Science Goals with Probe-Class Spectrometer

Spectrometer Working Group
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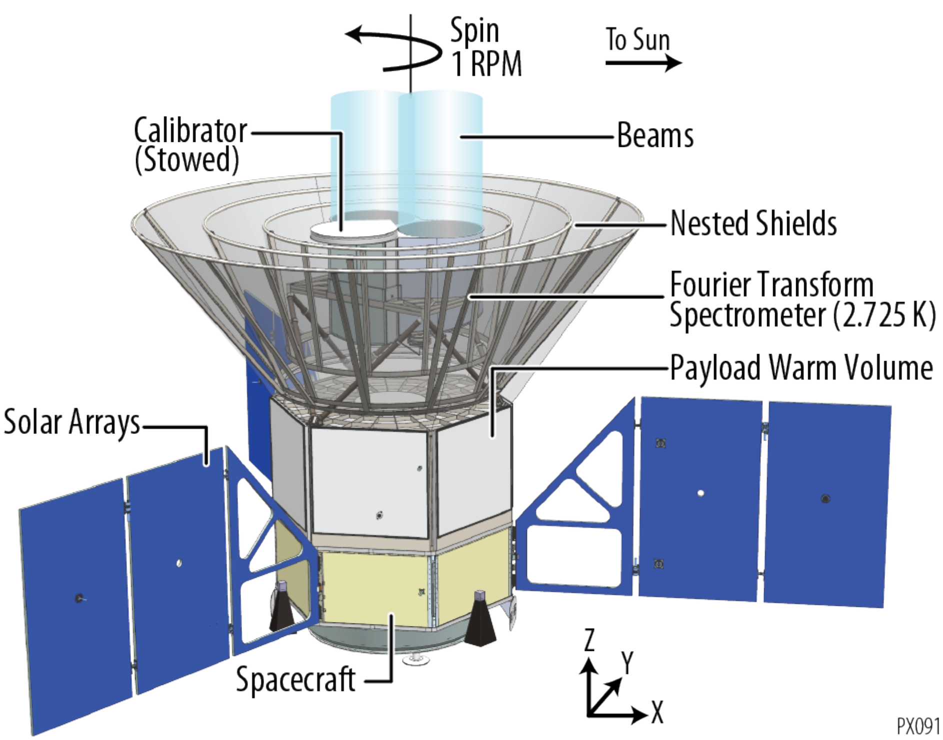
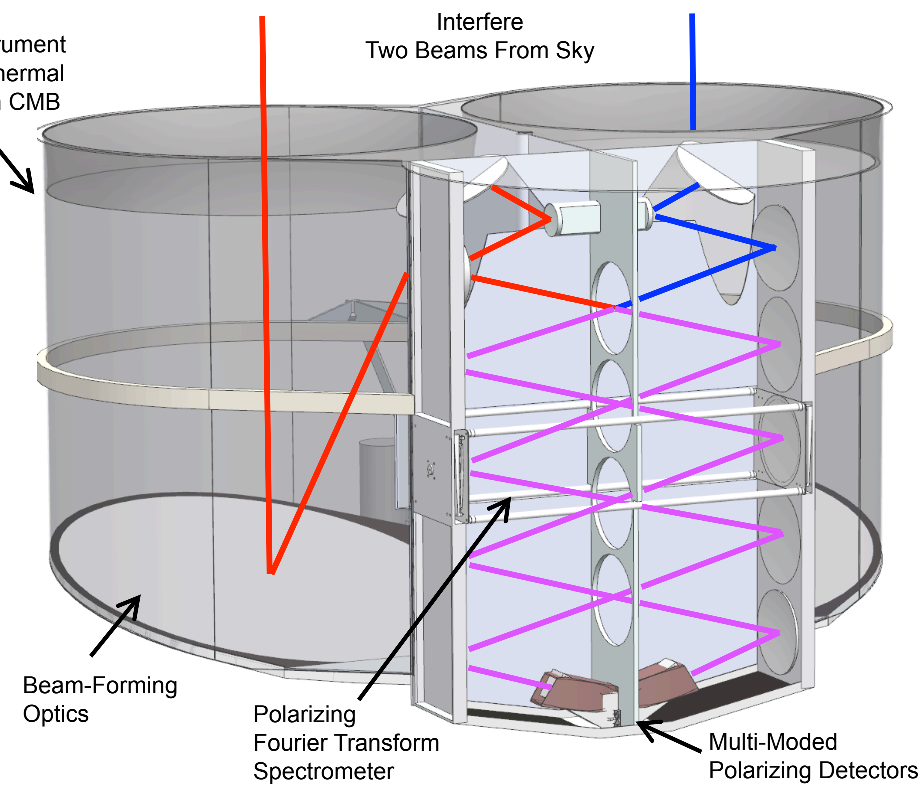
Spectrometer Basics

Based on 2016 PIXIE MIDEX concept, with possibility of x10 better sensitivity
Polarizing Fourier Transform Spectrometer with full-aperture blackbody calibrator





