Science to Measurement Requirements

Outline

1) In the CMB-S4 Decadal Survey Report
2) An example: the DESI CD-1 Requirements Document
3) Thoughts on
3) Questions for Discussion

The DSR Science to Measurement Requirements Chapter

Four Science Requirements (we called them 'goals')

#1

There are two primary quantitative science targets, related to primordial gravitational waves and light relics.

Primordial Gravitational-Wave (PGW) Science Goal:

If $r = 0$, *achieve a 95% confidence upper limit of* $r \leq 0.001$. *If* $r \geq 0.003$, *achieve a* 5σ *detection.*

Motivation: All inflation models that naturally explain the observed deviation from scale invariance and that also have a characteristic scale equal to or larger than the the Planck mass predict $r \geq 0.001$. A well-motivated sub-class within this set of models predicts $r =$ 0.003 to 0.004. A characteristic scale near the Planck mass arises in many models whether they emerge from string theoretic considerations, effective field theory, or a minimal-new-physics approach (Higgs inflation), precisely because of the role gravity plays in the origin of the scale. An upper limit at $r = 0.001$ would point us toward more complicated solutions that introduce a non-Planckian scale. The observed departure from scale invariance is a potentially important clue that strongly motivates exploring gravitational wave amplitudes down to $r = 10^{-3}$.

#2

Light-Relics (LR) Science Goal:

Achieve $\Delta N_{\rm eff} < 0.06$ *at 95% confidence.*

Motivation: We have the opportunity with CMB-S4 to detect new light particles thermally produced in the early Universe. The contribution to $N_{\rm eff}$ depends on both the nature of the particle and the energy at which it was in equilibrium with Standard Model particles. A natural target is to search for new particles back to before the QCD phase transition.

With CMB-S4, any particle that was in thermal equilibrium at the beginning of the QCD phase transition can be ruled out at 95% confidence. While that sensitivity is not sufficient to detect a real scalar at an epoch earlier than the QCD phase transition, the sensitivity of CMB-S4 allows a further two order of magnitude improvement in energy sensitivity to either a Weyl fermion or vector particle.

#3

We also have two Legacy Survey science goals that we have used to define measurement requirements.

Galaxy-Clusters (GC) Science Goal:

For galaxy cluster searches, achieve a lower mass limit that is below $10^{14}\,\mathrm{M}_\odot$ *at* $z \geq 2$.

Motivation: Galaxy clusters in the local Universe appear to have formed the bulk of their stars at $z \approx 2$–3. A catalog at these redshifts will provide new views on the astrophysics of galaxy clusters. This sensitivity will allow views of clusters similar to massive clusters that we see at $z \approx 0.5$, but at an earlier stage in their development when they were forming their stars.

