Shining Light into the Cosmic Dark Ages

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February 9, 2018
Aspen
Theory of Cosmic Evolution

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

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

$\tau_{\text{Universe}} \sim 14 \text{ Gyr}$
Challenges in Predicting Signals

- We don’t know how the Universe looked back then. Large parameter space.
- To simulate include: small scales (stars, AGN, XRBs) & large cosmological scales (star formation was rare, fluctuations in radiative backgrounds).
- Use: “hybrid” simulation with extensive use of sub-grid models.
- Running time: ~4h on a desktop (fast!).
- Explore parameter space.
Sources of Fluctuations

Initial conditions
- IC: \( \delta, v_{bc} \)
- Radiative backgrounds
  - X-rays
  - Ly-\( \alpha \)
  - Lyman-Werner
  - Ionizing

21-cm brightness temperature

Molecular cooling
- Velocity
- Density

Atomic cooling
- No feedback, No vbc
- No feedback
- Weak feedback
- Strong feedback
- Saturated feedback

Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

O’Leary, McQuinn 2012 Talks by Schauer, Ahn
Expected 21-cm Signal: An Example

Global Signal
Mean intensity of the line at every redshift

Drivers:
Galaxies, Quasars
XRB, BHs, etc.
First stars,
Feedbacks, velocity flows
Cosmology, Atomic physics, DM physics

\[ \delta T_b \propto x_{HI}(1 + \delta)(1 + z)^{1/2} \left[ 1 - \frac{T_{\text{CMB}}}{T_S} \right] \left[ \frac{H(z)/(z + z)}{dv_{||}/dr_{||}} \right] \]

Power at a fixed angular scale vs redshift

EoR X-rays Ly-\( \alpha \) Collisions

Neutral hydrogen
Ionized Bubble

z ~ 6 z ~ 10 z ~ 20 z ~ 30
Few Orders of Magnitude Uncertainty in Astro Parameters

Reionization

Minimal mass of star forming halos
Fialkov et al. (2013)
Supersonic velocity flow
Feedbacks

~200 models, 5 parameters
- \( f_* \sim 0.5\% - 50\% \)
- \( V_c = 4.2 - 76.5 \text{ km/s} \)
- \( \tau \geq 0.055 \)
- X-ray SED
- \( f_X = O(0) - O(1000) \)
However, Few Observations of EoR and CD Large Uncertainty in Astro Parameters & 21cm

→ exact shape and amplitude of the global 21-cm signal and fluctuations are still highly uncertain
Connection between Global Signal and Power Spectrum/Slope

Cohen, Fialkov, Barkana (2017b)
Observational Constraints

Disfavor weak heating, sharp reionization, late star formation

SARAS
Singh et al. 2017

Singh et al. (2017) + talk by S. Singh
Exploration Space is Ongoing!

Interpolation tool: Parameters $\rightarrow$ Global signal

From 200 models to $\sim$30k models!
Now 7 parameters

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

talk by R. Monsalve
Efficient Parameter Estimation

Requires fast realizations of signals.

- Analytical models (talk by J. Morocha) Global signal

We used our ~30k models to develop an emulator of the global signal Challenge: Global 21-cm signal experiments are very sensitive to continuity and smoothness of the signal

Cohen, Fialkov, Barkana, Monsalve in prep.
To reconstruct a signal from the physical parameters we need to:

- Predict weather this signal is positive (or negative) using decision trees
- Use PCA. Predict its 19 (or 13) parameters for PCA using NN. Out of total of ~30k cases we used ~90% for the training set and ~10% for the test set.

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Accuracy

10'th percentile error 0.72%

mean error 1.59%

95'th percentile error = 3.49

Currently: histogram of the errors for the 1,743 cases in the test set.
The predicted signal is smooth

Cohen, Fialkov, Barkana, Monsalve in prep.
Parameter Estimation

Monsalve et al. in prep. + talk by R. Monsalve
Constraining Cosmological FRBs and using them as Cosmic Beacons

Fialkov & Loeb (2016); Fialkov & Loeb (2017); Fialkov, Loeb, Lorimer (2017)
30 are published (online catalogue)

GBT: 1 FRB
0.7-0.9 GHz

ASKAP: 1 FRB
0.7-1.8 GHz

Parkes: 22 FRBs
1.4 GHz

UTMOST: 5 FRB
0.8 GHz

ARECIBO: 1 FRB
1.4 GHz

Lorimer et al. (2007)
Cosmological Origin (?)

