Characterization of CHIME's Complex Gains using New Transits of CygA and CasA

November 21 2018

[1] Department of Physics & Astronomy, University of British Columbia

Outline

① Motivation
- Cosmological purpose of CHIME
- Importance of calibration

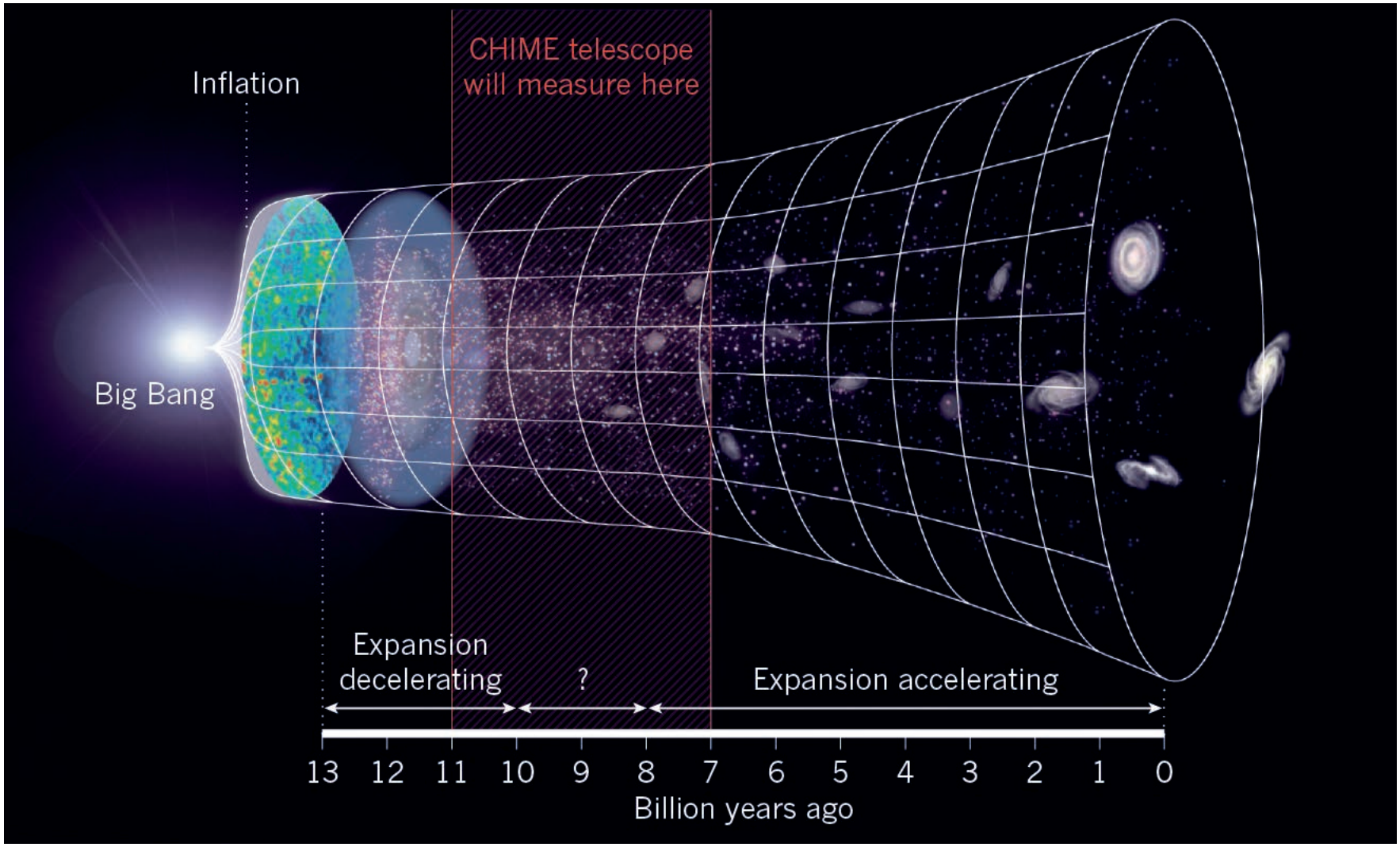
② Theory
- ΛCDM model
- Baryon acoustic oscillations

③ Experiment
- CHIME working principle
- Proposed research

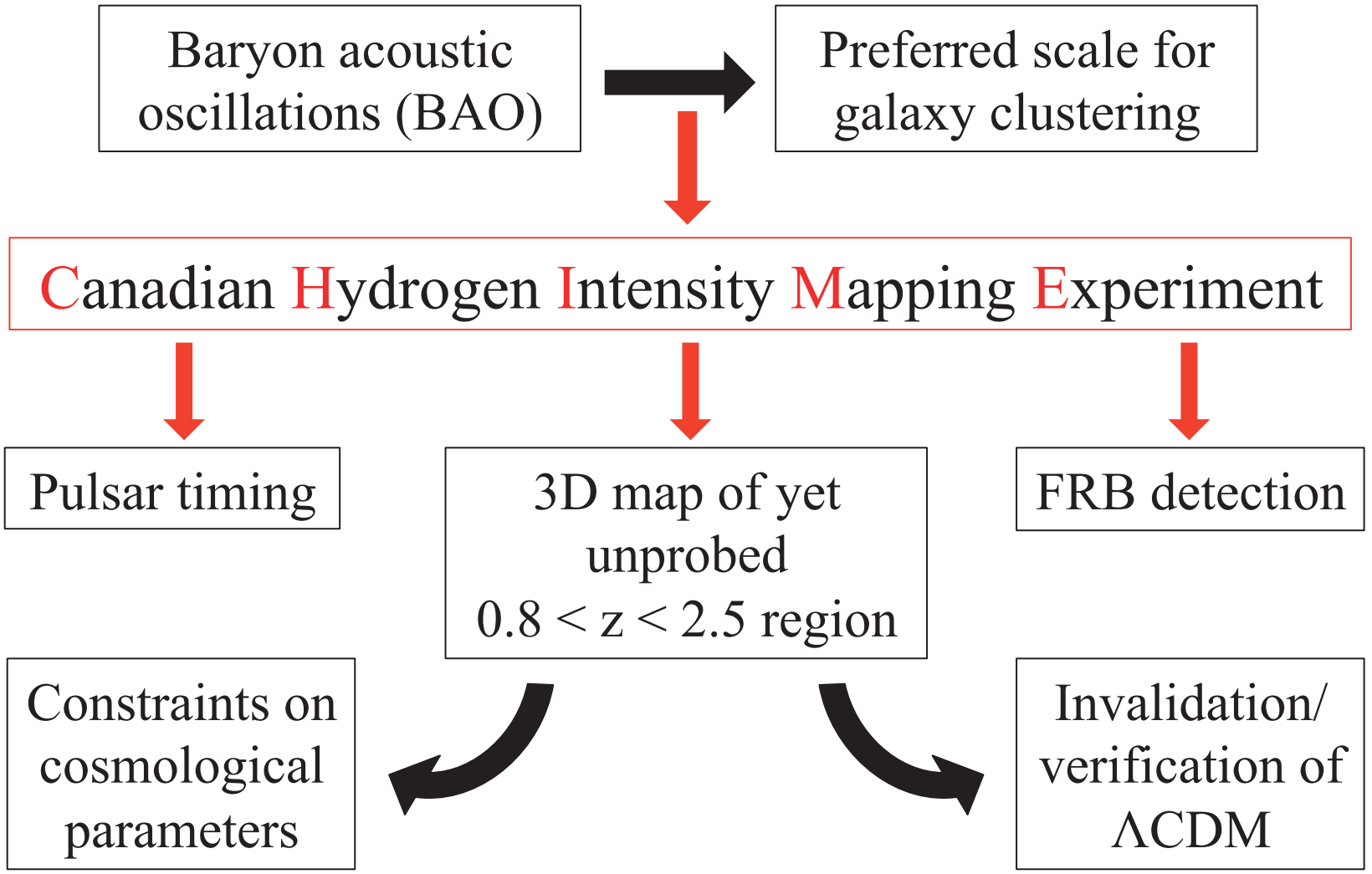
④ Resources

⑤ Summary

Motivation


Inflation
CHIME telescope
will measure here
Big Bang
Expansion
decelerating
?
Expansion accelerating
13 12 11 10 9 8 7 6 5 4 3 2 1 0
Billion years ago

Motivation


Baryon acoustic oscillations (BAO)
Preferred scale for galaxy clustering
Canadian Hydrogen Intensity Mapping Experiment
Pulsar timing
3D map of yet unprobed 0.8 < z < 2.5 region
FRB detection
Constraints on cosmological parameters
Invalidation/ verification of ΛCDM

Motivation

Calibration and thermal model

✧ Foreground 10^3 to 10^5 times brighter than cosmological signal
- ➢ Very accurate calibration is necessary

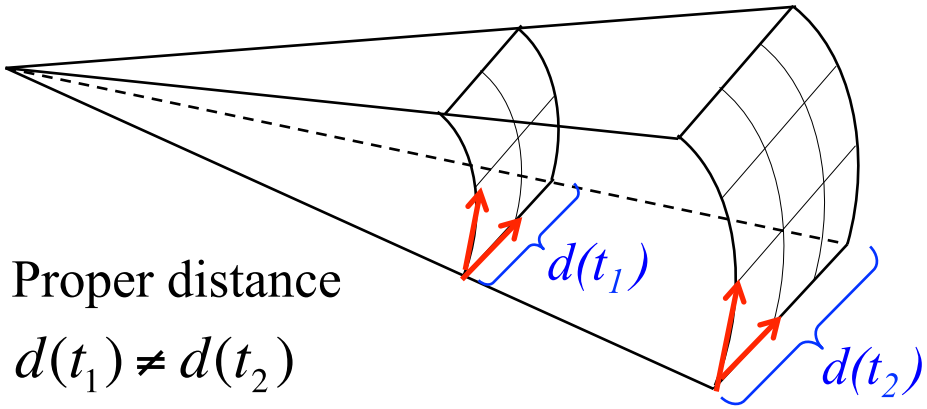
✧ Gains affected by thermal expansion of structures
- ➢ Thermal susceptibility needs to be determined

✧ Previous attempts unsuccessful
- ➢ Noise injection method not ideal

✧ New archive of stable CygA and CasA transits data
- ➢ Opportunity of using direct sky observations to calibrate

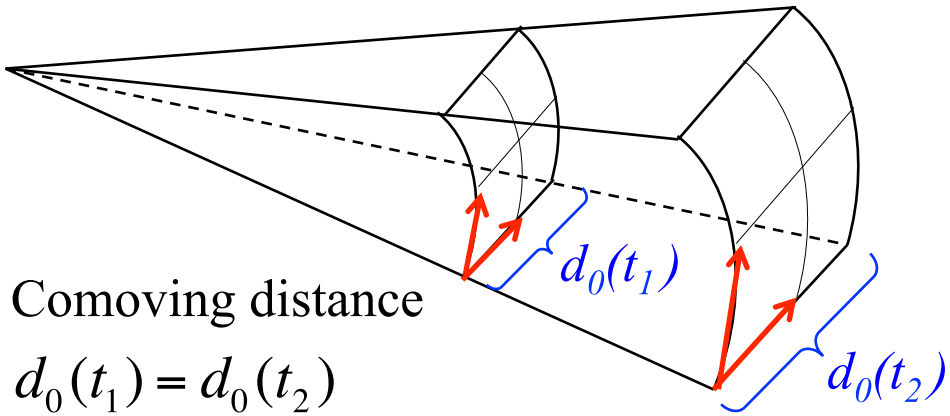
Cosmological concepts

Scale factor



Proper distance

$d(t_1) \neq d(t_2)$



Comoving distance

$d_0(t_1) = d_0(t_2)$

- d and d_0 connected by scale factor a:

$$d(t) = a(t) d_0(t)$$

- Relation between scale factor and redshift:

$$\frac{1}{a(t)} = 1 + z$$

- Hubble's parameter:

$$H(z) = \frac{\dot{a}(t)}{a(t)}$$

ΛCDM model

Friedmann equation

$$H(z)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

Critical density

$$\rho_c = \frac{3H(z)^2}{8\pi G}$$

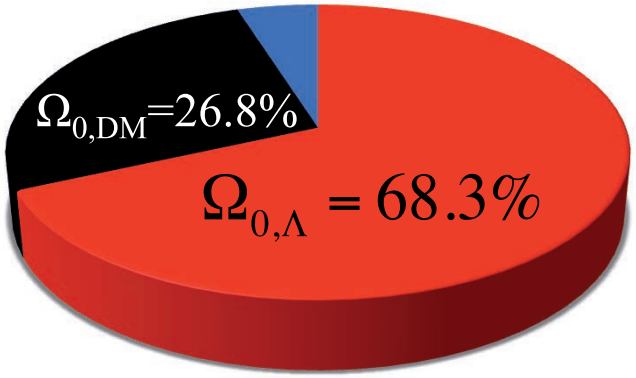
Equation of state

$$p_x = w_x \rho_x$$

$$\left(\frac{H(z)}{H_0}\right)^2 = \Omega_{0r} a^{-4} + \Omega_{0m} a^{-3} + \Omega_{0k} a^{-2} + \Omega_{0\Lambda} a^{-3(1+w_\Lambda)}$$

