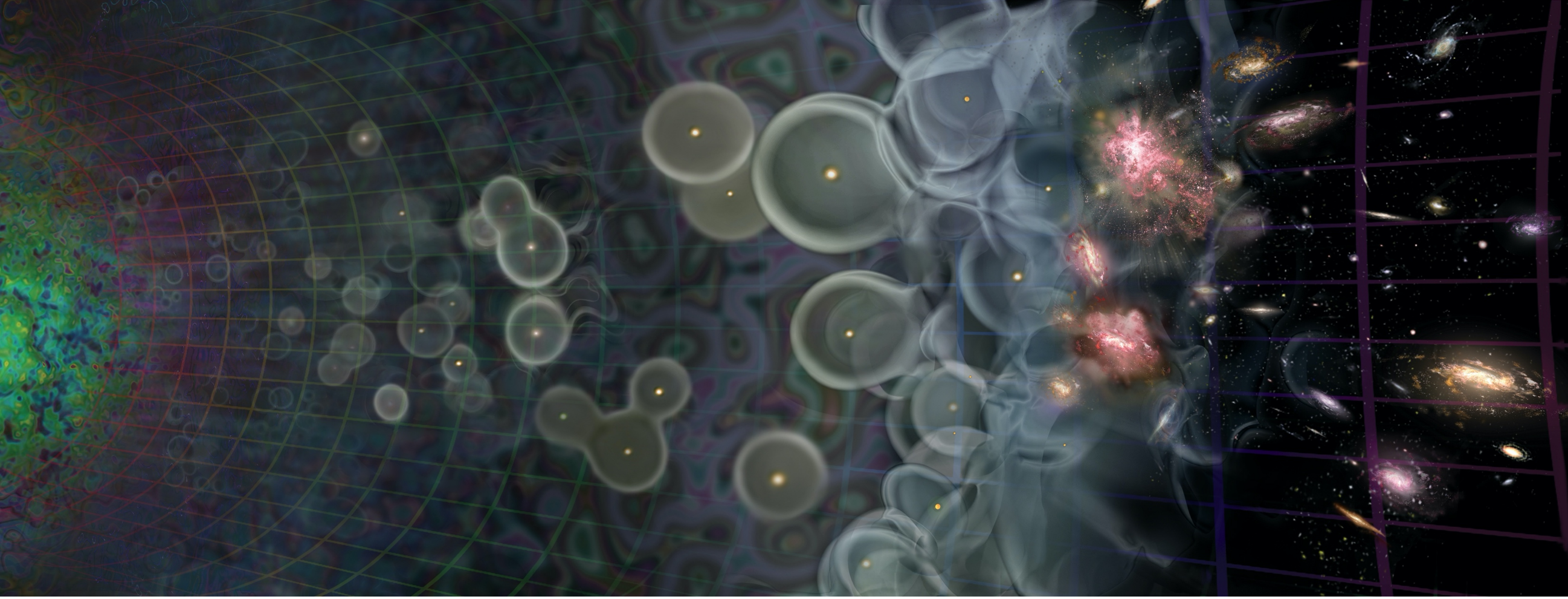

Extending the Cosmic Frontier into the Dark Ages

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Jacqueline N. Hewitt
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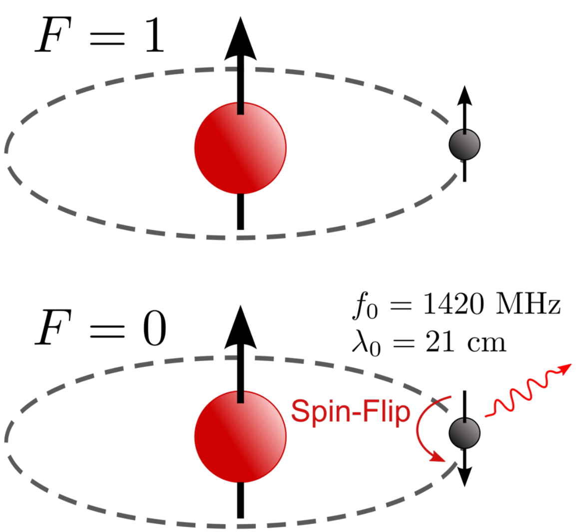
James Aguirre (University of Pennsylvania), Joshua S. Dillon (University of California, Berkeley), Steven Furlanetto (University of California, Los Angeles), Charles Lawrence (Jet Propulsion Laboratory, California Institute of Technology), Miguel F. Morales (University of Washington), Jonathan Pober (Brown University), Graça Rocha (Jet Propulsion Laboratory, California Institute of Technology), Andrew Romero-Wolf (Jet Propulsion Laboratory, California Institute of Technology), Anastasia Fialkov (University of Cambridge), Léon V. E. Koopmans (Kapteyn Astronomical Institute, University of Groningen), Cathryn Trott (International Centre for Radio Astronomy Research; Curtin University)

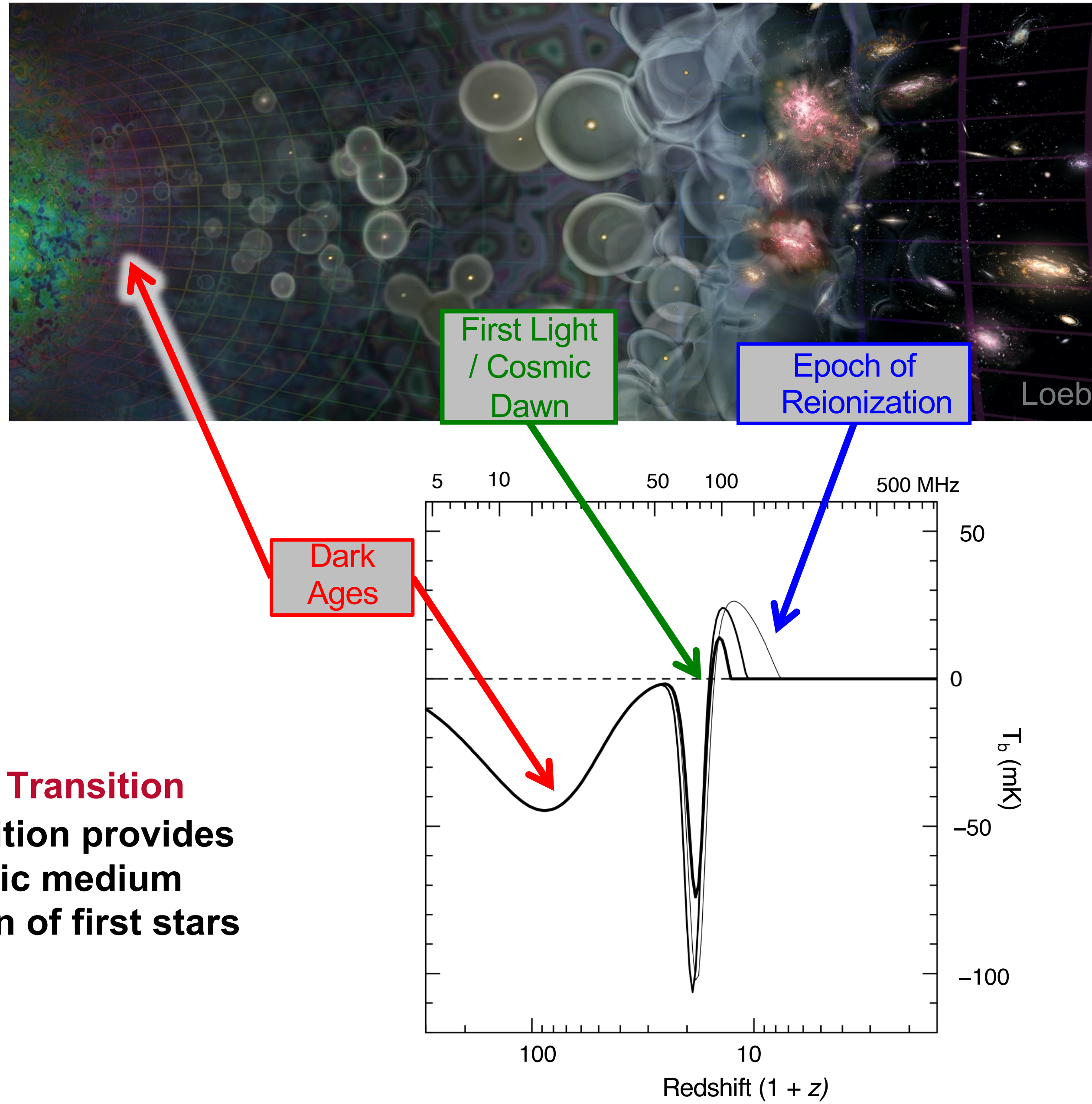
Jet Propulsion Laboratory
California Institute of Technology