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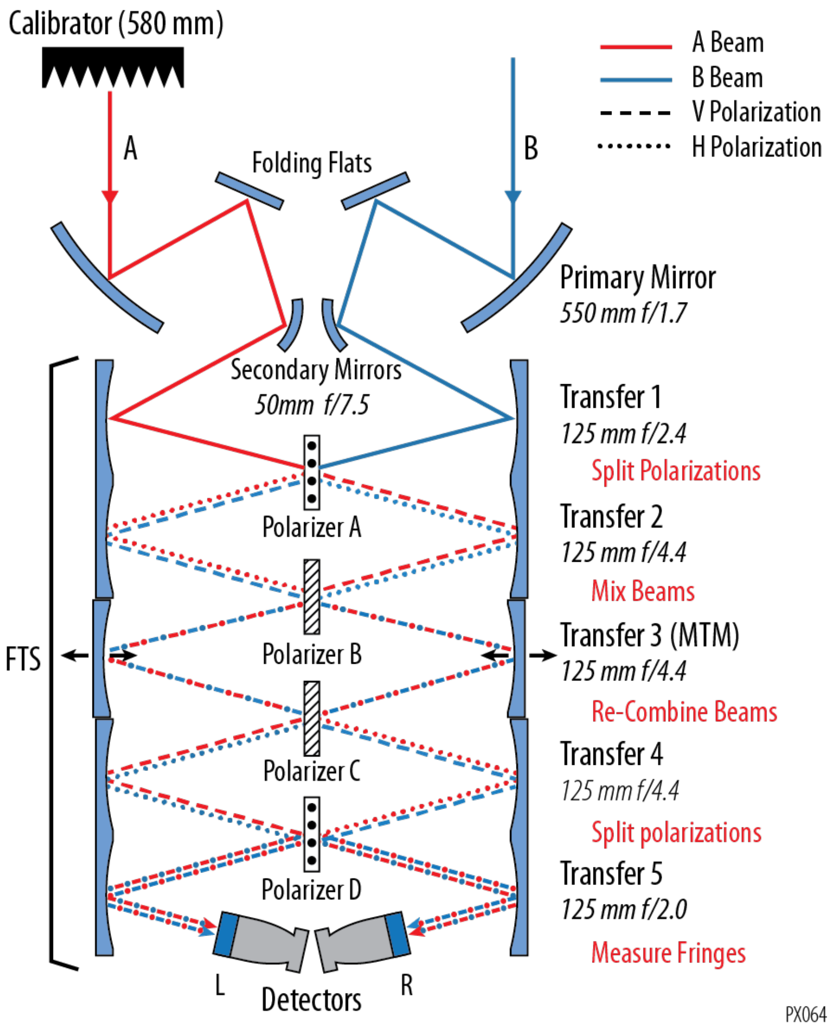
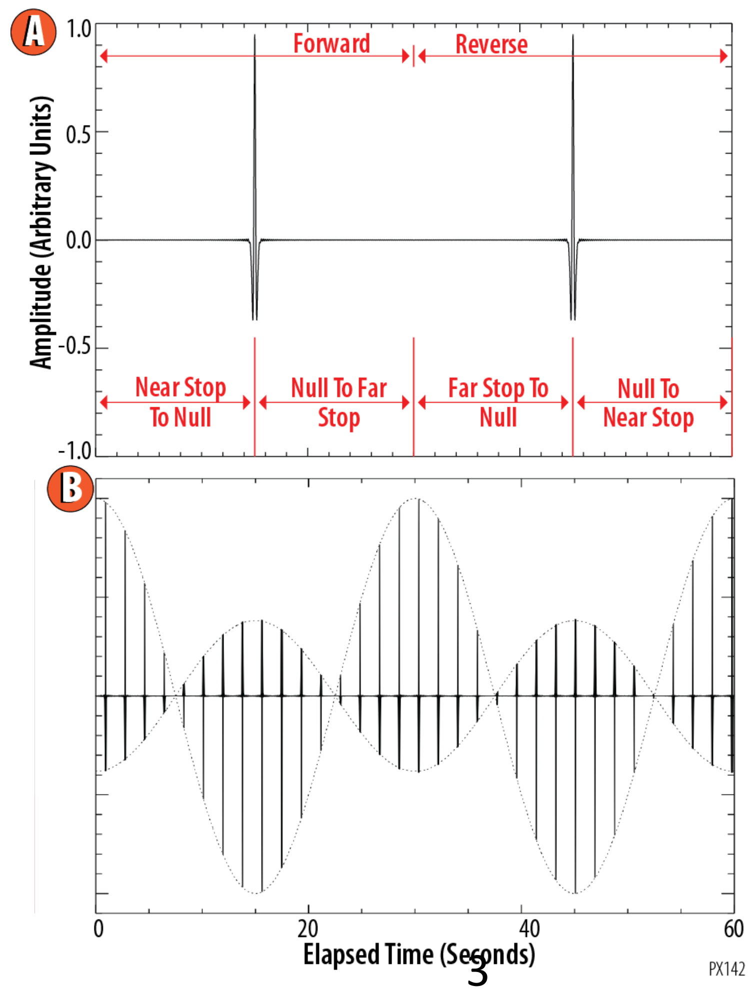
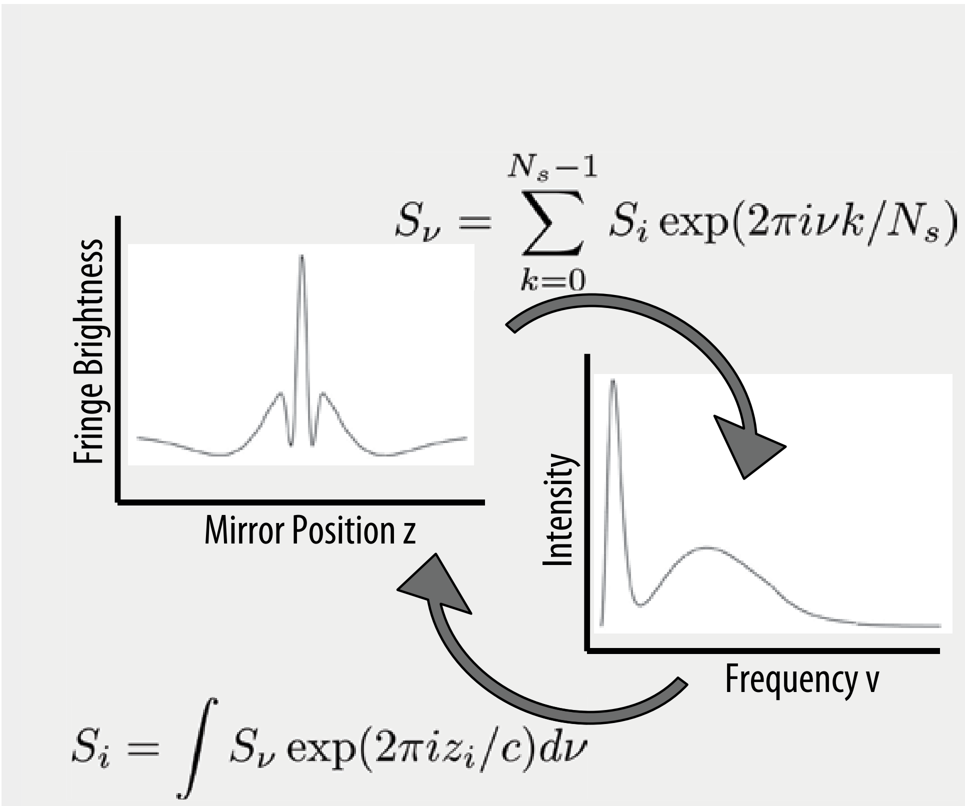




CMB Fringe Pattern

Spin Amplitude Modulation

Frequency Channels



Sample fringe pattern vs phase delay
Fourier transform to get synthesized spectra

