LOFAR workshop, April 2007

LOFAR and the Epoch of Reionization

Saleem Zaroubi

Kapteyn Astronomical Institute

University of Groningen

Overview

- Introduction
- The Astrophysics (Andrea's Talk)
  - Reionization:
    - What do we know?
    - What do not we know?
- The Physics
  - the 21 cm emission.
  - The spin and brightness temperature.
- The LOFAR-EoR project
  - The measurement
  - The simulations
  - Signal & Systematics.
  - The data products.
- Summary

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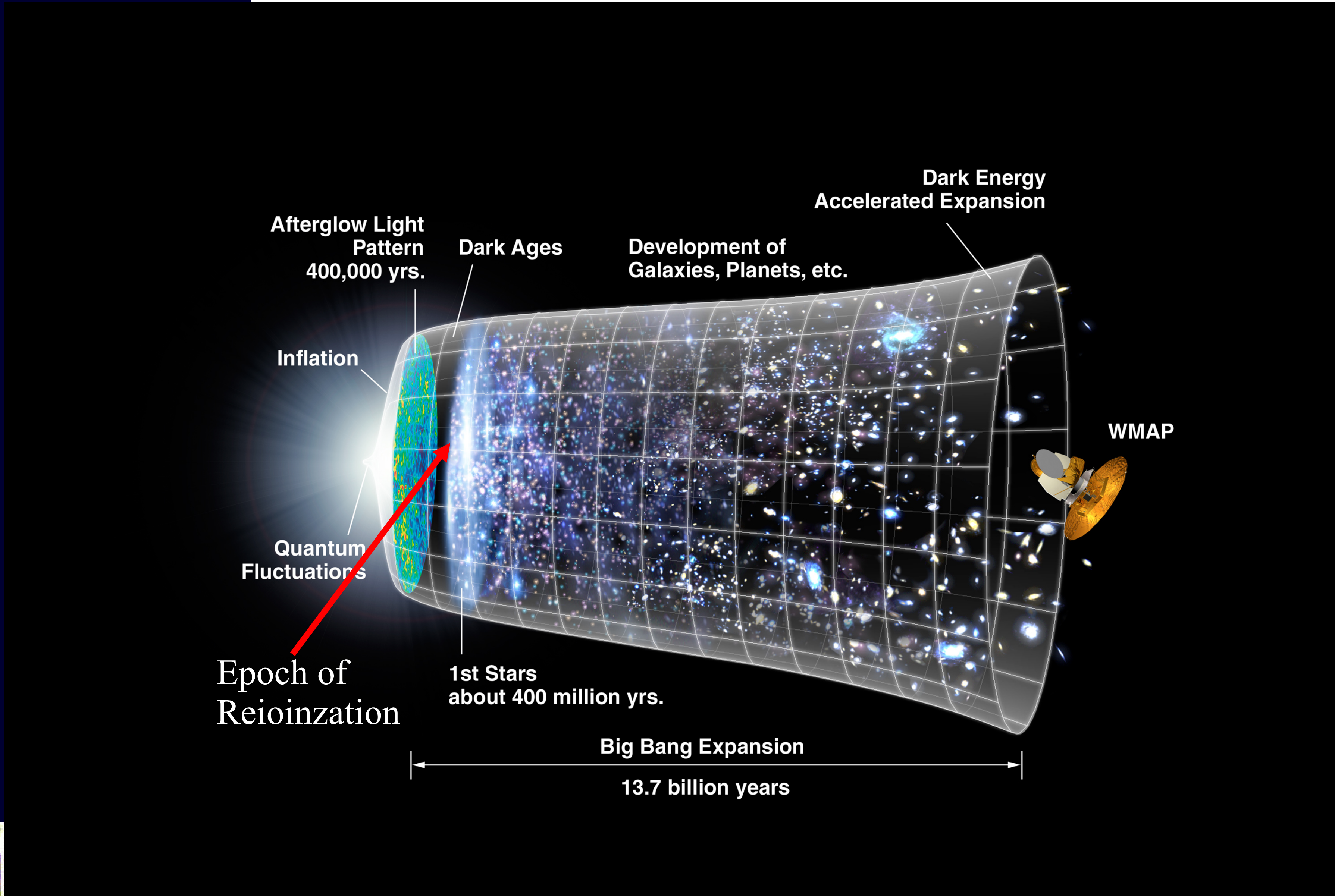
Introduction



Credit for picture: WMAP team

What do we know?

- The Lyman-alpha forest: At z<6 he Universe is completely ionized
- The Universe has completed its ionization by redshift 6: SSDS quasars
- The WMAP polarisation measurement suggest that ionization has happened at about z~10.

What don't we know?

- When did the reionization happen?
- What are the sources of ionizing radiation? Stars, miniqsos, decaying DM, exotic physics,…
- How fast did it spread and in what fashion?
- How did the reionization influence the subsequent galaxy and structure formation in the Universe?

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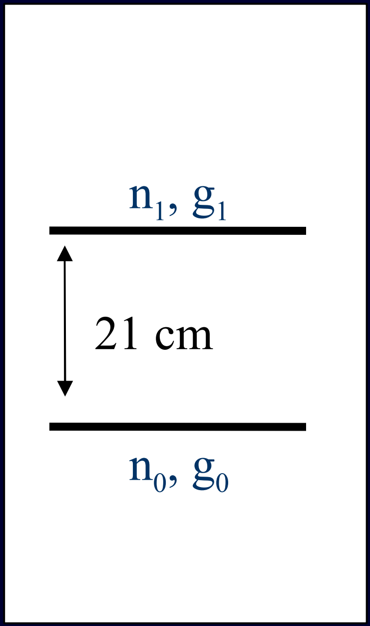
The physics of the 21 cm transition



- The 21 cm hyperfine transition is a forbidden transition between the two $1^2S_{1/2}$ ground level states of hydrogen.
- The relative population of the two states is given by the spin temp. T_s, i.e.,

  $$n_1/n_0=g_1/g_0 \exp(-T_*/T_s) \quad \text{with } T_*=0.068 \text{ k}$$

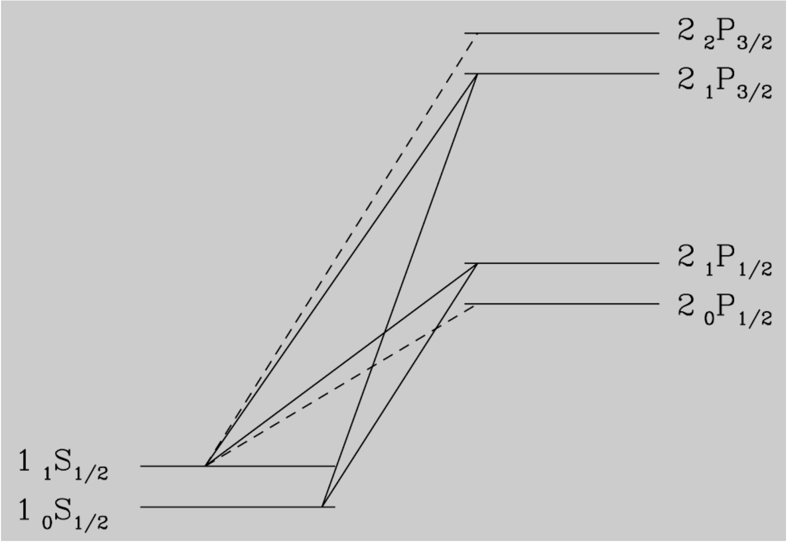
- The value of the spin temp. is given by the following equation:

$$T_s=(T_{CMB}+y_c T_K+y_\alpha T_K)/(1+y_c+y_\alpha)$$

Field 1958

Lyman-alpha Coupling

- The Wouthuysen-Field effect, also known as Lyman-alpha pumping.