Extending the Cosmic Frontier into the Dark Ages

- **How?**
- **Scientific Promise**
  - **Ultimate in cosmic variance-limited measurements**
  - **Physics beyond the Standard Model**
- **Technical Challenge**

Neutral Hydrogen





Neutral Hydrogen Hyperfine Transition

Hyperfine ("spin-flip") transition provides probe of neutral intergalactic medium before and during formation of first stars

ν = 1420.405752 MHz

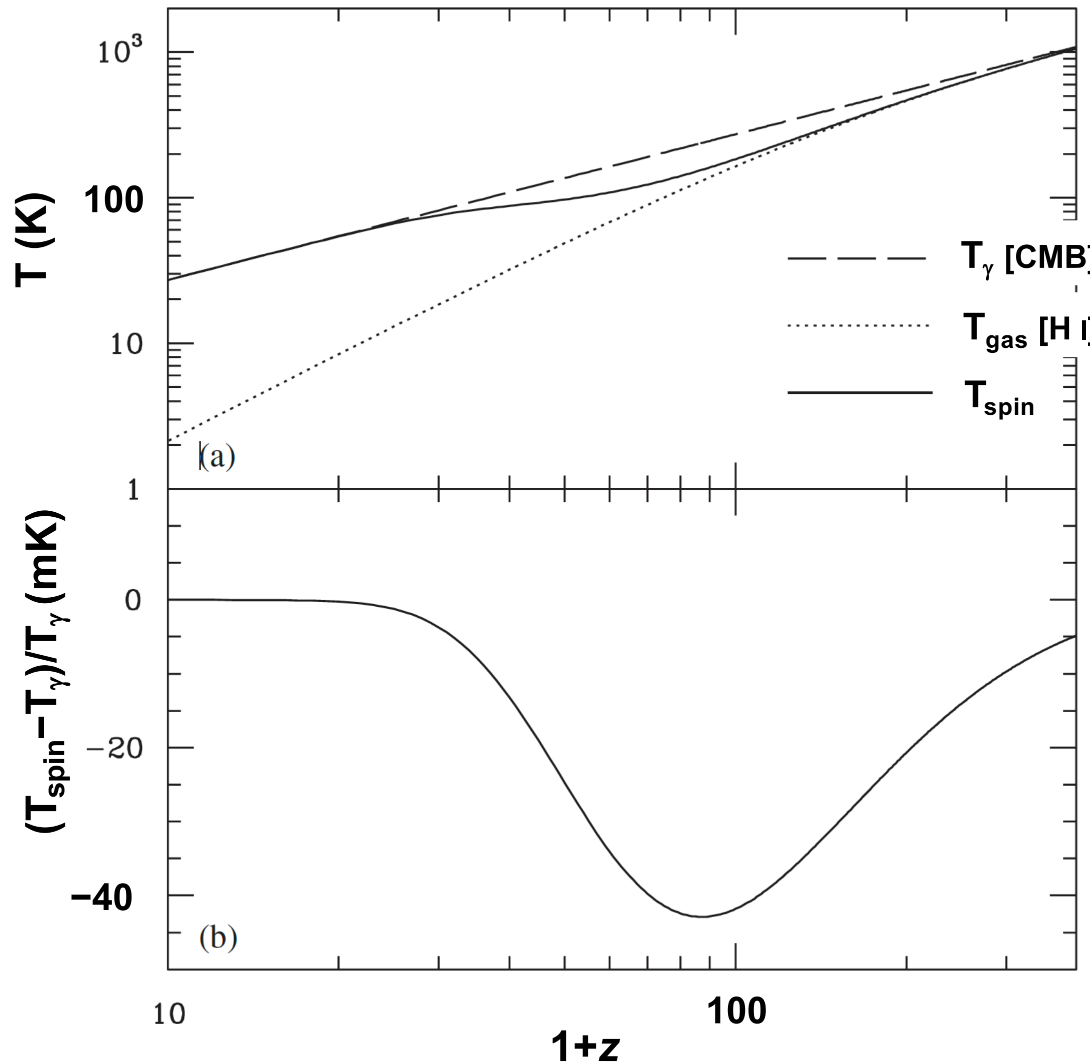
λ = 21 cm

Intergalactic Medium Temperature in the Dark Ages

During Dark Ages, Universe is simple

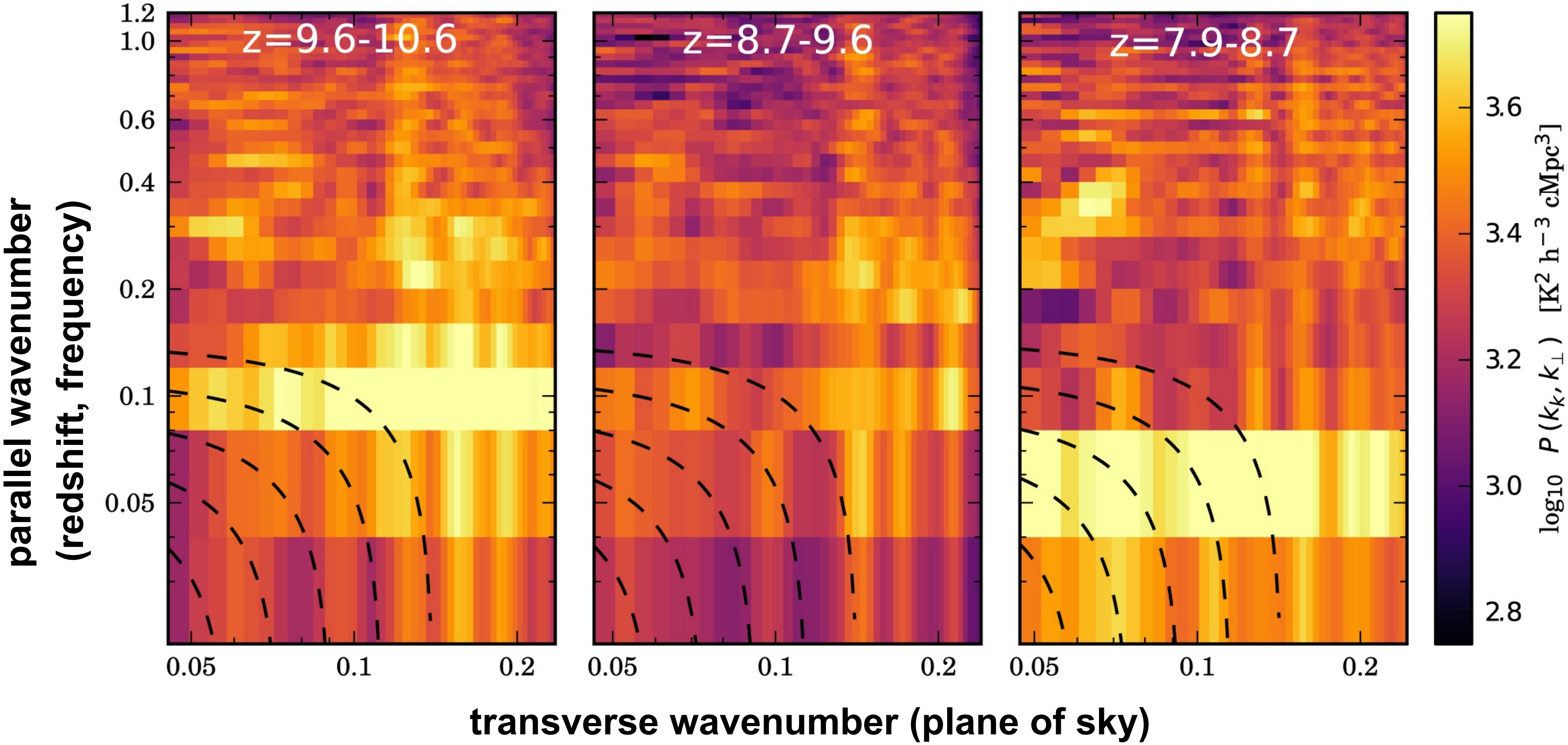
- **Photons**
- **Neutral hydrogen (H I) (+ Helium + …)**
- **Dark matter**
- **Cosmic neutrino background**

