Constraining WDM and Pop III stars with the Global 21-cm Signal (PATRAS)

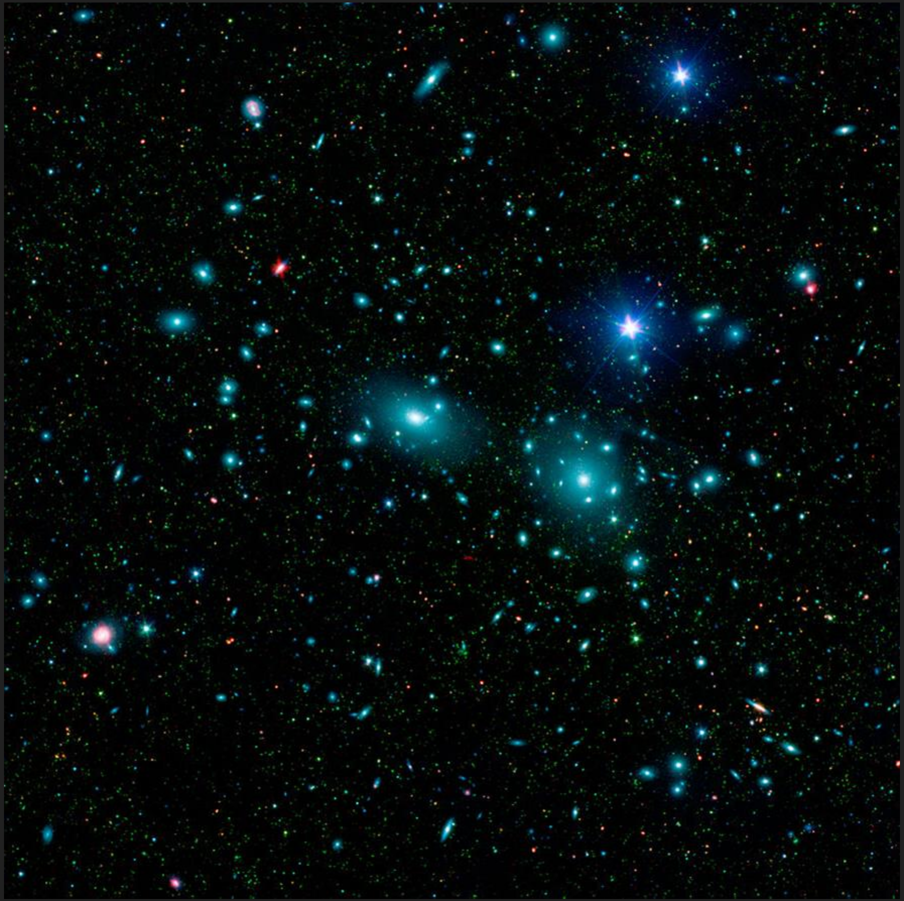
Joshua Hibbard, Jordan Mirocha, David Rapetti, Jack Burns,
Neil Bassett, Keith Tauscher

joshua.hibbard@colorado.edu
jack.burns@colorado.edu

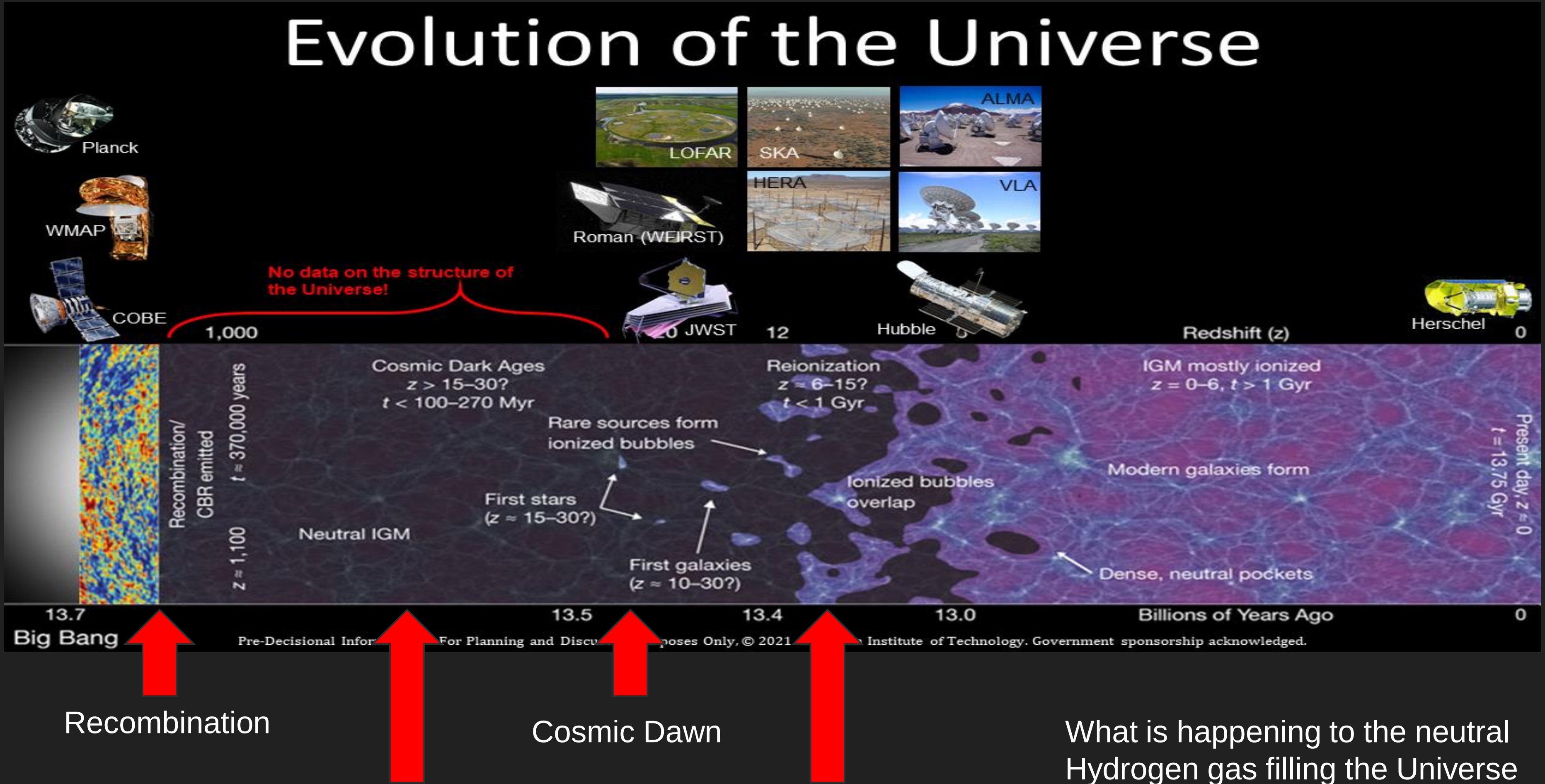
University of Colorado
Boulder

Overview

- A Brief History of the Universe
- The 21-cm Global Signal
    - Theory
    - Observational Challenges
- Warm Dark Matter
    - Overview and Motivations
    - Constraints using 21-cm Cosmology
- 21-cm Cosmology Lunar Telescopes



Coma Cluster, SDSS



Recombination

Cosmic Dark Ages

Cosmic Dawn

Reionization

What is happening to the neutral Hydrogen gas filling the Universe (the IGM) during these Epochs?

