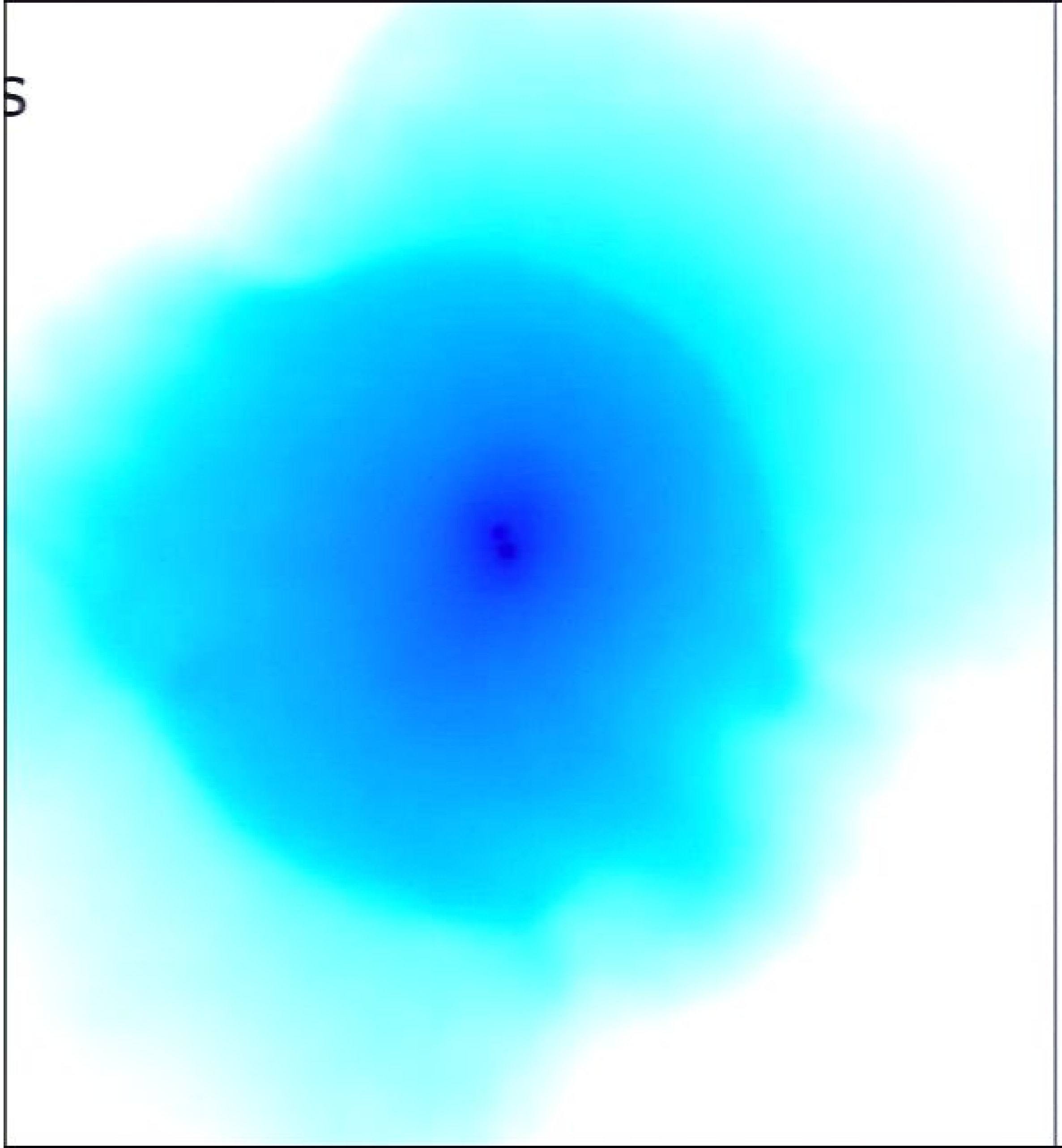
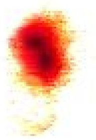
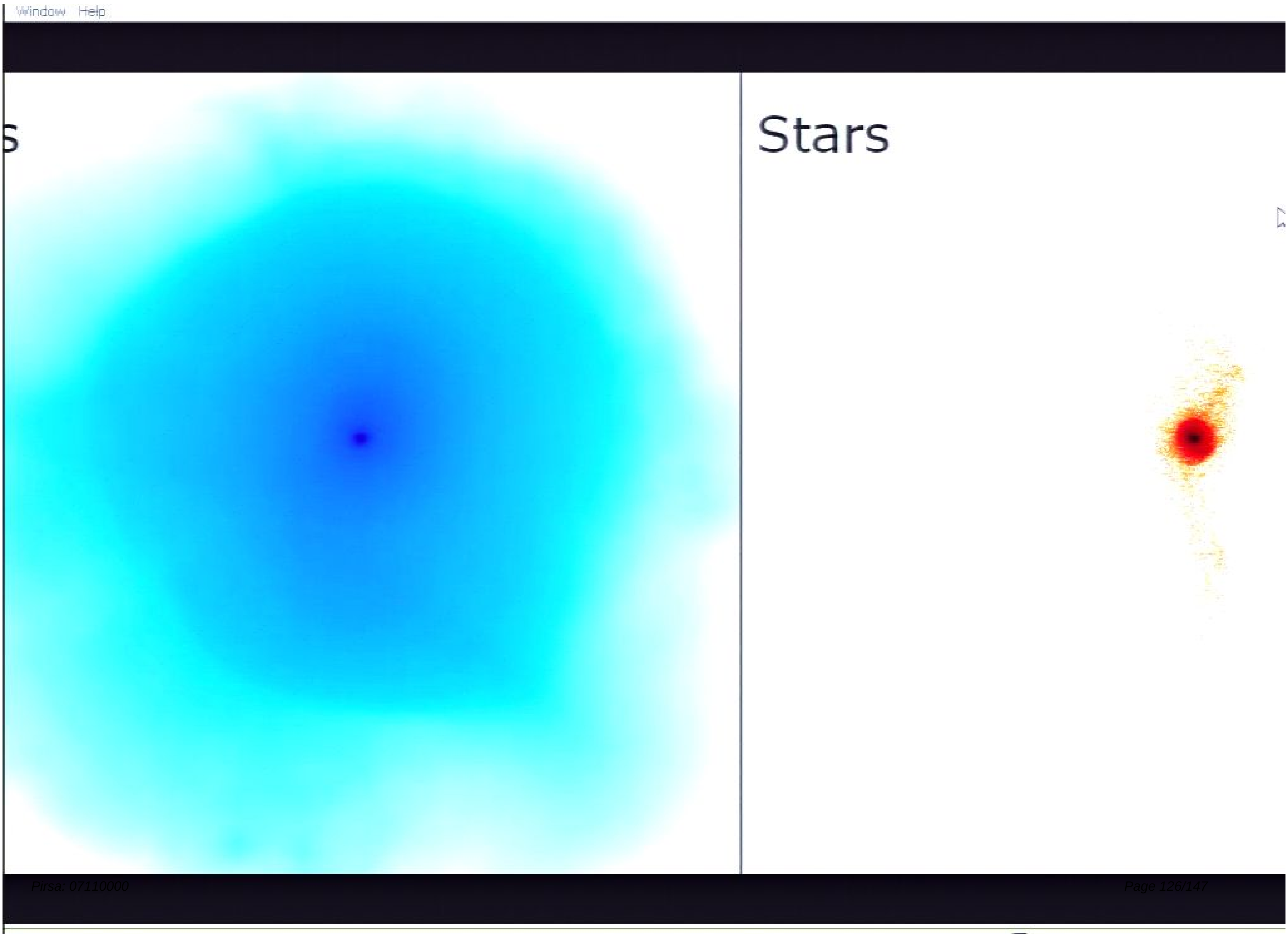