Channel width set by maximum phase delay

Δν = c / 2L

Number of channels = number of samples/2

N = Ns / 2

Channels are integer multiples of width

Δν, 2Δν, 3Δν, ... (N-1) Δν

One choice: Set width to match CO lines

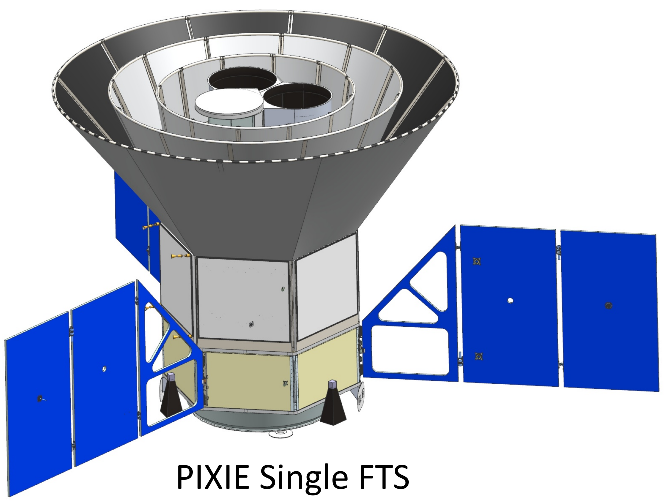
Δν = CO(1-0) / 8

= 14.4 GHz

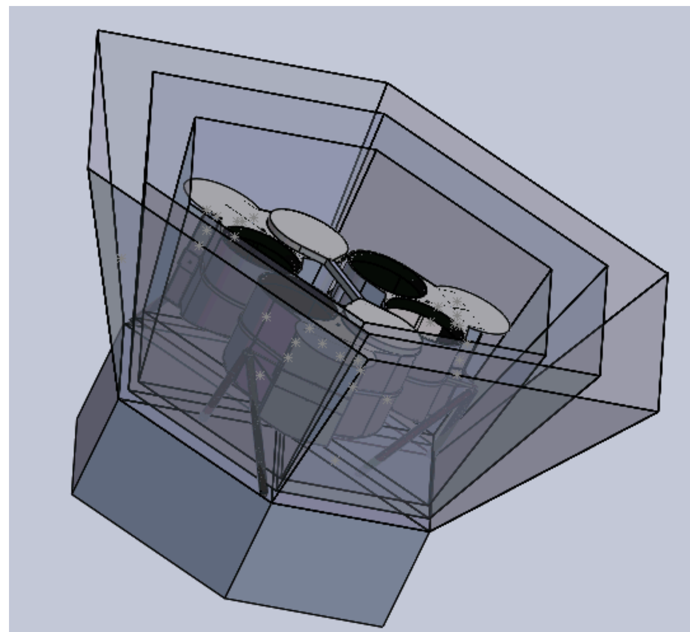
Note: Continuum sensitivity DECREASES as Sqrt(Δν)
Penalty for setting channel width too narrow

Fundamental Limits

Angular resolution	Multi-moded optics, sensitivity scales as $(A\Omega)^{1/2}$ PIXIE 1.2m instrument → 1.6 deg Gaussian equivalent
Sensitivity	Detector sees photon noise from full bandpass Limited scalability for multiple detectors