Dominant in both in the case of stars and Black-holes, due to photo and collisional excitations, respectively.

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Collisional Coupling

- H-H collisions that excite the 21 cm transition. This interaction proceeds through electron exchange.
- H-e collisions. Especially important around primordial X-ray sources (mini-quasars).
  - **This effect might also excite Lyman-alpha transition which adds to the T_s- T_{CMB} decoupling efficiency.**

Chuzhoy et al. 06

Zaroubi et al. 06

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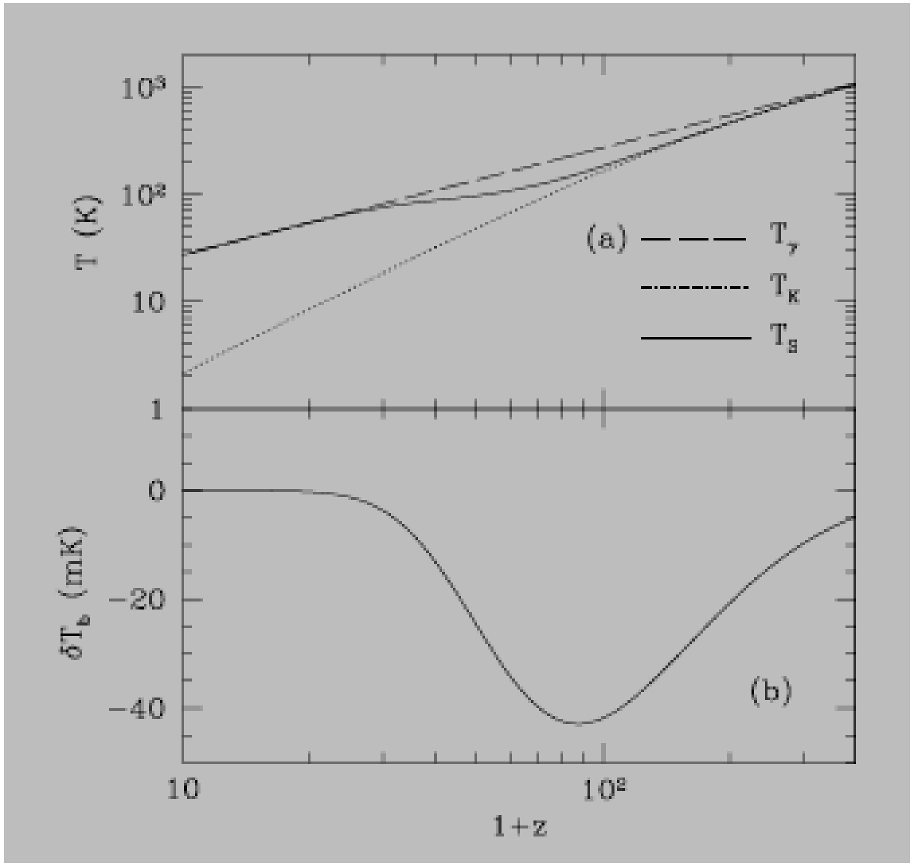
The Global evolution of the Spin Temperature

At z~10 T_s is tightly coupled to T_{CMB}. In order to observe the 21 cm radiation decoupling must occur.



Loeb & Zaldarriaga 04

The brightness temperature: The measured quantity

- The quantity that is measured with radio telescopes along a given line of sight and is given by:

$$\delta T_b(l,b,\nu) \approx 28\mathrm{mK}\,(1+\delta)\,x_{HI}\,\frac{T_s - T_{CMB}}{T_s}\,\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{1/2}$$

Field 1958

- The sources that ionize are probably the same as the ones that decouple

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Possible ionization sources
The first stars

Form favourably very massive stars very early on.

- First stars are different creatures from the ones we see in the local universe (no metals).
- Atomic cooling is efficient in halos with $T_{vir}>10^4k$ ($\sim10^9M_{sun}$). At smaller masses H_2 cooling probably produces very massive stars.
- Efficiency of producing stars!! In our environment the main question is why star formation is so inefficient.

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Abel, Bryan, Norman 00., Bromm Larson 00

Simulations

Ciardi & Ferrara.

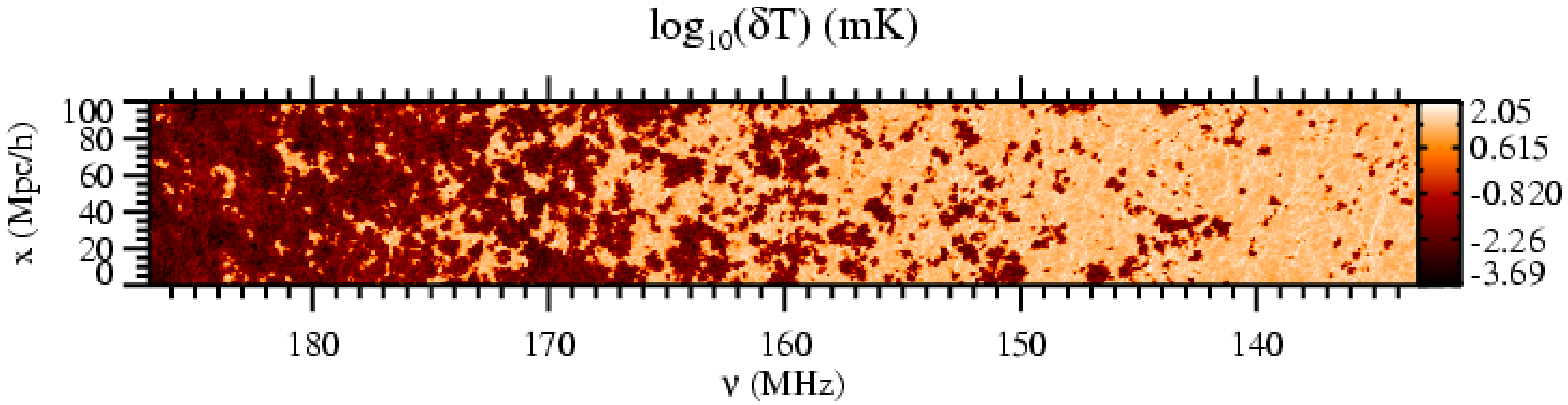
Gnedin

Mellema et al.

Khan et al.

and many others

- Most simulations assume stellar ionization sources.



Iliev et al. 07

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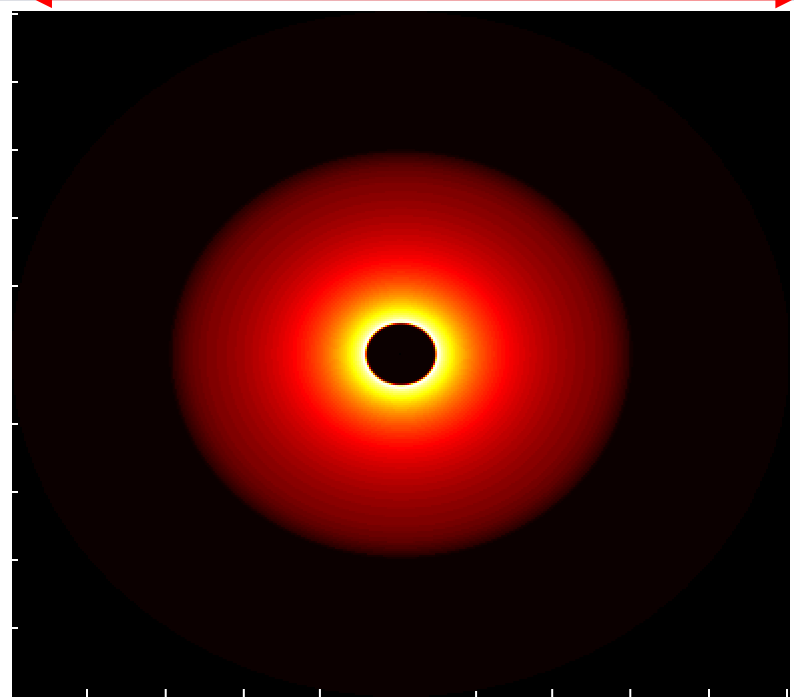
Possible decoupling sources

The first massive black holes

Quasars with Black-hole masses of $\sim 10^9 M_{sun}$ are seen at $z \sim 6.7$

~3 Mpc comoving



BHs with intermediate masses ($10^{3-6} M_{sun}$) could ionize the Universe and heat it up.