➢ **If we understand Cosmology + Standard Model, predicted evolution both accurate and (highly) precise**



Furlanetto, Peng, & Briggs; Pritchard & Loeb

2-D Power Spectra



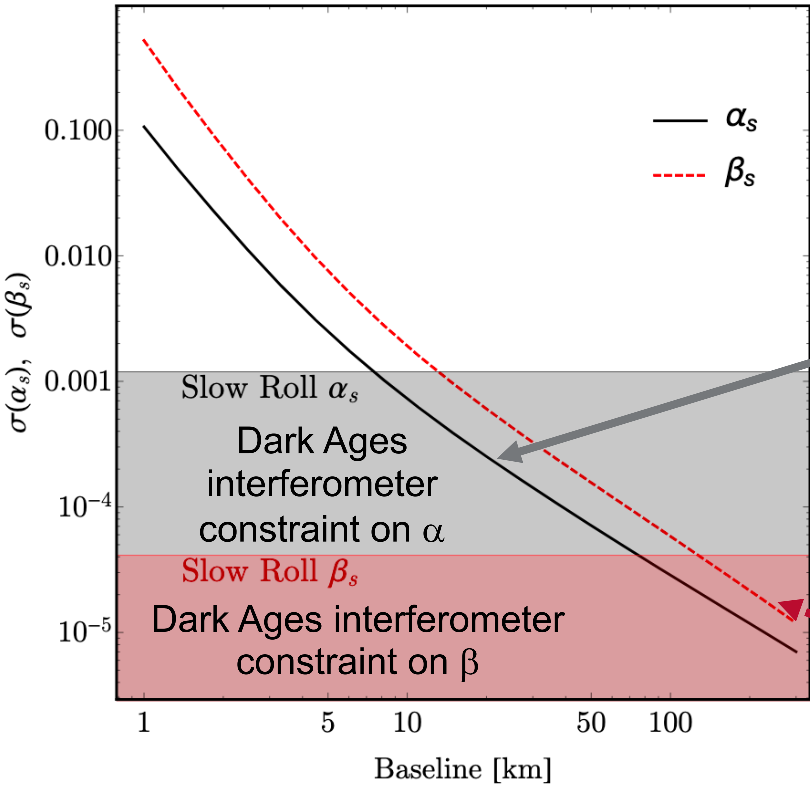
Patil et al.

Extending the Cosmic Frontier into the Dark Ages

- How?
- Scientific Promise
  - Ultimate in cosmic variance-limited measurements
  - Physics beyond the Standard Model
- Technical Challenge

Constraints on Inflation Models

Ultimate in Cosmic Variance-Limited Measurements



α – first running of scalar tilt (α = d*n*/d log *k*)

Single-field slow-roll inflation prediction

β – second running of scalar tilt (β = dα/d log *k*)

Single-field slow-roll inflation prediction

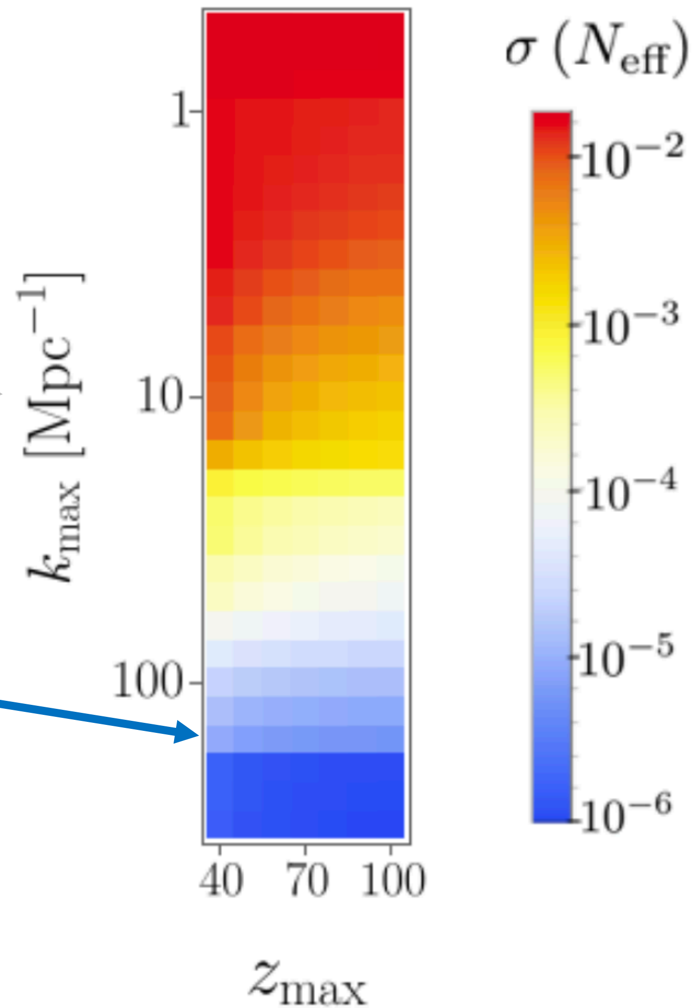
Muñoz et al.