Stars





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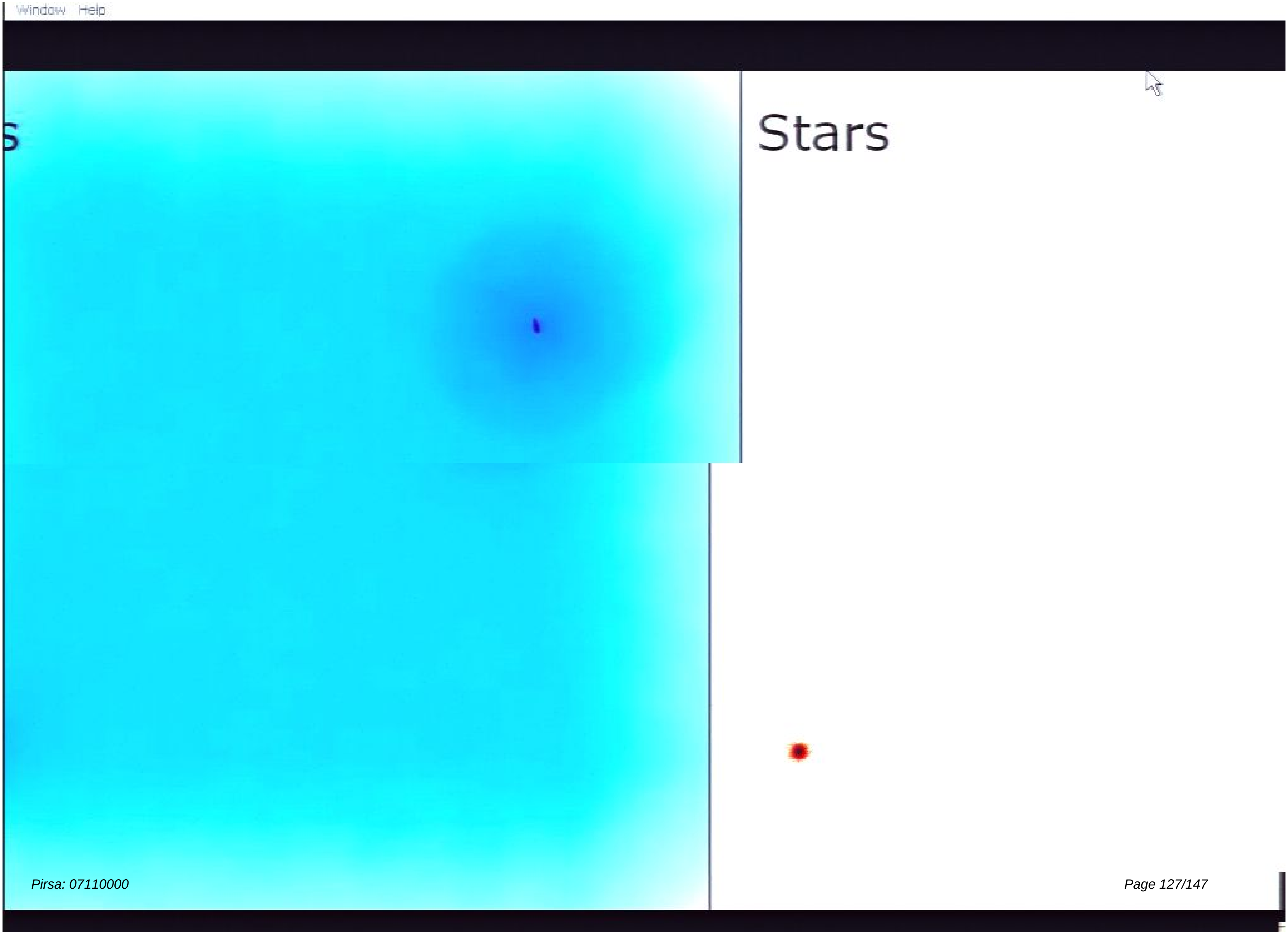
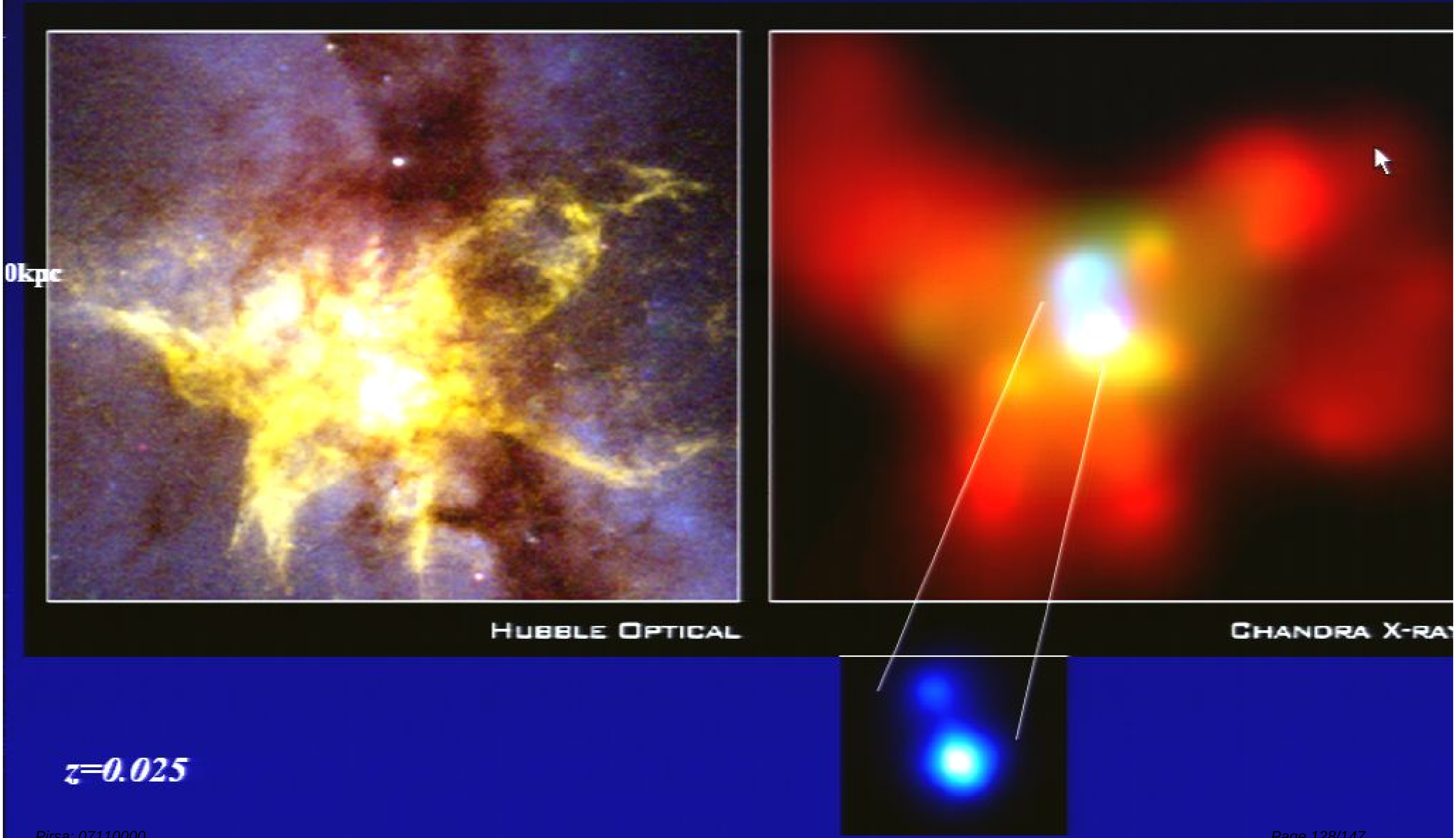