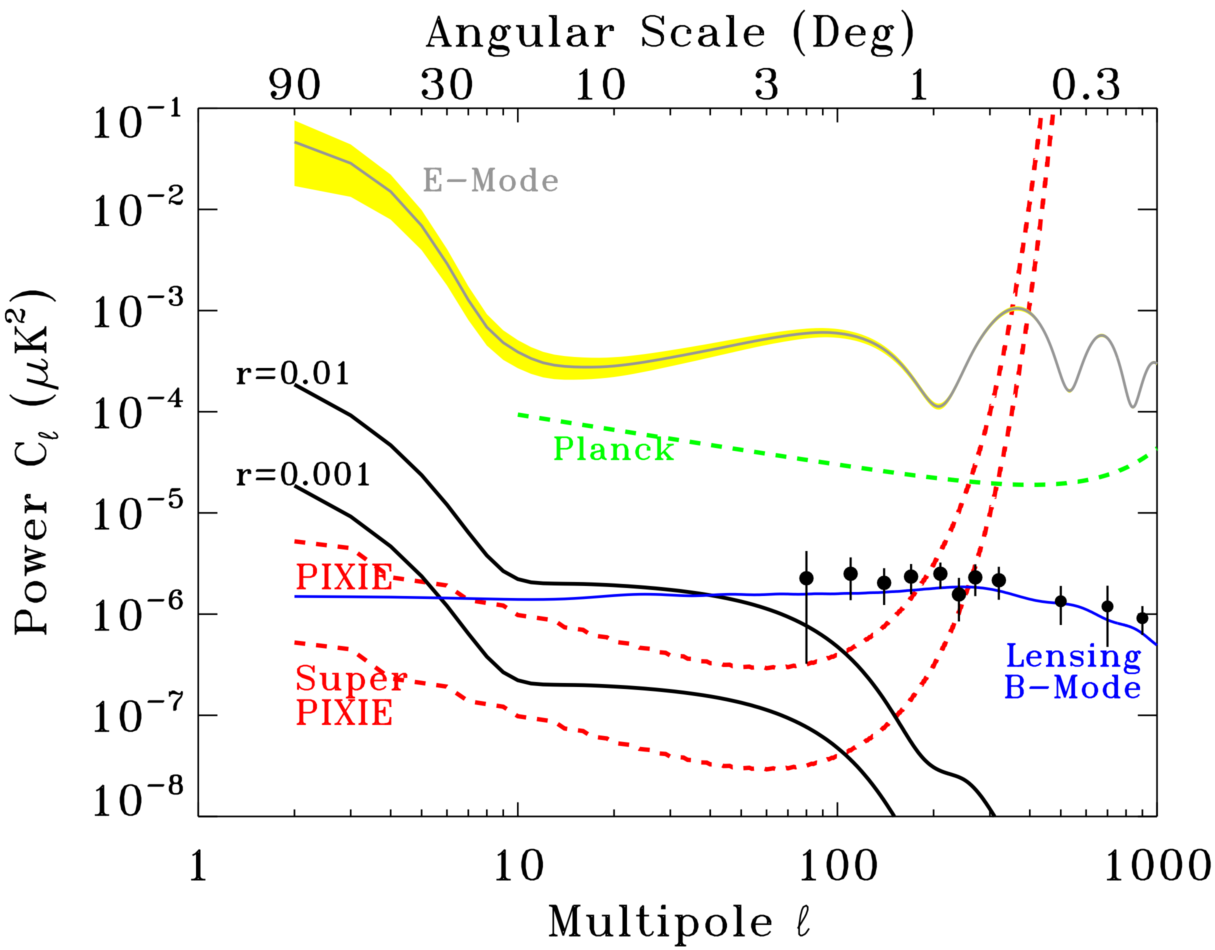


PIXIE Single FTS



Probe Multiple FTS

CMB Polarization

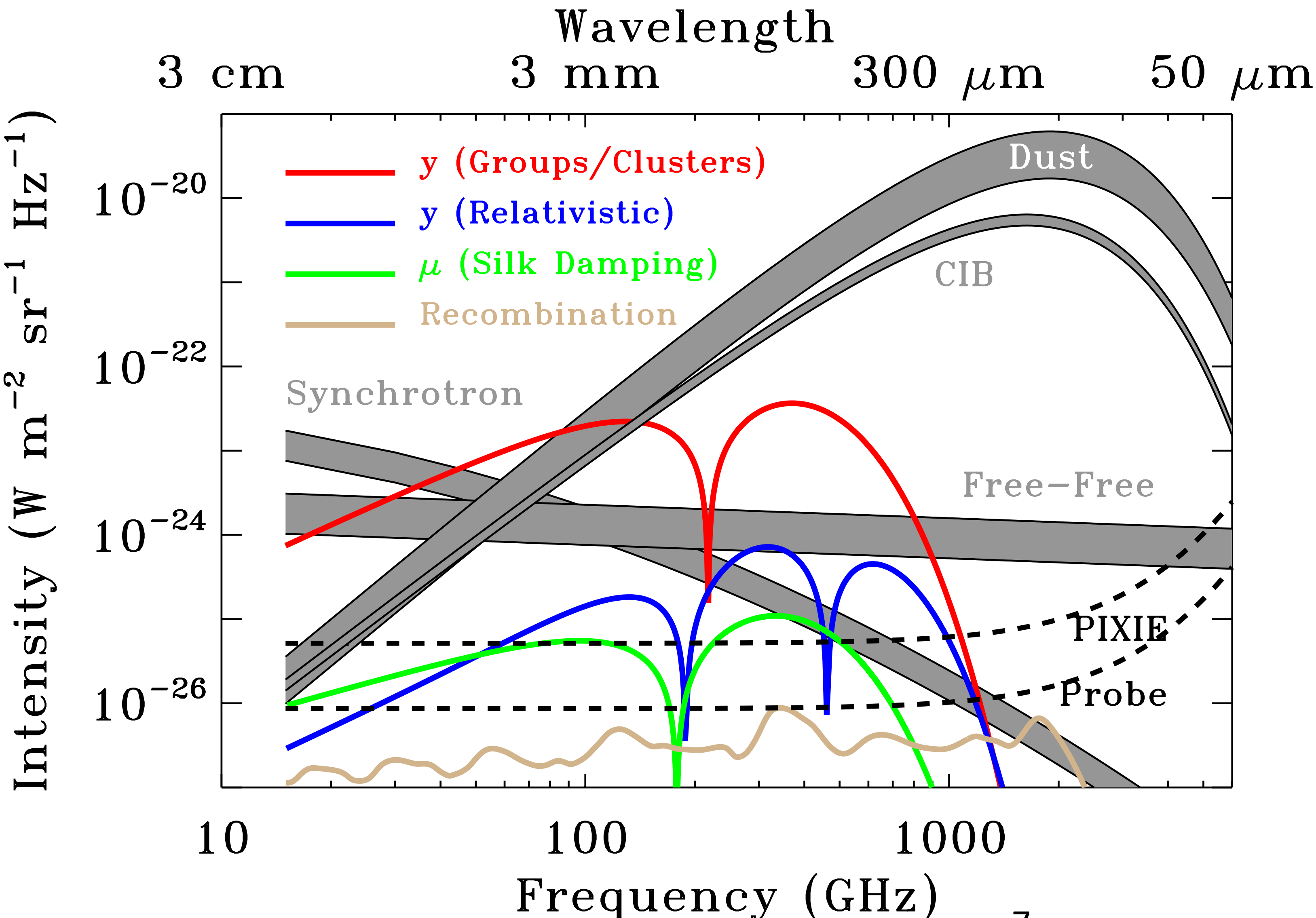


Inflationary B-Modes

r = 2 x 10^{-4} (PIXIE 1σ, 4-year)
Limited by low-freq foregrounds

Cosmic-variance limit to EE, tau

Spectral Distortions



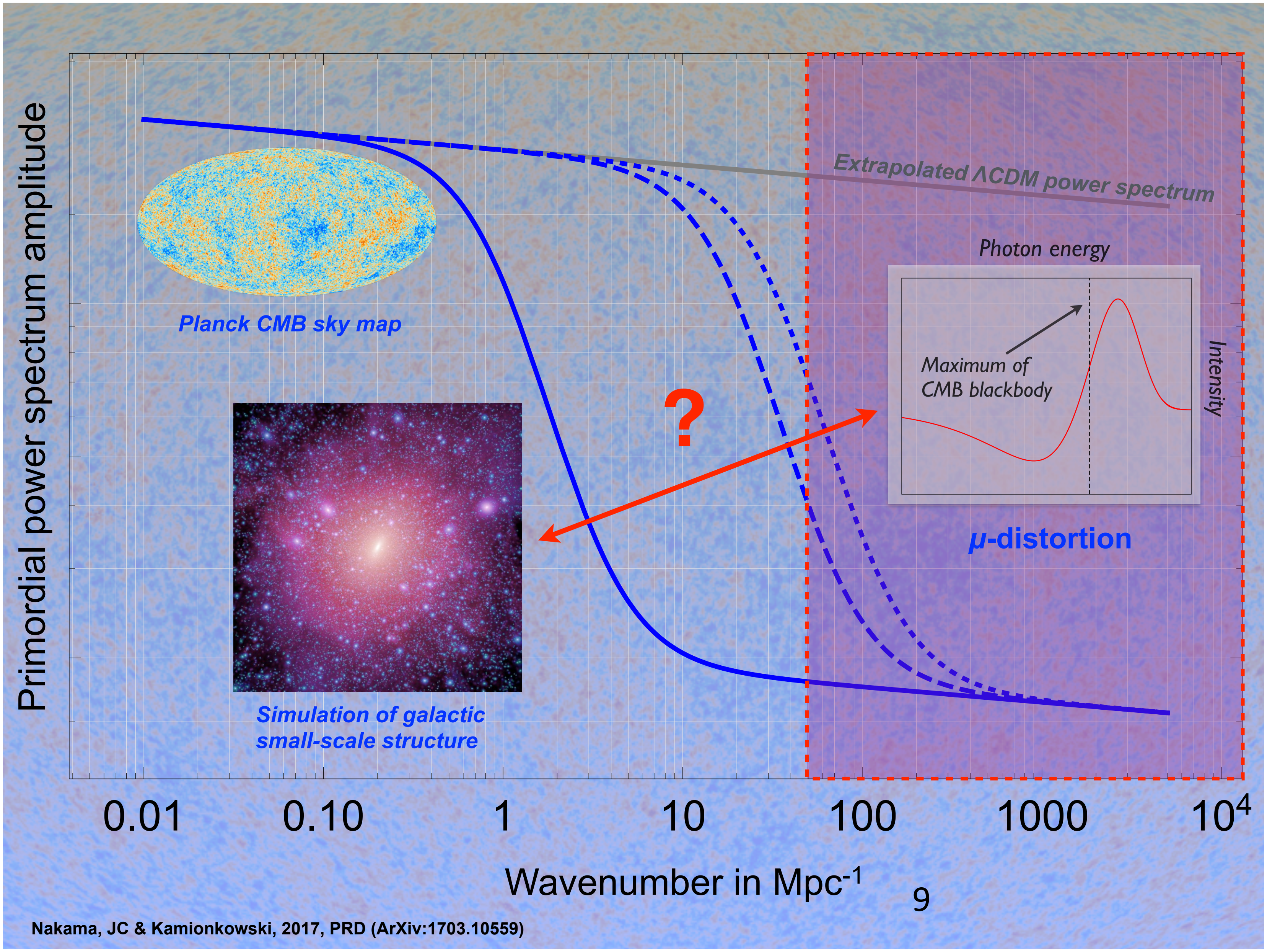
Science from Mu Distortions

(Jens Chluba)