Neutrino Species

Ultimate in Cosmic Variance-Limited Measurements

Dark Ages H I observations + CMB-S4

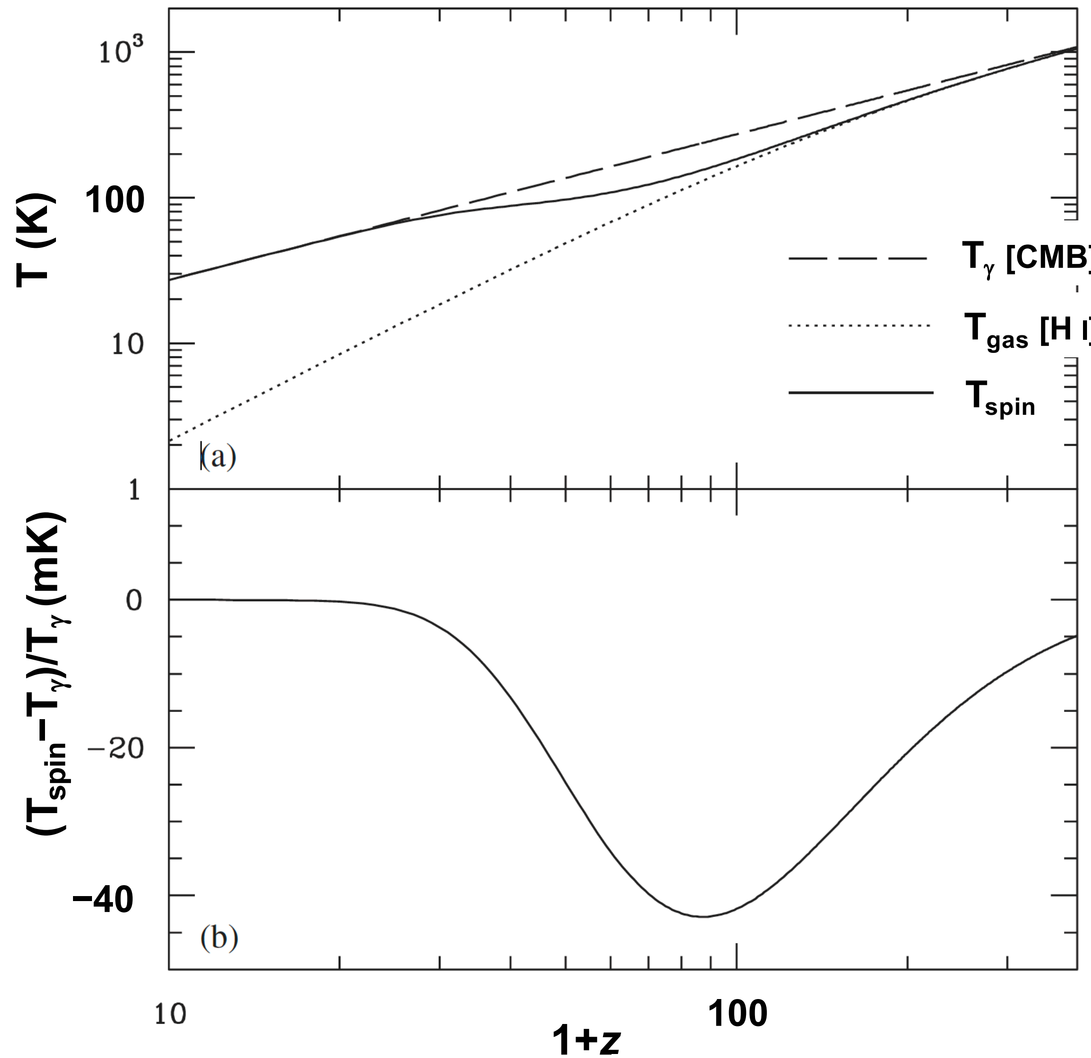
- **Access wide range of wavenumbers!**
- **For tomographic survey of H I at $z > 40$, then $\sigma(N_{eff}) <\sim 10^{-5}$**



Diacoumis & Wong

Intergalactic Medium Temperature in the Dark Ages

- If we understand Cosmology + Standard Model, predicted evolution both accurate and (highly) precise
  - decays of particles (Doroshkevich & Naselsky; Chen & Kamionkowski; Myers & Nusser)
  - effects of primordial magnetic fields (Schleicher et al.)
  - shocks due to H I-dark matter relative motions (O'Leary & McQuinn)
  - accretion onto primordial black holes (Bernal et al.)
  - spatial inhomogeneities in the CMB (Ansar et al.)
  - Dark energy (Linder)?



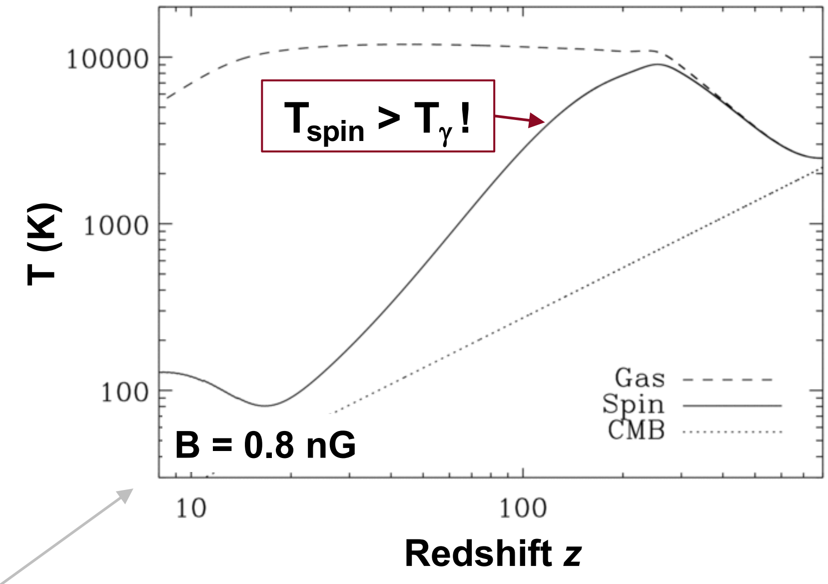
Furlanetto, Peng, & Briggs; Pritchard & Loeb

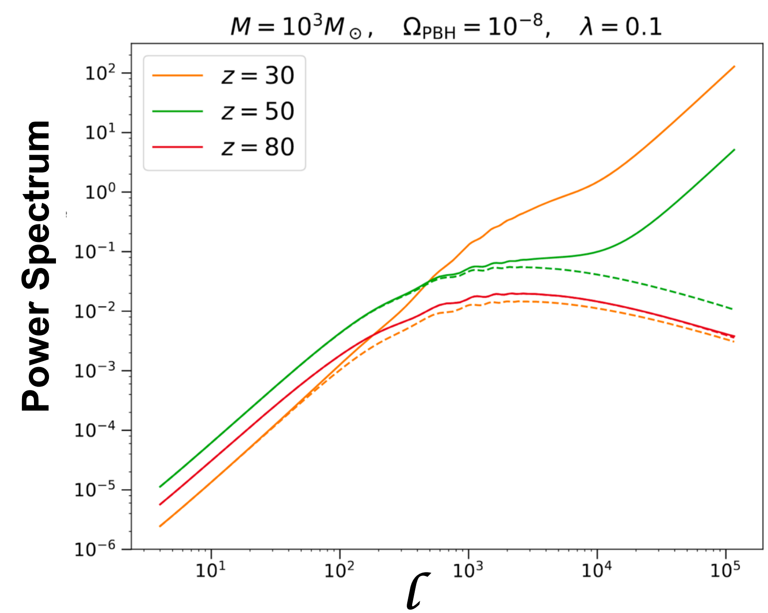
Beyond the Standard Model

- ***Any*** **energy injection into intergalactic medium (H I) changes temperature**
- **Causes deviations in spin temperature**
  - **Global signal**