Stars

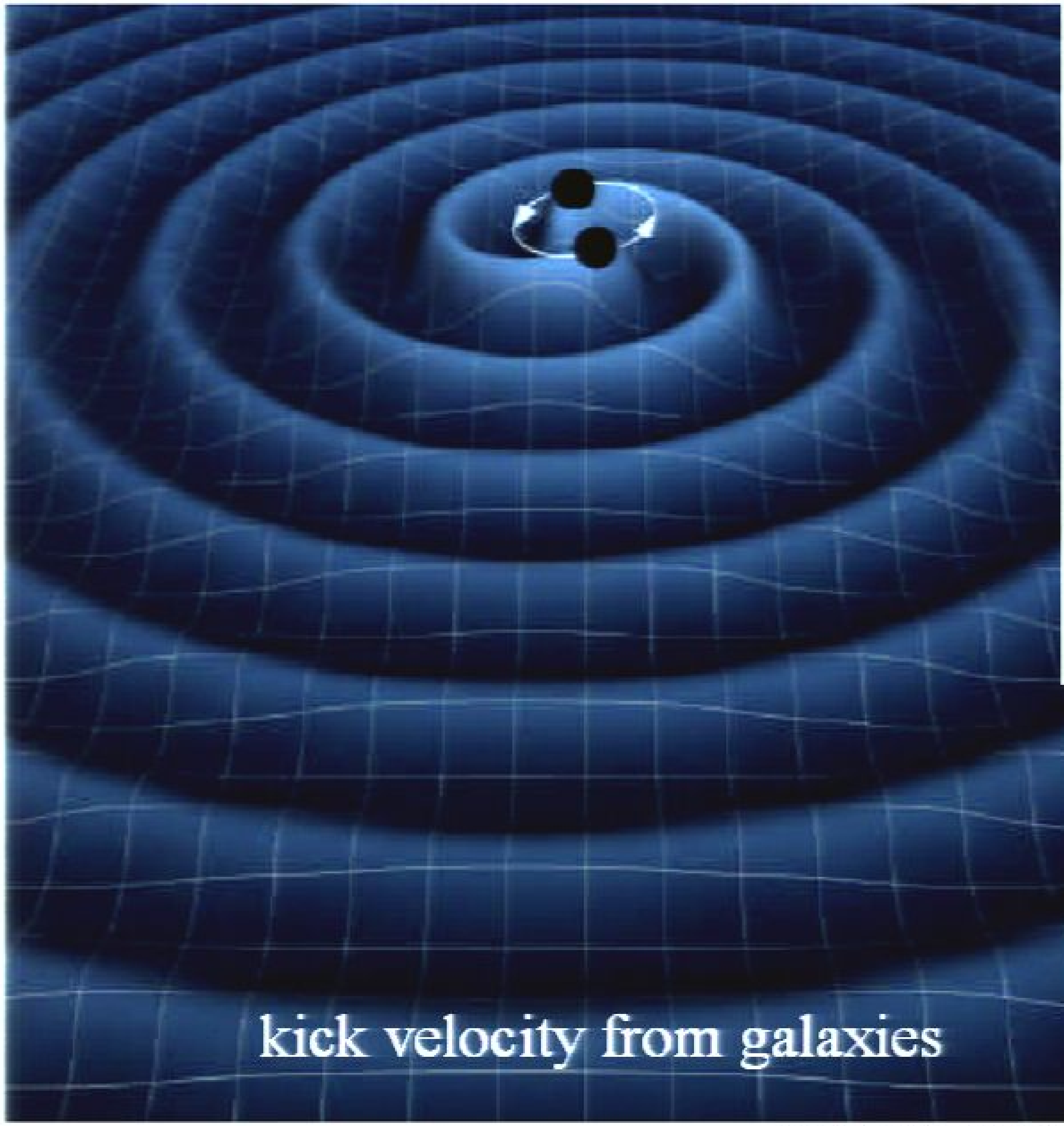
X-ray Image of a binary black hole system in NGC 6240



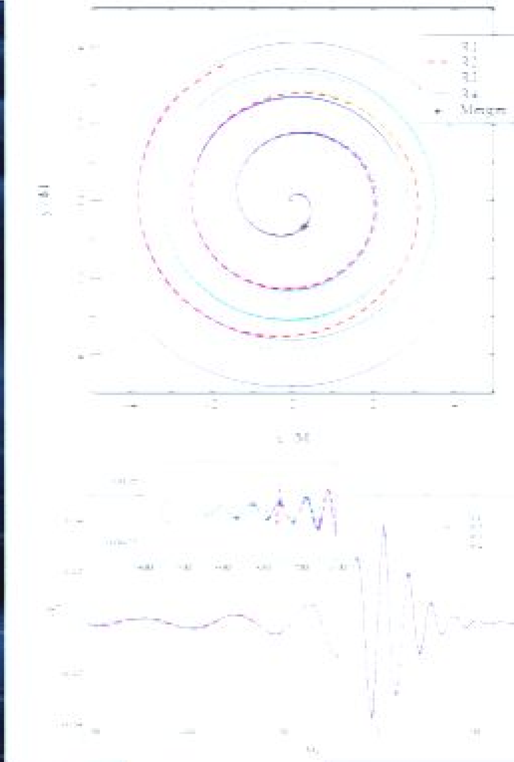
z=0.025

Komossa et al. 2002

Gravitational Waves



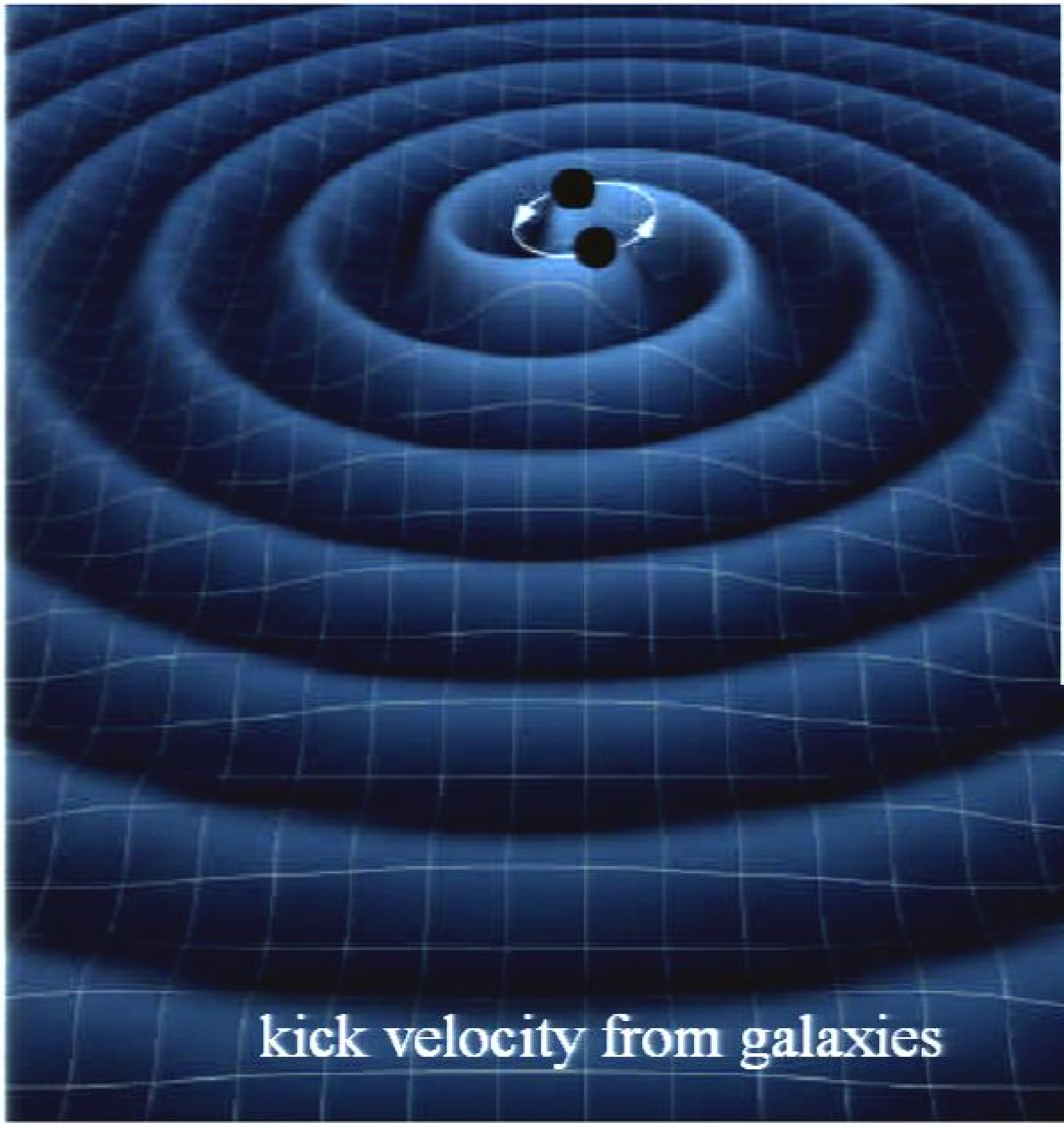
kick velocity from galaxies



lla et al.