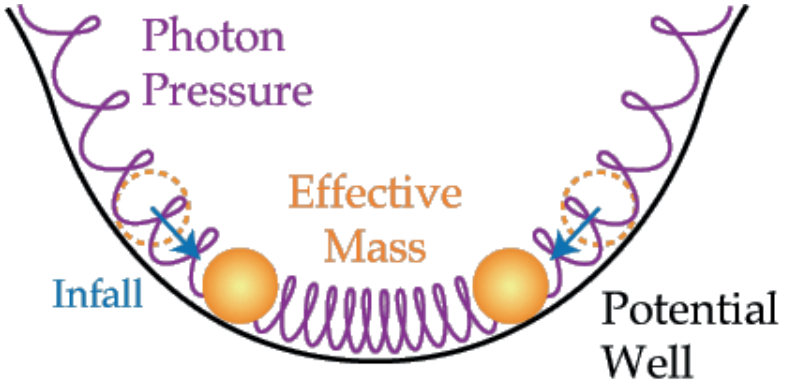
$$\Omega_x = \frac{\rho_x}{\rho_c}$$

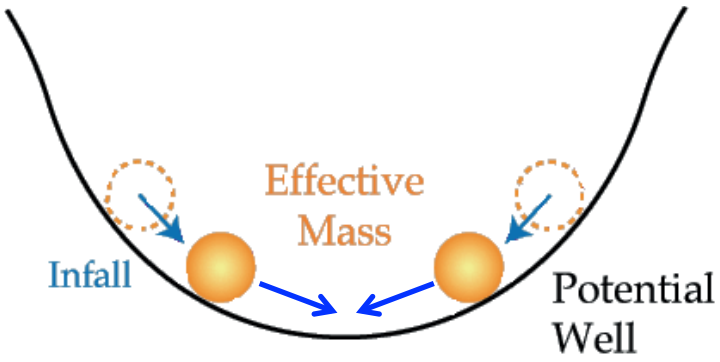
- Measurement of $H(z)$ => constraint on w_Λ
- ΛCDM assumes $w_\Lambda = -1$



Baryon Acoustic Oscillations

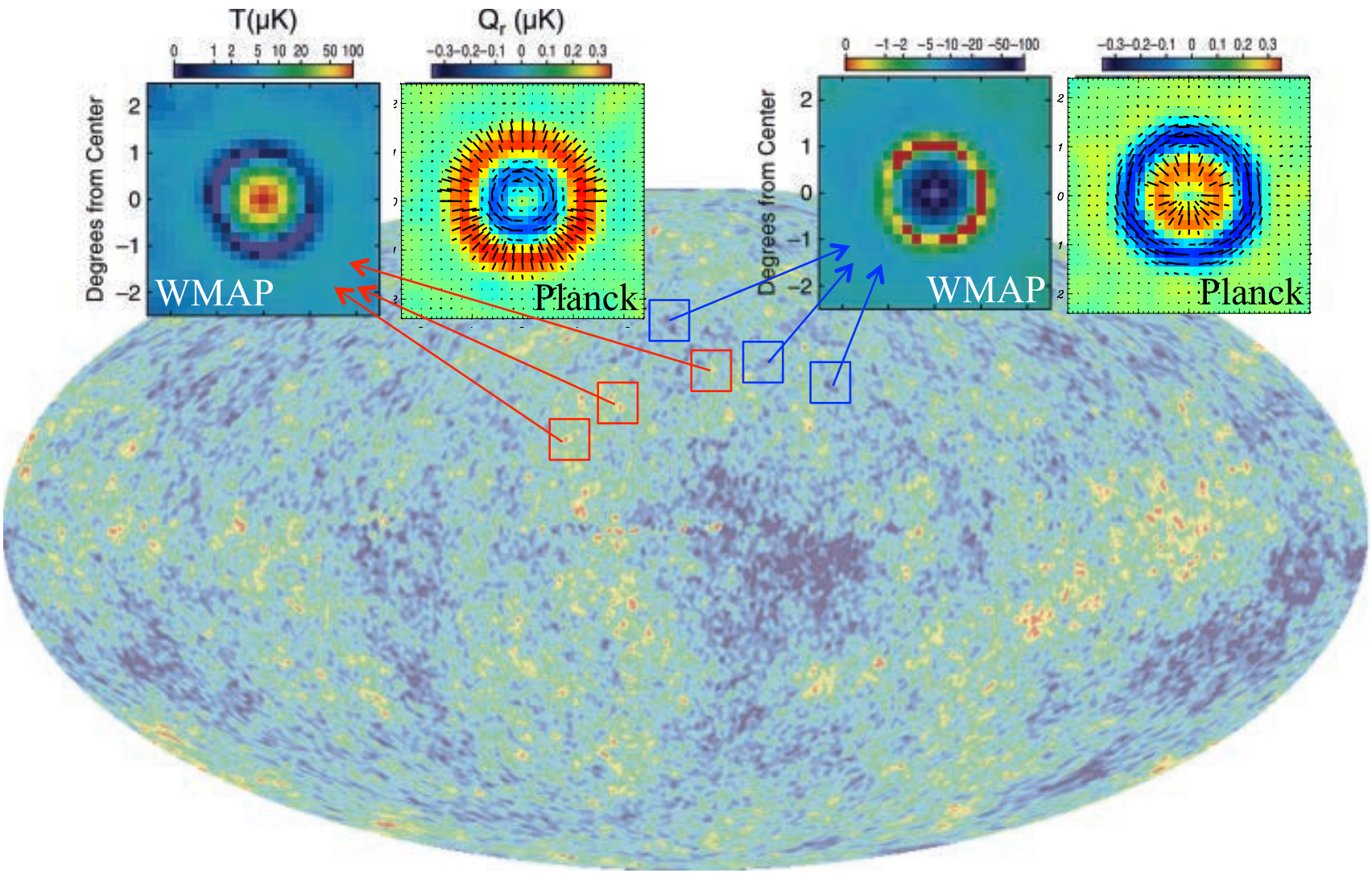
- Primordial density perturbations
  - Originating from inflation?
- Opposite influence of radiation pressure and gravity
  - Sound waves in baryon-photon plasma



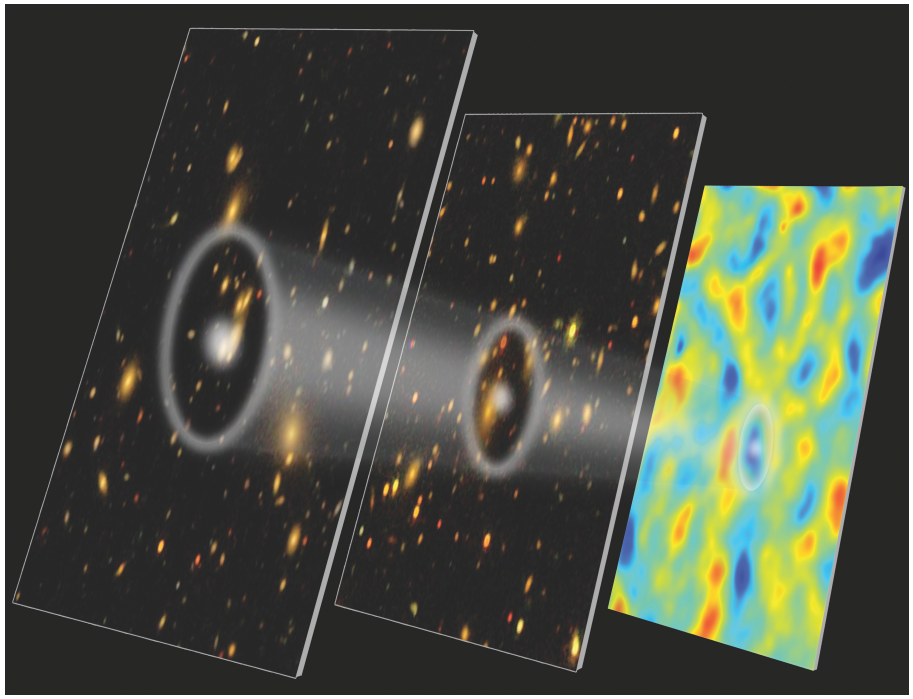


- Recombination: matter becomes neutral, photons decouple
  - Sound waves stop propagating
- Denser spherical shells of fixed comoving diameter

BAO in the CMB

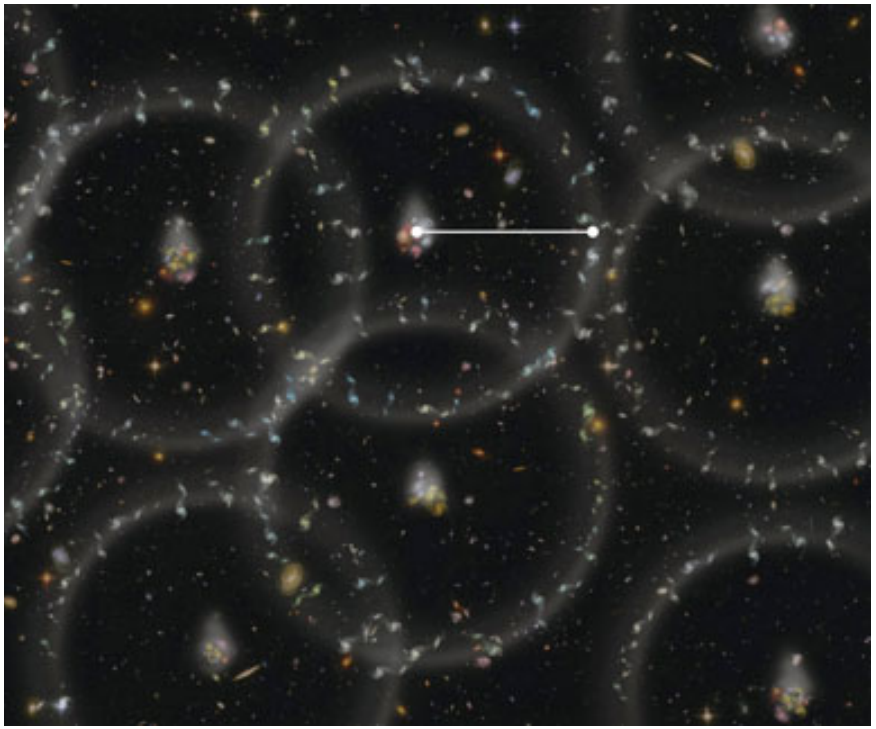


BAO as standard rulers



- Denser regions gradually attract dark and baryonic matter
- Preferred scale for galaxy clustering

- BAO structures have constant comoving radius
- Statistical standard rulers (SSR)



