21cm Cosmology: The New Age of Cosmic Exploration

Isla Guadalupe NW Mexican Pacific Ocean

Instituto Nacional de Astrofísica, Optica y Electrónica.

Coordinación de Astrofísica

Omar López-Cruz,
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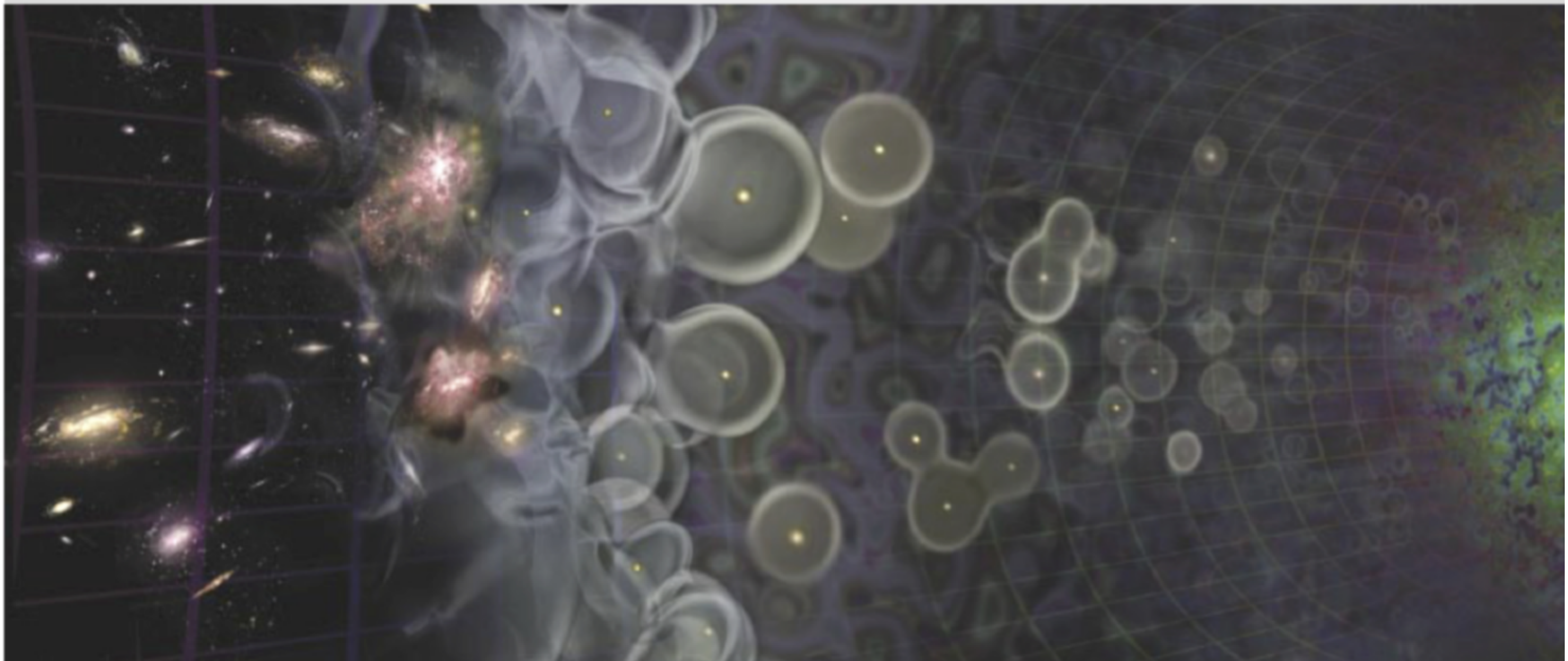
For the Sci-HI collaboration

II Taller de Gravitación, Físca de Altas Energías y Cosmologia, ICF-UNAM, Cuernavaca Morelos

A "new" probe of the high redshift intergalactic medium that has the *potential* to be a game-changer in cosmology, astrophysics & astroparticle physics.

The History of Hydrogen Gas



1 10 redshift 100 1000

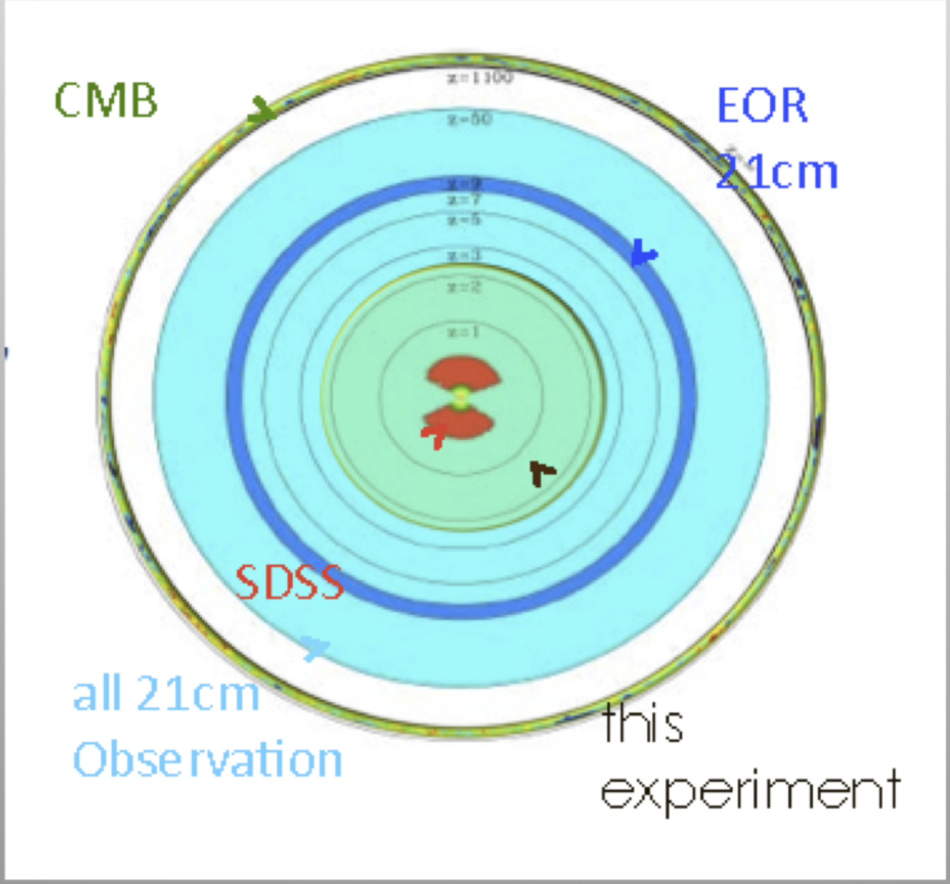
CRT
GBT
Arecibo

LOFAR
MWA
PAPER
GMRT
PaST/21CMA

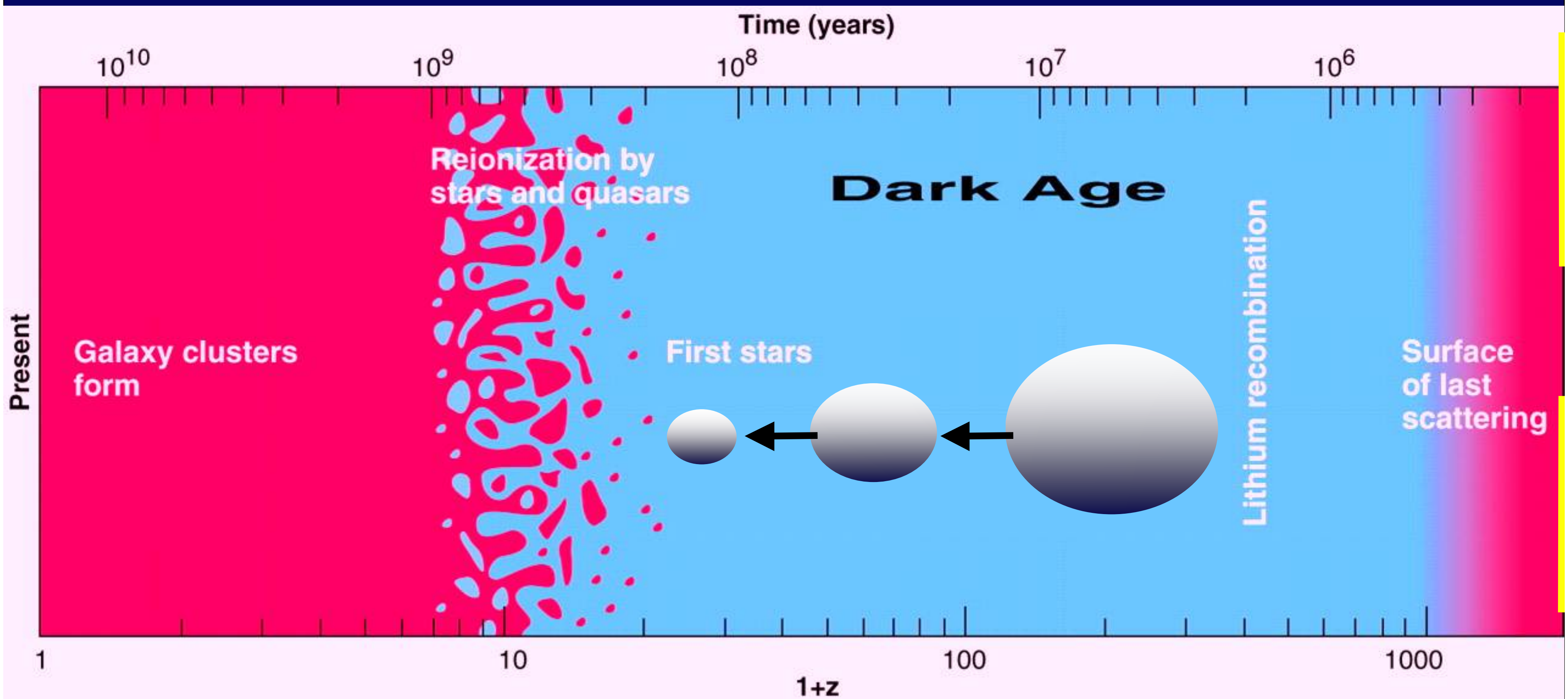
Lunar or
Antarctic Array

Image: Scientific American 2006

21-cm observations are three dimensional and can cover huge co-moving volumes



An Outline of the Cosmic History



Galaxy evolution

Reionization Era:
The Cosmic

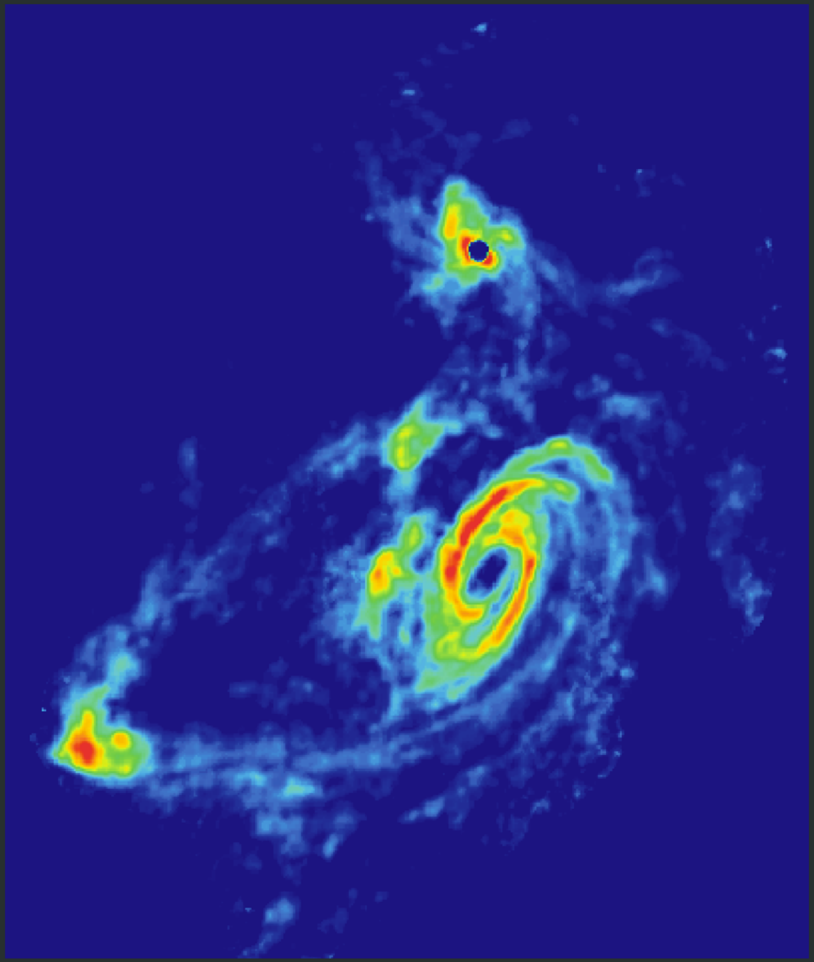
Dark Ages:
Collapse of Density

Recombination:
Release of the CMBR

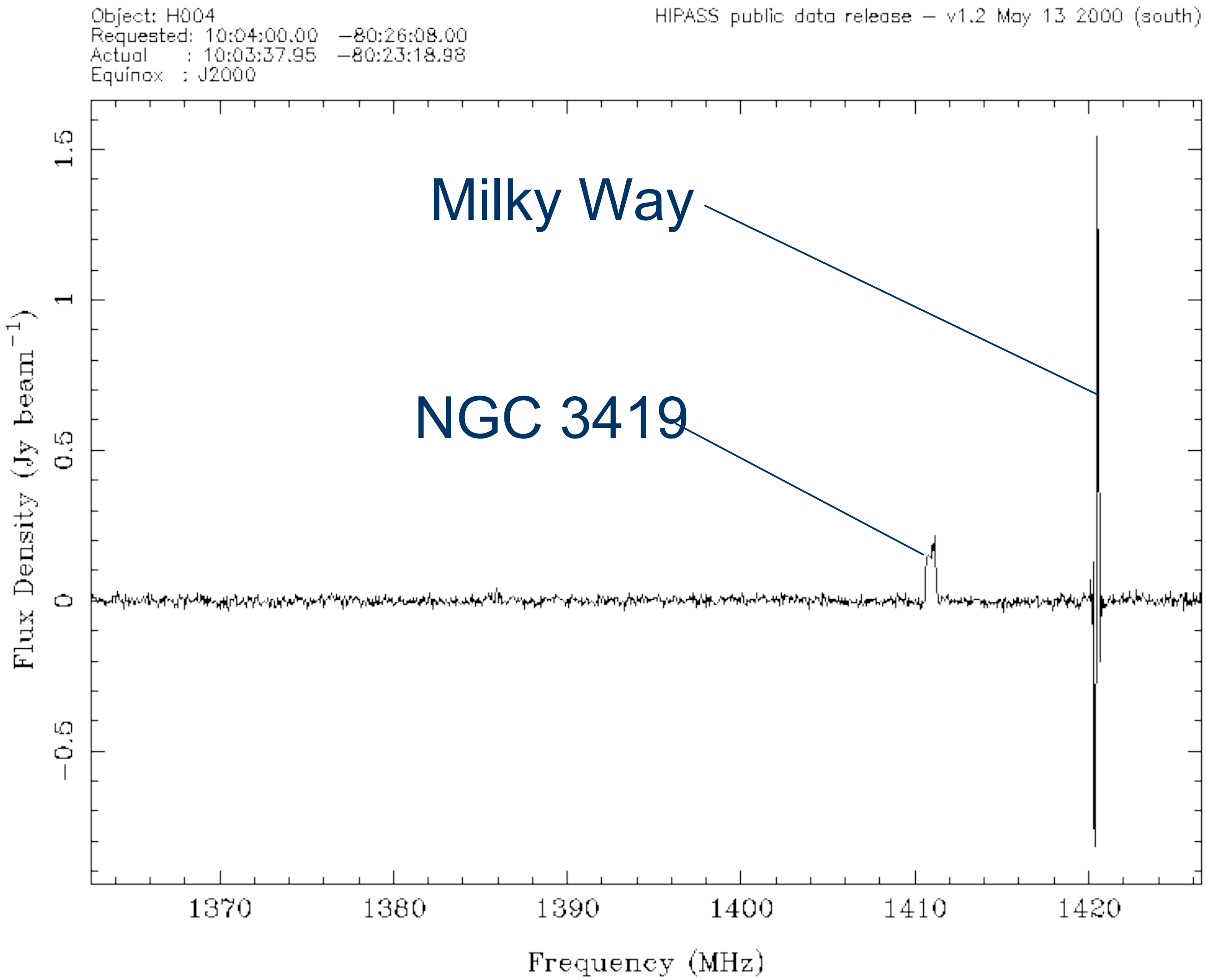
TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

