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U.S. DEPARTMENT OF ENERGY

Overview of Radio and mm Wave Astronomy

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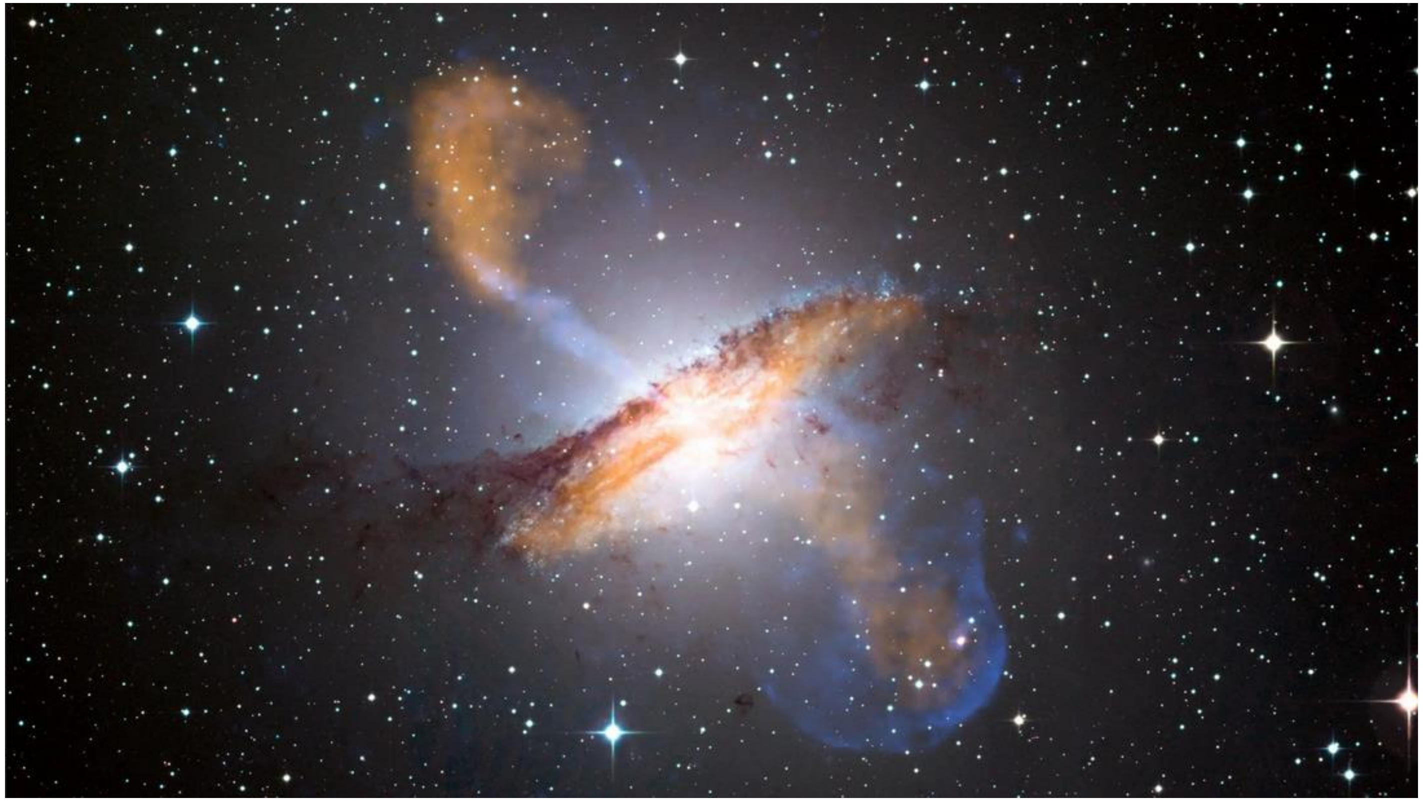
Outline

- What is radio astronomy?
- The CMB: What is it, and why is it interesting?
- The 21cm line: What is it, and why is it also interesting?
- Detour into Cosmology
- Survey of current experiments

Radio Astronomy

- Different astrophysical sources emit electromagnetic radiation at different wavelengths.
- We can learn different thing about the universe, or about different physical processes or objects by examining the universe at different wavelengths.
- Different detector technologies are required to observe radiation at different wavelengths.

Active Galactic Nucleus (AGN)



Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimeter); NASA/CXC/CfA/R.Kraft et al. (X-ray)

Radio Astronomy

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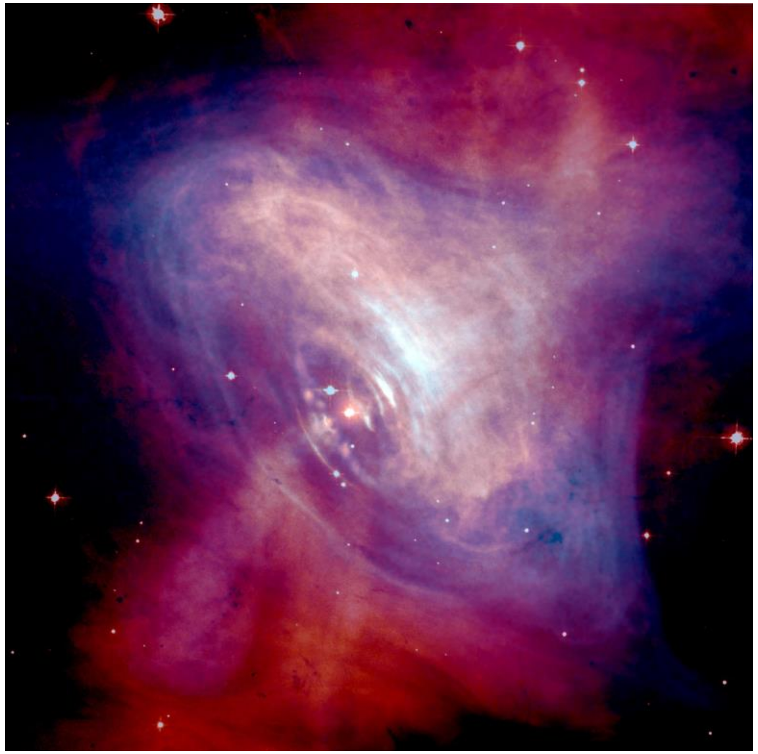
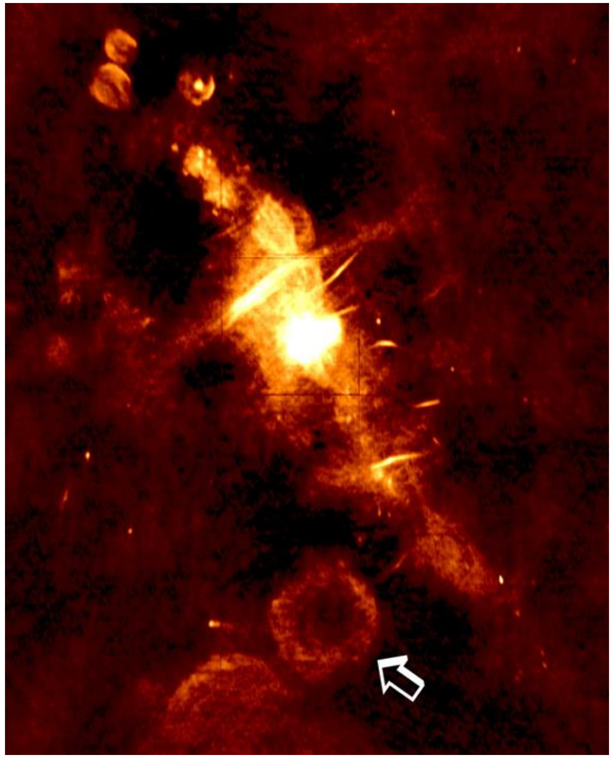
Crab Pulsar



Credit: Optical: NASA/HST/ASU/J. Hester et al. X-Ray: NASA/CXC/ASU/J. Hester et al.



Center of Milky Way, showing Supernova remnants

Credit: NRL/SBC Galactic Center Radio Group

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Radio Astronomy

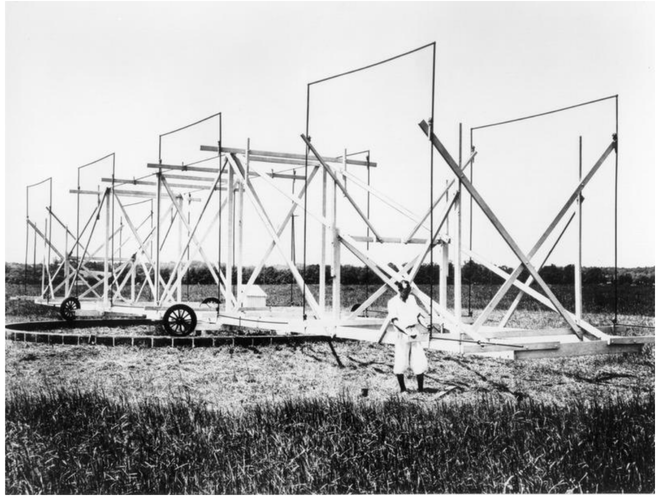
- Detector technology is “antennas”, or “feeds”: systems for converting electromagnetic radiation with mm to m scale wavelengths into electrical currents that can be measured and amplified.
- Telescopes can look like parabolic dishes which focus light onto an antenna, or like bare antennas, depending on the needs of the instrument.

