Understanding Cosmic Dawn

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Low Radio Frequency Observations from Space
Observation: Cosmological 21-cm Signal

- 21-cm line (hyperfine transition of neutral hydrogen)
- Can be observed today in Radio

\[ \lambda = 21 \text{ cm} \]
\[ \nu = 1420 \text{ MHz} \]

Spin Temperature
\[ n_1/n_0 = 3 \exp(-T_\ast/T_S) \]
\[ T_\ast = 0.068 \text{ K} \]
Observational Effort

$50 \lesssim \nu \lesssim 200 \text{ MHz},$

$5 \lesssim z \lesssim 30$
Cosmological context
Dark Ages, Cosmic Dawn and EoR

Cosmic Microwave Background:
- Cosmological model
- Initial conditions for structure formation

Cosmic Dawn and Reionization:
- Formation of first stars
- Black holes
- Radiative feedbacks

“Local” Universe:
- Stars and planets
- Galaxies
- Black holes
- Large scale structure

$t_{Universe} \sim 0.38 \text{ Myr}$

$t_{Universe} \sim 14 \text{ Gyr}$
**Existing observations**

**Cosmic Microwave Background:**
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Bowman et al. (2018)
21-cm: The Entire Frequency Range

Unique probe of high-redshift astrophysics and properties of Dark Matter

3D scan of the Universe

Space  Ground and space

Pritchard & Loeb (2011)
Cosmic Dawn

Onset of star and black hole formation

What are the progenitors of the supermassive BHs?

Hirano et al. 2017

LMC and SMC
\[ M_{\text{SMC}} \approx 7 \times 10^9 \, M_{\odot} \]
\[ M_{\text{LMC}} \approx 10 \times 10^9 \, M_{\odot} \]

Massive stars (Hirano et al. 2014)
“Traditional” Modeling
Cosmic Dawn and EoR

Reionization

Cosmic Dawn + EoR:
Minimal mass of star forming halos
Supersonic velocity flow
LW Feedback

~40000 models! 7 parameters

\[ f_* \leq 50\% \]
- \[ V_C = 4.2 - 76.5 \text{ km/s} \]
- \( \tau \geq 0.055 \)
- \( R_{mfp} = 10 - 50 \text{ Mpc} \)
- X-ray sources: \( \alpha = 1 - 1.5, \ f_X = 0 - 10, \nu_{min} = 0.1 - 3 \text{ keV} \)

Interpolation code

Cohen, Fialkov, et al. in prep.
Expected Global Signal and Power Spectrum

Parameter study based on 200 models (***) Now extended to 40k models, interpolation code. Varying properties of star formation, X-ray heating, structure formation, Reionization.

Cohen, Fialkov, Barkana (2017)  
Cohen, Fialkov, Barkana (2018)
Absorption Trough vs Astro Parameters

Parameter study based on 200 models
(*** ) Now extended to 40k models, interpolation code.
Varying properties of star formation, X-ray heating, structure formation, Reionization.

Cohen, Fialkov, Barkana (2017a)
Cohen, Fialkov, et al. in prep.
Constraints with EDGES High-Band

$v = 90 - 190$ MHz
$(14.8 > z > 6.5)$

Some 68% constraints:

\[ M_{\text{min}} < \text{few} \times 10^8 M_\odot \]
\[ f_X > 0.004 \]

$k = 0.1 \text{ Mpc}^{-1}$ - SKA

$k = 0.5 \text{ Mpc}^{-1}$

Soft SED

Hard SED

Cohen, Fialkov, Barkana (2018)
Cosmic Dawn with EDGES Low-Band

Best Fit in the Context of Standard Scenarios

Bowman, Rogers, Monsalve, Mozdzen, Mahesh (2018)

OL: “The biggest tension of the week”

SNR of 37

EDGES LB
Astro Cohen, et al. (2017)

Consistency of Cosmological Datasets: Evidence for New Physics?
28 May - 1 June 2018 at KICCG
What Do we Learn if Confirmed?

Timing:
- First stars formed around $z \sim 22$
- $M_{\text{min}} < \text{few} \times 10^8 \ M_{\text{sun}}$
- Steeper than expected UVLF (Mirocha & Furlanetto 2018)
- Heating starts around $z \sim 16$
- The Universe is heated by $z \sim 14$

The amplitude and shape don’t fit standard astro scenarios:

For the best-fit amplitude of 0.5 K:
- $T_{\text{Rad}}/T_S > 15$ at $z \sim 17$ (max is 7)
- $T_{\text{Rad}} > 104$ K (CMB $\sim 50$ K)
- $T_{\text{gas}} < 3.2$ K (min is $\sim 7$ K)

$v = 50 - 100$ MHz, $(26 > z > 14)$

$\delta T_b \propto x_{HI} \left[ 1 - \frac{T_{\text{Rad}}}{T_S} \right]$

Bowman et al. 2018
Deep Absorption via Extra Radio Background

\[ \delta T_b \propto x_{HI} \left[ 1 - \frac{T_{CMB}}{T_S} \right] \]

- Effect of neutrino or DM? Chianese et al. (2018)

Inspired by ARCADE2 excess (Fixen et al. 2011)
Also: LWA1 data (Dowell & Taylor, 2018)

Exotic quasars at high z? Ewall-Wice et al. (2018)

Feng, Holder 2018
Deep Absorption via Extra Cooling

\[ \delta T_b \propto x_{HI} \left[ 1 - \frac{T_{CMB}}{T_S} \right] \]

\( \chi \) \( \chi \)

\( \sigma(\nu_{bdm}) \)

\( b \) \( b \)

BEC Cooling

Sikivie 2018
Houston et al. 2018

Barkana (2018)
Smoking Gun Signature: Enhanced BAO

\[ \sigma (v_{b dm}) \]

\[ D_M = 0.01 \]

\[ f_{DM} = 0.01 \]

Fialkov, Barkana, Cohen (PRL)

Tight Constraints

Asher et al. 2018

See also Munoz & Loeb (2018), Barkana et al.(2018)
Observational Verification on the Way

- EDGES-Mid (75% scaled version) has been deployed, the first data analyzed (Nov-Jan).
- SARAS Low has been deployed. Optimization in progress.
- PRISM taking data (?)
- LEDA
  - Upper limit $T_{21} > -890$ mK at $z \sim 20$ (95%, Bernardi et al., 2016)
Dark Ages
Dark Ages $\nu \lesssim 40$ MHz
Only from Space

The signal is driven by atomic physics, cosmology
Dark Ages – unique cosmo. probe

Standard Physics

High-resolution Ly-a radiative transfer calculation, coupled to a state-of-the-art primordial recombination code

Lewis & Challinor (2007)

The Universe is bigger than the LHC! New tests of DM physics

Dark Ages – Window Into the Dark Sector

Dark matter

Courtesy of Illustris
Dark Ages as a Probe of DM Annihilation and Decay

Affects thermal and ionization histories.

Valdes et al. 2013

Example Temperature History

Example Ionization History

Liu & Slatyer (2018)
Dark Ages as a Probe of Dark Matter
B-DM Scattering

Affects thermal and ionization histories (cooling and heating)

Global 21-cm

Power Spectra

Fialkov, Barkana, Cohen, PRL, accepted
Conclusions: Exciting times for 21-cm cosmology!

21-cm: 3D scan of the Universe
Aspiration: Precision analysis at all redshifts

Cosmic Dawn & EoR: probe of astrophysics and DM. First stars & black holes.

Dark Ages: cosmology and DM physics

Bowman et al. 2018