K. Thorne (Caltech), T. Carnahan (NASA GSFC)

Gravitational Waves



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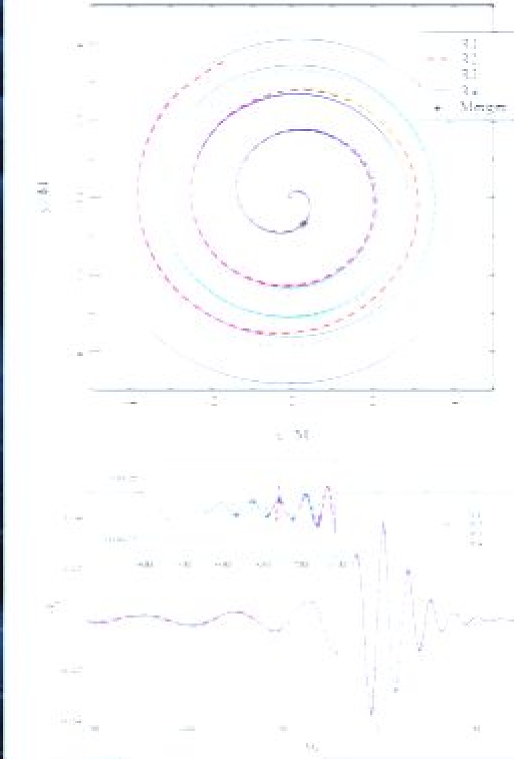
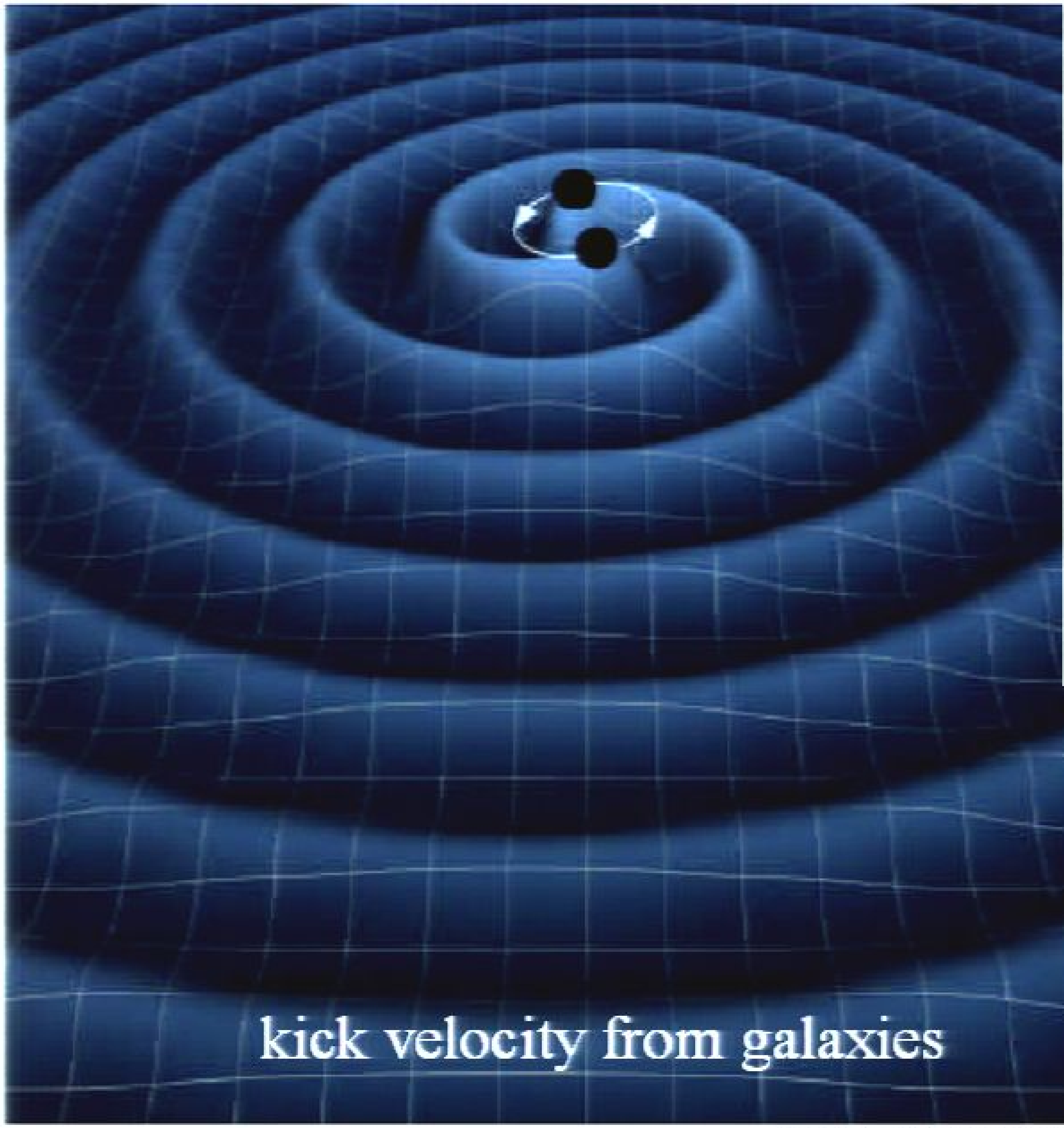


J.Centrella et al.
2007

Gravitational Waves



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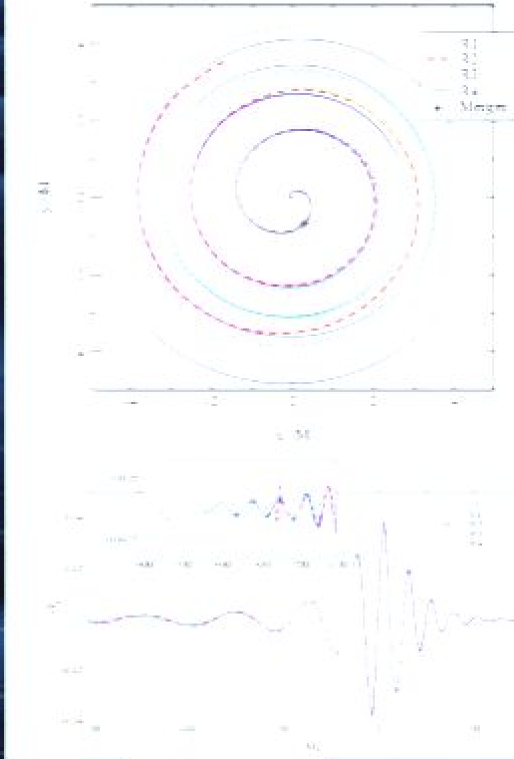

J.Centrella et al. 2007

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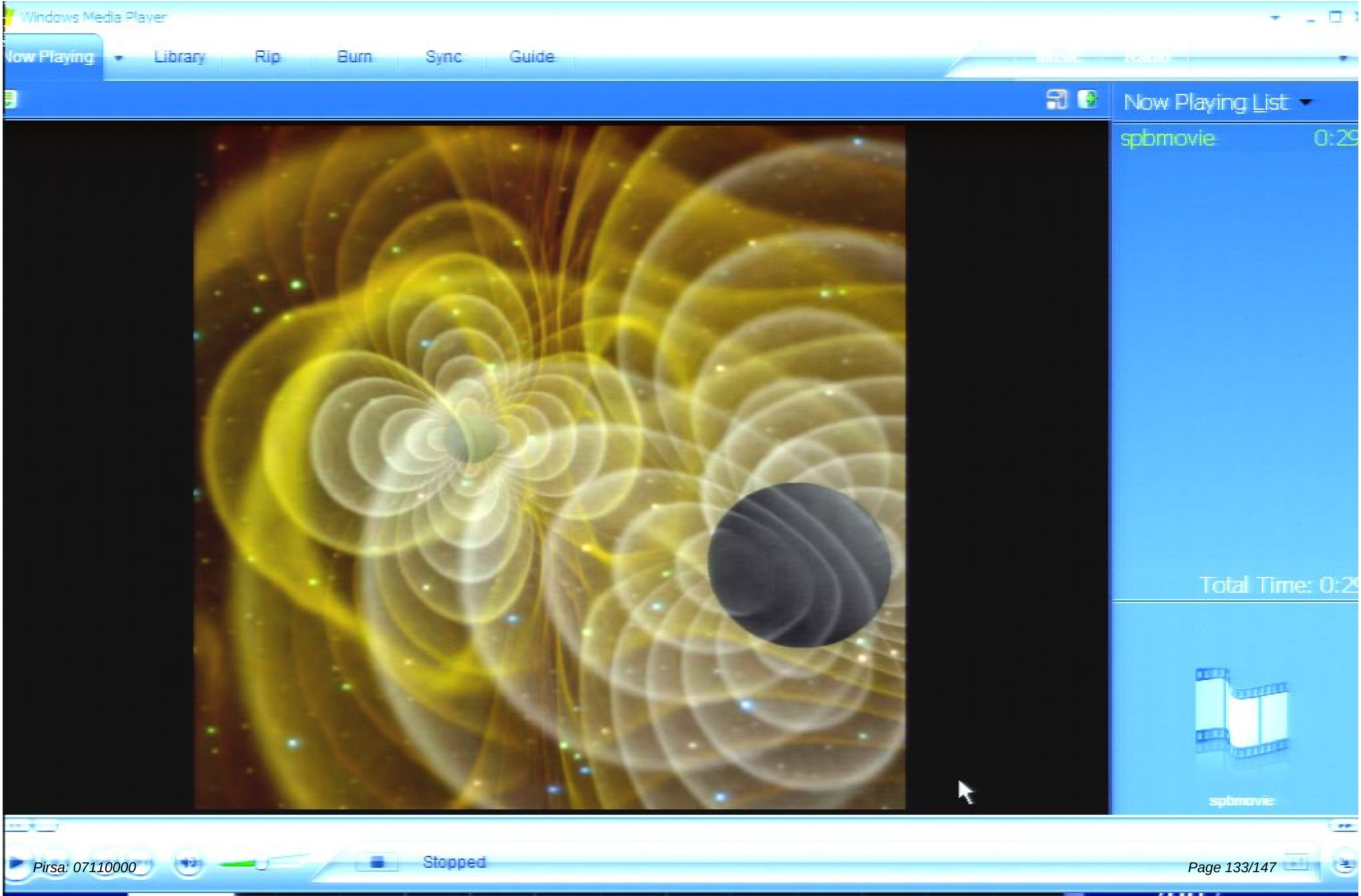