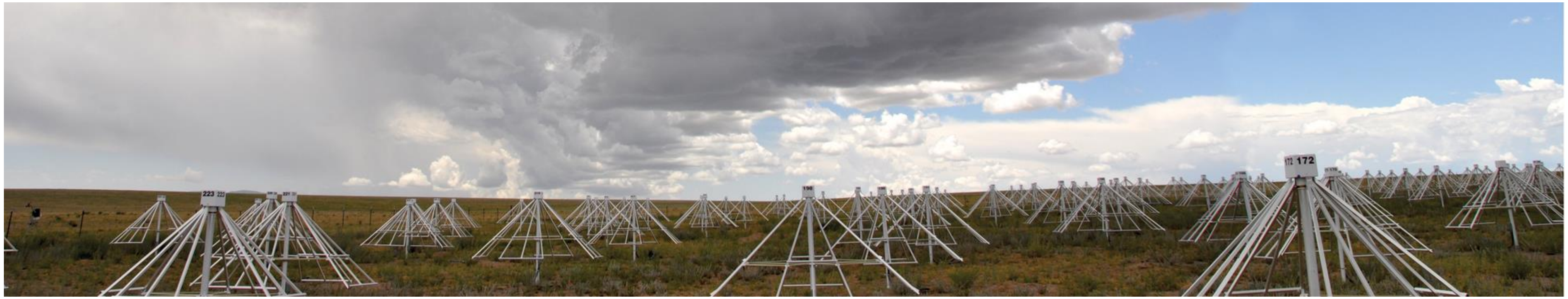
Very Large Array (VLA), New Mexico

Arecibo Telescope, Puerto Rico

Radio Astronomy

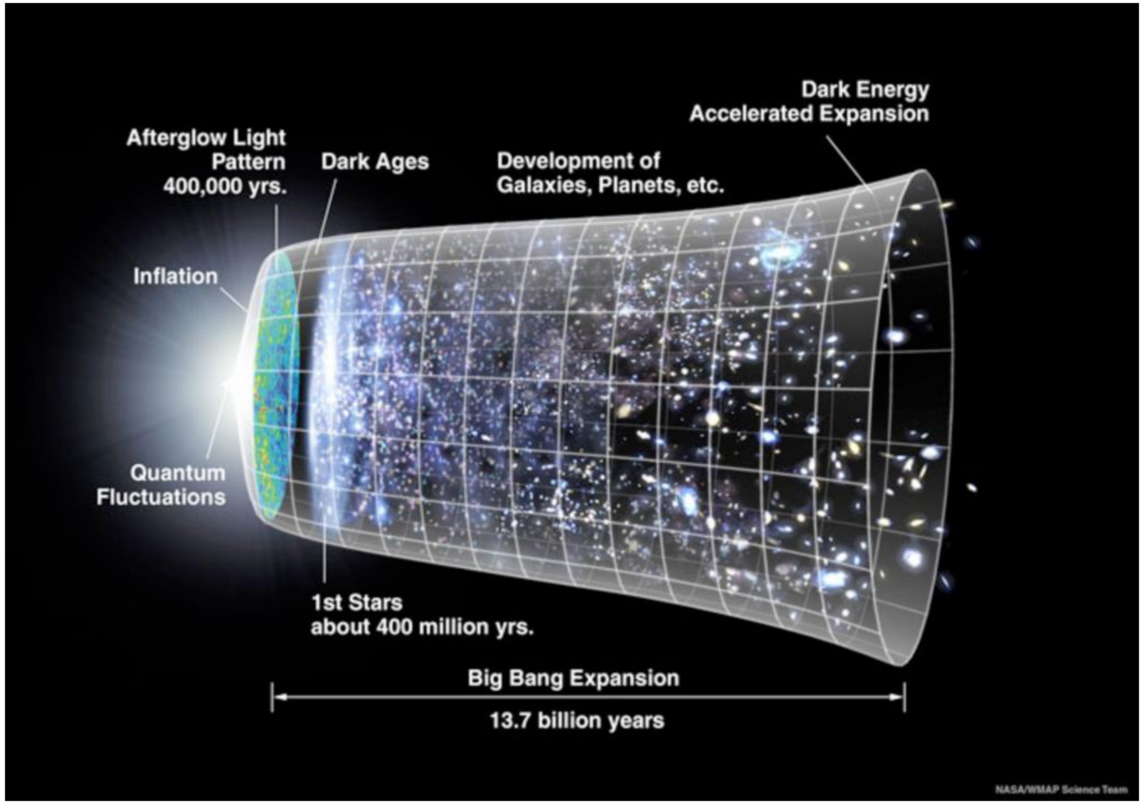
Jansky Telescope, 1930s

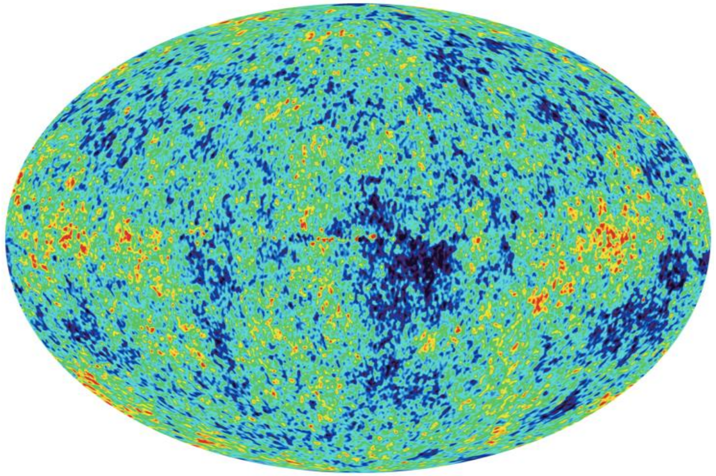




Long Wavelength Array, New Mexico

Cosmic Microwave Background (CMB)





Credit: Planck Collaboration

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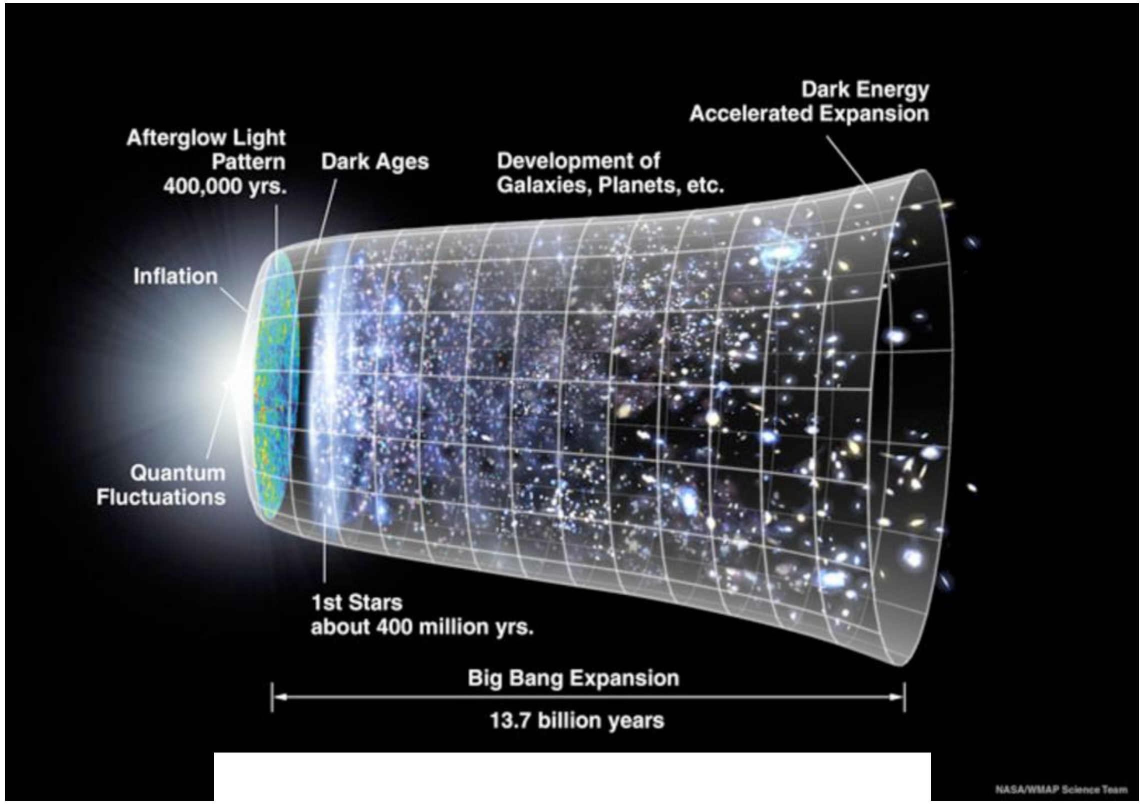
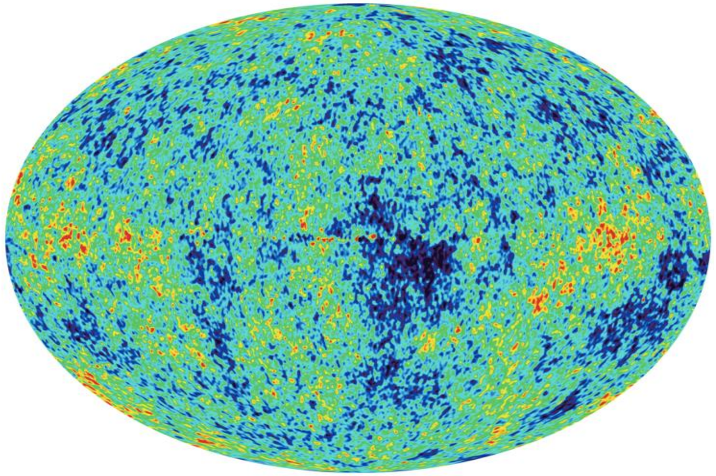
Cosmic Microwave Background (CMB)





Credit: Planck Collaboration

$$z \equiv \frac{\lambda_{\rm ob} - \lambda_{\rm em}}{\lambda_{\rm em}}$$

$$a(t_{\rm em}) = \frac{a(t_0)}{1+z}$$

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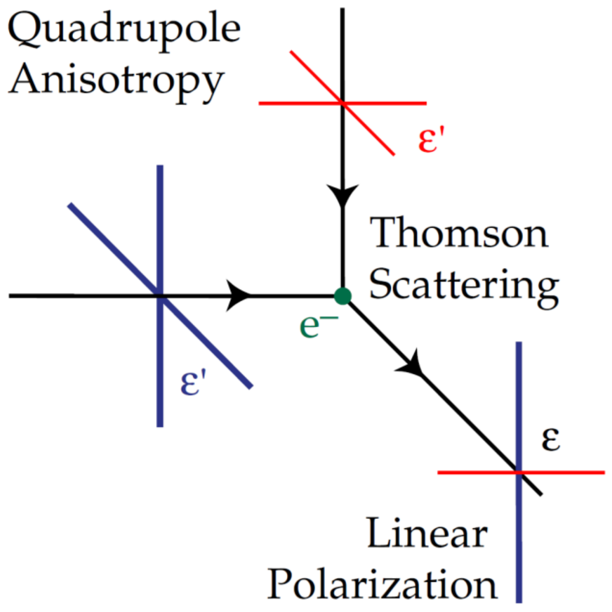
Cosmic Microwave Background (CMB)

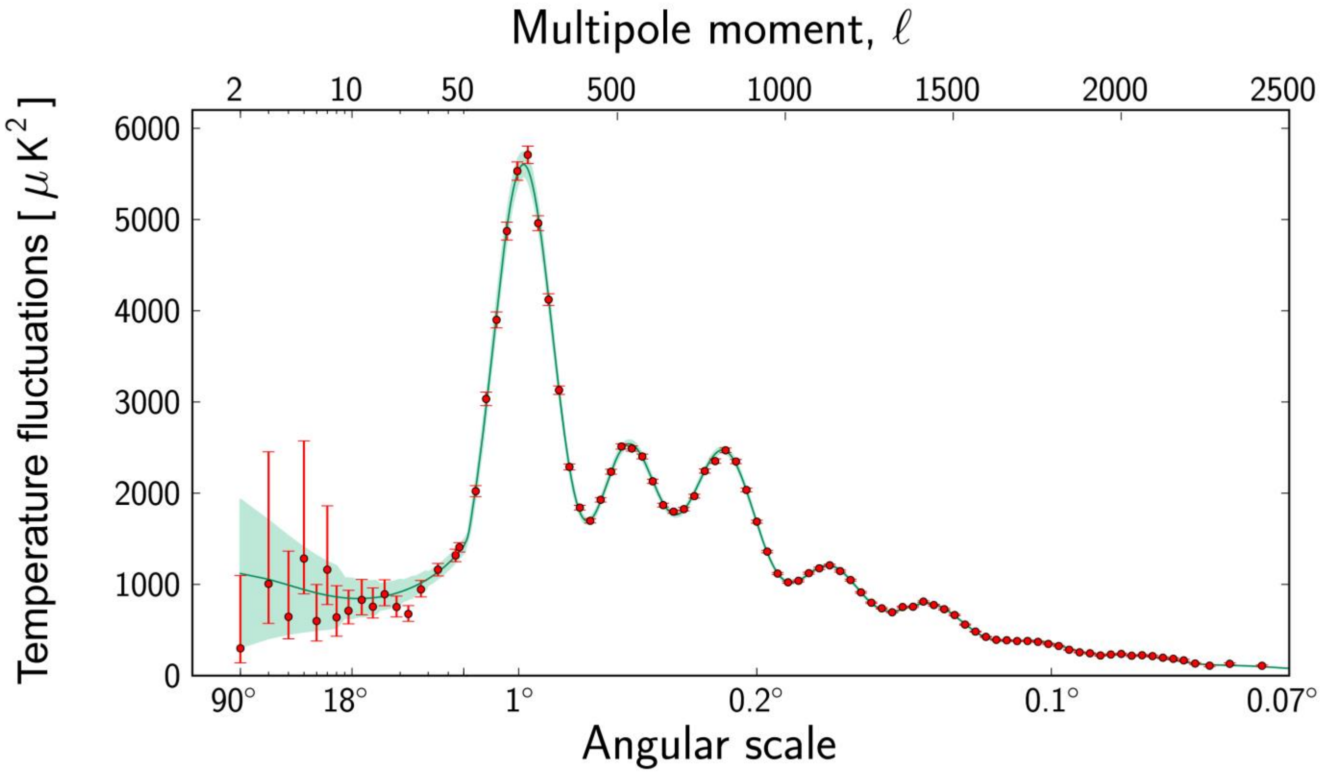
- To first order, CMB is uniform blackbody. Same temperature in all directions.
- The anisotropies in the CMB map are produced by thermal anisotropies in primordial plasma.
- Thermal anisotropies also produce polarized radiation, which can tell you more about state of early universe.