Thomas & Zaroubi 07

Decoupling through Miniquasars X-ray radiation

- The X-ray radiation from miniqsos results in T_s-T_{CMB} decoupling through collision heating and excitation.
- Since the mean free path of X-ray photons is quite large, the spin temperature will have different properties relative to that around stars.

Kuhlen, Madau & Montgomery 06

Zaroubi, Thomas, Sugiyama Silk. 2006

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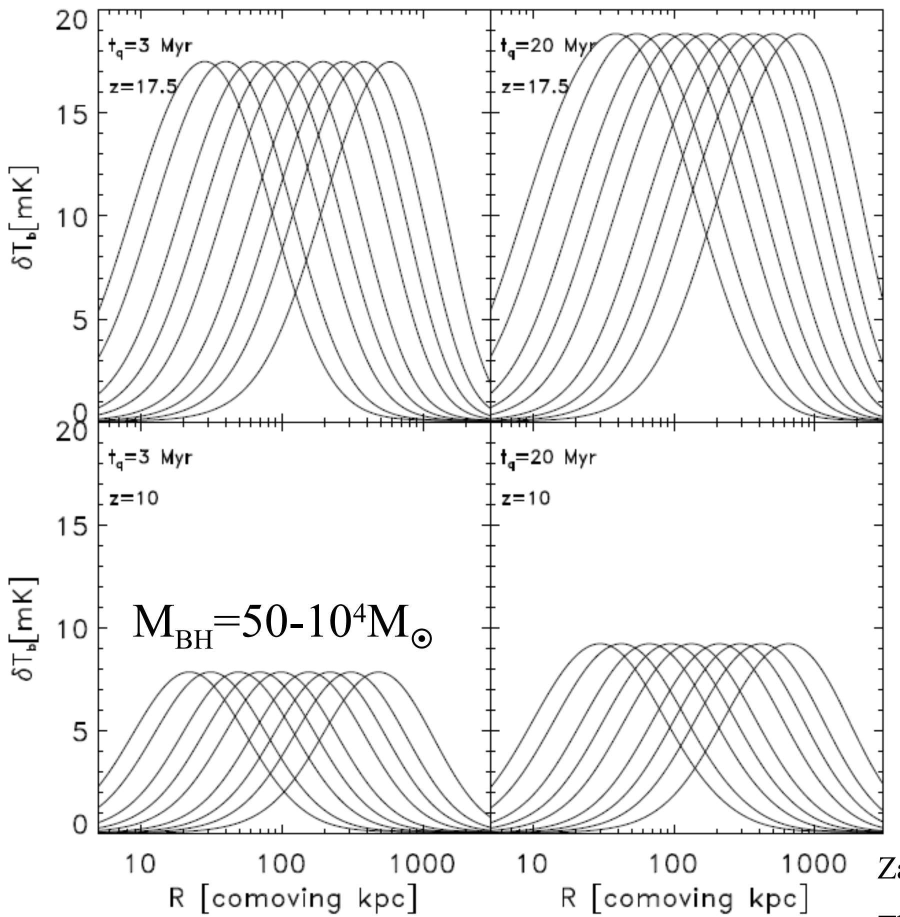
The Brightness temp. Around a single miniqso



M_{BH}=50-$10^4 M_\odot$

Zaroubi et al 2007

Thomas & Zaroubi, in prep

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LOFAR – The Instrument & Relevant Requirements for the EoR KSP -1-

- Frequency range: 115 – 205 MHz
  (30MHz settings of 195 subbands)

- Spectral resolution: 1 KHz within sub-band (RFI excision)
  10 KHz for storage (dt=10 sec)
  100 KHz for analysis

- HBA station: 96 tiles (4x4 dua pol. dipoles)
  40-50 m diameter station

- Sensitivity: rms=300 mK after 3 hrs (core; $\Delta\Theta$~3-5')
  ($\Delta\nu$=1MHz) rms= 30 mK after 300 hrs.

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The EoR key project: Scientific goals

- The plan is to statistically measure the EoR signal and as the data collection proceeds to refine our measurement and produce a full power spectrum and eventually maps.
- High order statistics
- The environment of very high z quasars.
- Cross correlate with other data sets:
  - CMB (Planck data).
  - Lyman-alpha emitters .
  - Other complementary data.
- The 21 cm forest (if a strong enough background source is found).