Image Credit: JPL

The 21-cm Global Signal: Theory

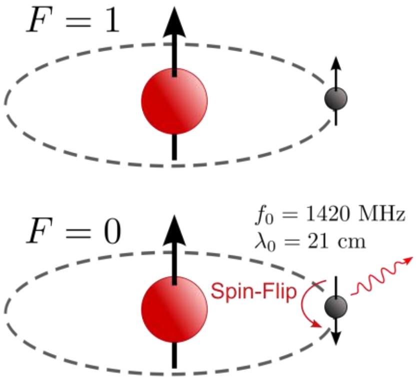
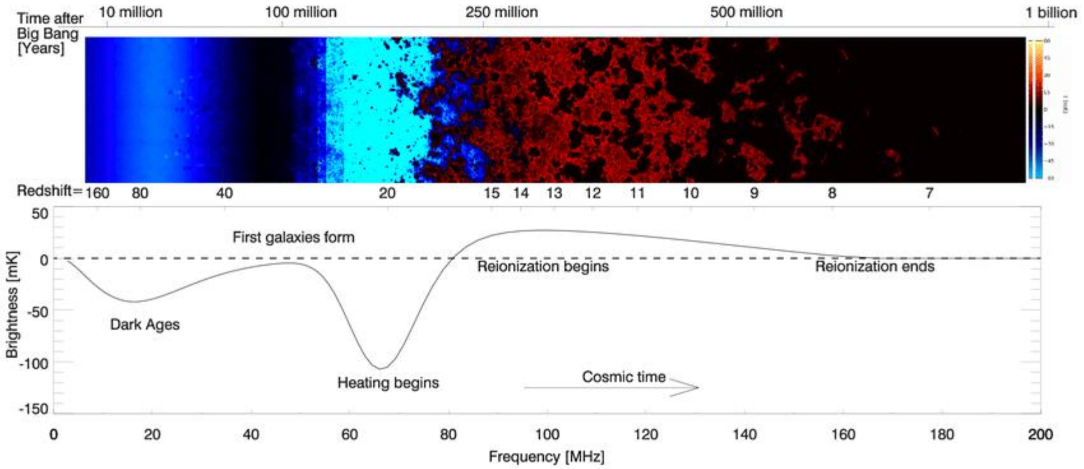


Image credit: Wikipedia

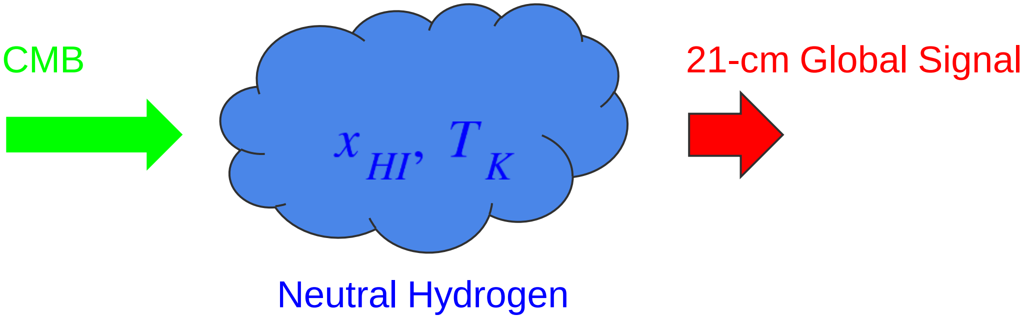


Takalana et al. 2019

The highly redshifted, hyperfine 21-cm, spin-flip emission line of HI allows us to map the thermal evolution of the Universe.

Each frequency corresponds to a slice of cosmic time.

The 21-cm Global Signal: Theory



CMB

x_{HI}, T_K

21-cm Global Signal

Neutral Hydrogen

The 21-cm Global Signal is the differential spin temperature of the IGM measured against the background brightness of the CMB.

$$\delta T_b(\nu)\ \alpha\ x_{HI}\left(1-\frac{T_R}{T_S}\right)$$

It depends upon the (brightness) Temperature of the CMB, and the kinetic Temperature and neutral fraction of the IGM.

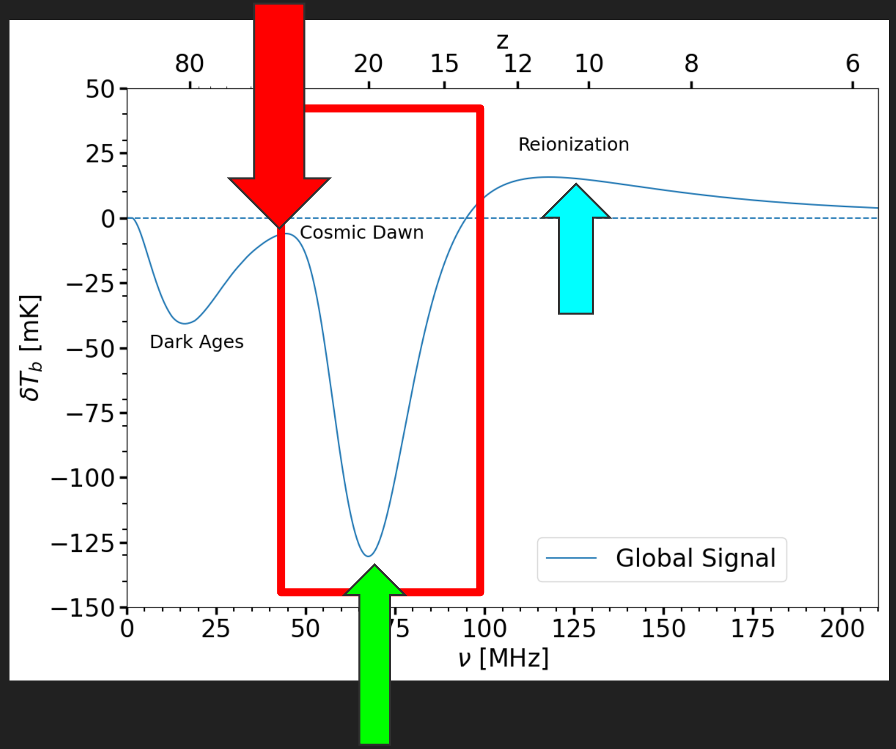
Cosmic Dawn and Reionization

Cosmic Dawn begins when the first luminous objects “turn on,” releasing

- Lyman-alpha photons
- X-ray radiation
- Ionizing radiation

Reionization then extinguishes the signal.

Sources turn on



Heating begins

Challenges to observing the Global Signal

Three primary systematics must be overcome:

1. Bright Foregrounds
2. Beam Chromaticity
3. Environmental effects: RFI, the ionosphere, vegetation, local topology, etc.

