Title: 21 cm: A New Window Into the Universe

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Abstract:

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Ilian T. Iliev
Canadian Institute for Theoretical Astrophysics

For further reading, see recent reviews:

Physics Reports, Volume 433, Issue 4-6, p. 181-301
Annual Review of Astronomy & Astrophysics, vol. 44, Issue 1, pp. 415-462

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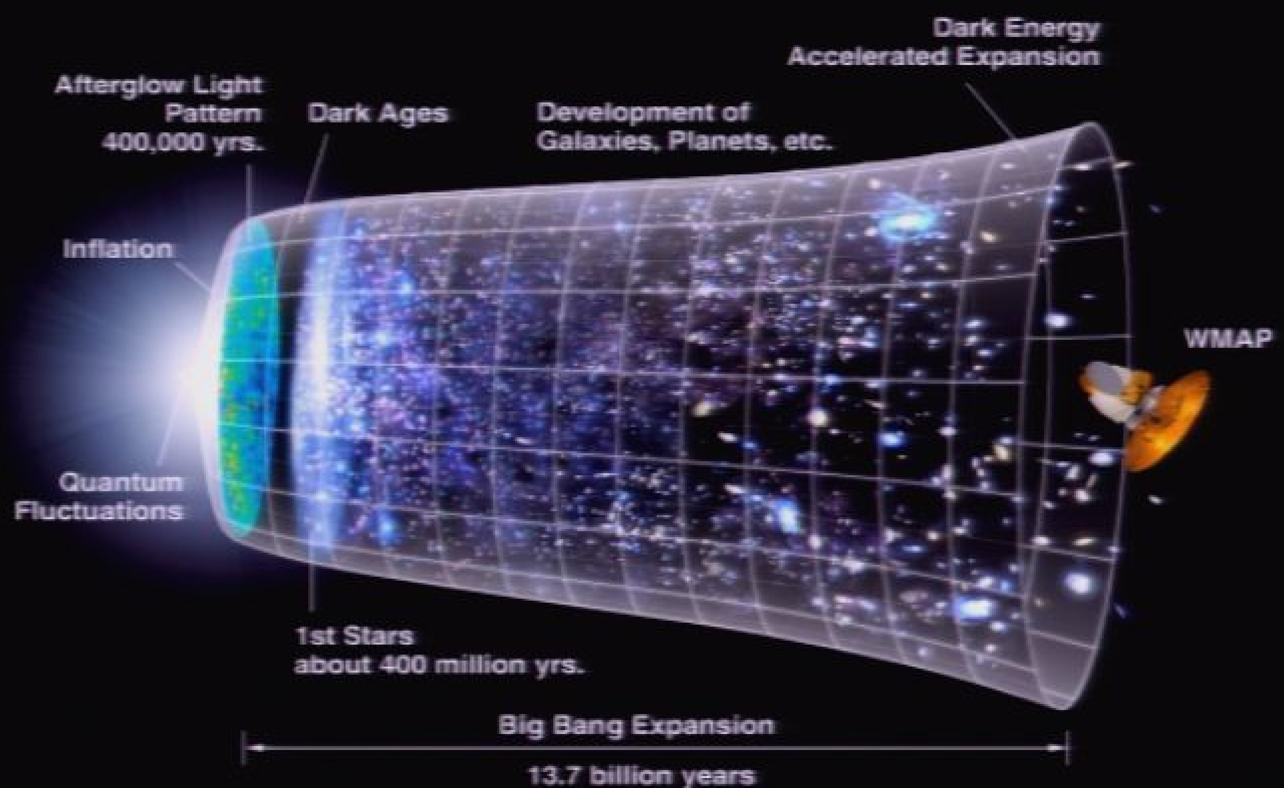
Brief History of the Universe



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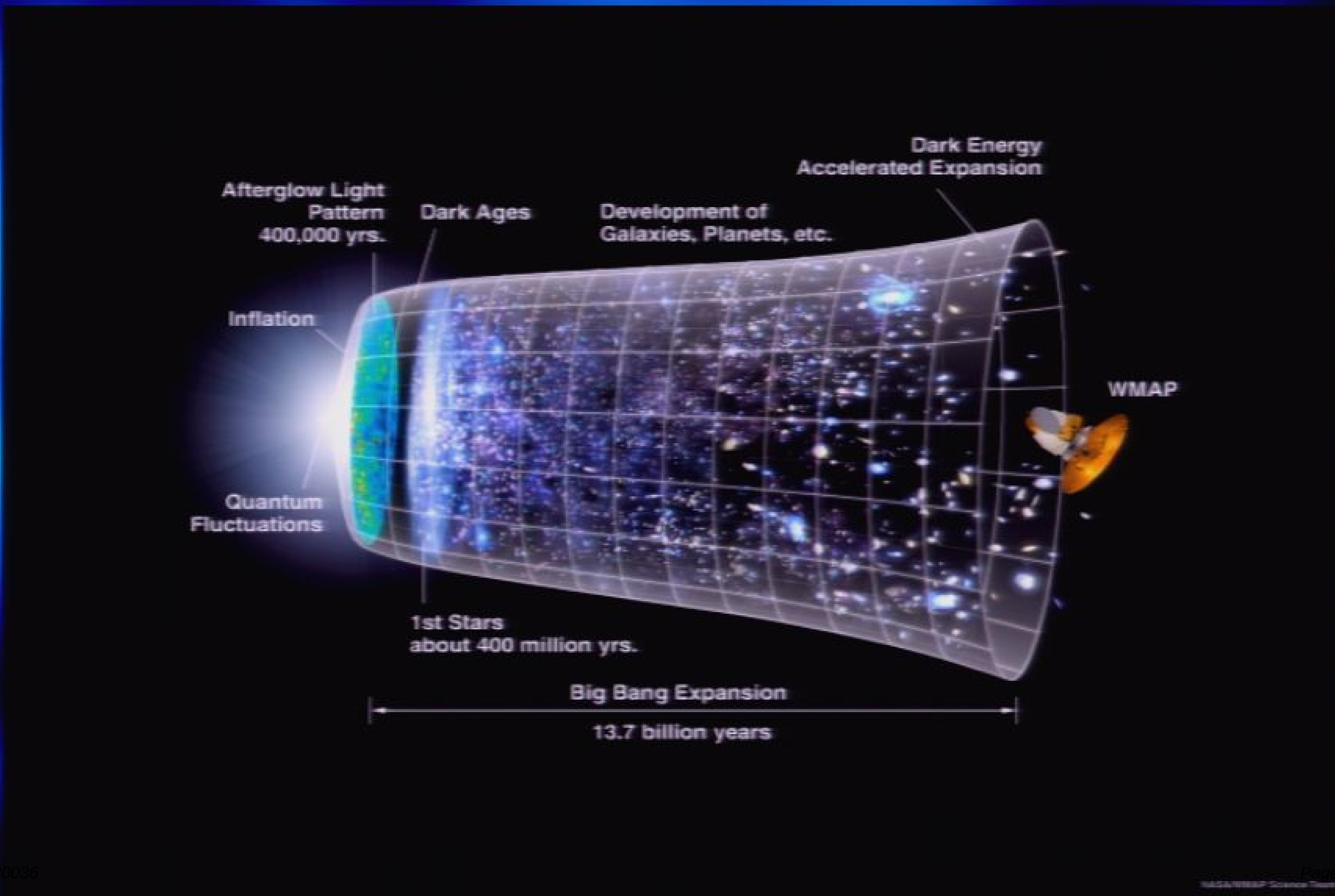
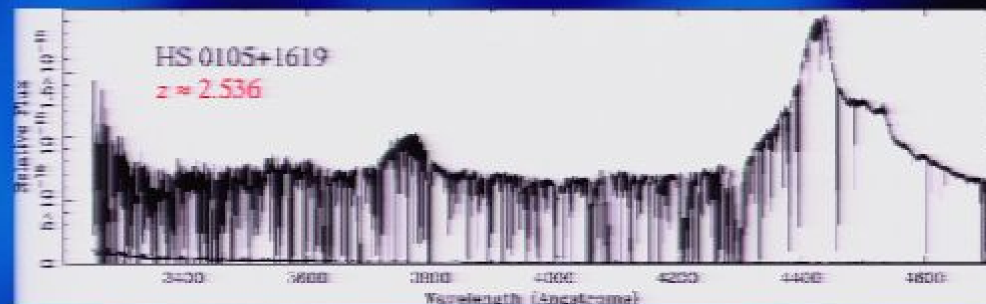


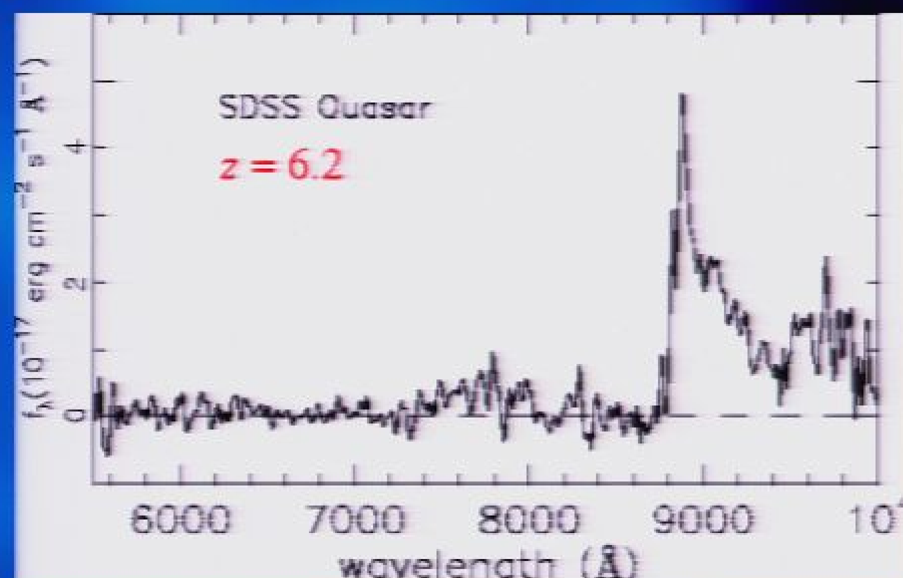
Cosmic Dark Ages and Epoch of Reionization

- Reionization: global transition of the IGM from neutral to highly-ionized which occurred by z~6 due to the ionizing radiation from the first galaxies.
- Significant, important and least-understood period in the history of the Universe (from age ~100 Myr to 1 Gyr). Complex, patchy evolution.
- Primordial fluctuations grow and the first nonlinear structures form during that period.
- It has profound effects on the state of the IGM and the subsequent galaxy formation.
- Currently very little observational data is available: difficult to constrain models of reionization; important to make reliable predictions for a number of upcoming experiments.

Gunn-Peterson Effect

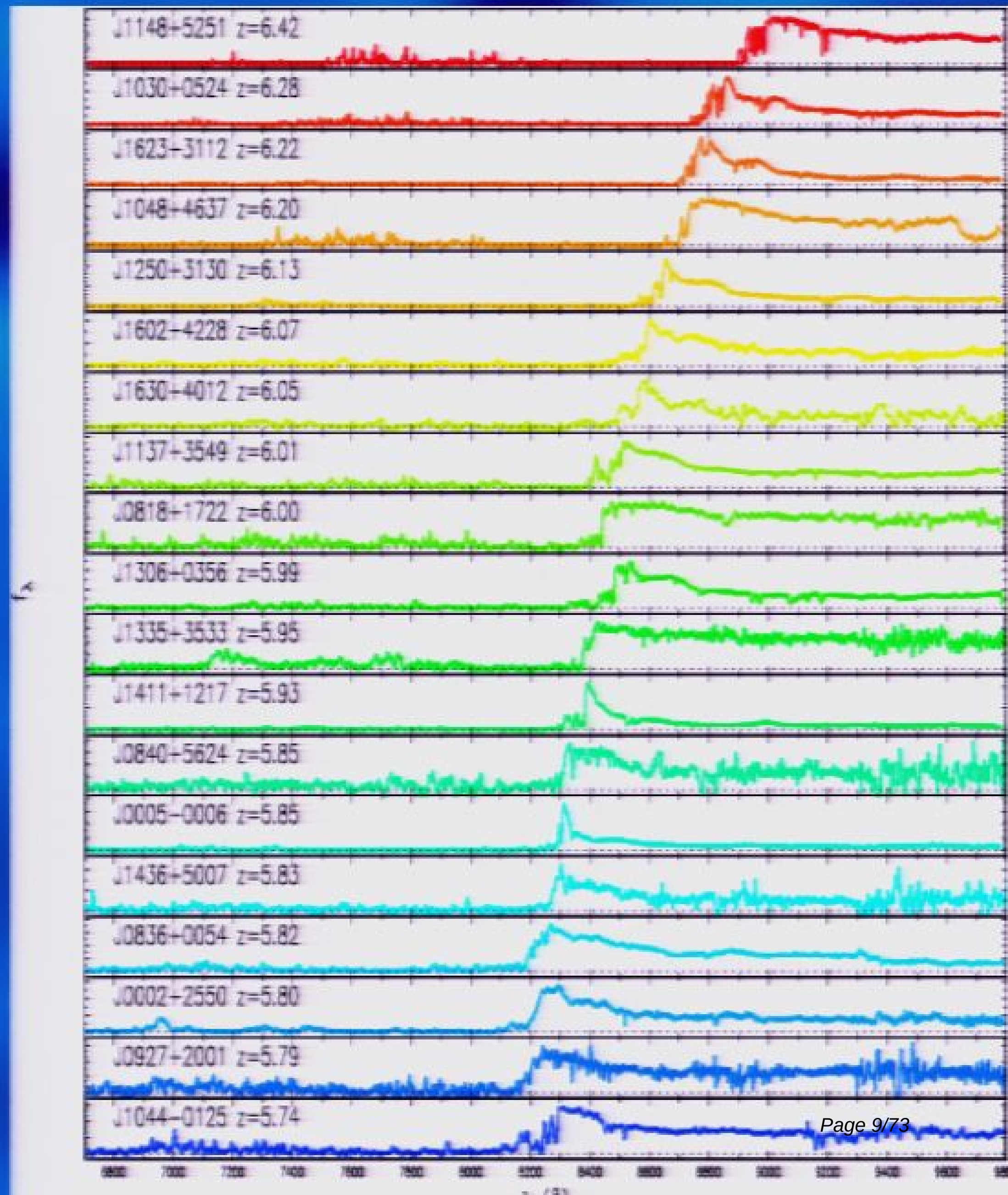
- How do we know the IGM is ionized?
- Distant quasars show only small scale absorption by neutral hydrogen blueward of their Ly-α line ('Ly-α forest').
- It cannot always have been ionized: 'Epoch of Reionization' (EoR).
- SDSS Quasars for z>6 indeed start to show large scale Ly-α absorption by neutral hydrogen (implying $x_{HI} > 10^{-4}$).





How do we know reionization occurred? (cont.)

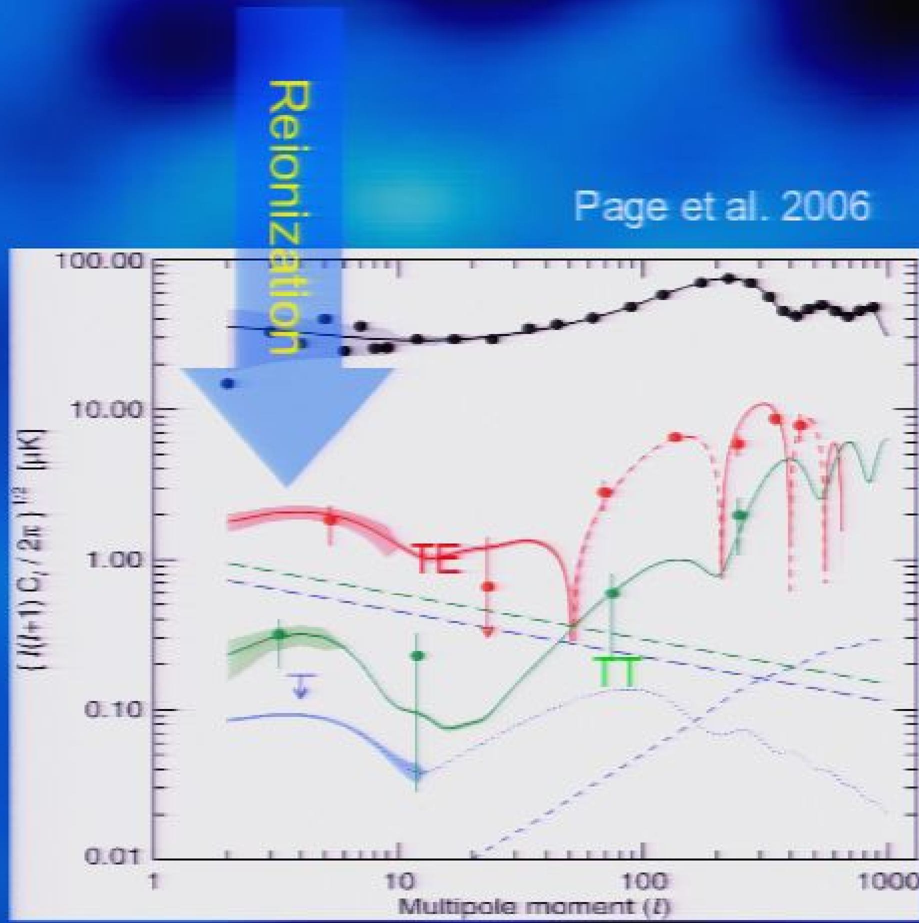
New and better data shows GP troughs quite clearly as one goes to ever-higher redshifts (Fan et al.)



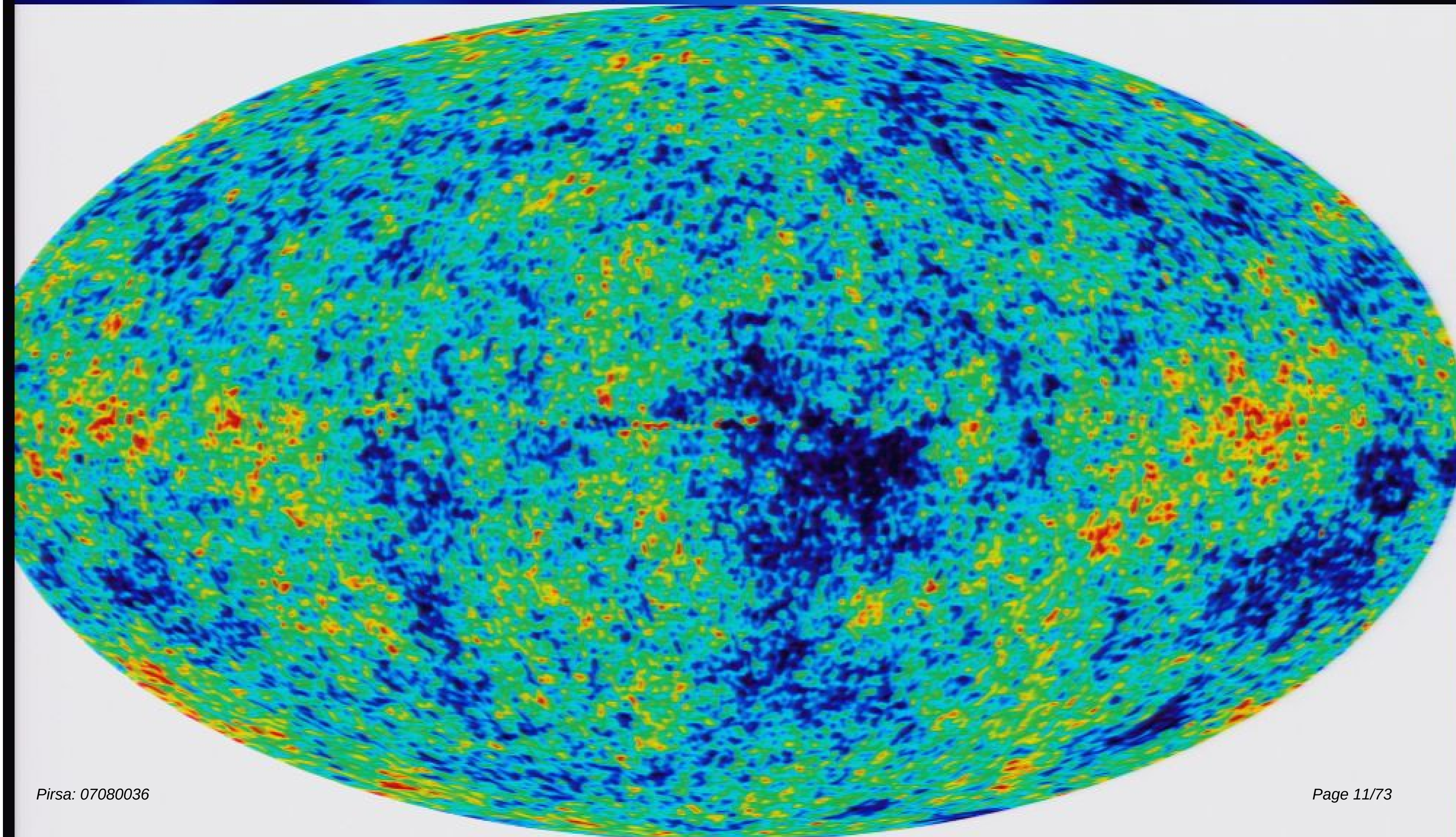
Cosmic Microwave Background signatures

- The power spectrum of the polarization of the CMB, allows us to measure the total average electron scattering optical depth between the recombination era and us.
- 3 year WMAP: $\tau \approx 0.09$.
- For step function: universe neutral beyond $z_r \sim 11$. (Note: earlier WMAP results had $\tau \approx 0.17$).