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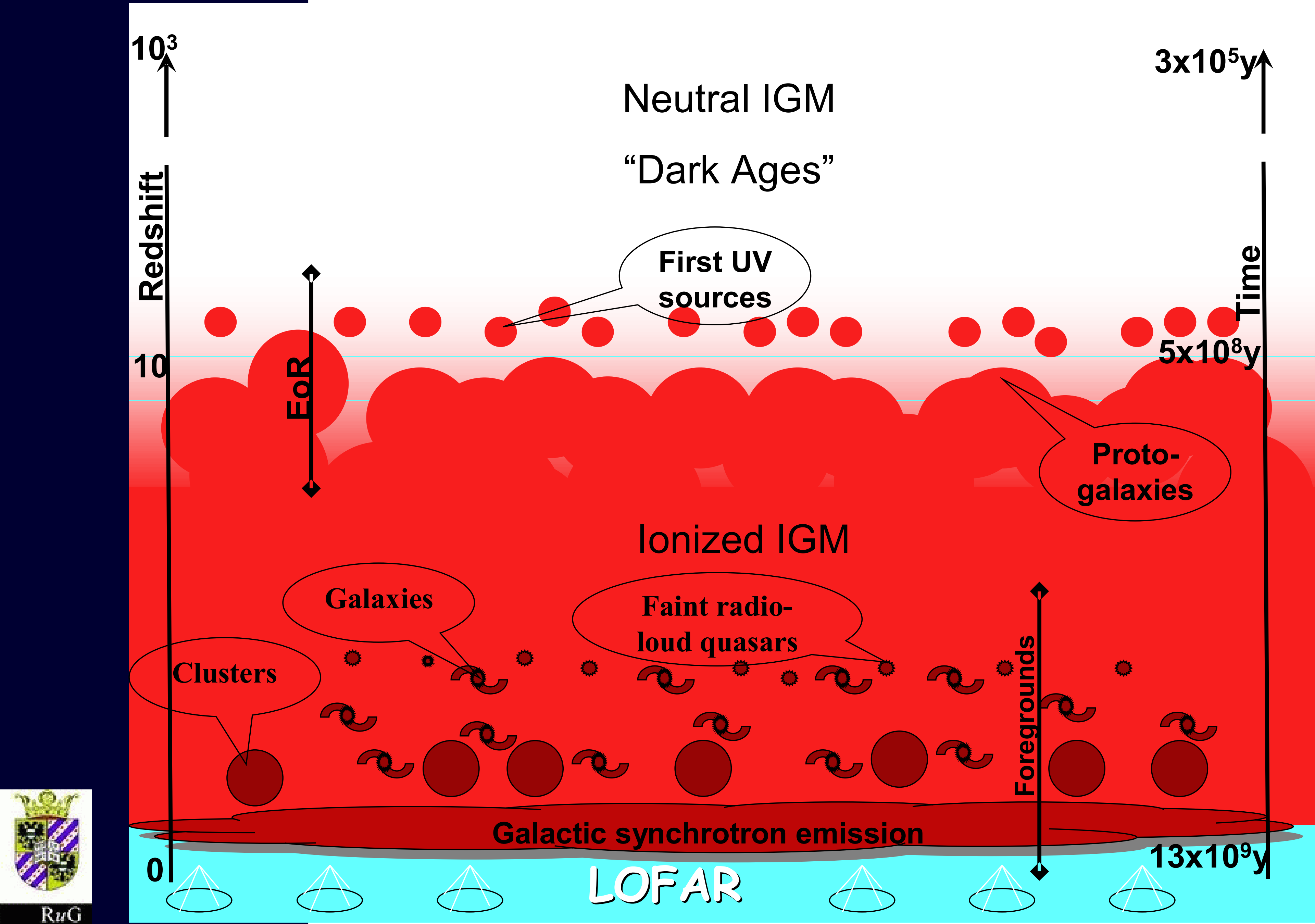
10^3
3x10^5y
Neutral IGM
"Dark Ages"
Redshift
Time
First UV sources
EoR
10
5x10^8y
Proto-galaxies
Ionized IGM
Galaxies
Faint radio-loud quasars
Clusters
Foregrounds
Galactic synchrotron emission
0
13x10^9y
LOFAR
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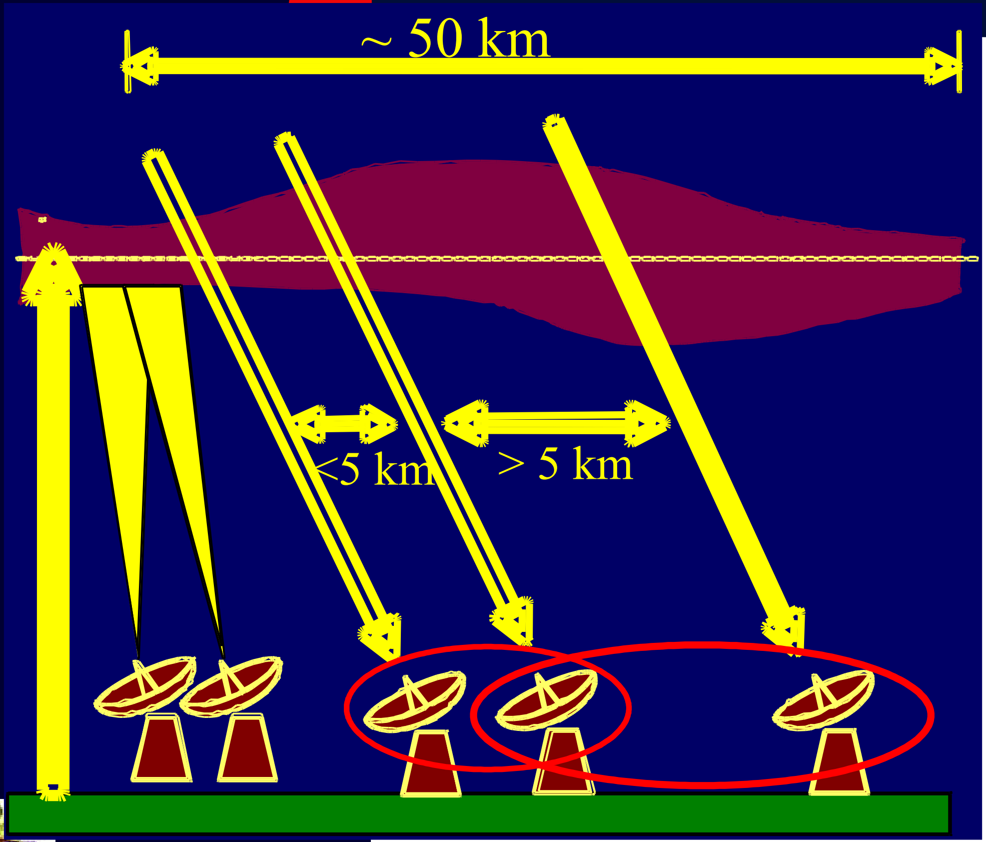
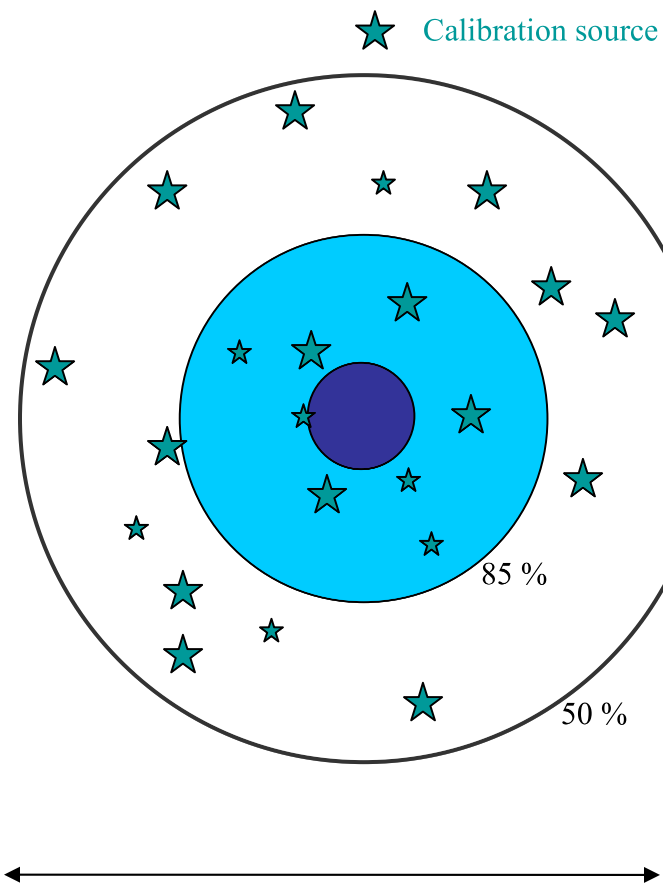
The Ionosphere and the calibration problem