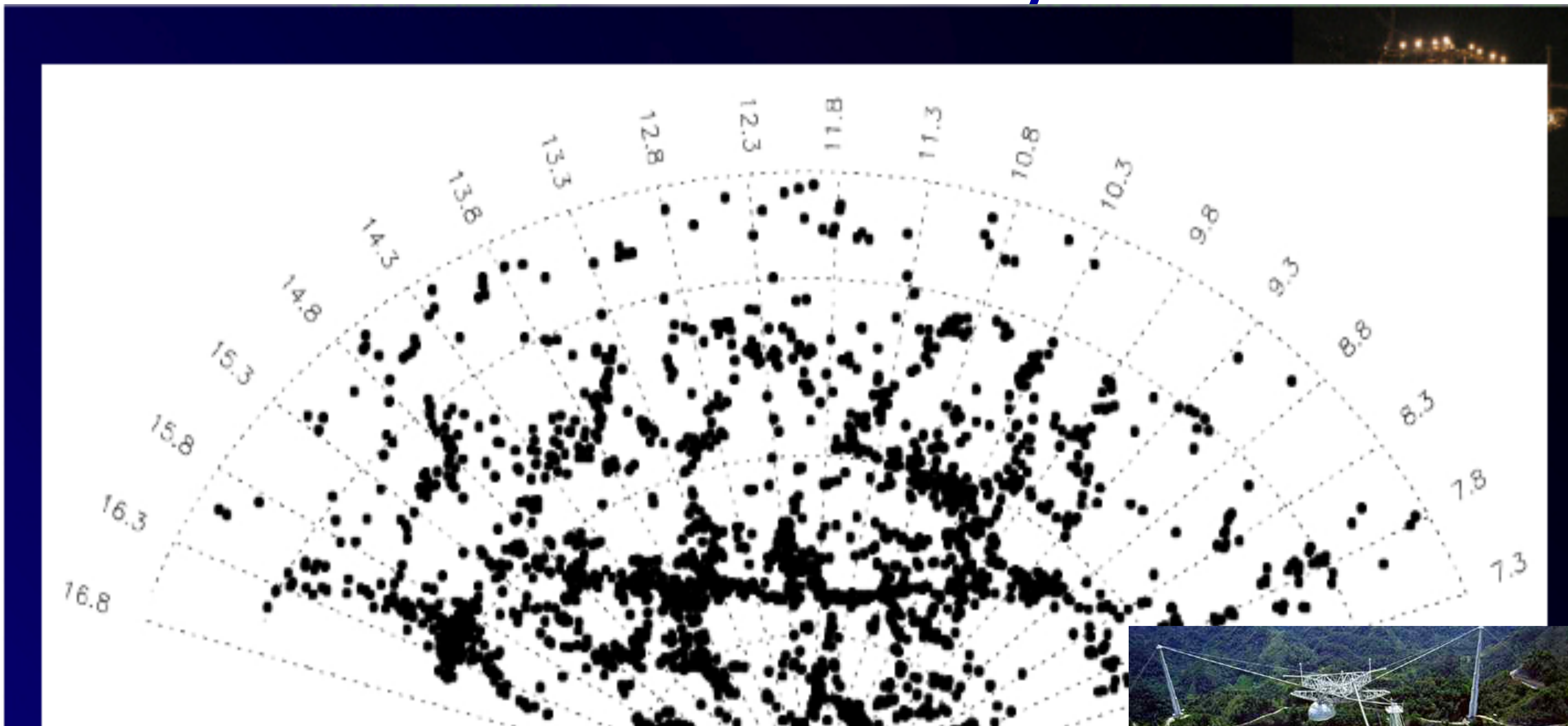
21 cm HI Distribution



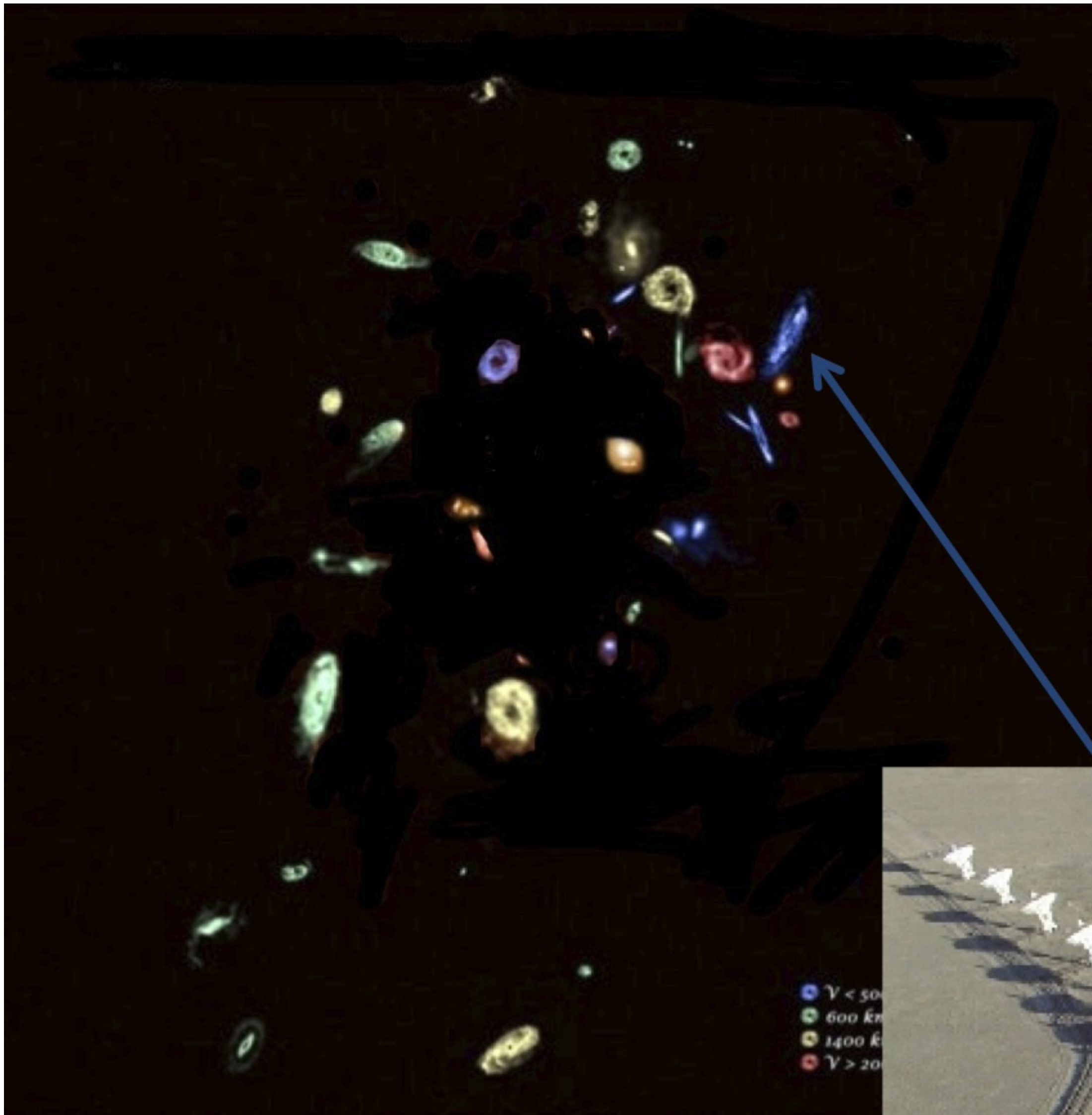
Data from Parkes Telescope



Alfalfa redshift survey

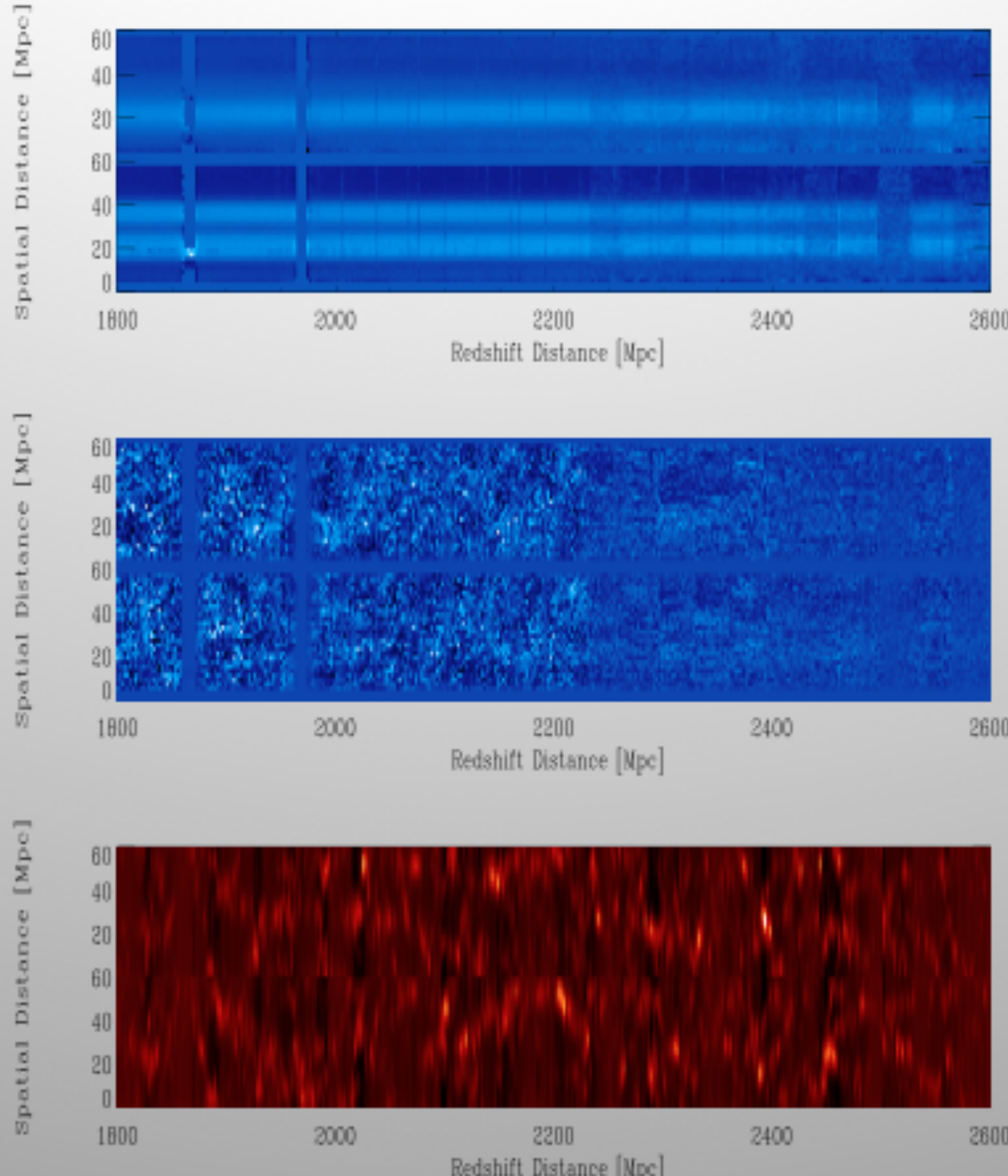


Large scale structure matches optical surveys

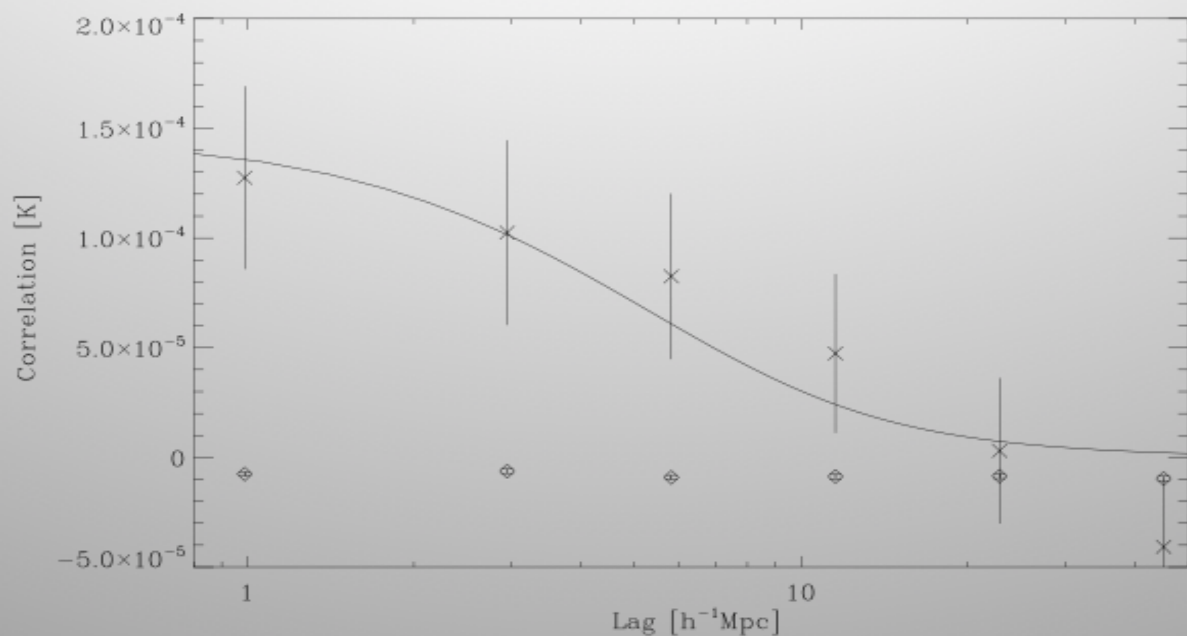


21 cm galaxy images,
Form the VIVA project.

Very Large Array


Spatial Distance [Mpc]
60
40
20
60
40
20
0
1800
2000
2200
2400
2600
Redshift Distance [Mpc]
Spatial Distance [Mpc]
60
40
20
60
40
20
0
1800
2000
2200
2400
2600
Redshift Distance [Mpc]
Spatial Distance [Mpc]
60
40
20
60
40
20
0
1800
2000
2200
2400
2600
Redshift Distance [Mpc]

21cm – DEEP2 cross correlation

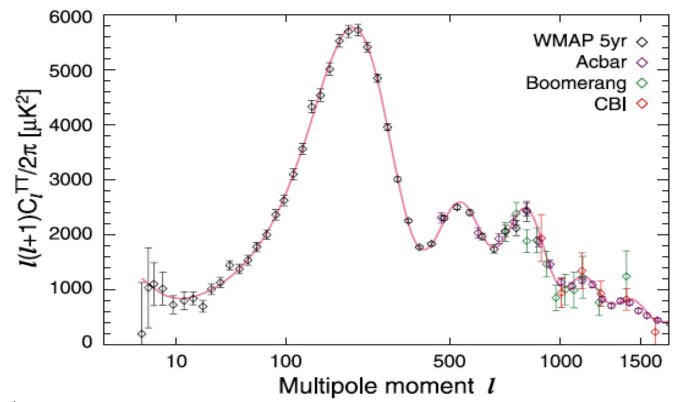


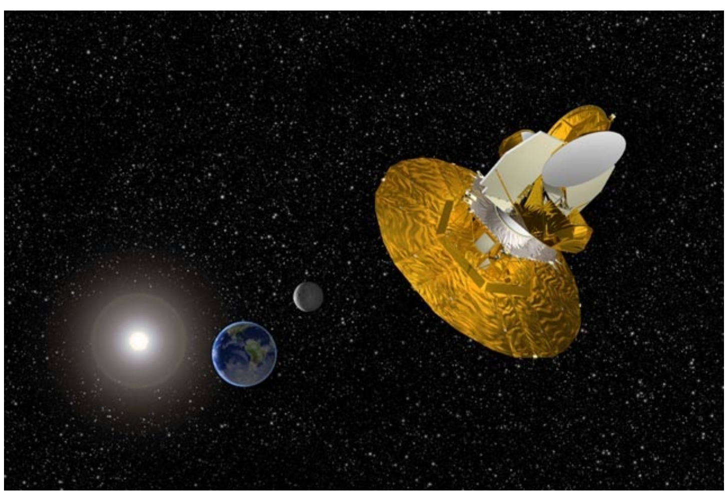
Chang, Pen, Bandura, JP, 2010

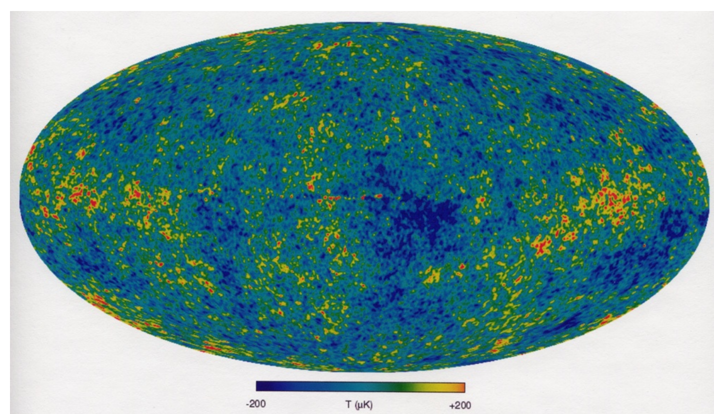
Baryon Acoustic Oscillations – Dark Energy Probe

CMB acoustic oscillations: imprinted standard ruler, 400 Mly.

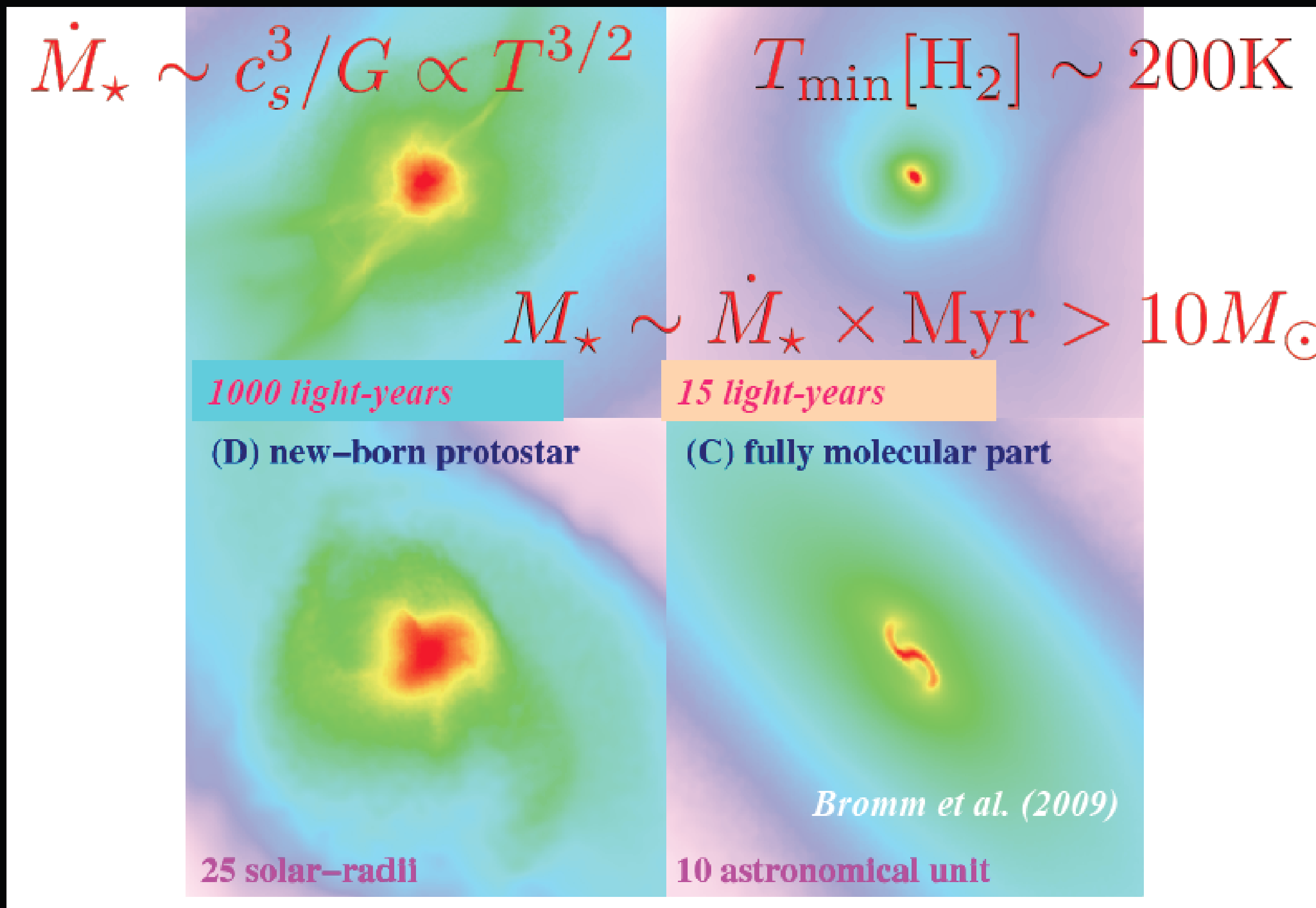
WMAP5 and other, Nolta et al (2008)

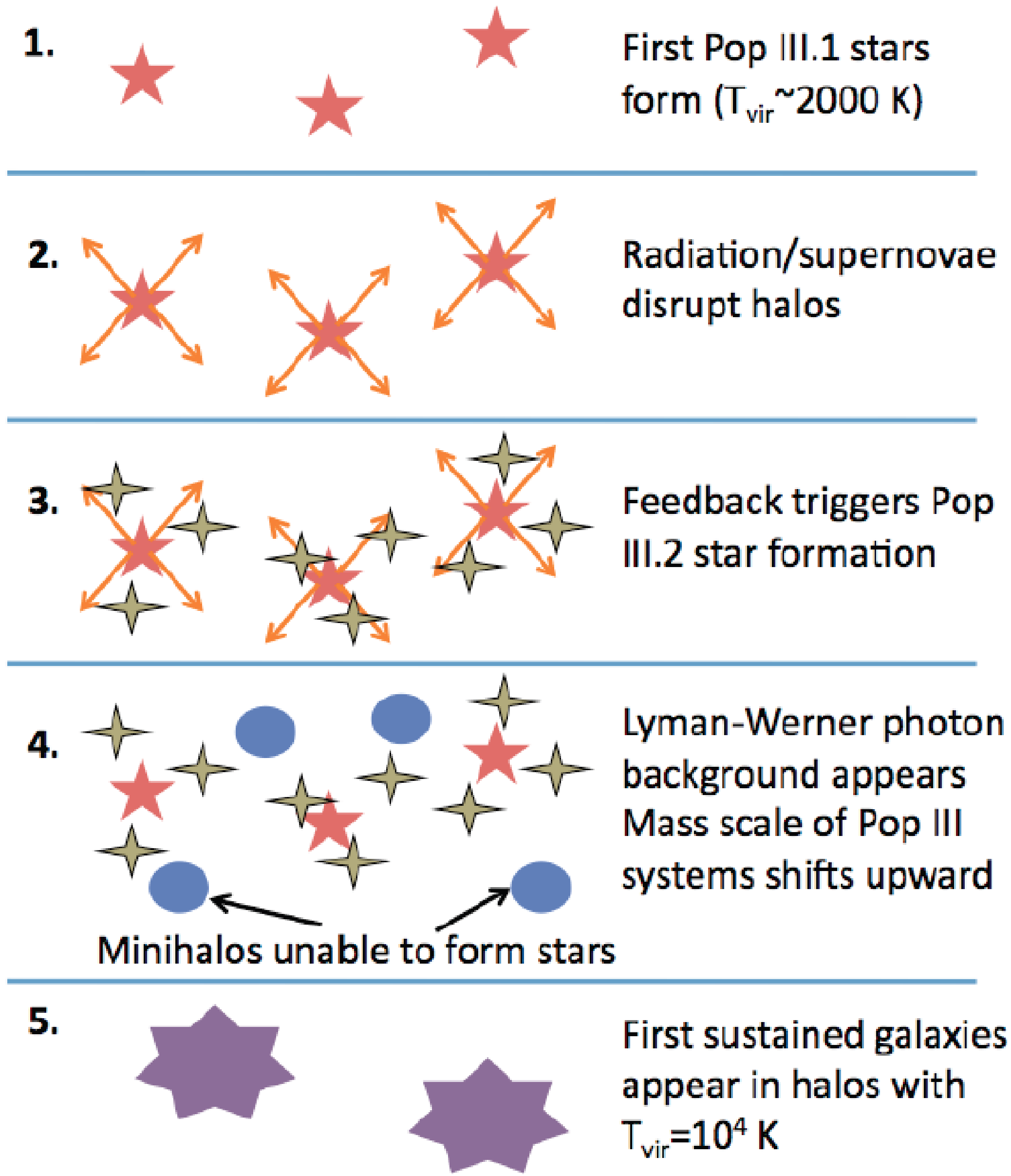




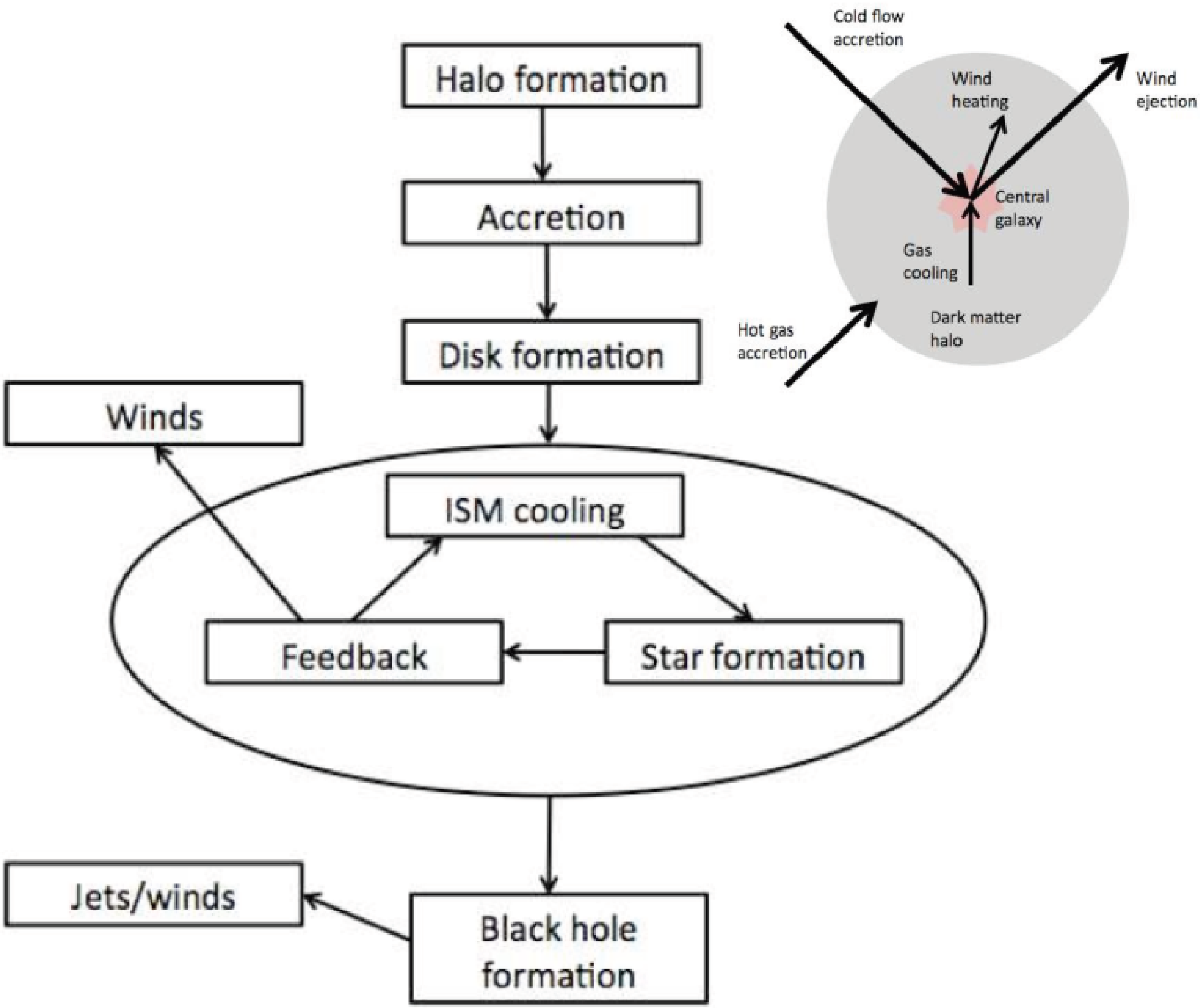


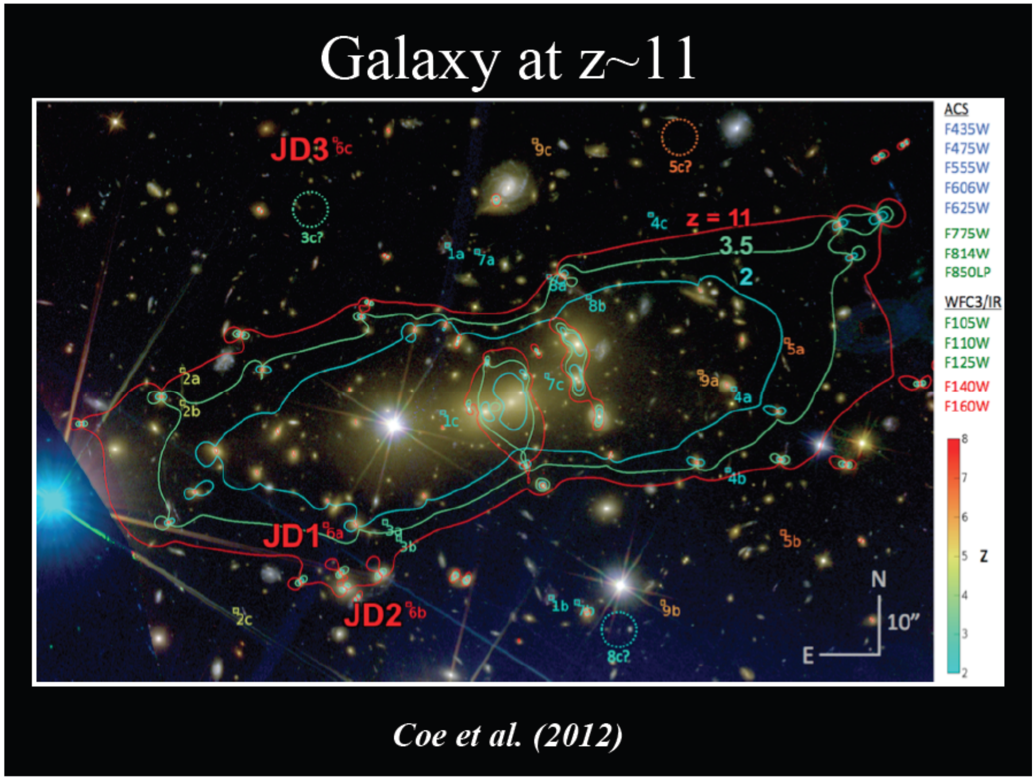
The First Stars Are Predicted to Have Formed ~100 Million Years After the Big Bang

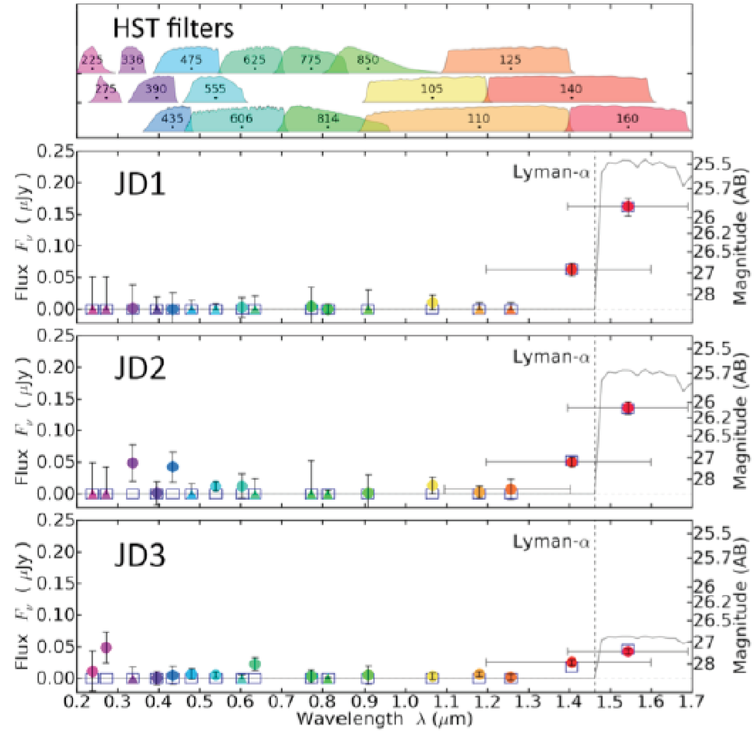


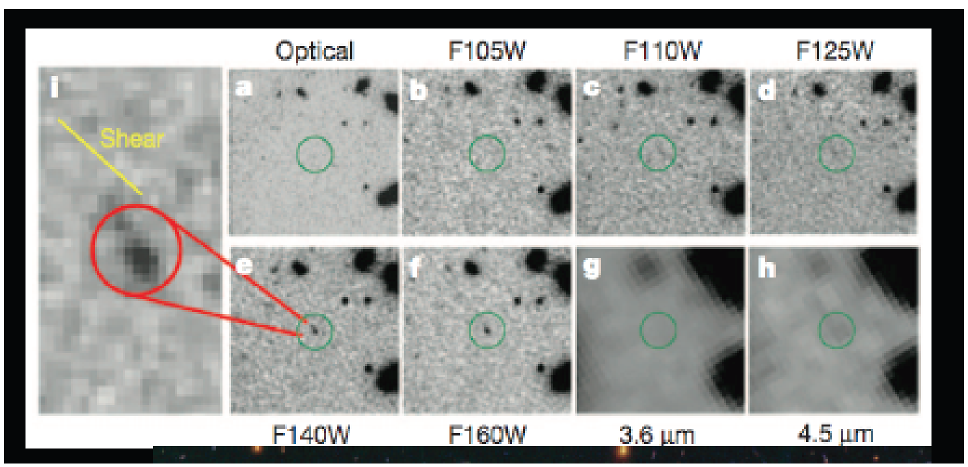


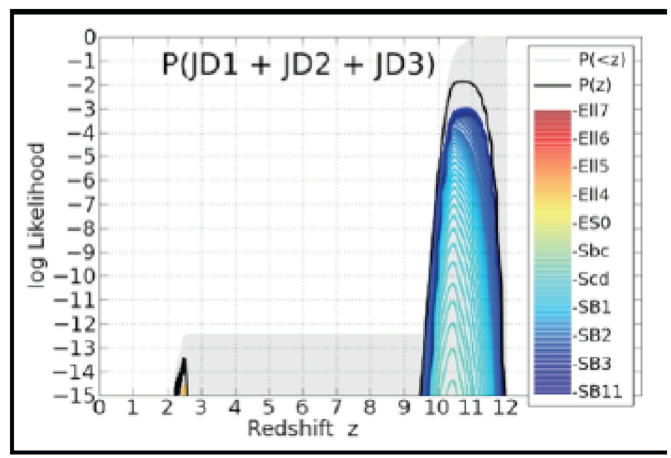
1.
First Pop III.1 stars form (T_{vir}~2000 K)
2.
Radiation/supernovae disrupt halos
3.
Feedback triggers Pop III.2 star formation
4.
Lyman-Werner photon background appears
Mass scale of Pop III systems shifts upward
Minihalos unable to form stars
5.
First sustained galaxies appear in halos with $T_{vir}=10^4$ K