Page et al. 2006

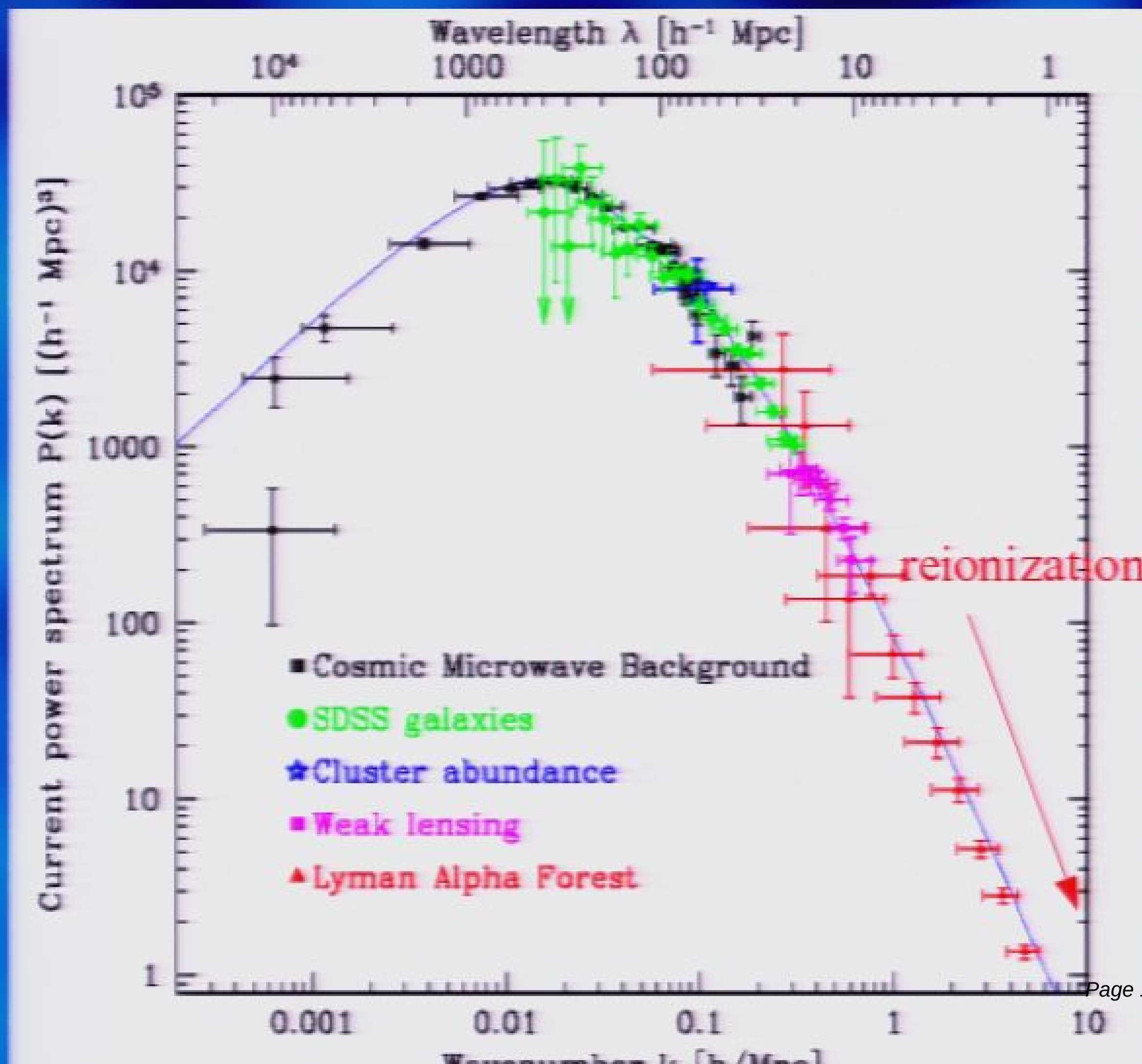


Primordial density fluctuations as seen by WMAP satellite

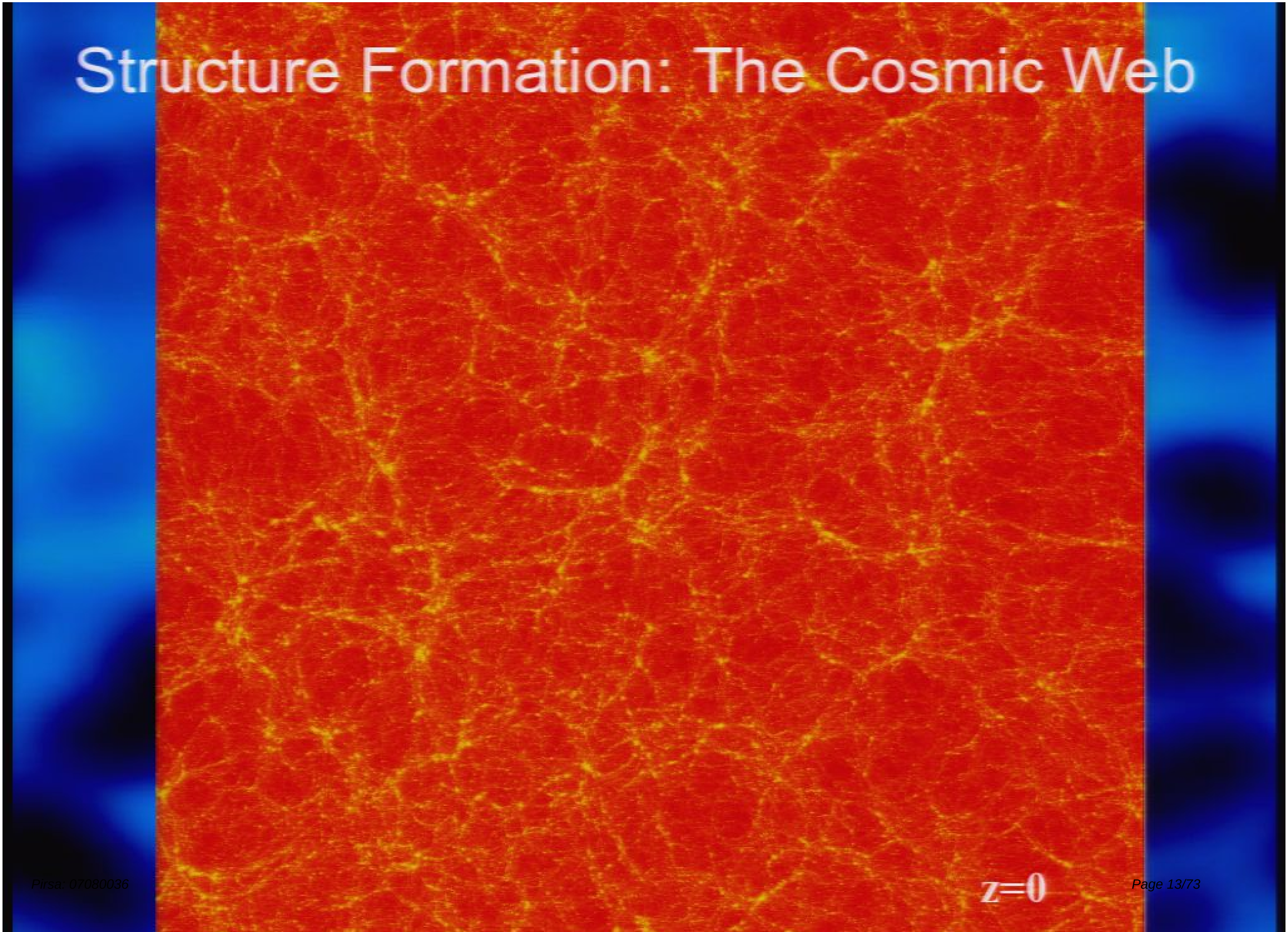


Primordial power spectrum of density fluctuations

Reionization depends mostly on scales k>>1/Mpc, a part of the P(k) density power spectrum well below the scales currently probed by other methods

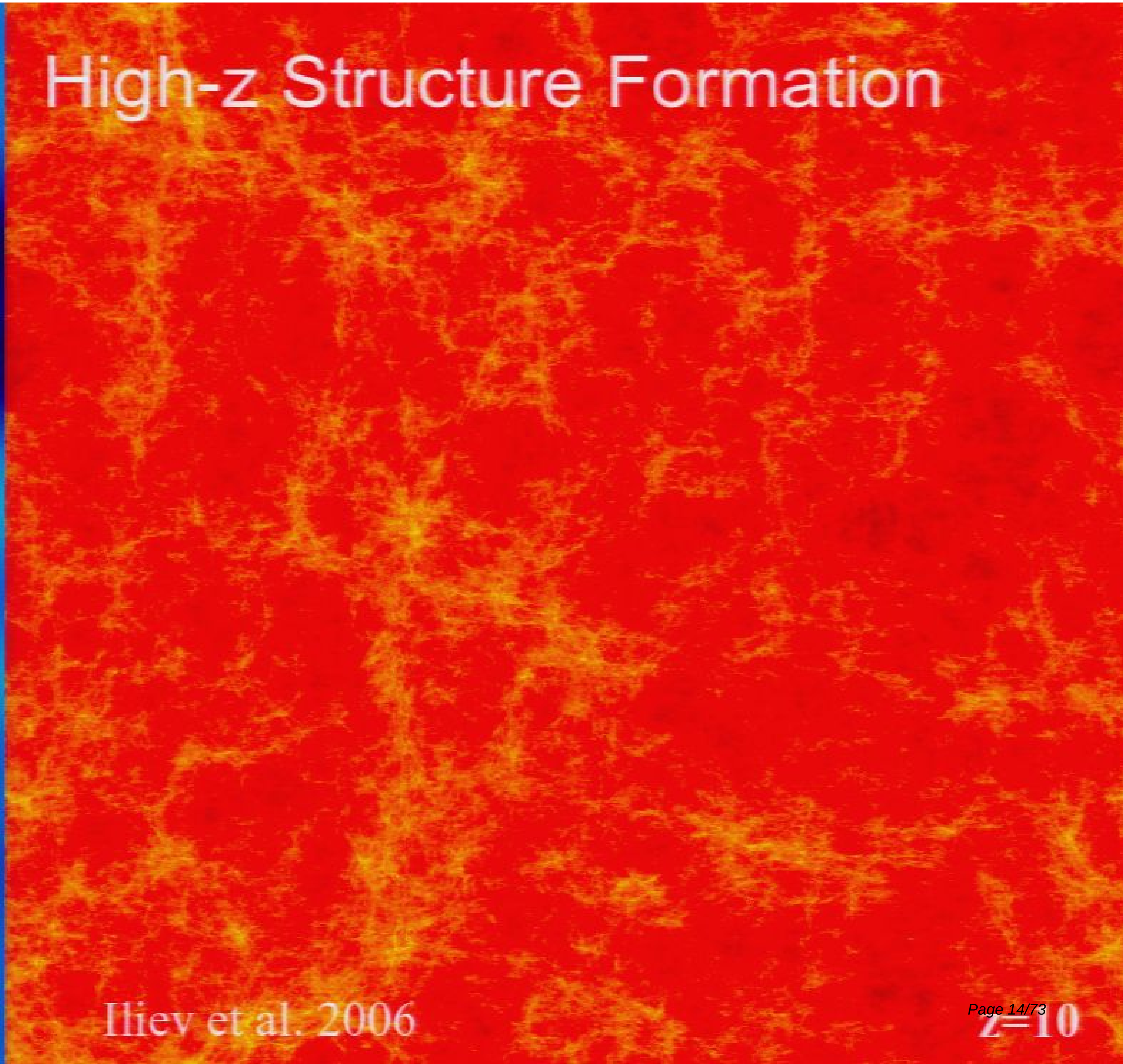


Structure Formation: The Cosmic Web

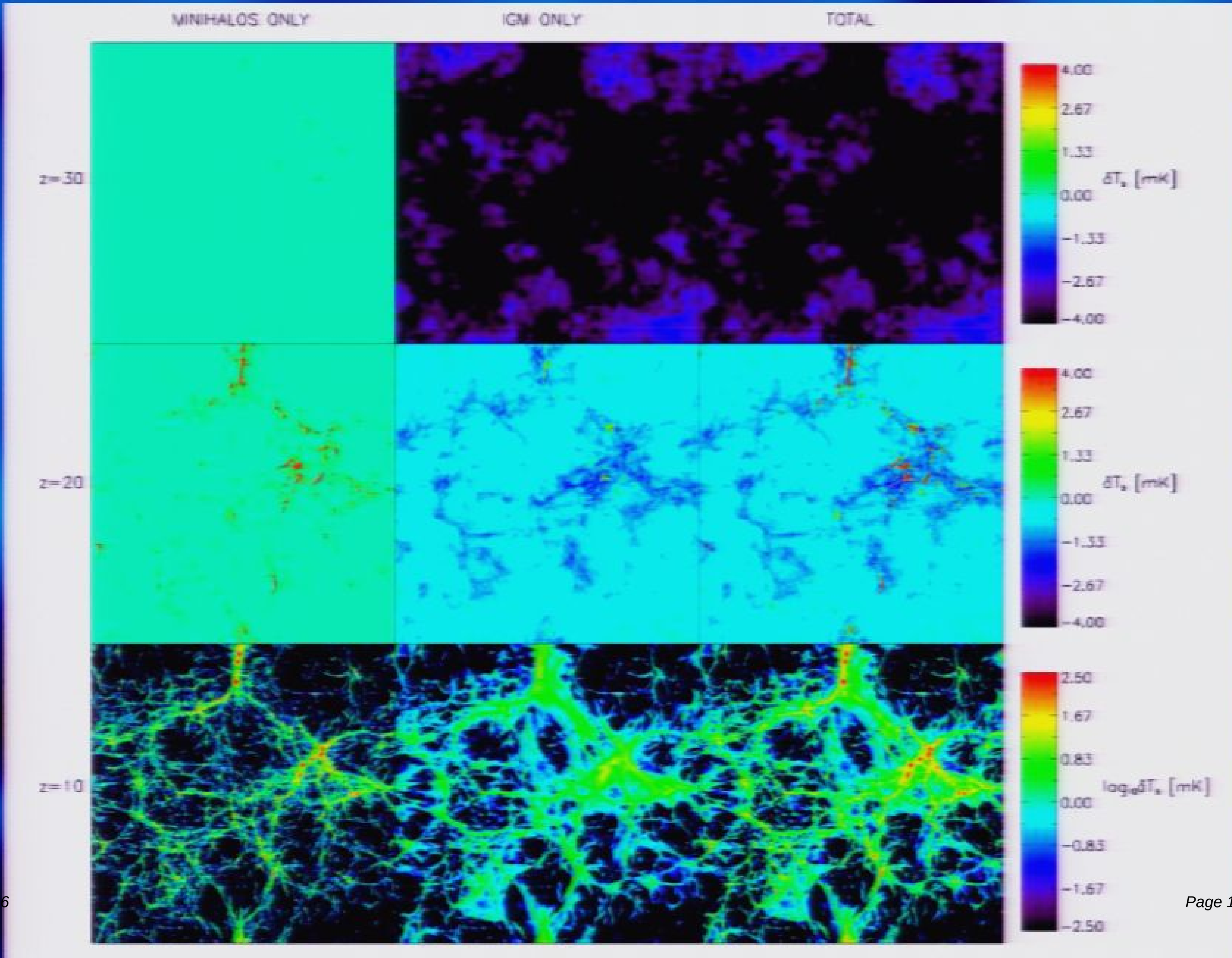


High-z Structure Formation

- Very high resolution N-body simulations of structure formation using PMFAST code developed at CITA (Merz, Pen & Trac 2004)
- 100/h box, 1624^3 particles (4.3 billion), 3248^3 cells. Up to 1-2 million halos identified (with >100 particles/halo $=2.5\times10^9 M_{solar}$)

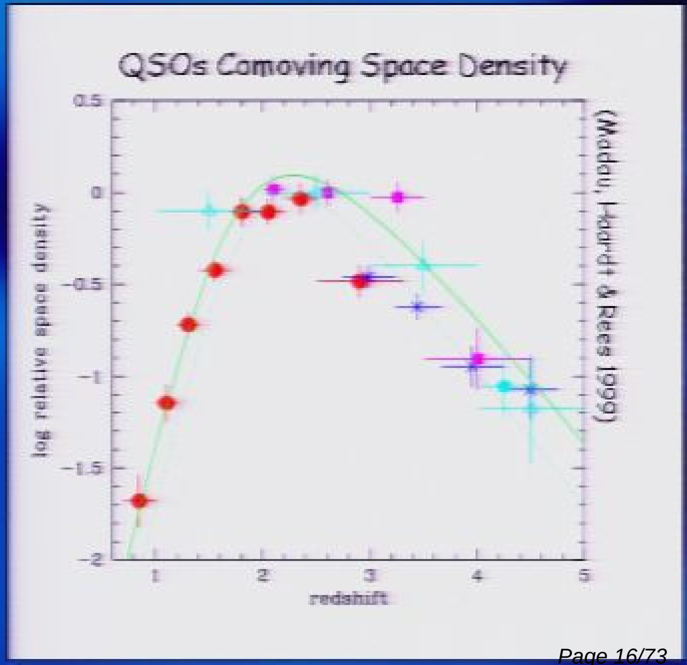


Observing the Dark Ages at 21-cm: collisional pumping



Sources of Reionization

- There are several possibilities for what could have caused reionization
  - Stars: metal abundance and populations of 'old' galaxies at high redshift suggest early star formation.
  - Quasars: too few
  - Mini-quasars: no evidence
  - Particle decay: speculative
- Conservative approach: Stars in atomically cooling halos ($M>10^8 M_\odot$).