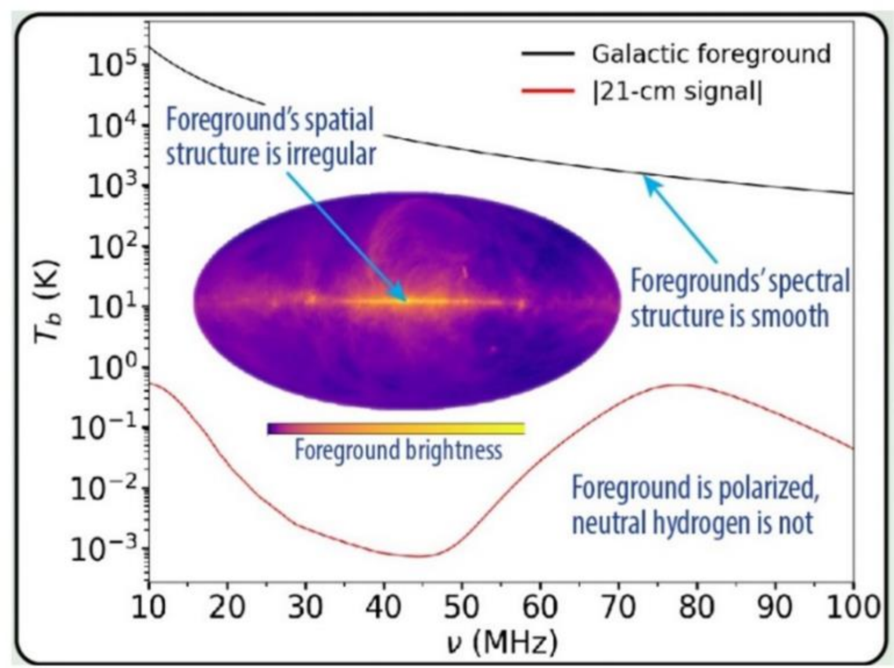
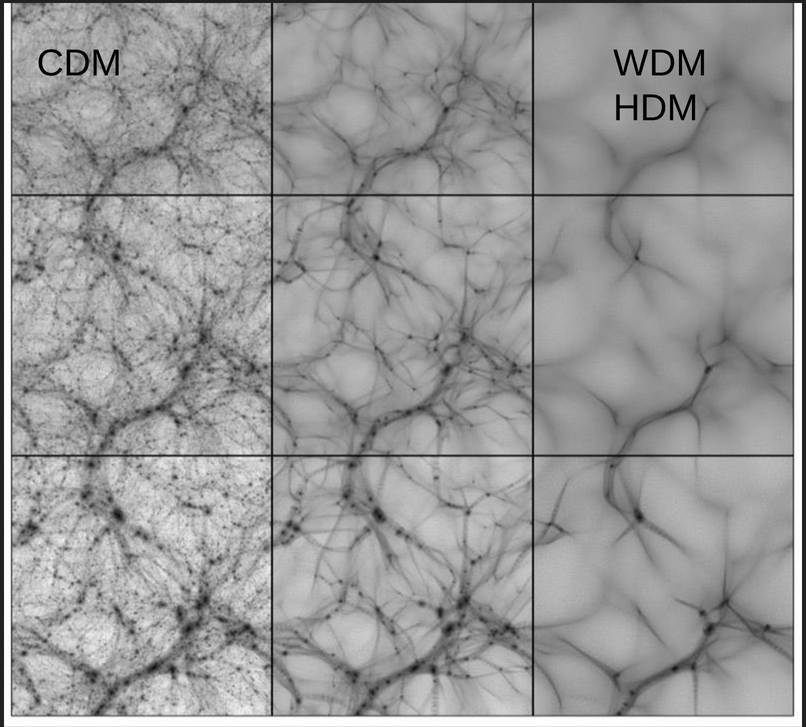


Image credit: Burns et al. 2019

Warm Dark Matter (WDM): Overview

Particles are "warm" (i.e. have a higher relic velocity, or a lower DM mass m_X) so they stream freely out of over-dense regions and cause the low-mass fluctuations to diffuse.

Fewer DM halos means fewer stars.



N-body simulation for various DM masses. From Bode & Ostriker 2018.

Observational Motivations for WDM vs. CDM

The motivations are all related to the apparent lack of small-scale structure predicted by CDM:

- Missing satellites
- Too-big-to fail
- Lack of halo structure between cosmological filaments.
- Could unmodelled baryonic processes explain these?

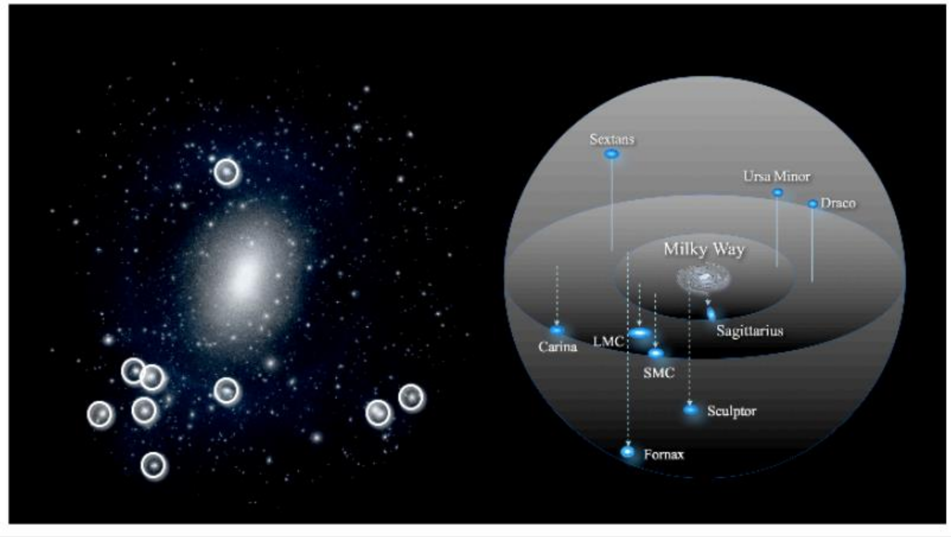
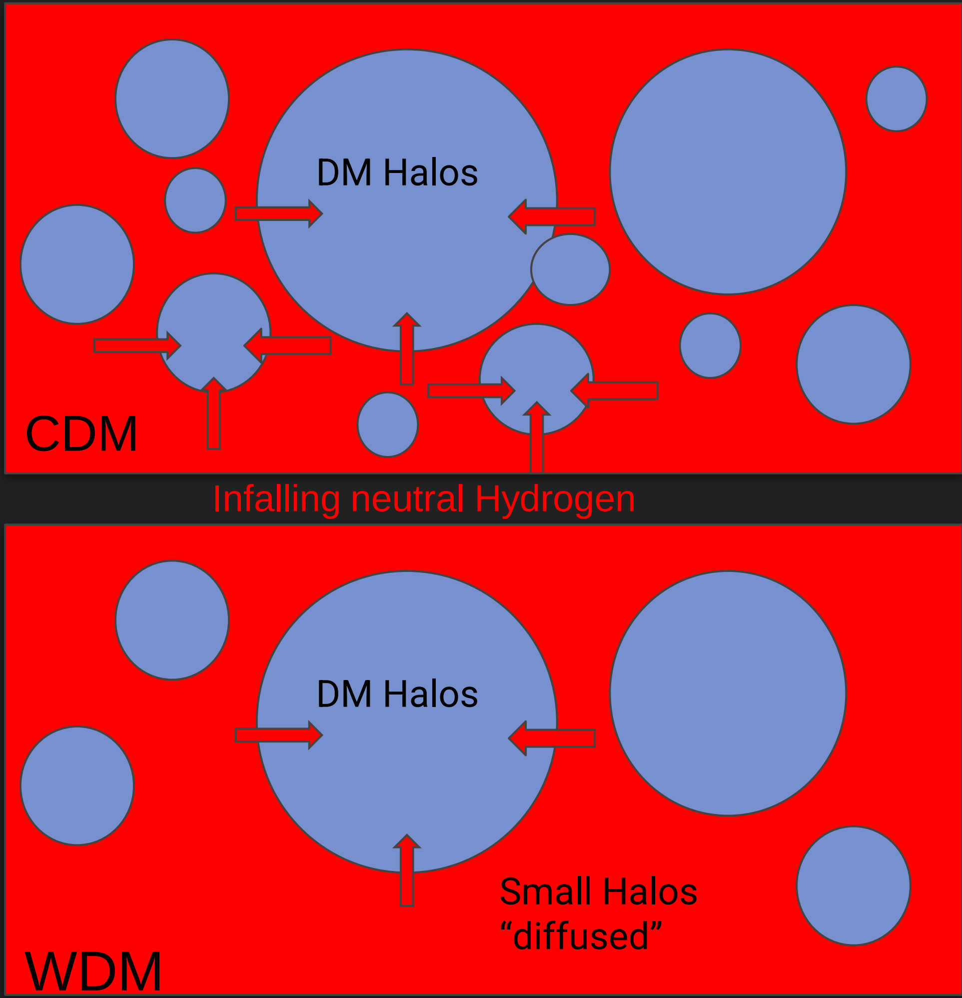


