Probing the Earliest Galaxies With a Lunar Radio Telescope

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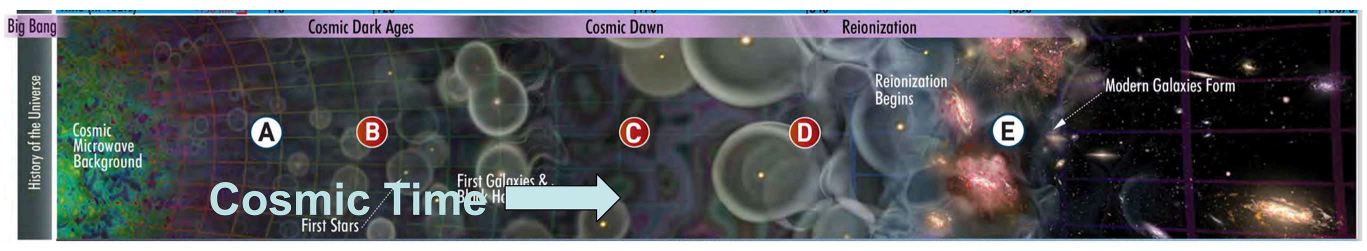
Introduction

The first galaxies to form in the universe are extraordinarily difficult to observe, because of their distance, rarity, small size, and intervening absorption. However, their integrated luminosity has strong effects on the surrounding hydrogen gas, which can be seen through the spin-flip line of neutral hydrogen at low radio frequencies (~100 MHz). The far side of the Moon is an excellent platform for such observations, as it avoids terrestrial interference as well as corruption due to the ionosphere. The great uncertainties on the properties of these objects require flexible, efficient models to guide planning these missions and to interpret future data. Here we present a model and demonstrate some of the signatures a future lunar radio telescope could observe.

The *Dark Ages Radio Explorer* (DARE), a radio telescope in lunar orbit, is a proposed mission that could observe this signal. The NESS team is also exploring concepts for a radio array on the lunar farside.

A Crash Course In: The First Stars

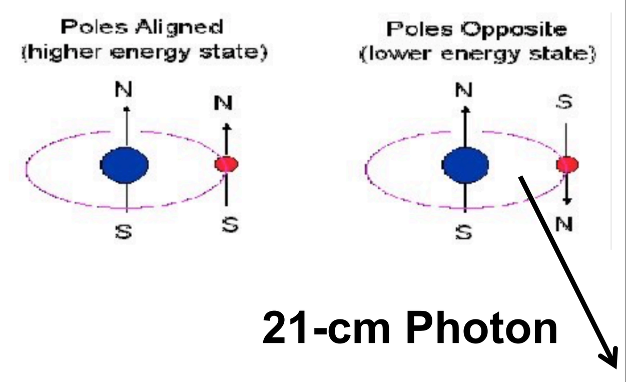
- *When?* The first generations of stars − called Population III or Pop III - have not yet been observed, but they are believed to have formed ~50 million years after the Big Bang.
- *Where?* The first stars formed inside tiny dark matter clumps, about one million times smaller than the Milky Way. Because their clouds are so fragile, the radiation and supernovae from these stars likely dramatically disrupted the gas clouds.
- *How?* These stars formed from differently than nearby stars, through clouds of molecular hydrogen without heavy elements. As a result, they were likely 10-100 times more massive than the Sun.
- *How long?* When these stars died, they produced heavy elements that changed the mode of star formation. Eventually, their sites transformed into normal Pop II star-forming galaxies.
- *What was left?* Because they were so massive, many of these stars may have left remnant black holes, which could then accrete gas from their surroundings and produce X-ray photons.