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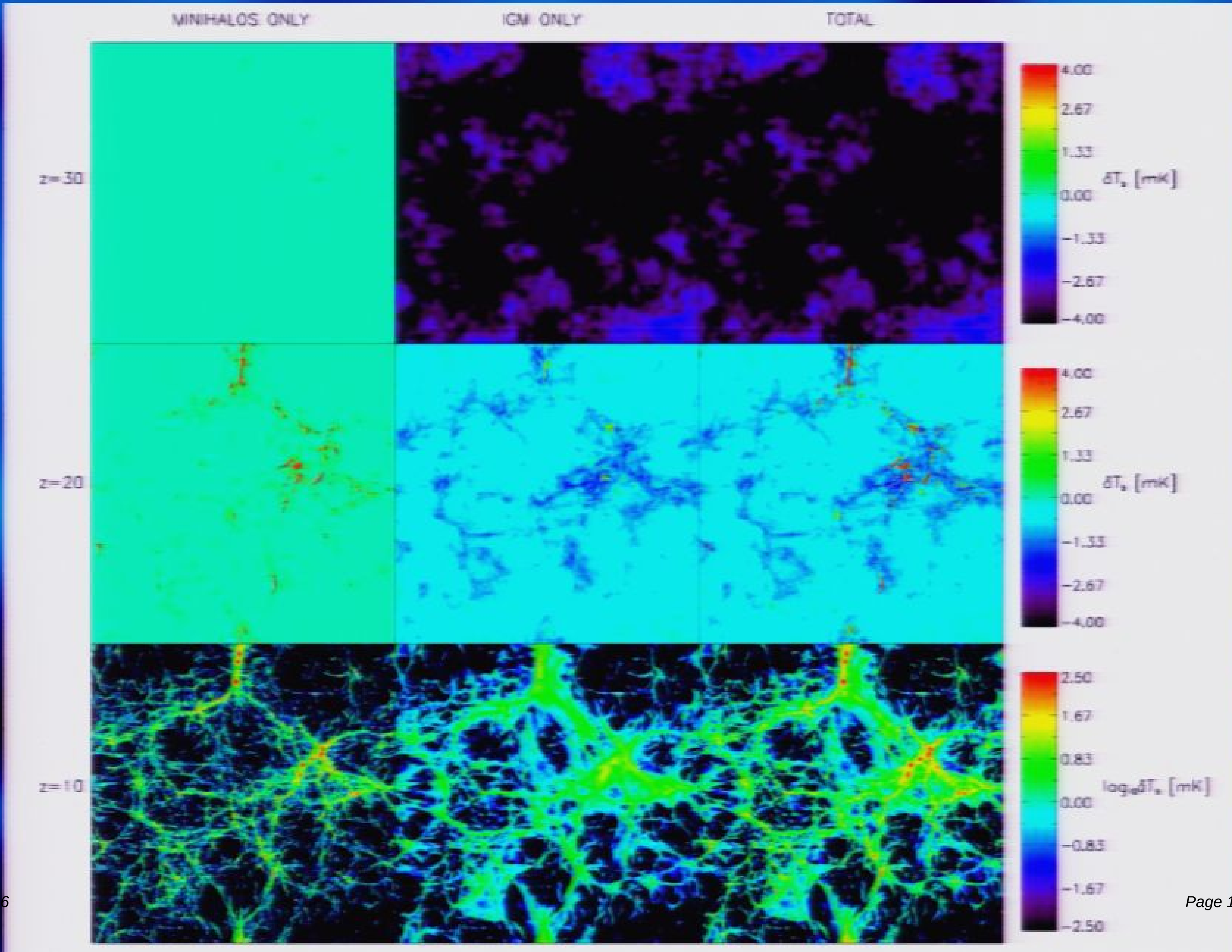

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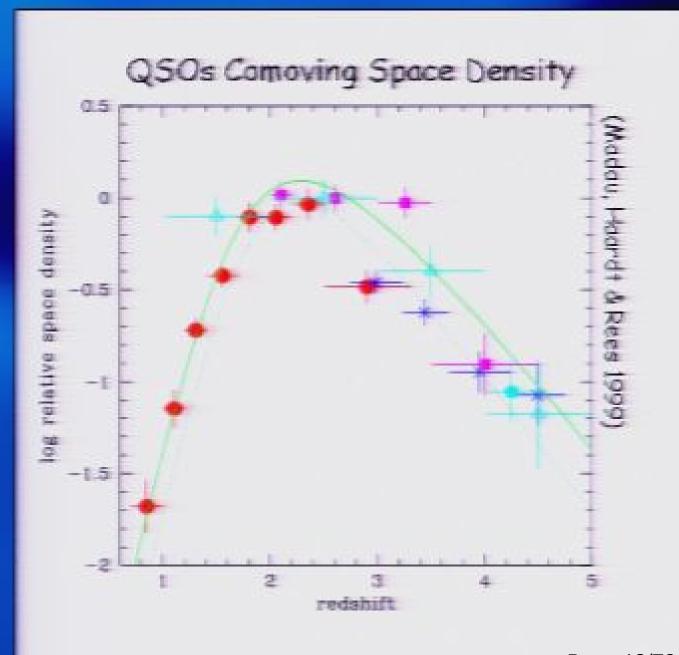
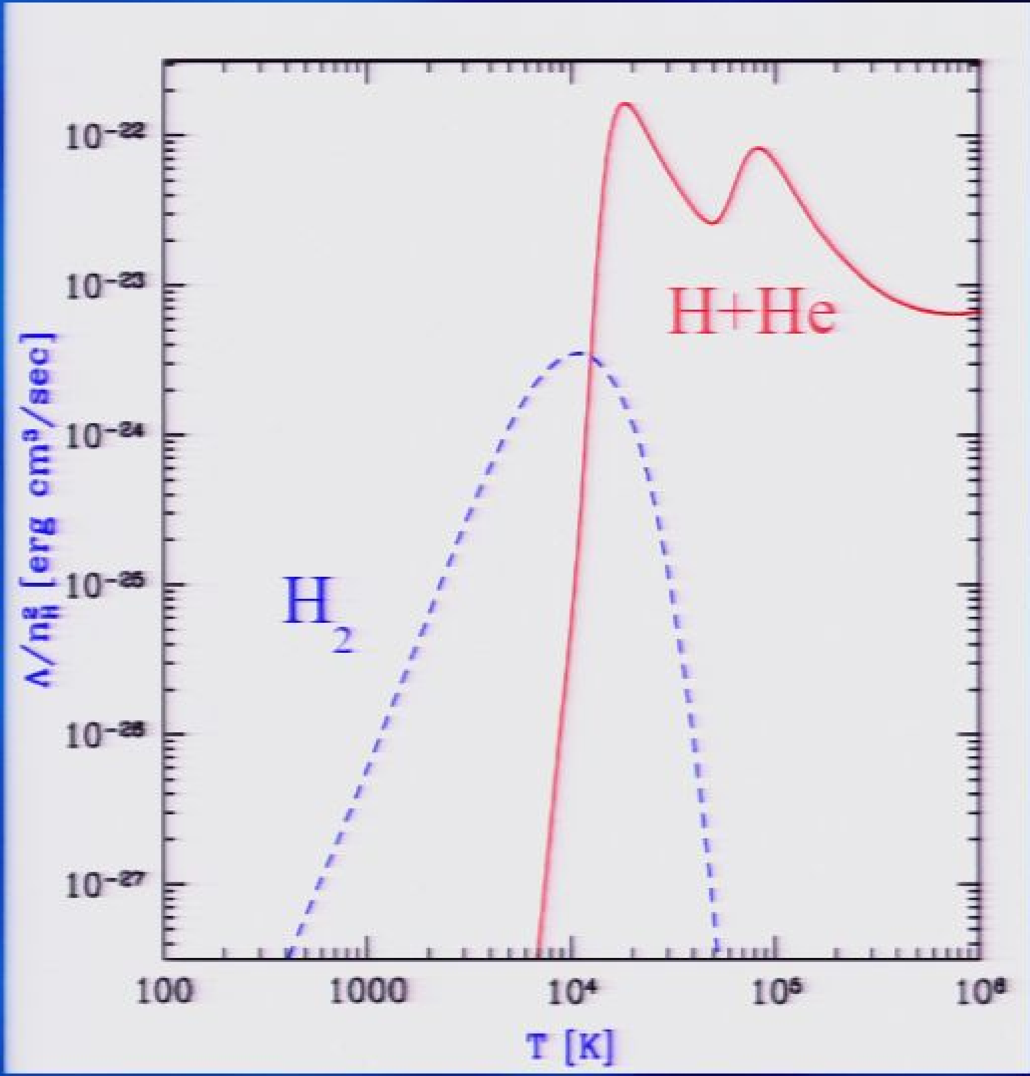


Hydrogen and Helium cooling

- Primordial-composition gas (before heavy-element enrichment by stars) consists of mostly H and He.
- Cooling:
  - high-T: radiavive through atomic lines
  - low-T: rotation and vibration of H_2 molecules
- Crucial for star formation – gas needs to be cooled to few x 100 K



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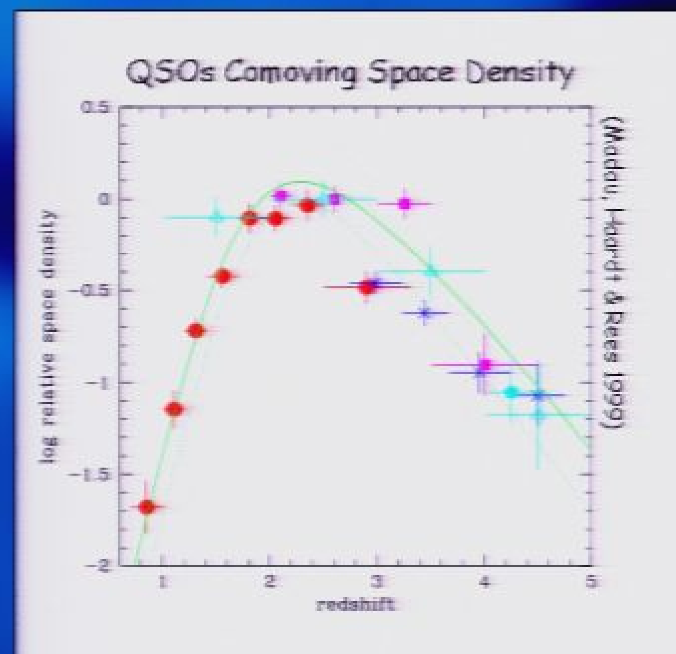

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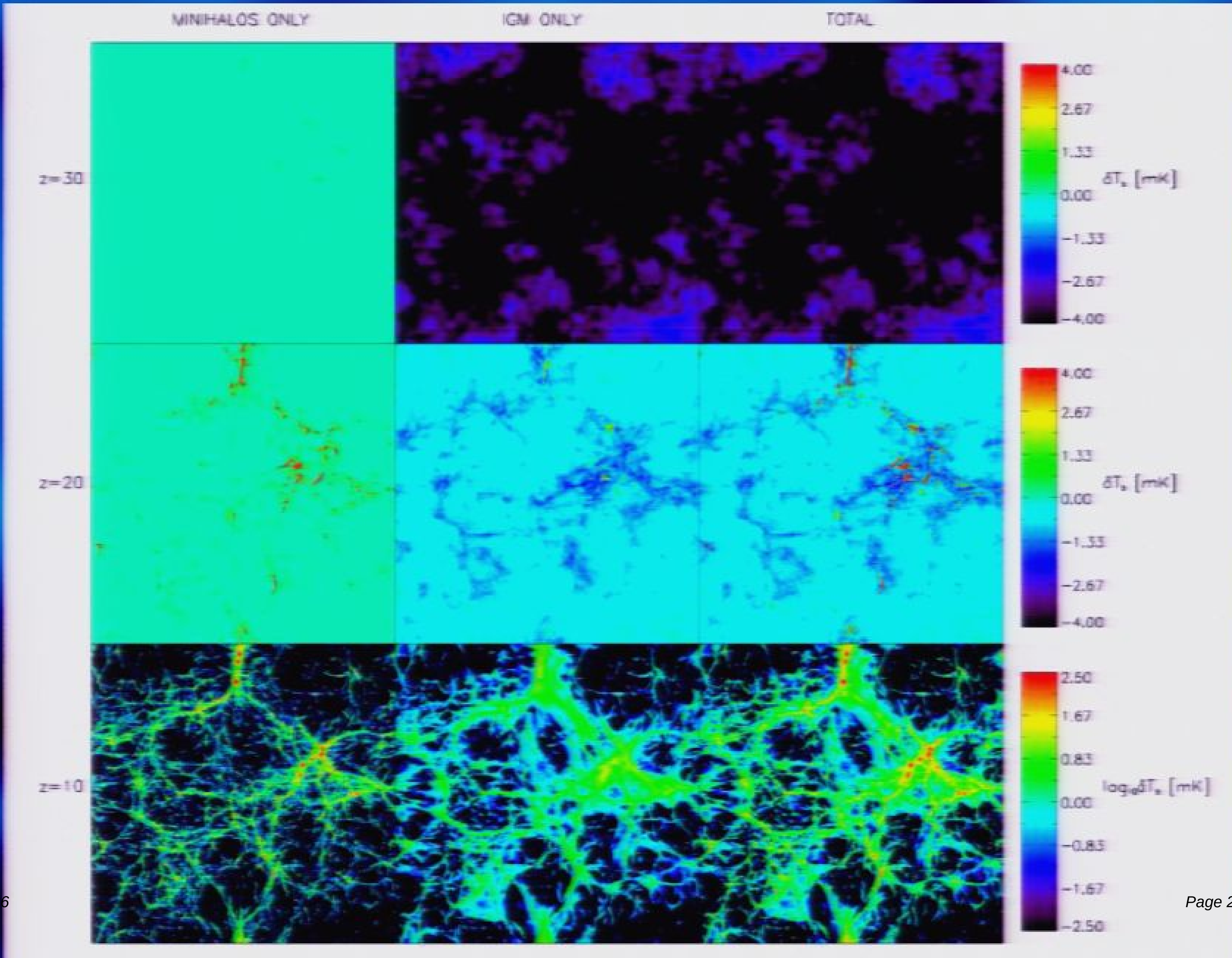

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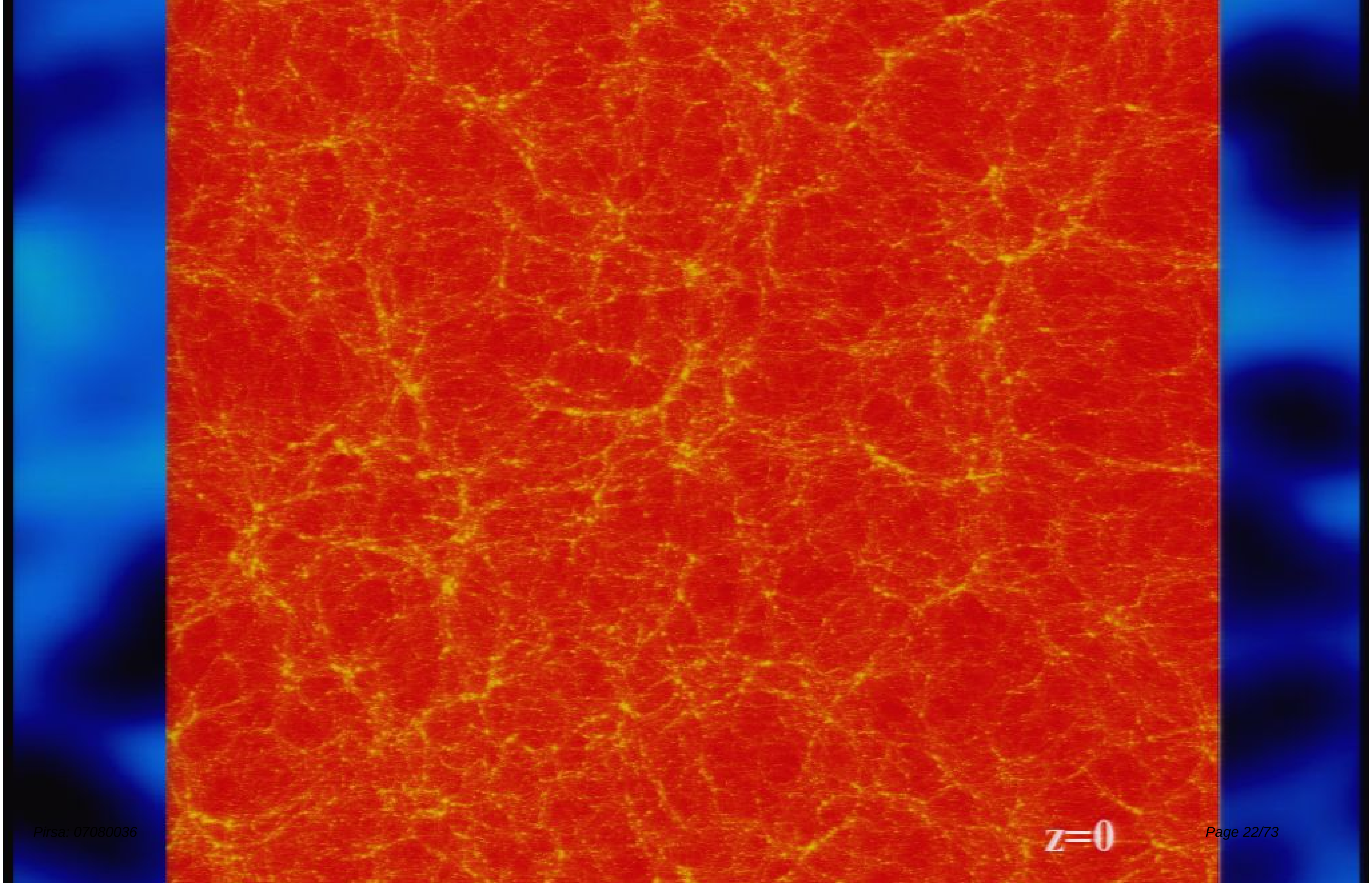

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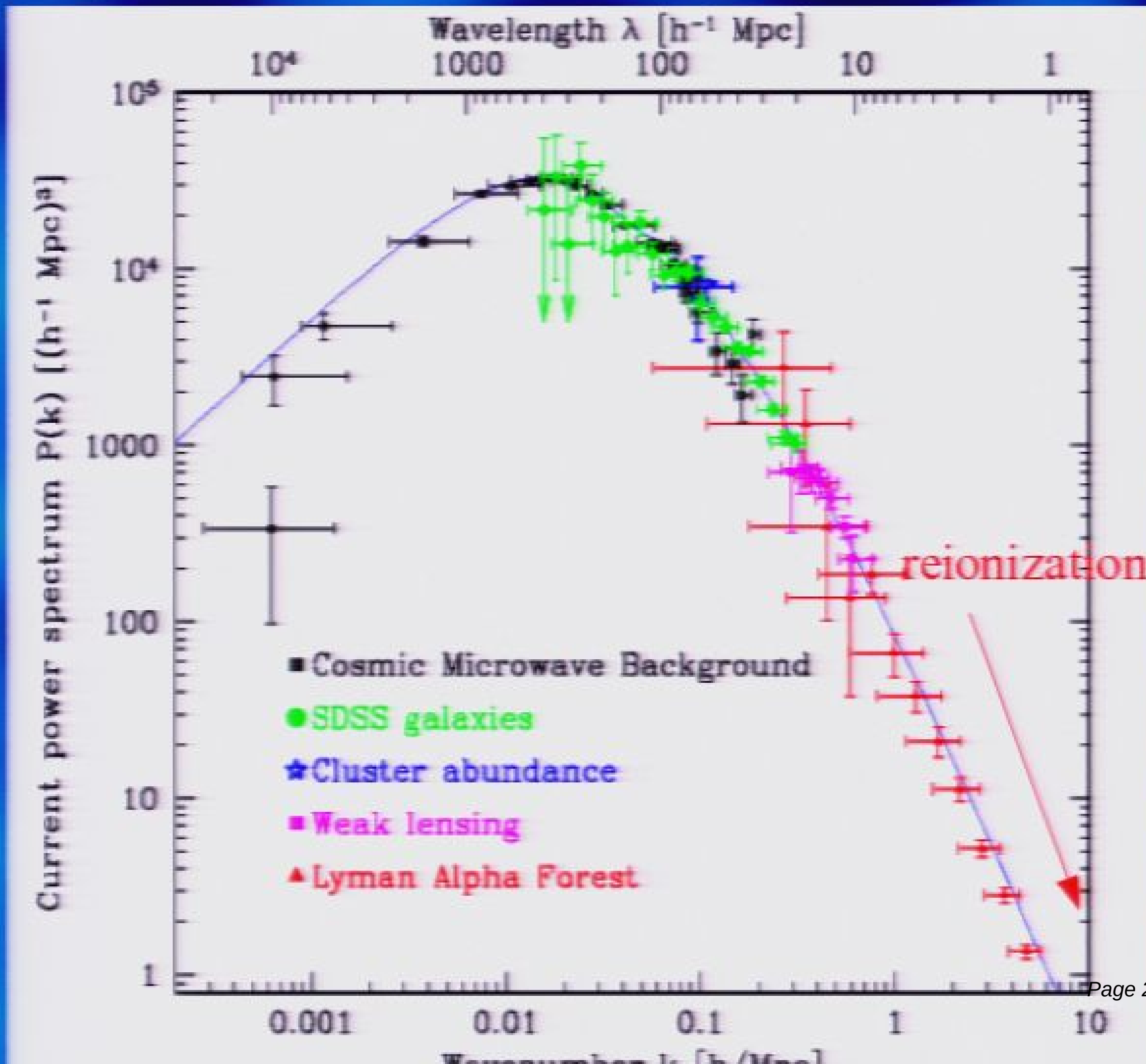