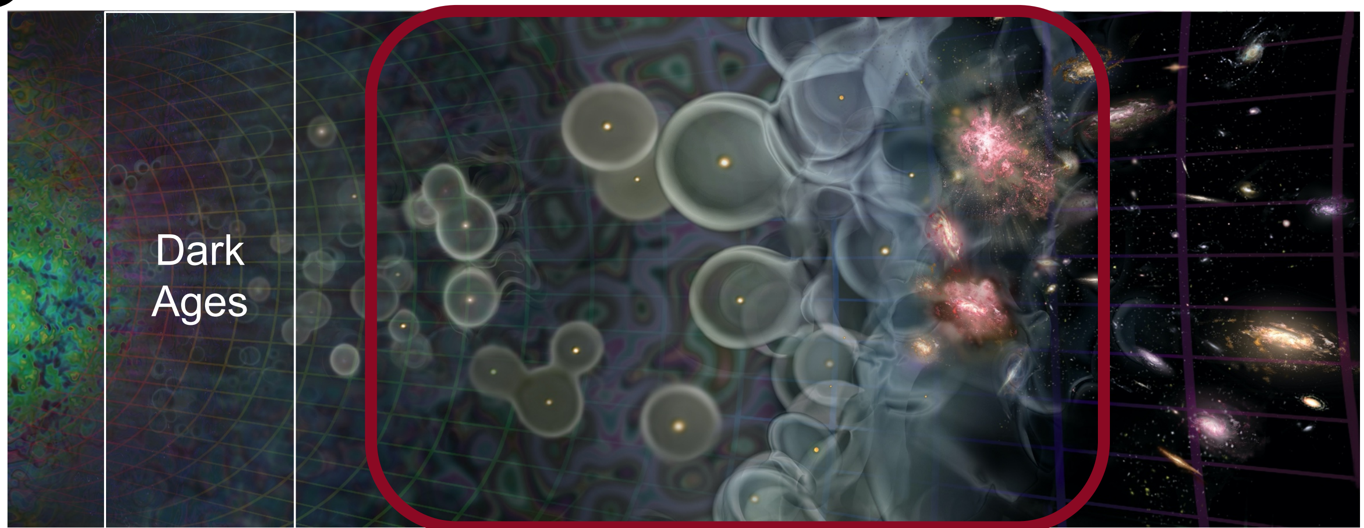
    e.g., Schleicher et al. show B = 0.8 nG field causes H I signal to be in emission relative to CMB
  - **Power spectrum**

    e.g., Bernal, Raccanelli, Verdea, & Silk show primordial BHs modify power spectrum at $\ell > 10^3$