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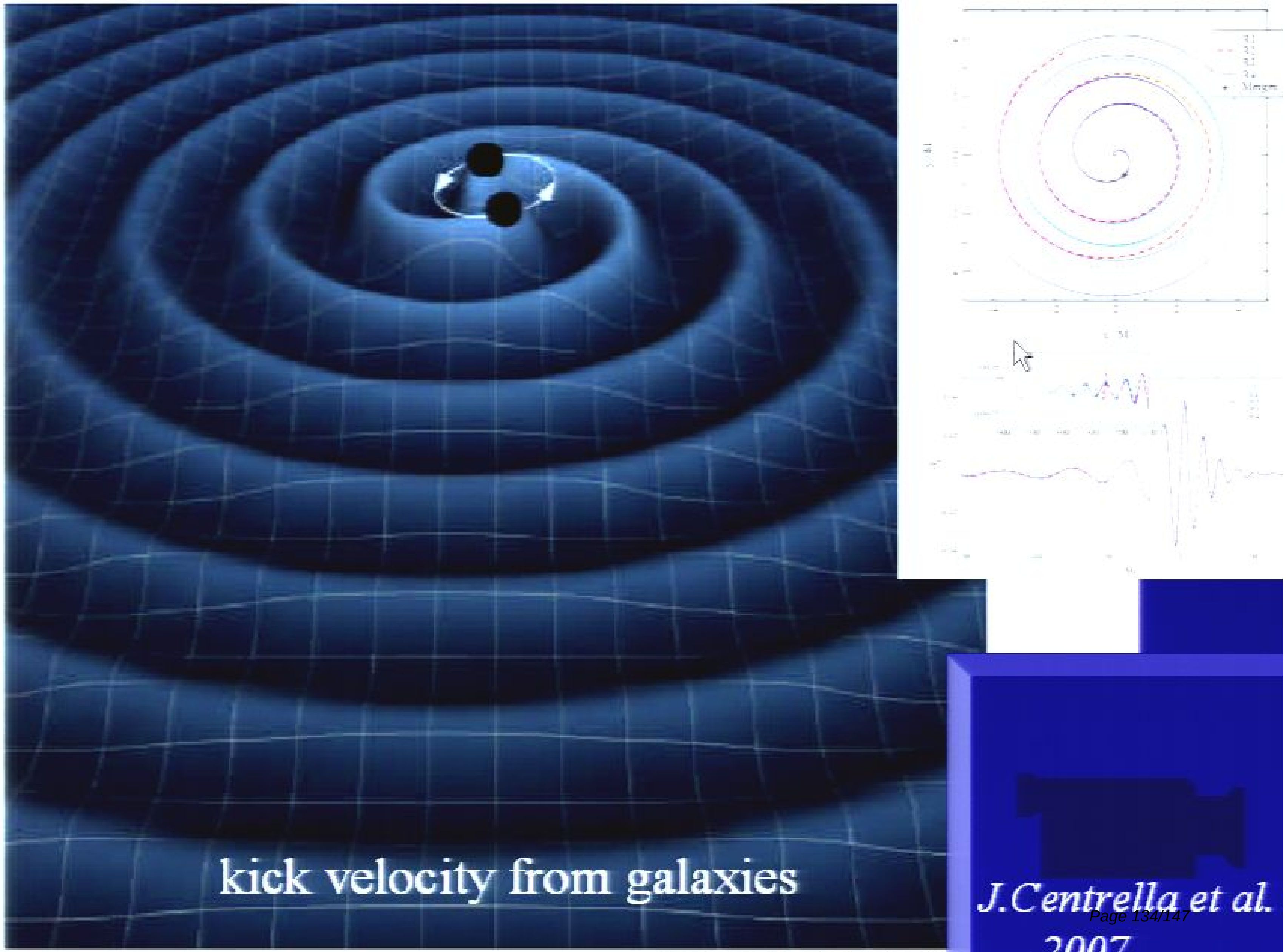
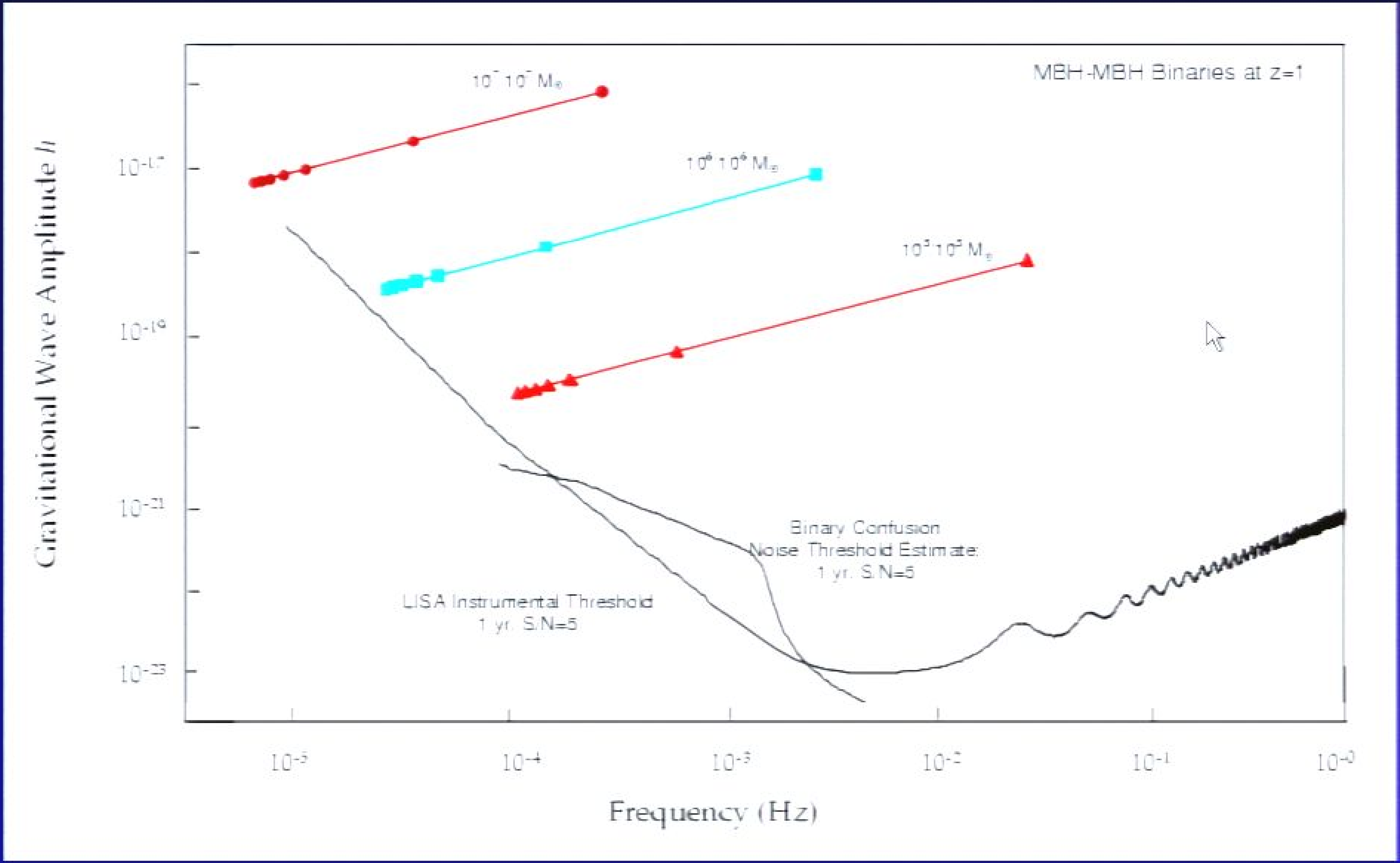


kick velocity from galaxies

K. Thorne (Caltech), T. Carnahan

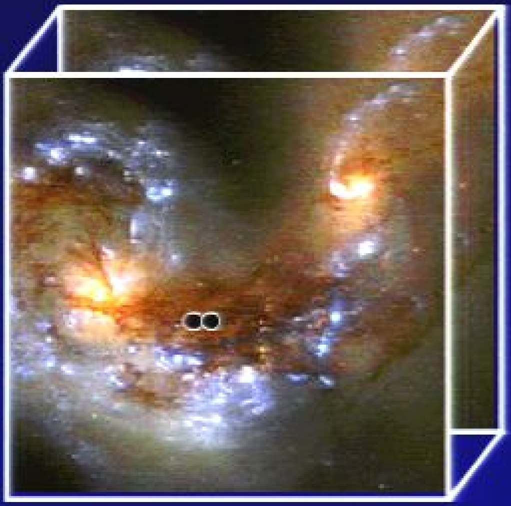
J.Centrella et al. 2007

Gravitational Wave Amplitude from a Black Hole Binary at z=1



Galaxies as "Bubble Chambers"

for BHs ejected by gravitational wave recoil



$R_{\rm in}$

$t_{\rm vis} \sim t_{\rm GW}$

$R_{\rm out} \sim \frac{GM}{v_{\rm ej}^2}$

Loeb, PRL, 2007; astro-ph/0703722

Galaxies as "Bubble Chambers"