A Crash Course In: The Spin-Flip Background

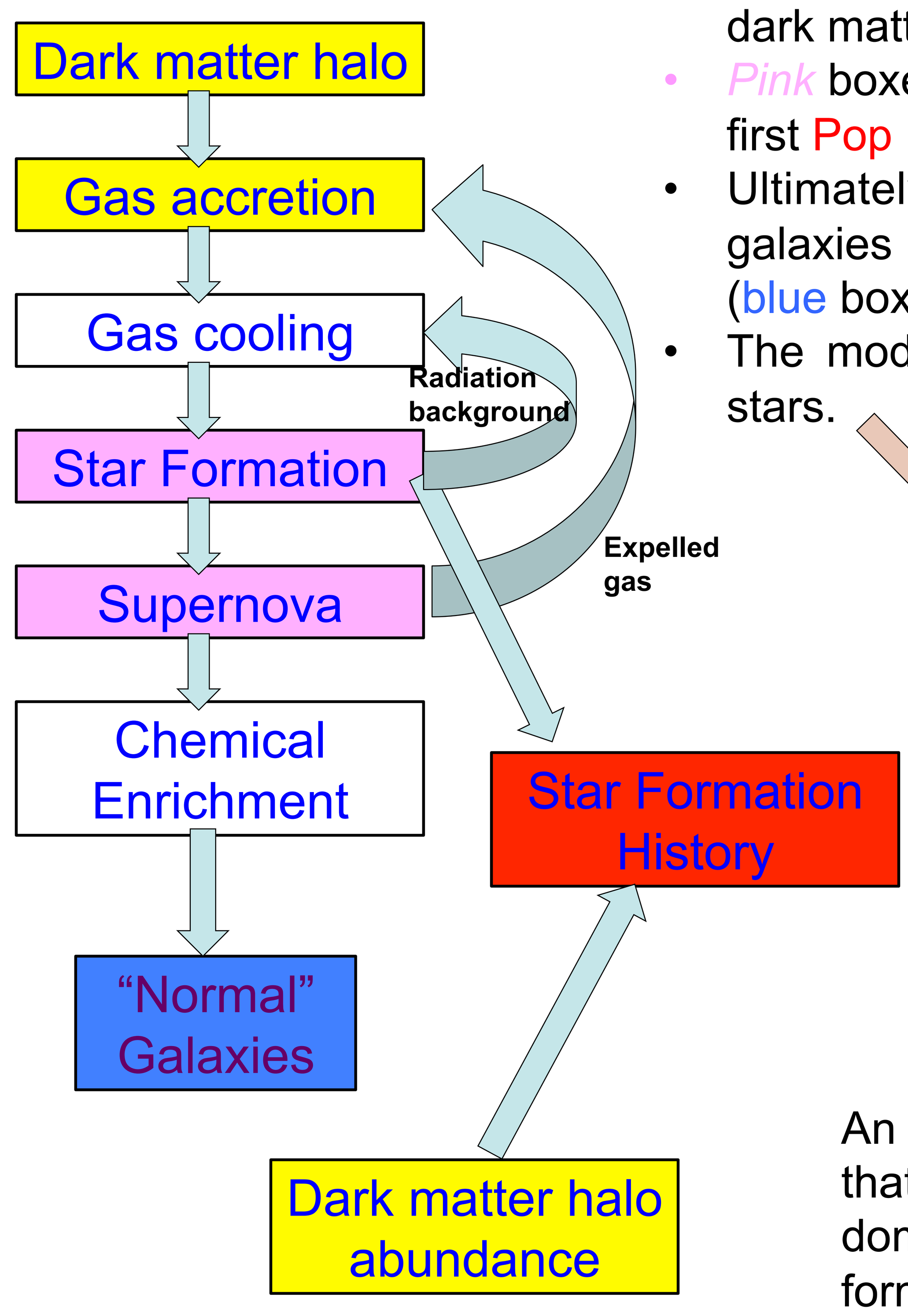
Origin: The spin-flip, or 21-cm, background is generated by the hyperfine transition of neutral hydrogen, which makes up more than 90% of the baryonic matter in the Universe during the epoch of the first stars. When ultraviolet light from the first stars illuminates this hydrogen, the spin-flip signal can be seen in **absorption** against the cosmic microwave background (which pervades the Universe). Once X-rays from the first black holes heat the matter, the signal transforms into **emission**, and it vanishes only when the hydrogen is reionized by later generations of stars.

Observations: The hyperfine transition produces photons with wavelengths of 21 cm, which then redshift as they travel through the expanding universe. Today, they are observable at low radio frequencies (40-200 MHz).