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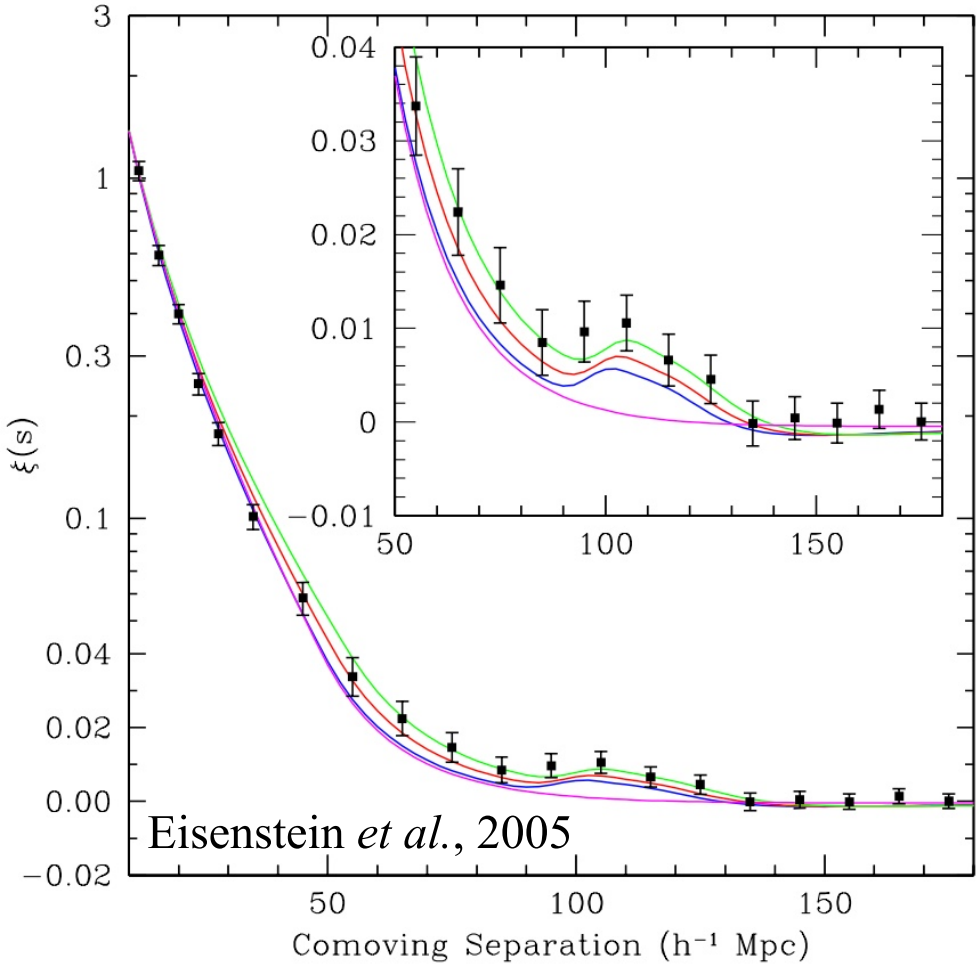
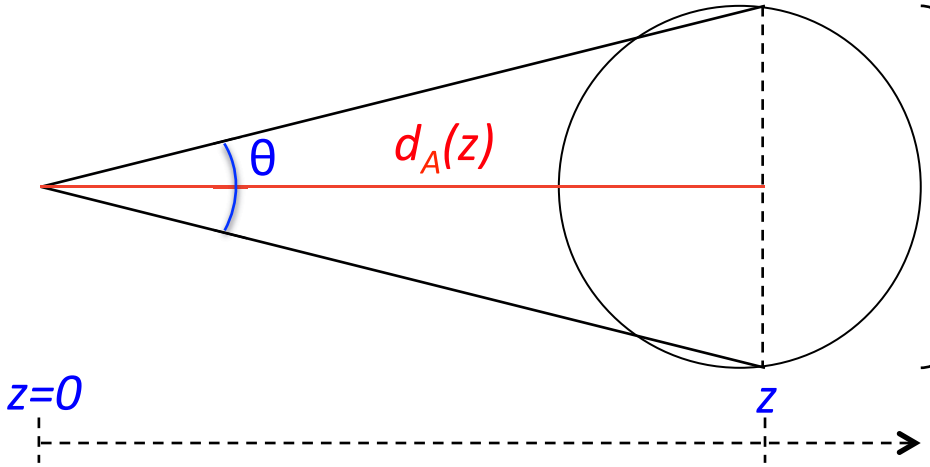


- BAO first detected in galactic survey in 2005
- Secondary peak in correlation function of galaxy distribution
- Measured sound horizon in good agreement with CMB data

BAO as standard rulers

✧ **Observation across the line of sight:**



$$s \cdot a(t)$$

$$= \frac{s}{1+z}$$

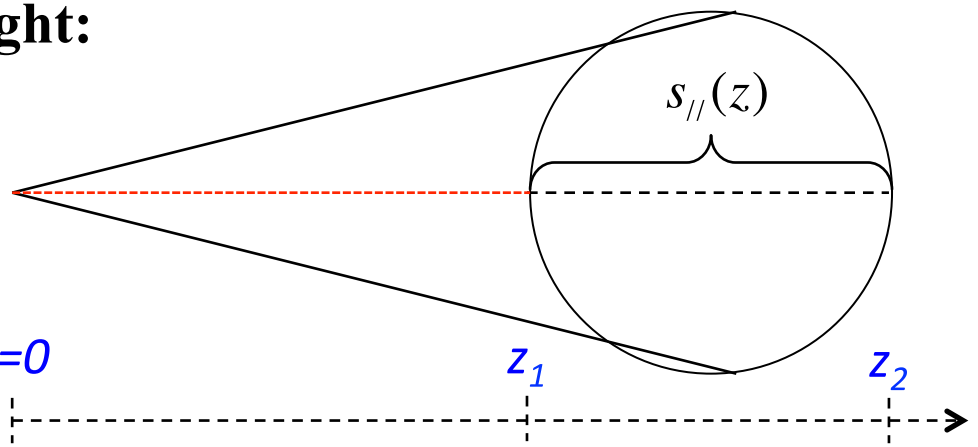
$$d_A(z) = \frac{s}{\theta(1+z)}$$

➢ Angular diameter distance

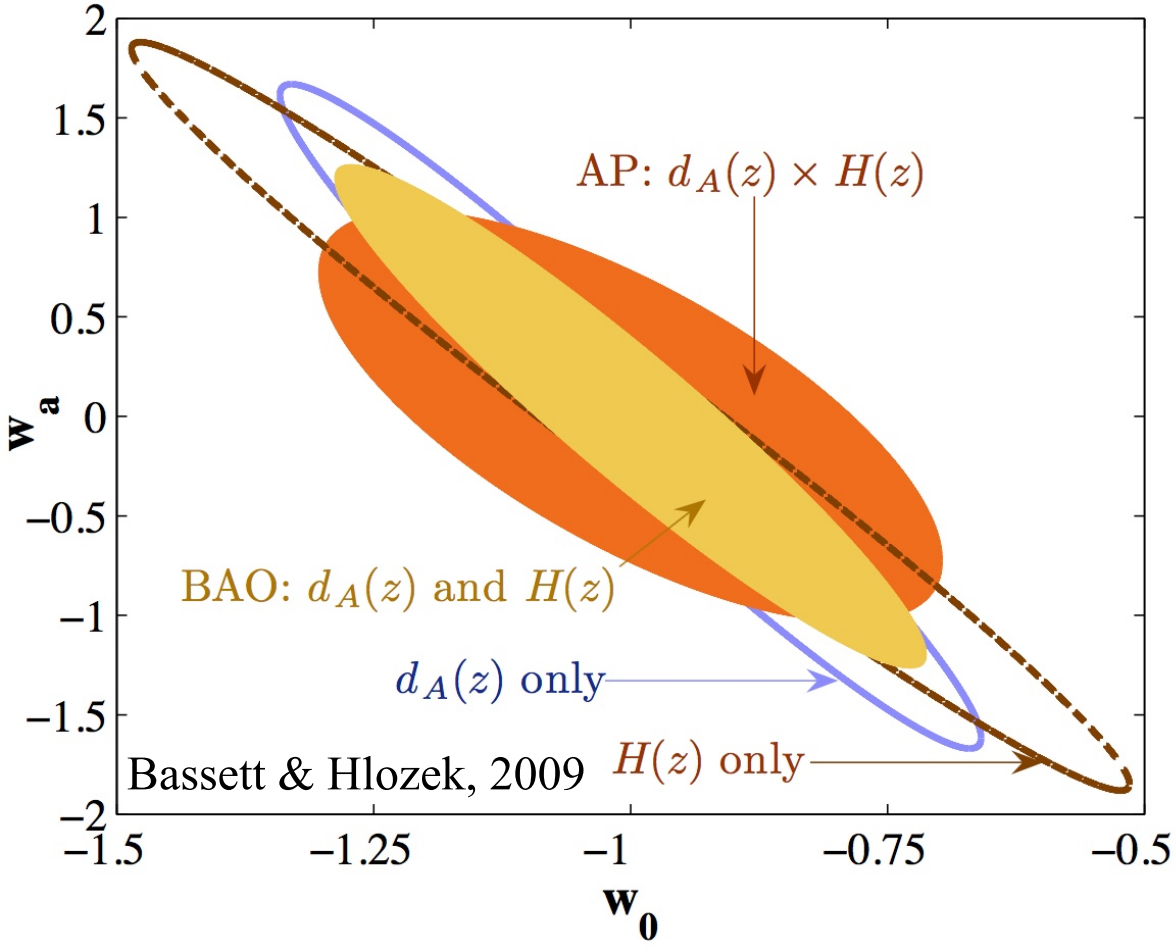
✧ **Observation along the line of sight:**

$$H(z) = \frac{c(z_2 - z_1)}{s_{//}(z)}$$

➢ Hubble's parameter



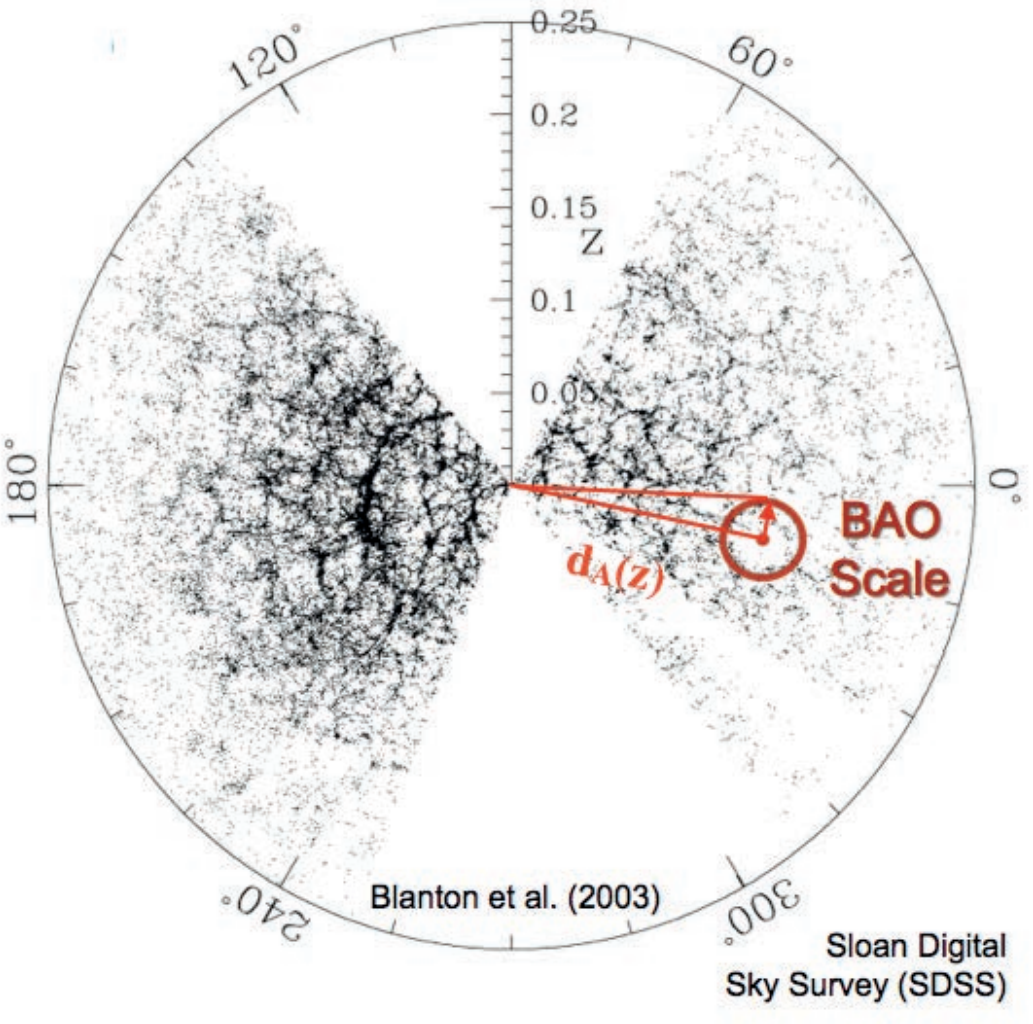
Constraints



A simultaneous measurement of $d_A(z)$ and $H(z)$ yields the tightest constraints!