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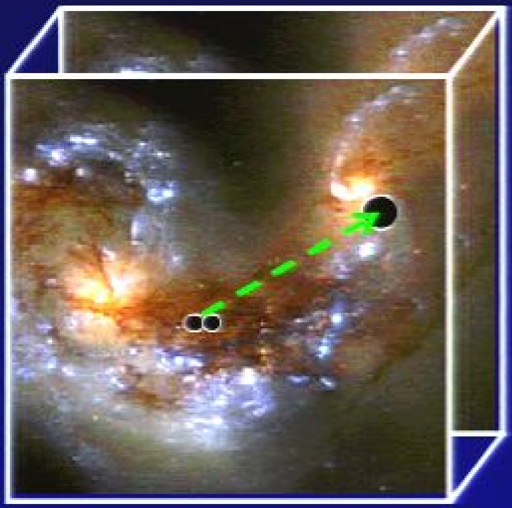
Schnittman & Buonanno 2007



- - - - *Ionization trail*

$$t_{\rm disk} \sim 10^7 {\rm yr}$$

$$d \sim v_{\rm ej} t_{\rm disk} \sim 10{\rm kpc}$$

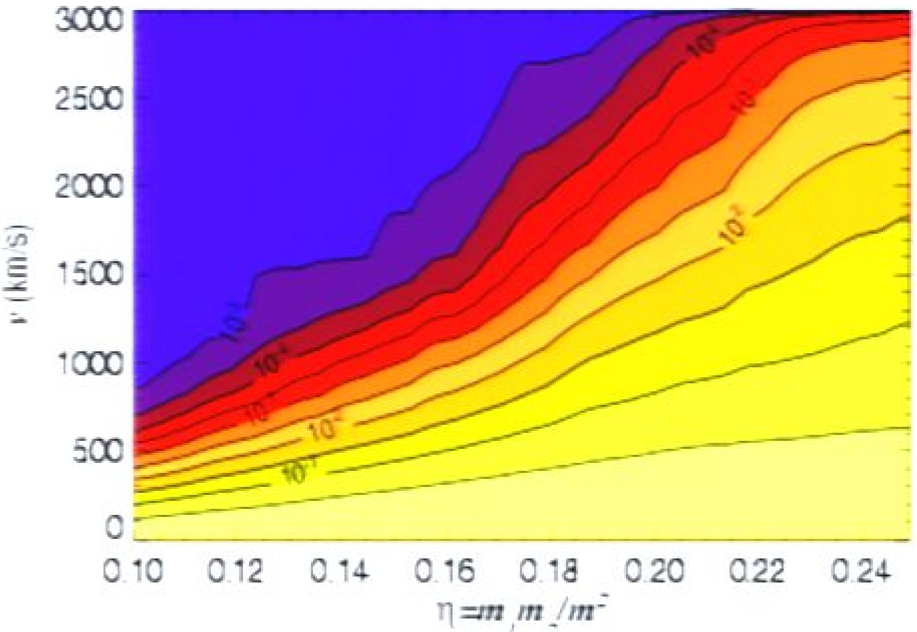


FIG. 4.— Cumulative probability distribution as a function of symmetric mass ratio η. The contours of $f(v;\eta)$ represent the probability of having a recoil velocity greater than v. The spins have amplitude $a_1 = a_2 = 0.9$ and random orientation.

Loeb, PRL, 2007; astro-ph/0703722

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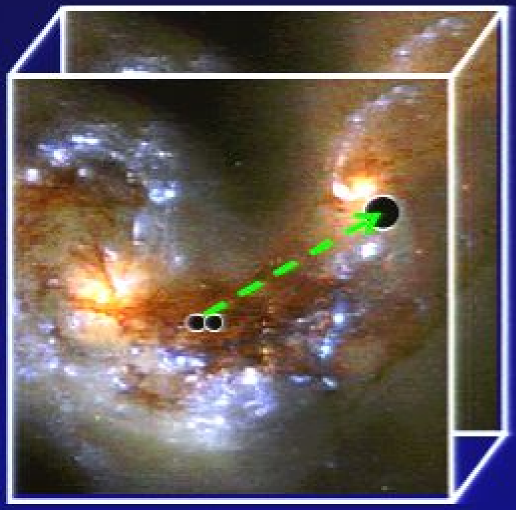

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Bonning, Shields & Salviander 2007

Quasar Velocity Offset

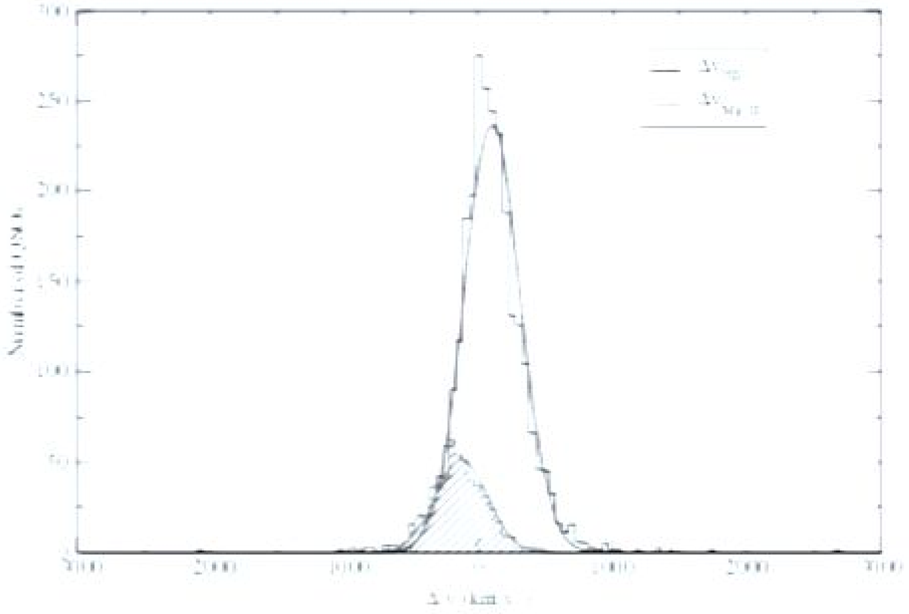


FIG ... g with Gaussian fits
to th ... der than a Gaussian.
with ... rs with $|\Delta v| > 1000$
km s

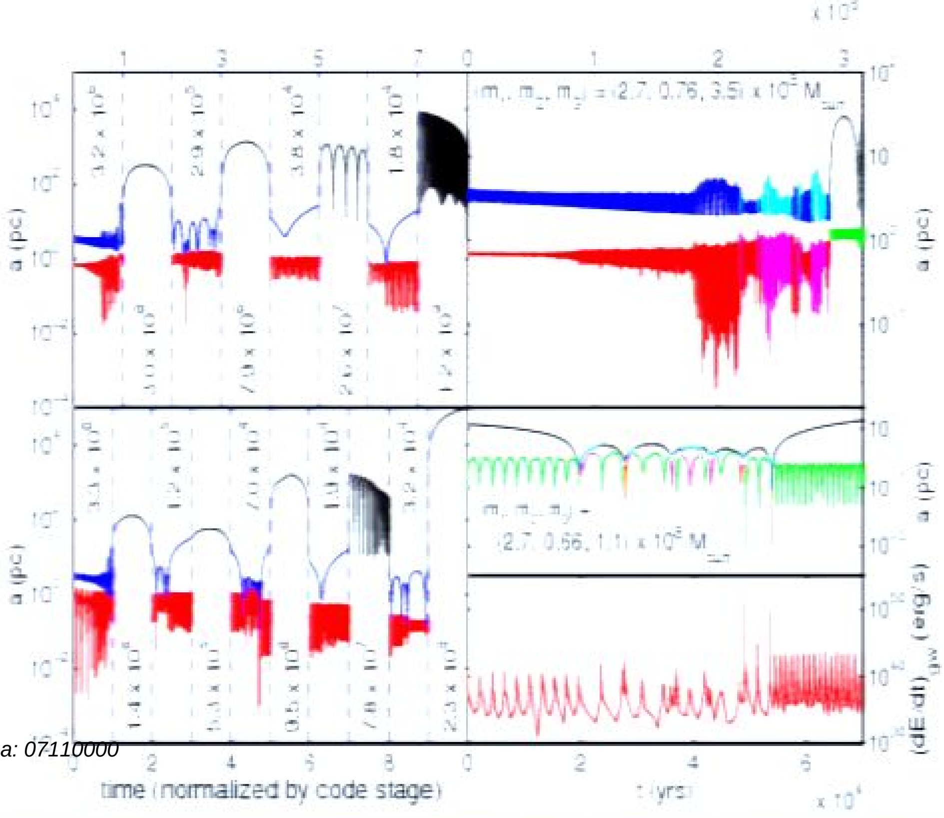
<4% with kicks >500 km s

<0.35% with >1000 km s

Loeb, PRL, 2007; astro-ph/0703722

Hierarchical Black Hole Triples

- Gravitational radiation kicks provide $v < 500\mathrm{km\ s}^{-}$
- Slingshot is a mechanism capable of ejecting SMBHs out of galaxy cores with $v \sim 10^3\ \mathrm{km/s}$