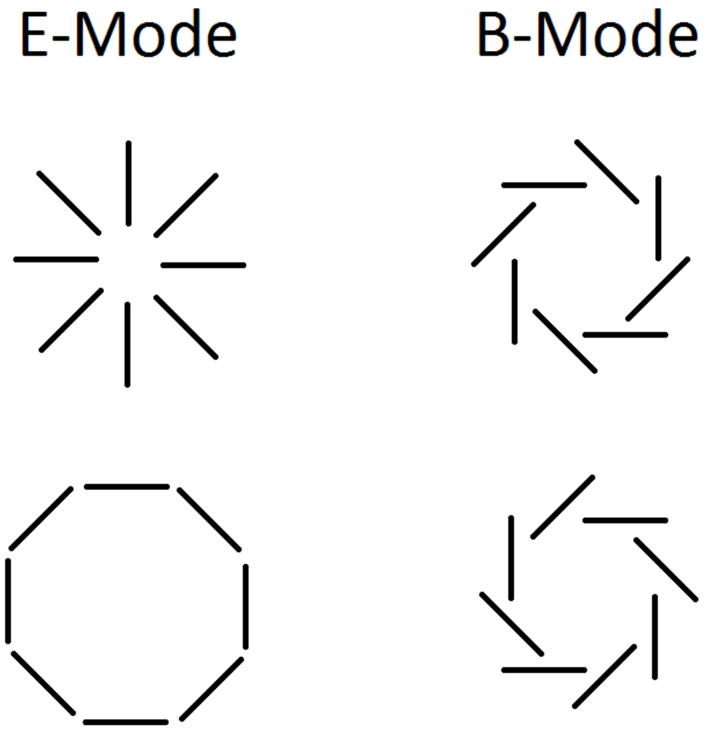
Credit: Hu and White

Cosmic Microwave Background (CMB)

- Power spectrum of anisotropies encodes information about plasma physics at range of physical scales, and information about systems in the later universe (galaxy clusters) that absorb CMB photons.



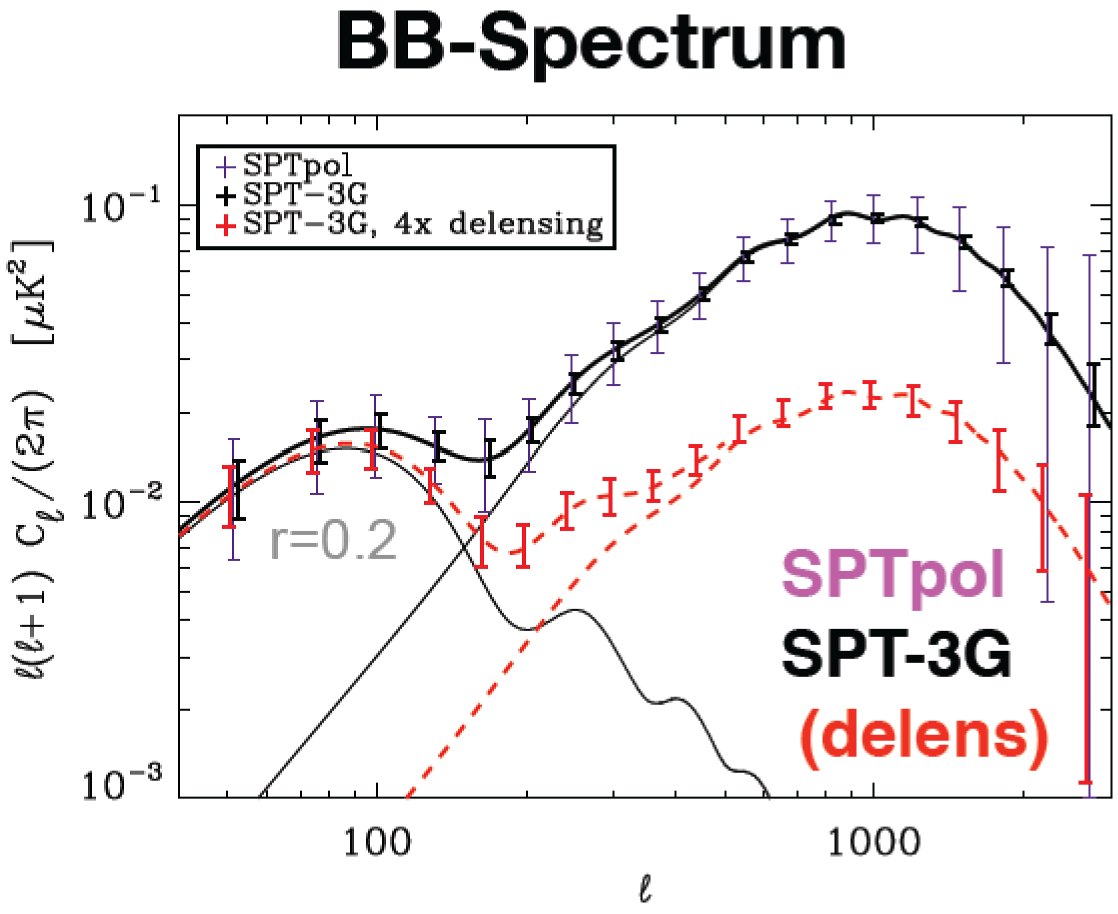
Cosmic Microwave Background (CMB)



- Temperature anisotropies can only produce polarization modes without curl. Divergence or "E-modes."
- Gravitational physics (lensing or gravity waves) can imprint modes with curl, "B-modes".
- Potential signature of physics from the Inflationary Epoch, ~10^-32 seconds after Big Bang.

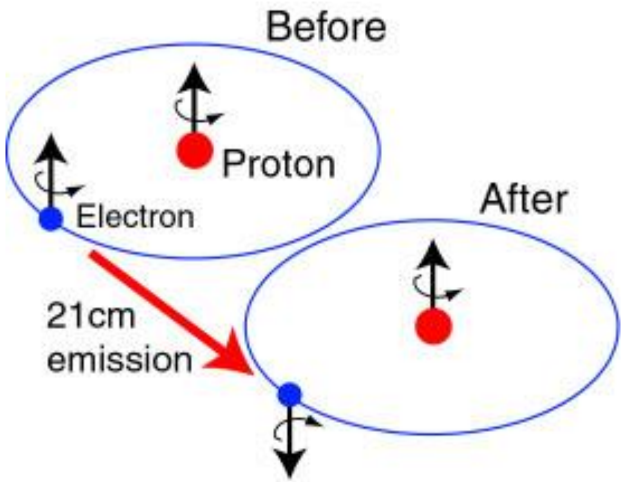
Cosmic Microwave Background (CMB)

- This signal from primordial gravity waves is expected to be several orders of magnitude smaller than currently detected E-mode polarizations.
- Will need much better sensitivity, and better foreground removal to detect it.
- One of the main goals of CMB cosmology currently.



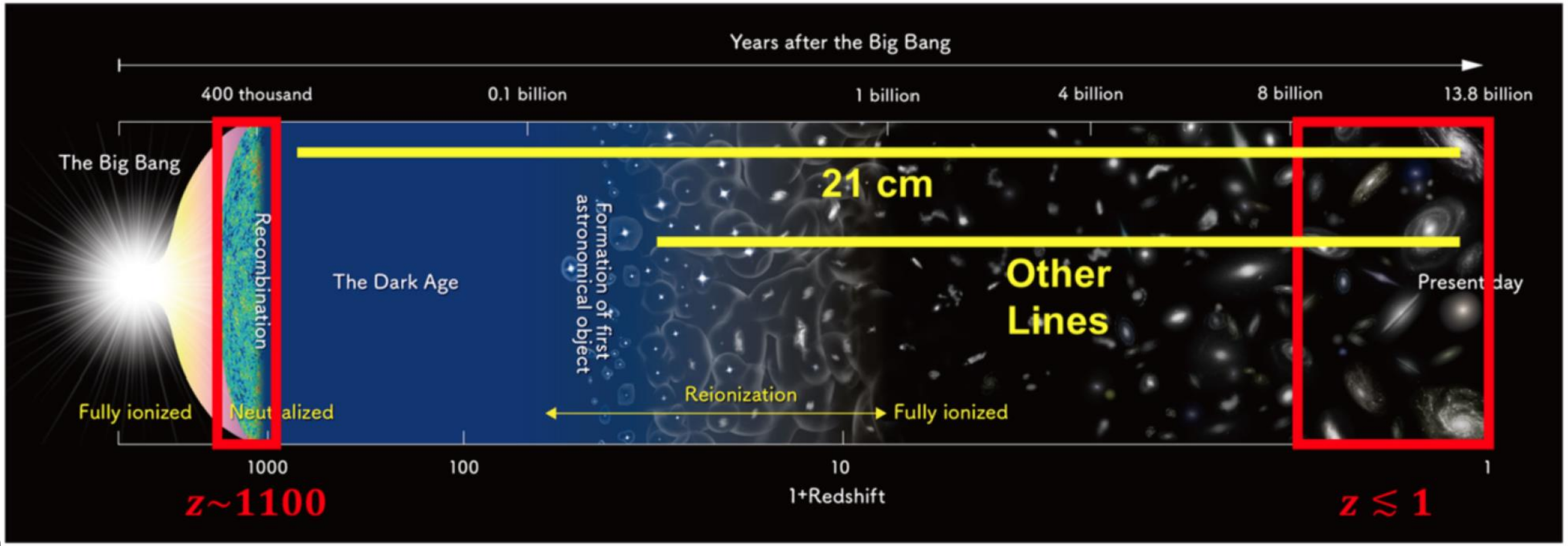
21 cm Line Radio Astronomy

- Hydrogen atom has slightly higher energy when electron and proton spins are aligned, this produces the hyperfine splitting of energy levels
- Transition in 1s orbital corresponds to emission of a photon with wavelength 21.1cm (1.42GHz)
- This is a “forbidden” transition, ~10Myr lifetime of excited state => observed frequency gives good measurement of redshift of emission.
- Long lifetime means kinetic temperature T_k (atomic motions) can decouple from spin temperature T_s, set by fraction of HI.



21 cm Line as Cosmological Probe

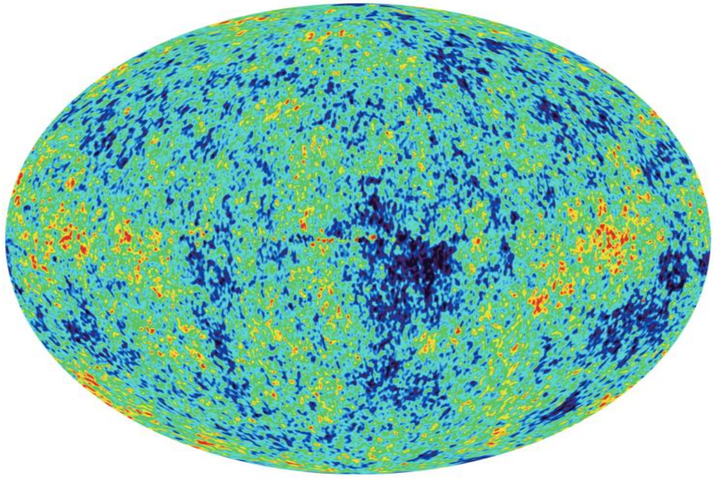
- 21 cm line is a promising cosmological probe, Hydrogen abundant, not much confusion from other lines
- Can use 21 cm line to study history of matter and growth of structure in universe over bulk of cosmological time
- Dark energy drives expansion of universe in late times: 21cm measurements of BAO provide standard ruler for measuring expansion



Line Intensity Mapping: 2017 Status Report (arxiv 1709.09066)

Origin of Baryon Acoustic Oscillations

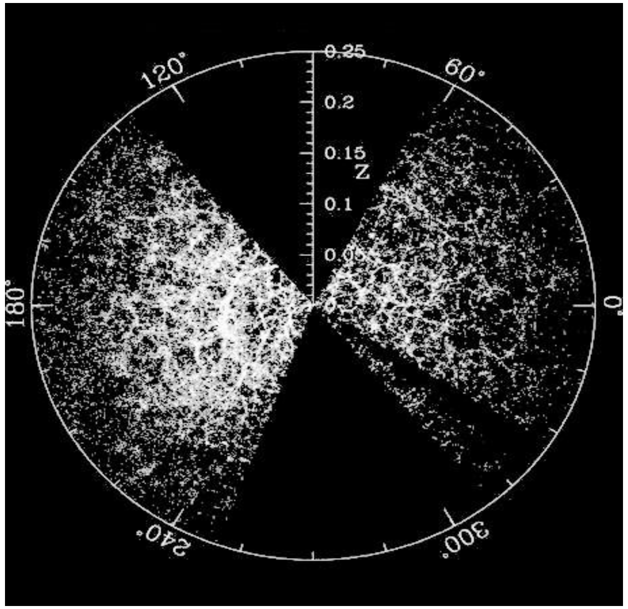
- Before CMB, sound waves in primordial plasma produce density variations. Gravity drives collapse, photon pressure provides restoring force.
- Photons coupled to matter by free electrons, density field produced by sound waves gets locked in when electrons recombine into neutral hydrogen.
- Sound horizon at recombination produces characteristic length scale in density perturbations (~150 Mpc).