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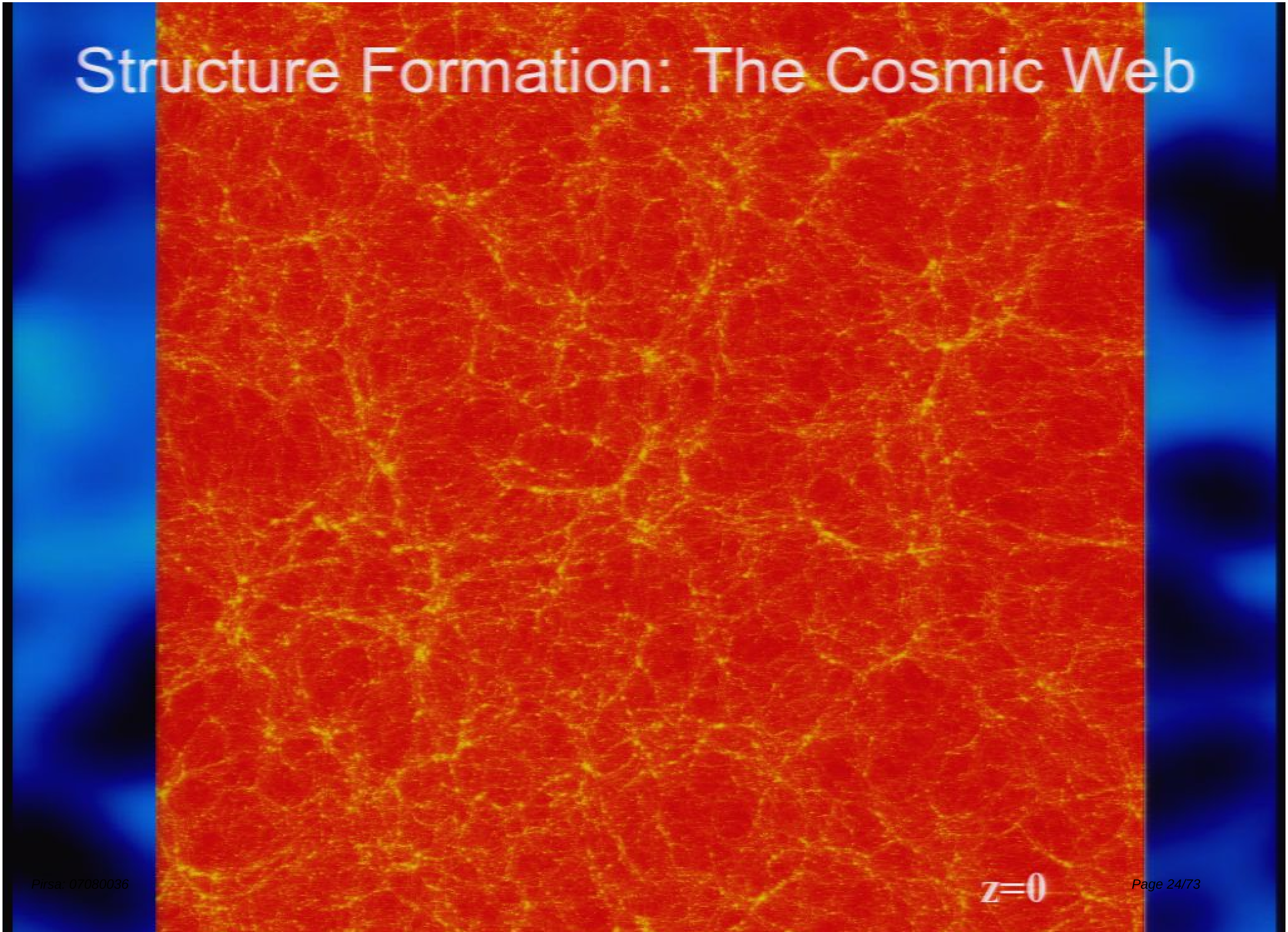

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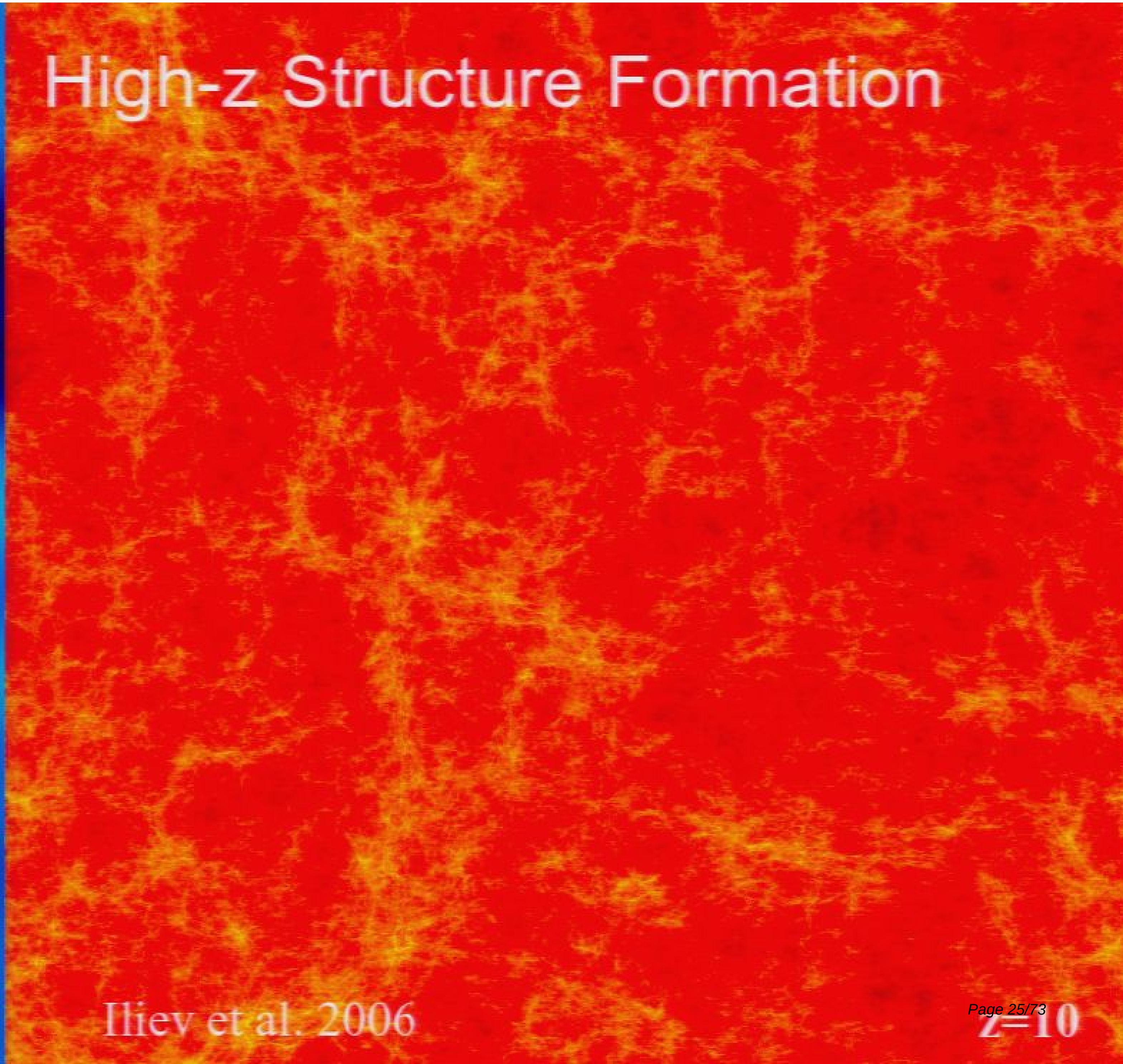

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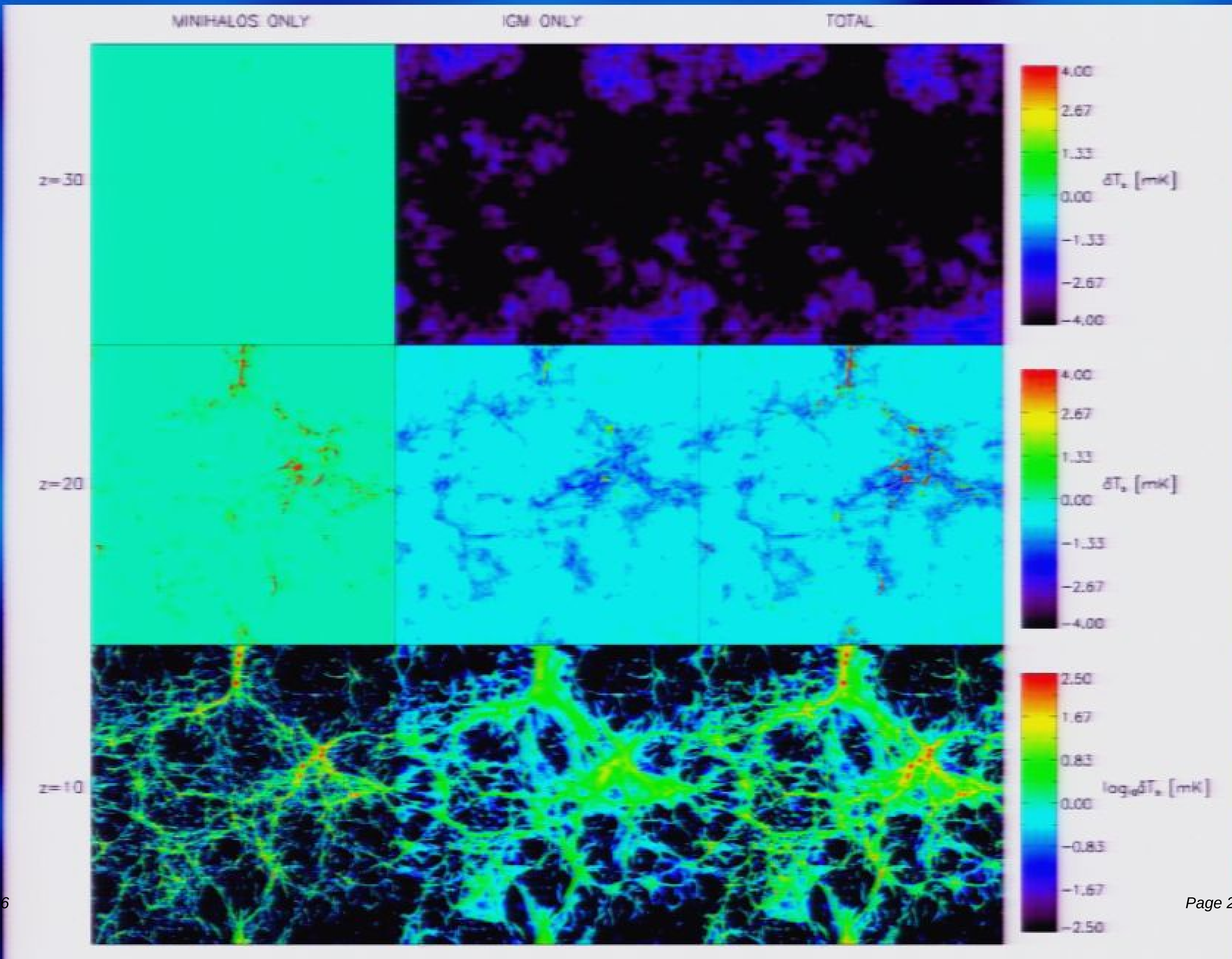

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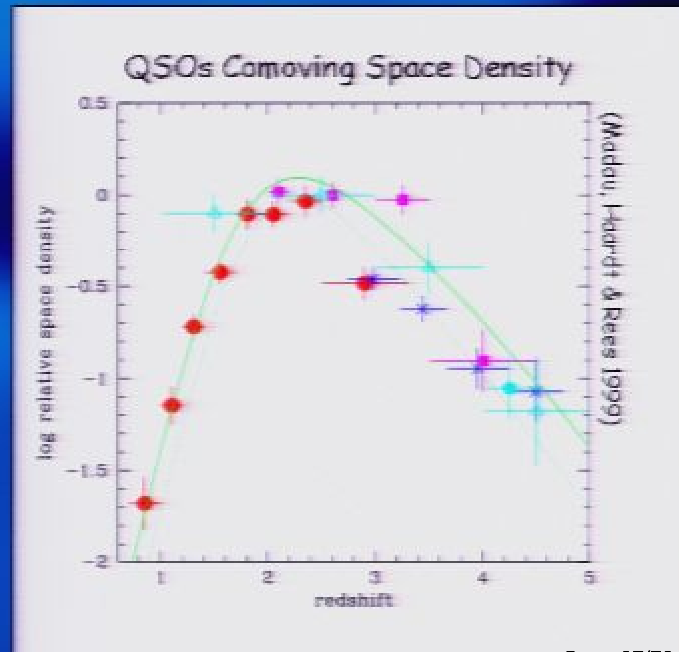

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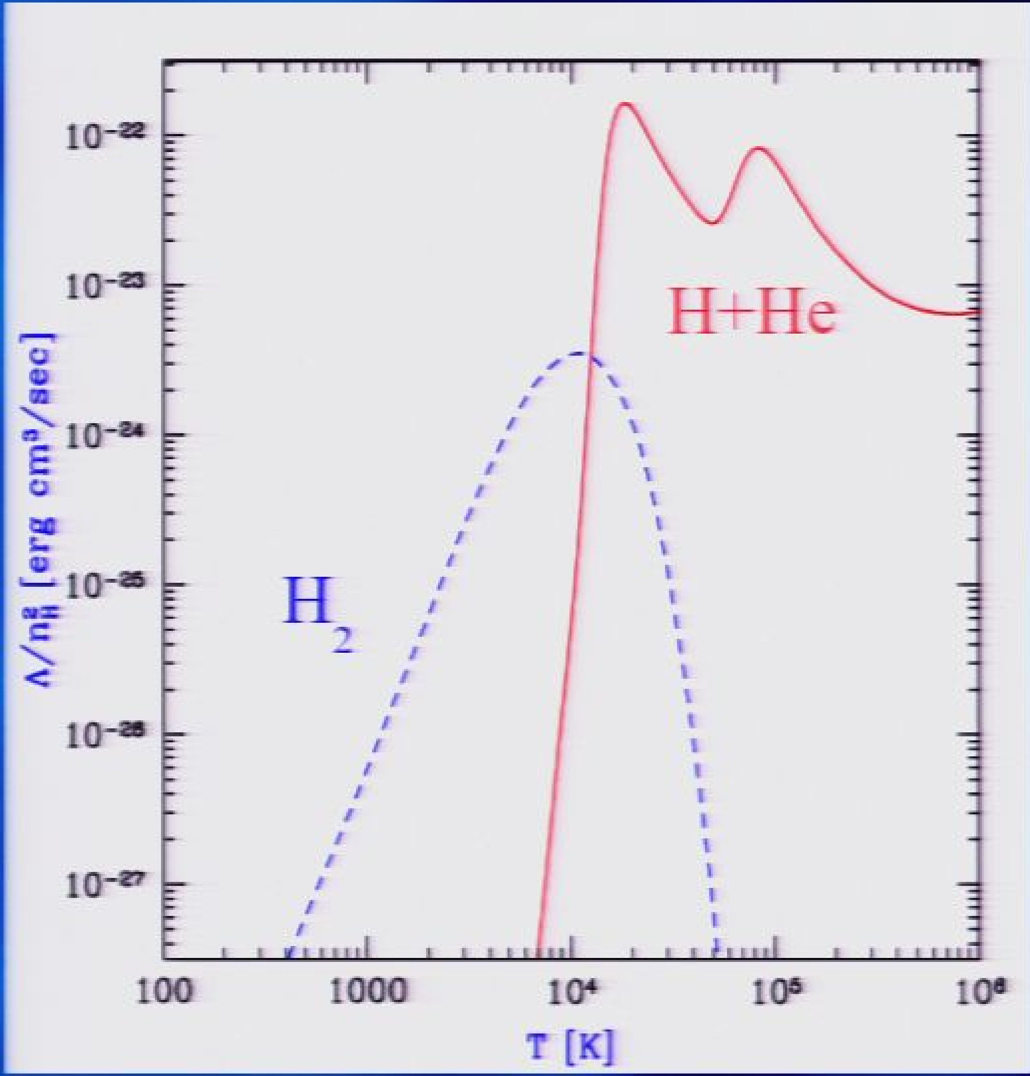


Early Star Formation

- First stars formed in collapsed halos of mass 10^5-10^6 $M_\odot$, and might have been massive (>100 $M_\odot$).
- In order for star formation to happen, energy generated in the gravitational collapse needs to be radiated away.
- Gas in proto-galaxies is thought to typically have the halo's 'virial temperature'.
- For $M_{halo} > 10^8 M_\odot$, $T_{vir} > 10^4$ K, and atomic H cooling can remove excess energy. For lower mass halos, H_2 is needed.

Early Star Formation

- H_2 is easily destroyed by UV photons from first stars, and not easily reformed. ⇨ First stars may have neutralized low mass halos in their vicinity, and stopped further star formation.
- Assumption: only halos with $M>10^8 M_\odot$ (atomically cooling) are reliable producers of stars.