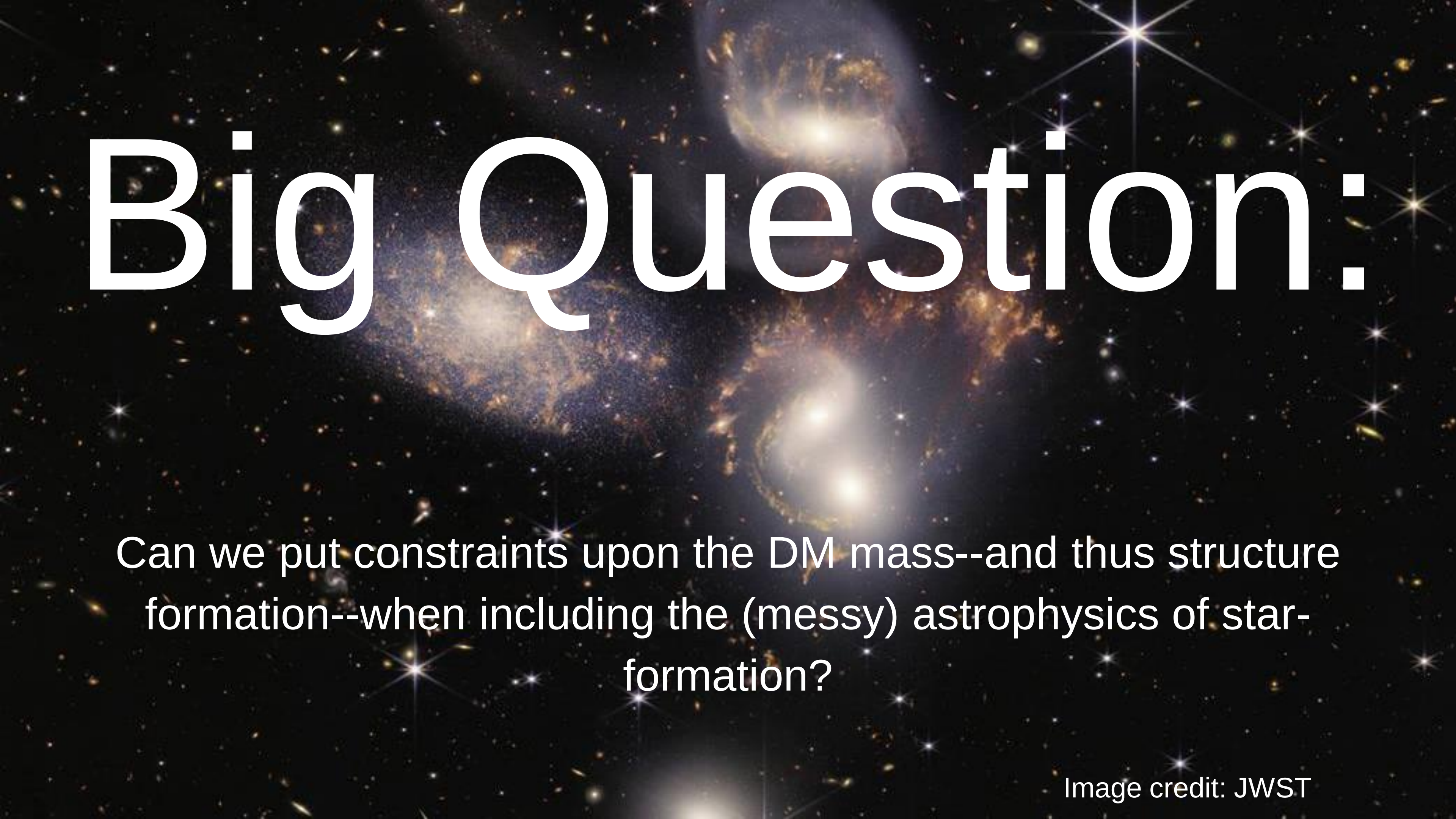
Image Credit: Astrobites

A New Way to Test DM

As WDM is primarily a theory about the abundance and turnover of low-mass halos, its effects will be readily apparent in the high-redshift Universe, before the largest DM halos have formed.

A measurement of the global signal allows us to place constraints on DM in epochs which entertain exquisite sensitivity to small-scale structure.





Big Question:

Can we put constraints upon the DM mass--and thus structure formation--when including the (messy) astrophysics of star-formation?

Image credit: JWST

First Things First: Add WDM to our Simulations!

To incorporate WDM, we must change the Halo Mass Function (HMF), or the number of halos of mass M+dM per co-moving volume.

We modified existing codes (e.g. *ARES*[1]*:* Accelerated Reionization Era Simulations, *HMF*[2]) to enable all these calculations.

1 https://github.com/mirochaj/ares

2 https://github.com/halomod/hmf

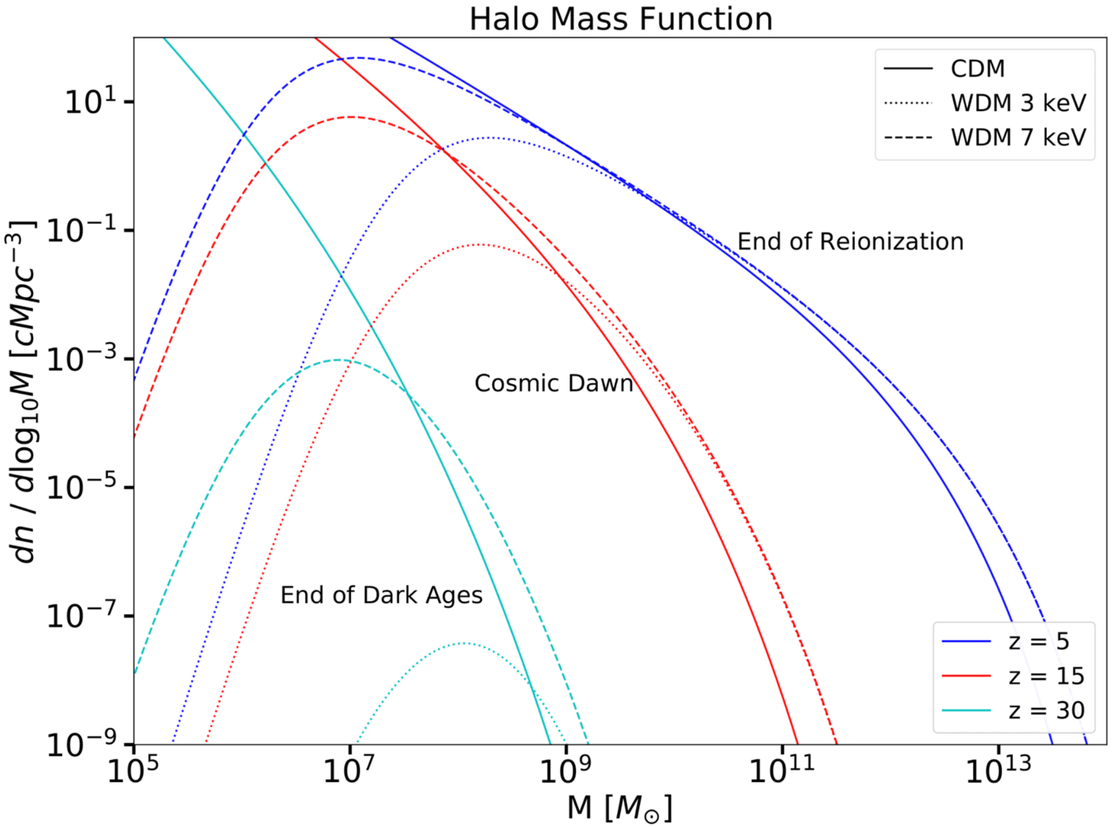


Figure from Hibbard et al. 2022.

Next: Star-Formation Models

We need to know:

Where do stars form, and how many?

We assume all DM halos host star-formation.

How much light do they produce?