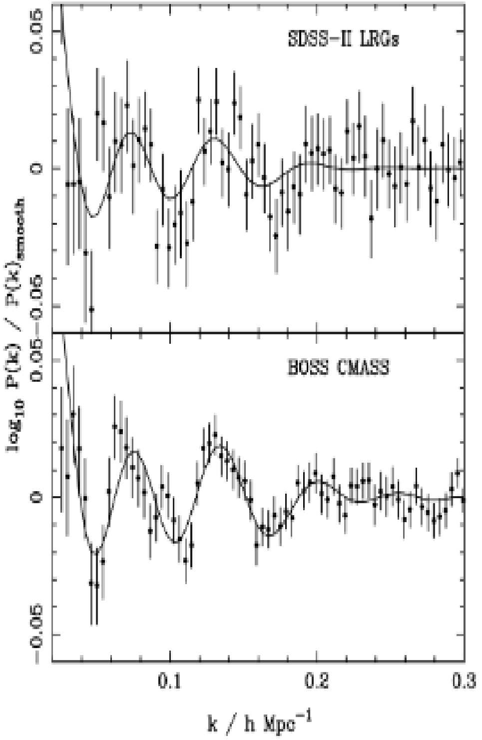


Credit: Planck Collaboration

Baryon Acoustic Oscillations

- Structures preferentially form in peaks of BAO density field.
- Should see rings of correlation in galaxy positions.
- BAO scale large, to do precision cosmology need lots of volume => large sky area, redshift range.





SDSS galaxy power spectrum (Image from SDSS).

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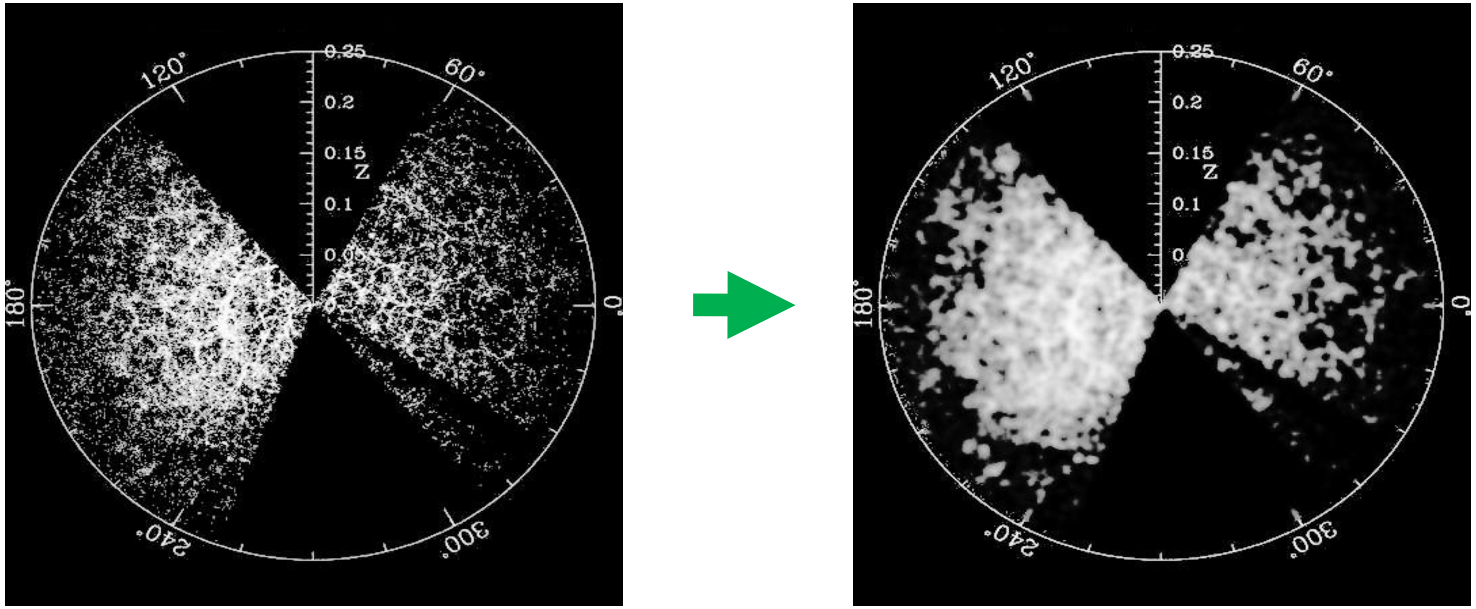
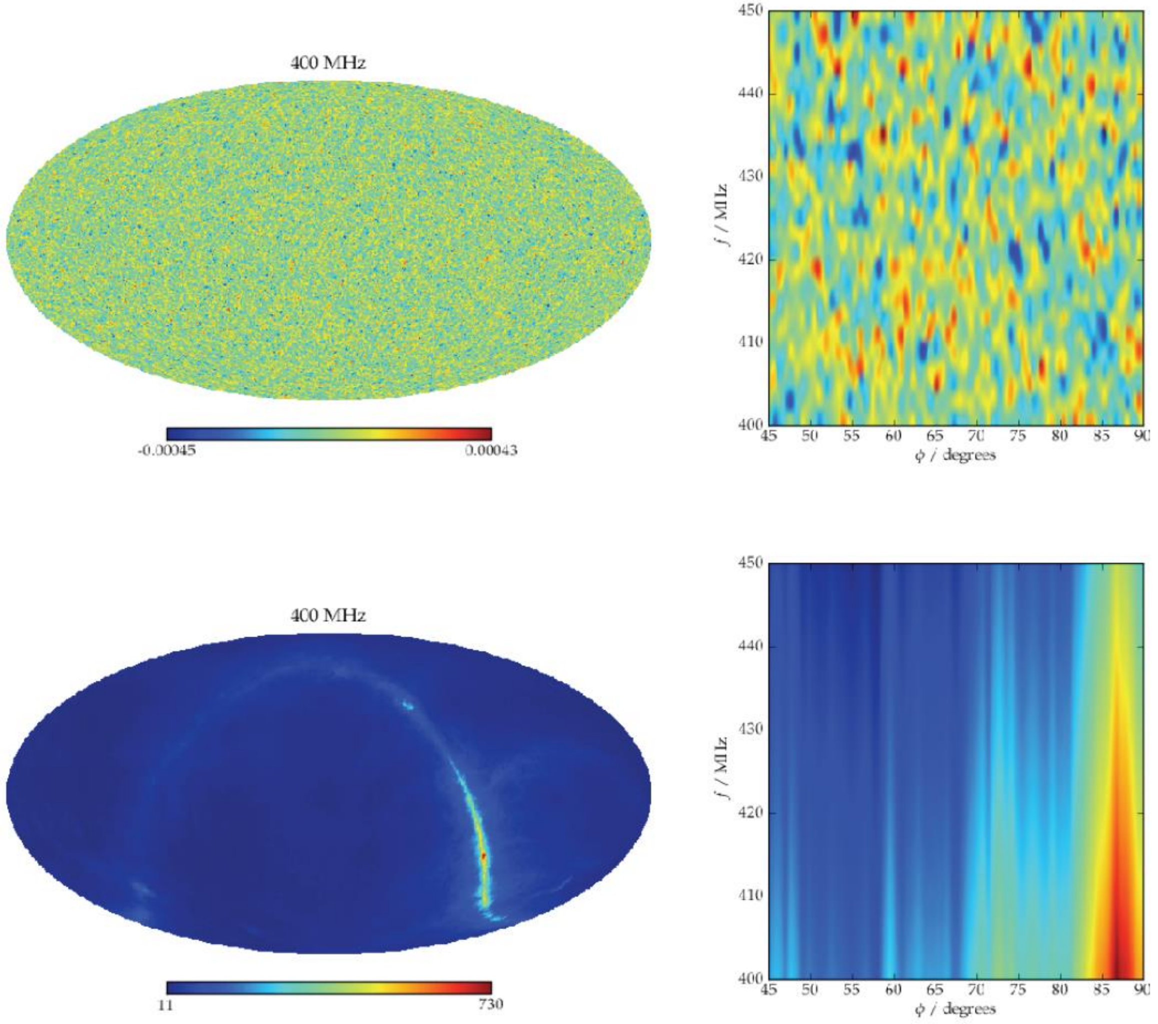
Baryon Acoustic Oscillations

- Have ~10^5 L_* galaxies/BAO volume - individual galaxies not that important. Use aggregate signal from many galaxies with low resolution survey.
- Since characteristic scale is large, fine resolution is not necessary.
- Large beams beneficial for increased mapping speed.



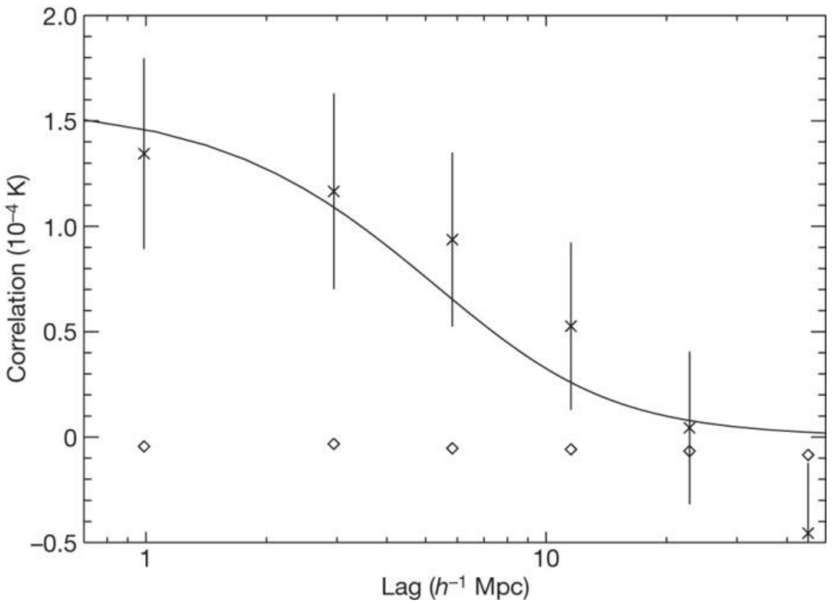
Intensity Mapping

- Signal is O(0.1 mK), while galactic foreground is O(10^5 K)



Intensity Mapping

- Signal is O(0.1 mK), while galactic foreground is O(10^5 K)
- Sample variance limits => map sensitivity of 1-2μJy necessary



- First HI intensity mapping detection, DEEP2 density field x GBT HI brightness temperature cross correlation at z=0.8

T-C Chang *et al.* *Nature* **466**, 463-465 (2010) doi:10.1038/nature09187

Why is 21cm Intensity Mapping Interesting?

- Orders of magnitude increase in number of measurable cosmological BAO modes over CMB and galaxy surveys
- Large period of cosmological time accessible, including only probe of epoch before formation of luminous objects “dark ages”
- Ability to probe very small (down to Jeans) and very large (large FOV) scales
- Breaking degeneracies in cosmological parameters (notably τ)
- Potential for cross-correlation with other observations (optical LSS, CMB lensing)
- “Secondary science” including EoR, FRBs, GR constraints from pulsar timing, neutral hydrogen absorbers, detailed studies of polarized radio emissions of Milky Way and IGM (i.e. “foregrounds”).