Intensity mapping

- No need to resolve individual galaxies
  - Much faster than galactic surveys
- Observe 21 cm HI spin-flip line
- Density anisotropies => brightness temperature variations



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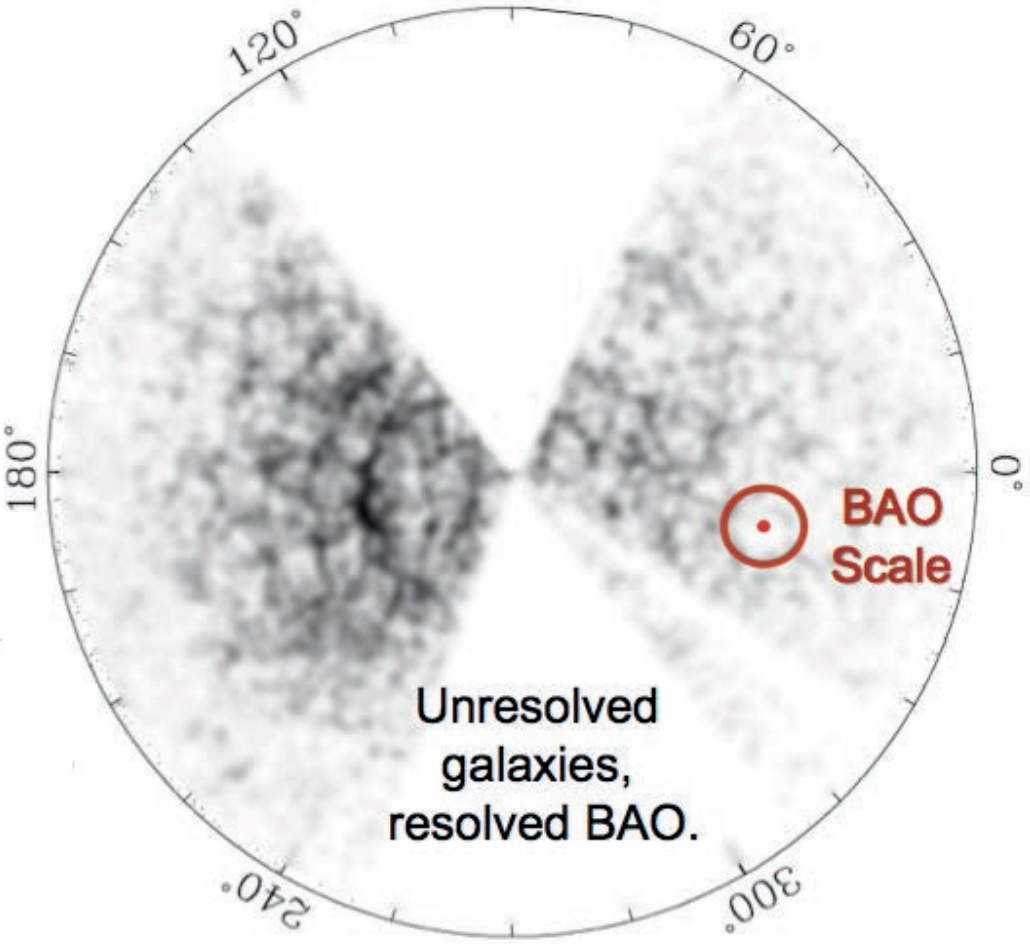
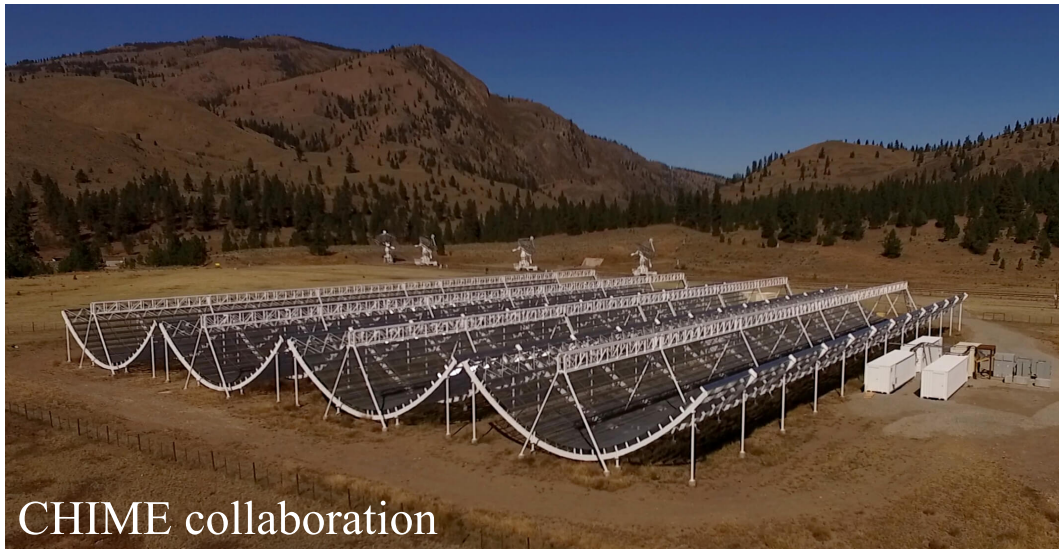
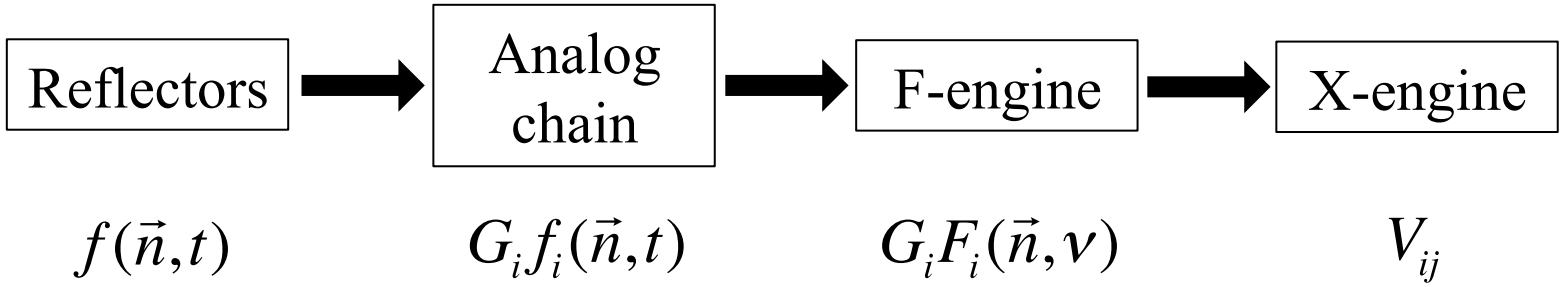


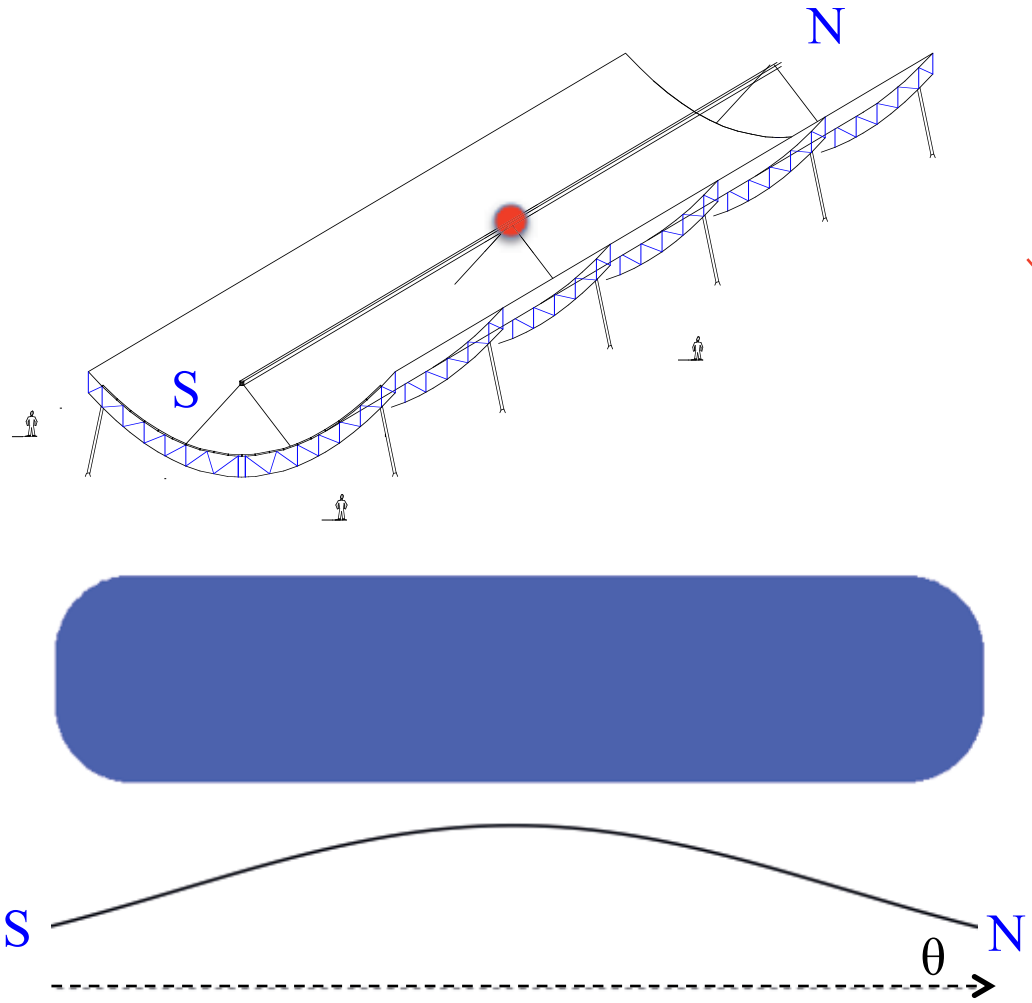
CHIME instrument

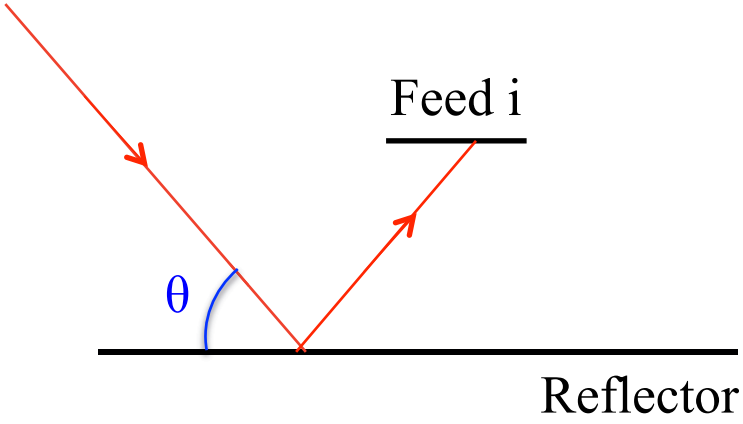


- Frequency range: 400-800 MHz
- 256 antennas on each cylinder
- 1024 frequency bins