Number of photons in each band, and how many of these photons escape the halos.

Two Different Star Formation Parametrizations

A simple model...

Collapse Fraction Model

Star-Formation is

→ proportional to the total amount of matter in DM halos, with

→ 4 parameters to describe photon production, and star-formation efficiency (SFE) is a constant.

...and a (more) realistic one:

Double-Power Law (DPL) Model

Star Formation is

→ different for Low-mass versus High-mass halos.

→ 6 parameters to describe SFE and photon production.

Including additional astrophysics:

Pop III Stars

Form in low-mass halos, in metal-poor environments, and release lots of photons!

Could be potentially degenerate with WDM and change the signal.

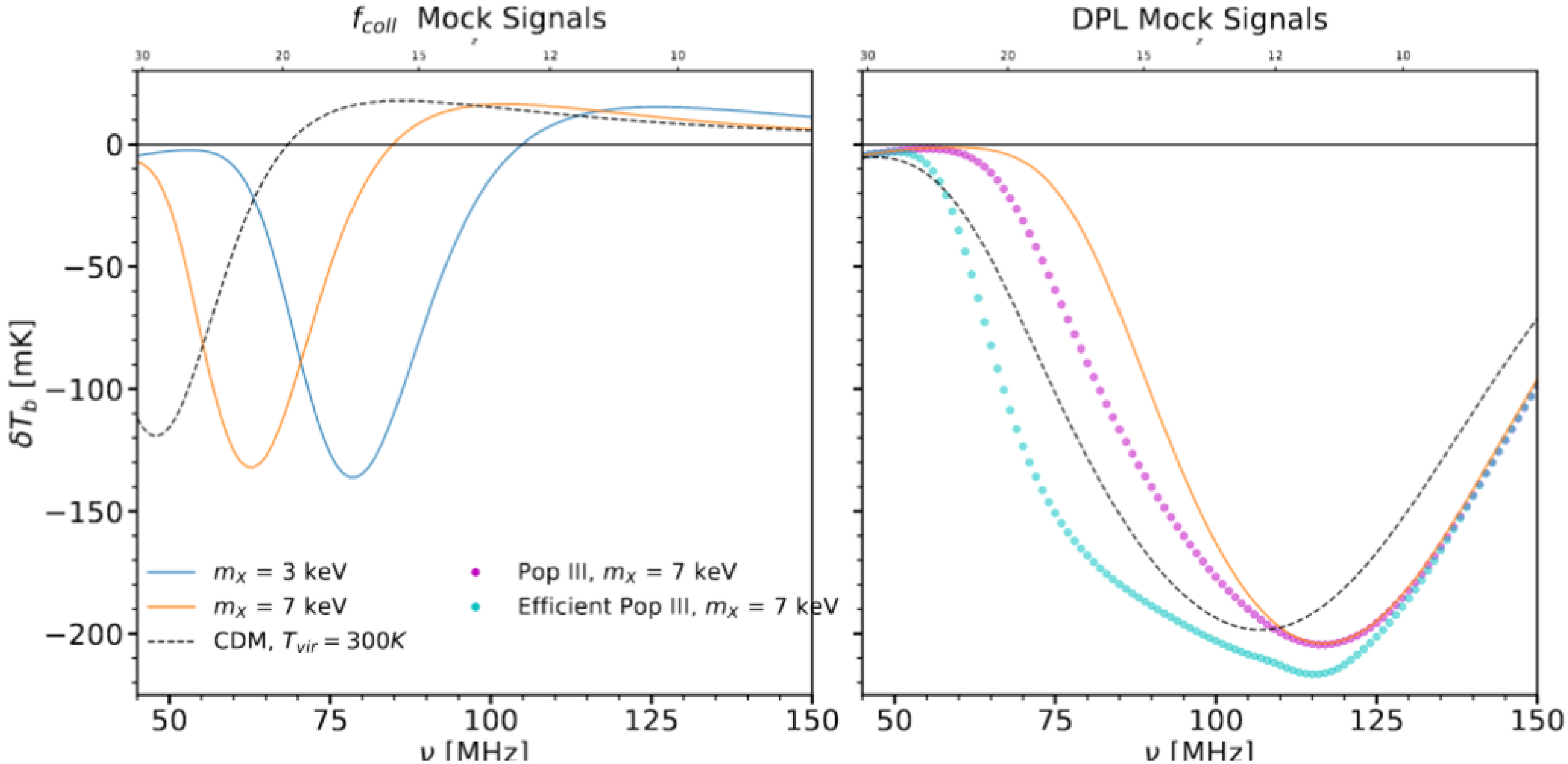
Also, we'll include...

DPL Extended Model

A phenomenological model that allows us to include the possibility of unmodelled physics at high-redshift.

$$f_\star \to f_\star \left[1 + \left(\frac{M}{a} \right)^b \right]^c$$

Here a, b, and c are nuisance parameters.

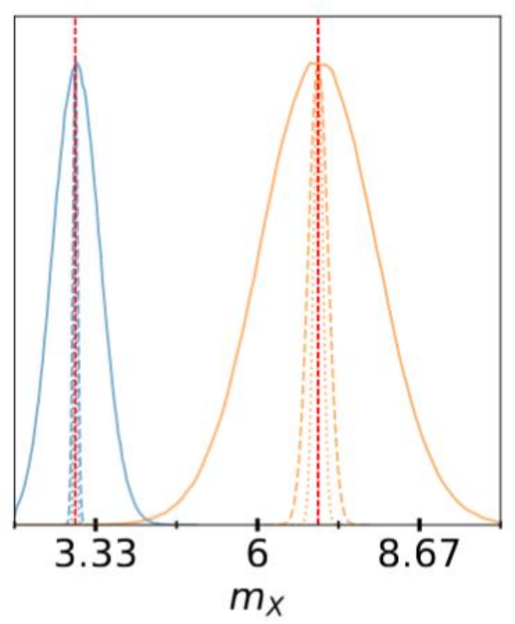


4 star-formation parameters + 1 WDM parameter

6 star-formation parameters + 1 WDM parameter

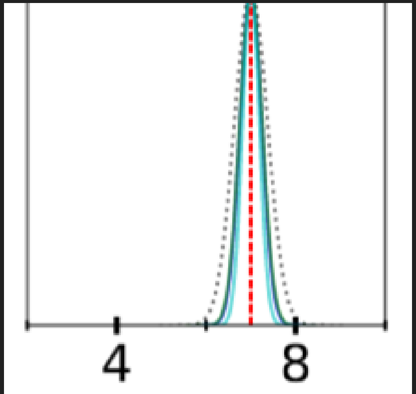
WDM Constraints Summary (95% confidence level)

Collapse Fraction Models

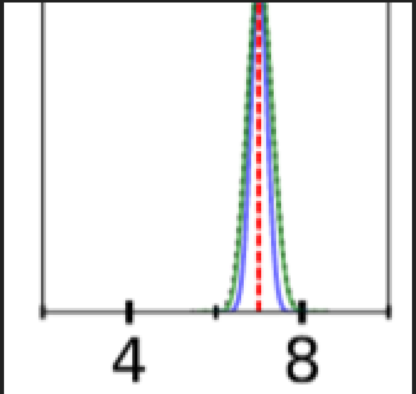


For fiducial thermal mass 7 keV:

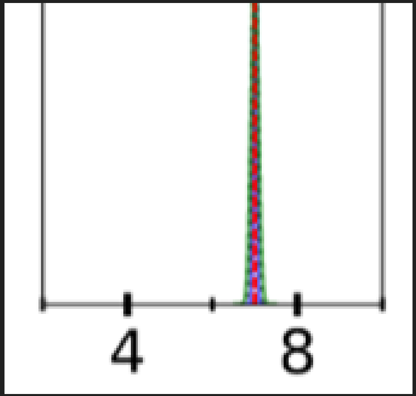
DPL Models



Pop II mock signal:



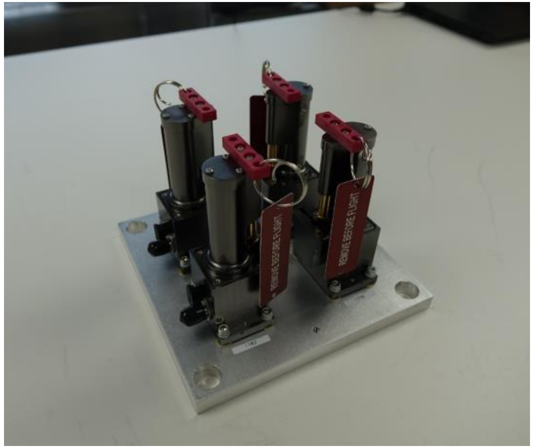
Pop III mock signal:



Efficient Pop III mock signal:

Figures from Hibbard et al. 2022.