Detour to Cosmology

Or: How to Parameterize a Universe

$$\mathrm{P} = w\rho$$ (equation of state)

$$\rho = a^{-3(1+w)}$$ (Use Einstein General Relativity + FLRW)

Scale factor: encodes cosmic size relative to today (a=1 today)

(scale factor – redshift relation)

$$a = 1/(1+z)$$

Detour to Cosmology

$$\mathrm{P} = w\rho$$ (equation of state)

$$\rho = a^{-3(1+w)}$$

↑

Scale factor:
encodes cosmic size
relative to today
(a=1 today)

Friedmann-Lemaitre-Robertson-Walker (FLRW) Metric:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho - \frac{\kappa c^2}{R_0^2 a^2}$$

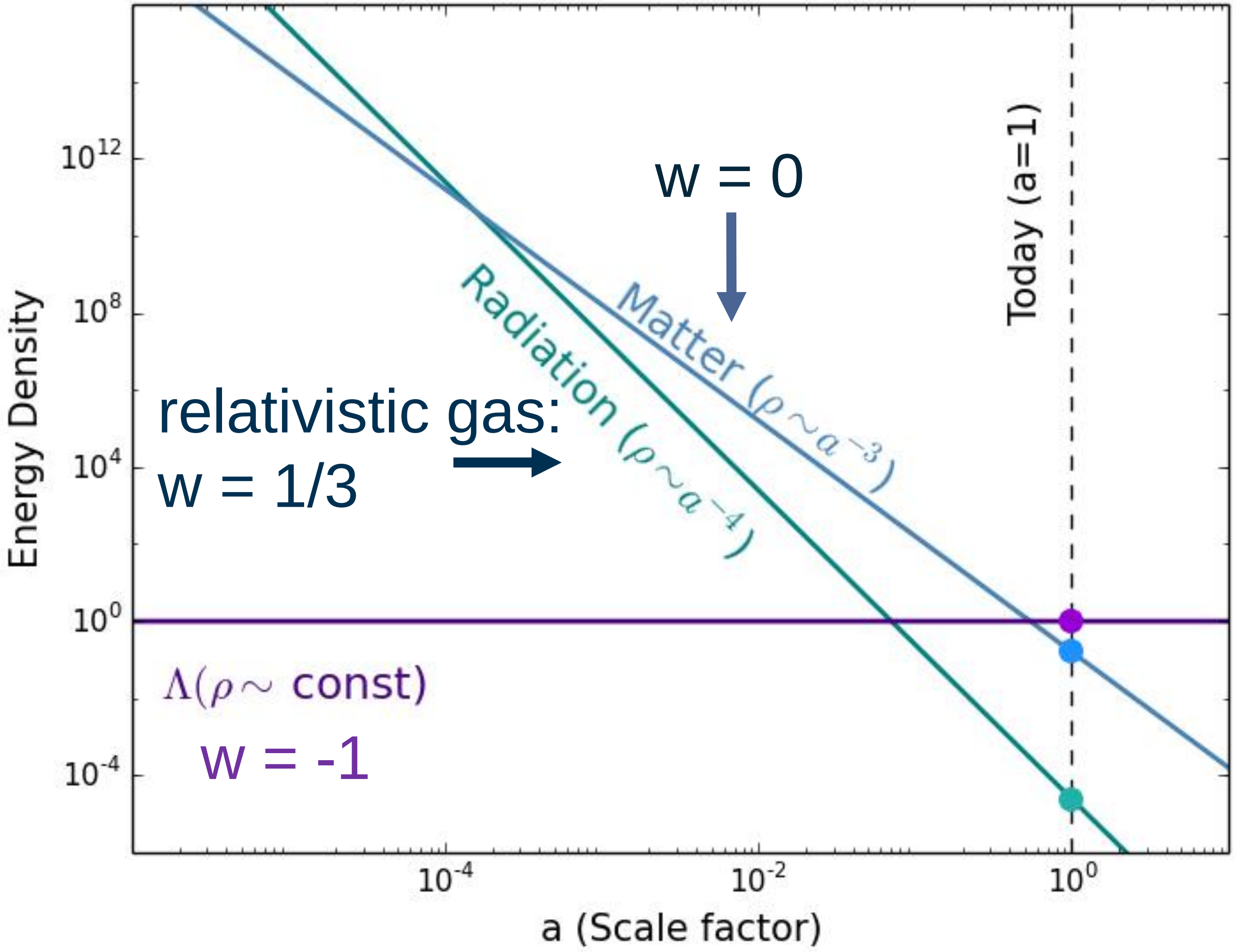
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3P)$$

Detour to Cosmology

$$\rho = a^{-3(1+w)}$$

$$\mathrm{P} = w\rho$$

(equation of state)



Detour to Cosmology

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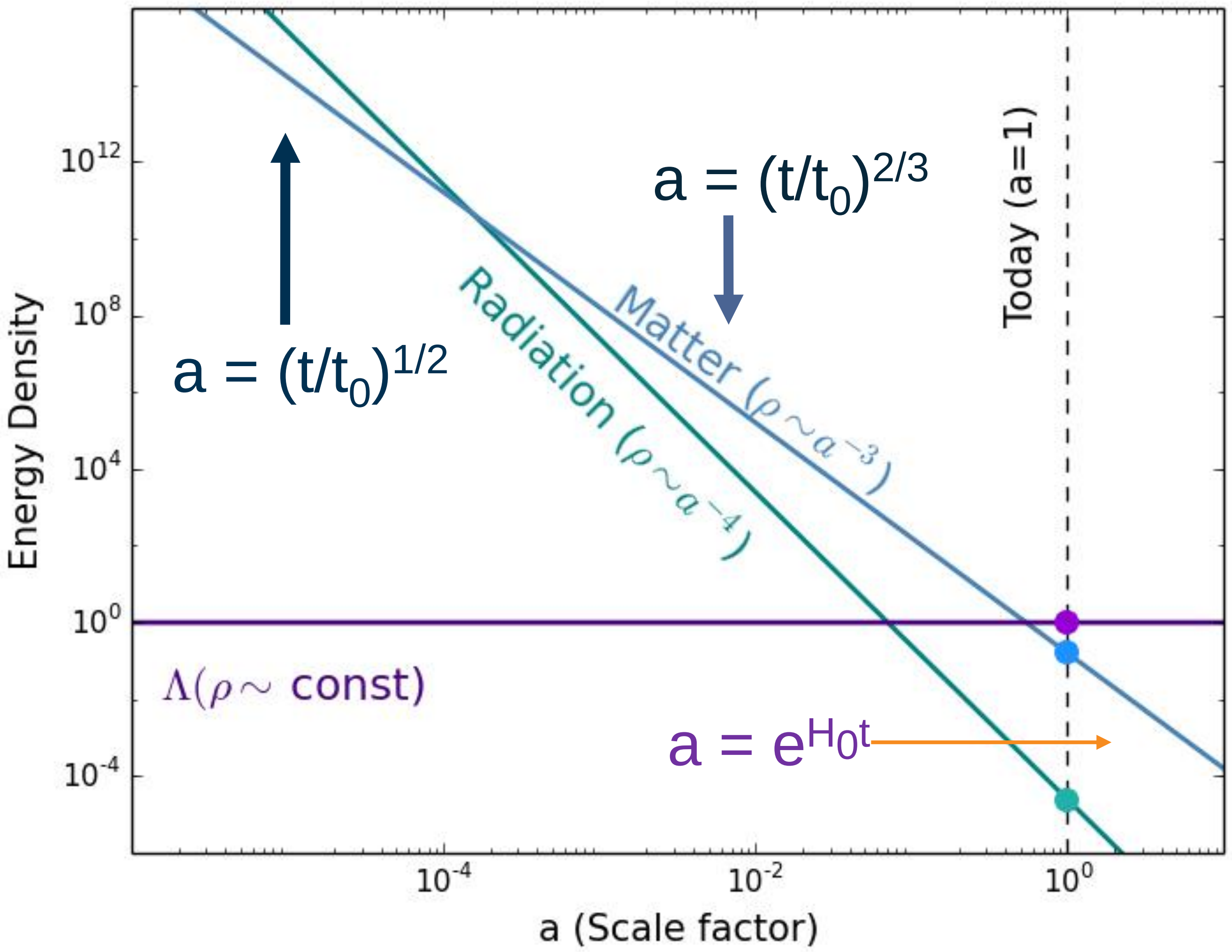


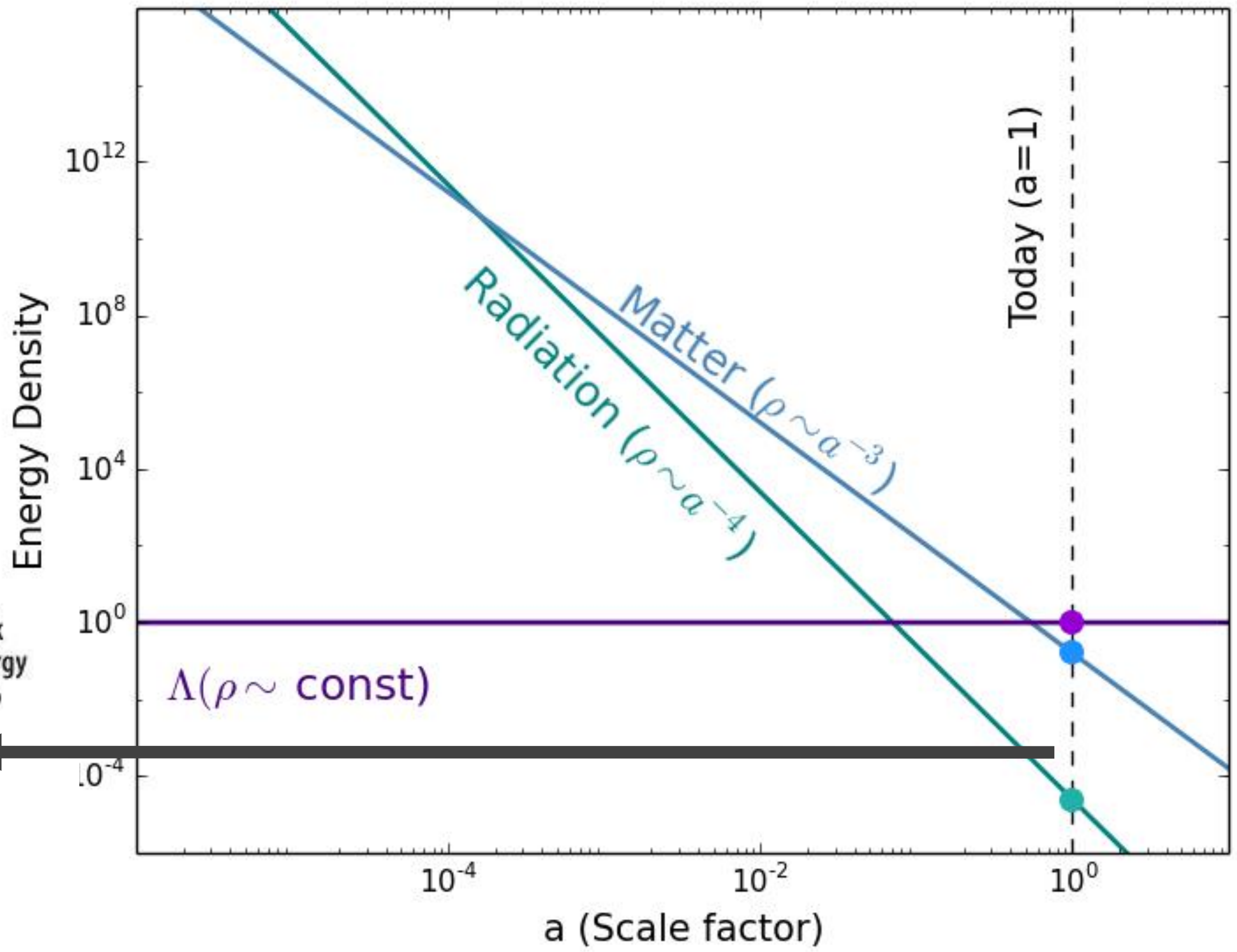
Detour to Cosmology

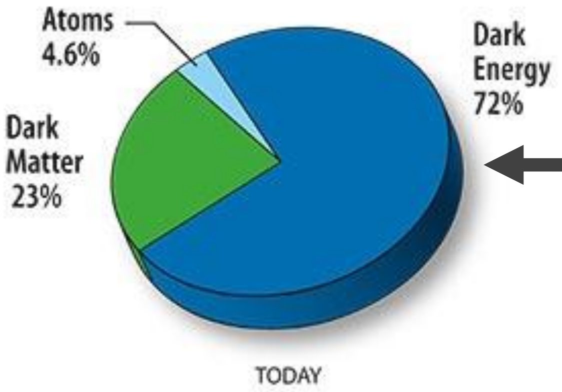
$$\rho = a^{-3(1+w)}$$

$$\mathrm{P} = w\rho$$

(equation of state)