Interferometry





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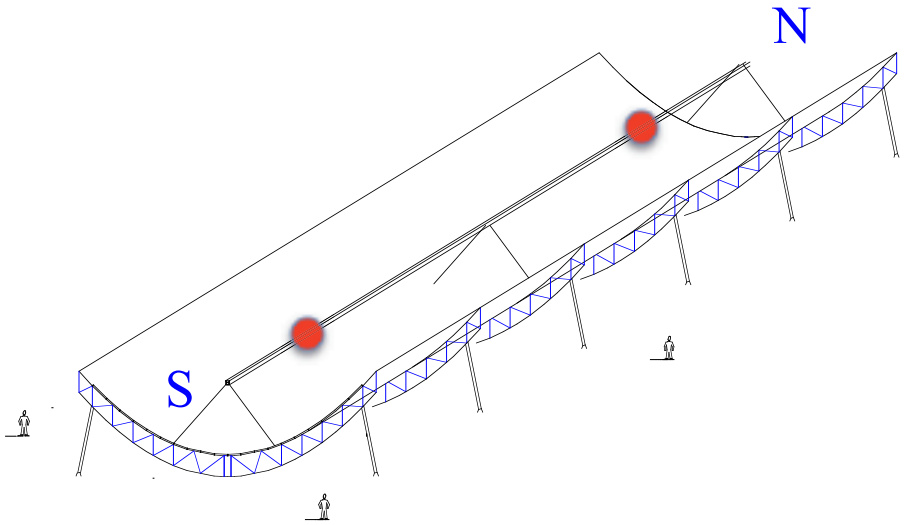
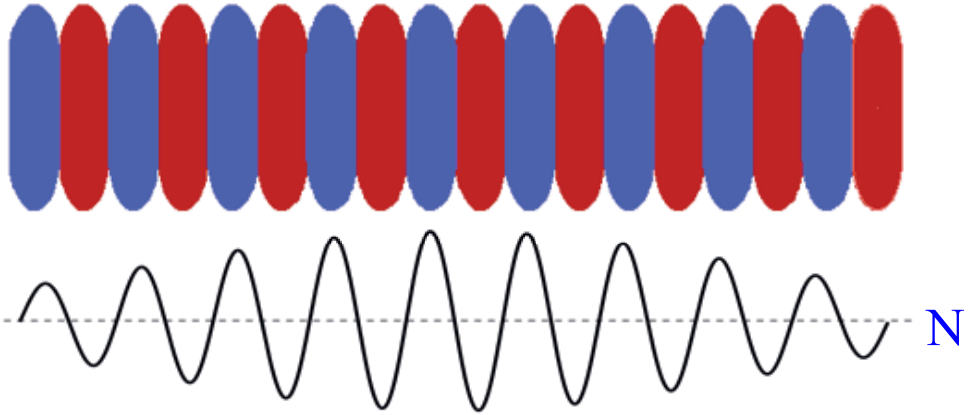
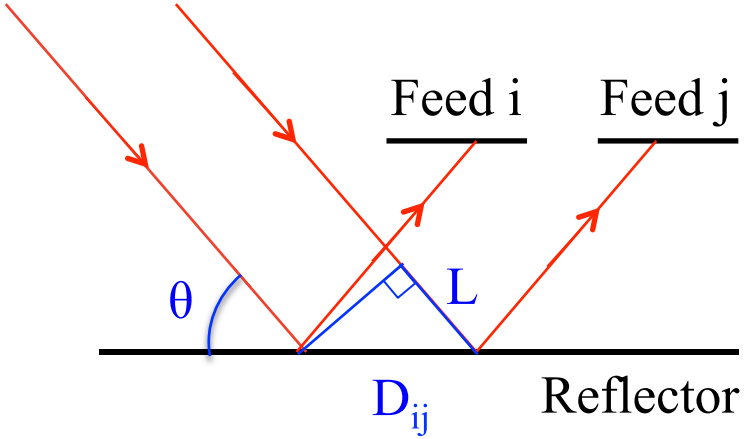
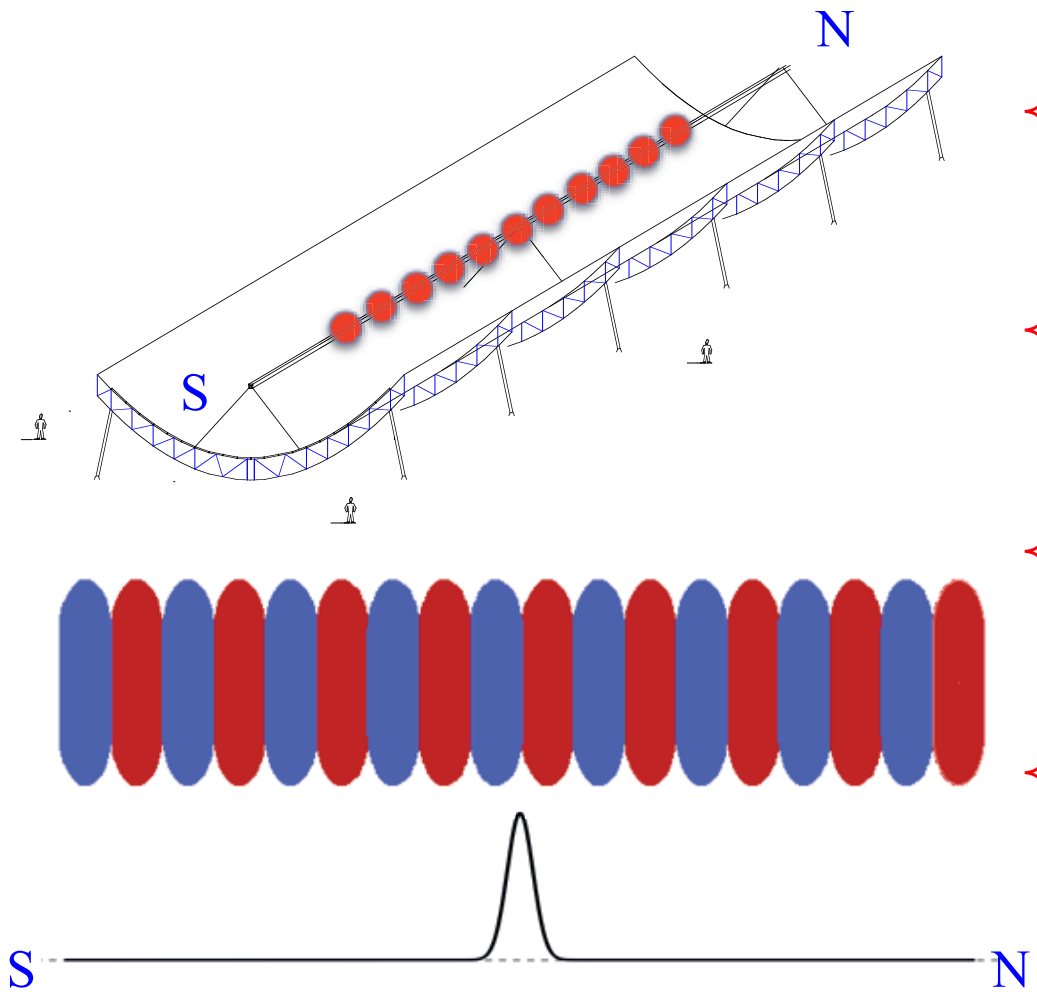




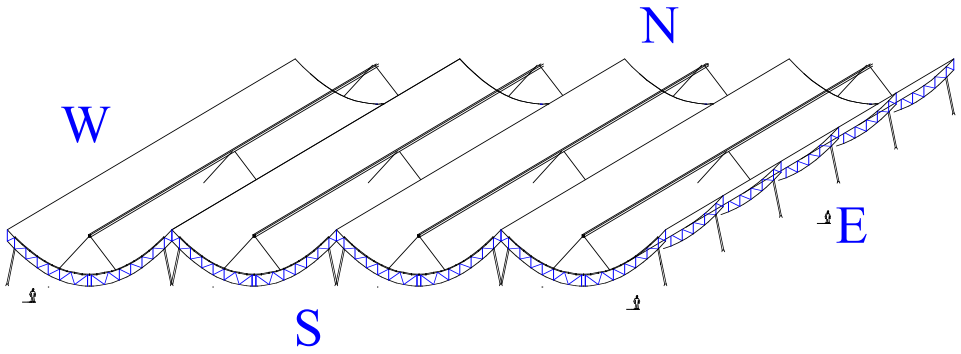


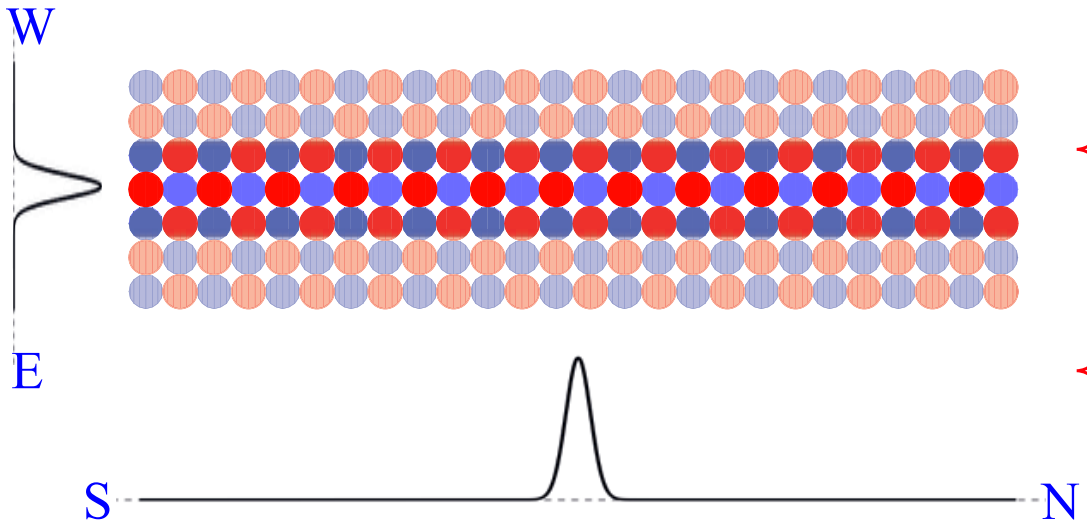
Interferometry



- Cross correlate signals from every pair of feeds
- 4×256 dual-polarization antennas
- 2048×2048 visibility matrix V_{ij} for each frequency bin
- Allows to accurately recover the original signal

Interferometry





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- 4×256 dual-polarization antennas
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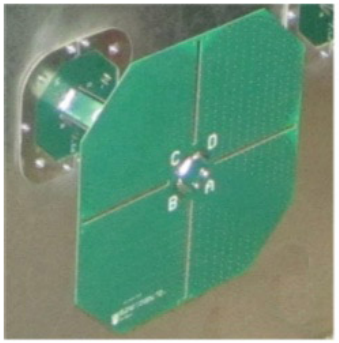
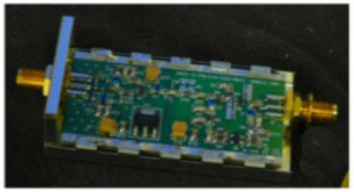
Analog signal chain

Feed antenna





Source of instrument's thermal susceptibility

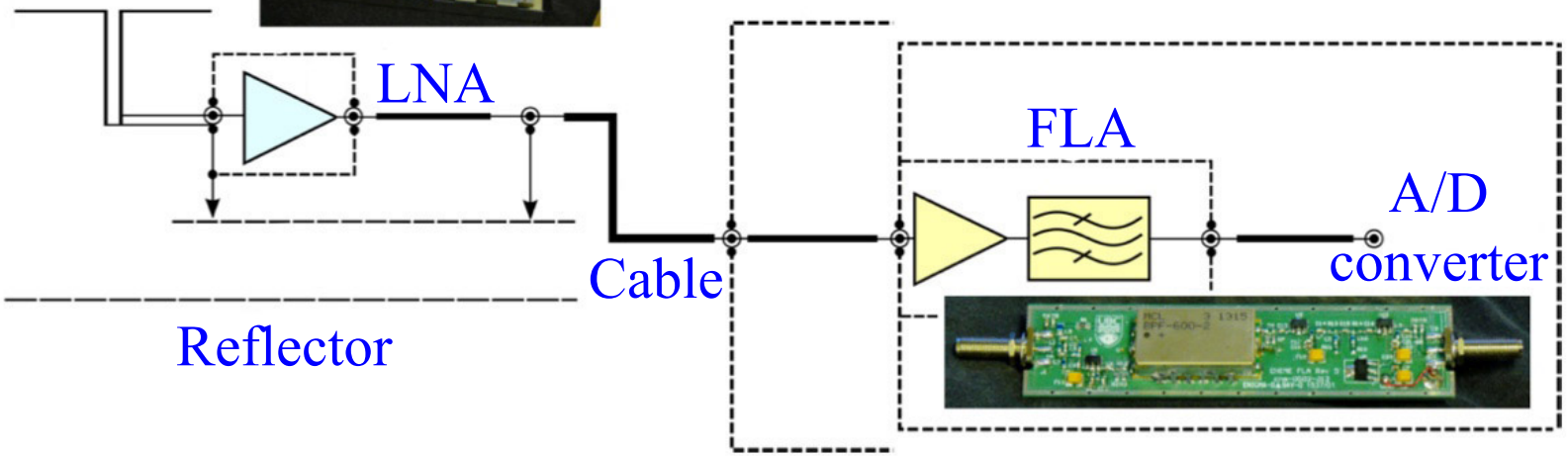
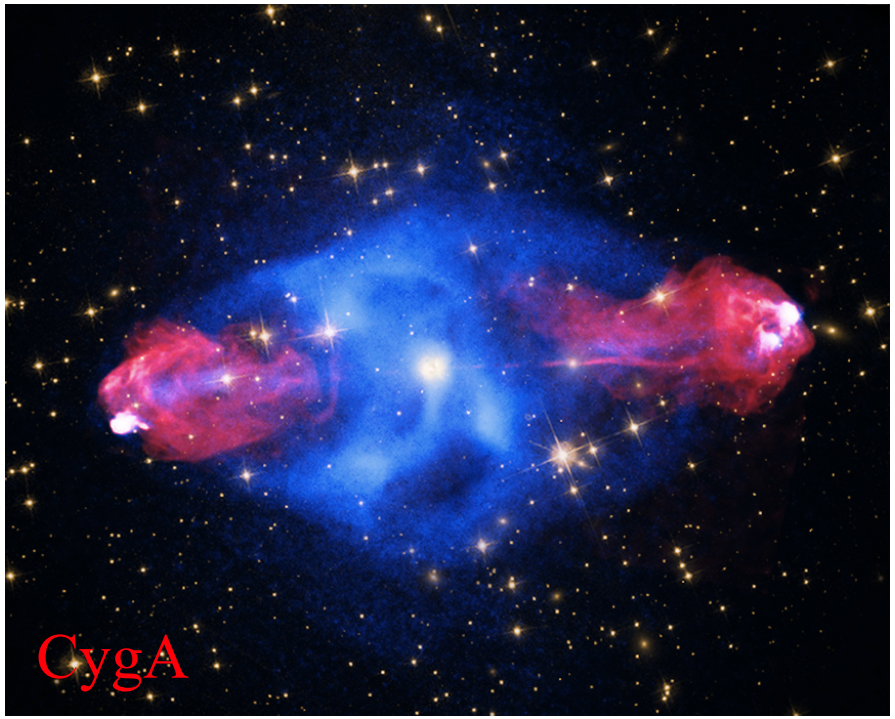