IM-1 with ROLSES antennas deployed



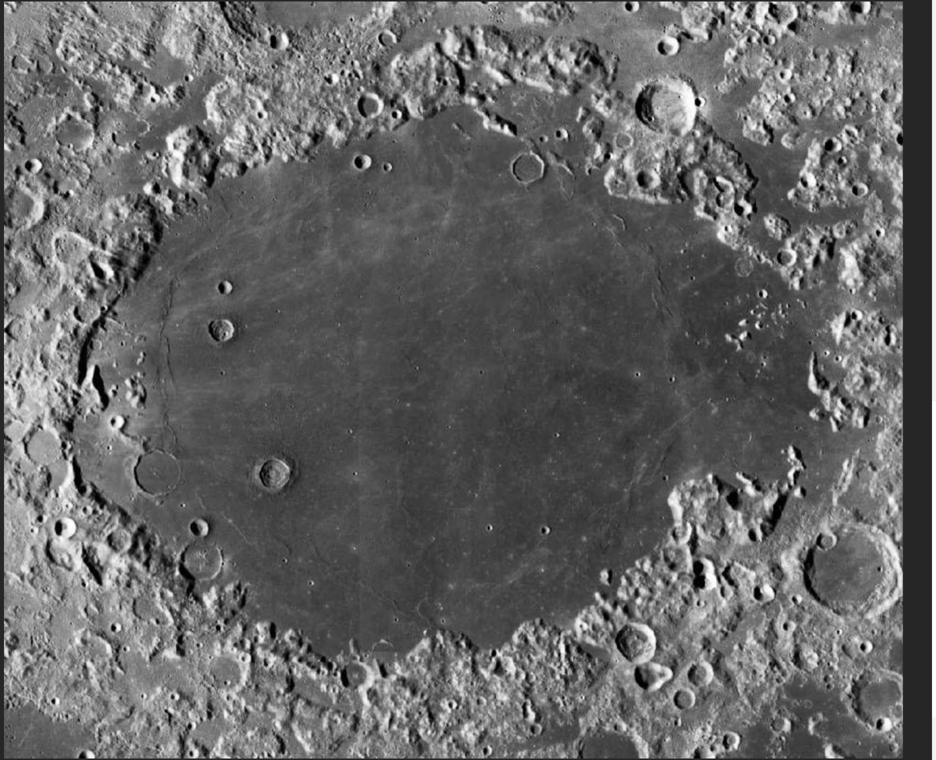
Stowed STACER antennas

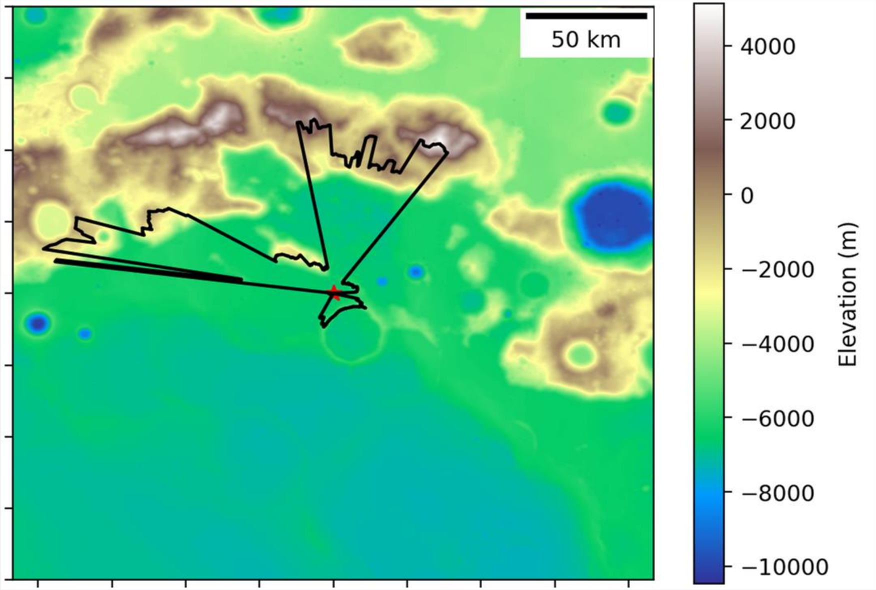
ROLSES spectrometer board

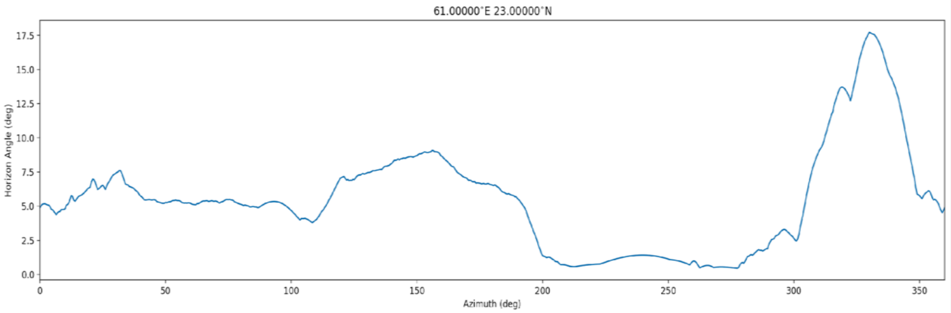
Radio wave Observations at the Lunar Surface of the photo-Electron Sheath (ROLSES)

- ROLSES Instrument Team: Robert MacDowall (PI), William Farrell, Jack Burns, Damon Bradley, Nat Gopalswamy, Michael Reiner, Ed Wollack, David McGlone, Mike Choi, Scott Murphy, Rich Katz, Igor Kleyner.
- ROLSES instrument is a new build with heritage from STEREO/SWAVES & SMAP:
  - Four 2.5-m monopoles forming cross-dipole antennas.
  - Radio spectrometer with 2 bands: 10 kHz – 1 MHz and 300 kHz – 30 MHz.
- Scheduled to land on lunar nearside using *Intuitive Machines (IM-1) Nova-C.*

Landing Site for IM-1: Mare Crisium







Horizon code developed from SSERVI funding: Bassett *et al.* 2021, ApJ,

ROLSES Science Goals

- Determine the photoelectron sheath density from ~1 to ~3 m above the lunar surface by measuring electron plasma frequency.
- Demonstrate detection of solar, planetary, & other radio emission from lunar surface.
- Measure Galactic spectrum at <30 MHz.
- Aid development of lunar radio arrays.
- Measure the local EM environment, including that from the lander.
- Measure reflection of incoming radio emission from lunar surface and below.