Halo formation
Accretion
Disk formation
Winds
ISM cooling
Feedback
Star formation
Jets/winds
Black hole formation
Cold flow accretion
Wind heating
Wind ejection
Central galaxy
Gas cooling
Hot gas accretion
Dark matter halo


Galaxy at z~11
JD1
JD2
JD3
z = 11
3.5
2
ACS
F435W
F475W
F555W
F606W
F625W
F775W
F814W
F850LP
WFC3/IR
F105W
F110W
F125W
F140W
F160W
z
N
E
10″
Coe et al. (2012)


HST filters
JD1
JD2
JD3
Lyman-α
Flux F_ν (μJy)
Magnitude (AB)
Wavelength λ (μm)


Shear
Optical
F105W
F110W
F125W
F140W
F160W
3.6 μm
4.5 μm

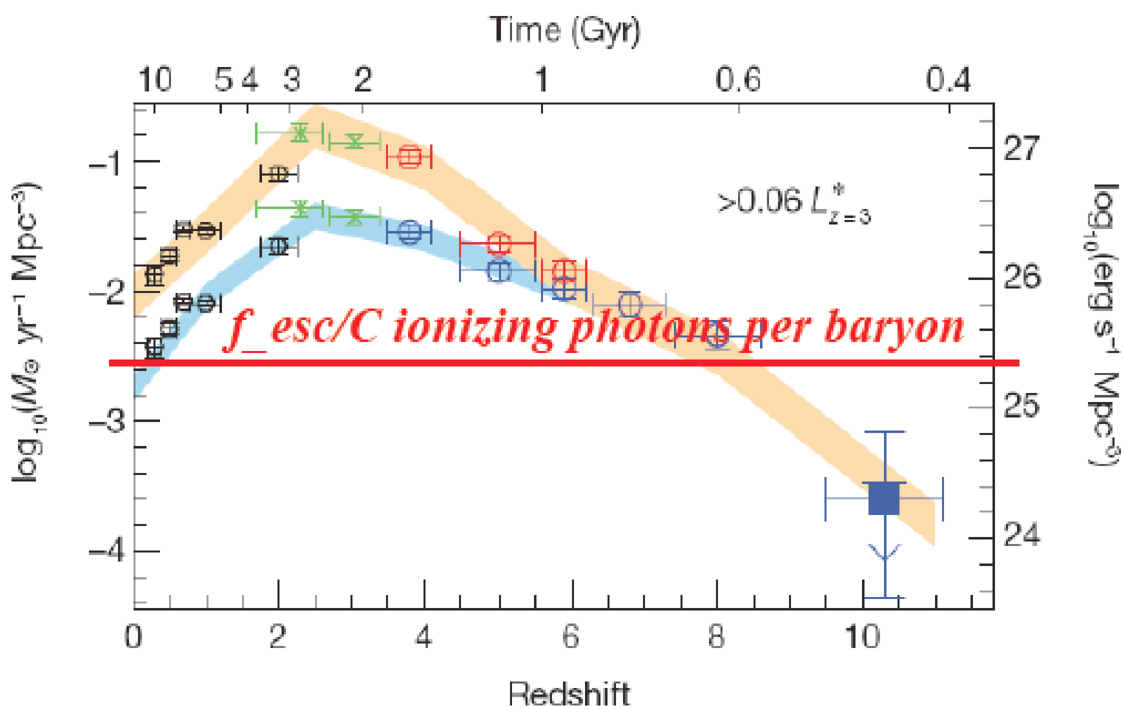

P(JD1 + JD2 + JD3)
log Likelihood
Redshift z
P(<z)
P(z)
Ell7
Ell6
Ell5
Ell4
ES0
Sbc
Scd
SB1
SB2
SB3
SB11

- To produce one ionizing photon per baryon:

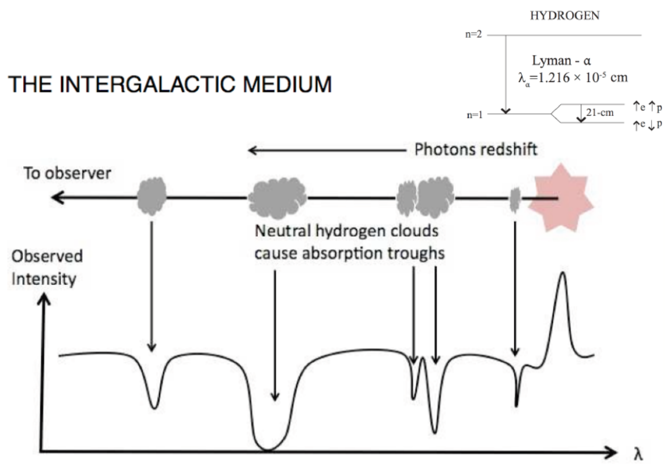
$$\rho_\star \approx 1.7 \times 10^6 f_{\rm esc}^{-1} \; M_\odot {\rm Mpc}^{-3}$$

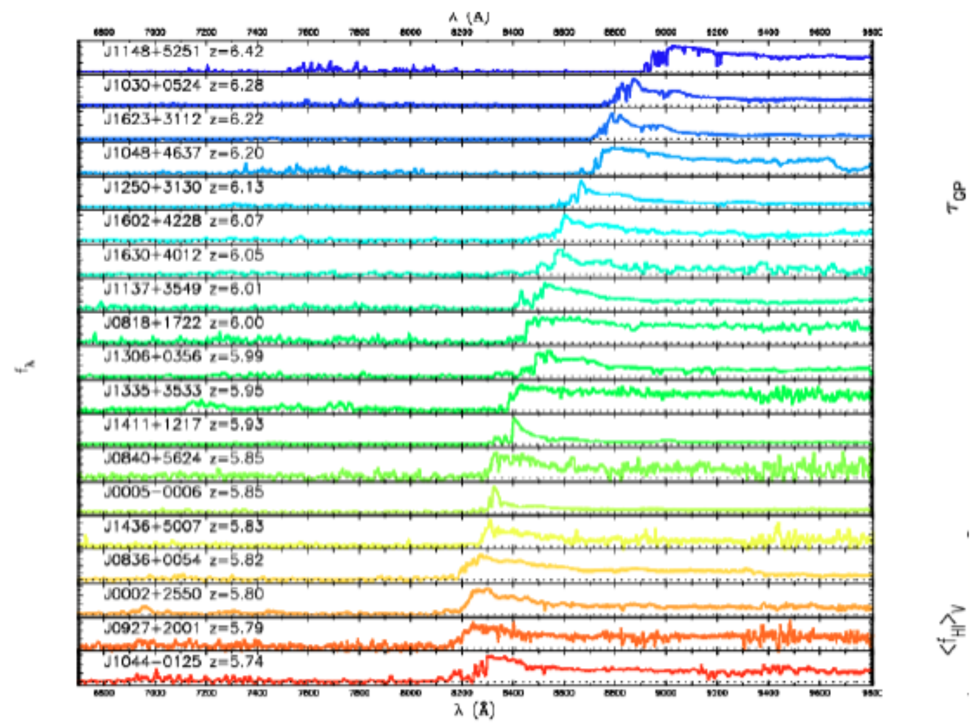
- To keep the IGM ionized by compensating for recombinations:

$$\dot\rho_\star \approx 2 \times 10^{-3} f_{\rm esc}^{-1} C \left(\frac{1+z}{10}\right)^3 \; M_\odot \; {\rm yr}^{-1} \; {\rm Mpc}^{-3}$$



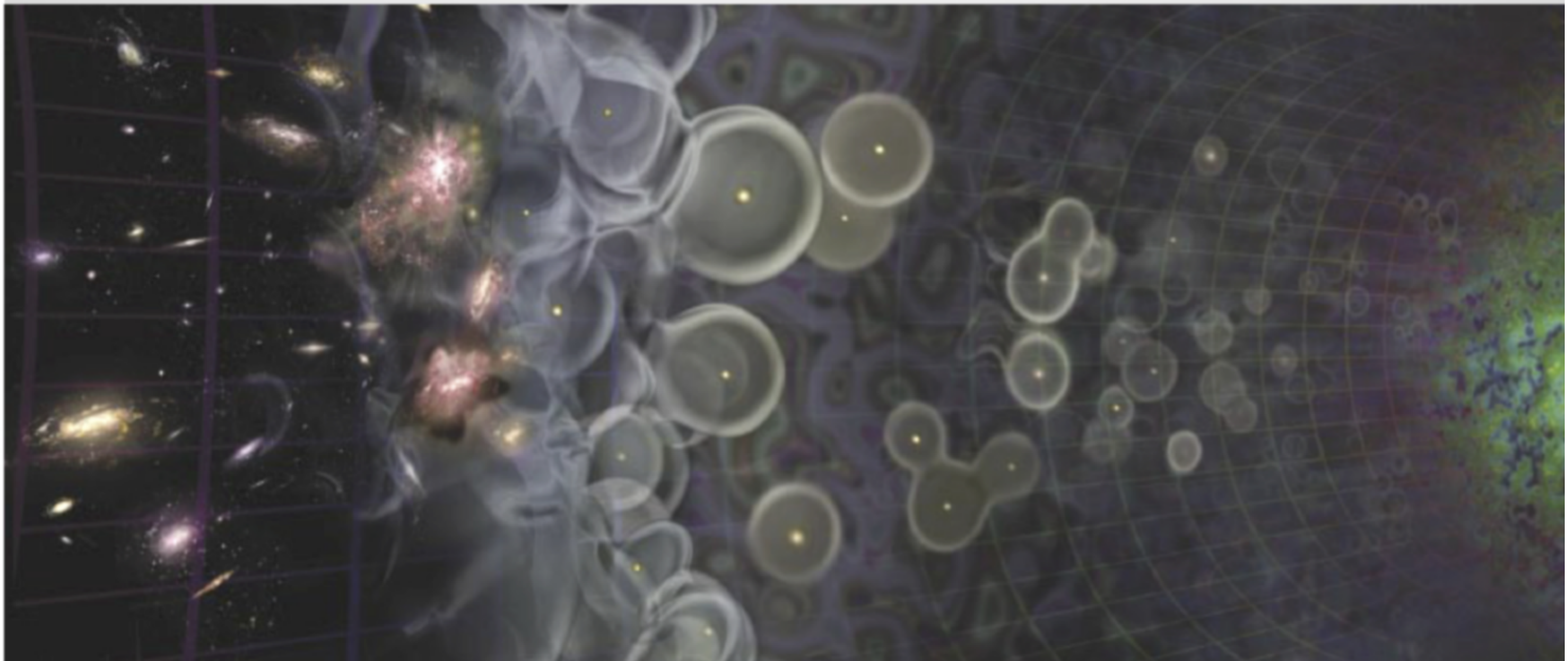
Observing Intergalactic Gas: mainly using high-z QSOs





Spectra of our sample of nineteen SDSS quasars at $5.74 < z < 6.42$. Twelve of the spectra were taken with Keck/ESI, while the others were observed with the MMT/Red Channel and Kitt

The History of Hydrogen Gas



1 10 redshift 100 1000

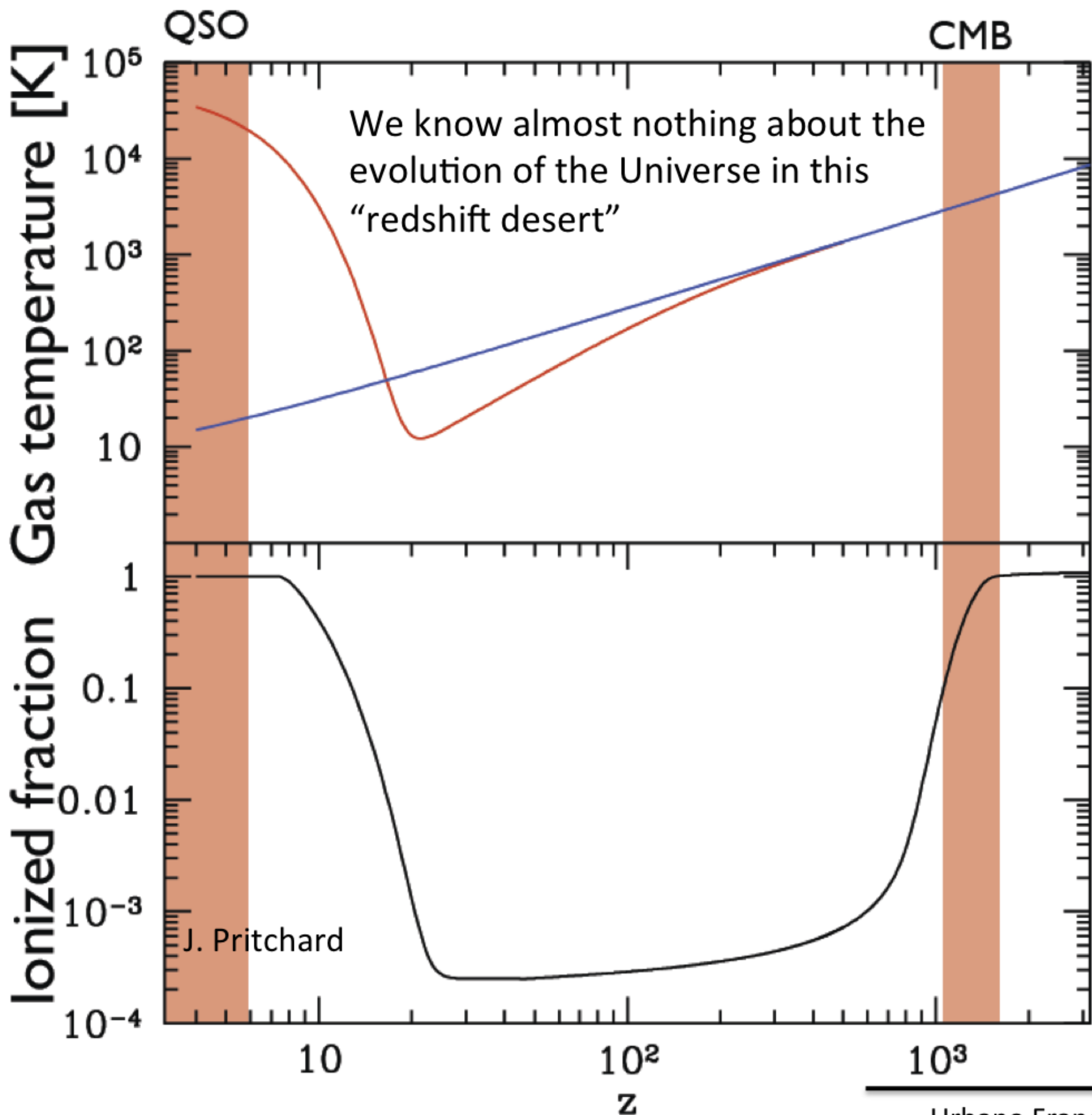
CRT
GBT
Arecibo

LOFAR
MWA
PAPER
GMRT
PaST/21CMA

Lunar or
Antarctic Array

Image: Scientific American 2006

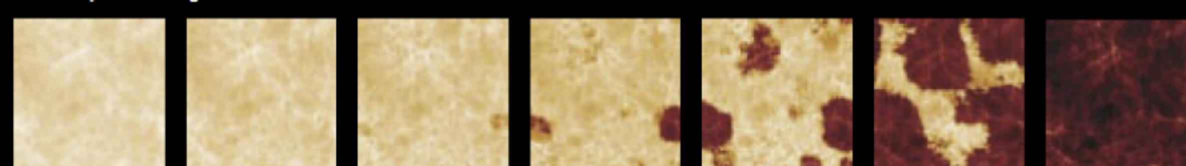
21-cm cosmology


QSO
CMB
We know almost nothing about the evolution of the Universe in this "redshift desert"
Gas temperature [K]
10⁵
10⁴
10³
10²
10
Ionized fraction
1
0.1
0.01
10⁻³
10⁻⁴
J. Pritchard
10
10²
10³
z

LIGHTING UP THE COSMOS

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

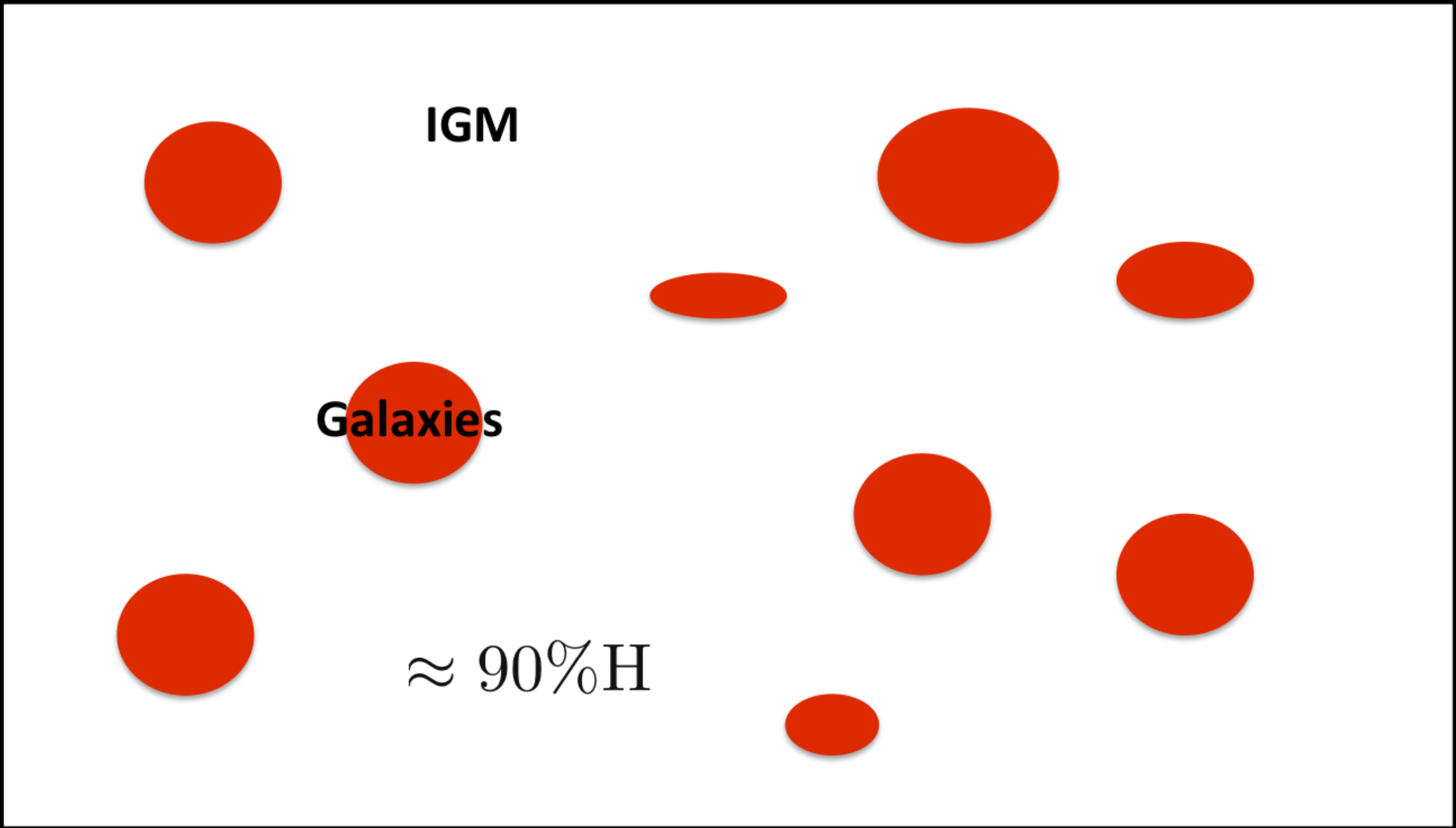
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-years
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 remaining neutral hydrogen is concentrated in galaxies.