HII Regions

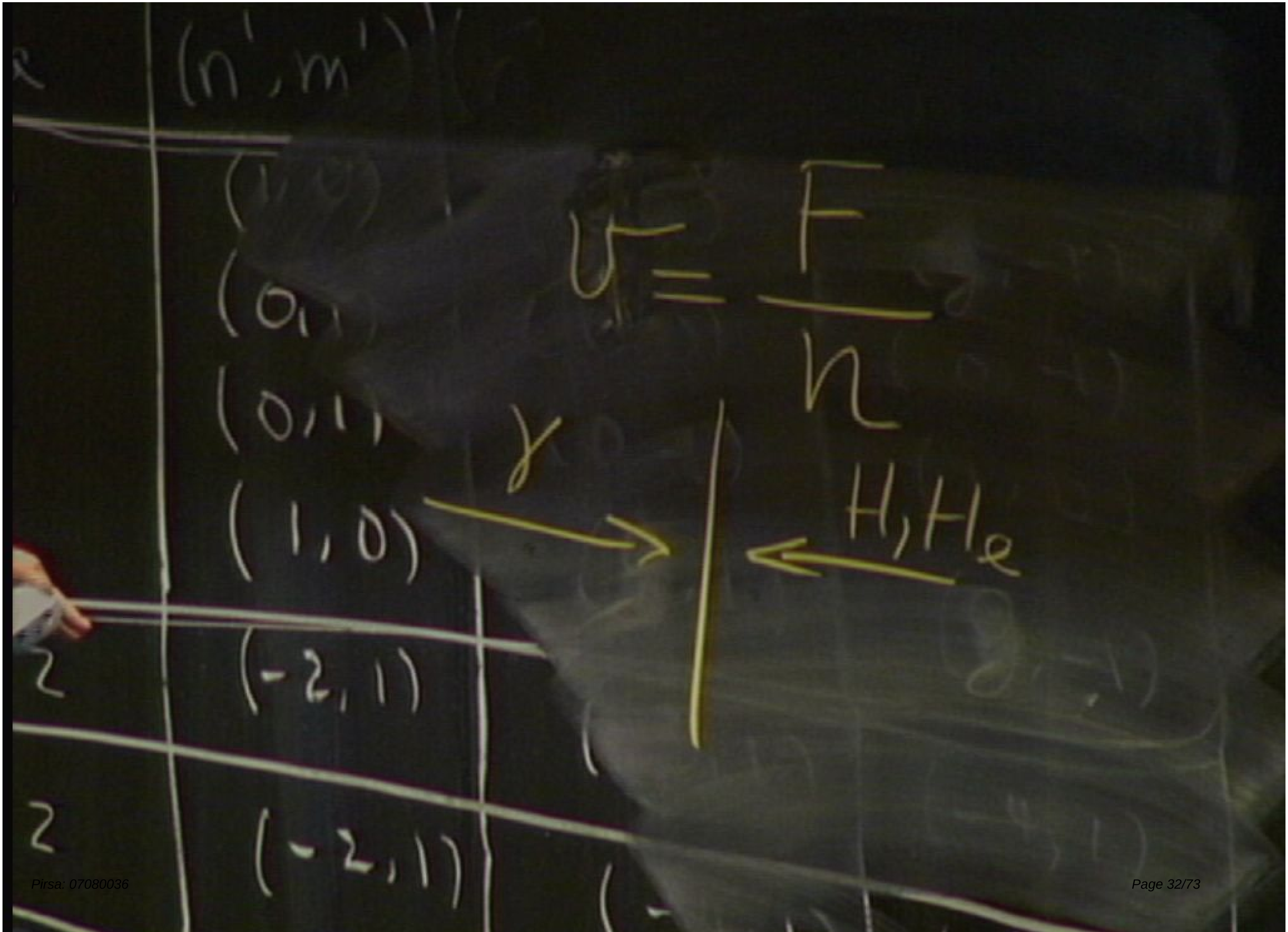
- EUV photons from hot stars ionize their surroundings, creating HII regions.
- The speed of growth of these regions is set by the supply of photons and the recombinations:

$$n\frac{\mathrm{d}z}{\mathrm{d}t} = J_0 - \alpha_{\mathrm{B}} \int n^2 \mathrm{d}z$$

- For constant density:

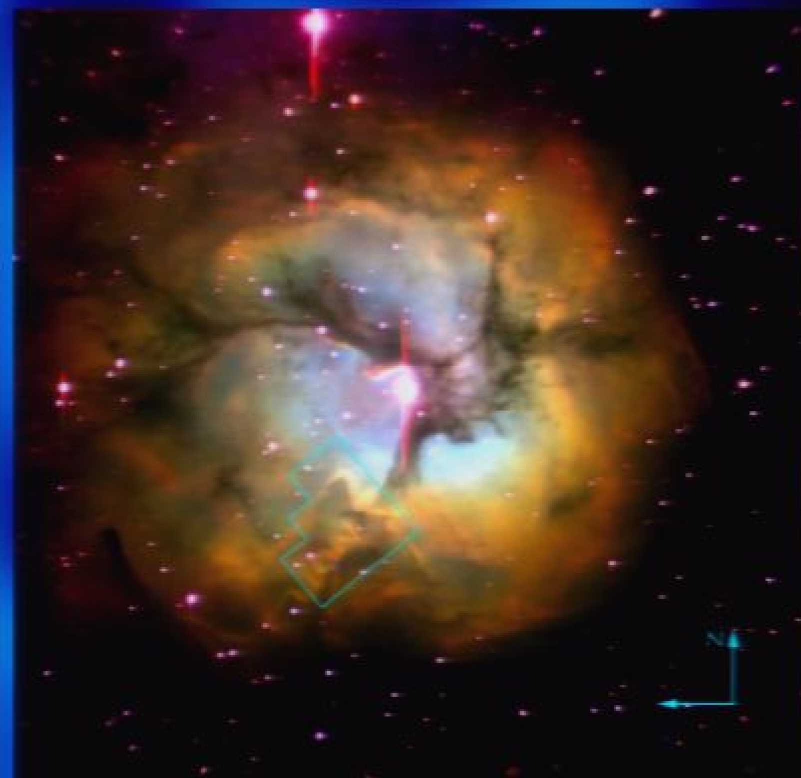
$$v(t) = \frac{J_0}{n} e^{-n\alpha_{\mathrm{B}} t}$$

Trifid Nebula


(n', m')
(0, 1)
(1, 0)
ν = E / h
γ
H, He
2
(-2, 1)
2
(-2, 1)

HII Regions

- When this speed falls below ~$2v_s$, the gas will start to respond hydrodynamically: transition from R-type to D-type ionization front (IF): shock front preceding ionization front (IF).
- Real HII regions do not grow in constant density media: speed and transition from R- to D-type will depend on position.



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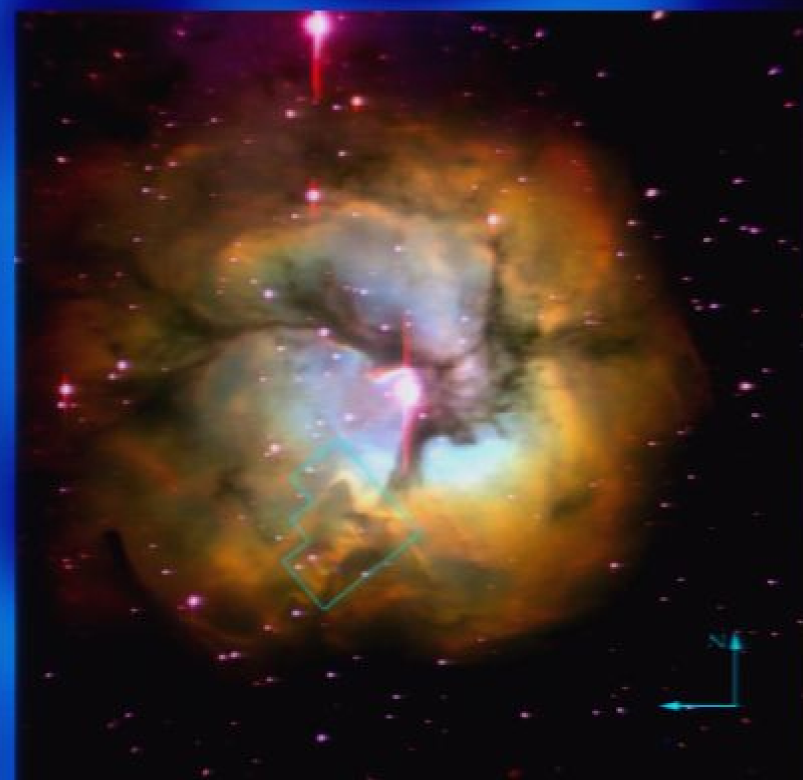

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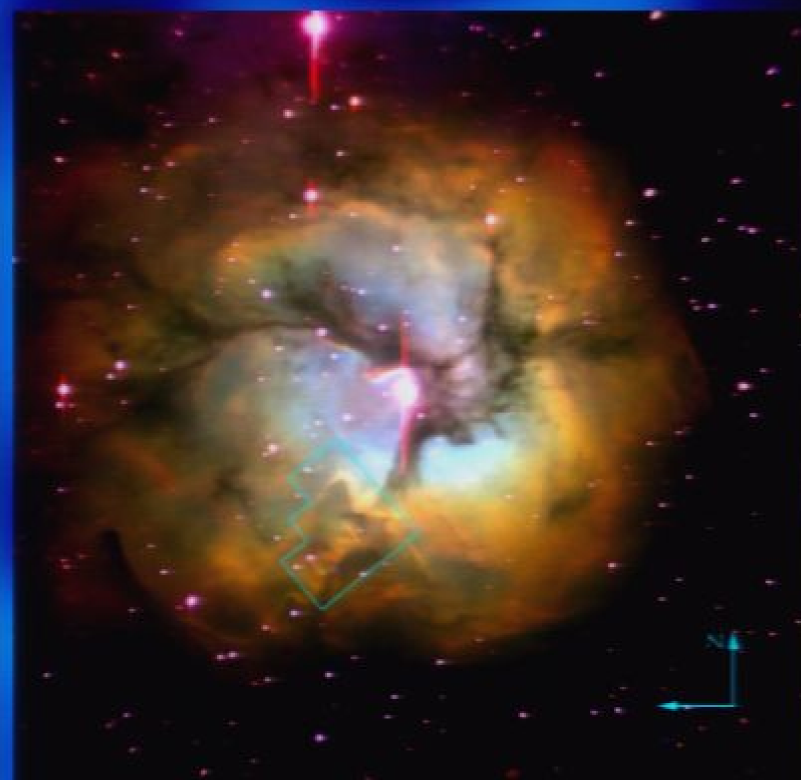

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Trifid Nebula

COSMOLOGICAL H II REGIONS

(Shapiro and Giroux 1987, ApJ, 321, L107)

Cosmological Stromgren Spheres

S(r,t) = number of ionizing photons emitted by source which pass thru sphere of comoving radius *r* per second.

a(t) = cosmic scale factor = $(1+z_i)/(1+z)$

$$\frac{\partial S}{\partial r} = -4\pi r^2 a^{-3} n_{H,i}^2 c_\ell \chi^2 \alpha_2$$

$$\begin{aligned} n_H &= n_{H,i} a^{-3} \\ c_\ell &= \langle n_H^2 \rangle / \langle n_H \rangle^2 = \text{clumping factor} \\ \chi &= \text{ionized fraction} \\ \alpha_2 &= \text{recombination coeff. to } n \geq 2 \end{aligned}$$

$$\begin{aligned} \Rightarrow r_S(t) &= \left[3N_{ph}/(4\pi\chi_{eff}\alpha_2 c_\ell n_{H,i}^2)\right]^{1/3} a(t) \\ &\equiv r_{S,i} a(t), \qquad N_{ph} \equiv S(0) \end{aligned}$$

Cosmological Ionization Fronts

Jump Condition: $n_{H,1} u_1 = \beta_i^{-1} J$

$u_1 = v_{I,pec} = a(dr_I/dt) =$ I-front peculiar velocity

$n_{H,1} =$ H atom density ahead of I-front

$J = S(r_I)/(4\pi r_I^2 a^2) =$ photon number flux

$\beta_i =$ # of positive ions created per H ionization

$= \chi_{eff} = 1 + pA(He)$

($p = 0, 1,$ or 2 if H only, HeI, or HeII ionized)

Evolution of $r_I(t)$: $dy/dx = \lambda(1 - y/a^3)$

$$y \equiv (r_I/r_{S,i})^3, \qquad x \equiv t/t_i,$$

$$\lambda \equiv \chi_{eff}\alpha_2 c_\ell n_{H,i} t_i = \frac{\text{age of universe at turn-on}}{\text{recomb. time at turn-on}}$$

Result

- Analytical solution $= fcn(q_0, z_i, c_\ell \Omega_b h)$
  [i.e. $\alpha_2 = \alpha(10^4\,K)$ and $\chi_{eff} = 1 - 1.2$]

- $r_I(t) <$ Strömgren radius, except for very large z_i

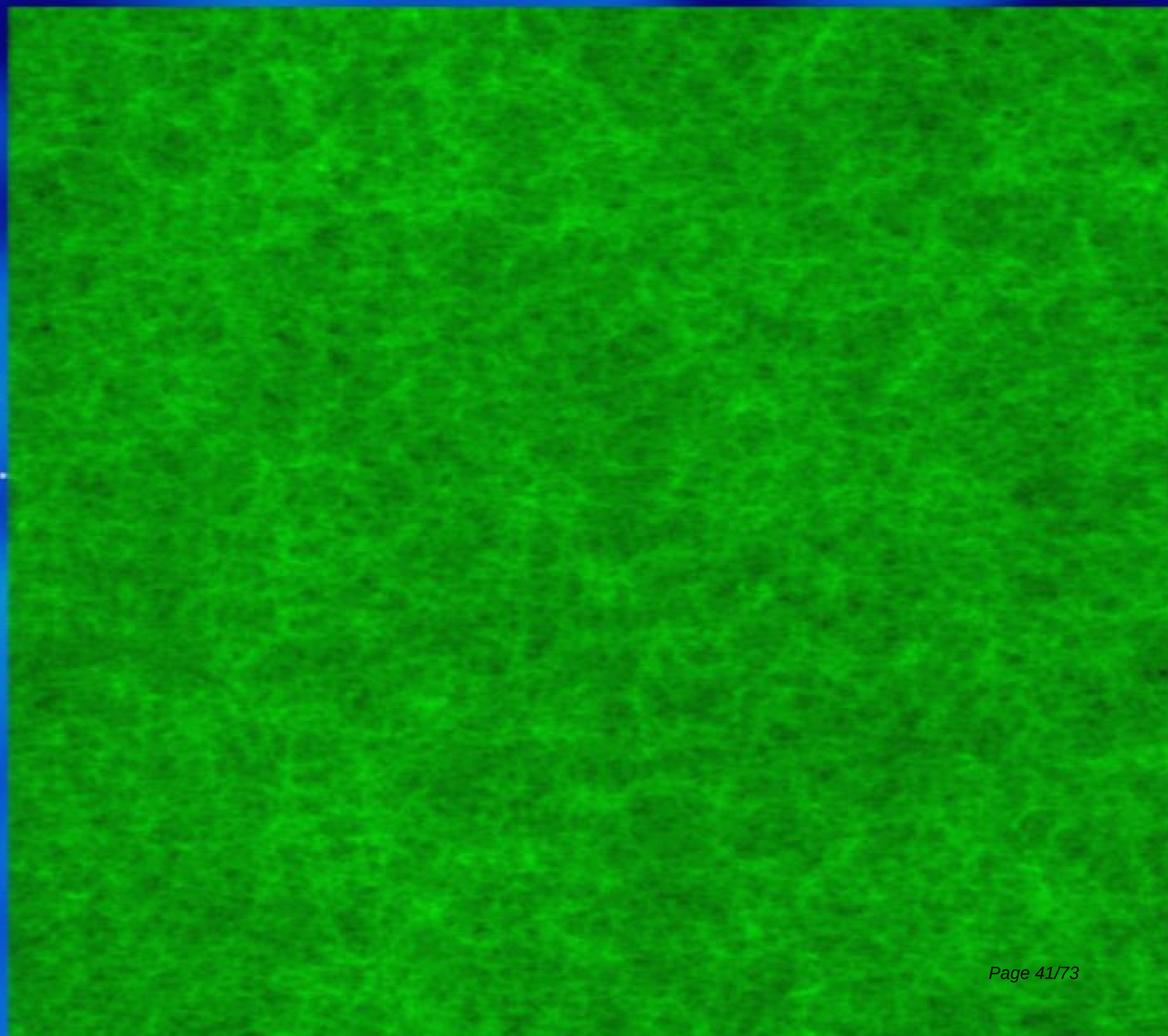
- $v_{I,pec}(t) >> c_{sound}$

$\Rightarrow$ weak, R-type front at all times.

Dark Ages and Epoch of Reionization

00/h Mpc box,
VMAP3
osmology
406^3 radiative
ransfer simulation
Evolution: z=20 to 11.

$2x10^9$ solar mass
alos resolved.



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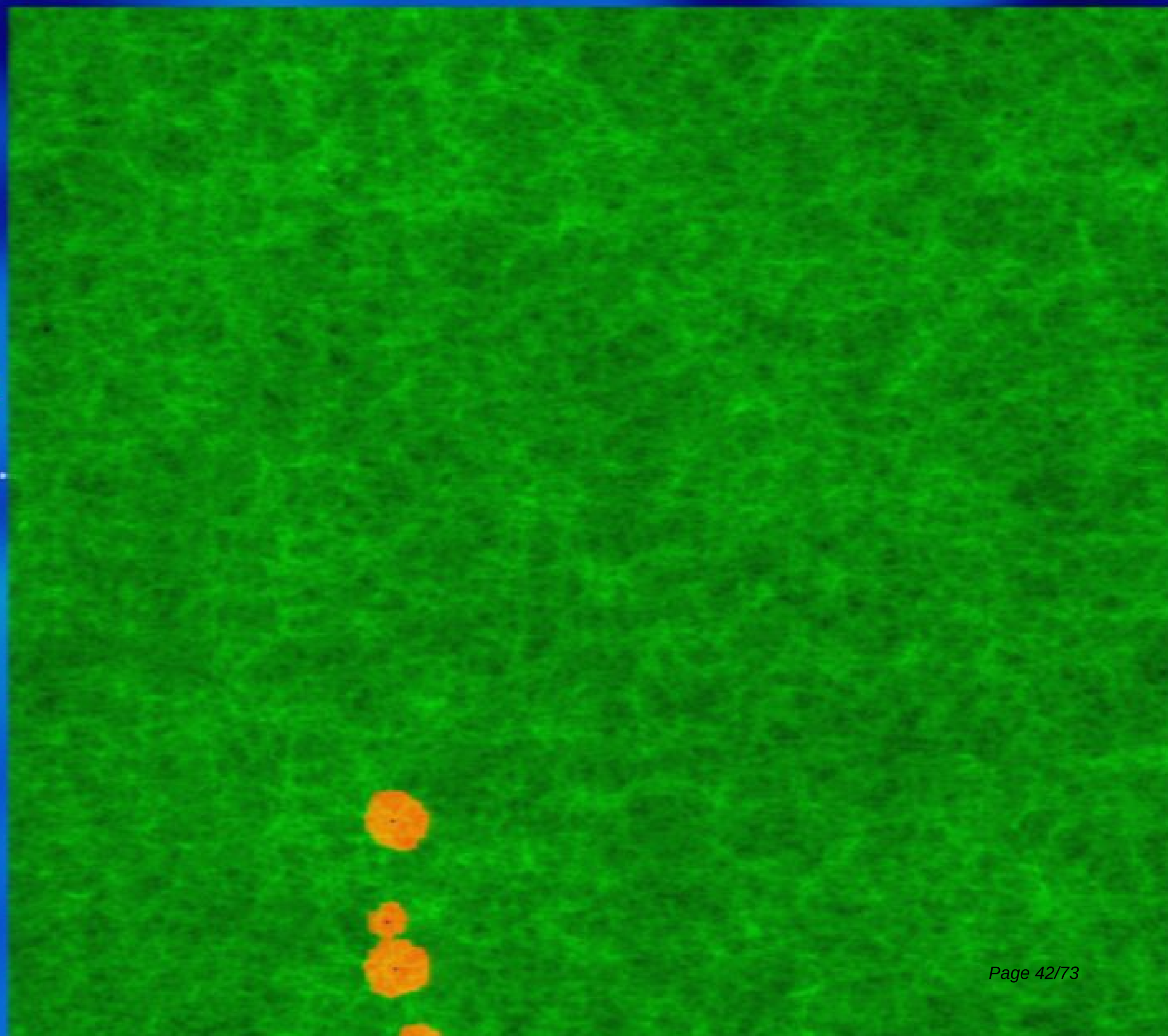