Wedge Effects: **Faraday rotation, refraction, absorption below 5 MHz**

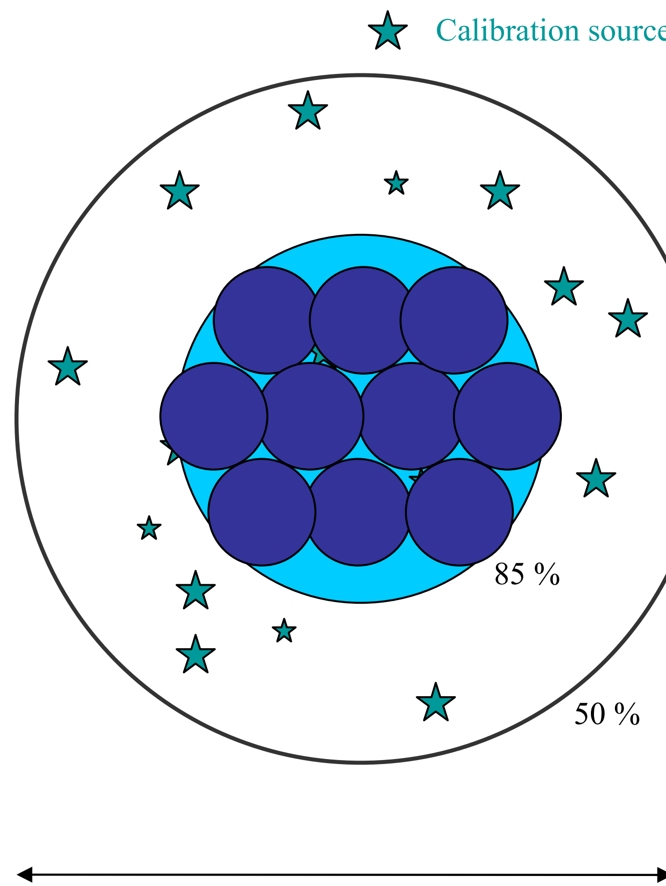
Wave and Turbulence Effects: **Rapid phase winding, differential refraction, source distortion, scintillations**