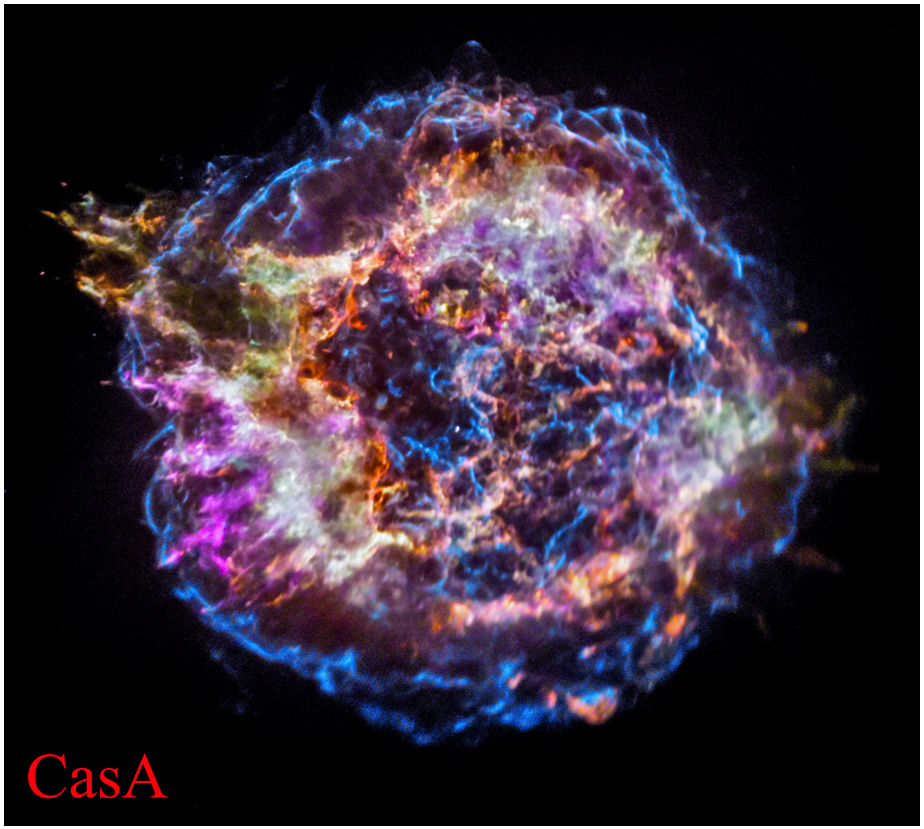
Image credit: CHIME collaboration

Proposed experiment



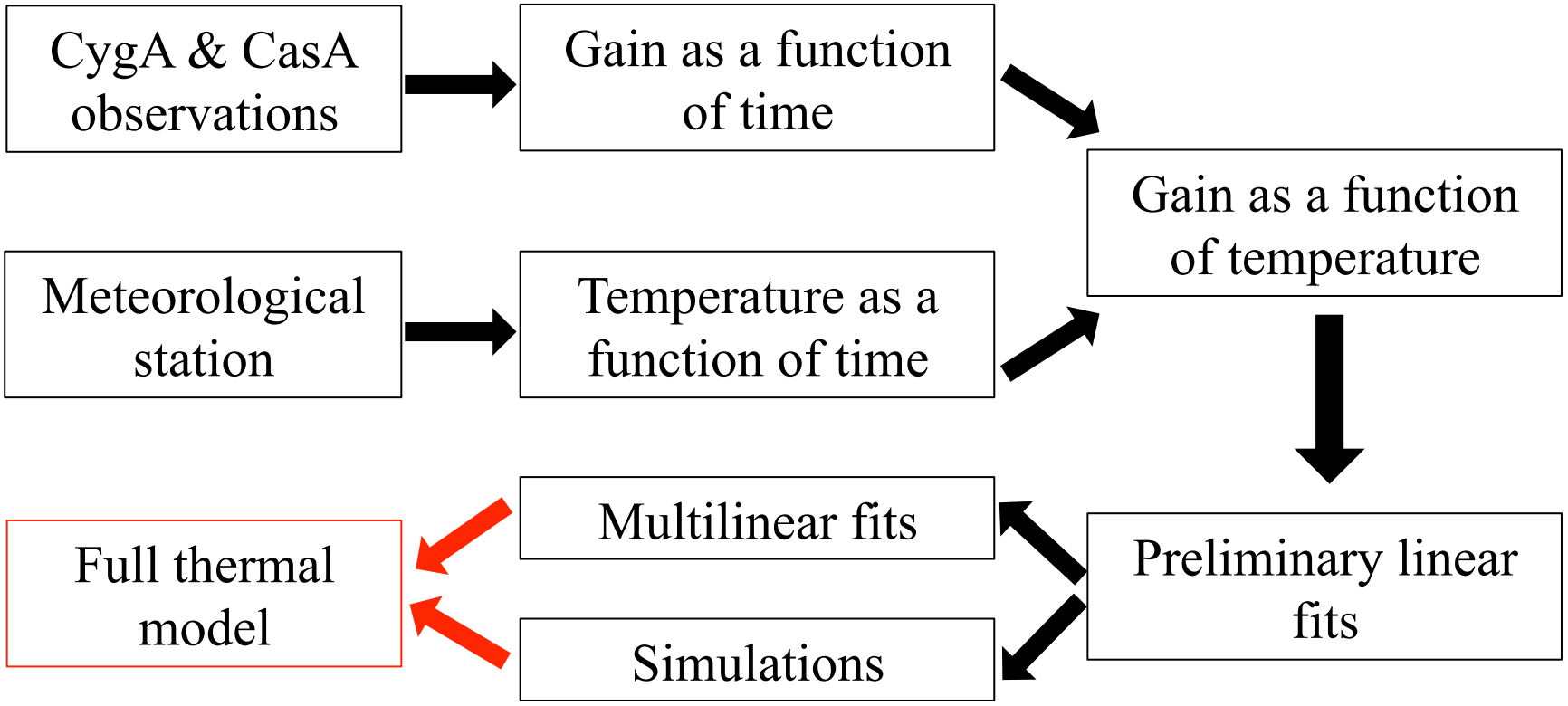
- Active galaxy
- 232 Mpc away

- Supernova remnant
- 11’000 light-years away



Proposed experiment

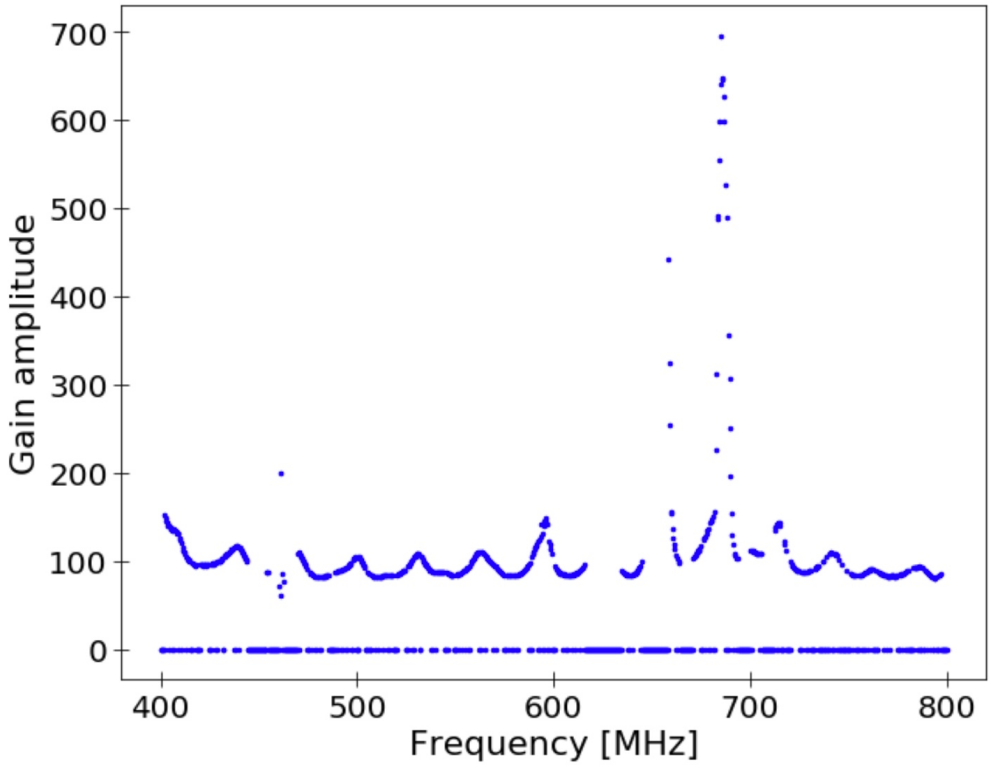
Objective: characterize analog chain's thermal susceptibility



Proposed experiment

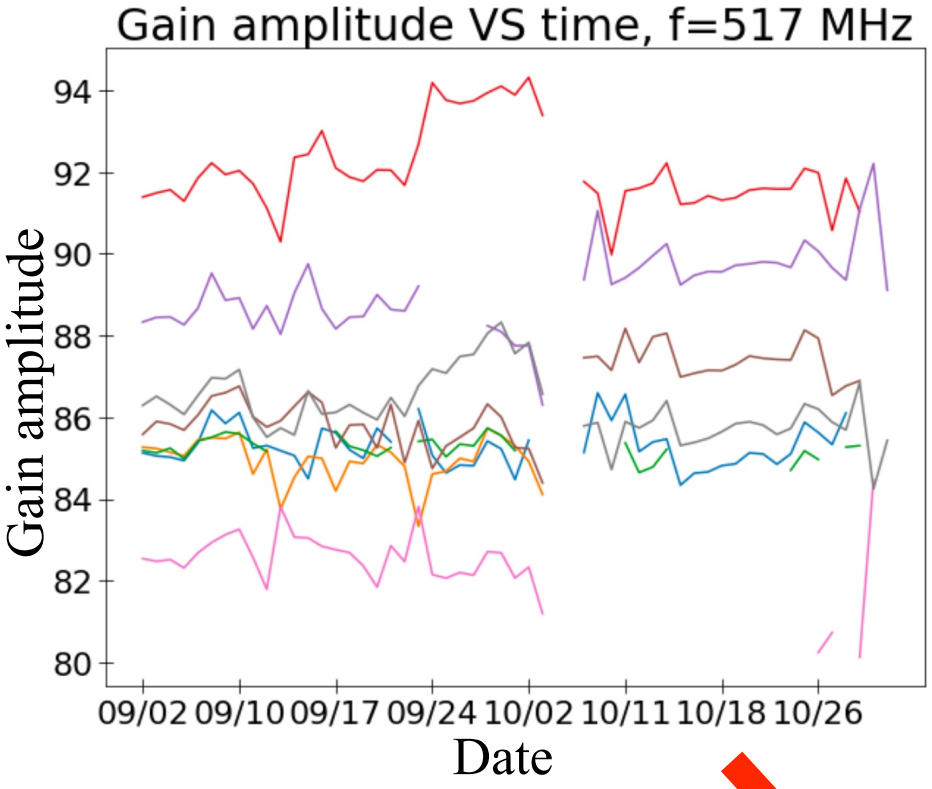
Typical unprocessed gain dataset

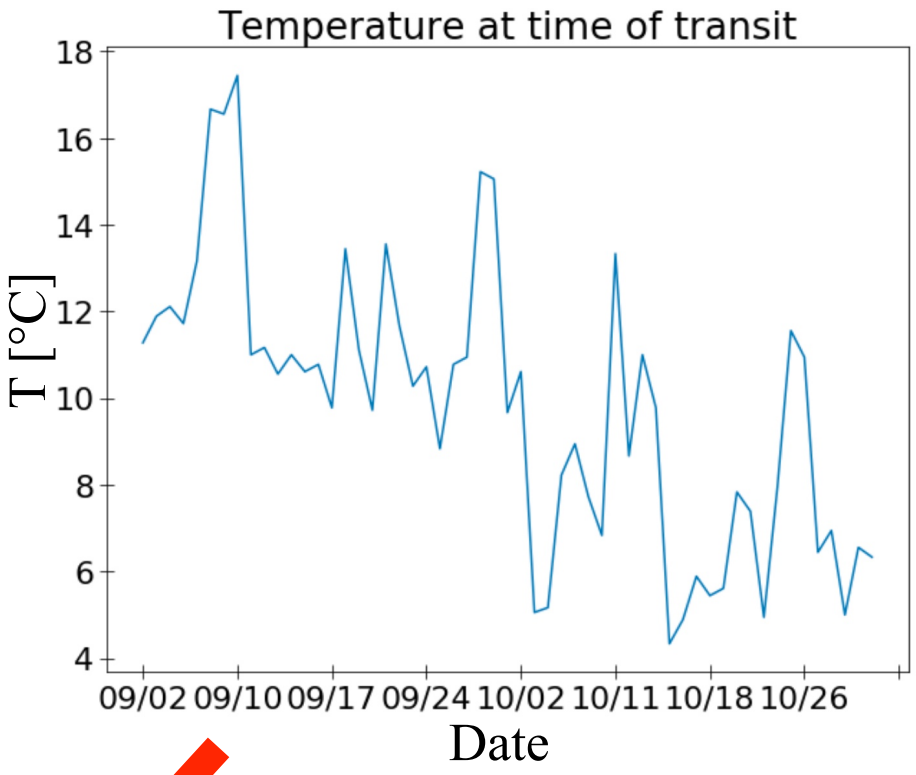
Channel 26, 13/09/18



- Peaks: foreground signals or measurement errors
- Null values: channel unresponsive to certain frequencies
- Outliers need to be removed