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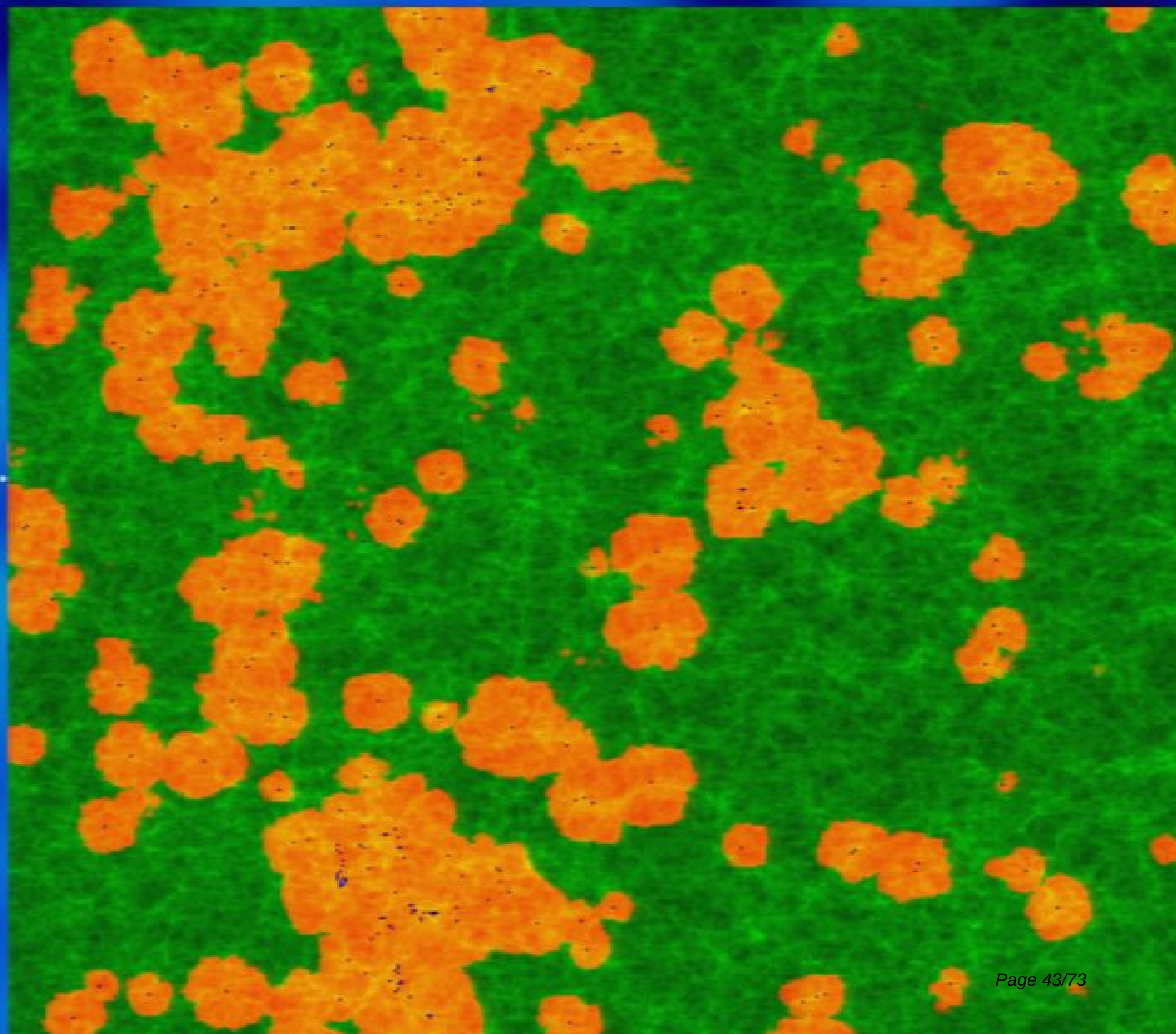

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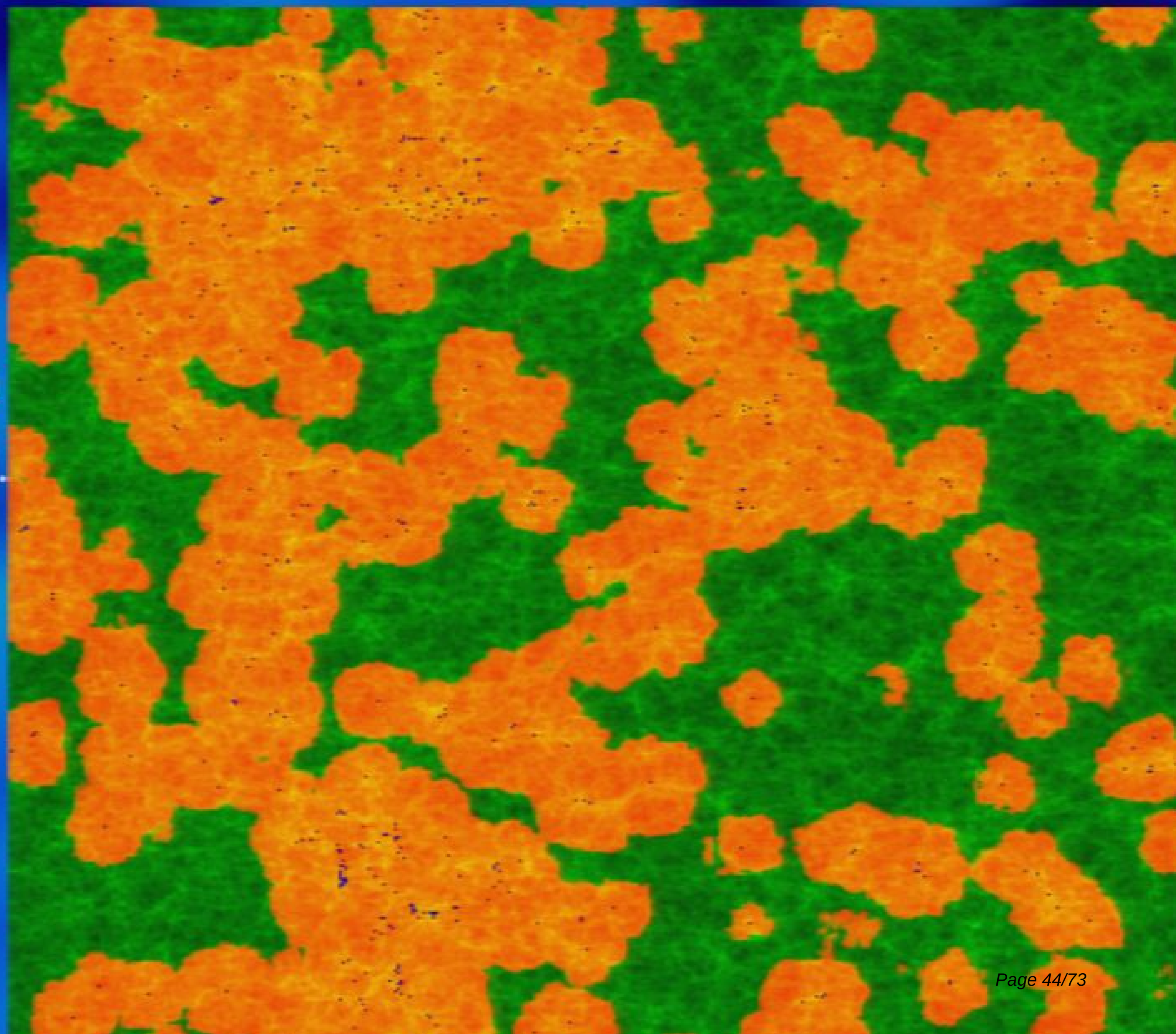

Other complications: Jeans Mass Filtering

- Lower mass halos cannot collapse/grow in an ionized (10^4 K) medium. This is known as Jeans mass filtering, a feedback effect from reionization on galaxy formation.
- Estimates of the effect vary between studies, and it is likely to be gradual (Thoul & Weinberg 1996, Navarro & Steinmetz 1997, Dijkstra et al. 2004).
- Star formation in halos below this limit is suppressed inside an HII region ('source suppression') -> reionization self-regulation

Key Results

- Reionization proceeds inside-out and is highly patchy in nature.
- HII regions are large, with a pronounced characteristic scale (5-20 Mpc) imprinted on all observables.
- Reionization is strongly self-regulated through Jeans-mass filtering of low-mass sources.
- Current constraints on reionization parameters (source efficiencies, gas clumping) are weak; τ_{es} and overlap epoch (GP troughs) are readily reproduced.
- Small-box/low dynamic range simulations are inadequate for faithful representation.

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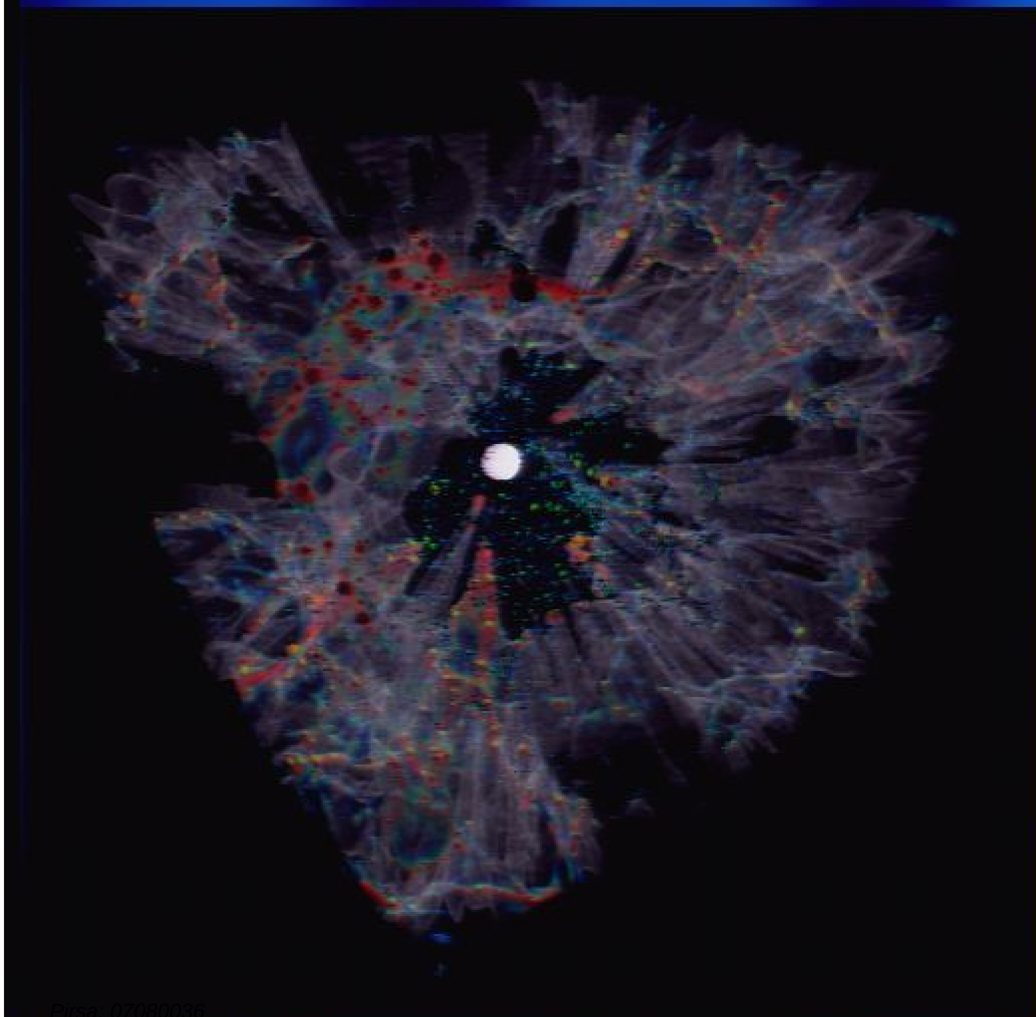
Zooming in: I-front propagation in a cosmological density field with minihalos

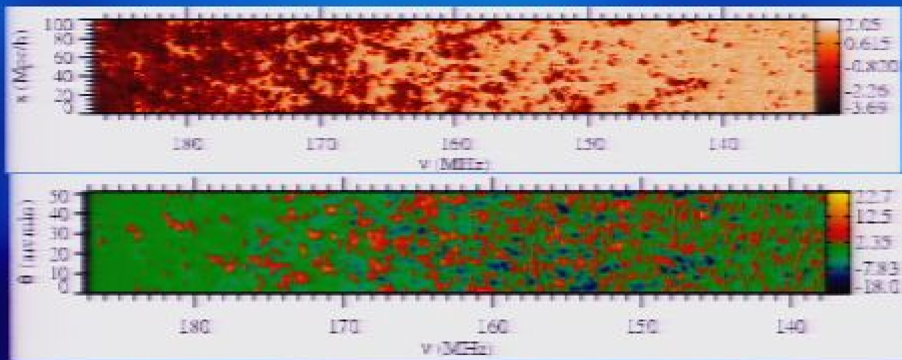


Visualization of an I-front propagation in a cosmological density field

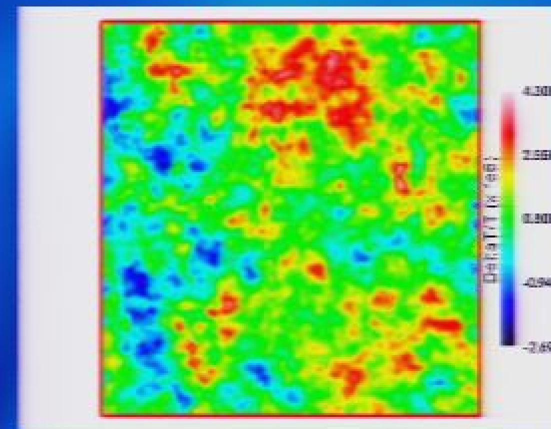
movie

Note: this is just one cell in the large-scale simulations!

(thanks M. Alvarez and UTexas Visualization Center)



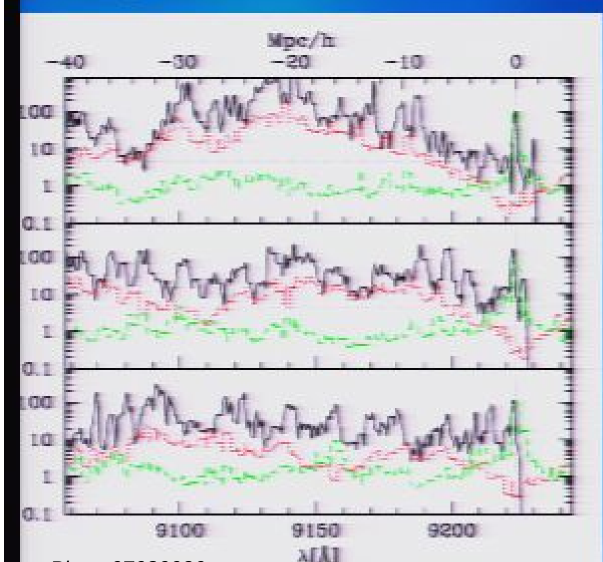
redshifted 21-cm



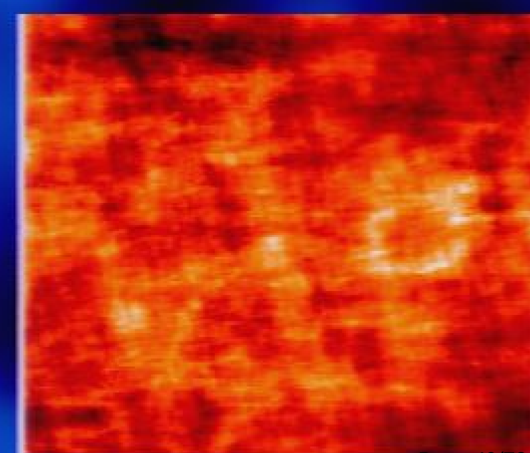
Observing the Reionization Epoch

kinetic Sunyaev-Zeldovich effect (kSZ)

Ly-α sources



CMB polarization



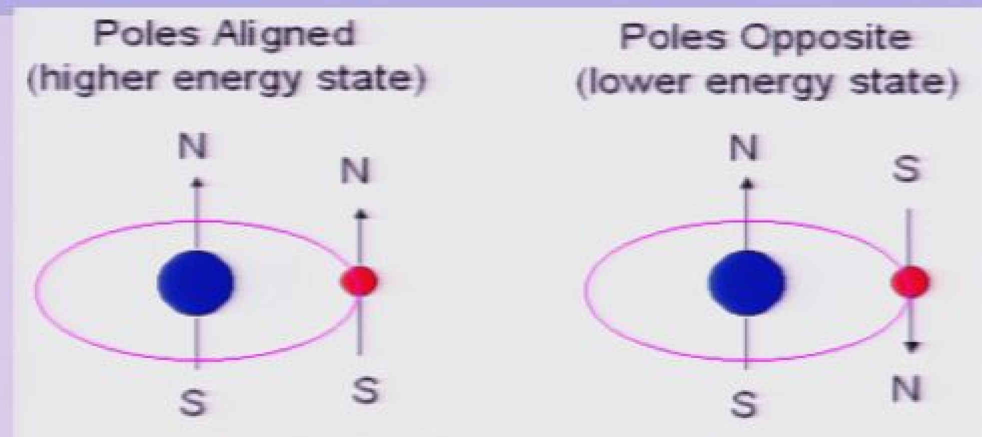
BB

Seeing Invisible Light From the Dark Ages

- Hydrogen atoms in the early universe can be detected in absorption or emission against the Cosmic Microwave Background (CMB) at redshifted radio wavelength 21 cm.
- Halos formed during the dark ages are dense and hot enough to appear in emission.
- The intergalactic medium, too, can appear in either emission or absorption.
- Future radio astronomy antenna arrays are being designed to detect this 21 cm emission.

21-cm Line of Atomic Hydrogen

- H atom ground state is split into two energy levels by electron-proton spin interaction. Emission or absorption of a photon of 21-cm wavelength and 1.42 GHz frequency will cause transition between these hyperfine levels.



$$\frac{n_2}{n_1} = 3\exp\left(-\frac{h\nu_0}{kT_{spin}}\right)$$

Level populations

21-cm Radiation Background

Foreground emission or absorption by H atoms at redshift z seen against CMB at redshifted wavelength 21(1+z) cm.

Emission $\leftrightarrow$ $T_{spin} > T_{CMB}$

Absorption $\leftrightarrow$ $T_{spin} < T_{CMB}$

Transparent $\leftrightarrow$ $T_{spin} = T_{CMB}$

3 Ways to Change the 21-cm Level Population:

- Absorb a 21-cm photon from the CMB (CMB Pumping)
- Collide with another atom (Collisional Pumping)
- Absorb a UV photon at 1215 Angstrom to make Lyman alpha transition of H atom, then decay to one of 21-cm levels (Lyman Alpha Pumping)

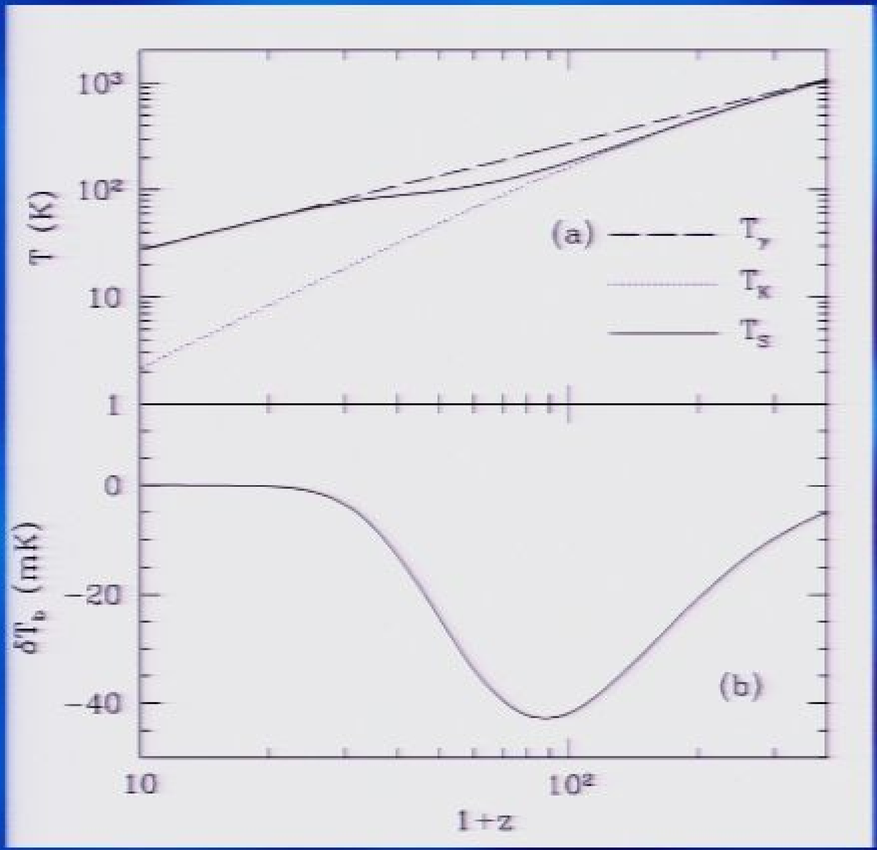
Stages of 21-cm Background

Dark Ages

- $z \geq 150$, $T_{spin} = T_{CMB}$ → nothing
- $20 \leq z \leq 150$, $T_{spin} < T_{CMB}$ → absorption
- $z \leq 20$, $T_{spin} > T_{CMB}$ in minihalos → emission