Dynamic ionospheric phase-screen mapping: --> 2-D phase screen



tile beam 20-25°

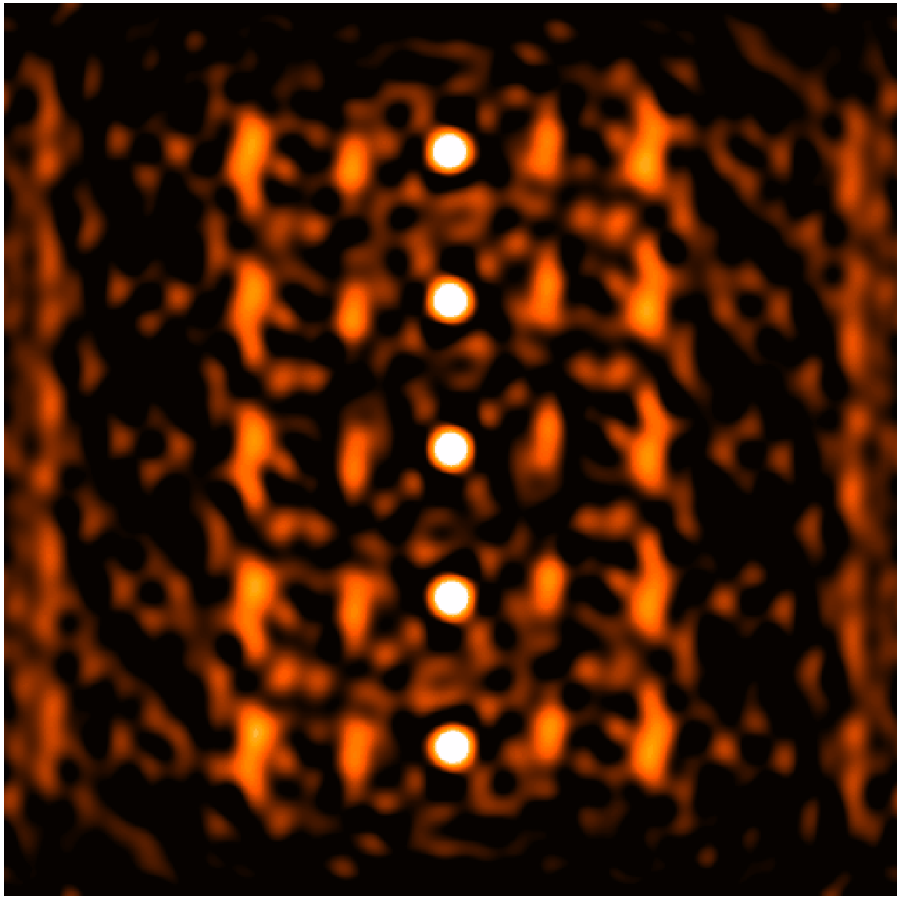
Year 1



tile beam 20-25°

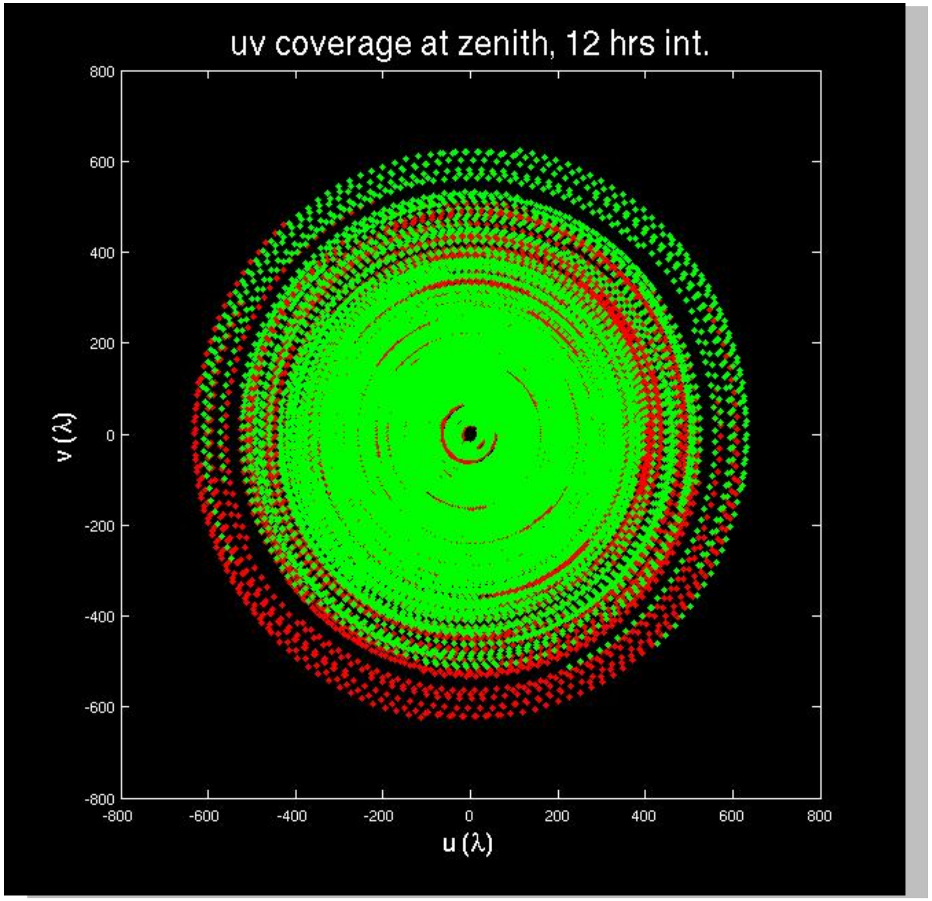
Year 2 - 4

The ionosphere



Simulations by
O. Smirnov

The UV Coverage



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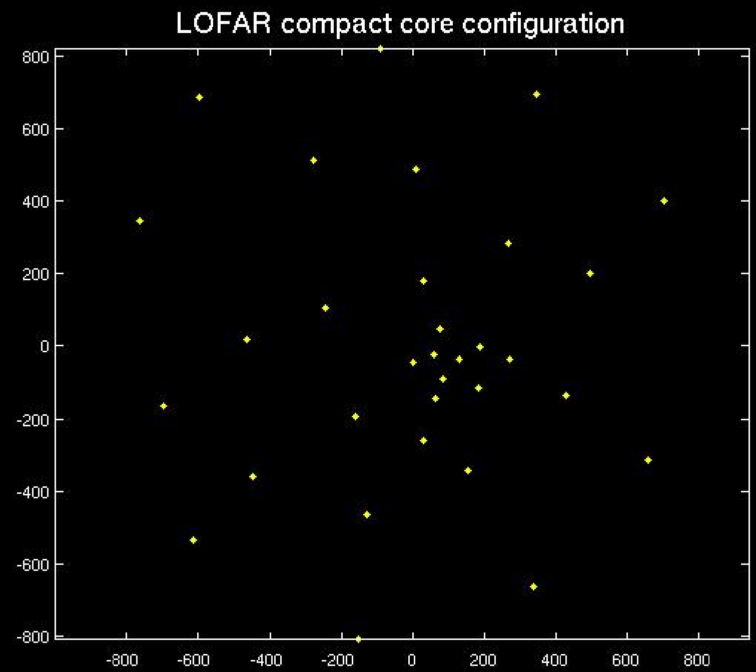
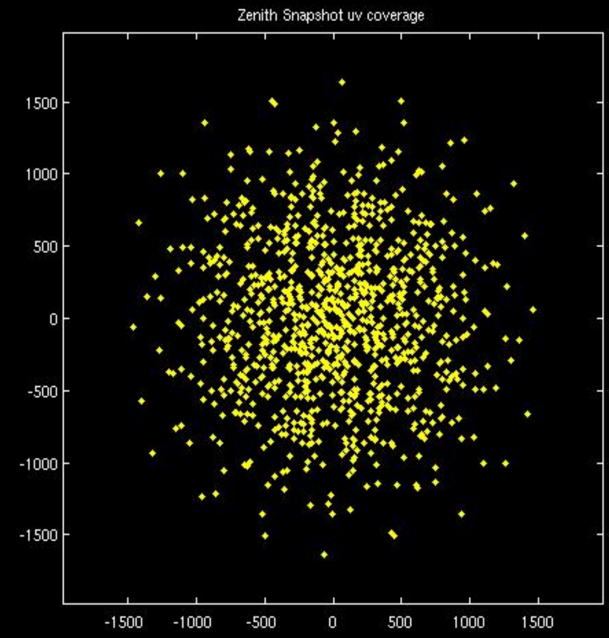
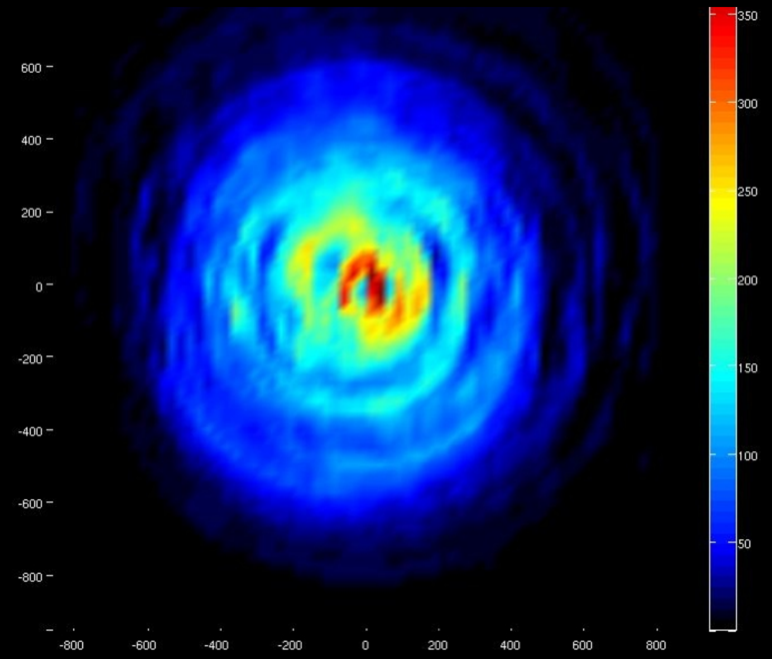
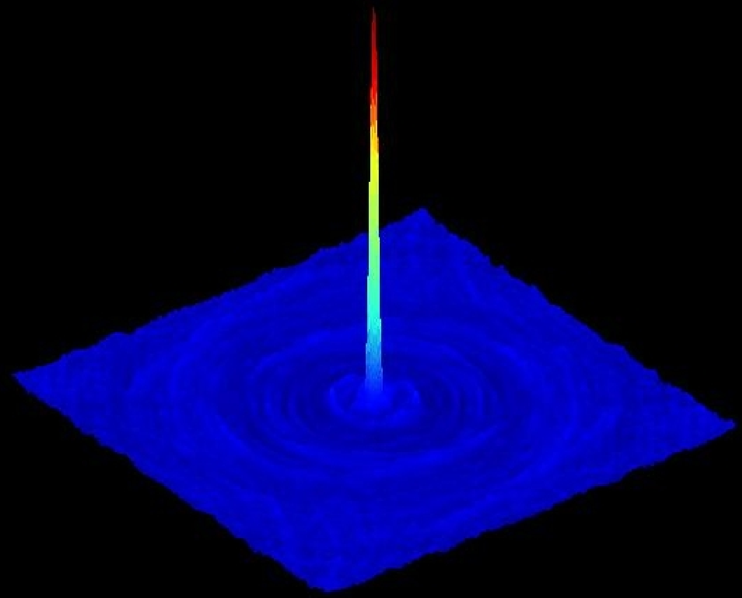
LOFAR work