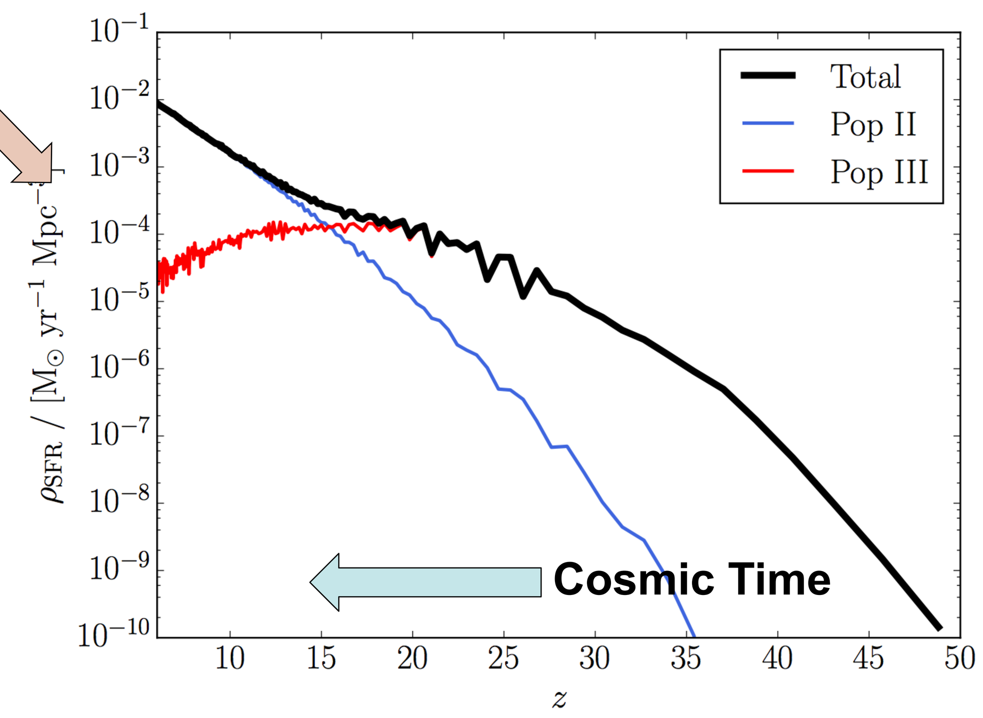


A Model of the First Stars

We have constructed a "semi-analytic" model of the first generations of stars and their transition to normal star-forming galaxies. It implements the key physical processes in a fast, flexible manner so that we can span the huge uncertainties in physical prescriptions for these unobserved objects. The diagram below illustrates some of the physics in this model.