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

Loeb 2006, *SciAm*

Poor man's view of the universe



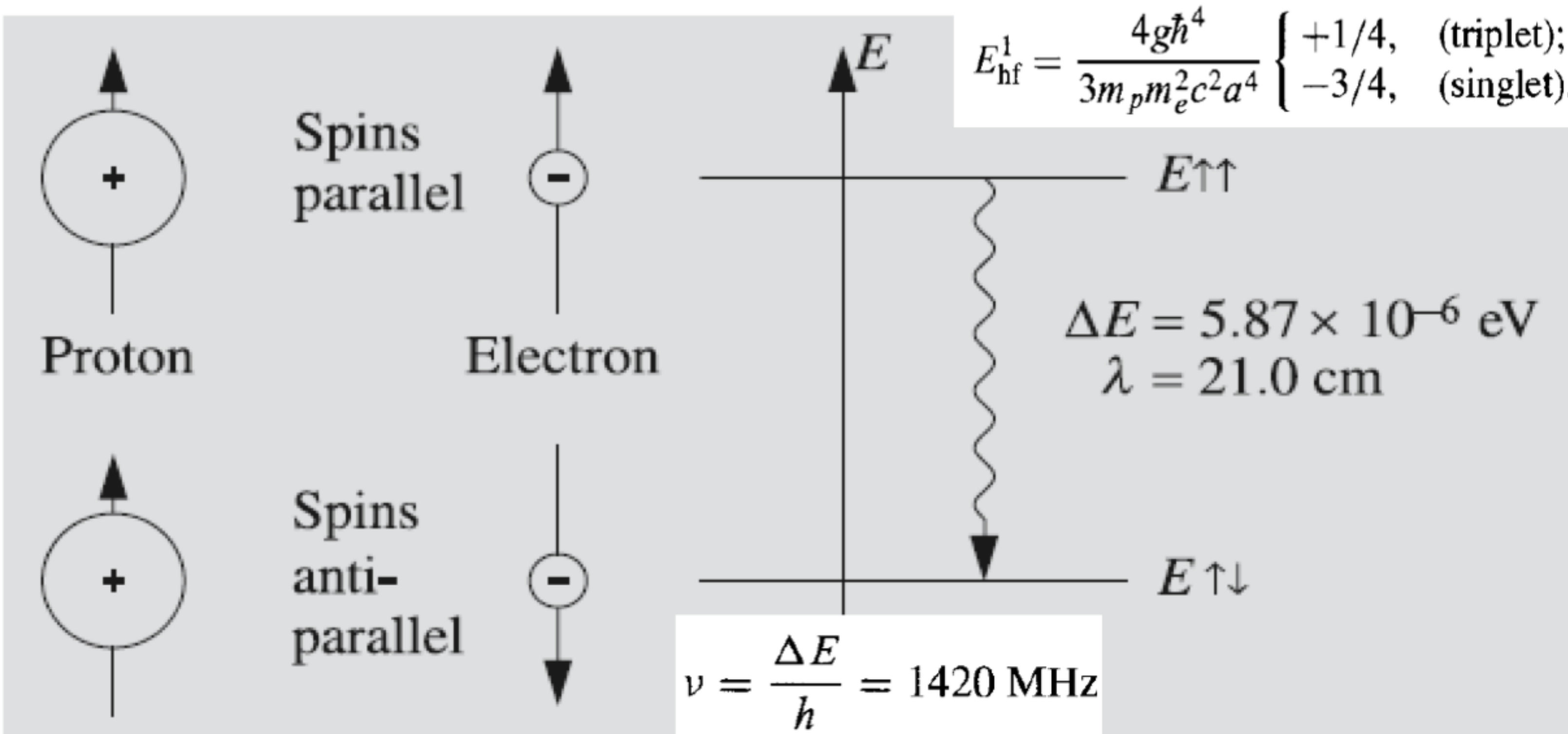


Fig. 5.8. The origin of the hydrogen 21 cm line. The spins of the electron and the proton may be either parallel or opposite. The energy of the former state is slightly larger. The wavelength of a photon corresponding to a transition between these states is 21 cm

Karttunen et al. 2007, *Fundamental Astronomy*

"But something stirs and something tries, And starts to climb towards the light" Pink Floyd (1970)

T_γ T_S T_b

$z = 13$

$\nu = 1.4\,\mathrm{GHz}$

$z = 0$

$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

$$T_b \propto 27(1 - x_i)\left[\frac{T_S - T_\gamma}{T_S}\right]\left(\frac{1+z}{10}\right)^{1/2} \mathrm{mK}$$

Neutral fraction

$$\frac{n_1}{n_0} \equiv 3\exp\left[\frac{h\nu_{21}}{kT_s}\right]$$

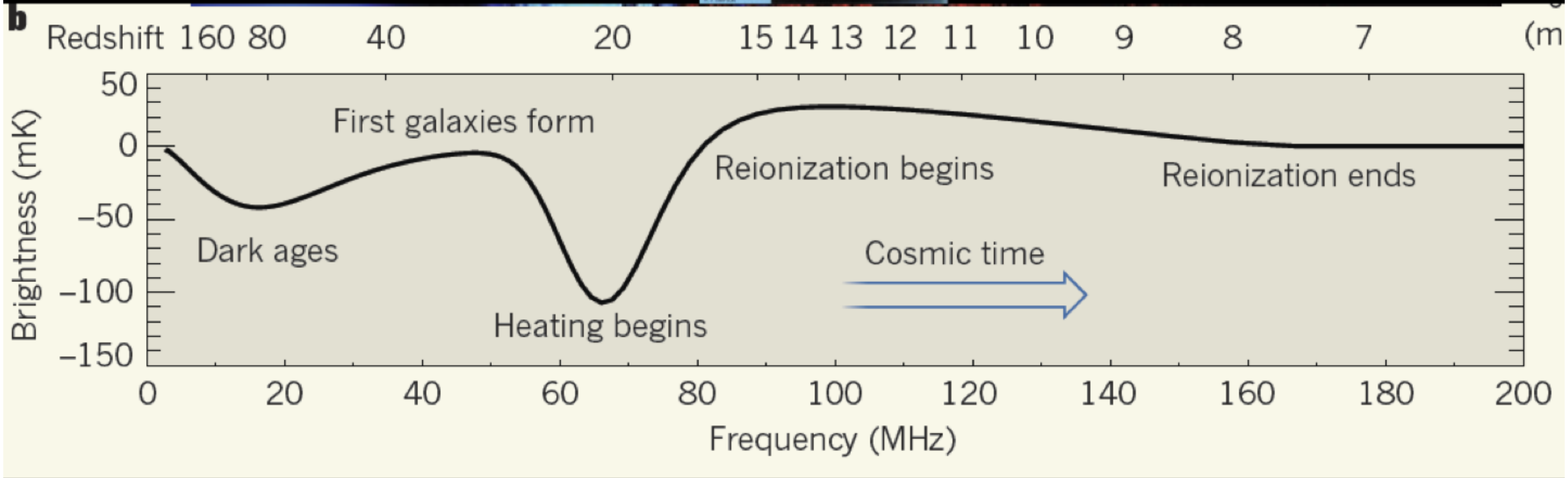
Spin temperature

Global: Average brightness temperature over the whole sky

Power spectrum: cross-correlation between different scales

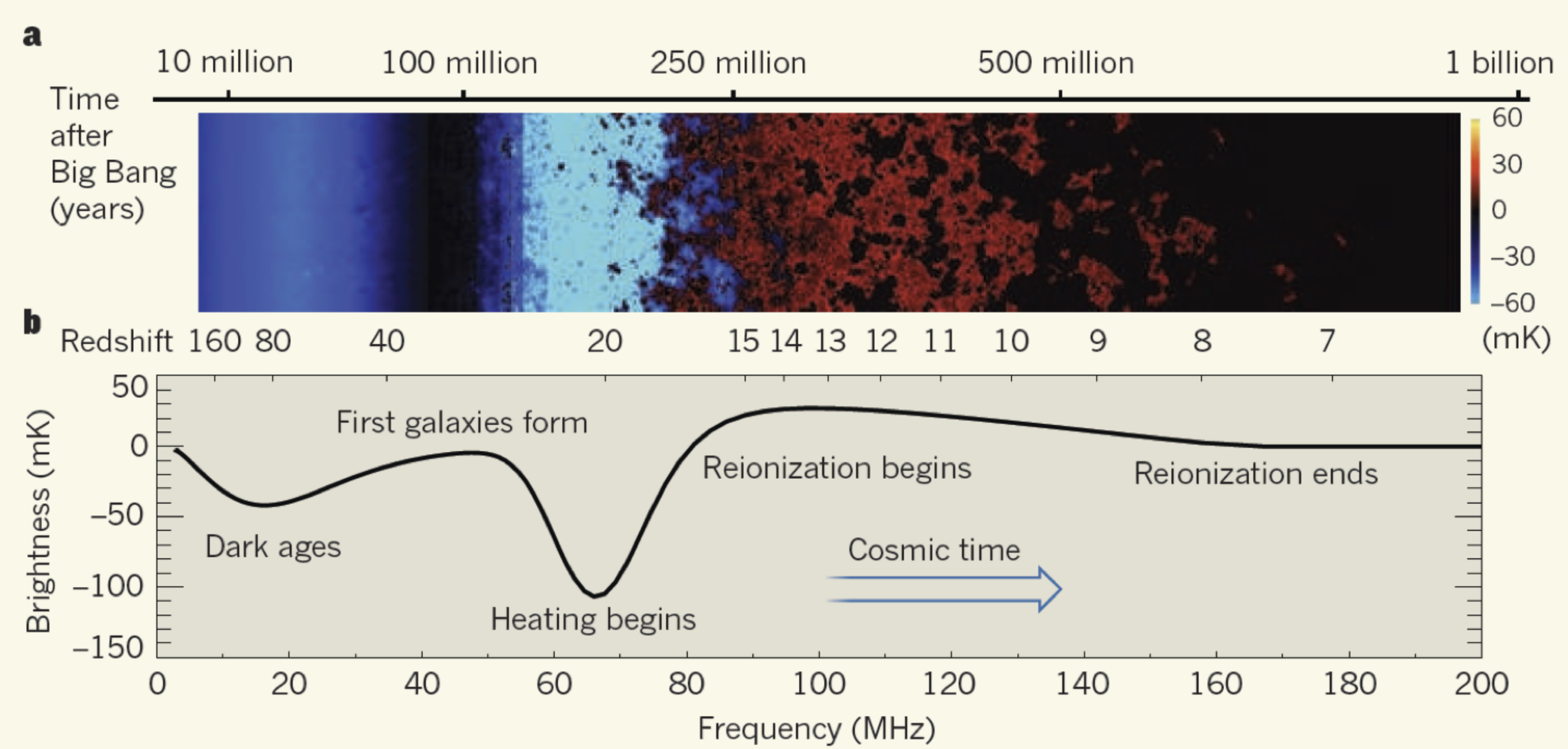
What does the (global) signal look like?

X-rays – gas heating/ionization



What does the (global) signal look like?

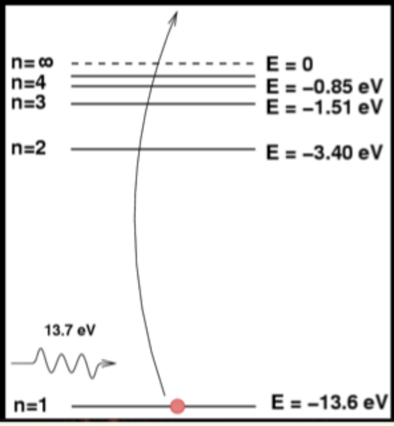
$$\text{Freq} = \frac{1420\text{MHz}}{(1+z)}$$

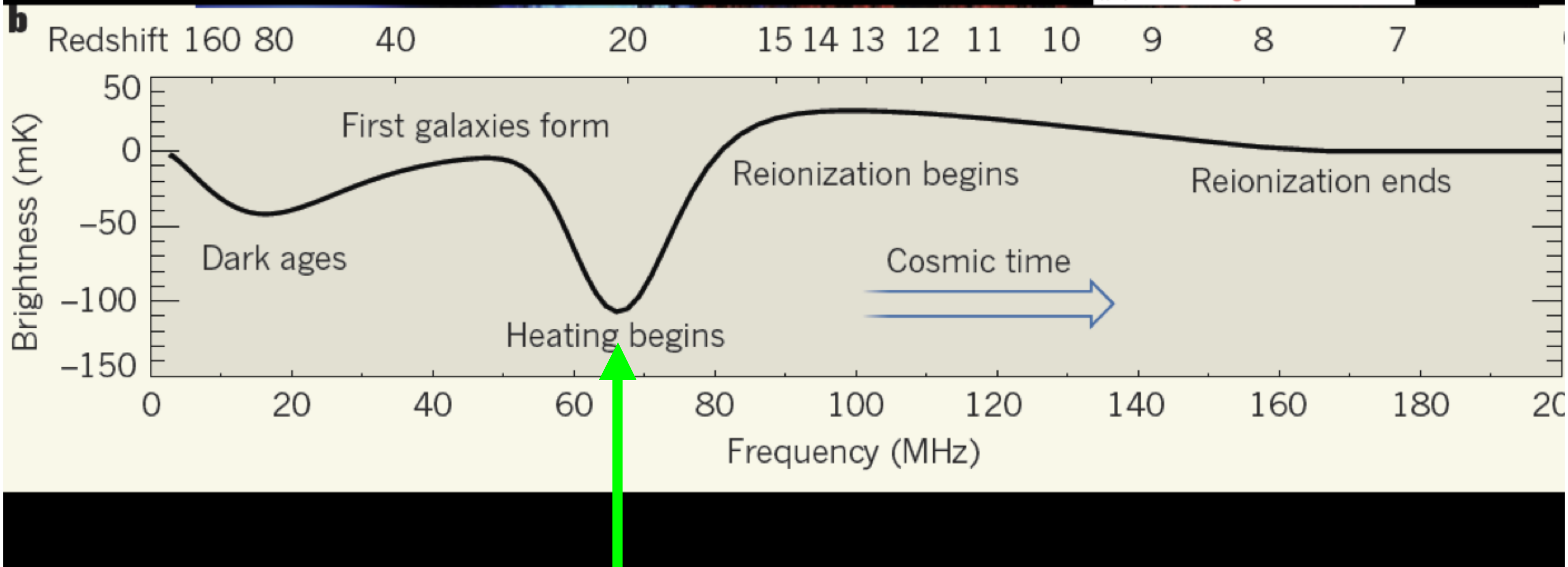


Pritchard & Loeb 2010, Nature

What does the (global) signal look like?

$$T_b \propto 27(1-x_i)\left[\frac{T_S - T_\gamma}{T_S}\right]\left(\frac{1+z}{10}\right)^{1/2} \text{mK}$$





The Wouthuysen-Field through

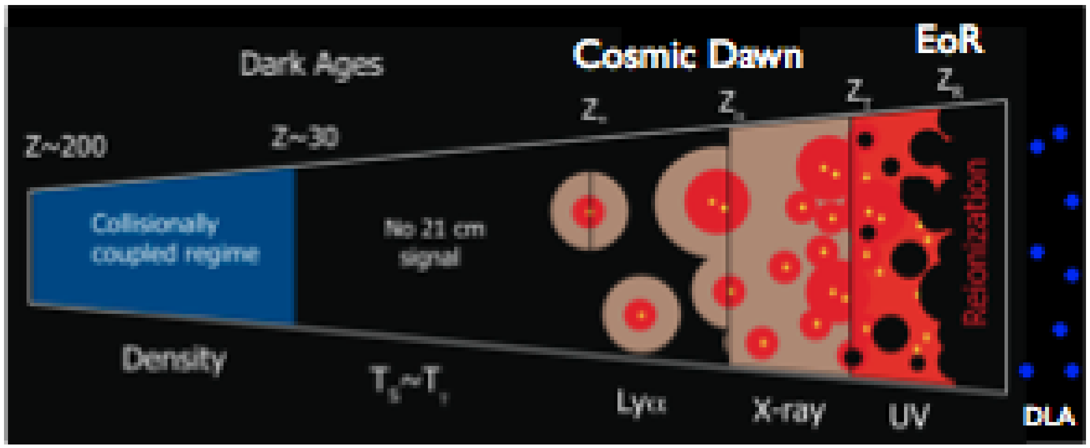


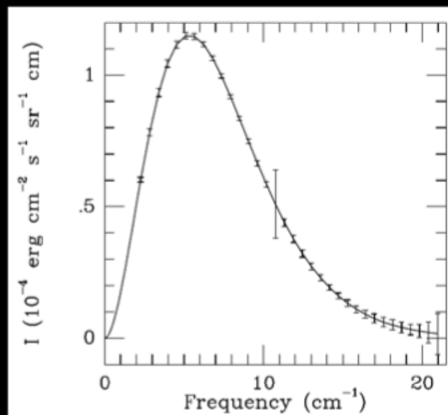
Figure 3. Cartoon of the different phases of the 21 cm signal. The signal transitions from an early phase of collisional coupling to a later phase of Lyα coupling through a short period where there is little signal. Fluctuations after this phase are dominated successively by spatial variation in the Lyα , X-ray, and ionizing UV radiation backgrounds. After reionization is complete there is a residual signal from neutral hydrogen in galaxies.

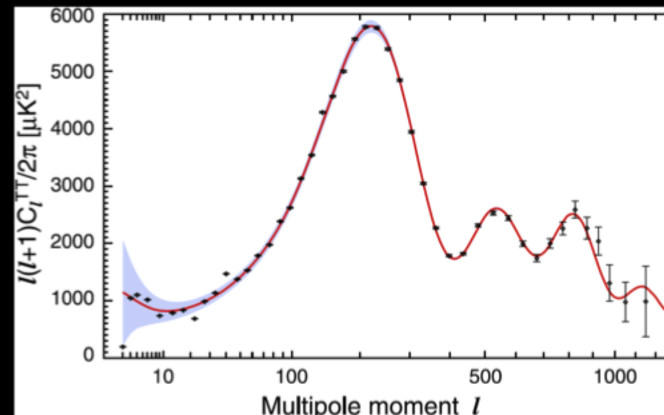
Compare that to CMB

Global

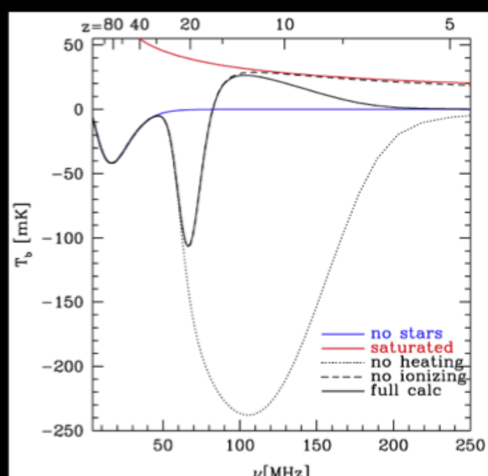
Fluctuations

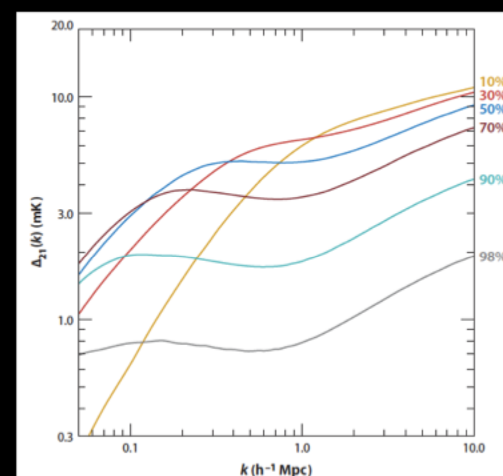
CMB





21-cm cosmo





People are looking for it!

Science, Vol. 325. no. 5948, pp. 1617 – 1619, 25 September 2009

IN SEARCH OF REIONIZATION ☹

	Location	No. of antennas	Baseline	Completion
Low Frequency Array (LOFAR)	The Netherlands	44,160	1500 km	2010
Murchison Widefield Array (MWA)	Australia	8,192	3 km	2010
21 Centimeter Array (21CMA)	China	10,287	6 km	2006
Long Wavelength Array (LWA)	New Mexico, U.S.A	12,800	400 km	2010
Precision Array to Probe Epoch of Reionization (PAPER)	Australia	32		2009
Experiment to Detect the Global EOR Signature (EDGES)	Australia	1		2009–2012

- *The GMRT-EoR Experiment: A new upper limit on the neutral hydrogen power spectrum at z~8.6,* Gregory Paciga, Tzu-Ching Chang, Yashwant Gupta, Rajaram Nityanada, Julia Odegova, Ue-Li Pen, Jeffrey Peterson, Jayanta Roy, Kris Sigurdson

Chippendale (Ph.D., 2009) 114-228 MHz [10.5 <(z+1) < 4.2]

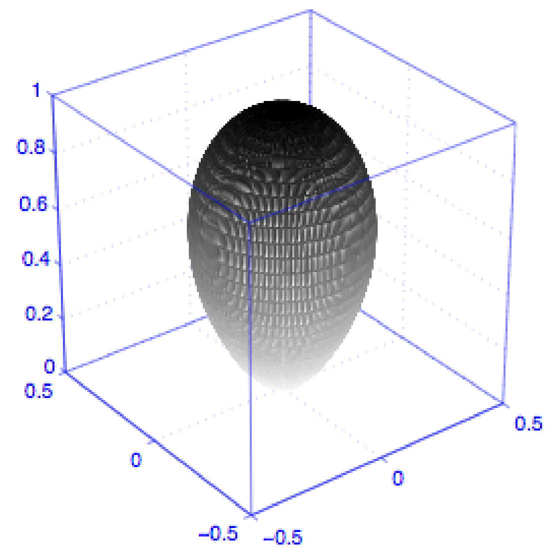


Fig. 4.7: Normalised power pattern of pyramidal spiral antenna on linear scale at 171 MHz.

21 cm Cosmology: Experiments and Observatorires

LOFAR

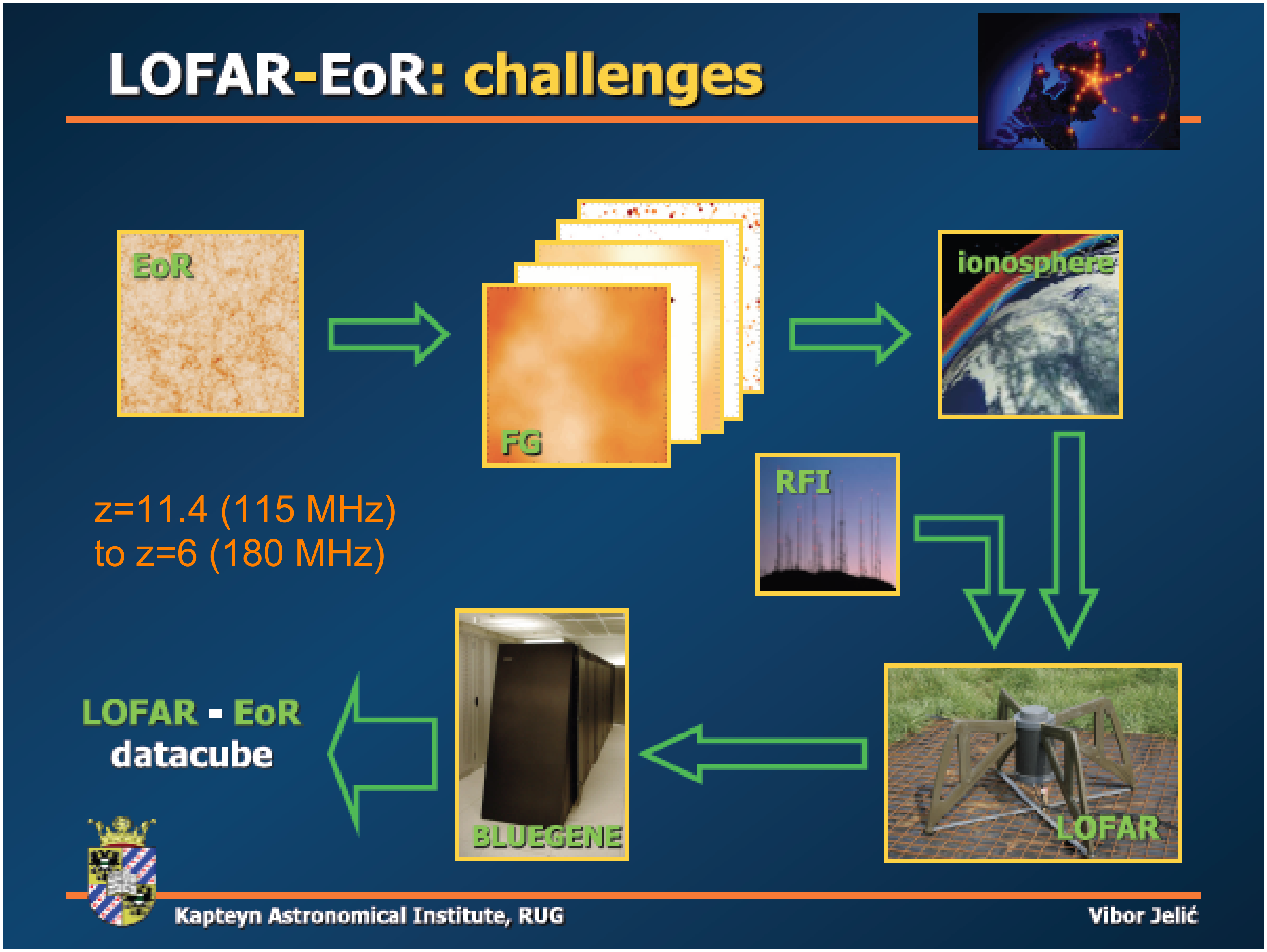
MWA

PAPER

GMRT

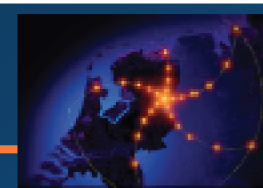
SKA

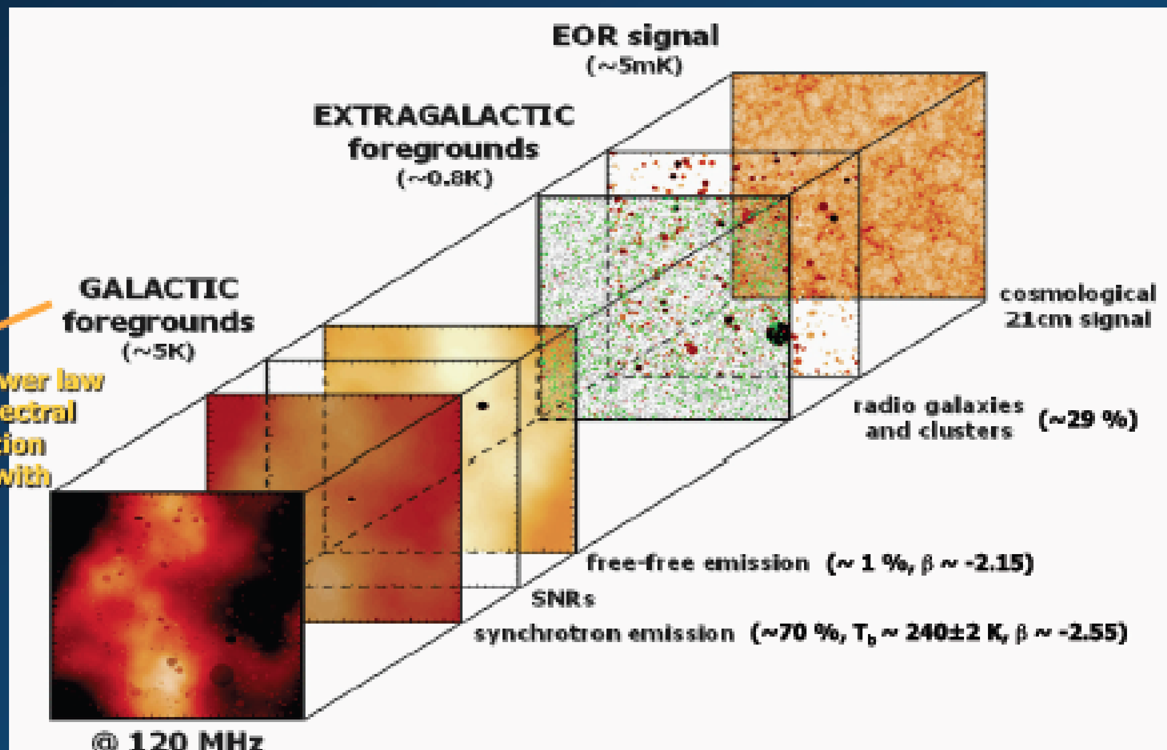
21CMA



LOFAR-EoR: challenges
EoR
FG
ionosphere
RFI
LOFAR
BLUEGENE
z=11.4 (115 MHz)
to z=6 (180 MHz)
LOFAR - EoR
datacube
Kapteyn Astronomical Institute, RUG
Vibor Jelić