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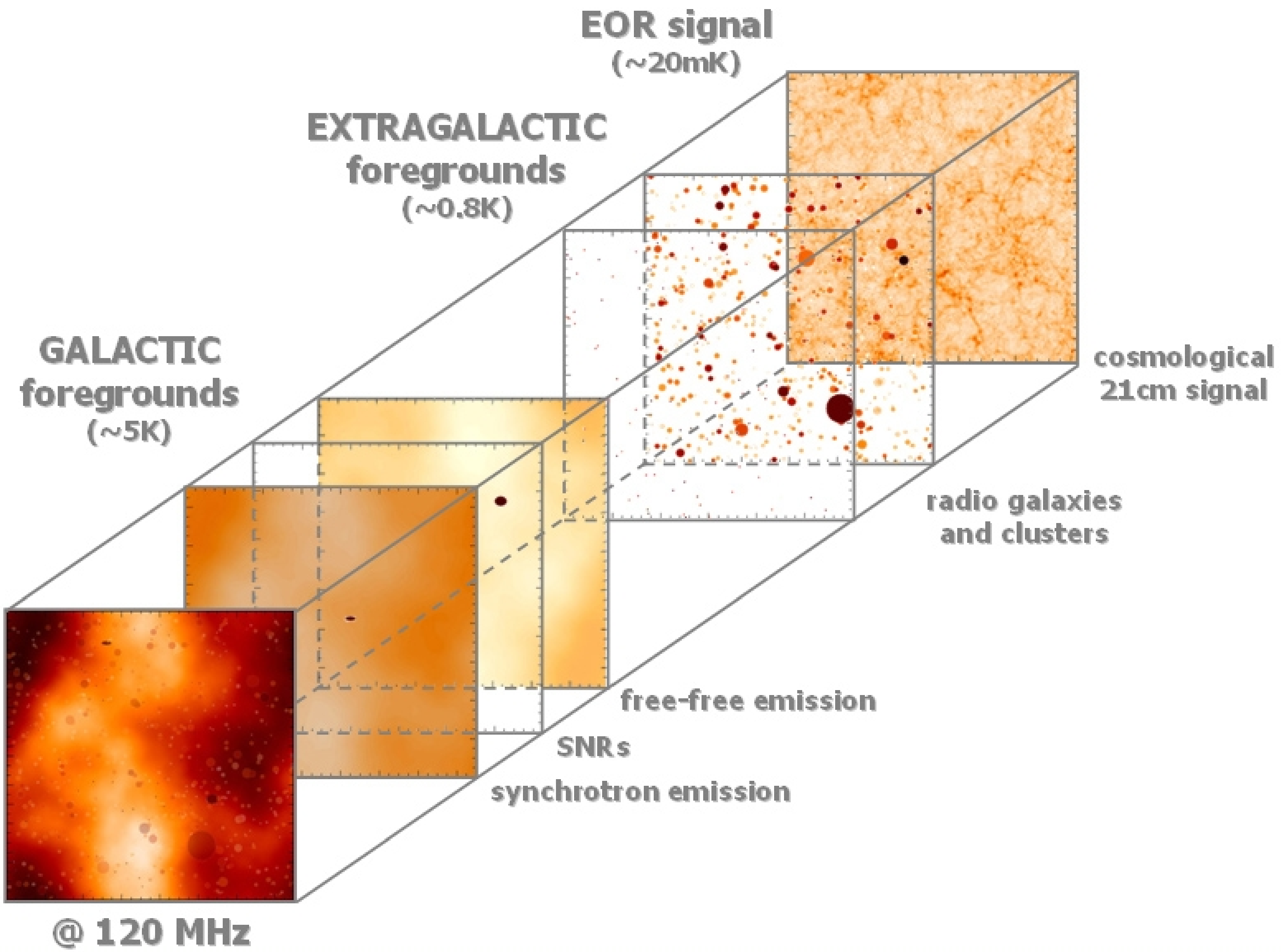
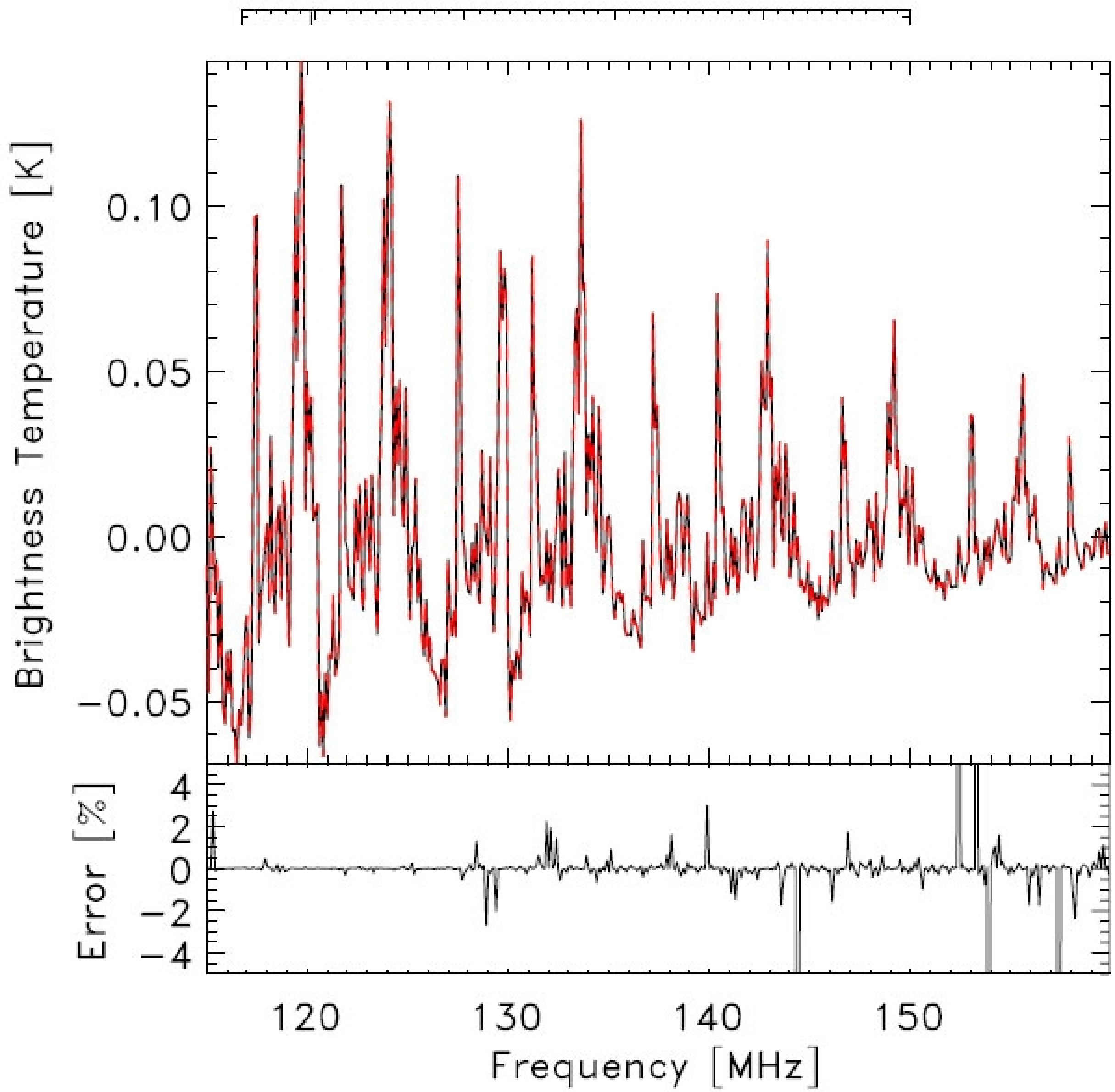
The foregrounds

- **galactic synchrotron emission (~70%)**
- **galactic thermal (free-free) emission (~1%)**
- **integrated emission from extragalac. Sources-(~27%)**
  - radio sources/AGNs, clusters

Shaver at al., di Matteo et al., Santos et al.