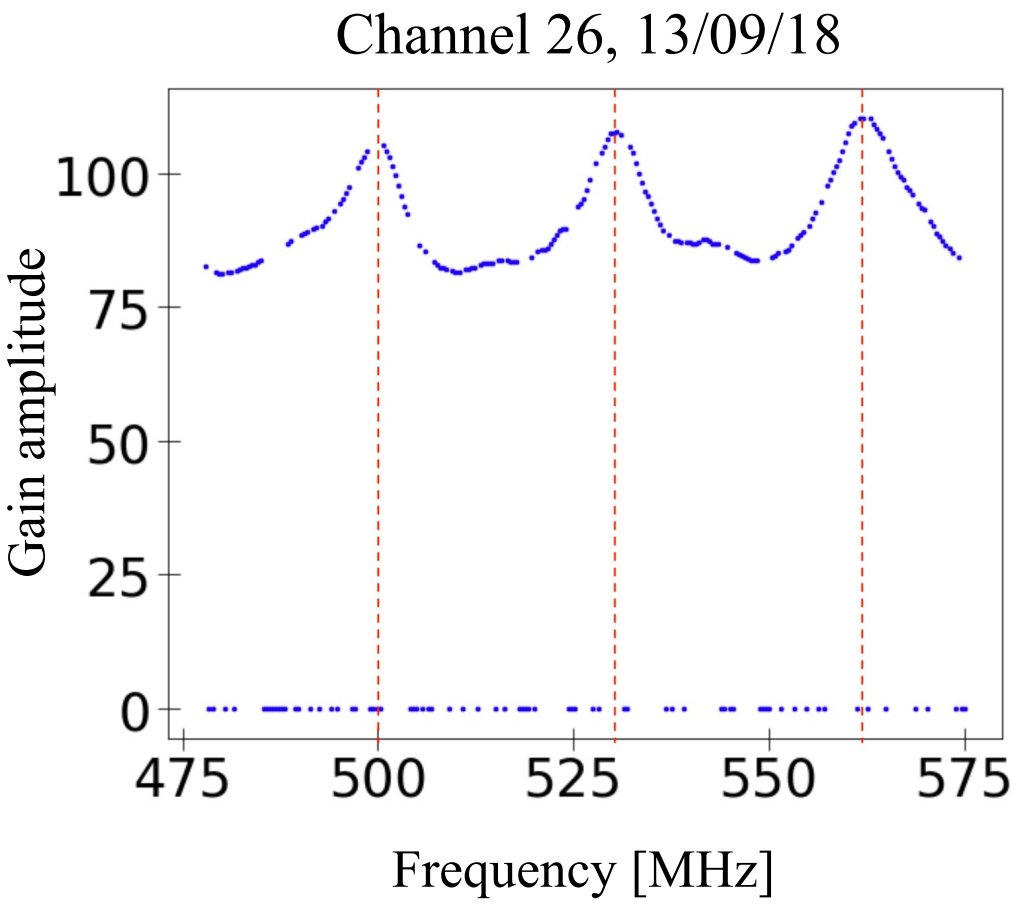
Proposed experiment





$$G(T) = G_0 + bT$$

Proposed experiment

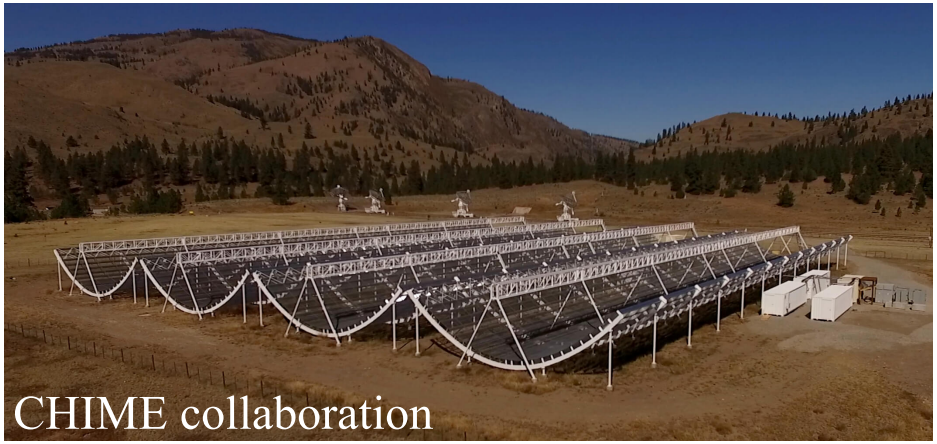


- 30 MHz oscillation pattern
- Interference figure due to multiple reflections
- Pattern shifts with temperature variations

- Analyze
- Simulate

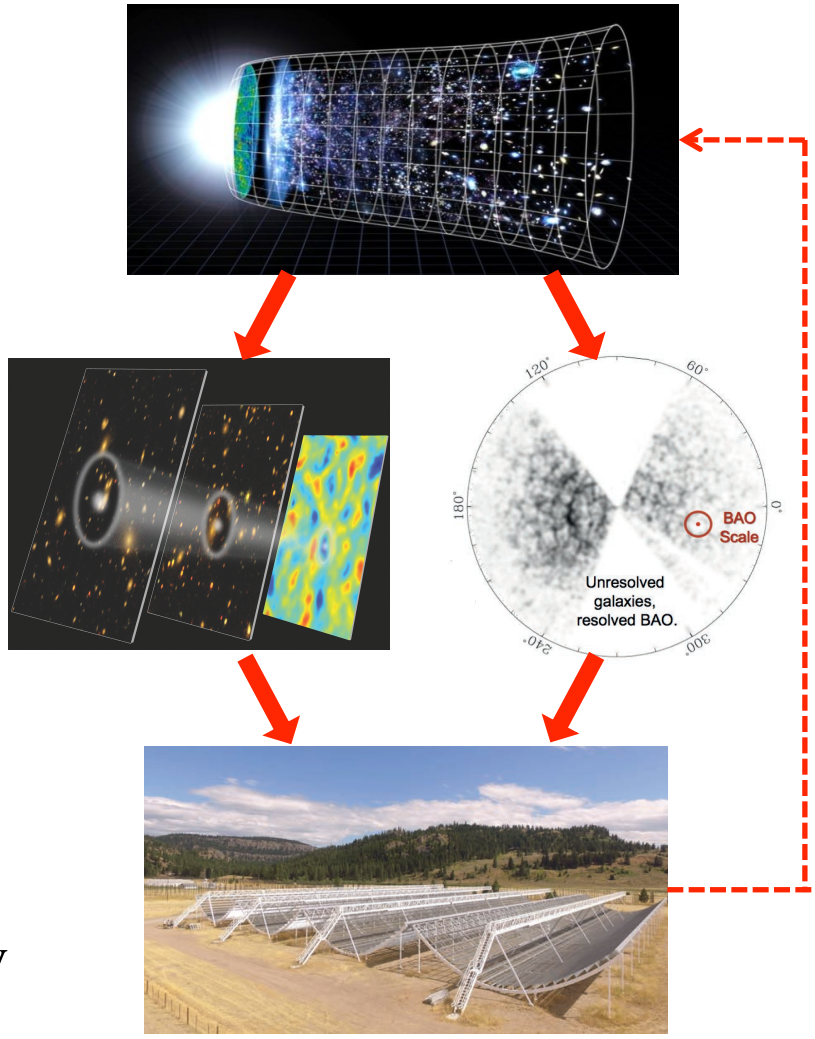
Resources

- CHIME telescope
- DRAO meteorological station
- Individual thermometers at LNAs
- On-site computers
- Jupyter notebooks

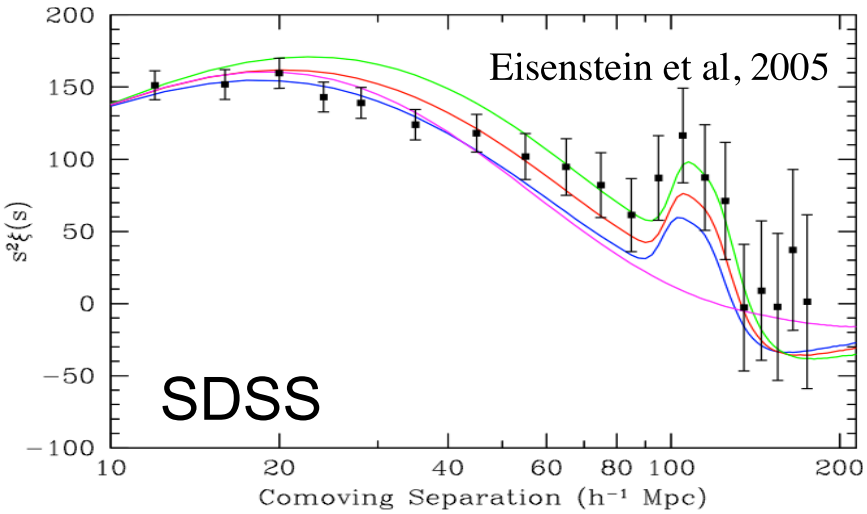

CHIME collaboration

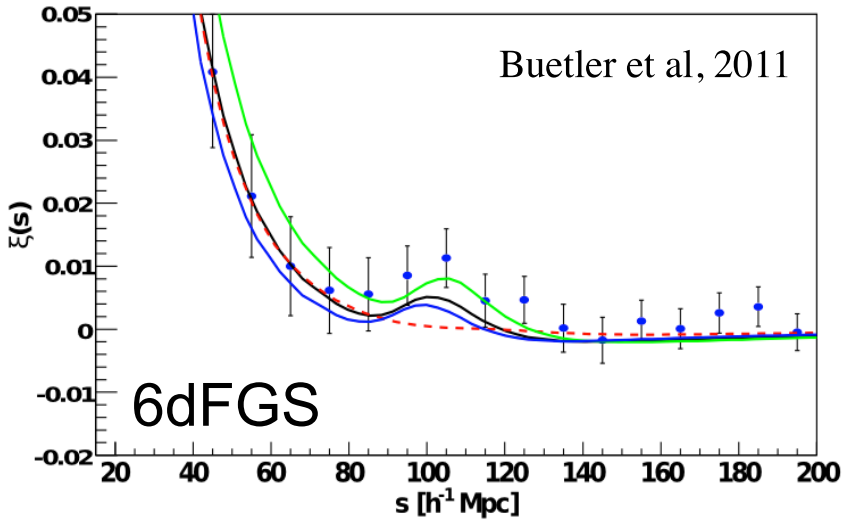
Summary

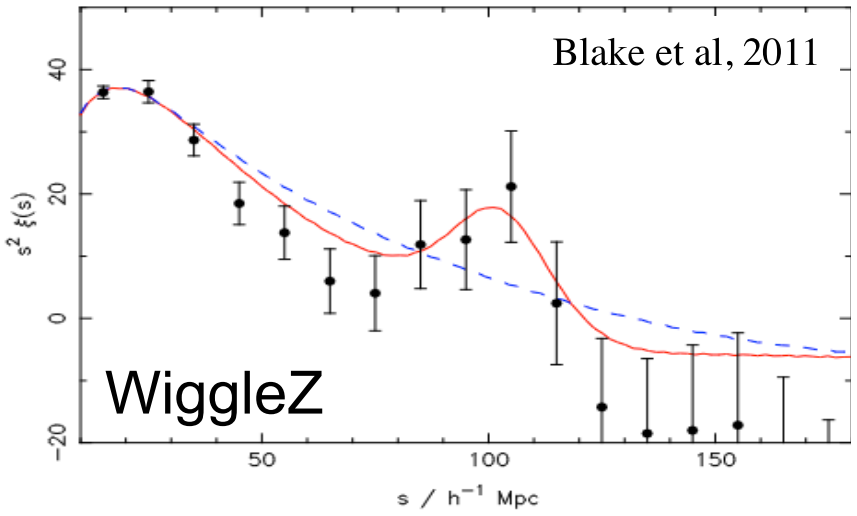
- ✧ Mysteries of cosmology
  - ➢ Dark energy
  - ➢ Inflation
- ✧ New observations techniques
  - ➢ BAO as standard rulers
  - ➢ Intensity mapping
- ✧ CHIME instrument
  - ➢ 3D map of yet unprobed region
  - ➢ New constraints on ΛCDM
- ✧ Calibration
  - ➢ Characterize thermal susceptibility
  - ➢ Direct sky observations