The Lunar Surface Electromagnetics Experiment (LuSEE)

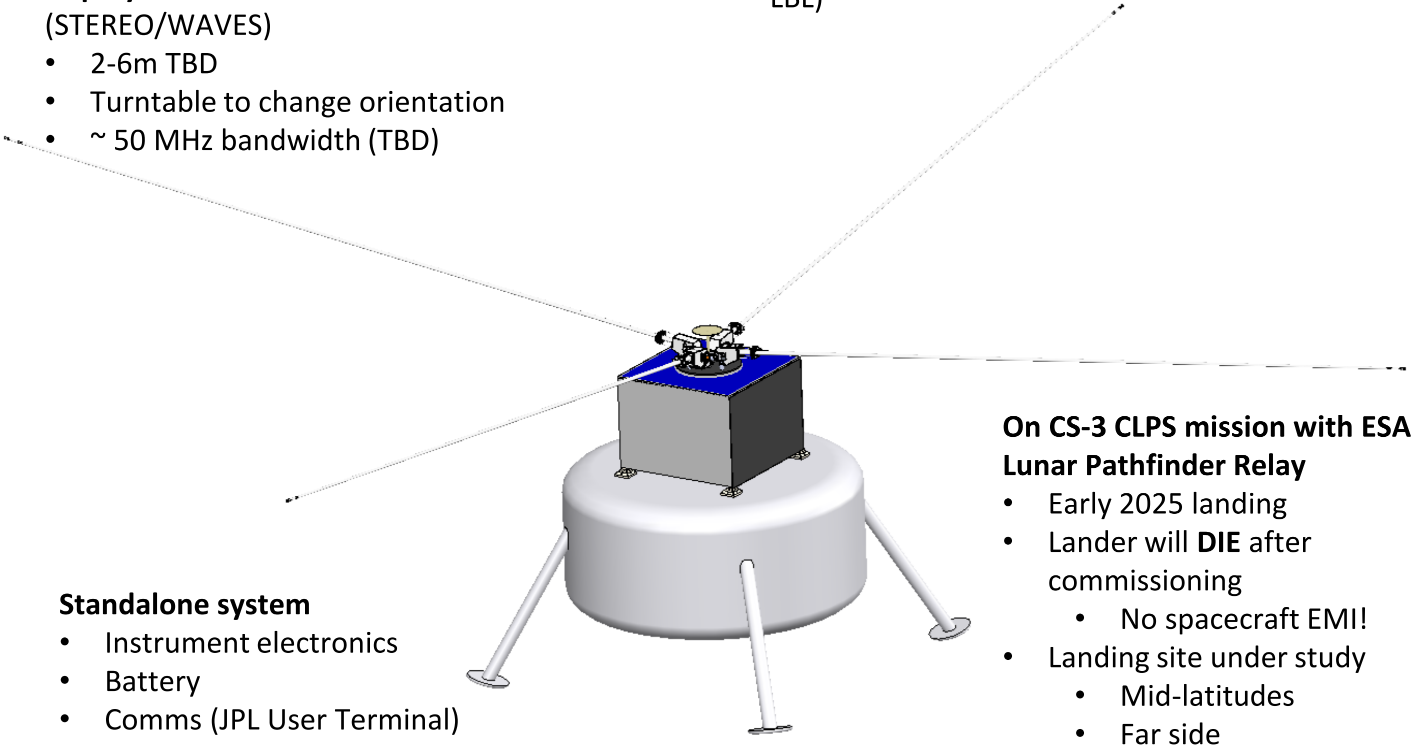
Stuart D. Bale (PI), Keith Goetz, Peter Harvey, John Bonnell, Jack Burns, Thierry Dudok de Wit, Bob MacDowall, David Malaspina, Marc Pulupa, Anze Slosar, Aritoki Suzuki + a big LuSEE science team

Overview

- LuSEE was **selected** in June 2019 by NASA in the Lunar Surface Instrument and Technology Payloads (**LSITP**) for the Commercial Lunar Payload Services (**CLPS**) program.
- Under contract by MSFC/PMPO and **in development.**
- Recent development: LuSEE program has been **split into 2 payloads:**
  - **LuSEE 'Lite'** to the Schrödinger Basin (south pole farside) in late 2024 on the CP-12 mission.
    - Surface plasma physics and waves, DC electrostatic potentials, dust impacts, and coordination with LITMS (magnetotellurics).
  - **LuSEE 'Nite'** to the farside mid-latitudes in early 2025 on the CS-3 mission in a major collaboration with the US Department of Energy (**DOE**).
    - Low frequency radio astronomy (~1-50+ MHz) with **standalone** operations through the lunar night.

LuSEE 'Nite' Design

Major involvement from US **DOE** (BNL and LBL)



Deployable stacer antennas (STEREO/WAVES)

- 2-6m TBD
- Turntable to change orientation
- ~ 50 MHz bandwidth (TBD)

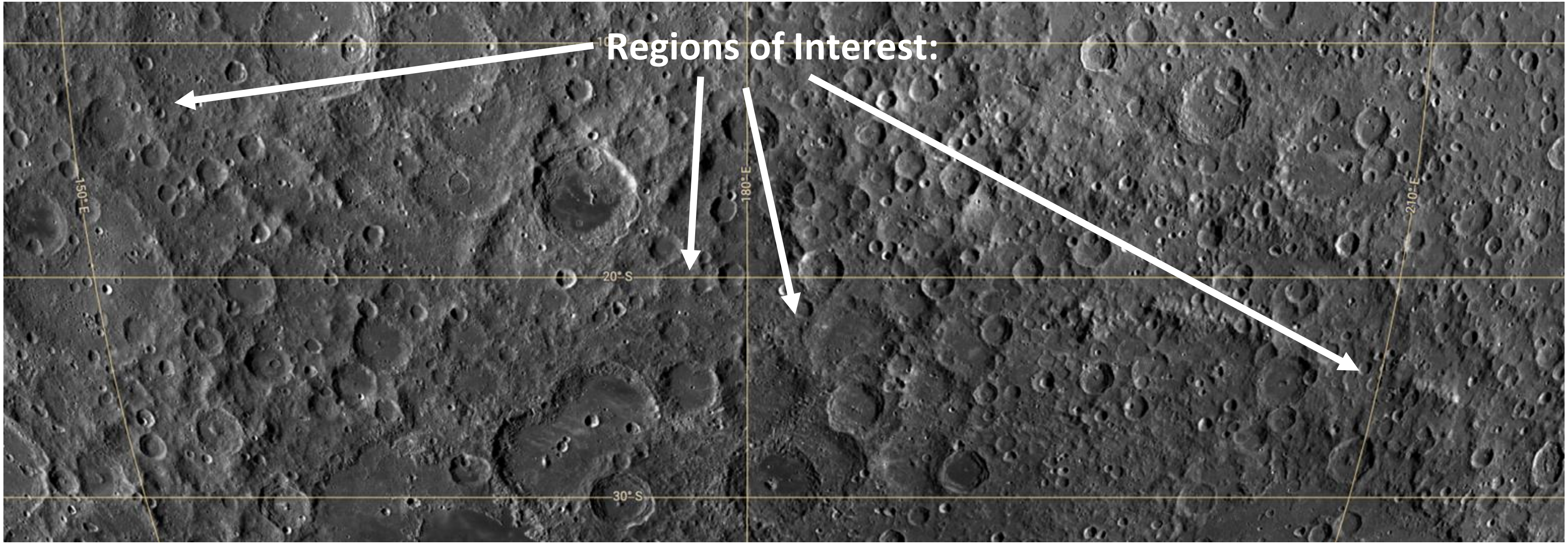
Standalone system

- Instrument electronics
- Battery
- Comms (JPL User Terminal)
- PRISM FSS-like thermal design

On CS-3 CLPS mission with ESA Lunar Pathfinder Relay

- Early 2025 landing
- Lander will **DIE** after commissioning
  - No spacecraft EMI!
- Landing site under study
  - Mid-latitudes
  - Far side
  - Slightly south?