LOFAR-EoR: FG simulations





- featureless power law
- variation in spectral index with position on the sky and with frequency

SIMULATIONS: 5° x 5° filed of view, ~ 0.6 arcmin resolution and freq. range: 115-180 MHz

Jelic et al., 2008, MNRAS accepted

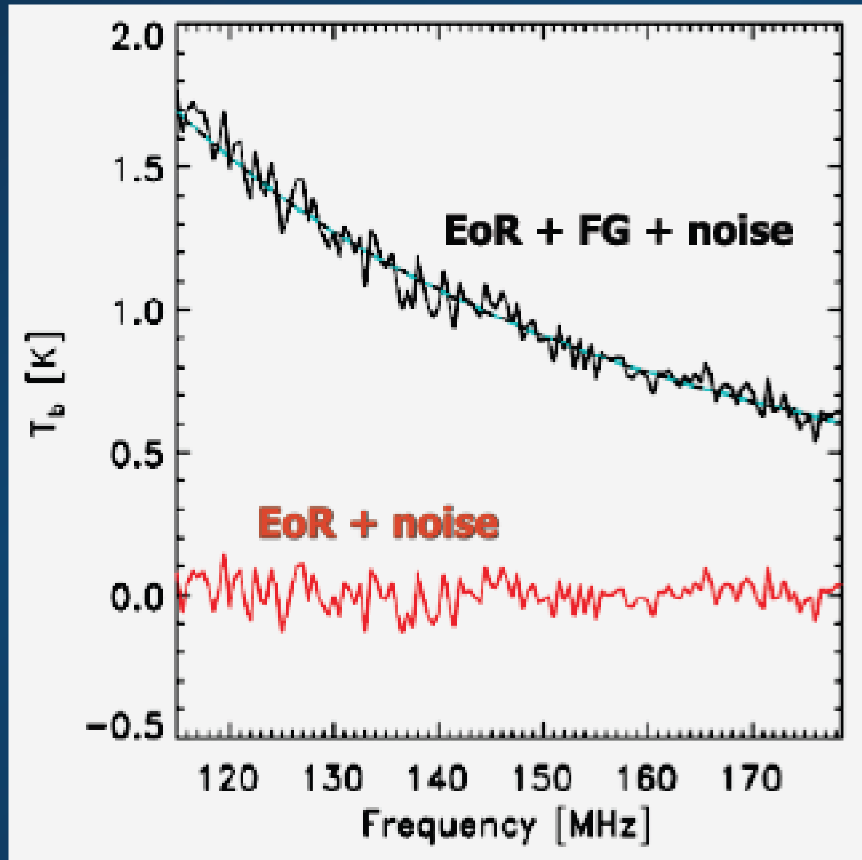
LOFAR-EoR: extraction I

ASSUMPTIONS:

- only diffuse FGs in total intensity
- perfect calibration and instrument

@150 MHz

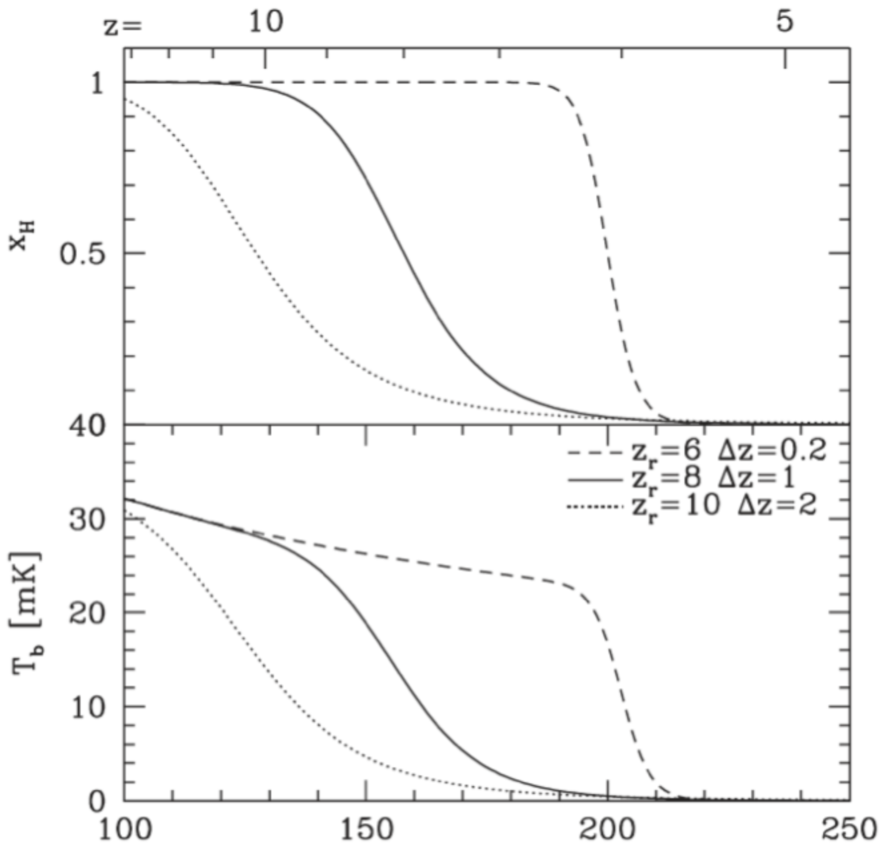
$T_{EoR} \sim 5$ mK
$T_{FG} \sim 2$ K
$T_{noise} \sim 52$ mK



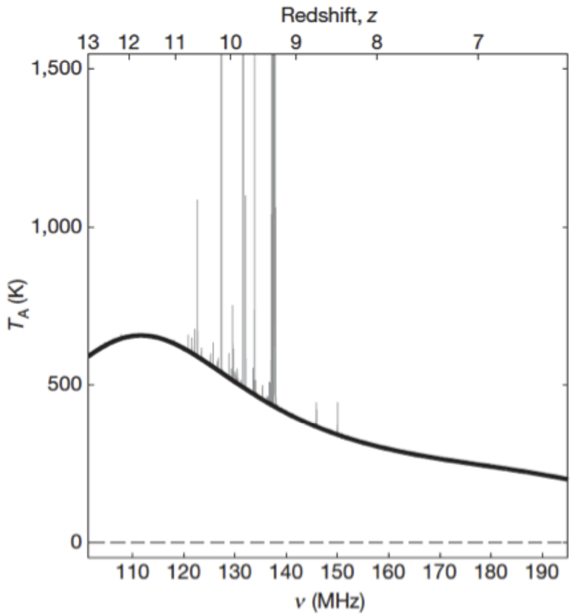
$$T_{sky}(\nu) = T_{fg}(\nu) + T_b(\nu)$$

EDGES Experiment

Bowman & Rogers



Pritchard & Loeb, 2010



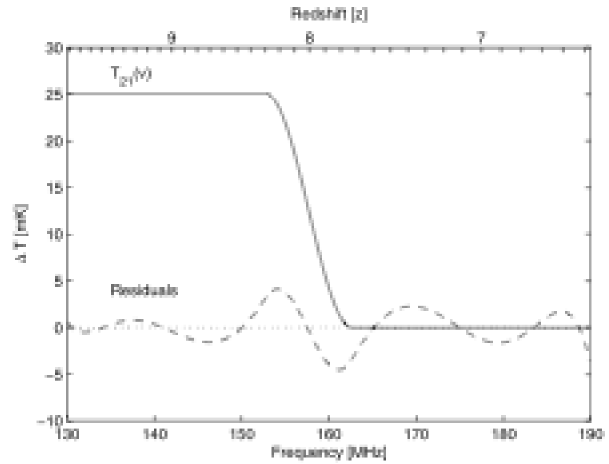


Fig. 1.—Example of redshifted 21 cm contribution (*solid line*) to T_{sky} based on the model described in § 4.1 with $\Delta T_{21} = 25$ mK, $z_r = 8$, and $\Delta z = 0.6$. The residuals are also shown for a seventh-order polynomial fit to a simulated spectrum between 130 and 190 MHz with (*dashed line*) and without (*dotted line*) the red-

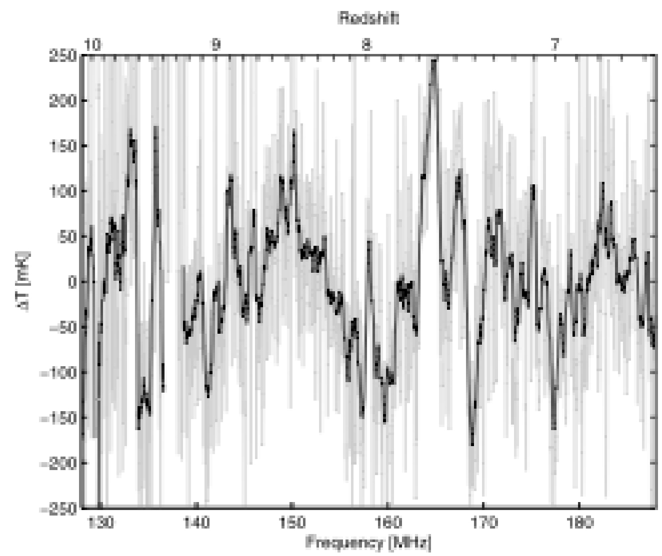


Fig. 4.—Residuals after subtraction of seventh-order polynomial fit to the measured spectrum shown in Fig. 3. The gray line is the raw spectrum with 122 kHz resolution. The black line is the spectrum after smoothing to 2.5 MHz resolution to reduce the thermal noise to below the systemic noise. The rms of the smoothed fluctuations is approximately 75 mK (see Fig. 5).

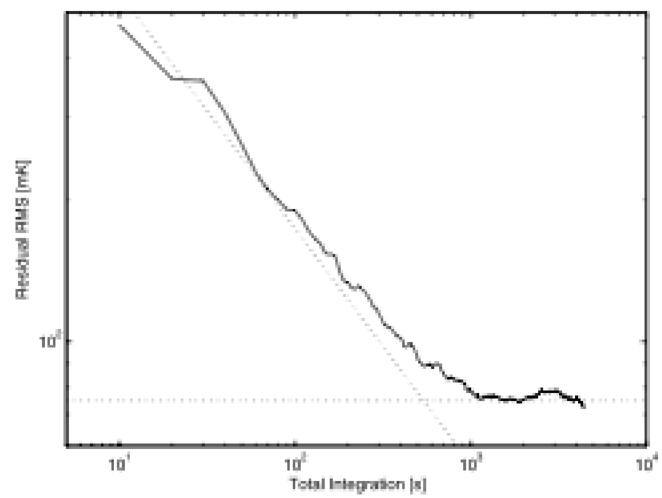
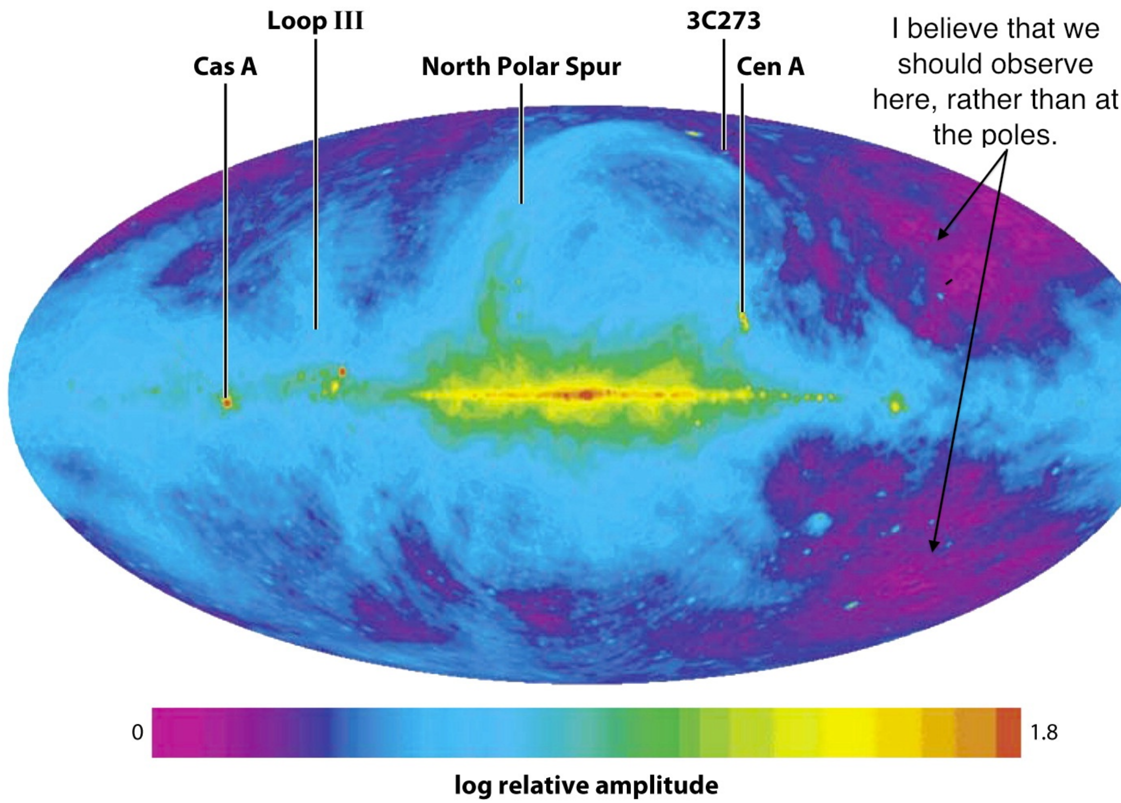


Fig. 5.—Characteristic amplitude of the residuals to the polynomial fit as a function of integration time on the sky. The rms follows a thermal $(b\tau)^{-1/2}$ dependency until saturating at a constant 75 mK noise level due to the instrumental errors introduced into the measured spectrum. The dotted lines are guides for the eye showing a $(b\tau)^{-1/2}$ profile and a constant 75 mK contribution.

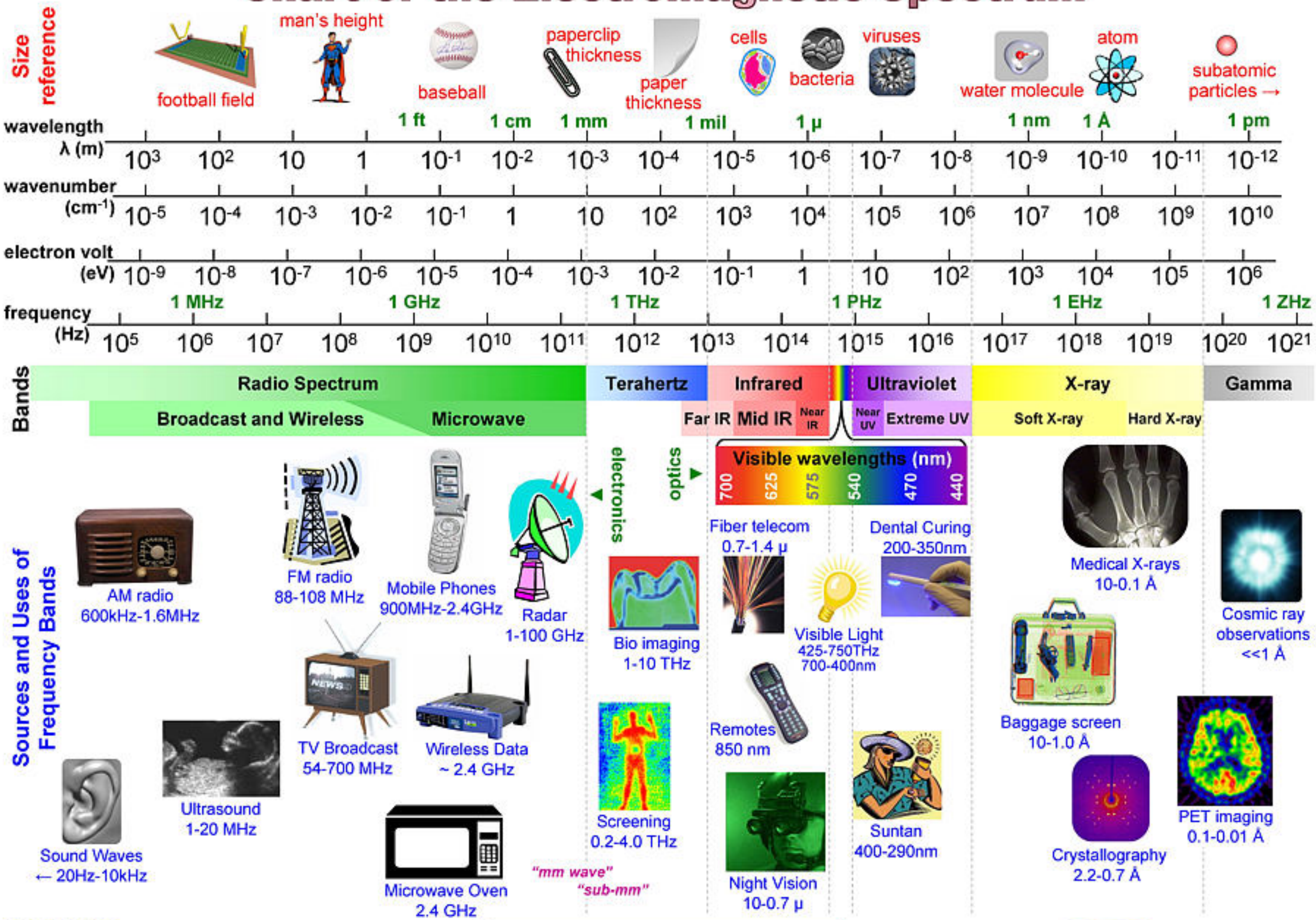
the frequency dependence of the redshifted 21 cm emission dur-

The Main Enemy:



Morales MF, Wyithe SB. 2010.
Annu. Rev. Astron. Astrophys. 48:127–71

Chart of the Electromagnetic Spectrum



$\lambda = 3\times10^8/\text{freq} = 1/(\text{wn}*100) = 1.24\times10^{-6}/\text{eV}$

SURA Southeastern Universities Research Association ®

Sci-HI: First Results

Sonda Cosmológica de las Islas para la Detección de Hidrógeno Neutro (Sci-HI)

Isla Guadalupe NW Mexican Pacific Ocean

Instituto Nacional de Astrofísica, Optica y Electrónica.

Coordinación de Astrofísica

Omar López-Cruz,
(omarlx@inaoep.mx)

For the Sci-HI collaboration

Kapteyn Institute
April 9th, 2014

Sci-HI Collaboration

Jeff Peterson (CMU)   Omar López-Cruz (INAOE)

Tabitha Voytek (CMU)   Edgar Castillo Dominguez (INAOE)

Alma González (CN-UNAM) José Miguel Jáuregui G. (INAOE)

Urbano Friaça (AHEP Group), Tonatiuh Matos (CINVESTAV), Mark Birkinshaw (U. Bristol), Dick Bond (CITA), Octavio Valenzuela (IA-UNAM), Axel de la Macorra (IF-UNAM, IAC), Raúl Michel (IA-UNAM-E)

With collaborators at IAC, IAUNAM, CINVESTAV, ININ, ESFM-IPN, UAC, UAS, IATE, GECI, INECOL, Reserva de la Biosfera de Mapimí, Reserva de la Biosfera de la Isla Guadalupe, SEGOB, & SEMAR.

Searching for funding: CONACyT (Proy. de Grupo), NSF, Templeton Foundation, Packard Foundation. Fundación Alfredo Harp Helú, and contributors like yourselves.

Mexico: Reserves of the Biosphere

Mexico: EEZ

Maybe La Zona del Silencio is a good Bet…

Google maps México Dirección

Para obtener todos los detalle
aparecen en la pantalla, utiliza e
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Mis mapas Editar Imprimir Correo electrónico

zona del silencio - Google Maps

Google maps México Dirección

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Mis mapas Editar Imprimir Correo electrónico

http://maps.google.com.mx/

Jeff and I went to La Zona del Silencio Guided by Pelón

Jeff Peterson and Omar Lopez-Cruz at Zona del Silencio, May 1, 2010. We used this antenna to measure the intensity of radio signals.

This was unexpected!!!

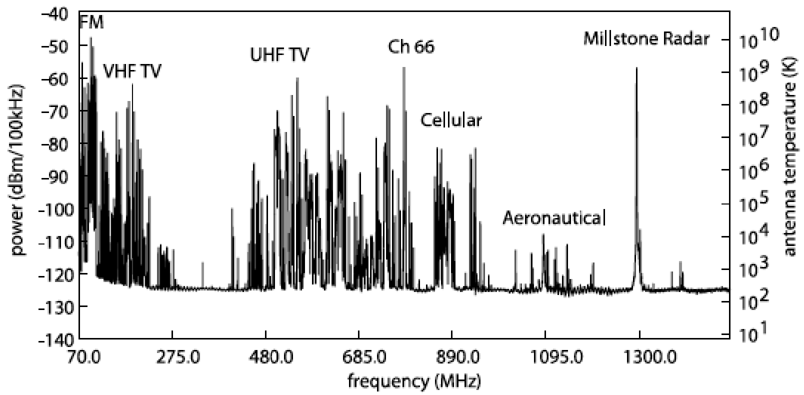
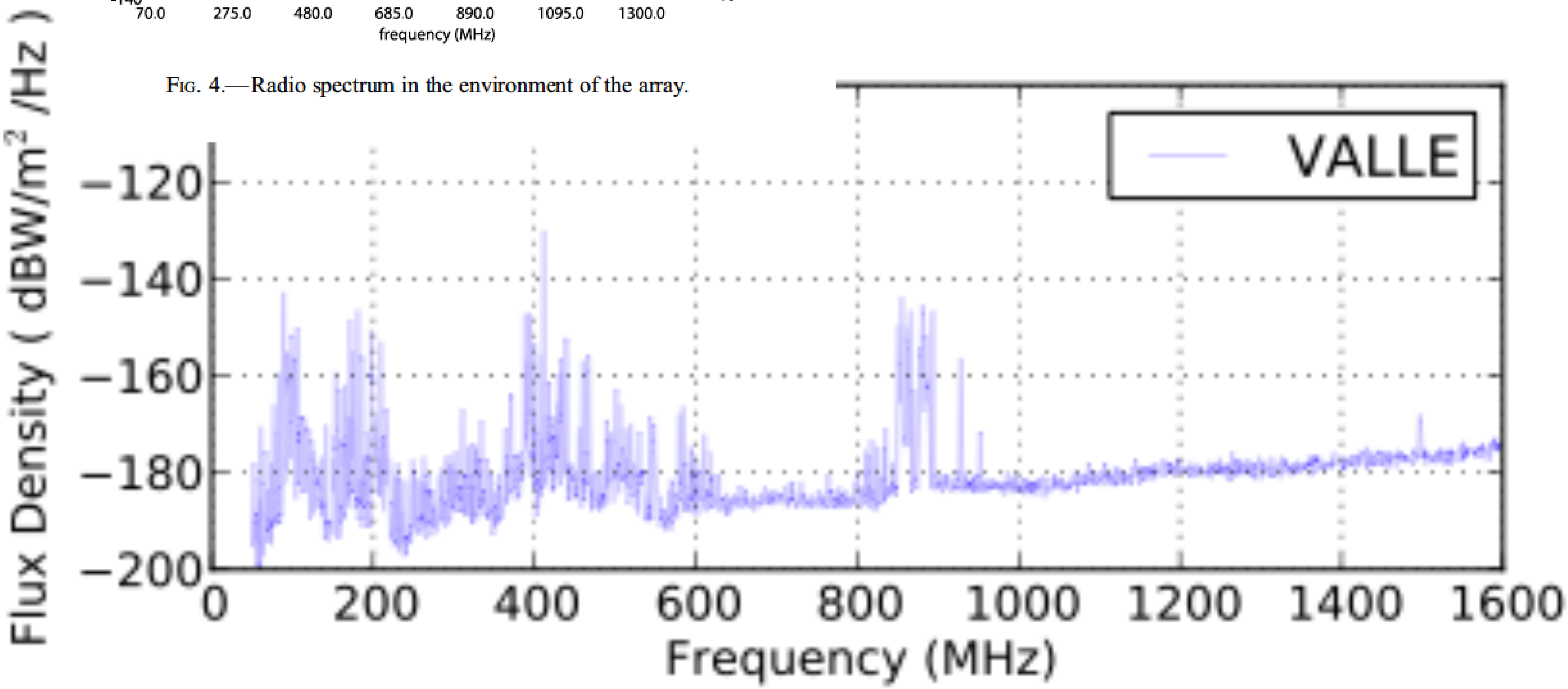


FIG. 4.—Radio spectrum in the environment of the array.