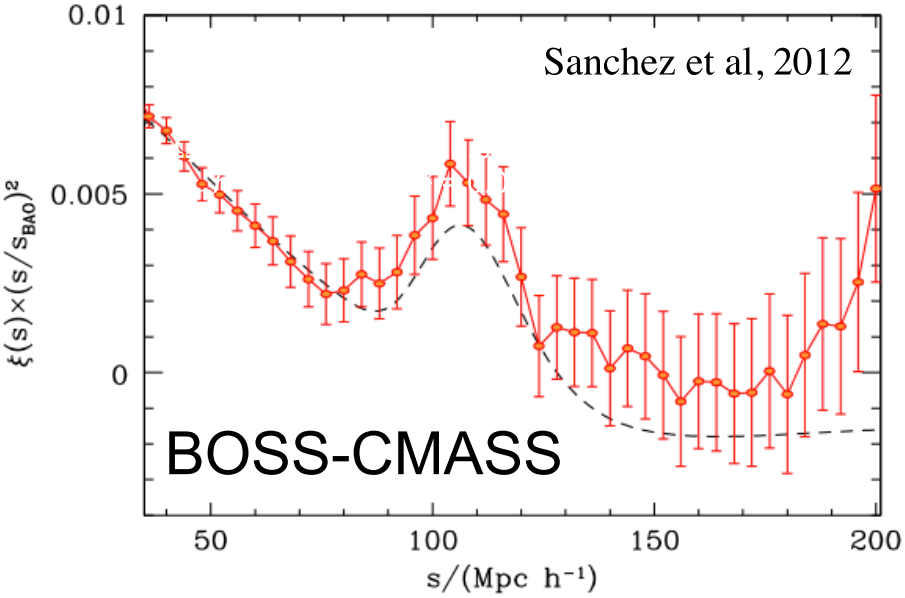


Other BAO observations









6-parameter ΛCDM

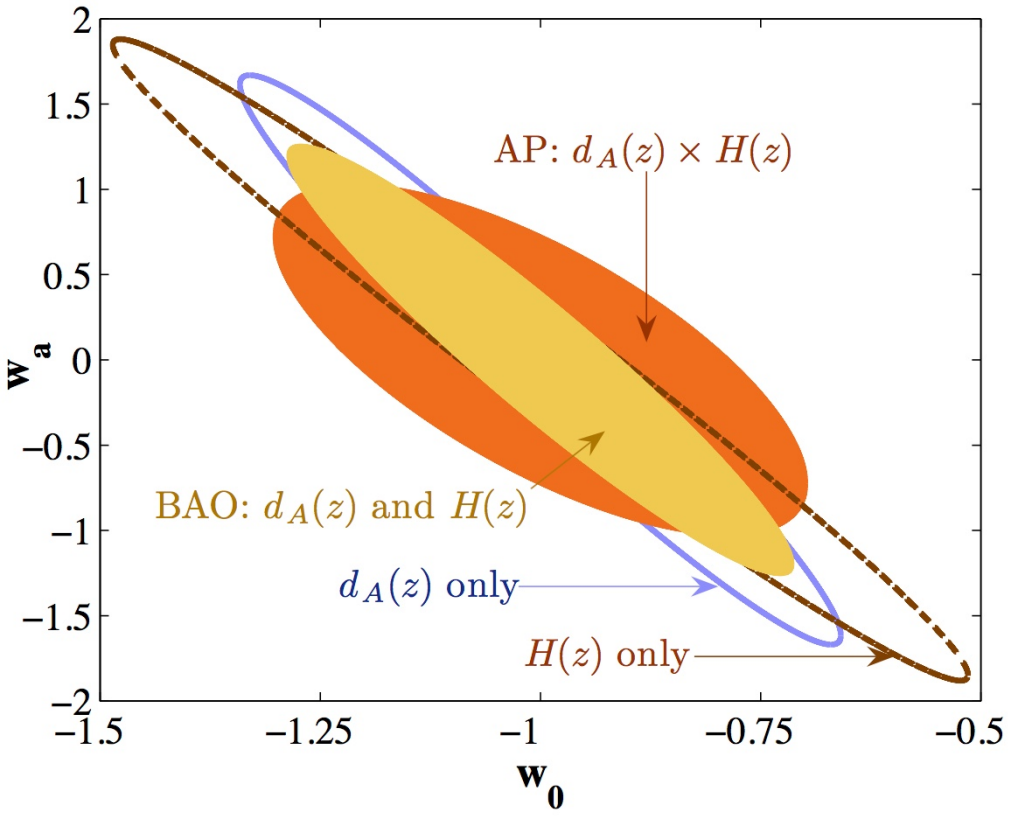
Assumptions: flat universe ($\Omega_k=0$), cosmological constant ($w_\Lambda=-1$)

Parameter	Symbol	*WMAP* data	Combined data[b]
Fit ΛCDM parameters			
Physical baryon density	$\Omega_b h^2$	0.02256	0.02240
Physical cold dark matter density	$\Omega_c h^2$	0.1142	0.1146
Dark energy density ($w = -1$)	Ω_Λ	0.7185	0.7181
Curvature perturbations, $k_0 = 0.002$ Mpc^{-1}	$10^9 \Delta^2_{\mathcal{R}}$	2.40	2.43
Scalar spectral index	n_s	0.9710	0.9646
Reionization optical depth	τ	0.0851	0.0800
Derived parameters			
Age of the universe (Gyr)	t_0	13.76	13.75
Hubble parameter, $H_0 = 100h$ km/s/Mpc	H_0	69.7	69.7
Density fluctuations @ $8h^{-1}$ Mpc	σ_8	0.820	0.817
Baryon density/critical density	Ω_b	0.0464	0.0461
Cold dark matter density/critical density	Ω_c	0.235	0.236
Redshift of matter-radiation equality	$z_{\rm eq}$	3273	3280
Redshift of reionization	$z_{\rm reion}$	10.36	9.97

Hinshaw *et al.*, arXiv/1212.5226

Dark energy parameters

CPL parametrization:

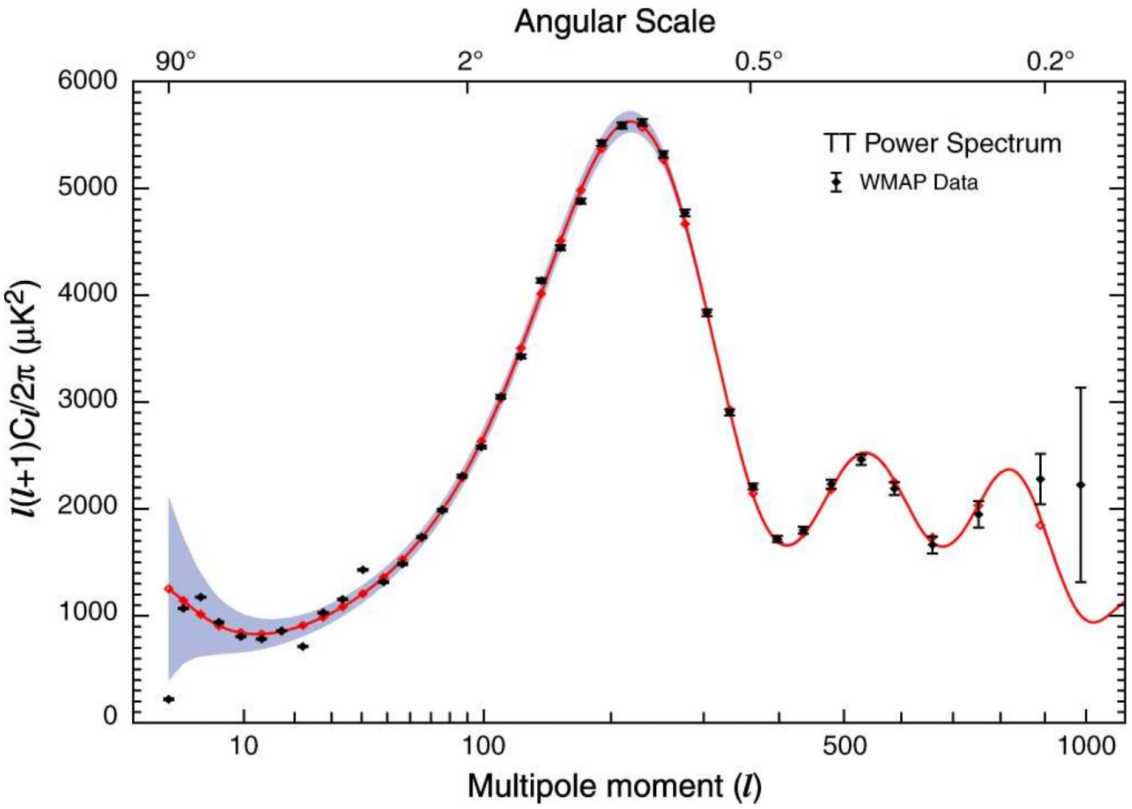


$$w_\Lambda(z) = w_0 + w_a \frac{z}{1+z}$$

- ΛCDM: w_0=-1, w_a=0
- Constraints on allowed values of both parameters
- Looking for deviations from ΛCDM

Calibration of sound horizon

Acoustic scale calibrated using BAO power spectrum:



$s = 146.8 \pm 1.8$ Mpc

Standard candles

$$m - M = 5\log(d_L) - 5$$

- **Type Ia supernovae**
  - Explosion of white dwarfs in binary systems
  - Always releases roughly the same amount of energy
  - First observation of accelerated expansion
  - Can measure cosmological distances

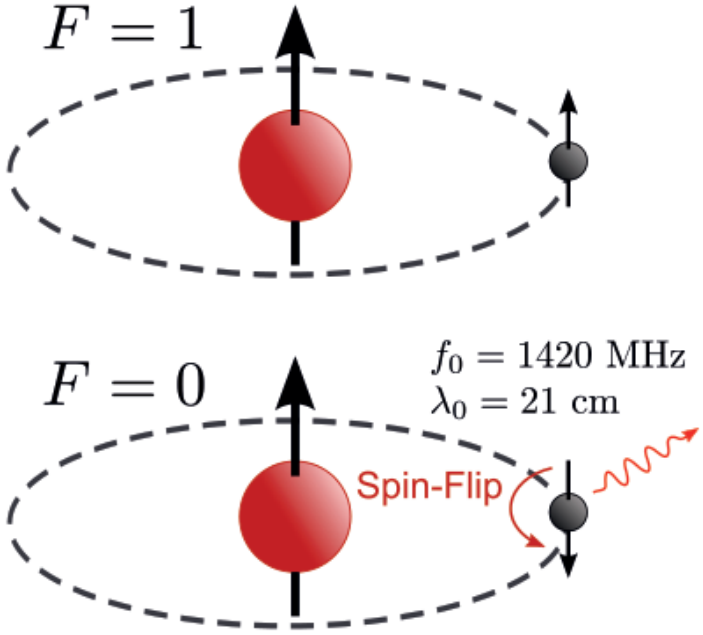

SN1994D

- **Cepheid variables**
  - Absolute luminosity proportional to period of variability
  - Used in local group of galaxies

$$d_L(z) = (1+z)^2 d_A(z)$$

Hydrogen spin-flip

- Transition between two energy levels in the ground state of the H atom
- Proton and electron spins can be parallel (higher energy) or antiparallel (lower energy)
- Transition results in emission of 21 cm light wave (1420.4058 MHz)
- Extremely rare: transition rate is 2.9×10^{-15} s^{-1}
- Intensity mapping => matter power spectrum



Visibility matrix

$$V_{ij} = \int |A(\hat{n})|^2 G_i(\lambda)^* G_j(\lambda) e^{-2\pi i \frac{\hat{n}\cdot\vec{r}_i}{\lambda}} e^{2\pi i \frac{\hat{n}\cdot\vec{r}_j}{\lambda}} d^2\hat{n} + n_{ij}$$

Eigendecomposition

Calibration

Data collection

Known

$A(\hat{n})$

$G_i(\lambda), G_j(\lambda)$

Unknown

$G_i(\lambda), G_j(\lambda)$

$A(\hat{n})$

Image sources

- Title image: https://chime-experiment.ca/
- Slide 2: http://www.nature.com/polopoly_fs/7.28425.1438163812!/image/CHIME%20expanding%20universe-NEW.png_gen/derivatives/fullsize/CHIME%20expanding%20universe-NEW.png
- Slide 7: http://background.uchicago.edu/~whu/physics/oscillator.gif
- Slide 9: http://galaxies-cosmology-2015.wdfiles.com/local--files/baryon-acoustic-oscillations/sdss_bao.png http://www.astro.ucla.edu/~wright/BAO-cartoon.jpg
- Slide 18: https://apod.nasa.gov/apod/image/1501/iyl_cyga.jpg https://www.nasa.gov/sites/default/files/styles/full_width_feature/public/thumbnails/image/casa_elements.jpg
- Slide 24: https://ichef.bbci.co.uk/news/660/cpsprodpb/12DF9/production/_99550377_universe_expansion_funnel_print.jpg https://chime-experiment.ca
- Appendix IV: https://www.astro.umd.edu/~miller/teaching/astr422/lecture21.pdf
- Appendix V: https://upload.wikimedia.org/wikipedia/commons/thumb/a/a2/SN1994D.jpg/550px-SN1994D.jpg
- Appendix VI: https://upload.wikimedia.org/wikipedia/commons/thumb/9/96/Hydrogen-SpinFlip.svg/440px-Hydrogen-SpinFlip.svg.png