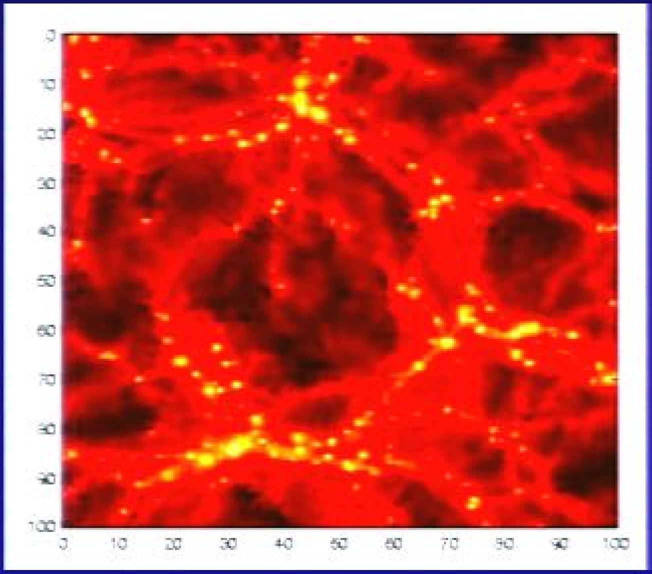


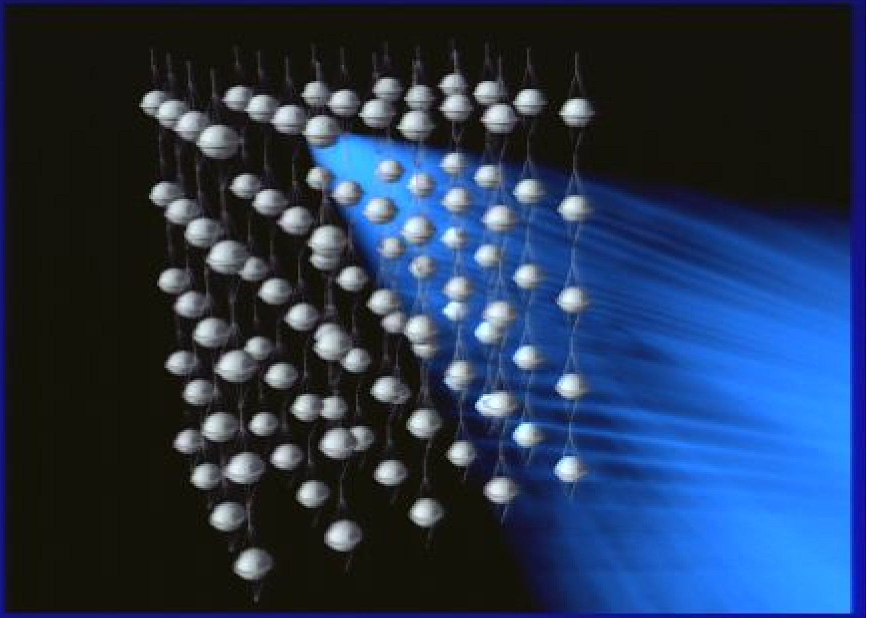
. Left panels: Entire run, with time spent in each code stage normalized to unity. Actual times in years are indicated by the numbers on the plot. The red (inner binary) and blue (outer binary) portions show the close encounters, while the black portions show the calls to the RK4 integrator. Upper right: Zoom in on the first close encounter in the run at left. Lines are color-coded according to which pair is closest, to highlight the exchanges. Lower right: Zoom in on the third close encounter of the lower run, showing also the total gravitational radiation power averaged over Bulirsch-Stoer timesteps.

(Hoffman & Loeb astro-ph/0612517)

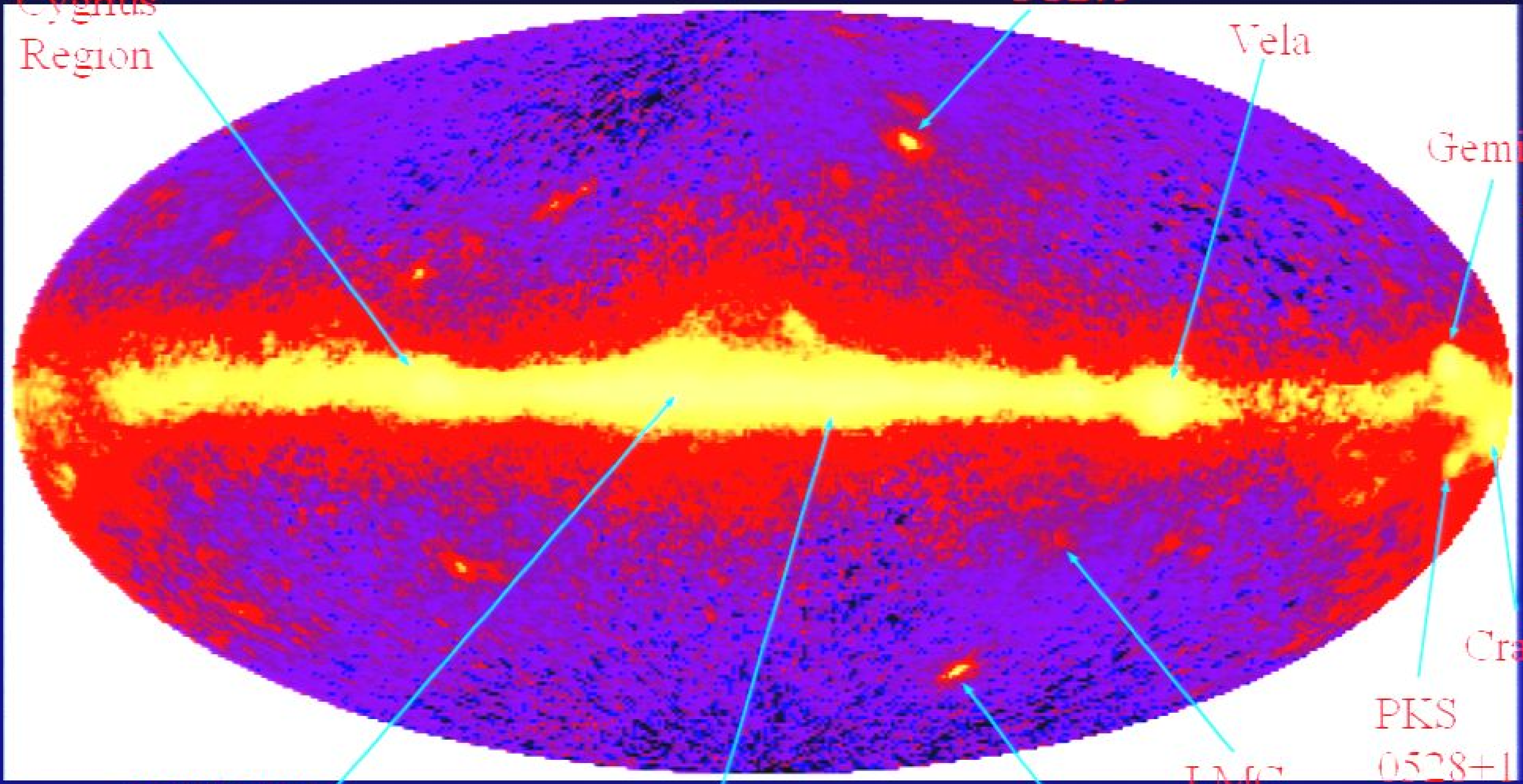
Cosmic Accelerators:

high-energy (billion TeV) particles





EGRET All Sky Map (>100 MeV)