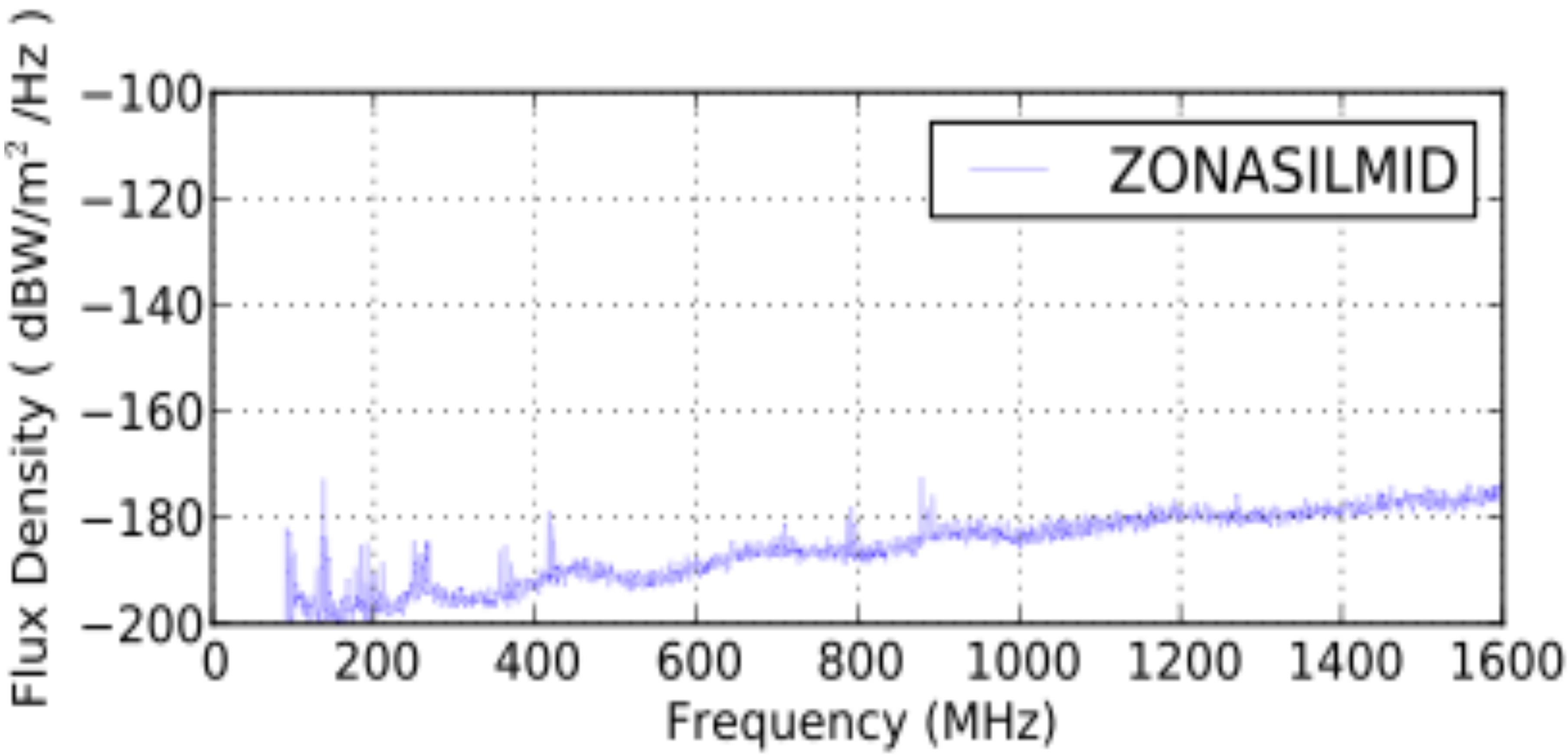
La Cuneta between Sierra Negra and Pico de Orizaba, in the vecinity of the Gran Telescopio Milimétrico (LMT/GTM) site, April 30th, 2010. 19:30 hrs



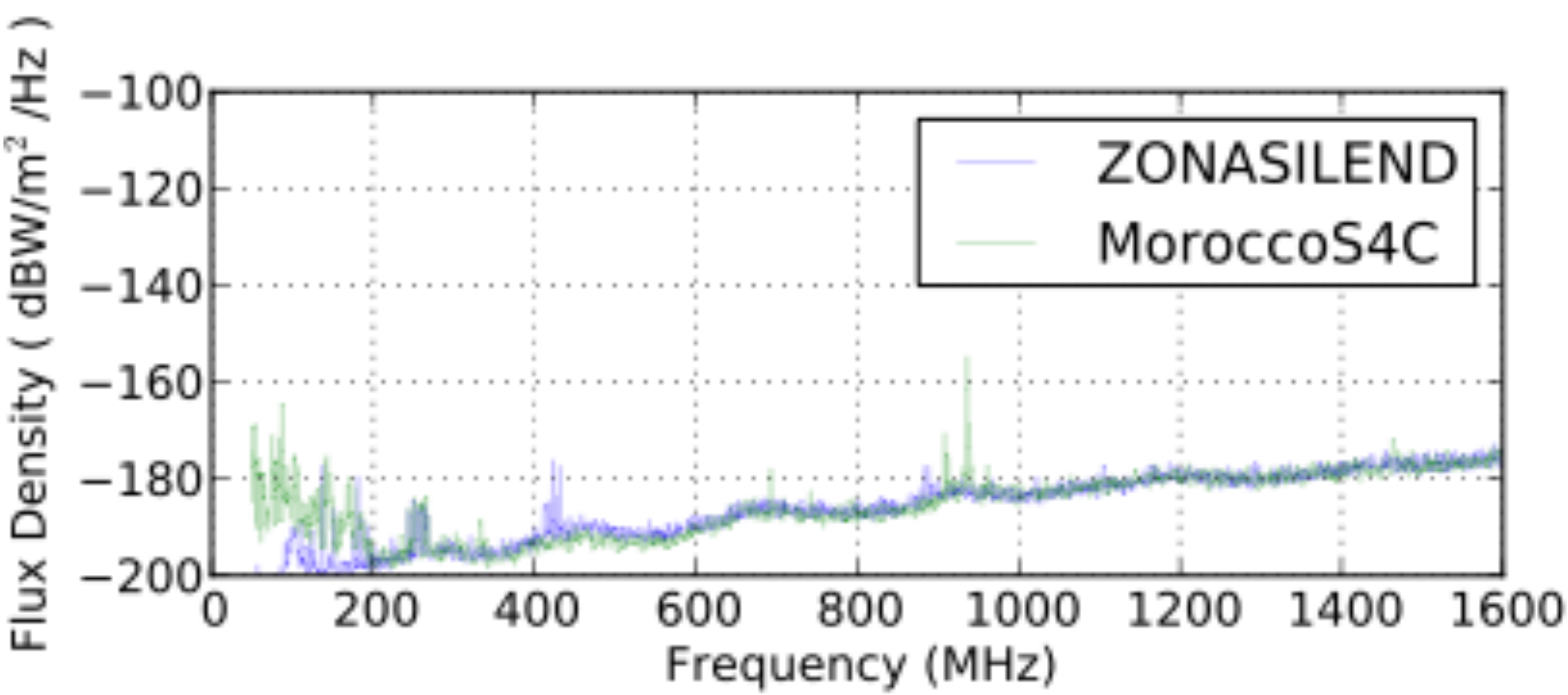
The Large Millimeter Telescope

This was most unexpected!!!

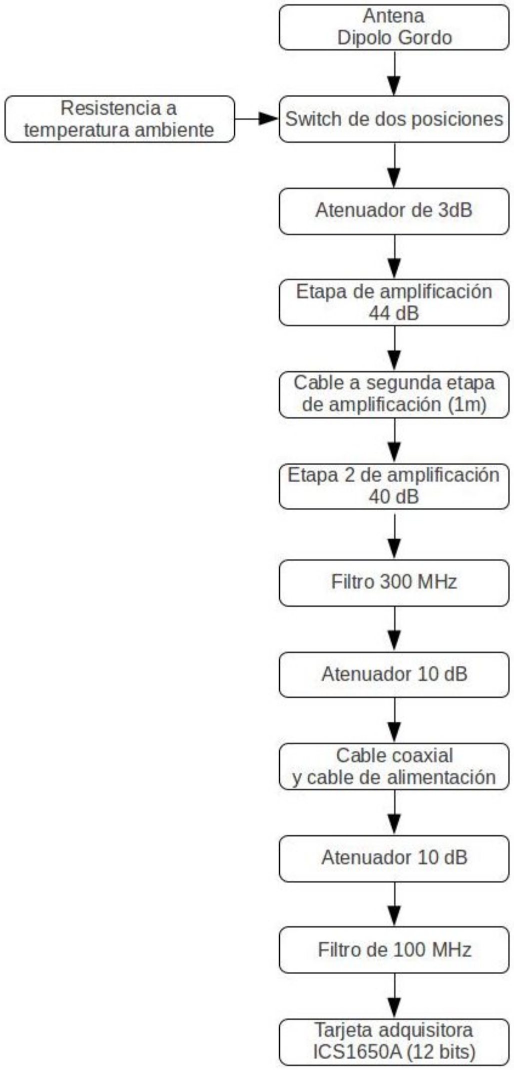
Zona del Silencio, May 1, 2010, 20:10 hrs.



La Zona del Silencio is one of the Best Sites in the whole World!!!

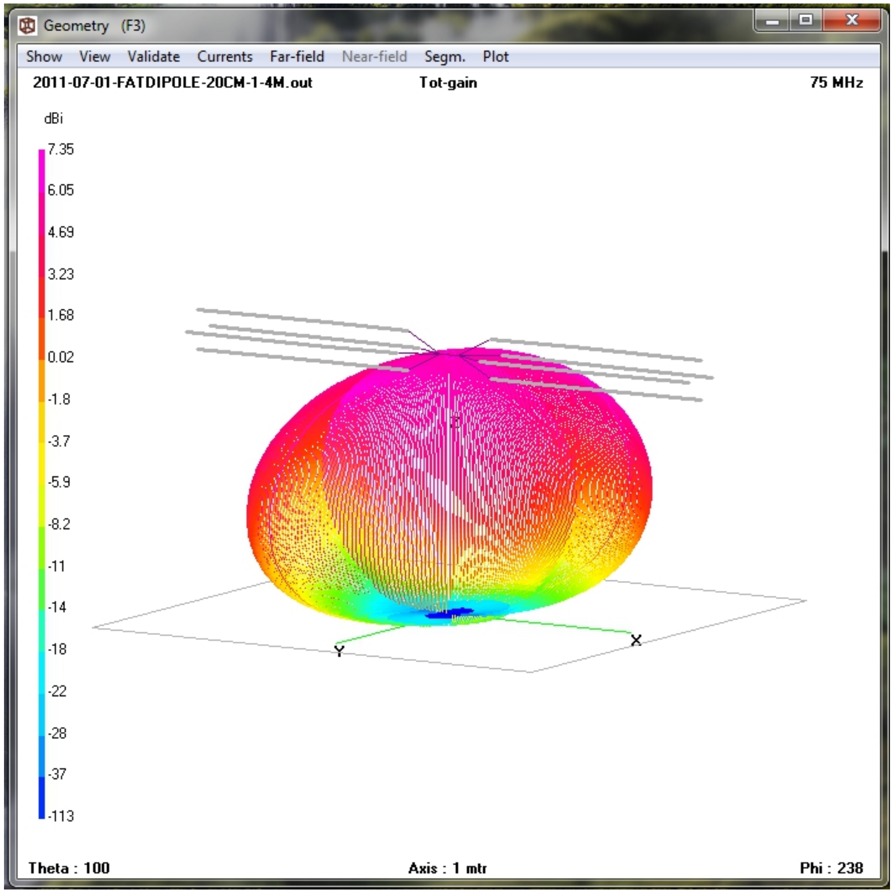


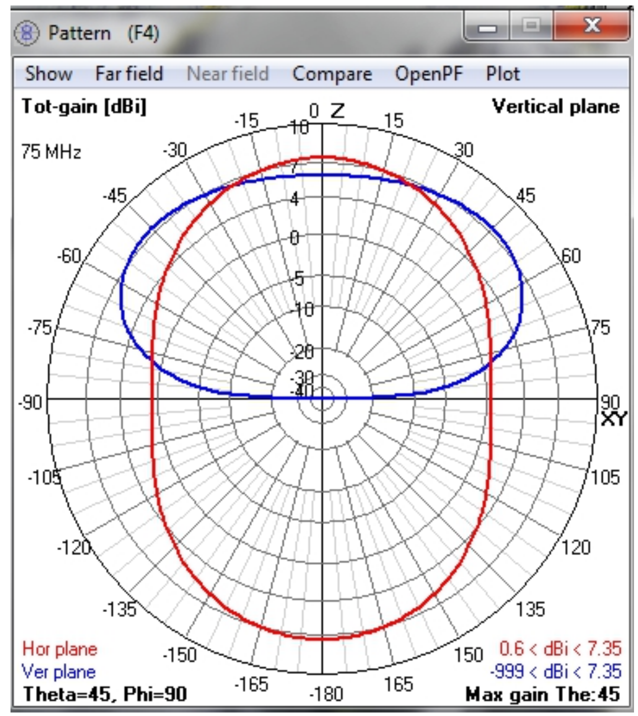
The SCI-HI



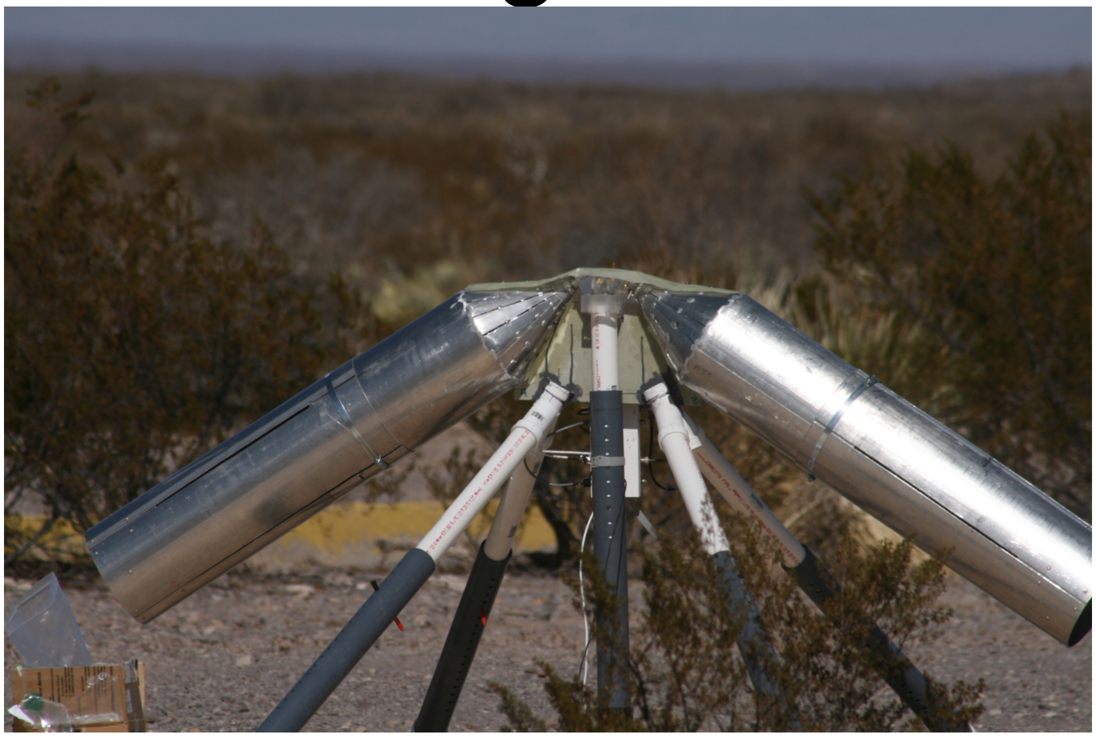
Working at 40-125 MHz (10 < (z+1) <34)

Antenna Pattern

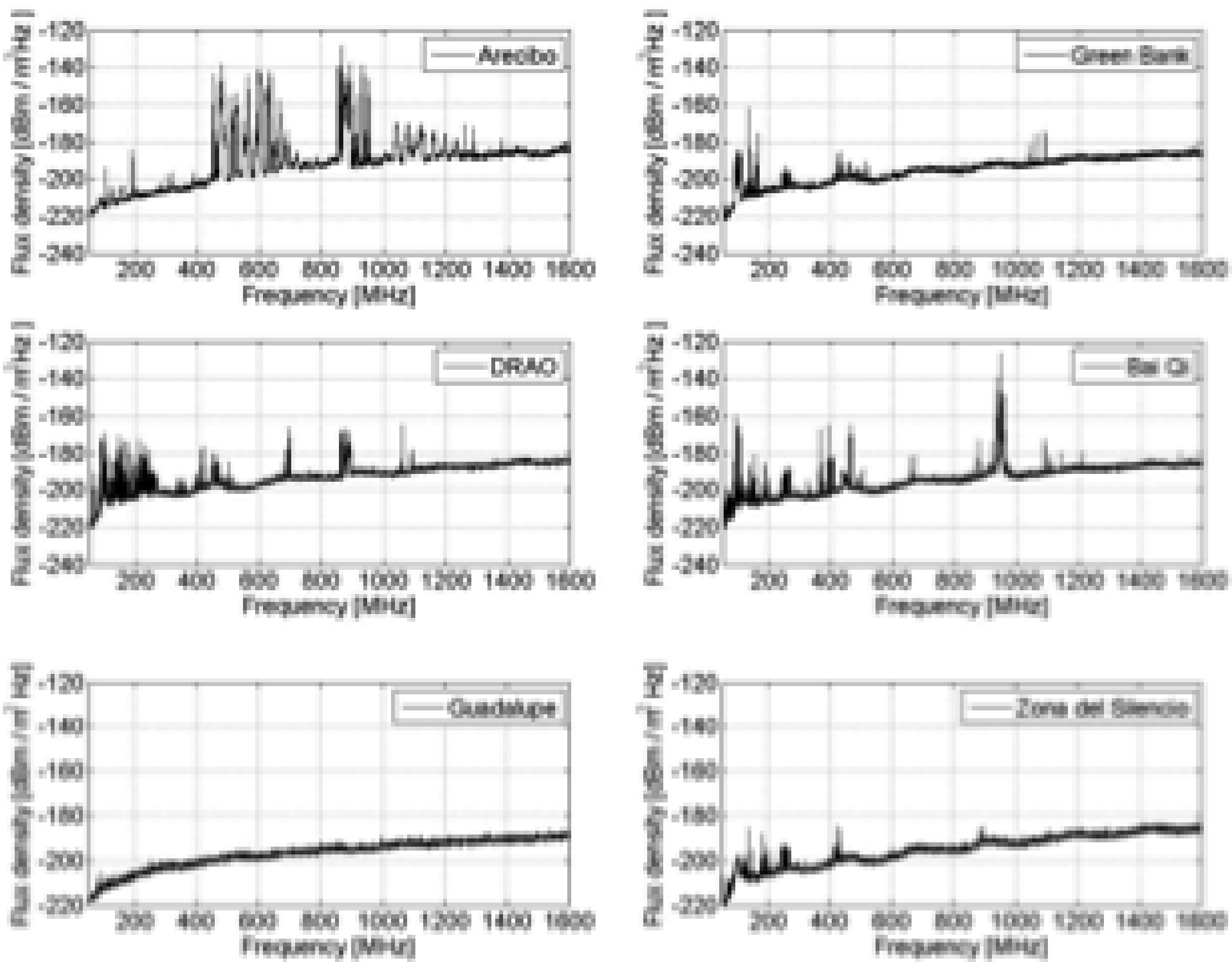




Testing at Zona del Silencio



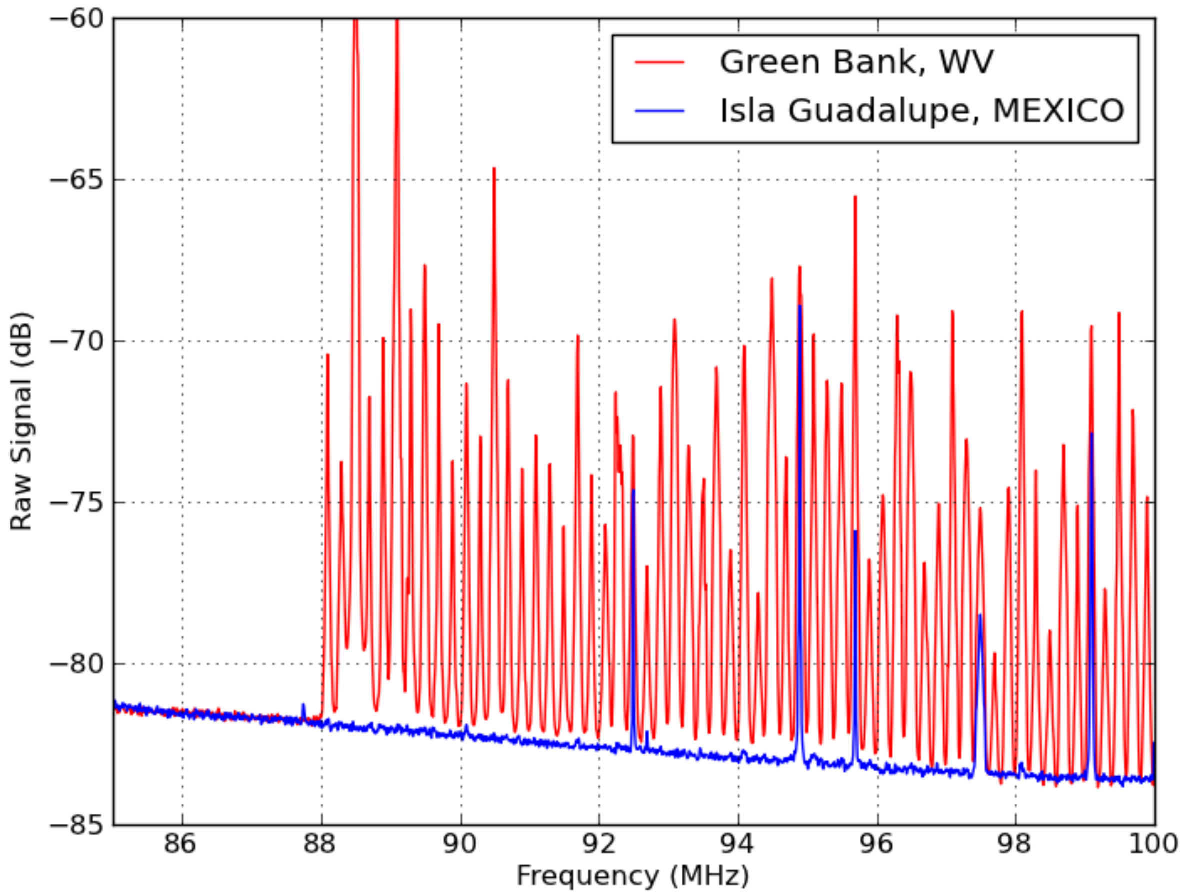
We went to Isla Guadalupe



This is the best Place

Arriba se muestra la localización de la Isla Guadalupe (lat: 28° 58'24" N, long: 118° 18'4" O). También se muestra la ubicación del sitio seleccionado. Por ser la Isla Guadalupe una Reserva de la Biosfera, Sci-HI será retirada de la isla una vez terminadas las observaciones. Se buscará la promoción de leyes para proteger a la Isla Guadalupe como zona radio-silente, este también es un recurso natural cada vez más escaso.

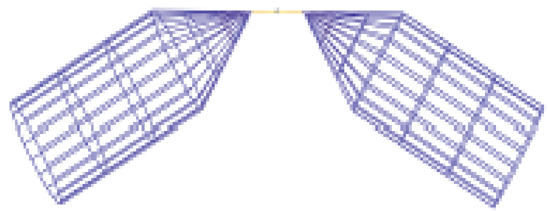
Sci-HI vs. Green Bank



Sci-HI: First Run

Sci-Hi: First Run (Oct-2012)

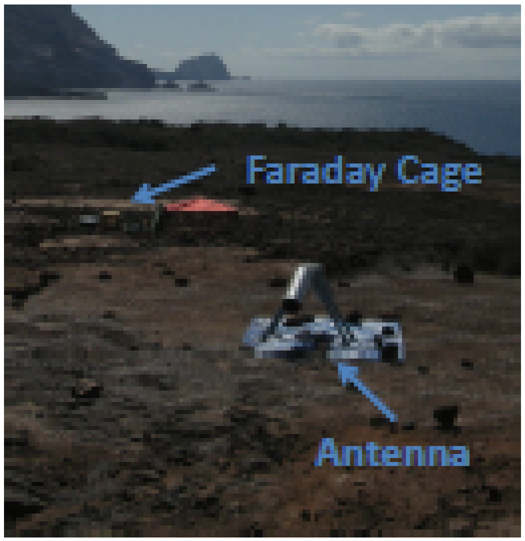
Antenna Design and Construction



The antenna was designed and simulated using numerical electromagnetics code (NEC). Its shape is a "fat, drooping dipole" The dipole can be tuned to different optimal frequencies by changing the length of the cylindrical sections.