Best constraints show:
w ~ -1





Detour to Cosmology

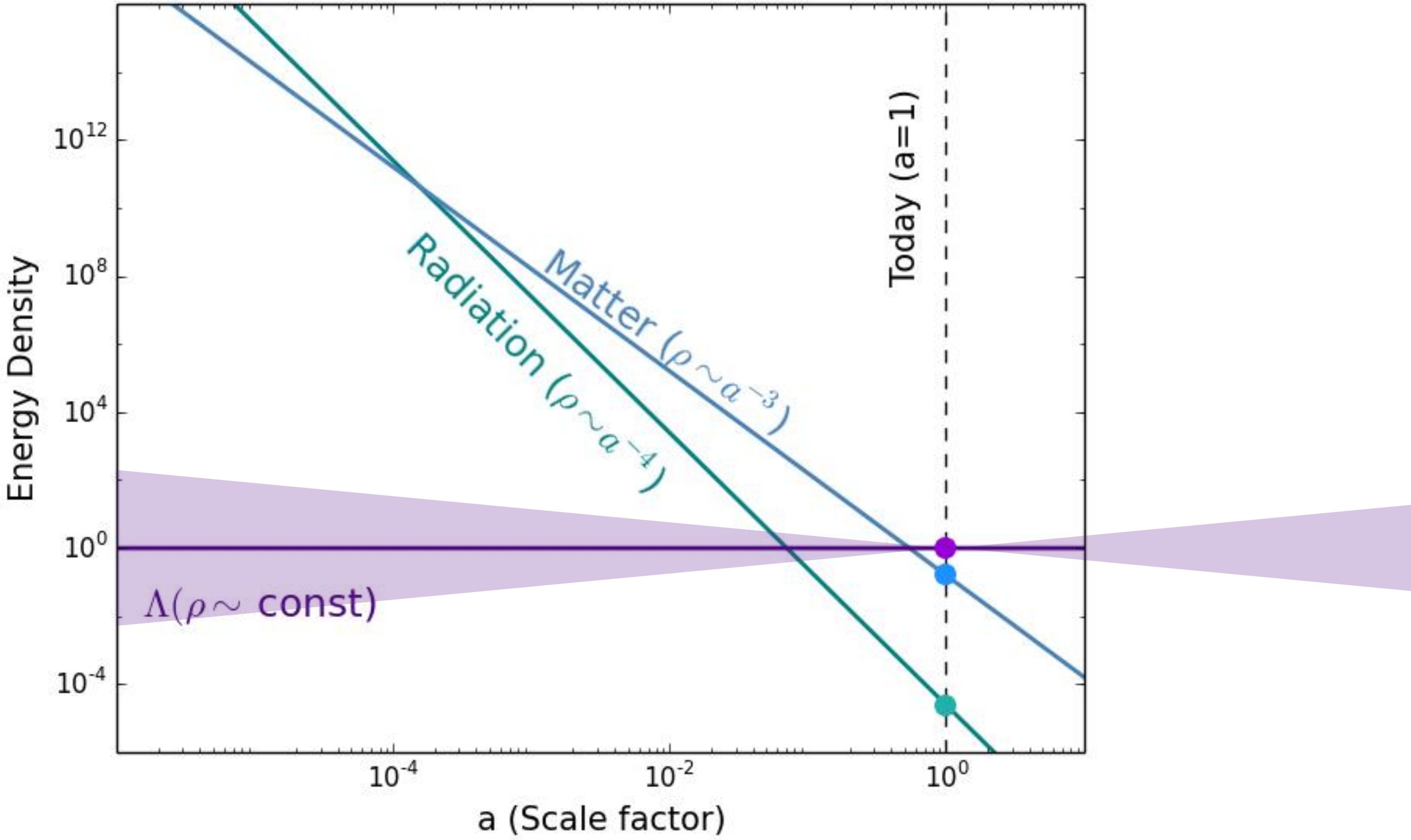
$$\rho = a^{-3(1+w)}$$

$$\mathrm{P} = w\rho$$

(equation of state)

Best constraint so far:

w = -1.06 ± 0.07
(a ~0.6)



Detour to Cosmology

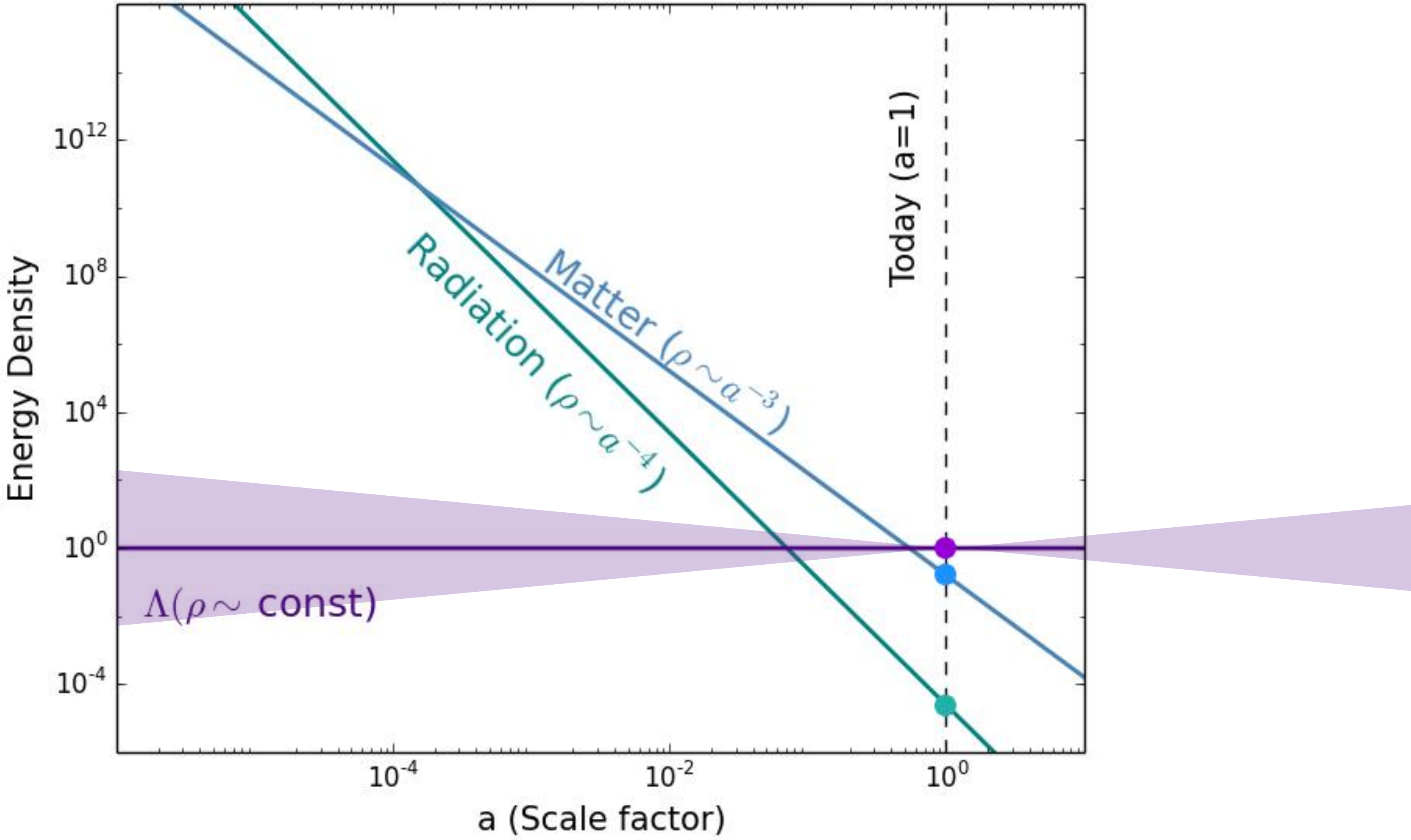
$$\rho = a^{-3(1+w)}$$

$$\mathrm{P} = w\rho$$

(equation of state)

Simplest model extension:

$\omega = \omega_0 + \omega_1 f(z)$



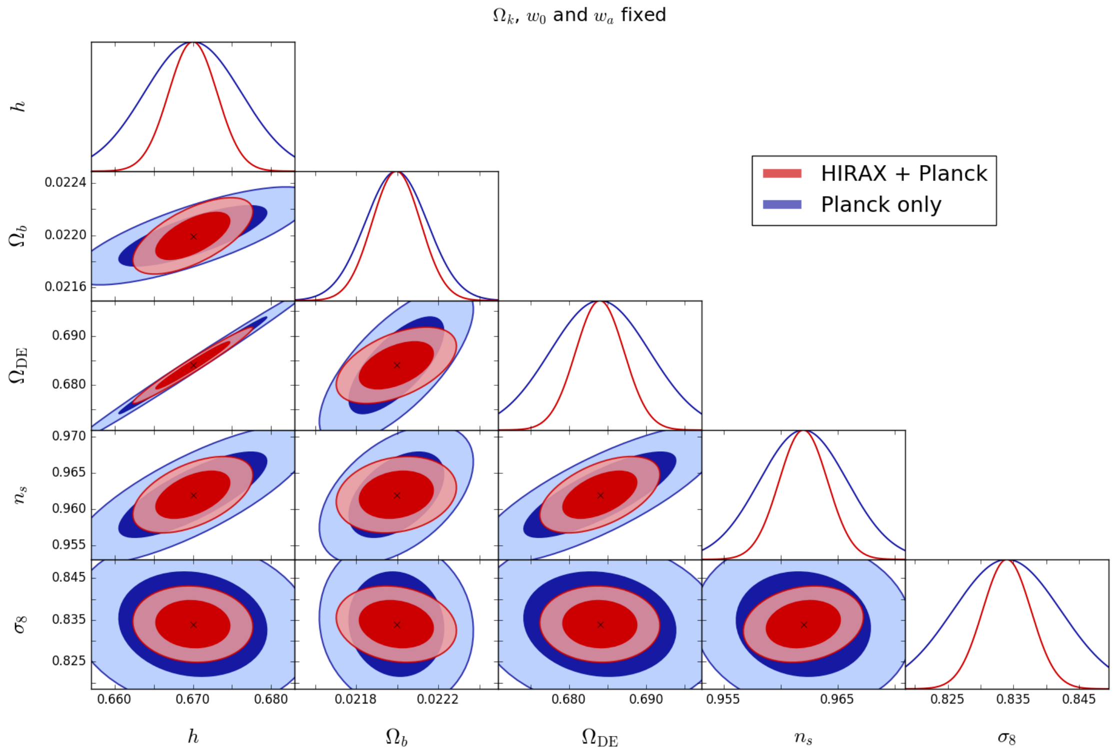
Detour to Cosmology

Standard six-parameter ΛCDM

- Ω_b : baryon density
- Ω_c : dar matter density
- t_0 : age of universe
- n_s : scalar spectral index
- Δ^2_R : spatial curvature fluctuations
- τ : optical depth to reionization

Cosmological Parameter Forecasts

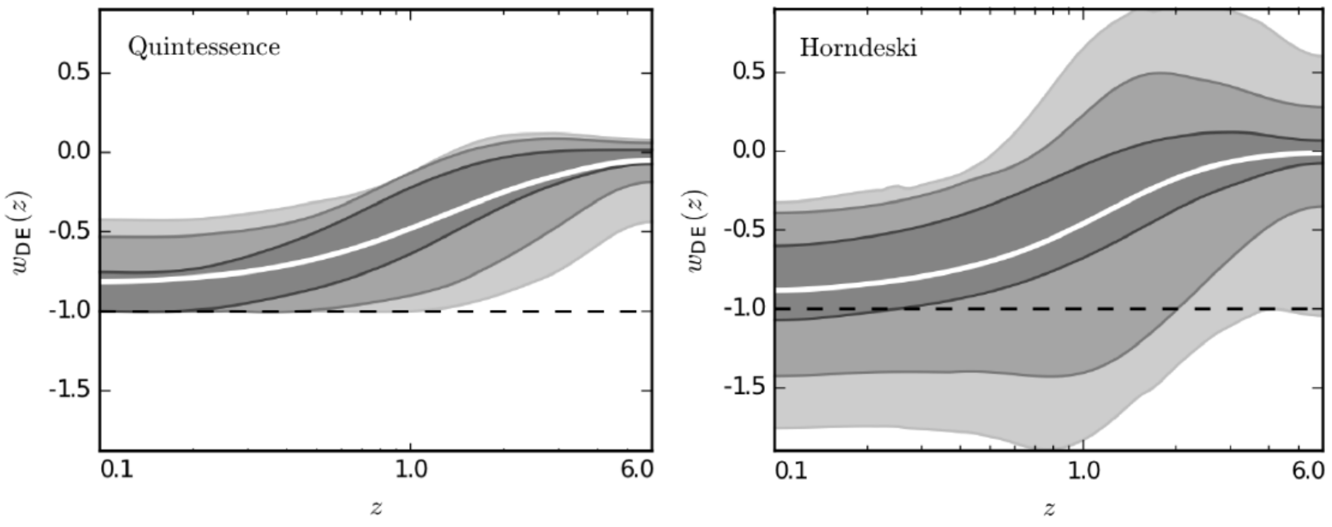
- Example forecast of "current gen" constraints, for HIRAX based on 2000 sq deg survey with 1024 element array, 50K noise temperature, and 10,000 hours observing, with Planck priors
- Expect to improve constraints on late-time cosmological parameters (σ_8, Ω_b, Ω_{DE}, n_s) to <1%