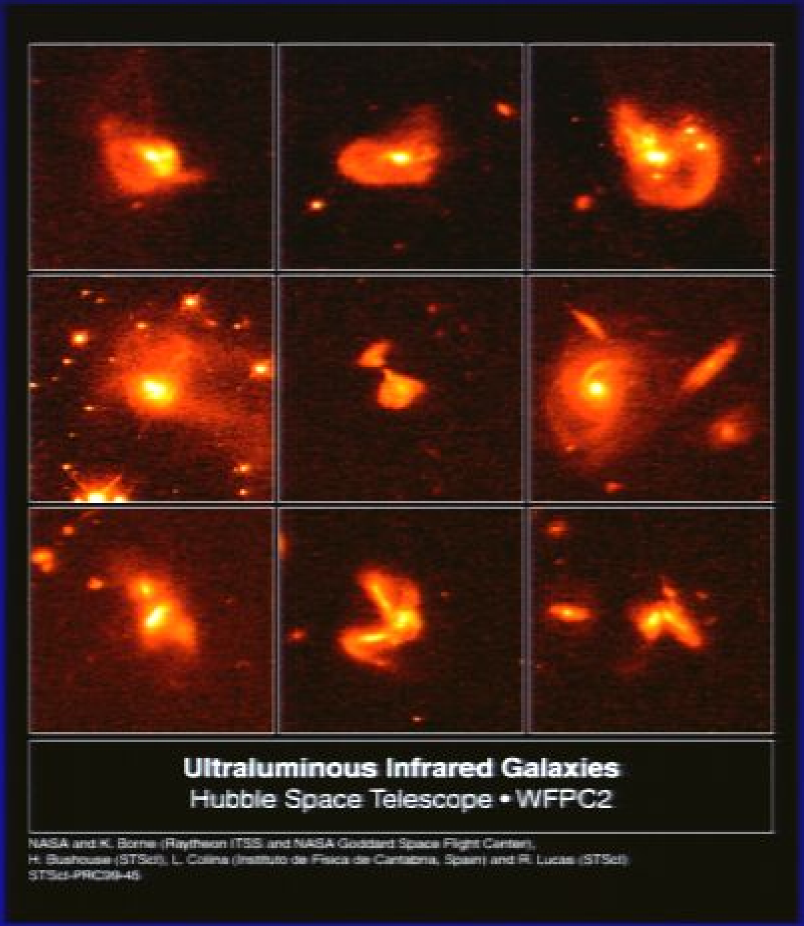


“Accelerator Beam Dump” for collisionless shocks in galaxies

“Accelerator Beam Dump” for collisionless shocks in galaxies

Ultraluminous Infrared Galaxies (ULIRGs):
Factories of High-Energy Neutrinos

- ULIRGs discovered by IRAS in mid 80’s
- $L_{FIR} > 10^{12} L_{\odot} >> L_{optical}$ (dusty)
- Disturbed Morphologies: Mergers
- Powered by nuclear starbursts &/or obscured AGN (much debated)
- Key phase in growth of elliptical galaxies and massive black holes



Ultraluminous Infrared Galaxies
Hubble Space Telescope • WFPC2

NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center),
H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)
STScI-PRC99-45

Fate of Injected Cosmic-Rays

- The energy loss time of a relativistic proton

$$\tau_{\rm loss} \sim (0.5 n \sigma_{pp} c)^{-1} ; \sigma_{pp} \sim 50 {\rm mb}$$

- The starburst lifetime (a few dynamical times)

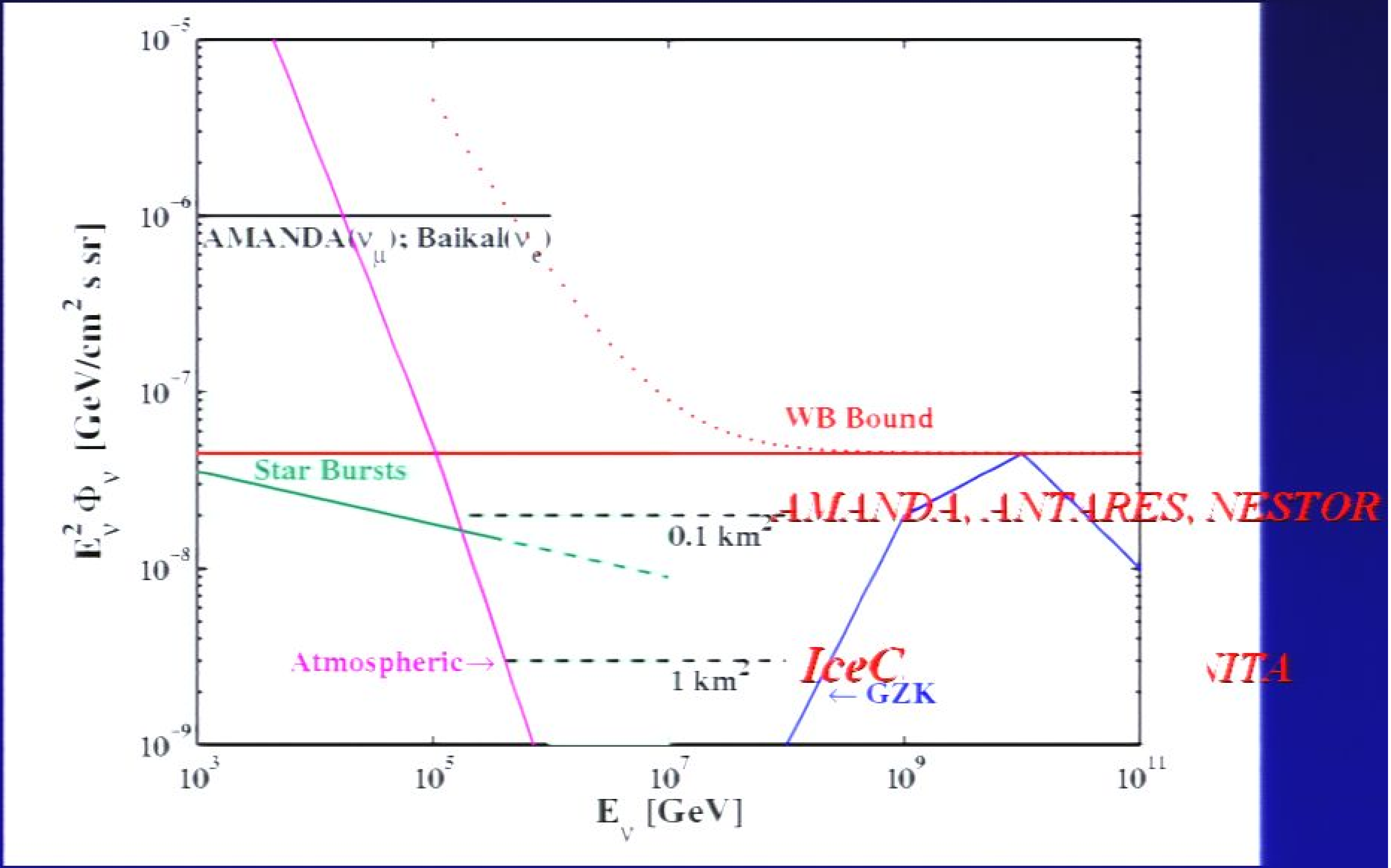
$$t_{\rm dyn} \sim (300{\rm pc}/300{\rm km/s}) \sim 10^6 {\rm yr}$$

- SN injected protons will dissipate all their energy if $\tau_{\rm loss} < t_{\rm dyn} \rightarrow \Sigma_{\rm gas} > \Sigma_{\rm crit}$

$$\Sigma_{\rm crit} \equiv \frac{m_p v}{\sigma_{pp} c} = 3 \times 10^{-2} \left(\frac{v}{10^{-3} c}\right) \ {\rm g/cm^2}$$

Matches the minimum surface density of starburst galaxies!

Cosmic Background of High-Energy Neutrinos



Loeb & Waxman, astro-ph/0601695

UHECRs

- Present-day energy production rate of relativistic protons in starburst galaxies

$$12\nu(\frac{dL_v}{dV})_{\rm GHz} \approx 10^{44}{\rm ergs/Mpc^3/yr}$$

is comparable to the energy production rate of ultra high-energy cosmic-rays, potentially because the former applies to $\Sigma_{\rm gas} > \Sigma_{\rm crit}$ and the latter to $\Sigma_{\rm gas} < \Sigma_{\rm crit}$, with the two matching at $\Sigma_{\rm gas} \sim \Sigma_{\rm crit}$

Highlights

- *Redshifted 21cm from $3<z<200$ provides the largest data set on the initial conditions of the universe*
- *Direct imaging of the nearest supermassive black holes might become feasible within the next decade*
- *Cosmic shocks and starburst galaxies accelerate particles to energies well above those accessible by the Large Hadron Collider*