- **Standard ΛCDM prediction from Silk damping:** $\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$
  (JC, 2016, ArXiv:1603.02496)
  - provides a *natural target* that cannot be reached with PIXIE at this stage
  - requires significantly *improved low-frequency coverage / sensitivity*
    (Abitbol et al., 2017)

- **An improved upper limit on *μ* would place constraints on:**
  - *long-lived decaying particle* models with lifetimes *t* ~ 10^6-10^{10} seconds
    (JC & Jeong, 2013)
  - the *amplitude of primordial perturbations*: $A_\mathrm{s}(k \simeq 740\,\mathrm{Mpc}^{-1}) < 2.8 \times 10^{-8} \left[\frac{|\mu|}{3.6 \times 10^{-7}}\right]$
  - Constrain *DM interactions* with standard particles
    (Ali-Haimoud, JC & Kamionkowski, 2016)
  - Shed light on the *small-scale crisis*
    (Nakama, JC & Kamionkowski, 2017)
  - Could reveal a connection of recent BH mergers with enhanced primordial small-scale power (JC in prep.)
  - Could constraint many non-standard scenarios (primordial magnetic fields, strings, axions, PBH evaporation, etc.)

Dissipation of Primordial Perturbations

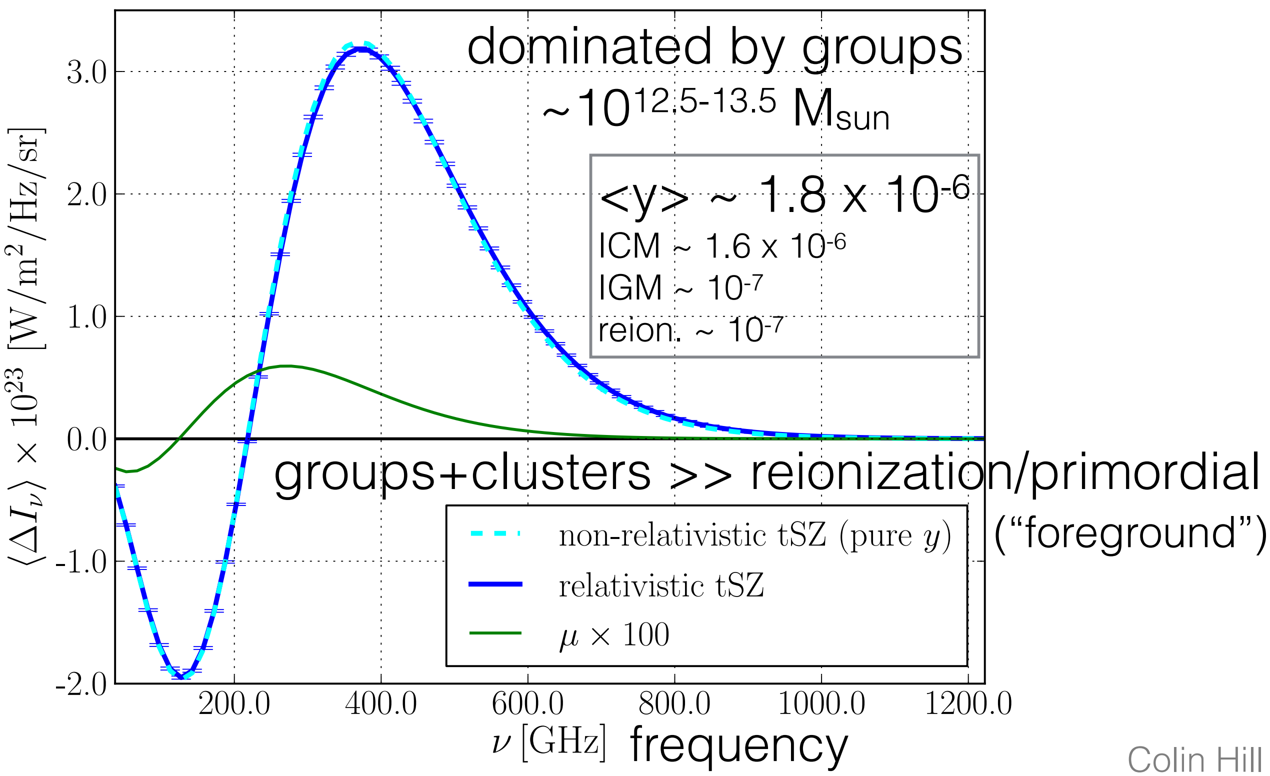


y-Distortions

(Colin Hill)

Compton-y: guaranteed signal(s)

non-relativistic thermal Sunyaev-Zel'dovich (tSZ) effect
+ relativistic corrections due to high electron temperatures



JCH+ (2015); see also Dolag+ (2015) & de Zotti+ [1] (2016)