Newburgh et al. 2016 Plots by Amadeus Witzemann

Time Variations in Dark Energy

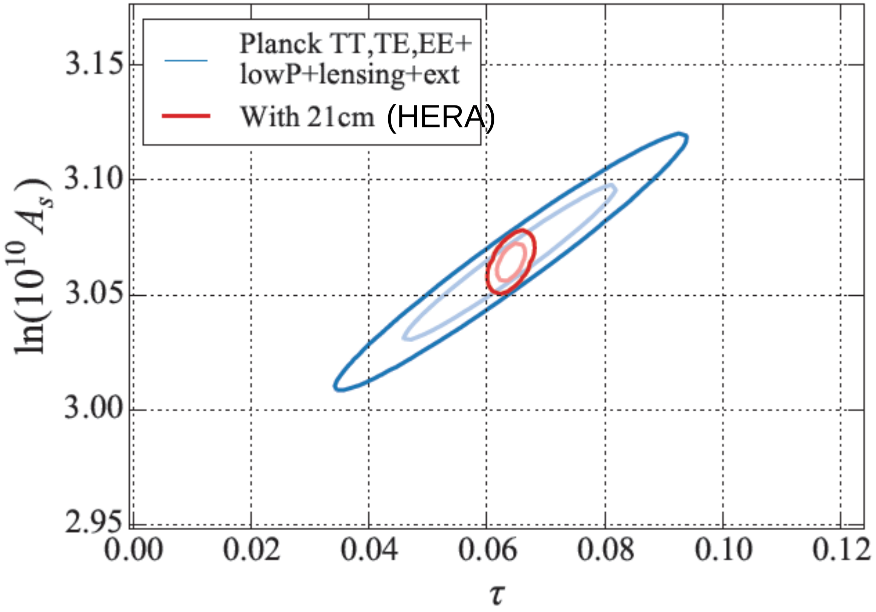
- Moving beyond standard ΛCDM model, dynamics of dark energy are easiest to distinguish from cosmological constant at early times ($z > 1$) when dark energy is first turning on.
- 21cm observations have potential to give powerful statistical measurements at appropriate redshifts.



Line Intensity Mapping: 2017 Status Report (arxiv 1709.09066)

Breaking Degeneracies

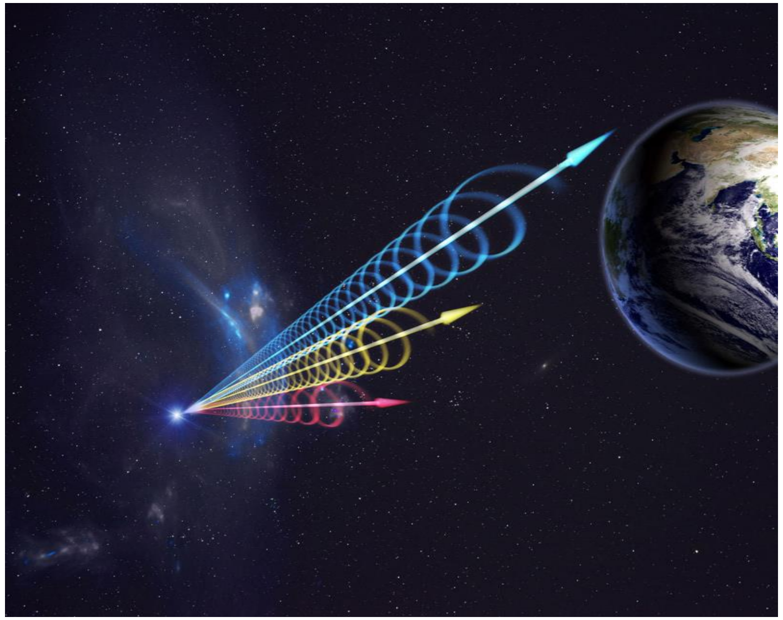
- 21cm observations provide a measurement of the optical depth to Recombination, τ, which is independent of CMB derived τ.
- This allows 21cm to break degeneracies in existing CMB measurements, and significantly improve cosmological parameter constraints.

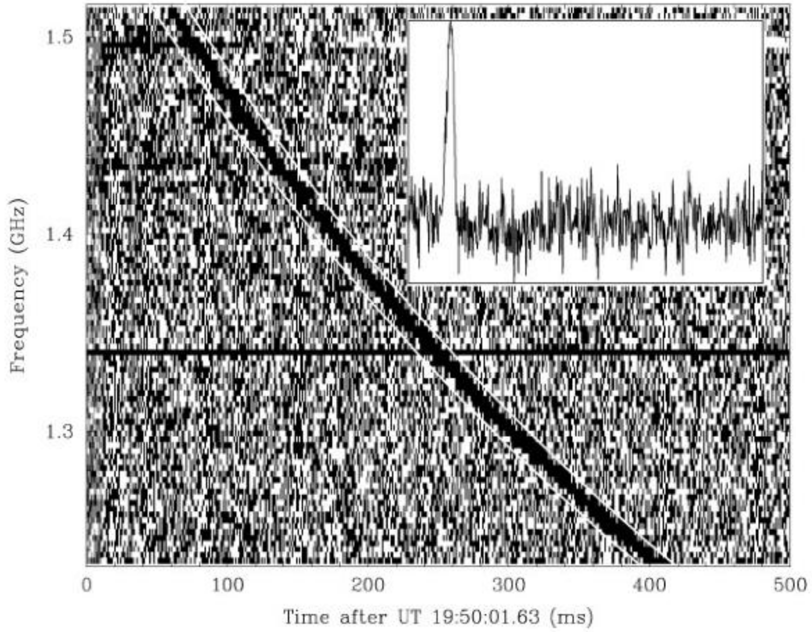


Cosmology with the Highly Redshifted 21cm Line (arxiv 1903.06240)

Fast Radio Bursts

- Fast radio bursts: short (~ms), bright (~Jy) radio transients
- Distances are likely cosmological because of observed dispersion measure (integrated column density of free electrons between observer and source)
- Few hundred detected, but total event rate ~10^4 per day over full sky
- Event rate prop. to D_dish*N_beams, so full CHIME/HIRAX arrays should detect dozens per day
- Potentially new method to independently constrain τ





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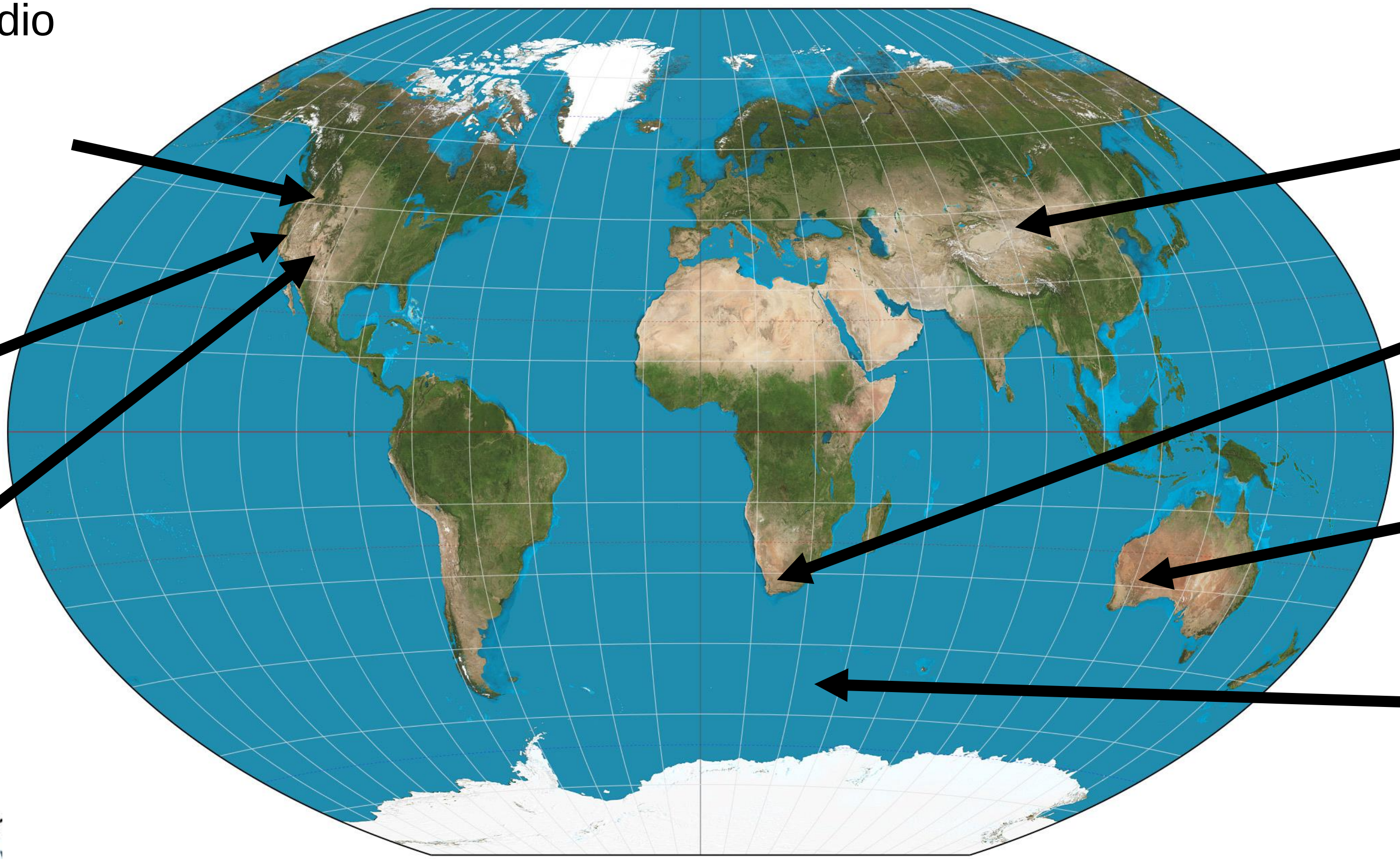
Current Experiments: An International Endeavor!