LuSEE-Nite Landing Site: ~10°S- 30°S latitude, 150 °E to 210°E longitude



LROC Wide Angle Camera (WAC) basemap

- Low slopes (<10 degrees)
- Low likelihood of hazards (e.g. craters and boulders >~1-2 meters in scale)
- Low surface roughness
- Avoid locations within craters
- Maximize amount of visible sky
- Not considering a landing site on the floor of a large crater

Summary and Conclusions

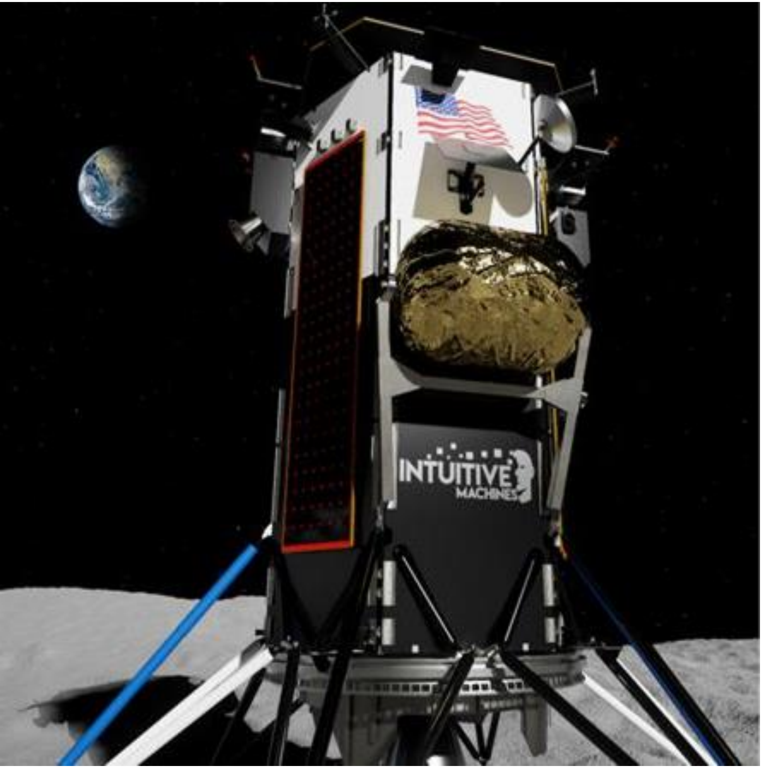
- DM has an effect upon the thermal evolution of the high-redshift Universe.
- A measurement of the global signal would thus allow us to characterize DM in epochs never before tested where its effects should be quite apparent.
- We can constrain the WDM thermal mass to reasonable limits, even including multiple source populations and star formation parametrizations.
- The stronger the effects of Pop III stars, the better the constraints on the WDM thermal mass.
- Two radio telescopes are going to the Moon within the next five years as part of the NASA CLPS program to make the first lunar observations of the 21-cm signal and characterize the lunar systematics.

EXTRA SLIDES

FARSIDE: Farside Array for Radio Science Investigations of the Dark ages and Exoplanets

Principal Investigator: Jack Burns, University of Colorado Boulder
Deputy P.I.: Gregg Hallinan, Caltech
Design Lead: Lawrence Teitelbaum, JPL

Image courtesy of Blue Origin,



The Path Forward

- NASA’s CLPS program is a high risk/high reward program that could be a game-changer with regular access to the lunar surface 2-3 times per year.
- The first NASA radio science payload, ROLSES, is planned to land on the near side later this year. It will measure the photo-electron sheath near the surface, the Galaxy spectrum at <30 MHz, and the EM interaction with the dielectric lunar subsurface.
- LuSEE is planned for a landing on the far side in 2025. Batteries will allow operation during the lunar night for the first time. Observations from 1-100 MHz, corresponding to the early Universe’s Dark Ages and Cosmic Dawn, are planned.
- These CLPS radio science missions will prepare the way for a future array of low frequency radio antennas on the lunar surface.

NASA Commercial Payload Services (CLPS)

- "NASA's Commercial Lunar Payload Services (CLPS) initiative allows rapid acquisition of lunar delivery services from commercial companies for payloads that advance capabilities for science, exploration or commercial development of the Moon…under the Artemis approach"
- **Delivery Timeline**
  - *Astrobotic* will carry 11 payloads to Lacus Mortis, a larger crater on the near side of the Moon.
  - *Intuitive Machines* will carry six payloads, including our ROLSES radio science experiment, to Mare Crisium on the lunar near side with landing expected by end of the year.

DPL UV-Luminosity Functions

We can use the observations of high-redshift (z ~ 6), Pop II UVLFs to help constrain the SFE of the DPL model.

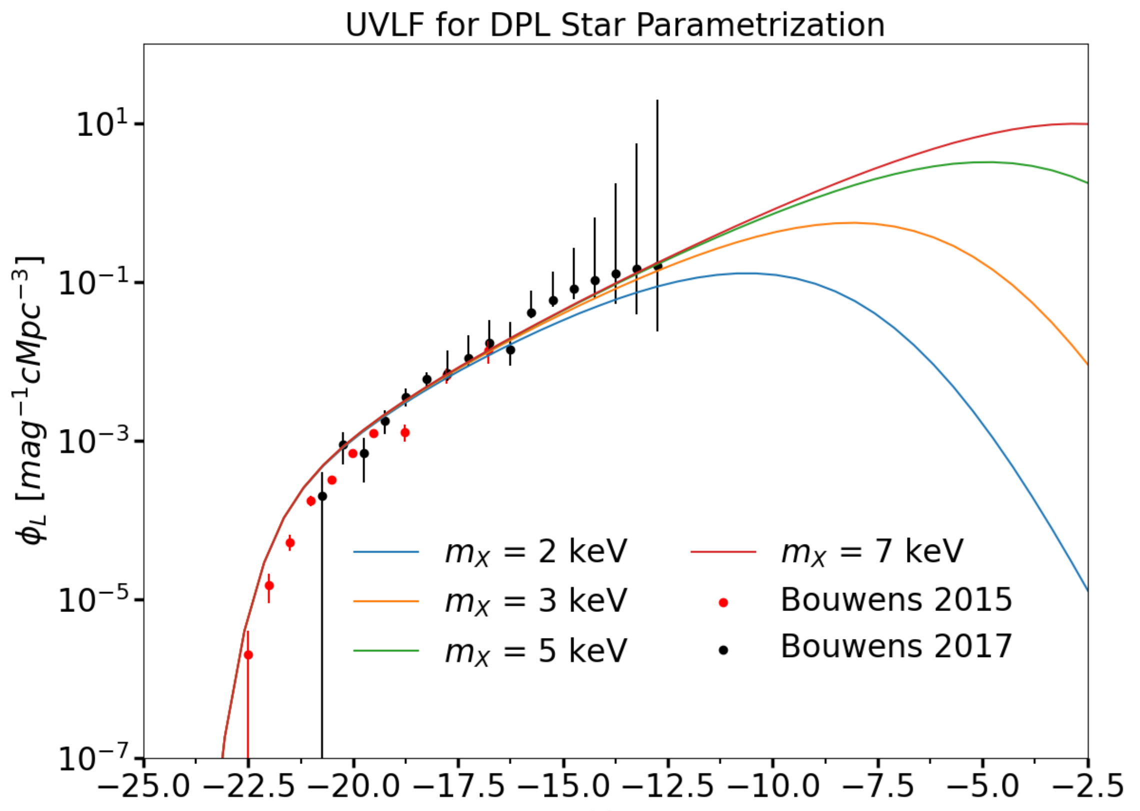


Figure from Hibbard et al. 2022

The Spin Temperature T_S

Quantifies the number of states in the triplet versus singlet state.

$$\frac{n_1}{n_0} = 3\,exp\left(-\frac{E_{10}}{k_B T_S}\right)$$

Depends upon things like collisions and the background radiation field.