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Columbia

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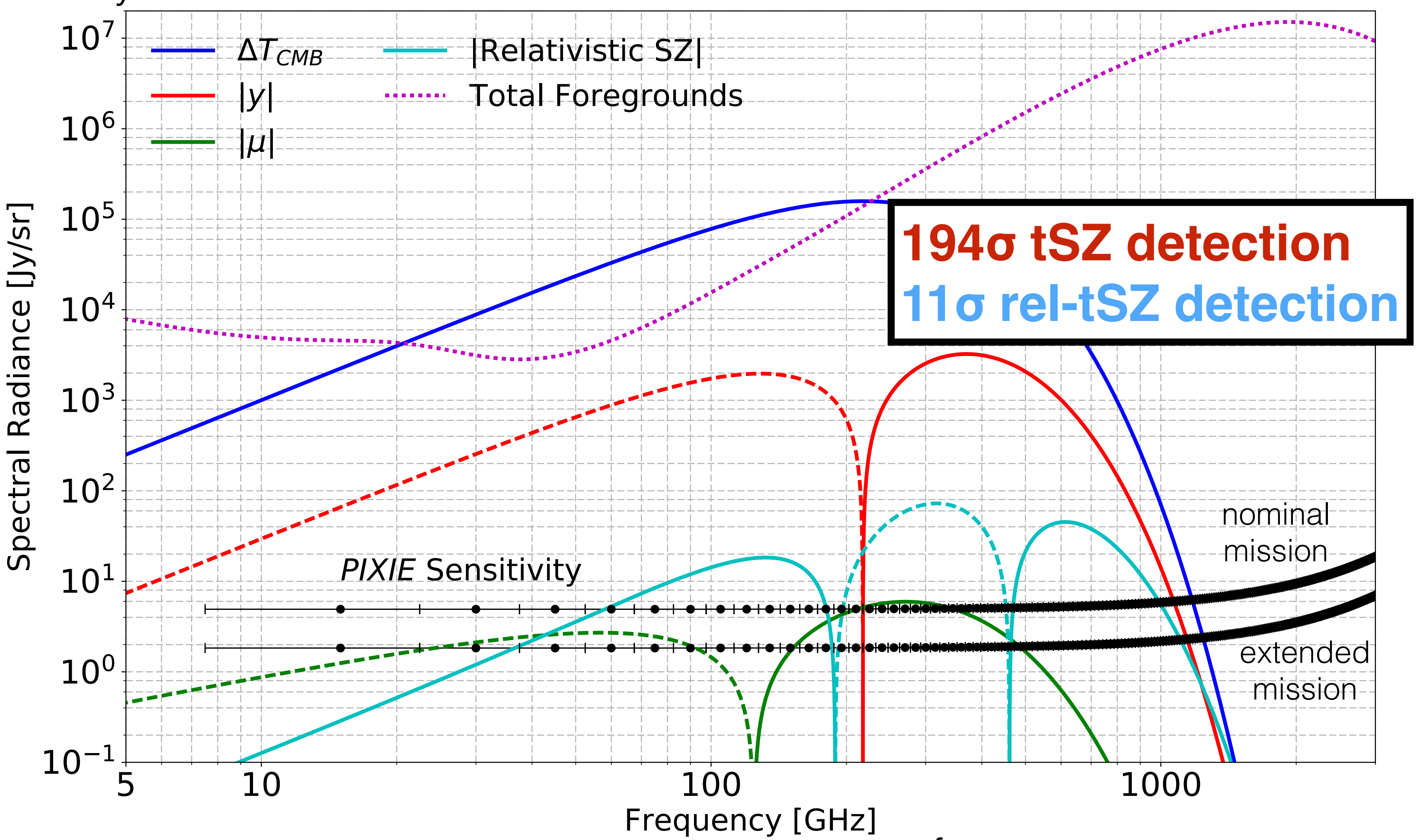
Signals vs. Foregrounds

specific
intensity



frequency

Abitbol, Chluba, JCH, & Johnson (2017)

2

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What will we learn?

- Measurement of total thermal energy in electrons

$$\langle y \rangle = \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}} c^2} \int \frac{d^2\hat{\mathbf{n}}}{4\pi} \int dl P_{\mathrm{e}}(\hat{\mathbf{n}}, l) \;\propto E_{\mathrm{e}}^{\mathrm{th,tot}}$$

- "Integral constraint" on feedback energy injected over cosmic time (analogous to τ for reionization)

$$E_{\mathrm{e}}^{\mathrm{th,tot}} = E_{\mathrm{e}}^{\mathrm{coll}} - E_{\mathrm{e}}^{\mathrm{cool}} + E_{\mathrm{e}}^{\mathrm{inj}}$$

- Crucial ingredient for understanding baryonic effects on matter power spectrum (necessary for, e.g., upcoming weak lensing surveys)

- Calibration of X-ray T—M relation with relativistic tSZ

- If low-z contributions can be isolated (e.g., via cross-correlation with galaxy surveys), new reionization constraint

JCH+ (2015); Battaglia, JCH+ (in prep.)

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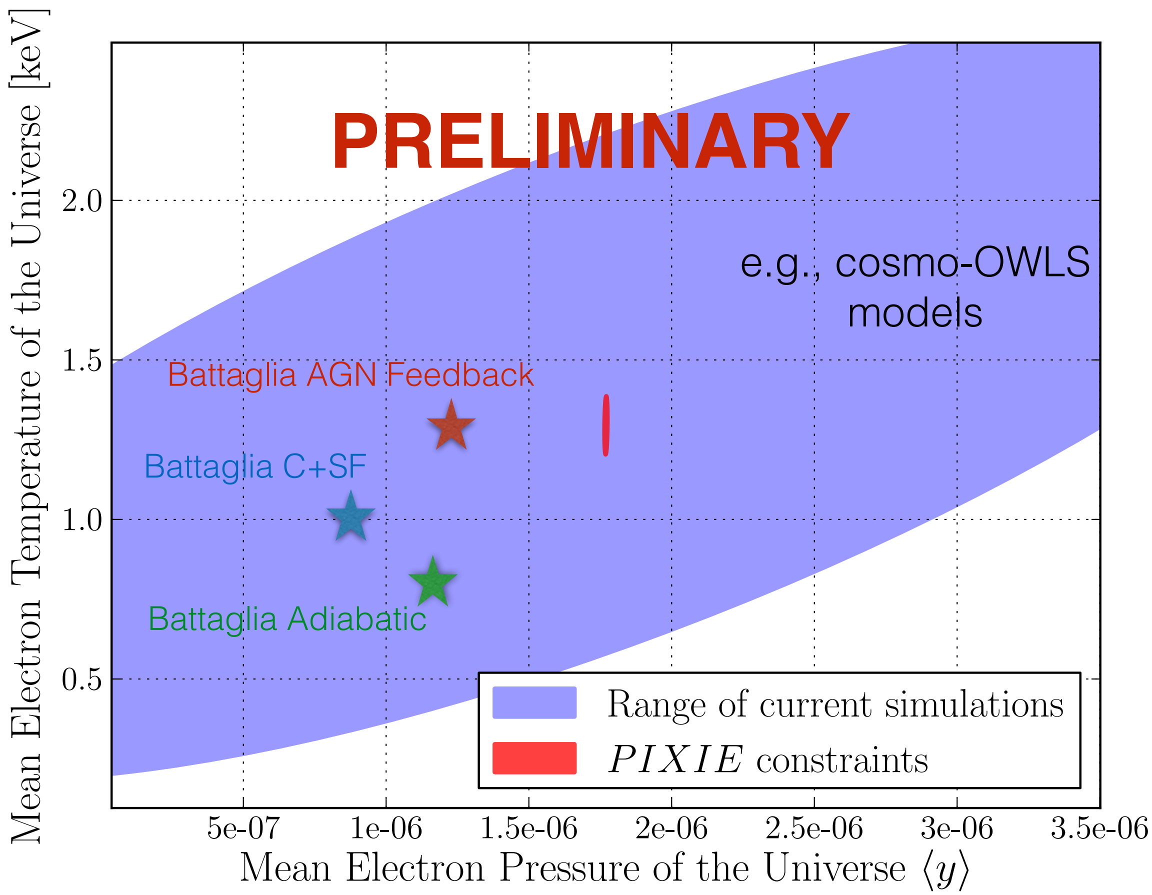
What will we learn?

sub-percent constraints on structure formation models

mean
gas
temp.
in the
universe



mean gas pressure in the universe

JCH+ (2015); Battaglia, JCH+ (in prep.)