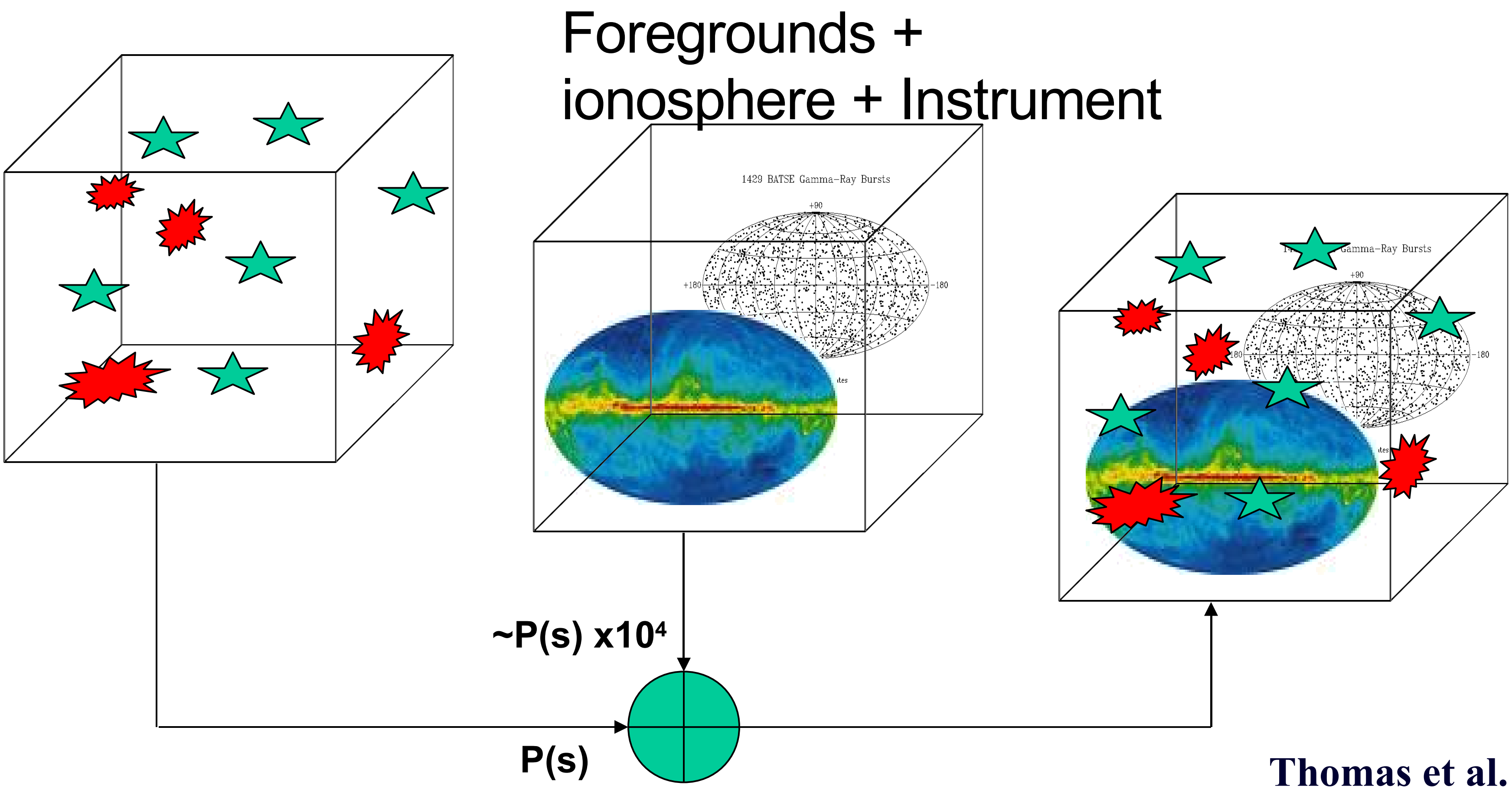


Jelic & Zaroubi 07



Jelic & Zaroubi 07

Simulating the data



Thomas et al. 07

The Measurement Equation

$$\vec{V}_{ij}(u,v) = \sum_{k} \int df \int dt \, \left(J_{ik} \otimes J^{*}_{jk}\right) S \, \vec{I}_{k}$$

- Hamaker-Bregman-Sault formalism
- Station-pair (i,j): Vector of 4 ‘correlations’
- Matrix equation: full polarization
- Instrumental Jones matrices J (2x2)
- Stokes matrix S (4x4)
- Sum over sources (k): Flux [I,Q,U,V]
- Integral over time-freq domain

See Panos' Talk

For more detail

Measurement

- Sensitivity
  about 0.15 k for 1 hour integration at 120 MHz

$$\Delta T^{N} = \frac{1}{\eta_{e}} \frac{T_{sys}}{\sqrt{\Delta \nu \, t_{int}}}$$

- Data Model

$$\mathbf{R}_k = \mathbf{A}_k \mathbf{B} \mathbf{A}_k^{+} + \sigma^2 \mathbf{I}$$

$$\mathbf{A}_{ik} = \mathbf{A}_k^{gain} \mathbf{A}_{ik}^{delay} \mathbf{A}_k^{offset} \mathbf{A}_k^{Faraday} \mathbf{D}_k$$

B is the brightness vector.

A is the response

σ is the noise

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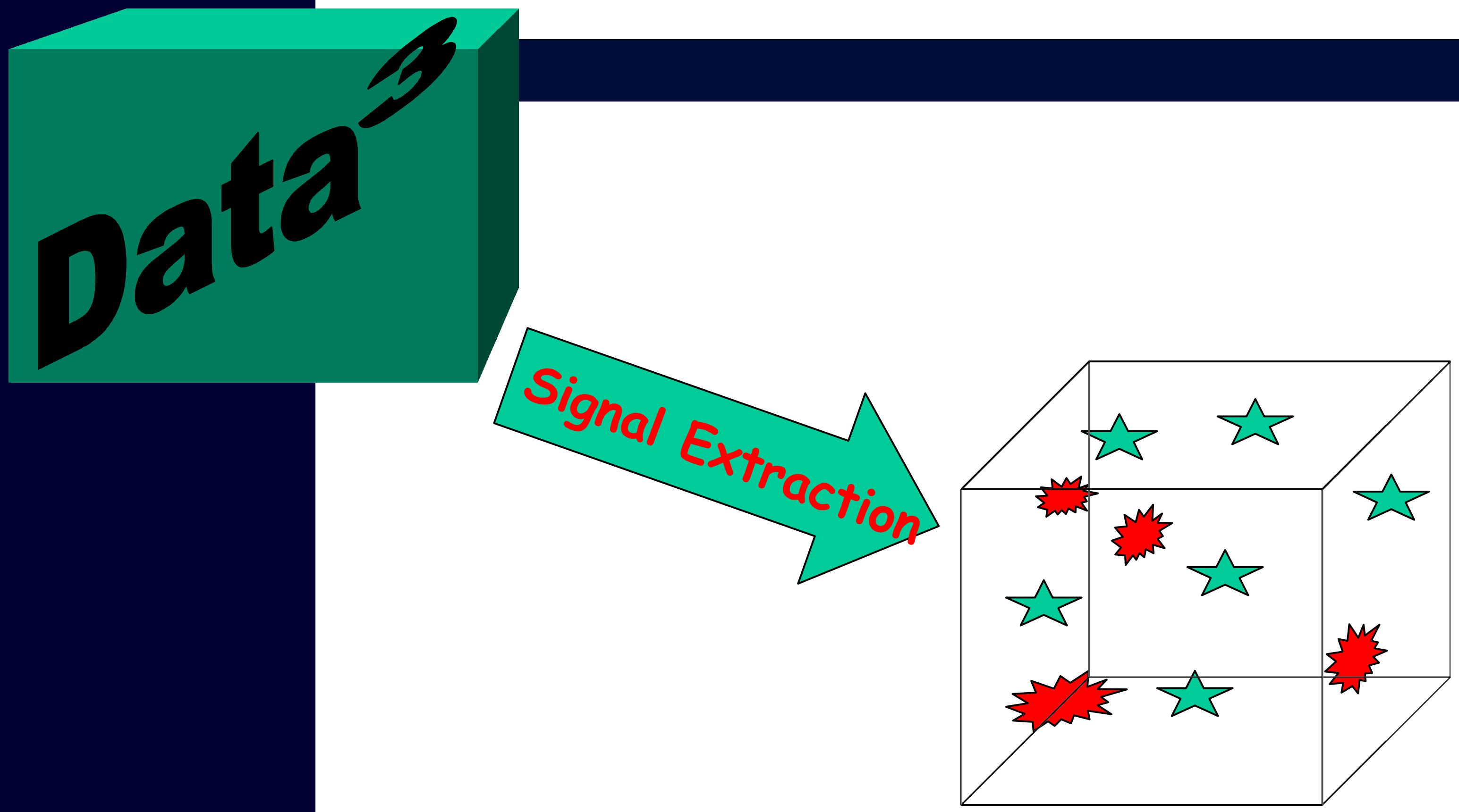
Data Simulation Pipeline



Tomography of the Reionization Process: What will we learn?

Pre	The dark ages: Fluctuations PS at z~10.(Non)-Gaussianity, Universe's Geometry (AP test).
During	o First objects and their properties. o How fast and in what fashion did reionization spread.
Post	Influence on subsequent galaxy and structure formation in the Universe

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