The Epoch of Reionization

Andrea Ferrara
SISSA/International School for Advanced Studies
At $z=1000$ the Universe has cooled down to 3000 K. Hydrogen becomes neutral ("Recombination").

At $z < 20$ the first "PopIII" star (clusters)/small galaxies form.

At $z \sim 6-15$ these gradually photo-ionize the hydrogen in the IGM ("Reionization").

At $z < 6$ galaxies form most of their stars and grow by merging.

At $z < 1$ massive galaxy clusters are assembled.
Redshift

Lyman Forest Absorption
Transmission Gaps
Black Gunn-Peterson trough
CLASSICAL REIONIZATION TESTS

GUNN-PETERTSON EFFECT

Spectra of high-z QSOs

Ly\(\alpha\) optical depth

Ly\(\gamma\) \(\propto (1+z)^{10}\)

Ly\(\beta\) \(\propto (1+z)\)

Ly\(\alpha\) \(\propto (1+z)^{4.3}\)
CLASSICAL REIONIZATION TESTS

**WMAP3 RESULTS**

Polarization Maps
Q Stokes Parameter

\[ \tau_e = 0.09 \pm 0.03 \]
Self-consistent treatment of the evolution of ionized regions and thermal history

Follow evolution of neutral, HII and HeIII regions

Three sources of ionizing radiation:

- **PopIII stars**: early redshifts, Salpeter IMF, zero metallicity
- **PopII stars**: Salpeter IMF, sub-grid PopIII-PopII transition model
- **Quasars**: significant @ $z < 6$, using $\sigma$-$M_{\text{BH}}$ relation

Radiative feedback suppressing SF in low-mass halos, set by:

- Molecular cooling in neutral regions
- Photoionization temperature in ionized regions
GLOBAL REIONIZATION MODELS

Choudhury & AF 2005, 2006

Graphs showing:
- The reionization history
- Photoionization rate
- Star formation history
- PopIII
- Total electron scattering optical depth
- Lyα G-P optical depth
- Lyβ G-P optical depth
- Lyman Limit Systems
- Temperature

Graphs with axes labeled and data points indicating the evolution of various parameters over redshift (z).
IONIZING PHOTON BUDGET

$f_\gamma > 80\%$ of the ionizing power from $M < 10^9 \, M_\odot$ halos
GAP STATISTICS

Gallerani+ 2006

NEW REIONIZATION TESTS

Early reionization

Late reionization
NEW REIONIZATION TESTS

Gallerani+ 2006

GAP STATISTICS

![Graph showing gap statistics for different redshifts (z=5.7-6.3 and z=6.0-6.6). The graph plots $f_{\text{los}}$ against $W_{\alpha}^{\text{max}}$ (Å). The data points are labeled as Early and Late.](image)
THE (NOT SO LOFAR) FUTURE
• Instrument sampling
  100 stations, 360 km baseline
  Instantaneous u-v coverage, $\delta_0 = \pi/2$

• Instrument sensitivity
  $\Delta v = 128 \text{ kHz}, \Delta t = 1000h$

• Gaussian beam convolution
  $\sigma = 3 \text{ arcmin}$
HINTS FROM COUPLED 21CM/CMB OBSERVATIONS

Salvaterra, Ciardi, AF & Baccigalupi 2005

late reionization  early reionization

\[(\delta T/T_0)_{\text{CMB}}\]

\[(\delta T_b/T_0)_{21\text{CM}}\]

CROSS CORRELATE

115 MHz  90 MHz

ALMA
HINTS FROM COUPLED 21CM/CMB OBSERVATIONS

HII REGION SIZE EVOLUTION

Size of HII region (Mpc) from zero of correlation fct.

Bandwidth

early

late
NATURE OF DARK MATTER

21CM SIGNAL FROM DM DECAY/ANNIHILATION

Valdes+ 2007

\[ \Delta \delta T_b (\text{mK}) \]

\[ \Delta \delta T_b / \Delta \nu (\text{mK/MHz}) \]

\[ T \]

\[ T_{\text{cmb}} \]

\[ T_s \]

\[ T_k \]

\[ T_s^{\text{DM}} \]
Reionization started by metal-free stars @ $z=20$; 90% complete @ $z=8$

Reionization @ $z > 7$ not in contrast with any constraint from QSOAL data

$f_\gamma > 80\%$ of the ionizing power at $z \geq 7$ from halos of $M < 10^9 M_\odot$

Gap statistics to discriminate early/late reionization from analysis of QSOAL spectra

Significant progress expected from HI 21cm detection from $z > 6$

Cross-correlate of 21cm & CMB data to reconstruct reionization history

21 cm from pre-reionization epochs: cleanest possible DM tracer