System Layout (Field Experimental Setup)

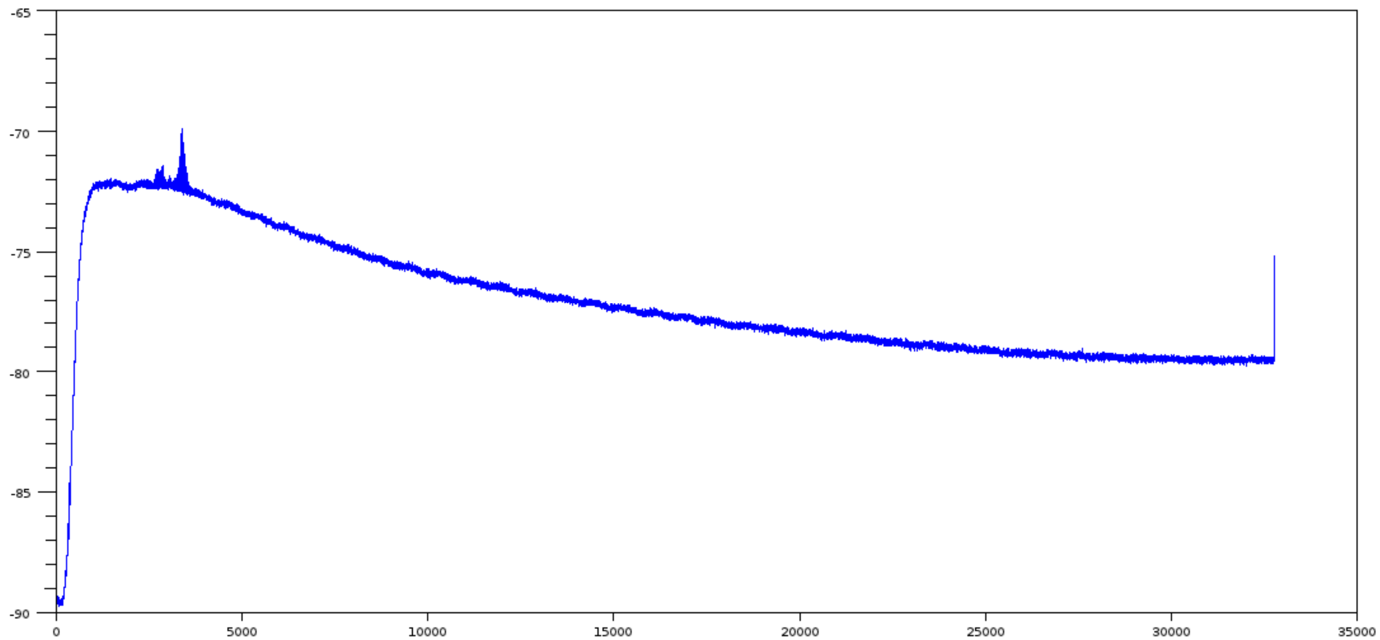
Sci-HI: First Run



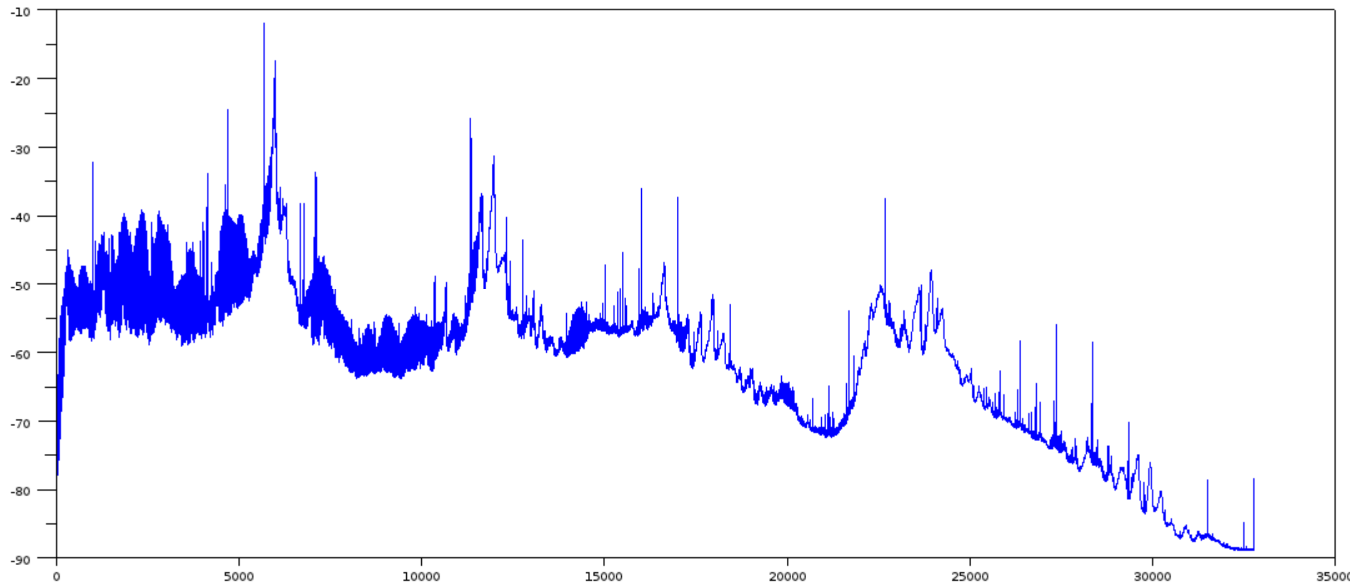
Full System Setup at Isla Guadalupe

View from Inbound Cessna

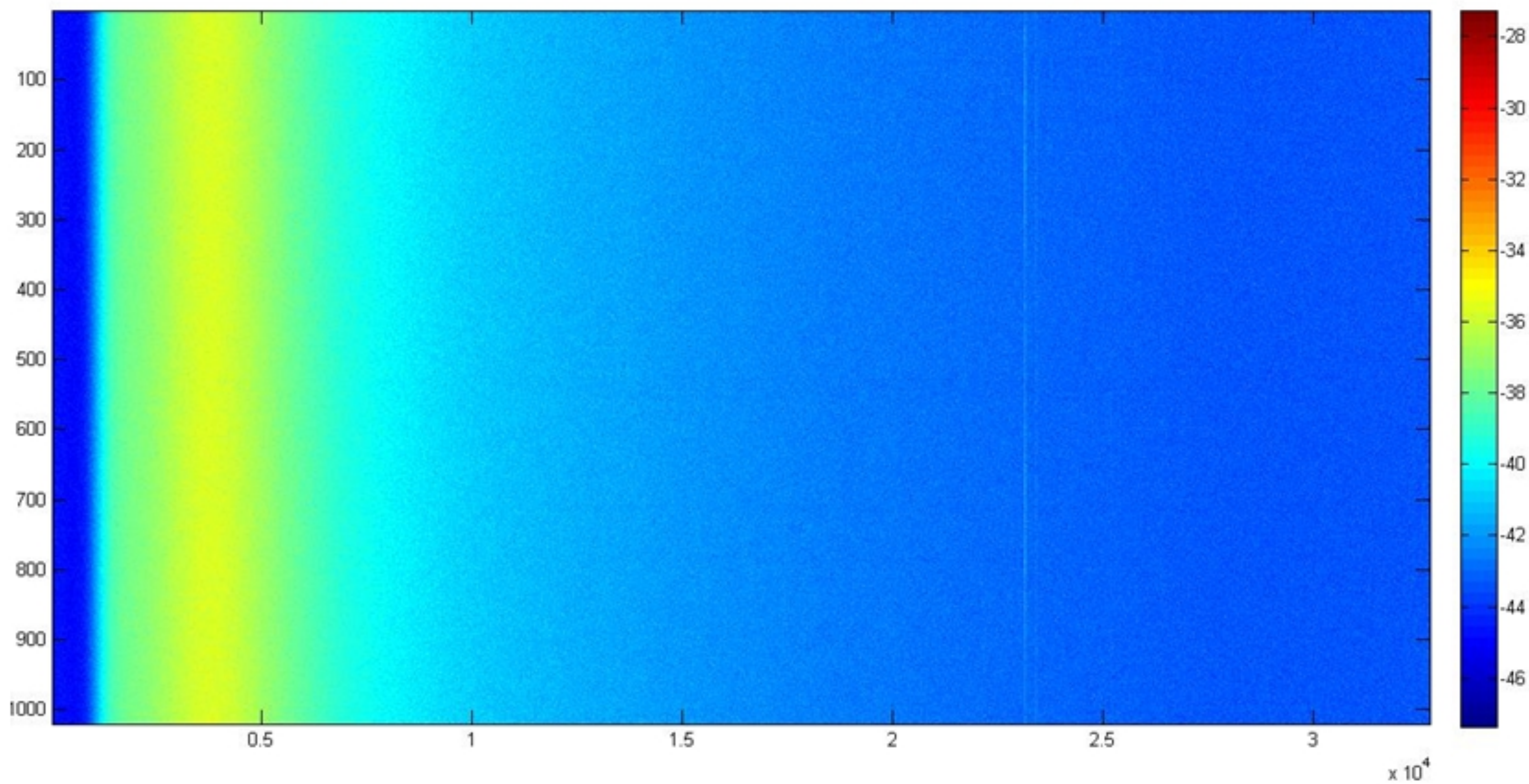
Detections from ZDS, January 2012



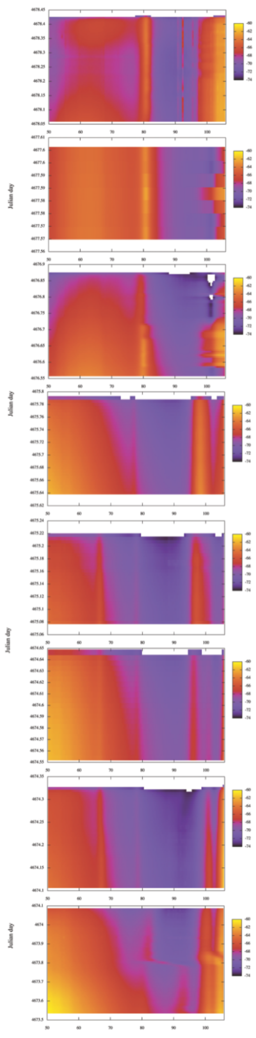
Detections from ZDS, January 2012

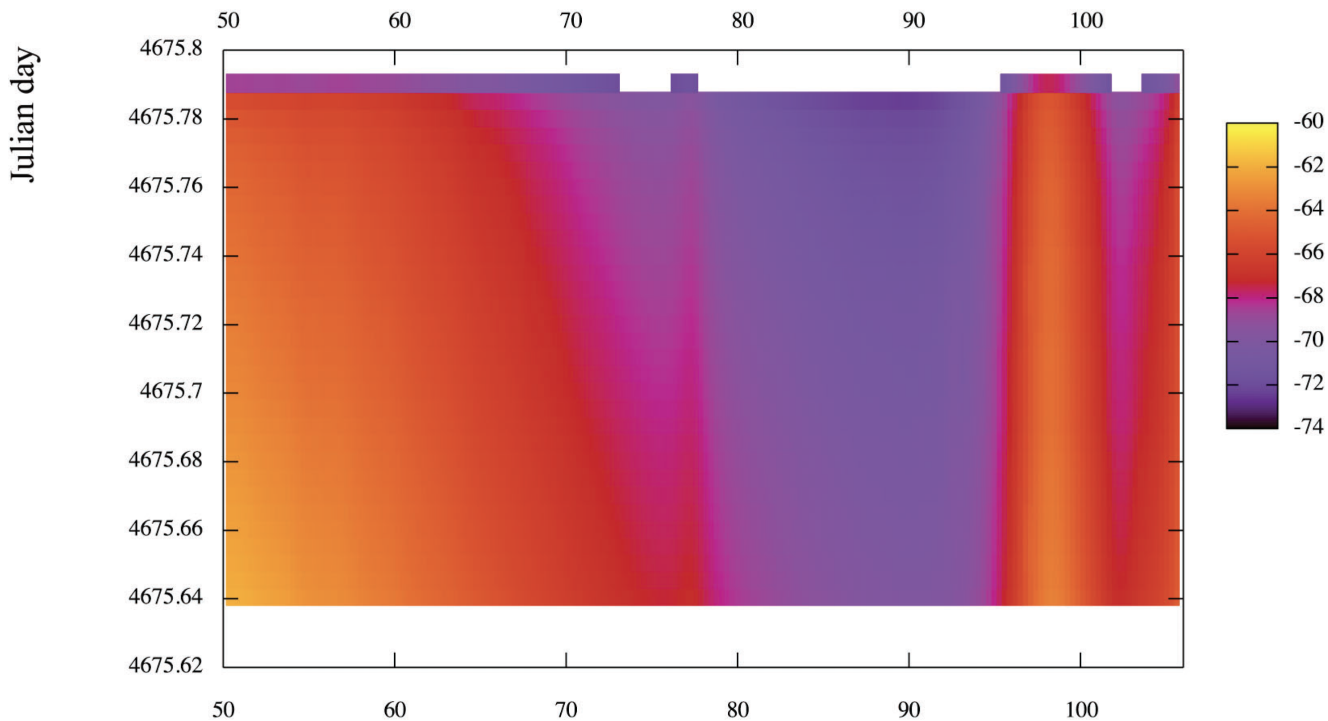


Data Waterfall

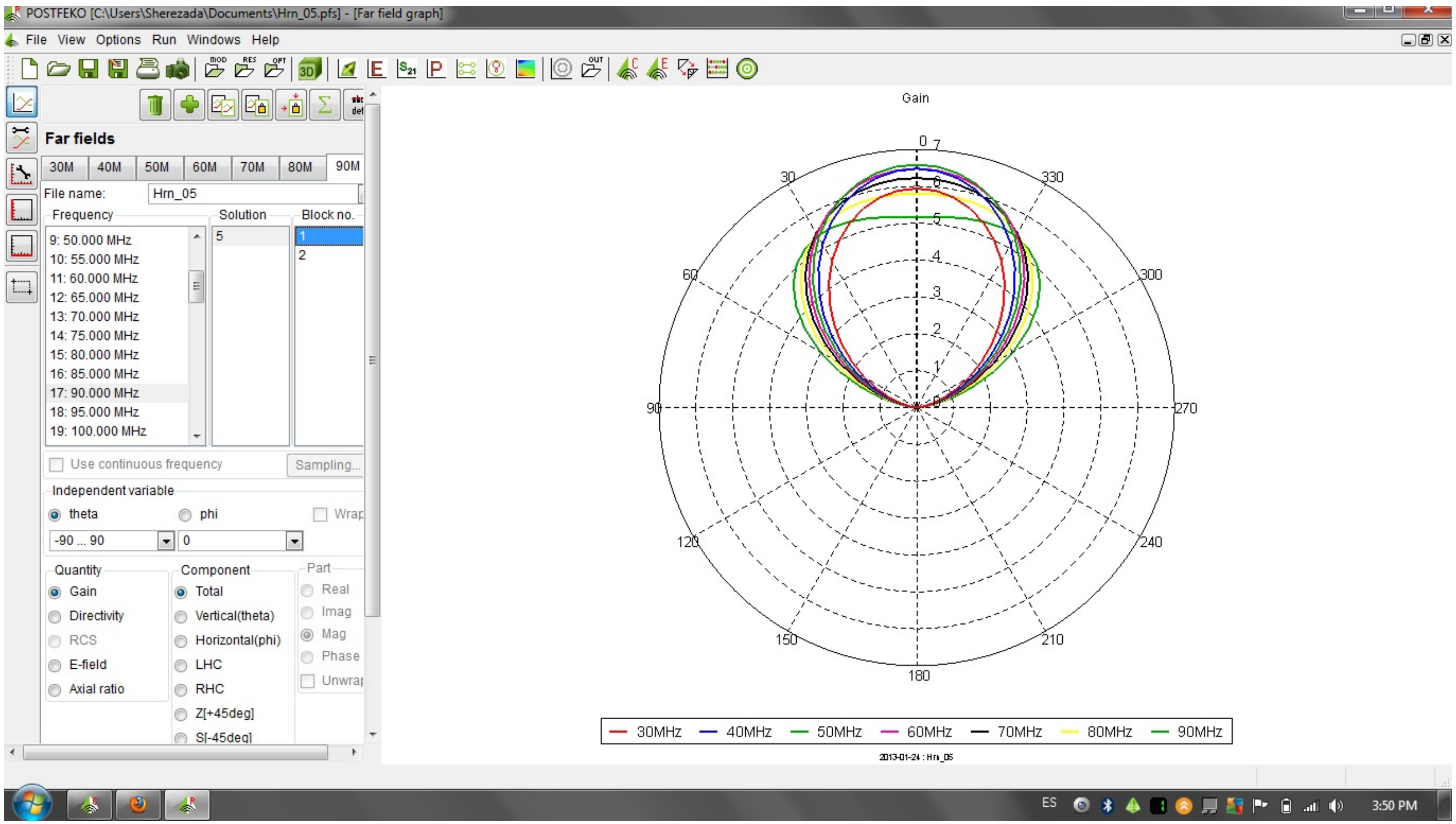


Sci-HI: First Run

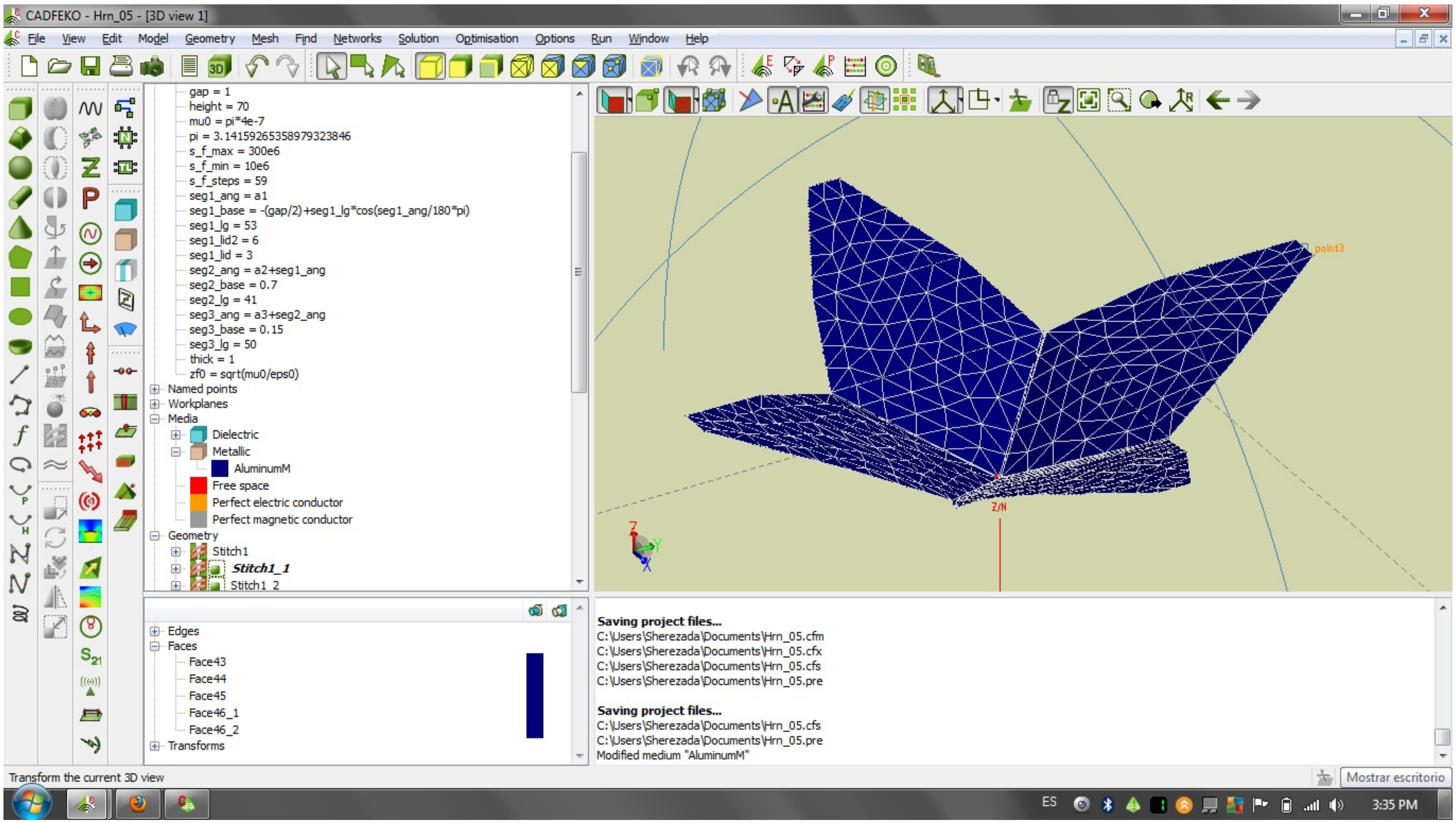




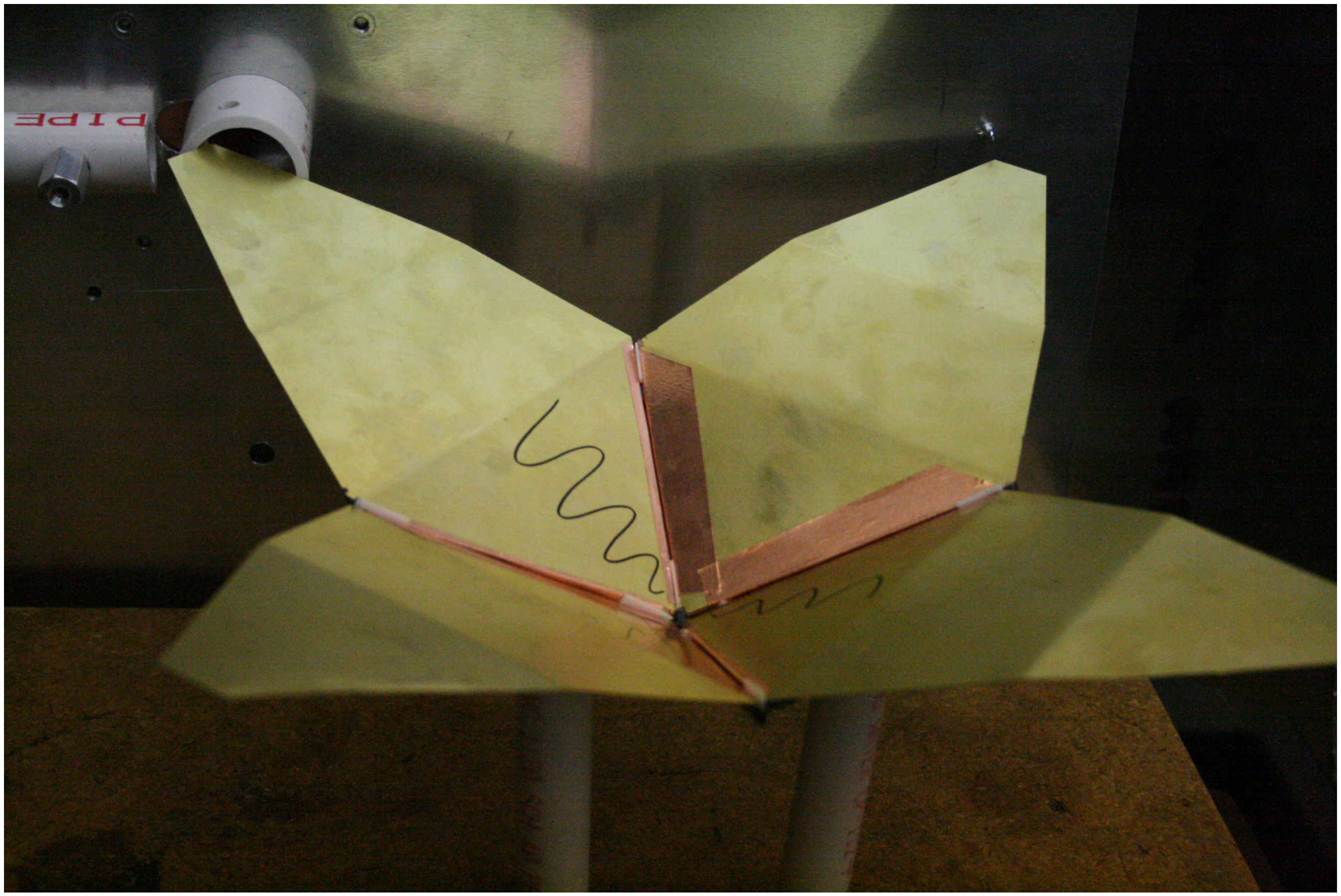
Antenna: New Design



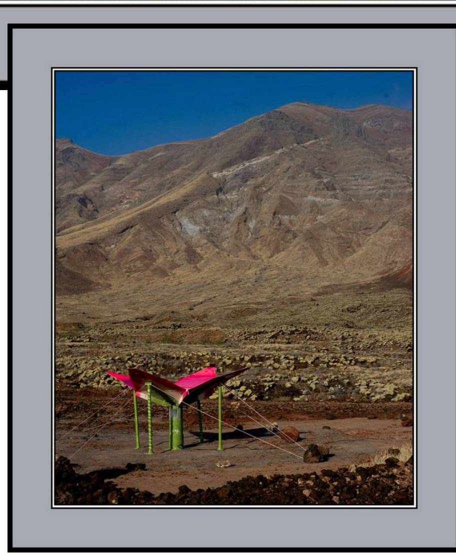
Antenna: New Design



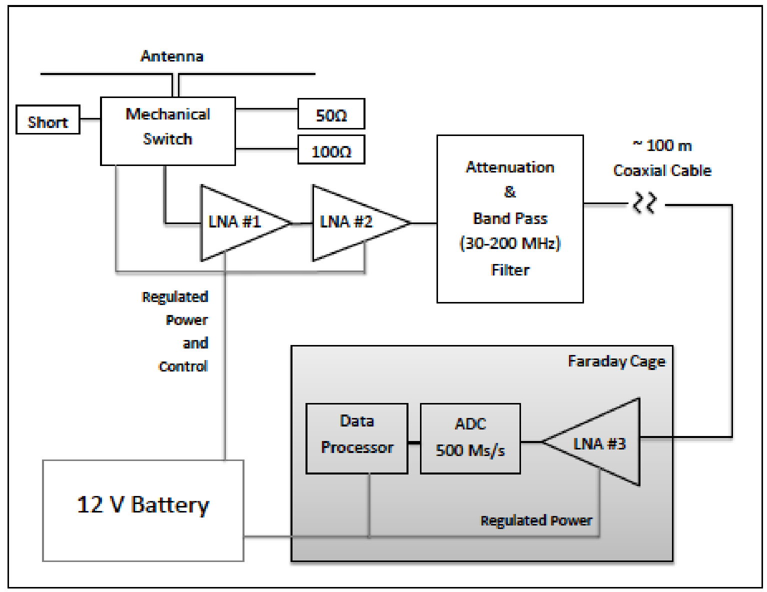
Antenna: New Design



Sci-HI: Isla Guadalupe



Sci-HI


Antenna
Short
Mechanical Switch
50Ω
100Ω
LNA #1
LNA #2
Attenuation & Band Pass (30-200 MHz) Filter
~ 100 m Coaxial Cable
Regulated Power and Control
Faraday Cage
Data Processor
ADC 500 Ms/s
LNA #3
12 V Battery
Regulated Power