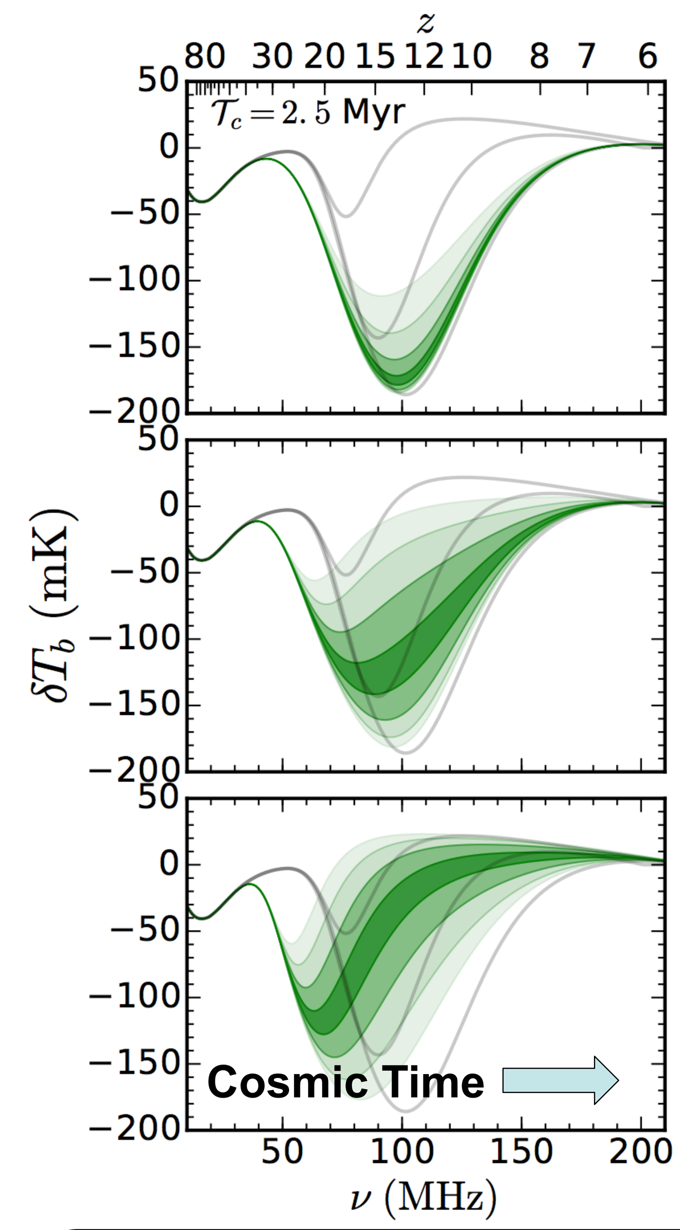


- *Yellow* boxes show our cosmological inputs, describing how dark matter clumps form and grow.
- *Pink* boxes show the key uncertainties in the model: how the first Pop III stars form and affect their environments.
- Ultimately these clumps transition to normal (Pop II) galaxies when supernovae have enriched them sufficiently (blue box).
- The model produces the star formation history for Pop III stars.



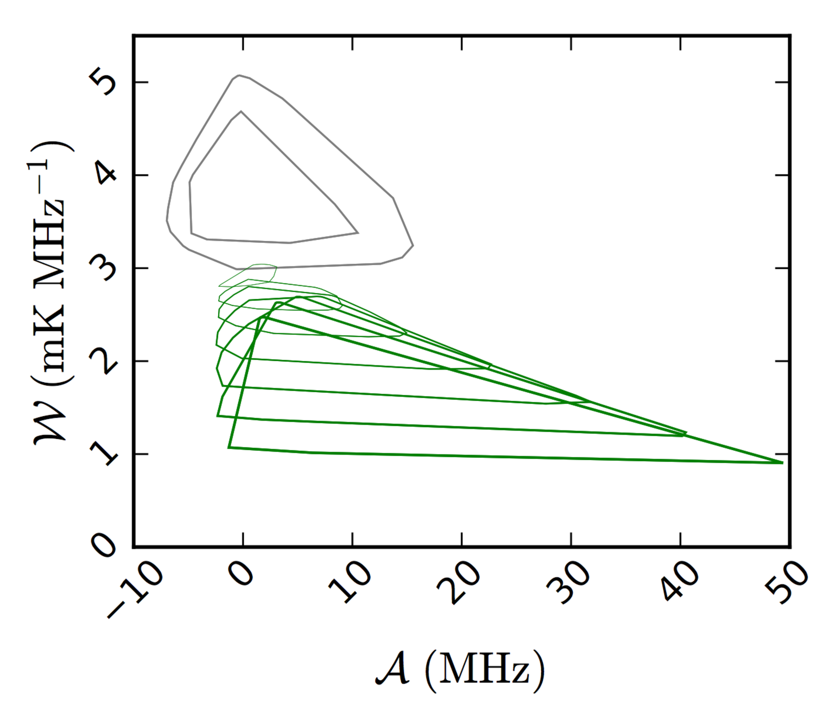
An example star formation history. Generically, we find that Pop III stars "self-regulate" and eventually become dominated by normal Pop II stars. However, Pop III star formation typically persists for long times after the transition.

The First Stars and the Spin-Flip Background



At left, we show examples of the spin-flip background in our models. The gray curves show examples that ignore Pop III star formation entirely. The green curves include them, with a range of star formation efficiencies (top to bottom panels) and X-ray heating efficiencies (green bands). The addition of Pop III stars does not dramatically shift the extrema of the signals but does affect their shapes.

At right, we show these sets of models in a space defined by two custom statistics: *W* characterizes the width of the trough relative to its height, while *A* characterizes its asymmetry. **Even when Pop III stars are rare, shape signatures provide a unique, robust way to distinguish them.**



The Bottom Line: Lunar radio telescopes can probe the otherwise unobservable first stars in the universe by measuring the **shape** of the spin-flip background spectrum.

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This work was partially supported by SSERVI through the Network for Exploration and Space Science, by the University of California Multi-campus Research Initiatives, and by NASA.