Future possibilities

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- Constraints on local-type primordial non-Gaussianity via <yT> cross-correlation [Emami+ (2015)] or scale-dependent halo bias in <yy> power spectrum [JCH & Pajer (2013)]

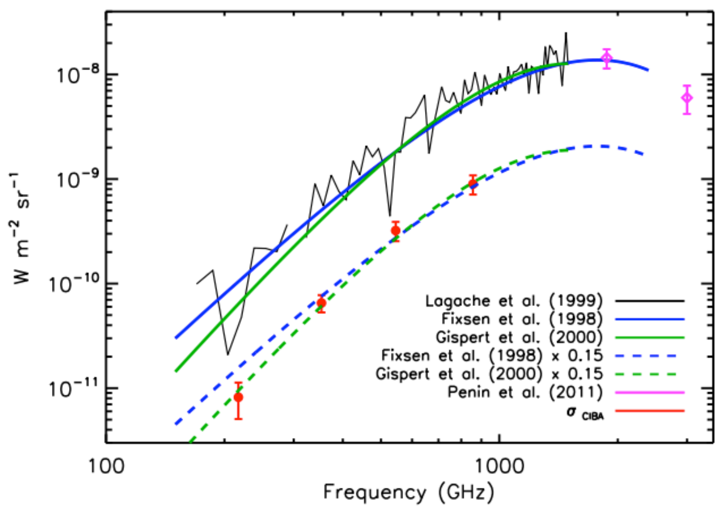
- Detection of higher-order moments of the electron temperature distribution (beyond $\langle T_e \rangle$)

- Detection of polarized SZ: probe of local quadrupole at each cluster's location, and thus a way around cosmic variance [Kamionkowski & Loeb (1997)]

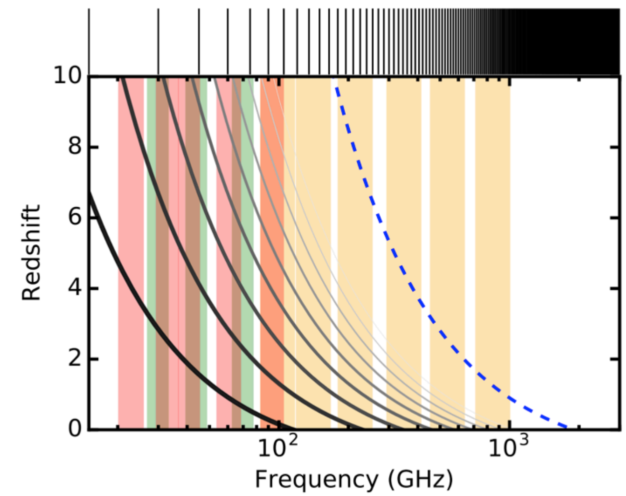
- Many stacking and cross-correlation possibilities using halo catalogs/lensing maps, contingent on angular resolution

Intensity mapping and CIB measurements

Switzer / Dore



The CIB monopole from FIRAS (black) and inferred from IRAS (pink), and Planck CIB anisotropy (red) relative to models. PIXIE will be ~1000x more sensitive than FIRAS, allowing more stringent tests of galaxy population and evolution models.

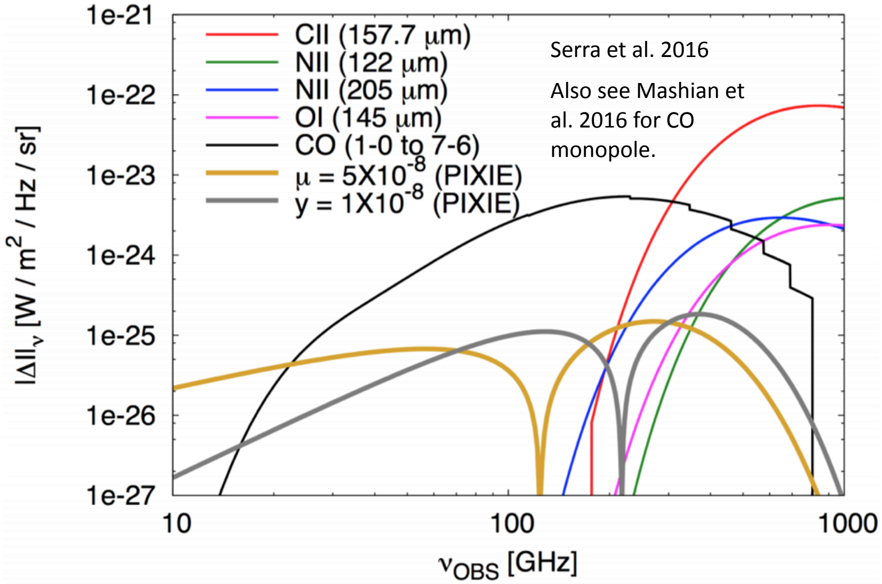


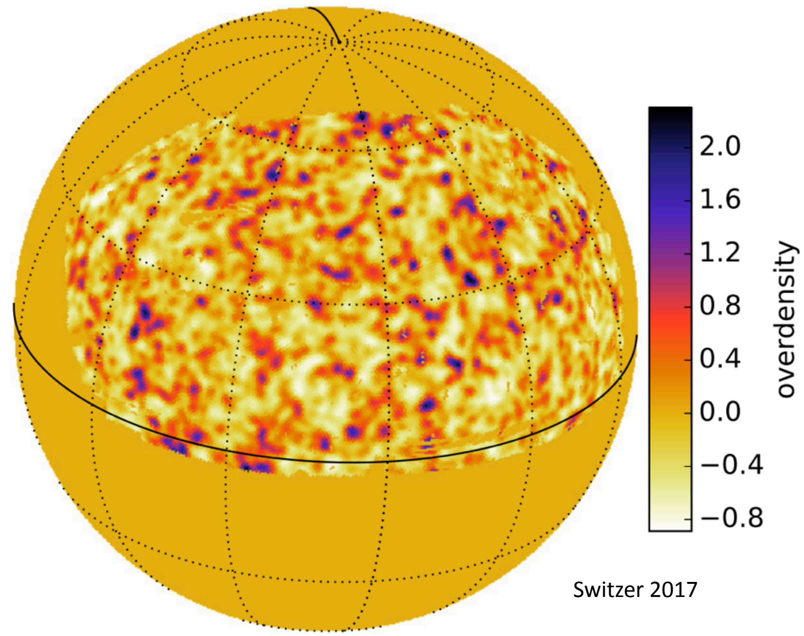
Visibility of the CO (black for J = 1 − 0 to light gray moving up the ladder) and [C II] (dashed blue) lines as a function of redshift. WMAP (red) and Planck (LFI in green and HFI in orange) have sensitivity in wide, photometric bands, over which density contrast is washed out. PIXIE's bands (black edges along the top) sample [C II] and CO from the present to reionization.