Data Reductions

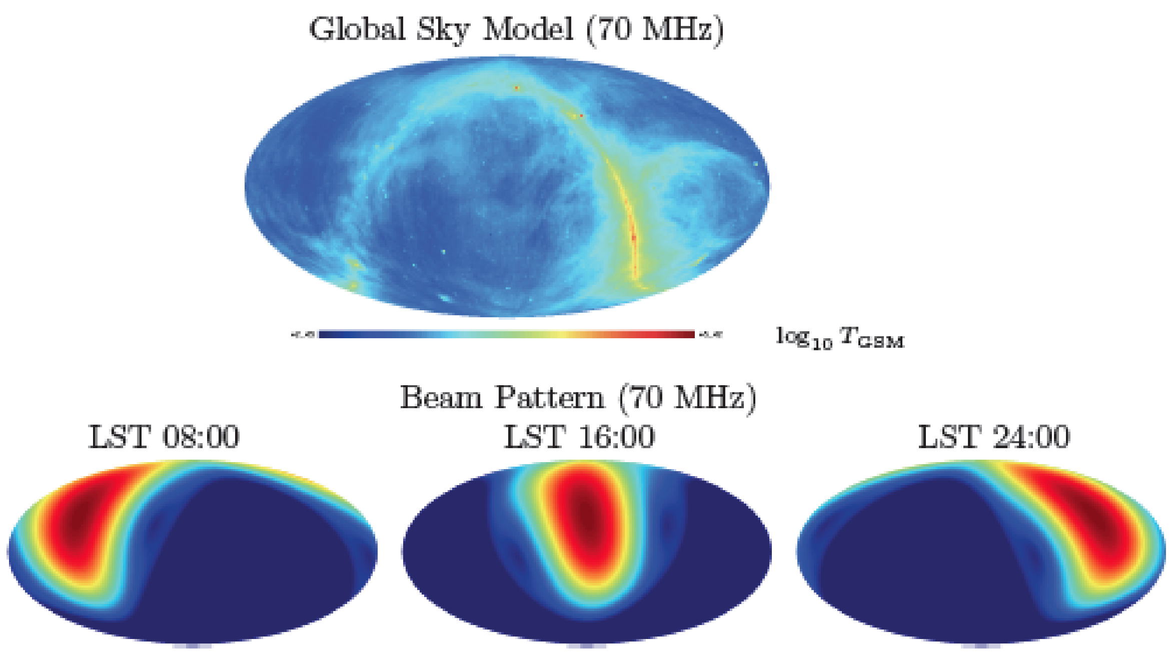
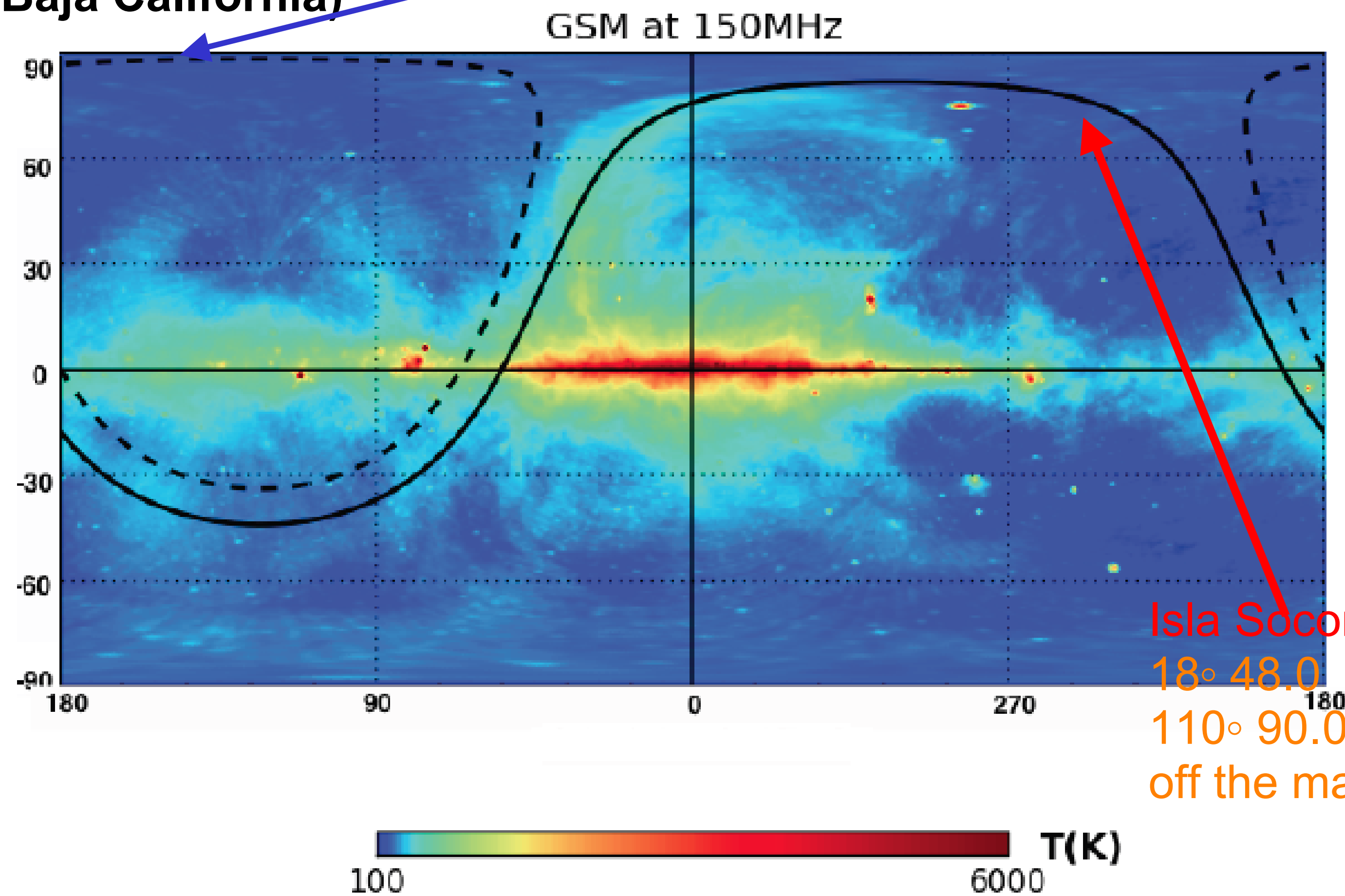


FIG. 3: Sky temperature and antenna beam pattern in (RA, DEC) coordinates. The top row shows the sky temperature (logarithmic) at 70 MHz, from the Galactic Global Sky Model (GSM). The bottom row shows the simulated antenna beam pattern at 70 MHz at different LST, plotted for the latitude of Isla Guadalupe.

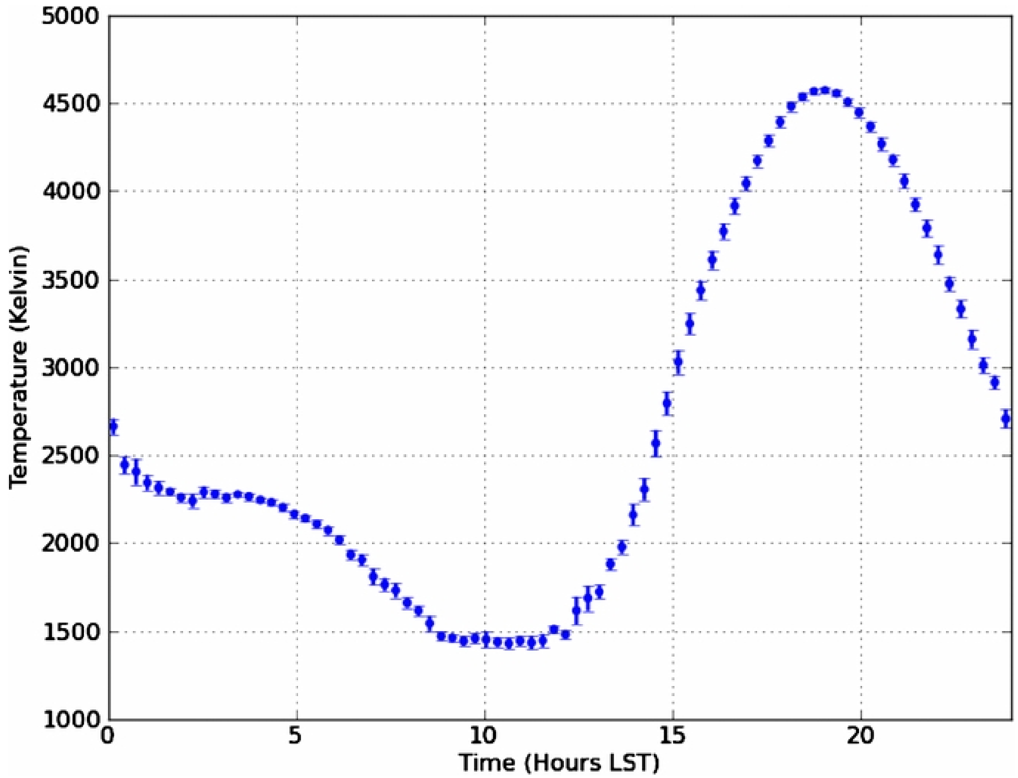
Sci-HI Scanning Paths

Isla Guadalupe **(latitude 28◦5824 N, longitude 118◦184 W), 260 km off the Baja California)**



Isla Socorro (latitude 18◦ 48.0 N, longitude 110◦ 90.0 W), 600 km off the mainland.

Data Reductions



Diurnal variation of a single 2 MHz wide bin centered at 70 MHz. Calibrated mean with rms error bars from day-to-day variation are shown for nine days of observation binned in ~18 minute intervals. Larger error bars correspond to LSTs where the quantity of useable data is smaller.

Sci-HI: First Results

THE ASTROPHYSICAL JOURNAL LETTERS, 782:L9 (5pp), 2014 February 10

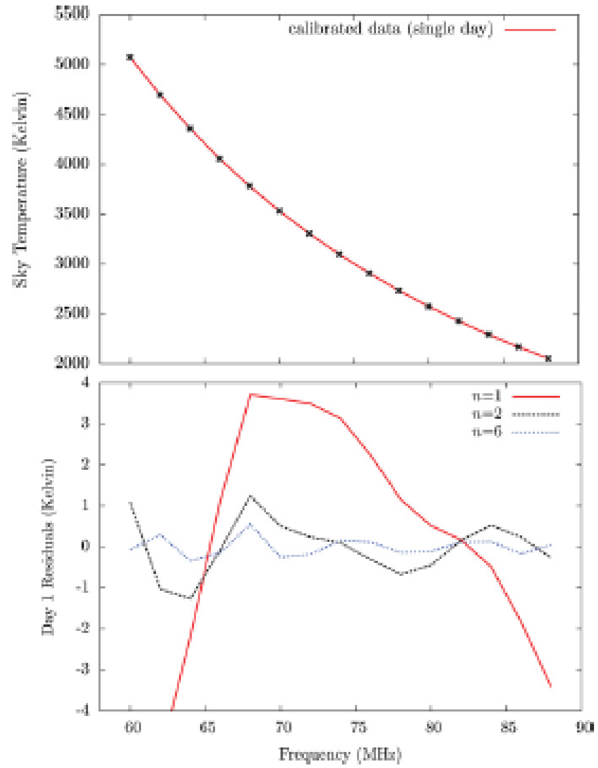


Figure 4. Data calibrated using K_{GSM} (de Oliveira-Costa et al. 2008). The top plot shows mean data from a single day of observation (~50 minutes integration time) binned in intervals of 2 MHz. The best fit plot for $n = 2$ is also shown ($a_0 = 3.548$, $a_1 = -2.360$, $a_2 = -0.164$, for June 1st). The bottom plot shows the residuals after the fit was subtracted. A simple power law ($n = 1$) results in a poor fit, while $n = 2$ substantially improves the fit.

(A color version of this figure is available in the online journal.)

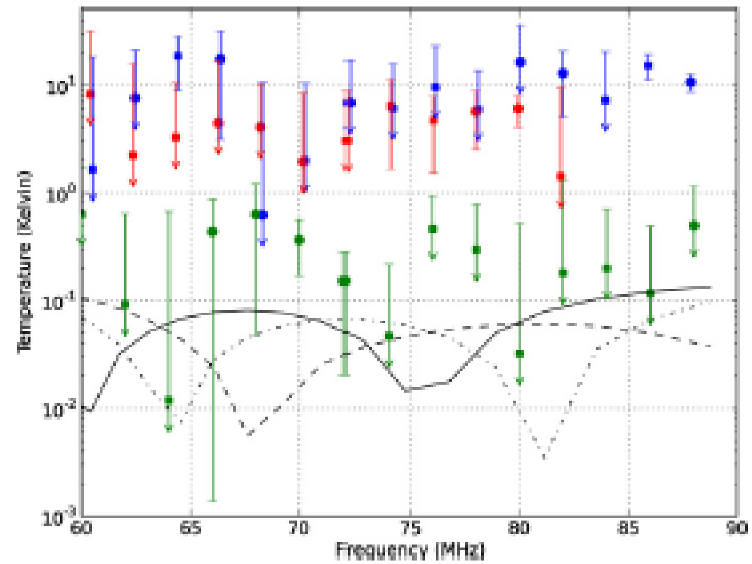


Figure 5. Log of the magnitude of the combined residuals from 4.4 hr of integration time using three different calibration techniques. Green is the residuals from K_{GSM}, while red is the residuals from $K_{\Delta GSM}$ and blue is the residuals from K_{JNC}. Circles are positive values and squares are negative values. $K_{\Delta GSM}$ fits are done on a smaller frequency range of 60–82 MHz. Error bars show the daily variance of the residuals. Also shown are the predictions from three reionization models. These models differ in their star formation efficiency and X-ray heating and the mean brightness temperature is subtracted from each of the theoretical models.

(A color version of this figure is available in the online journal.)

First Sci-HI Article Accepted

The Astrophysical Journal Letters, 782:L9 (5pp), 2014 February 10 doi:10.1088/2041-8205/782/1/L9

PROBING THE DARK AGES AT $z \sim 20$: THE SCI-HI 21 cm ALL-SKY SPECTRUM EXPERIMENT

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Received 2013 October 31; accepted 2014 January 8; published 2014 January 27

ABSTRACT

We present first results from the SCI-HI experiment, which we used to measure the all-sky-averaged 21 cm brightness temperature in the redshift range $14.8 < z < 22.7$. The instrument consists of a single broadband sub-wavelength size antenna and a sampling system for real-time data processing and recording. Preliminary observations were completed in 2013 June at Isla Guadalupe, a Mexican biosphere reserve located in the Pacific Ocean. The data was cleaned to excise channels contaminated by radio frequency interference, and the system response was calibrated by comparing the measured brightness temperature to the Global Sky Model of the Galaxy and by independent measurement of Johnson noise from a calibration terminator. We present our results, discuss the cosmological implications, and describe plans for future work.

Key words: cosmology: observations – dark ages, reionization, first stars – methods: observational – radio continuum: general

Online-only material: color figures

Sci-HI is getting There

- **The race for the detection of the end of end of the Dark Ages and EoR using high-z 21 cm has begun.**

Isla Guadalupe is one of the best radio quiet zones in the World. Mexico can play an strategic role in this race. ***Sci-HI is searching into the Dark Agein z-space. We are improving over the sensitivity over EDGES*****.**

- **We need people, for data reduction, modeling of the 21 cm spectrum through cosmic time, astronomers, radio-astronomers, cosmologists, physics, computer gurus, ecologists, geologists…**

- **We must act to protect La Zona del Silencio and Isla Guadalupe and keep them Radio Quiet. We should declare them National Radio Quiet Zones (Area Natural Protegida de Ondas Electromagnéticas de Origen Artificial: Zonas Radio-Silentes).** Estrategia Nacional para la Conservación y el Desarrollo Sustentable del Territorio Insular Mexicano (SEMARNAT, 2012). (OL-C, Asesor Nacional)

- **Next destination: Isla Socoro, Archipielago de Revillagigedo & The Antartic (Argentina)**

ASTROPHYSICS | PHYSICS

Though astrophysicists have developed a theoretical framework for understanding how the first stars and galaxies formed, only now are we able to begin testing those theories with actual observations of the very distant, early universe. We are entering a new and exciting era of discovery that will advance the frontiers of knowledge, and this book couldn't be more timely. It covers all the basic concepts in cosmology, drawing on insights from an astronomer who has pioneered much of this research over the past two decades.

Abraham Loeb starts from first principles, tracing the theoretical foundations of cosmology and carefully explaining the physics behind them. Topics include the gravitational growth of perturbations in an expanding universe, the abundance and properties of dark matter halos and galaxies, reionization, the observational methods used to detect the earliest galaxies and probe the diffuse gas between them—and much more.

Cosmology seeks to solve the fundamental mystery of our cosmic origins. This book offers a succinct and accessible primer at a time when breathtaking technological advances promise a wealth of new observational data on the first stars and galaxies.

- Provides a concise introduction to cosmology
- Covers all the basic concepts
- Gives an overview of the gravitational growth of perturbations in an expanding universe
- Explains the process of reionization
- Describes the observational methods used to detect the earliest galaxies

Abraham Loeb is professor of astronomy and director of the Institute for Theory and Computation at Harvard University.

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"Abraham Loeb, a leading figure in exploring the emergence of first galaxies and stars, introduces the astrophysics of the first billion years. With a strong emphasis on the underlying physics, this book will be an essential starting point for both observers and theorists who are interested in this rapidly evolving area of cosmology."
—**David Spergel**, Princeton University

"A lucid, concise account of our current understanding of how light burst from darkness when the first stars and galaxies formed early in the expansion of the universe. Starting from basic physical principles, Loeb describes the physical processes that shaped the evolution of the universe, how they led to the formation of the first black holes, quasars, and gamma-ray bursts, and how upcoming observations will test these ideas."
—**Christopher F. McKee**, University of California, Berkeley

"This is a lively, well-written book. L[illegible] an excelle[illegible] who is als[illegible] research o[illegible] first stars [illegible] frontier fo[illegible] tors have [illegible] framewor[illegible] [illegible]ational possibiliti[illegible] are rapidly developing. The timing of this book couldn't be better."
—**Richard S. Ellis**, California Institute of Technology

"This is an extremely good book. Loeb guides readers through the early, formative history of the universe. He does not shy away from key calculations, but always tries to make things as simple as possible. His style is truly engaging, with a constant eye on the big picture. It makes for a thrilling read. Indeed, I found it difficult to put down."
—**Volker Bromm**, University of Texas, Austin

ISBN 978-0-691-14516-7
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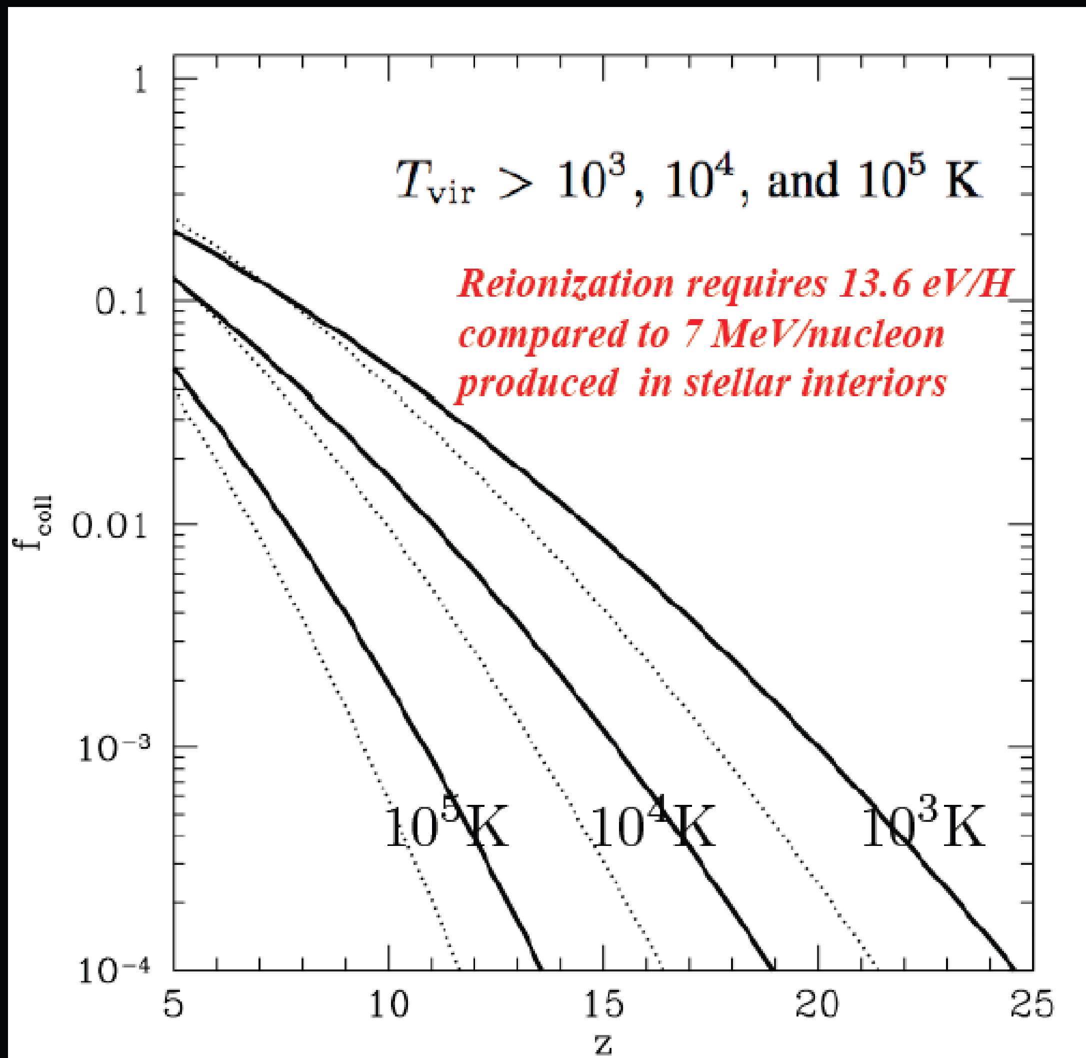
LOEB How Did the First Stars and Galaxies Form?

ABRAHAM LOEB

How Did the First Stars and Galaxies Form?

Fraction of collapsed matter



Cooling Rate of Primordial Gas (H,He)