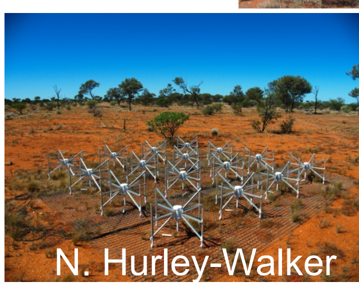


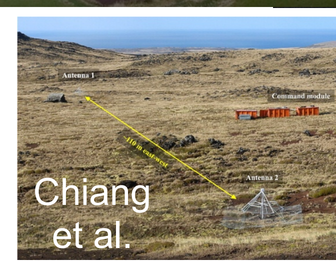


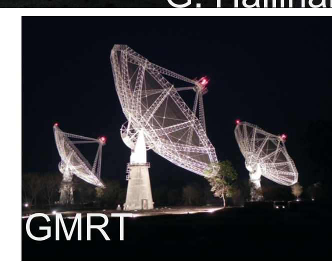
H I @ $z > 6$



Redshift range being probed with current ground-based telescopes

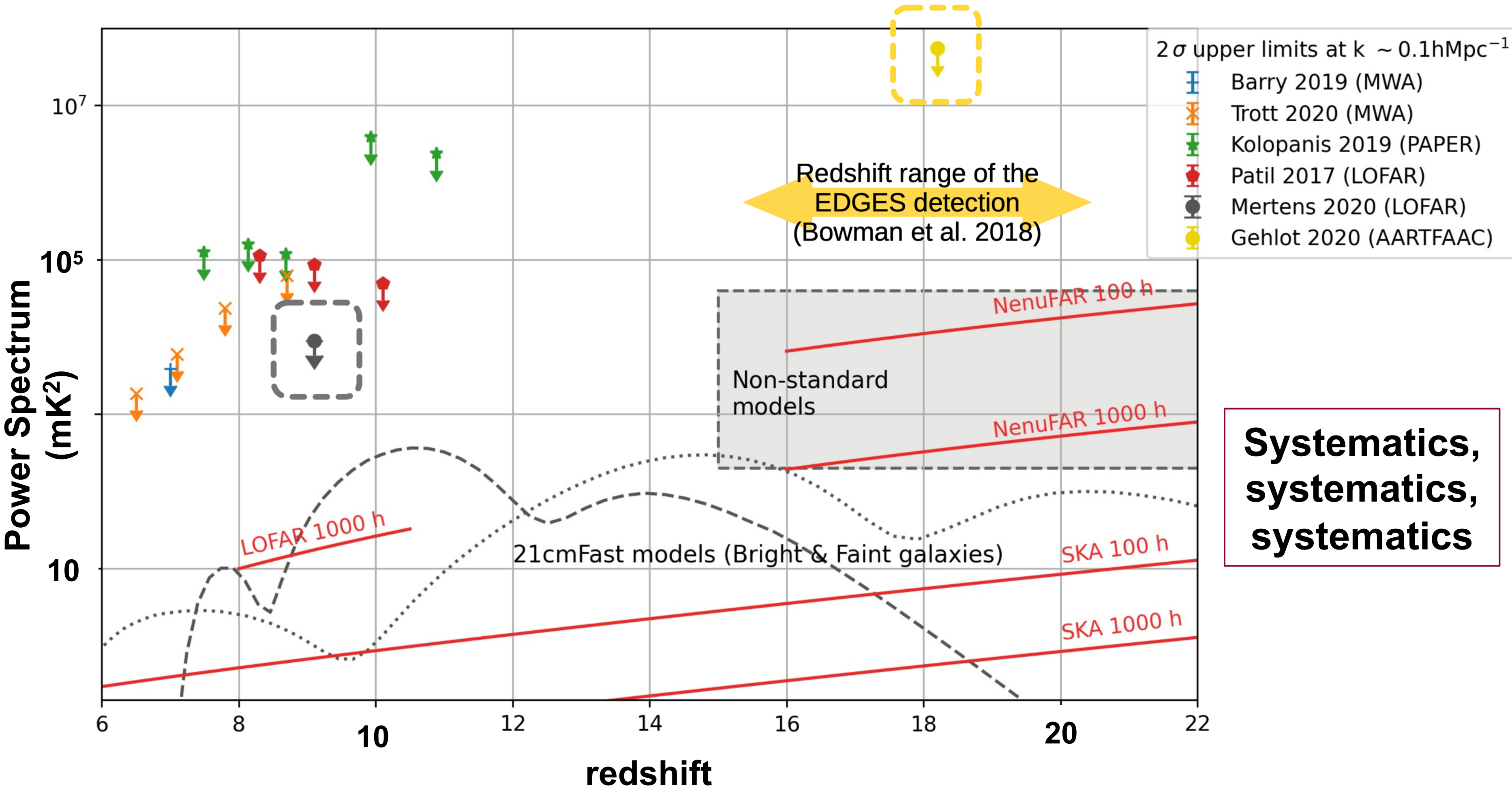






H I Power Spectra @ $z > 6$

State of the Art

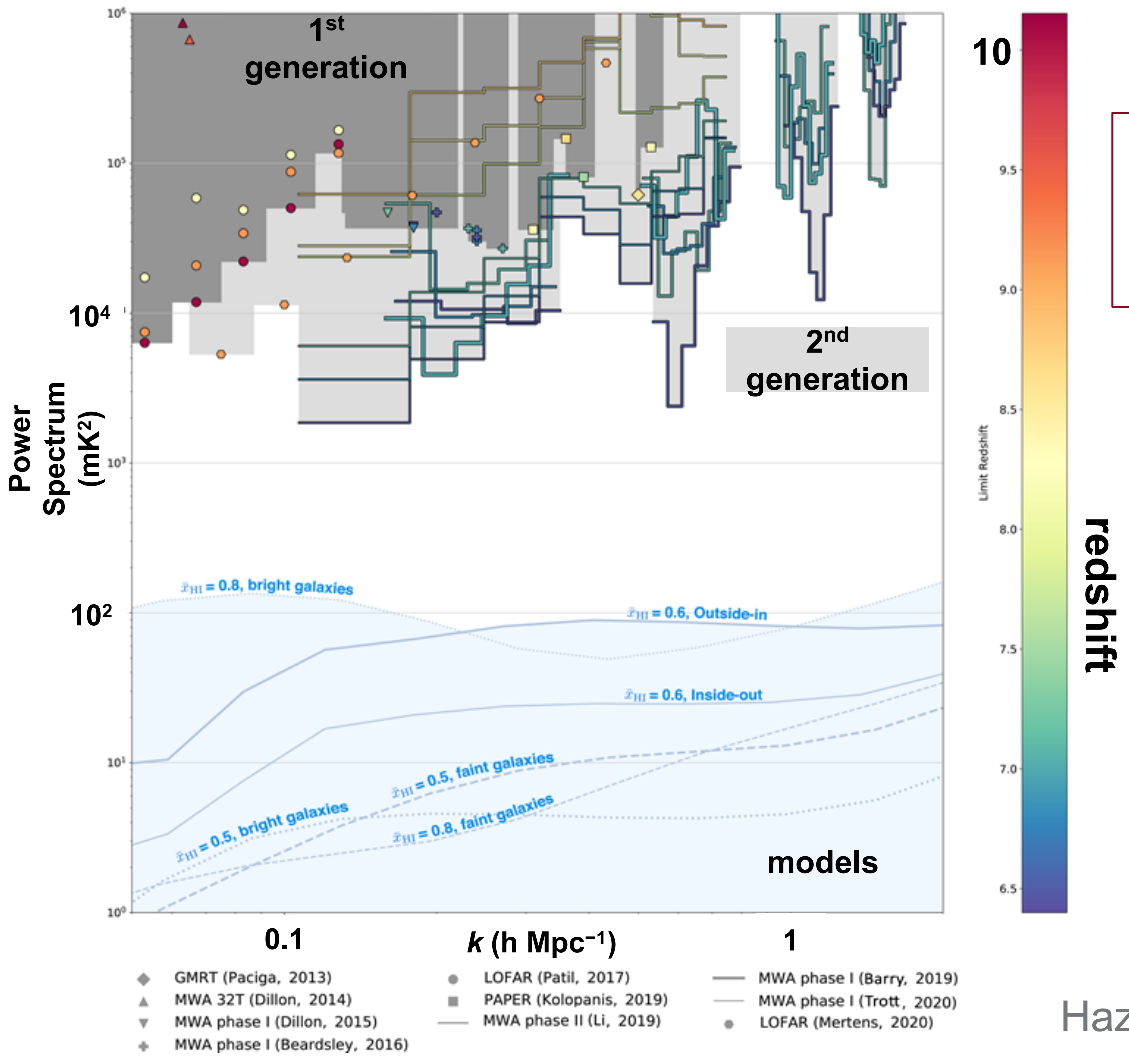


Systematics, systematics, systematics

Merten, Koopmans, et al.

H I Power Spectra @ $z > 6$

State of the Art



Systematics, systematics, systematics

Hazelton, Pober, Morales

EDGES – H I @ $z \sim 17$

A “Dry Run”

nature
International journal of science

Access provided by Jet Propulsion Laboratory

Altmetric: 1936 Citations: 1 More detail »

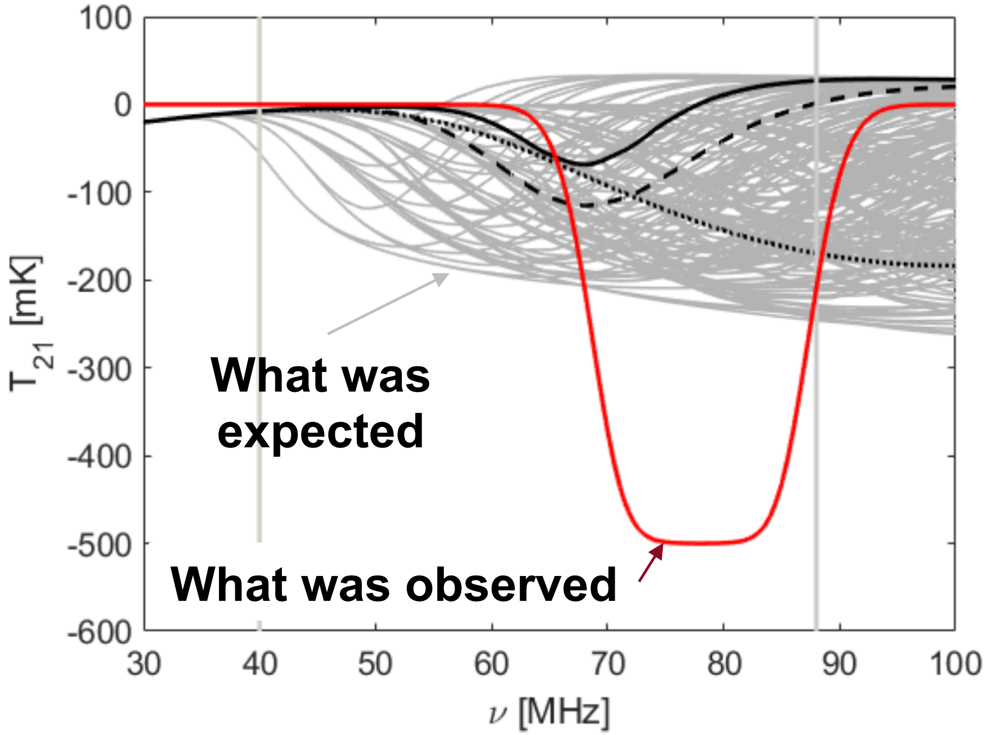
Letter

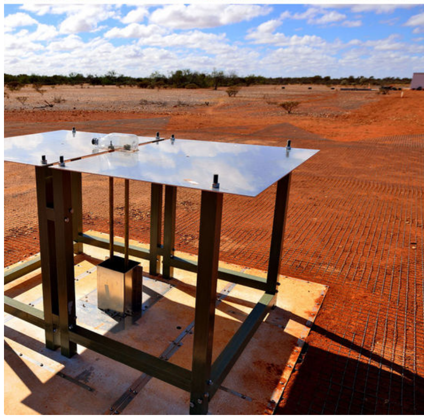
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

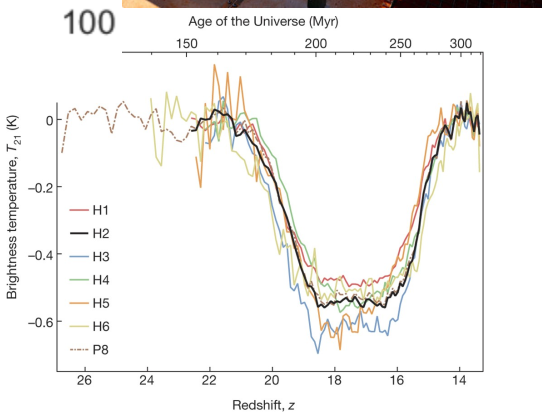
Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

Who ordered that?