Dominion Radio Astronomy Observatory, Canada

Owens Valley Radio Observatory, CA, USA

NRAO, NM, USA



Tianlai Observatory, China

South African Karoo Radio Quiet Zone

Australian Radio Quiet Zone

Marion Island Research Station, SA

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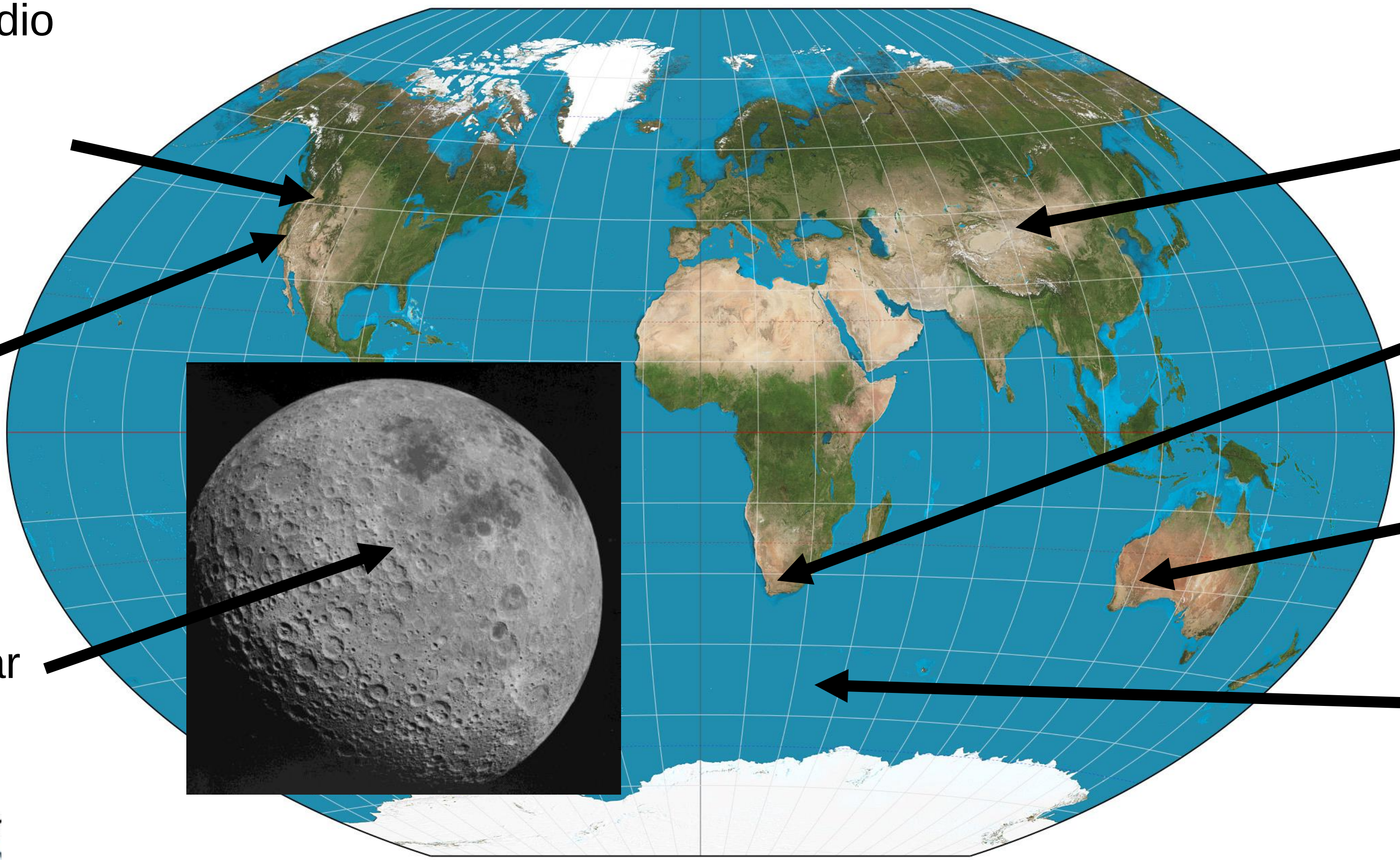
Current Experiments: An International Endeavor!

Dominion Radio Astronomy Observatory, Canada

Owens Valley Radio Observatory, USA

LuSEE, Lunar Farside



Tianlai Observatory, China

South African Karoo Radio Quiet Zone

Australian Radio Quiet Zone

Marion Island Research Station, SA

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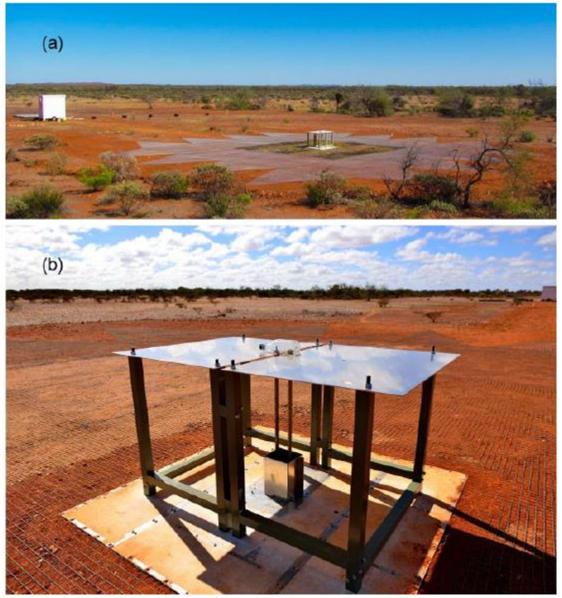
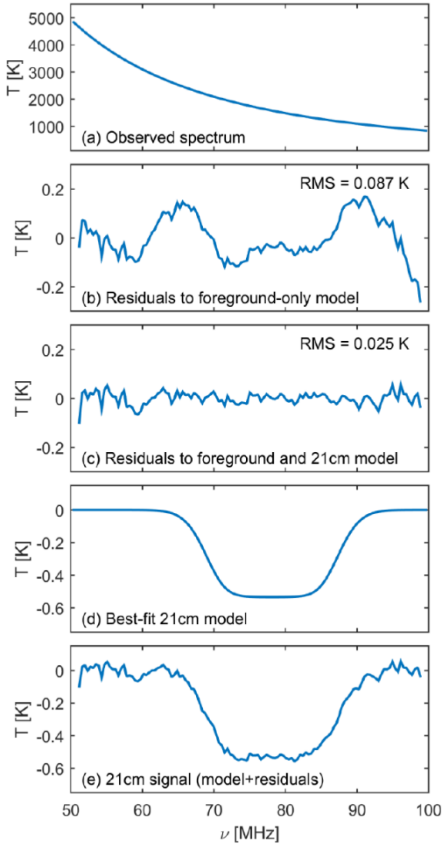
Current Experiments: EDGES

- In Australian outback, measures “global” or “monopole” 21cm signal at high redshift
- Low band: 50-100 MHz, 27 < z < 13
- High band: 90-190 MHZ, 15 < z < 6.5
- Measure absorption profile indicating first stars at z~180 My after Big Bang
- Cosmological implications of depth of absorption disputed
- PRIZM and LEDA will make measurements in similar redshift range.

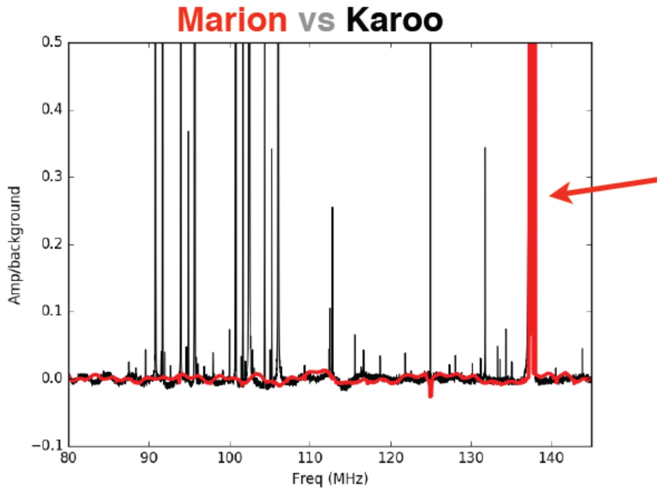




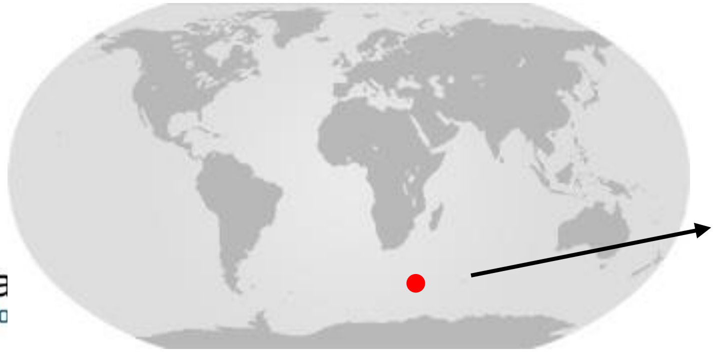
EDGES collaboration (arxiv 1810.05912)

Current Experiments: PRI^{Z}M

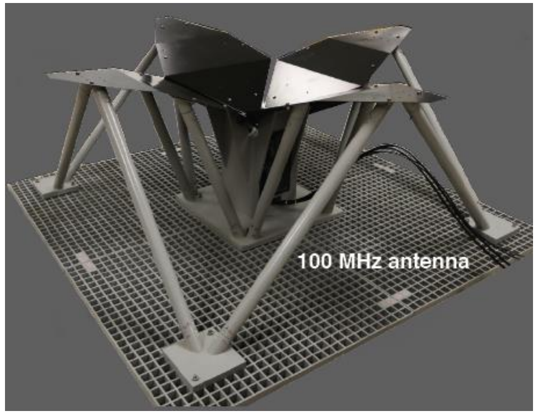
- Located at Marion Island, 2000 km south of South Africa
- 70 MHz and 100 MHz antennas, $9 < z < 25$
- Pristine RF environment for low frequency instruments



Orbcomm Satellites 137-138 MHz

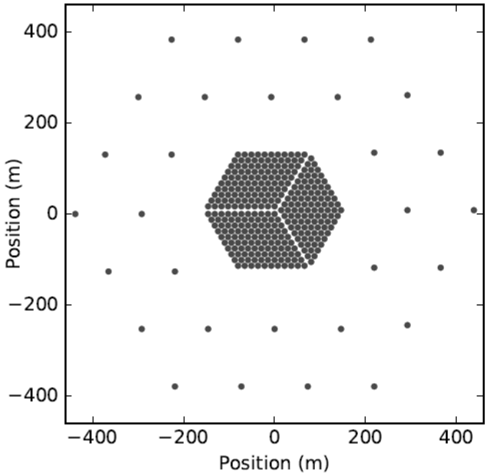


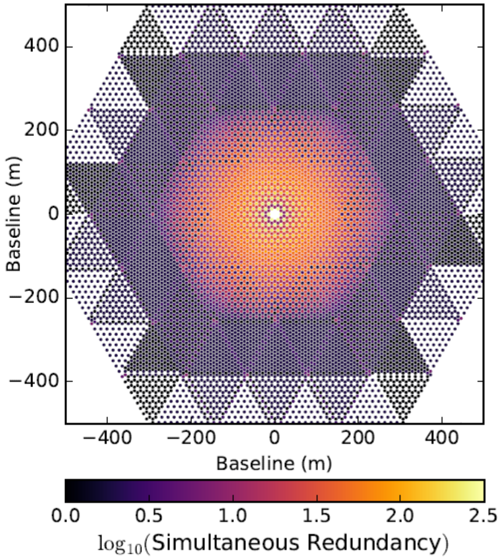
20 km x 12 km



Current Experiments: HERA

- 350 14m diameter dishes, located at the SKA-SA site
- 100-200 MHz ($6 < z < 30$), designed to probe reionization history
- Highly redundant array layout for ease of calibration
- Intentionally broken symmetry (offset diamond sections) plus outriggers improves *uv* coverage, and suppresses grating lobes in synthesized beam





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Current Experiments: HIRAX and CHIME

	CHIME	HIRAX
Site	DRAO, Canada	SKA site, South Africa (lower RFI, no snow)
Telescope	Cylinder array	Dish array (easier to baffle)
Field of view	100° NS, 1°– 2° EW	5° – 10° deg
Beam size	0.23° – 0.53°	0.1° – 0.2°
Collecting area	8000 m^2	28,000 m^2
Sky coverage	North	South
Frequency	400-800 MHz	
Redshift	0.8-2.5	
δz/z	0.003 (min)	
Goals	BAO cosmology, radio transient searches, pulsar searches/timing, neutral hydrogen absorbers, diffuse polarization of Milky Way	

Current Experiments: LuSEE

- Site: the literal farside of the moon
- Bandwidth: 500kHz – 50MHz, redshift of $1100 < z < 27$ – The Cosmic Dark Ages!
- Largely a technology demonstrator: prove that we can operate radio telescope in the harsh environment of the moon, survive 2 weeks of night, and deal with foregrounds
- Will produce best constraints of low frequency sky, even if Dark Ages 21cm signal not detected.

Conclusions

- Opening observations to wider range of wavelength gives more information about the universe.
- Different technologies are required to detect emissions at different wavelengths.
- There is a vast amount of cosmological information that has not been probed that is accessible through 21cm and CMB observations, including some epochs that may only be accessible at these wavelengths.
- There are significant technical and technological challenges to making such measurements, but good progress is being made by a cohort of current experiments.
- The future is (radio) bright!