Goal: Intensity mapping (IM) allows us to understand average galaxy properties and their evolution in the context of ΛCDM. In particular for dusty galaxies: what halos best host star formation? How does star formation evolve relative to the growth of structure? What is the abundance, evolution and metallicity of the cold gas that forms stars? How does the mean dust temperature evolve?

Approach: Radiation from stars excites thermal emission from dust, and atomic and molecular line emission. A CMB spectral survey is sensitive to both the zero-point and anisotropy of the sum of reprocessed radiation over the history of the universe. Cross-correlation of the spectral survey with galaxy redshift surveys separates the cumulative SED contributing to the CIB at each redshift (Serra et al. 2014, Switzer 2017). Cross-correlation between multiple frequencies identifies coherence in the CIB, and emission of different lines at common redshift (Serra et al. 2016). An estimate of the cross-correlation amplitude does not suffer cosmic variance, and is robust to galactic foregrounds.

Intensity mapping and CIB measurements





A CMB spectral survey can access several redshifted tracers of the ISM that probe different phases of gas:
CO 115N GHz (for J=N to N-1): traces molecular gas
CII 158 μm: traces neutral and ionized gas, star formation
NII 122, 205 μm: traces ionizing photon rate, [NII]/[CII] give metallicity
OI 146 μm: traces dense gas near star-forming regions.

Each line also acts as a foreground that contributes uncorrelated variance to each slice.

The BOSS CMASS-North unitless overdensity δ in a slice of 0.51 < z < 0.53, smoothed to PIXIE's 1.65◦ FWHM effective beam. The redshift range is equivalent to Δv = 15 GHz for observations of [C II] at 1245 GHz. PIXIE's sensitivity per 1x1° region is ~1 kJy/sr. The expected CII brightness is ~kJy/sr, giving SNR ~1 measurements of the fluctuation modes.

Intensity mapping and CIB measurements

Spectral resolution is essential to measuring redshifted line emission. C_l scales as ~$1/\Delta\nu$ (until 1% bandwidth) as large-scale structure is washed out in thicker slabs (Breysse et al. 2014). CO and CII cannot be detected in WMAP data and may be possible with Planck (Pullen et al. 2013). A decisive measurement of evolution requires a spectrometer.

Spectral resolution and adjacency are essential to suppressing foregrounds: Foregrounds for CII can be 1000x larger than the signal. Dust emission is highly coherent between adjacent bands, while the IM signal is largely incoherent, so foregrounds can be removed efficiently with a linear combination of bands (Switzer 2017). Broad, separated bands make it more difficult to subtract the dust continuum. Foreground separation requires high interband-calibration smoothness and stability. The PIXIE calibrator is black to 3×10^{-7} and is continuously differenced with the sky signal.

A spectrometer is better matched to galaxy surveys: Cross-correlations with galaxy redshift surveys provide unambiguous detection of CIB and line emission (Masui et al. 2013, Serra et al. 2014). Wide photometric bands are not well-matched to galaxy redshift surveys, which often provide many narrow slabs over a more limited redshift range. A spectrometer also potentially contains more redshift information, which is very useful to calibrate redshift estimation in photometric surveys such as LSST (Alonso et al. 2017).

Moving beyond PIXIE: $\Delta\nu$ =15 GHz and $\Delta\nu_{min}$~45 GHz limits measurement of CO J=1-0, which has a cleaner interpretation than higher-J CO emission. An instrument with twice the linear size would have 2x lower frequency and 2x higher spatial/spectral resolution, making it a better match to CO J=1-0. It would also provide more low-frequency information for synchrotron cleaning of CMB polarization.

A spectrometer with low angular resolution is not well matched to inference of SFR(M, z) from the CIB anisotropy (Wu & Doré 2017), and many factors of resolution are needed to be competitive, despite having a large number of bands. Its strength is in constraints of the integrated, monopole spectrum.

Still To Study ...

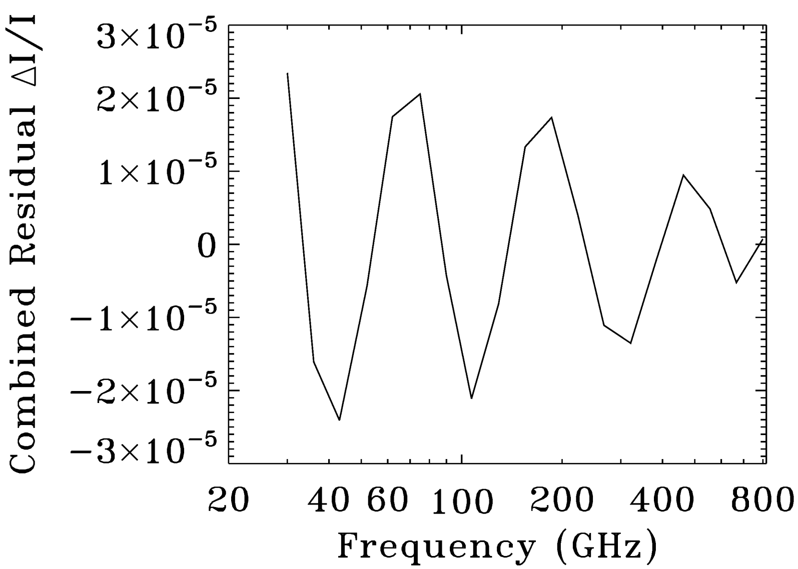
Combined Spectrometer + Imager: Can we use "Best of Both Worlds" approach?

Spectrometer: Shallow survey over broad frequency range

- Characterize foreground spectral energy distribution
  - Provide spectral template for imager
  - Demonstrate robustness of foreground model
- Compelling science goals from spectral distortions

Imager: Deep survey in a few selected bands

- Use foreground spectral templates from spectrometer
- Just fit foreground amplitudes
- Simplified focal plane, still get high angular resolution



Concern for Foreground Bias

Input: Power-lay synch, broad dust distribution

Fit: Power-law synch, 2-component dust

Fit matches input to few parts in 10^5

BUT ... Bias in r of order few x 10^{-3}

Kogut & Fixsen 2016