60+ papers explaining difference with physics beyond Standard Model







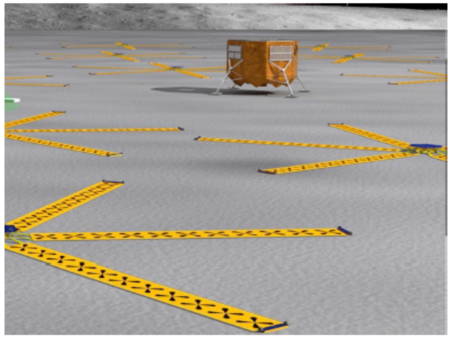
Extending the Cosmic Frontier into the Dark Ages

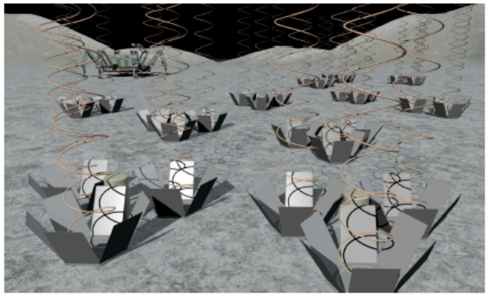
- How?
- Scientific Promise
  - Ultimate in cosmic variance-limited measurements
  - Physics beyond the Standard Model
- **Technical Challenge**

Technical Challenge

Extending the Cosmic Frontier into the Dark Ages

The Lunar Radio Array (LRA)





Concept study funded by the Astrophysics Strategic Mission Concept Studies for Astro2010

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LARC team:
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Technical Challenge

Extending the Cosmic Frontier into the Dark Ages

- **Analysis methods**
- **Low-frequency, wide bandwidth, low-mass science antennas**
- **Ultra-low power, radiation-tolerant digital and analog electronics**
- **High data rate [lunar surface] data transport**
- **Autonomous low-power generation**
- **Low-mass, high capability, autonomous rovers**

Only relevant for lunar surface

Original LRA White Paper

Technical Challenge

Extending the Cosmic Frontier into the Dark Ages

- **Analysis methods**
- **Low-frequency, wide bandwidth, low-mass science antennas**

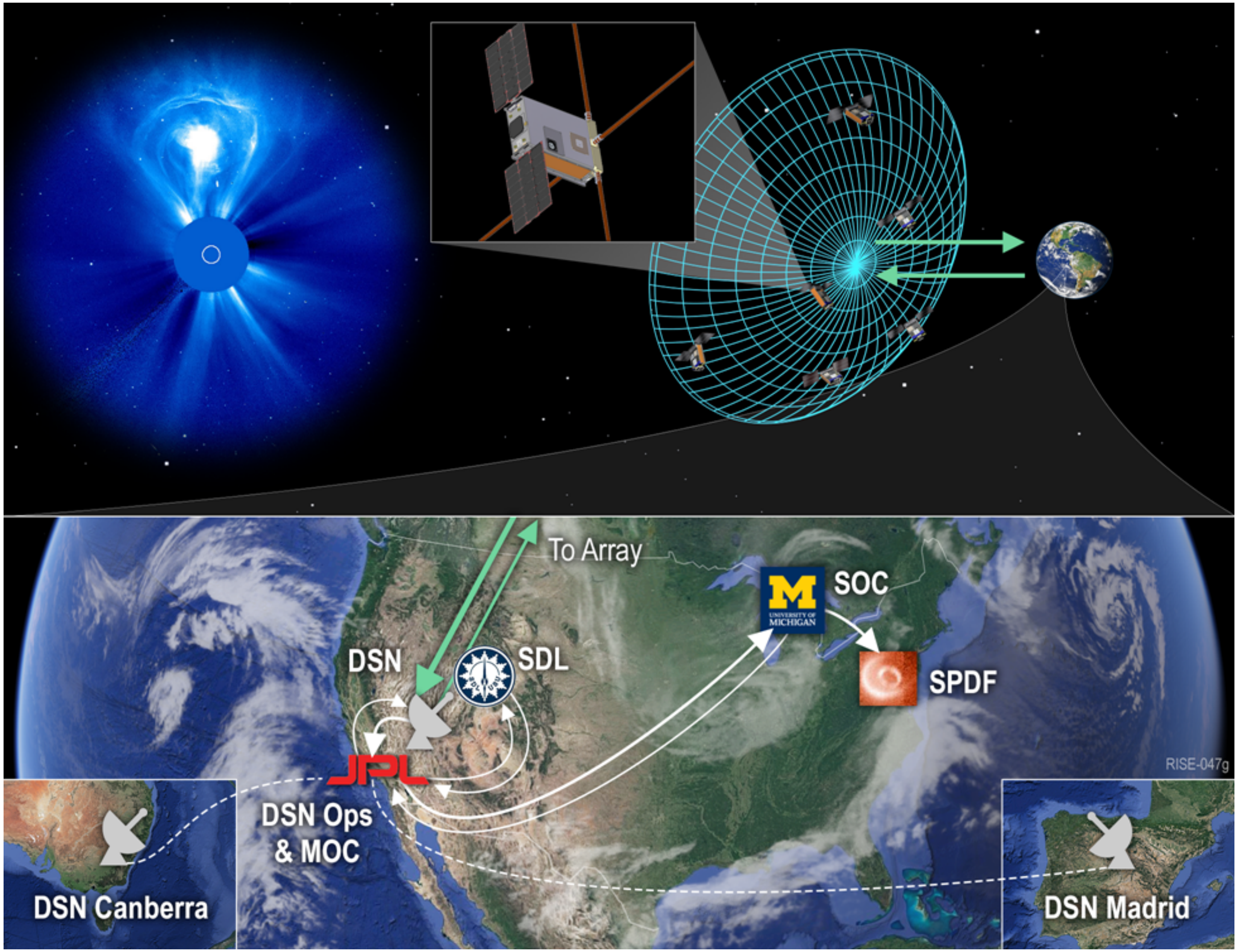
Ground-based Telescopes and Research

- **Ultra-low power, radiation-tolerant digital and analog electronics**
  - **DOE expertise a la particle accelerators**
- **High data rate [lunar surface] data transport**
  - **Optical/laser communications?**
- **Autonomous low-power generation**
  - **DOE expertise?**
- **Low-mass, high capability, autonomous rovers**

Only relevant for lunar surface

Technical Challenges

Space-based Pathfinders



Sun Radio Interferometer Space Experiment (SunRISE)