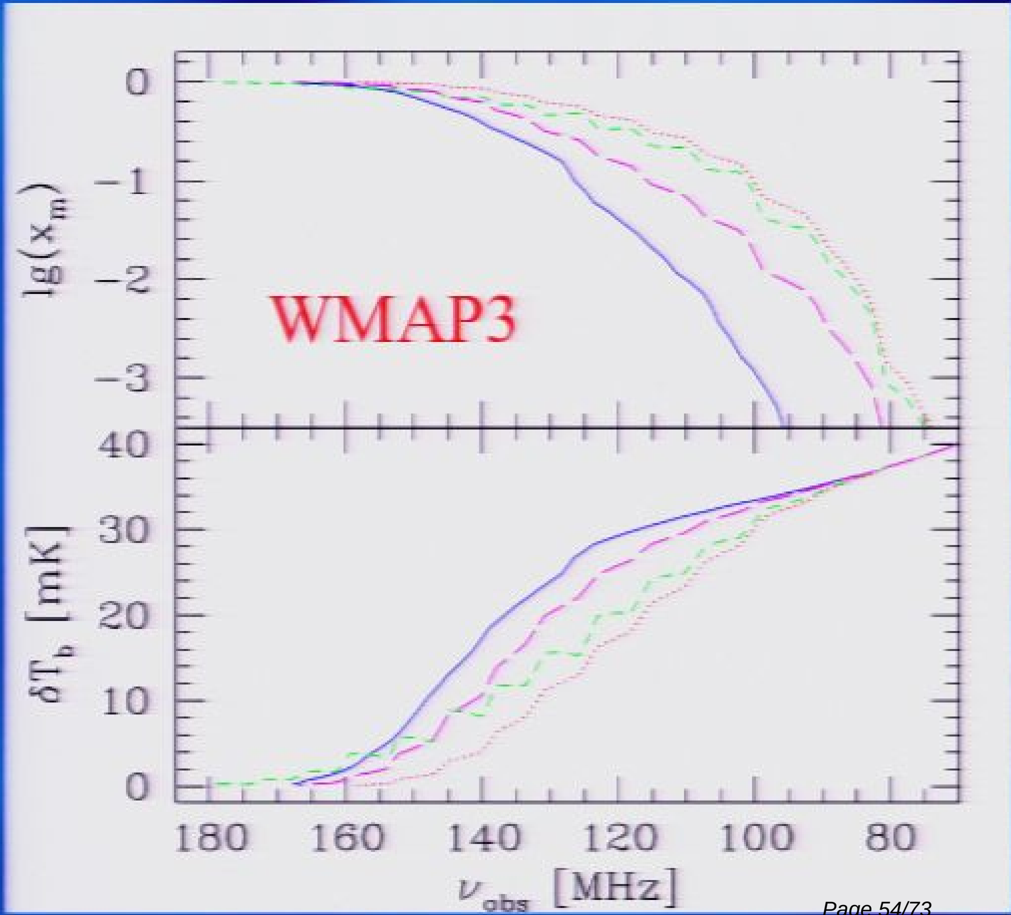
Epoch of Reionization ($6 \leq z \leq 20$)

- $T_{spin} > T_{CMB}$ in minihalos → emission
- After sources turn on, Lyman alpha pumping →
  - Without heating, $T_{spin} < T_{CMB}$ → absorption
  - With heating, $T_{spin} > T_{CMB}$ → emission



Global Step in 21-cm background due to reionization

- Average signal over all lines of sight: global step (Shaver et al. 1999).
- Sharp change with frequency.
- Simulations show gradual transition, instead:~20 mK over ~20 MHz.



The Image Cube

- Frequency ⟷ Redshift ⟷ Time.
  - Observations of fields $\Delta\theta$ by $\Delta\theta$ over $\Delta\nu$: image cube.

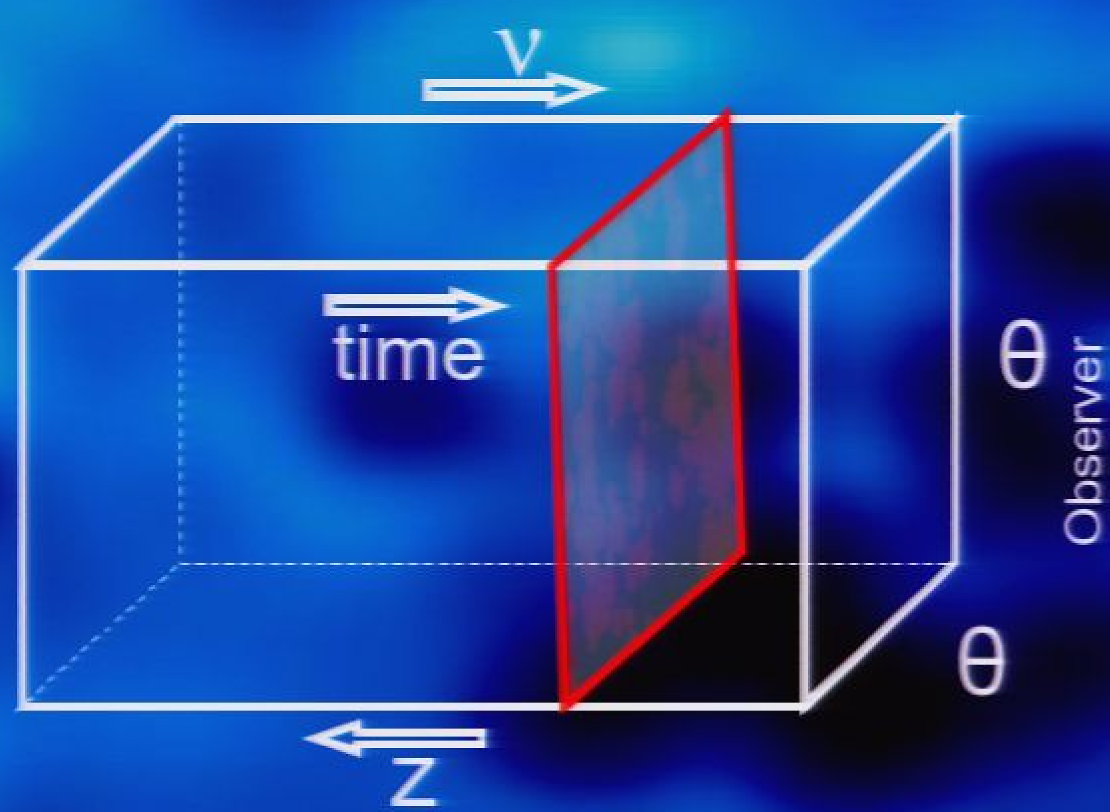


Image Slice

$T_S >> T_{CMB}$ $W(\delta\theta, \delta\nu)$

x_{HI}, δ δT

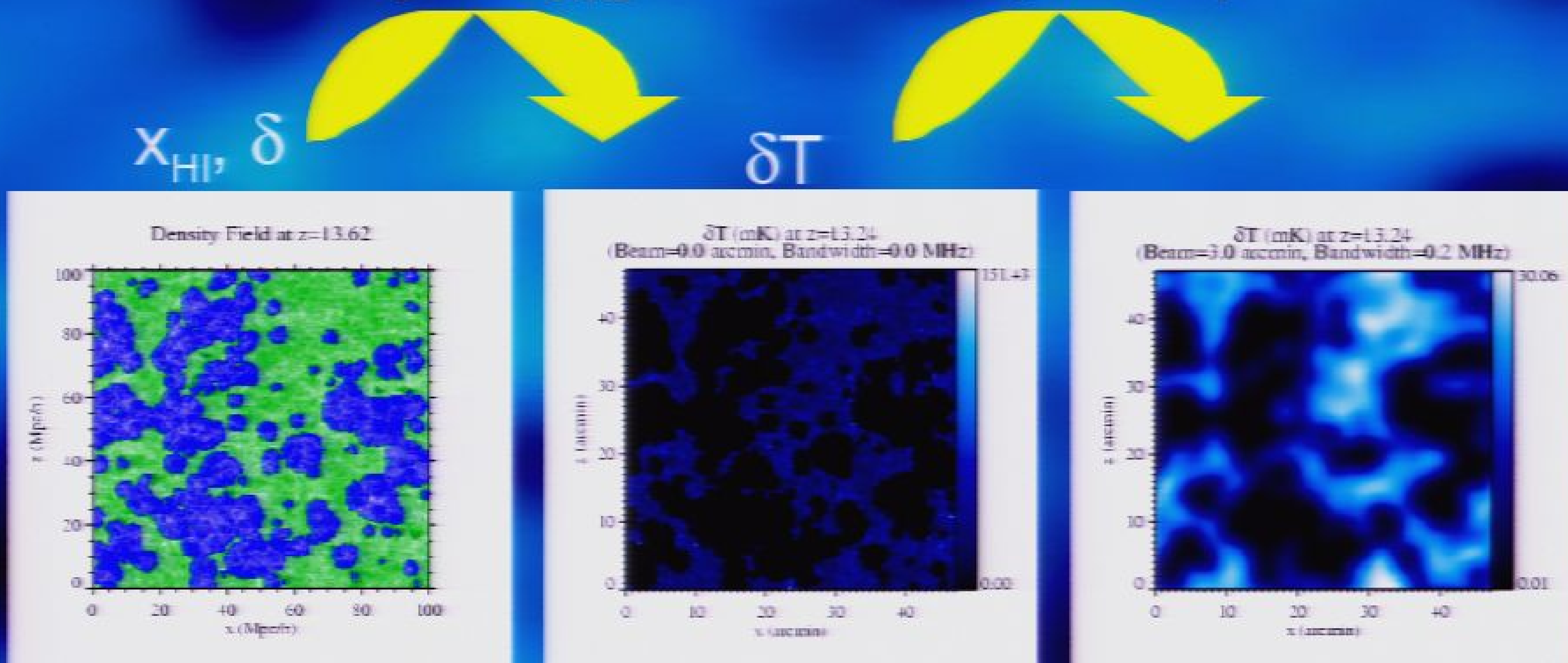


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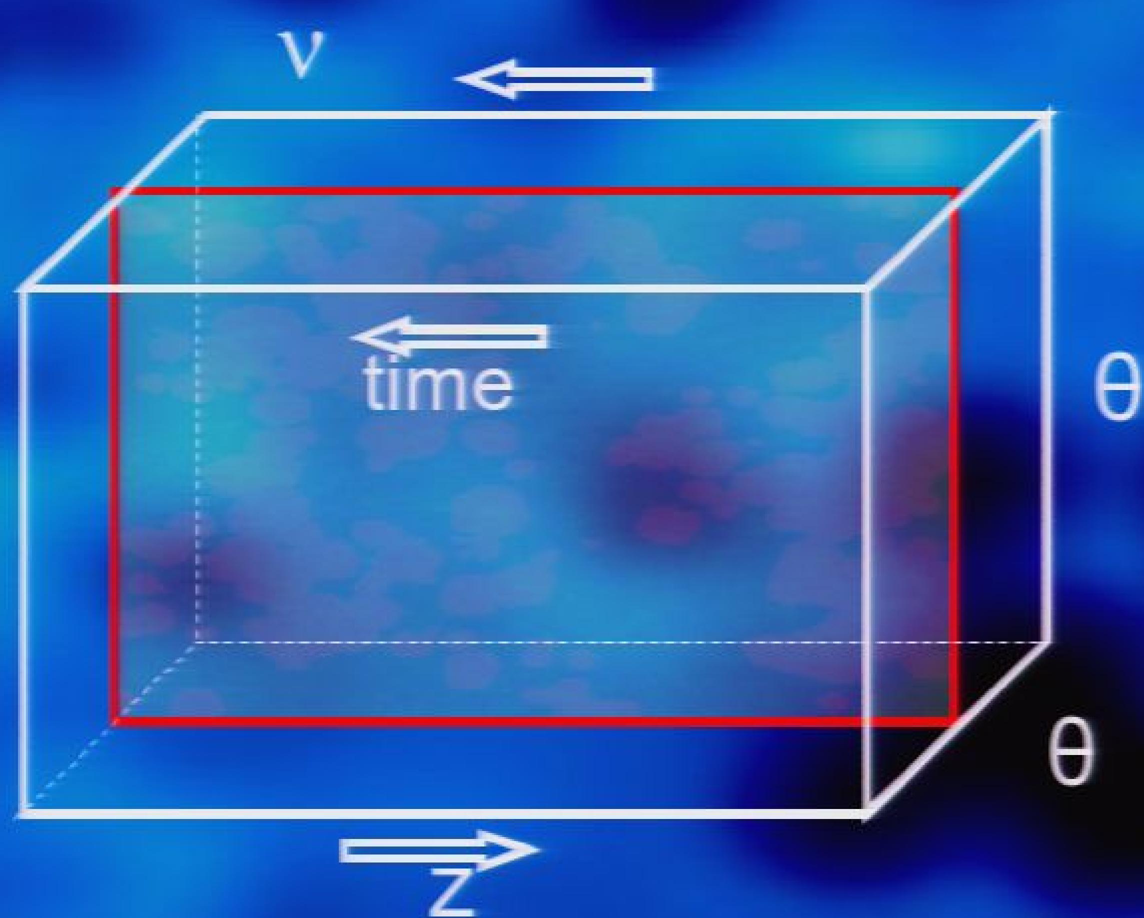
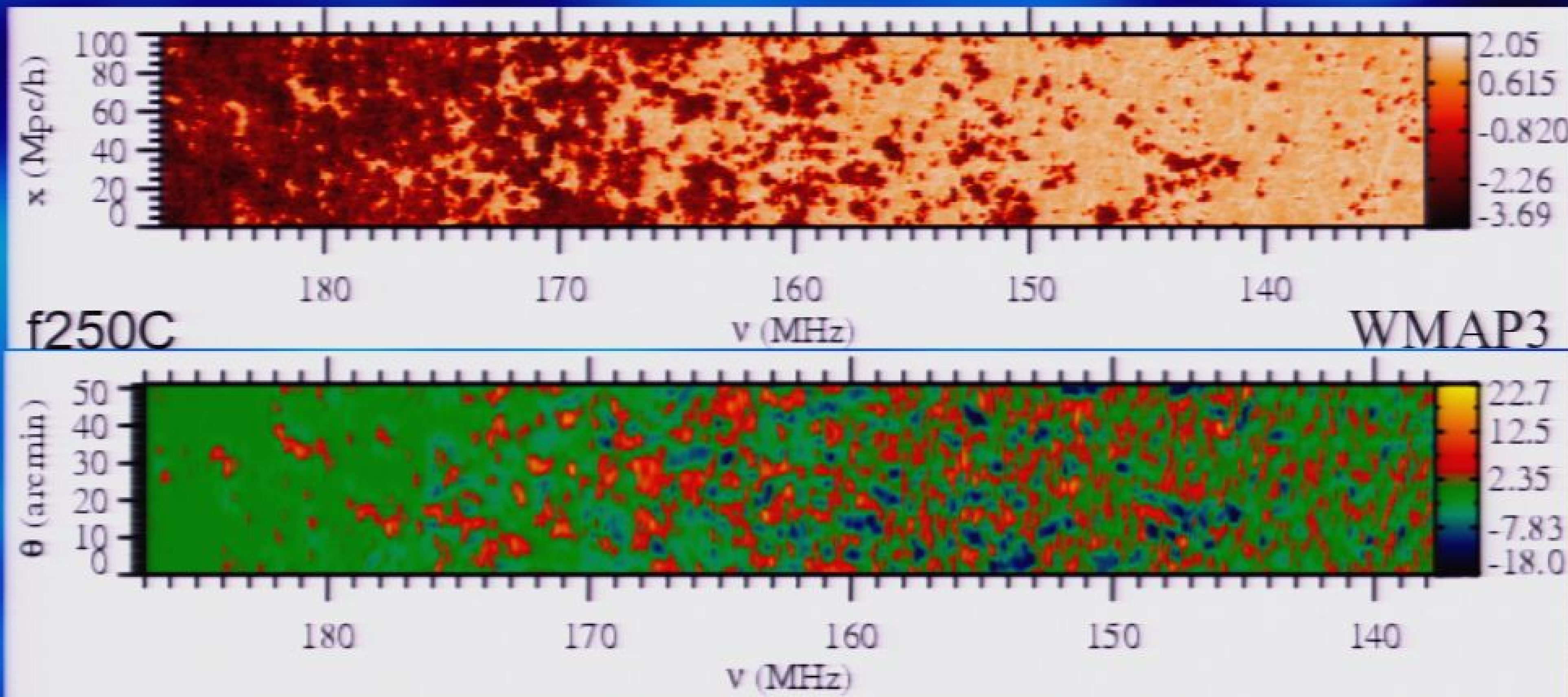
Image Cube: Redshift Slice



Evolution Slices at 21-cm line



Shown is (log/linear) differential (to CMB) brightness temperature: top: high-res; bottom: beam- and bandwidth-smoothed (LOFAR: will see large ion. bubbles!).