- **FRB121102** (Chatterjee et al. 2017, Nature) is cosmological ($z = 0.19$, $DM \sim 560$ pc cm$^{-3}$)
- Located in small metal poor galaxy 4-7 $10^7$ M$_{\text{sun}}$ (Tendulkar et al. 2017)
  “This set of galaxies account for less than 20% of the star formation of the local Universe”. More abundant at high redshifts.
- **FRB160102** has the highest dispersion measure $DM = 2596.1 \pm 0.3$ pc cm$^{-3}$ detected to date, $z = 2.1$ (Bhandari et al. 2017).

Cosmological Implications

Ionized plasma along the LoS leaves fingerprints on observed radiation
- FRBs are dispersed
- CMB scatter off ionized gas → $\tau$

$$\tau(z) = \left[ DM(z)(1 + z) - \int DM(z')dz' \right] \sigma$$

$$DM = \int_{0}^{z} \frac{n_e}{1 + z} dl$$

Fialkov & Loeb (2016)
Use DM to constrain $\tau$:

If FRBs exist prior to the end of EoR, DM saturates. Precision measure of $\tau$

$DM = \int_0^z \frac{n_e}{1 + z} dl$

$\Delta DM \sim 100 \text{ cm}^{-3} \text{pc} \rightarrow \Delta \frac{\tau}{\tau} \sim 0.3\%$

Much better than CMB $\sim 24\%$

To probe $\tau = 0.055$:
FRBs from $z \sim 6-7$
DM of 6100 pc/cm$^3$

Fialkov & Loeb (2016)
Predicted rates with SKA-MID

Fialkov & Loeb (2017)
Testing the population: FRB Rates from Galaxy Clusters

Is it better to stare at a cluster or do a random FRB search?

The answer depends on the properties of FRBs:

- Luminosity function (Schechter vs Standard Candles)
- Spectrum (Gaussian vs flat)
- Progenitors (young vs old stars)
Proof of Concept: Virgo

Virgo (16.5 Mpc, 1598 galaxies)
A great candidate if the faint population is abundant

Important:
- Luminosity Function:
  - If SC, background wins
  - If Sch, Virgo wins
- Low-luminosity cutoff
- SED: If narrow-band, Virgo wins

Not so important
- Progenitors

Fialkov, Loeb, Lorimer (2017)

Realistic distribution of FRBs from Virgo.
Using Virgo galaxy catalog (Kim et al. 2014)
Best Targets

For 1deg$^2$ beam, 30 mJy survey:
- Close to us (Virgo) – can see all the faint ones
- Rich clusters at ~200-800 Mpc
- Poor clusters at 300-500 Mpc – optimal # of galaxies per beam

Clusters from 2dF Einasto et al. 2007

Best Targets

Fialkov, Loeb, Lorimer (2017)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Cluster name</th>
<th>$N_{gal}$</th>
<th>$D^a$ Mpc</th>
<th>R.A. deg</th>
<th>Dec. deg</th>
<th>Boost</th>
<th>$N^{cl}_{1,deg^2}/\bar{N}_4$</th>
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<tr>
<td>1</td>
<td>Virgo (Kim et al. 2014)</td>
<td>1598</td>
<td>16.5</td>
<td>188.28</td>
<td>13.58</td>
<td>3.69</td>
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<td>2</td>
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<td>3175</td>
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<td>3</td>
<td>N 512 (Einasto et al. 2007)</td>
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<td>4</td>
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<td>1.93</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>235+017+0089 (Liivamagi et al. 2012)</td>
<td>54</td>
<td>398</td>
<td>235.16</td>
<td>18.14</td>
<td>1.71</td>
<td>1.01</td>
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<td>9</td>
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<td>1.60</td>
<td>0.95</td>
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<tr>
<td>11</td>
<td>133+000+0108 (Liivamagi et al. 2012)</td>
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<td>474</td>
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<td>0.75</td>
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<tr>
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<tr>
<td>13</td>
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<tr>
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<td>147+007+0127 (Liivamagi et al. 2012)</td>
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<tr>
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<td>0.84</td>
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<tr>
<td>16</td>
<td>N 170 (Einasto et al. 2007)</td>
<td>415</td>
<td>478</td>
<td>200.94</td>
<td>1.08</td>
<td>1.42</td>
<td>0.84</td>
</tr>
</tbody>
</table>
Summary

21-cm is a great probe of astrophysics
First observational constraints on EoR and Cosmic Dawn
New emulator based on PCA & NN
FRBs might provide a new way to constrain EoR