Orbiting Array vs. Lunar Surface Array

Earth-Moon Lagrange vs. Sun-Earth L2 point vs. Lunar Surface

Potential considerations*

? **To what levels must (terrestrial) radio interference be avoided or suppressed?**

? **How can the (extreme) levels of systematic error control or knowledge be obtained?**

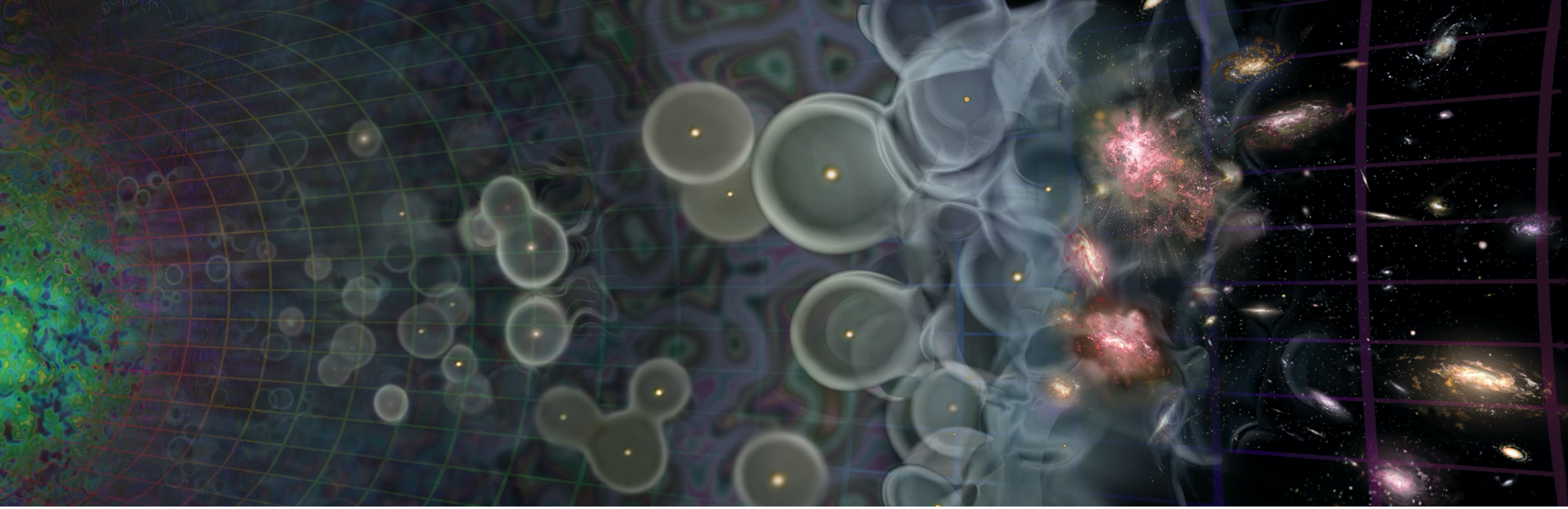
? **Can antenna locations be determined sufficiently well?**

? **What is the potential effect of communication and navigation networks?**

LunaNet communications satellites

? **What is the effect of the lunar plasma environment on a lunar surface radio telescope?**

*** An incomplete list?**



Extending the Cosmic Frontier into the Dark Ages

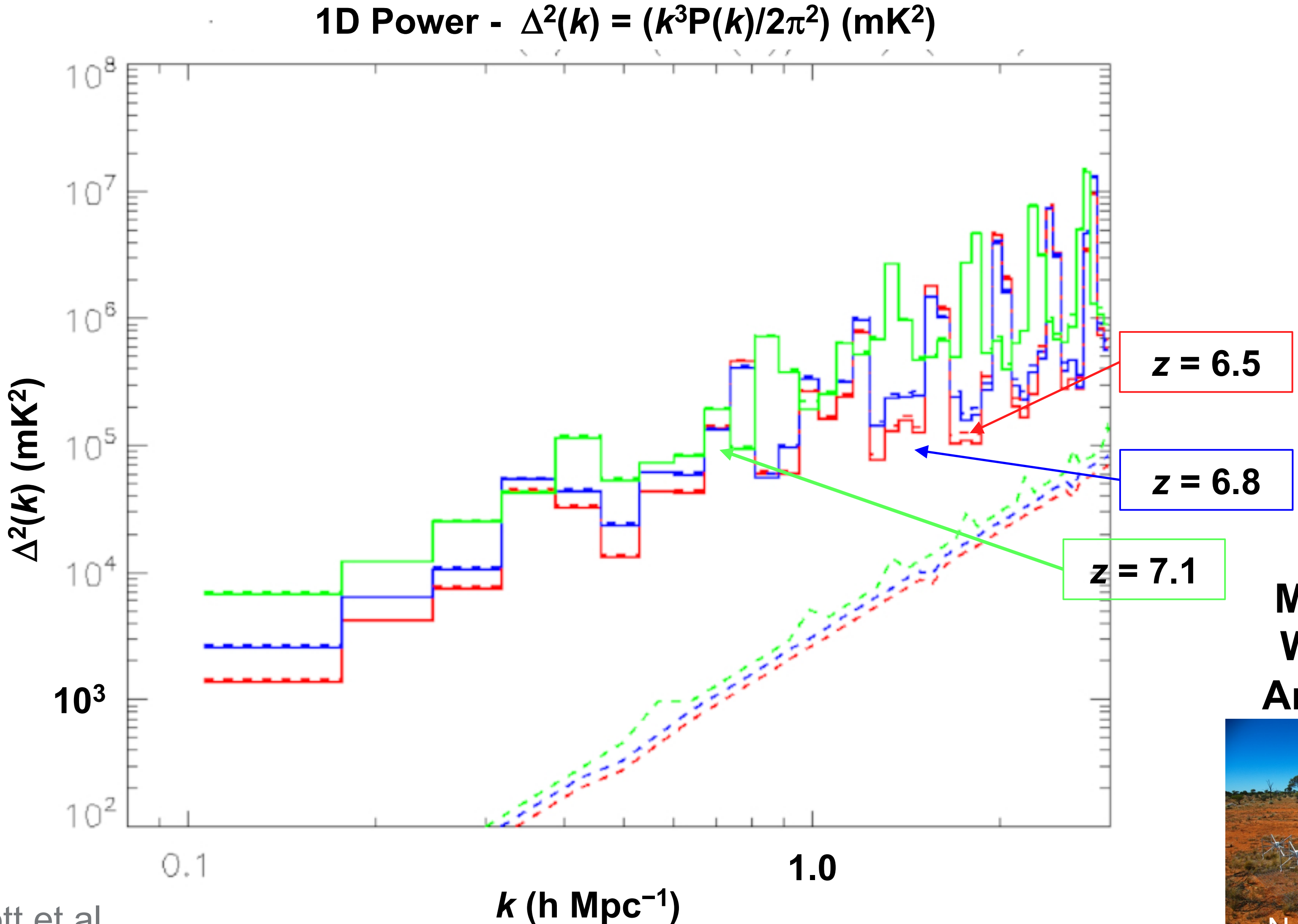
Neutral Hydrogen Signal (21 cm) is powerful probe with considerable scientific promise

- **Ultimate in cosmic variance-limited measurements**
- **Physics beyond the Standard Model**

Technical Challenges

- **None insurmountable, considerable ground-based experience, ample collaboration opportunities**

H I Power Spectra @ $z > 6$



Trott et al.

Murchison Wide-field Array (MWA)