Reionization in action seen at 21-cm

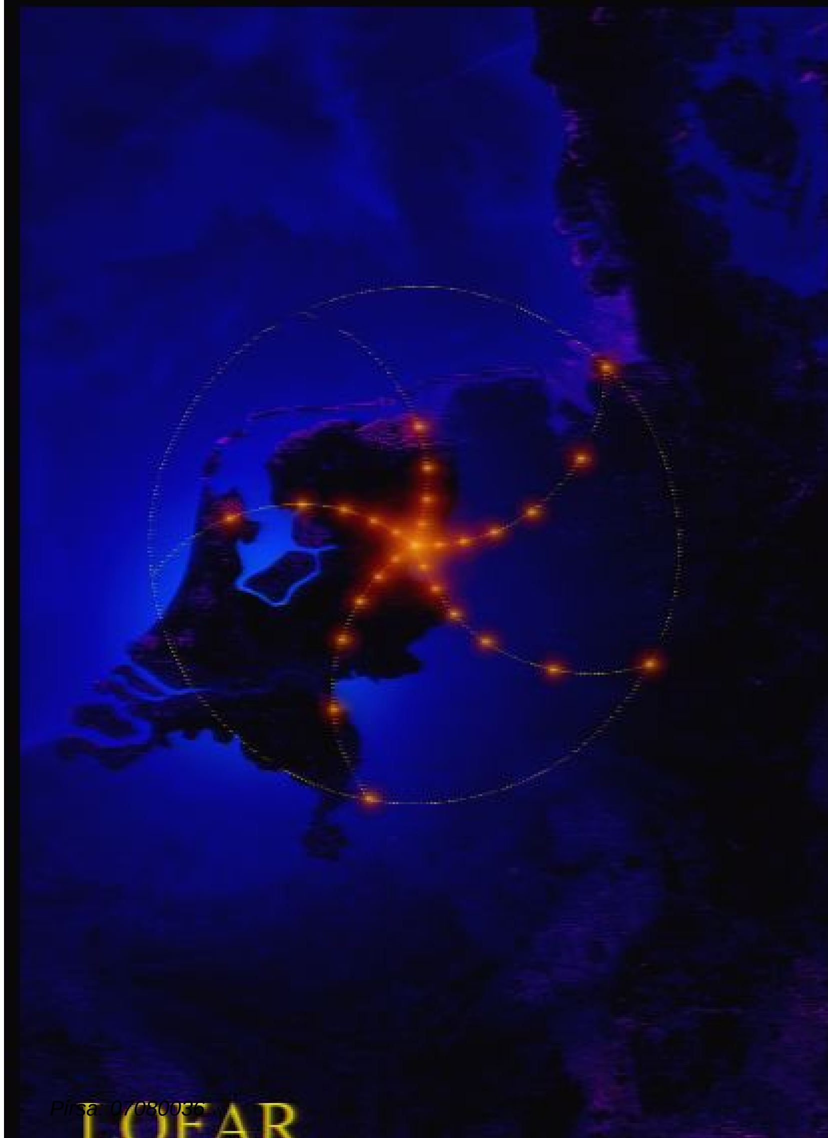
21-cm view of reionization

Reionization in action seen at 21-cm

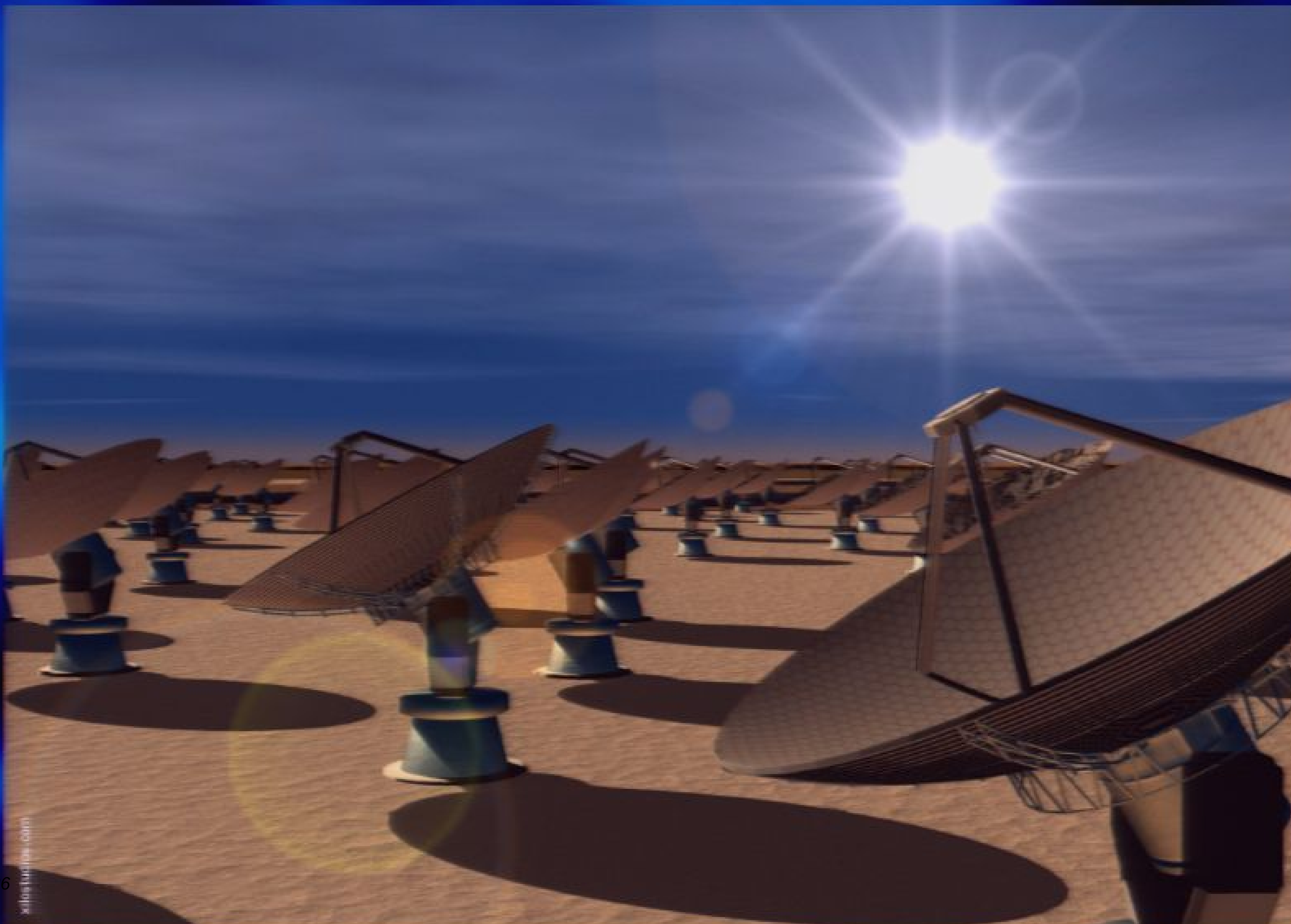
21-cm view of re

Reionization in action seen at 21-cm

How are we going to observe that signal? Giant Radio Interferometer Arrays



The Future: SKA



LOFAR EoR Experiment

- The plan is to observe three different fields of 2° by 2° for 100 nights with the 'virtual core', starting in 2008.
- After initial calibration at 1 s and 1 kHz resolution, the observations will be saved at 10 s and 10 kHz resolution for further processing. Total storage ~1PB.
- The final sensitivity should be of order 20-30 mK per beam.
- Resolution will be ~3', or ℓ~7000.

21cm Challenge: Foregrounds

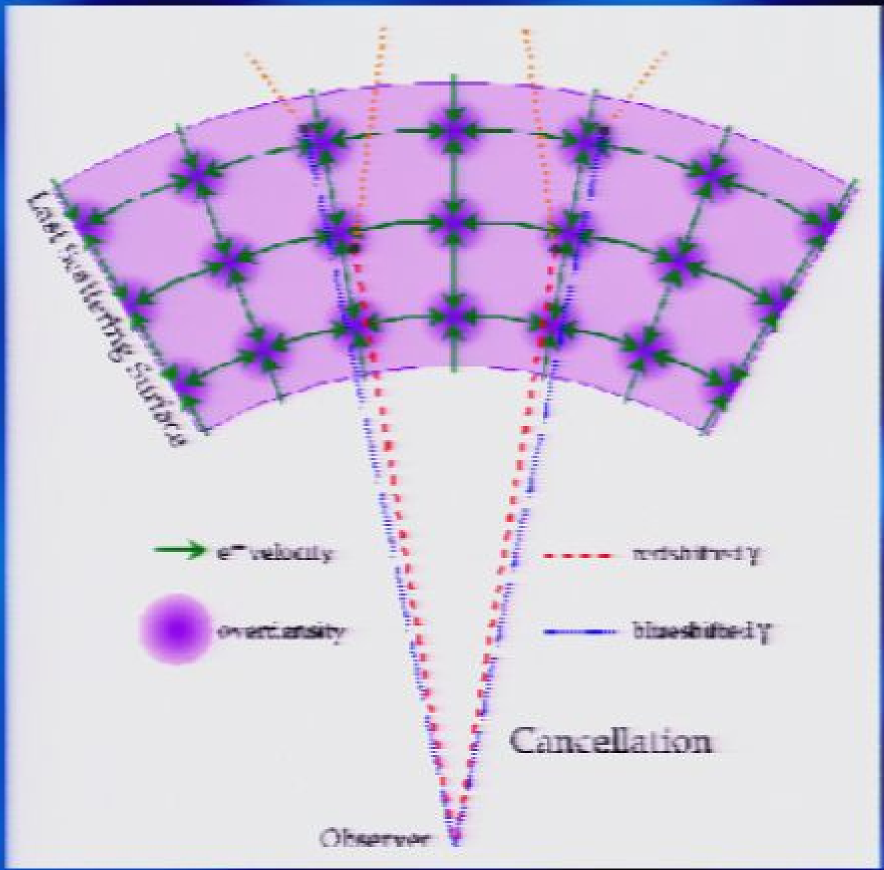
- Continuum Foregrounds:
  - Galactic Synchrotron (~100K)
  - Radio Galaxies (~10K)
  - Radio Halos & Relics (~10K)
  - Galactic & Extragalactic free-free emission (~1K)
- Smooth continuum should allow subtraction. Complications: foreground polarization, angular variations.
- Radio recombination lines.
- Ongoing observation campaign with WSRT/LFFE to characterize the foregrounds.

Implications for LOFAR

- LOFAR noise level will not allow imaging of redshifted 21cm.
- Analysis will be done on statistical data such as fluctuations as a function of frequency, and 2D (3D) power spectra.
- Perhaps some extreme peaks/valleys can be picked up, but only at the 2σ level.
- Maximum resolution (ℓ~7000) does capture the peak of the power spectrum; its location is slightly dependent on source efficiency.

Kinetic SZ Effect

- Free electrons back-scatter CMB photons, resulting in loss/gain of energy
- To first order the kinetic scatterings cancel out.
- Electron density fluctuations needed:
  - Linear density fluctuations in IGM (Ostriker-Vishniac or OV effect).
  - Non-linear density fluctuations in clusters (kSZ in narrow sense)
  - Patchy reionization



kSZ from patchy reionization

- Temperature variations given by LOS integral:

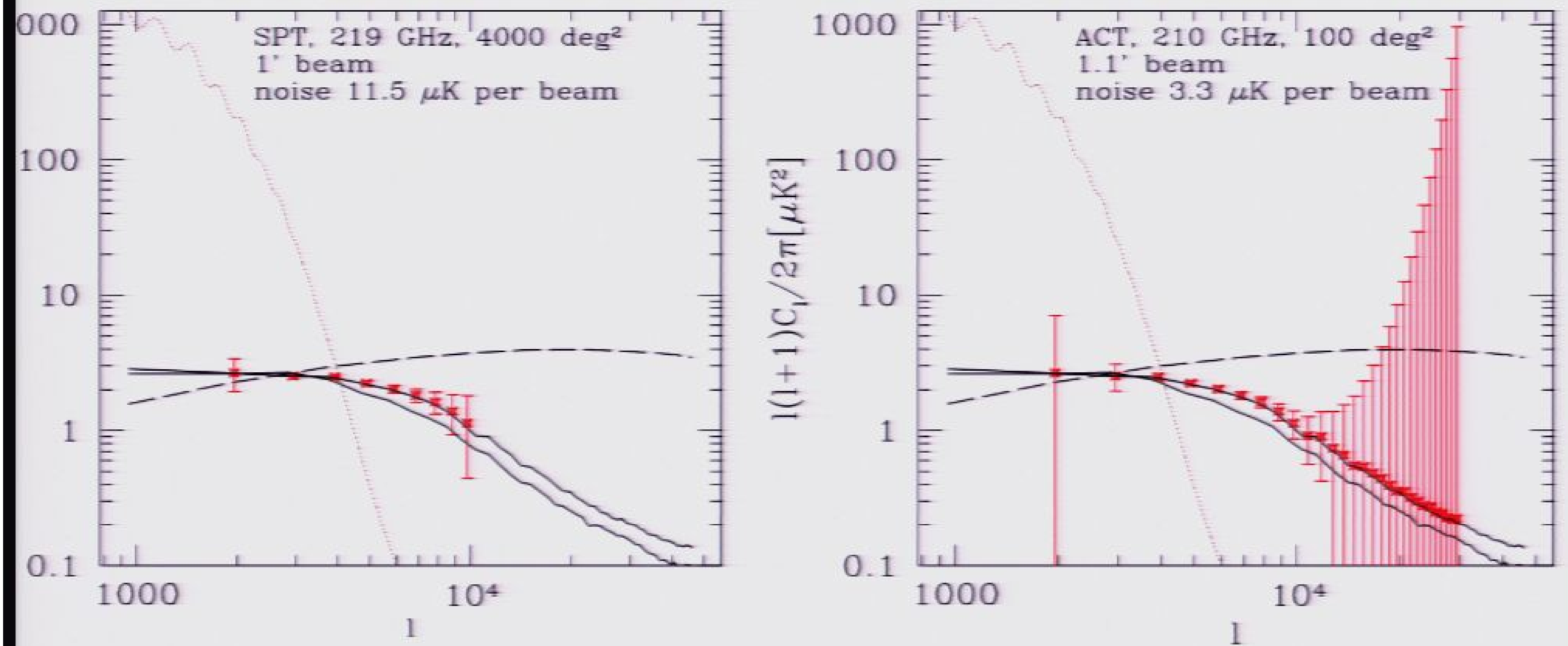
$$\frac{\Delta T}{T}(\hat{\mathbf{n}})_{\mathrm{kSZ}} = \sigma_T \int \mathrm{d}\eta \mathrm{e}^{-\tau(\eta)} a n_e \hat{\mathbf{n}} \cdot \mathbf{v},$$

- Method for extracting the signal from simulations:
  - find all integrals along LOS for available outputs
  - every light-crossing time interpolate between closest two outputs
  - to avoid periodicity artefacts change directions (x-y-z) and do random translations (using box periodicity) and/or 90 degree rotations

CMB telescopes: kSZ effect

Detectability of kSZ

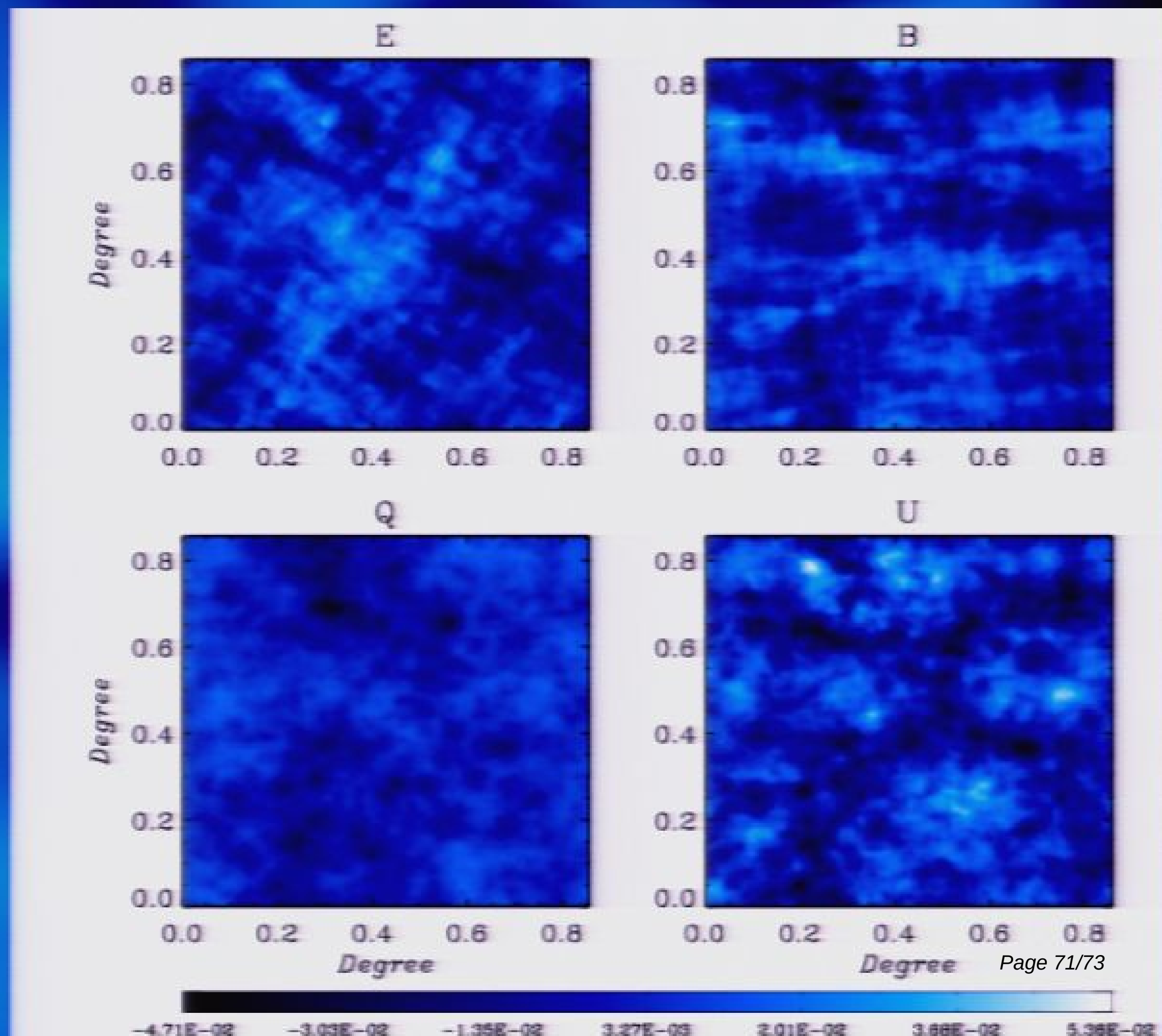
(example)



Sky power spectra of patchy EoR kSZ vs. expected noise levels of SPT and ACT. Includes noise from primary CMB and post-EoR kSZ (shown). tSZ is

CMB polarization signatures from patchy reionization

- The EoR patchiness yields significant fluctuations of τ at arcminute scales.
- This creates characteristic signatures in CMB polarization at small scales.



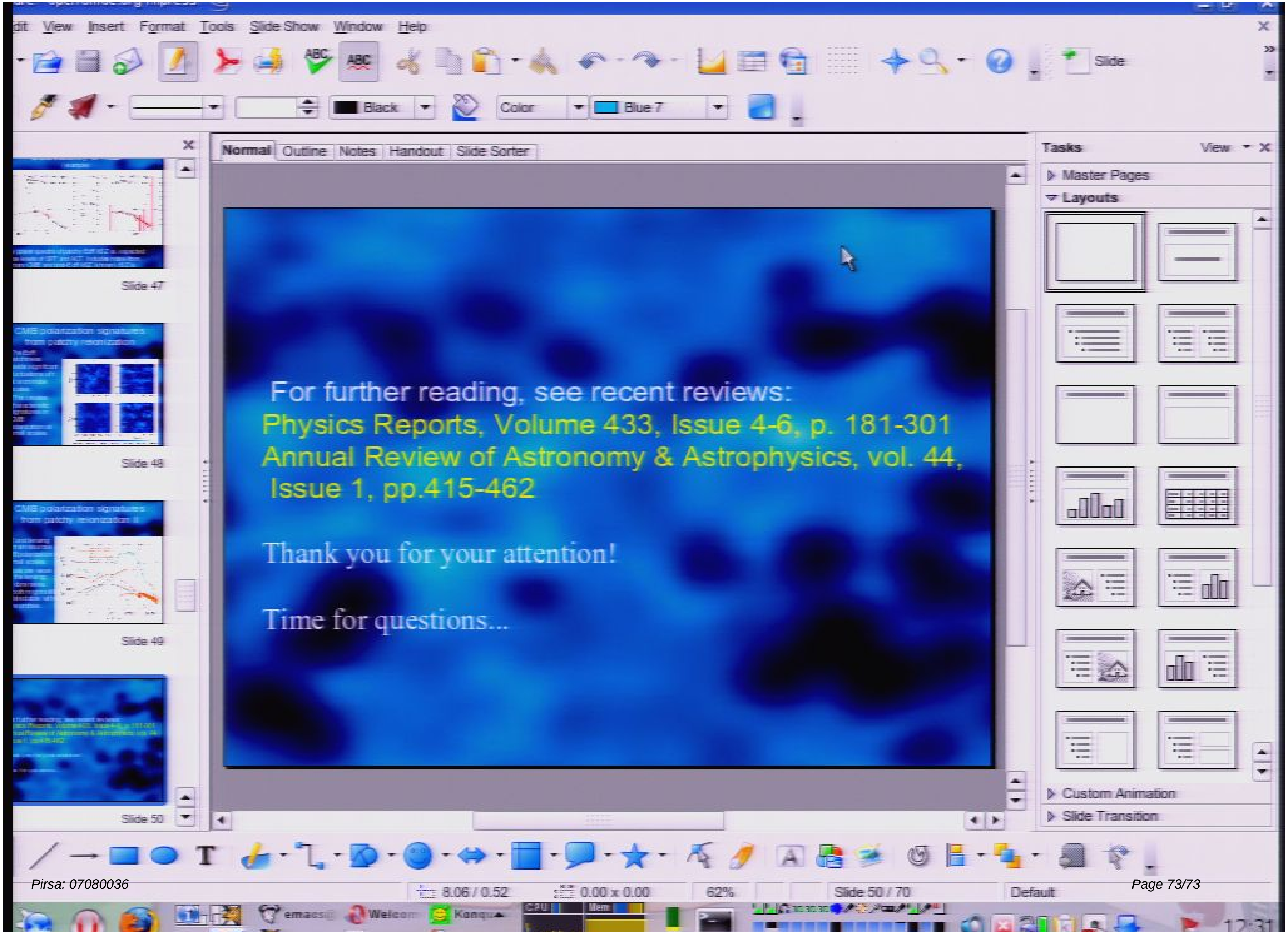
For further reading, see recent reviews:

Physics Reports, Volume 433, Issue 4-6, p. 181-301

Annual Review of Astronomy & Astrophysics, vol. 44, Issue 1, pp.415-462

Thank you for your attention!

Time for questions...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