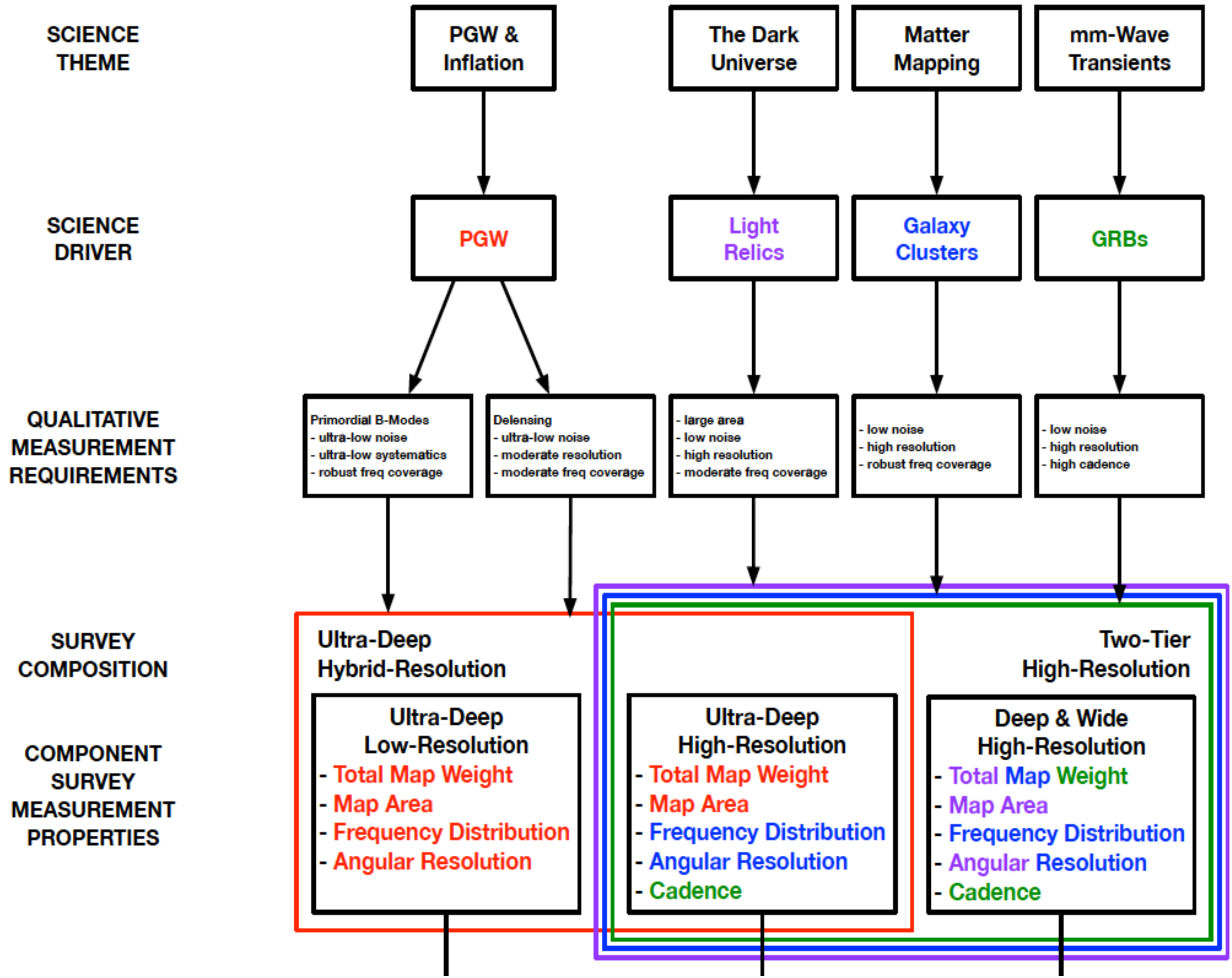
#4

Gamme-Ray Burst (GRB) Science Goal:

Measure many gamma-ray burst afterglow light curves.

Motivation: Gamma-ray burst afterglows contain a wealth of information about the central engine and the surrounding medium. The peak wavelength of the emission evolves with time, passing through mm-wavelengths a few days after the burst. Measurements made at this time will provide key information in particular about the density of the surrounding medium, uniformly for all bursts in the survey area.

There are numerous additional science goals, presented in the previous chapter. Those additional goals are all enabled by the CMB-S4 survey, but none are design drivers.



SCIENCE THEME
SCIENCE DRIVER
QUALITATIVE MEASUREMENT REQUIREMENTS
SURVEY COMPOSITION
COMPONENT SURVEY MEASUREMENT PROPERTIES
PGW & Inflation
The Dark Universe
Matter Mapping
mm-Wave Transients
PGW
Light Relics
Galaxy Clusters
GRBs
Primordial B-Modes
- ultra-low noise
- ultra-low systematics
- robust freq coverage
Delensing
- ultra-low noise
- moderate resolution
- moderate freq coverage
- large area
- low noise
- high resolution
- moderate freq coverage
- low noise
- high resolution
- robust freq coverage
- low noise
- high resolution
- high cadence
Ultra-Deep Hybrid-Resolution
Two-Tier High-Resolution
Ultra-Deep Low-Resolution
- Total Map Weight
- Map Area
- Frequency Distribution
- Angular Resolution
Ultra-Deep High-Resolution
- Total Map Weight
- Map Area
- Frequency Distribution
- Angular Resolution
- Cadence
Deep & Wide High-Resolution
- Total Map Weight
- Map Area
- Frequency Distribution
- Angular Resolution
- Cadence

Aside on nomenclature

$$\text{Legacy Survey} \neq \text{Deep and Wide Survey}$$

"Legacy Survey" is the whole thing, viewed as enabling Legacy Survey science goals.

Note that the ultra-deep high-resolution survey (aka "de-lensing survey") is part of the Legacy Survey

Measurement Requirements

We'll take Deep & Wide High-Resolution survey as an example

Deep & Wide High-Resolution
- Total Map Weight
- Map Area
- Frequency Distribution
- Angular Resolution
- Cadence

Map area:

- Driven by Neff goal
- Pushes to widest area possible
- We investigated sky coverage with Reijo's observation simulations.

Measurement Requirements

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Frequency Distribution:

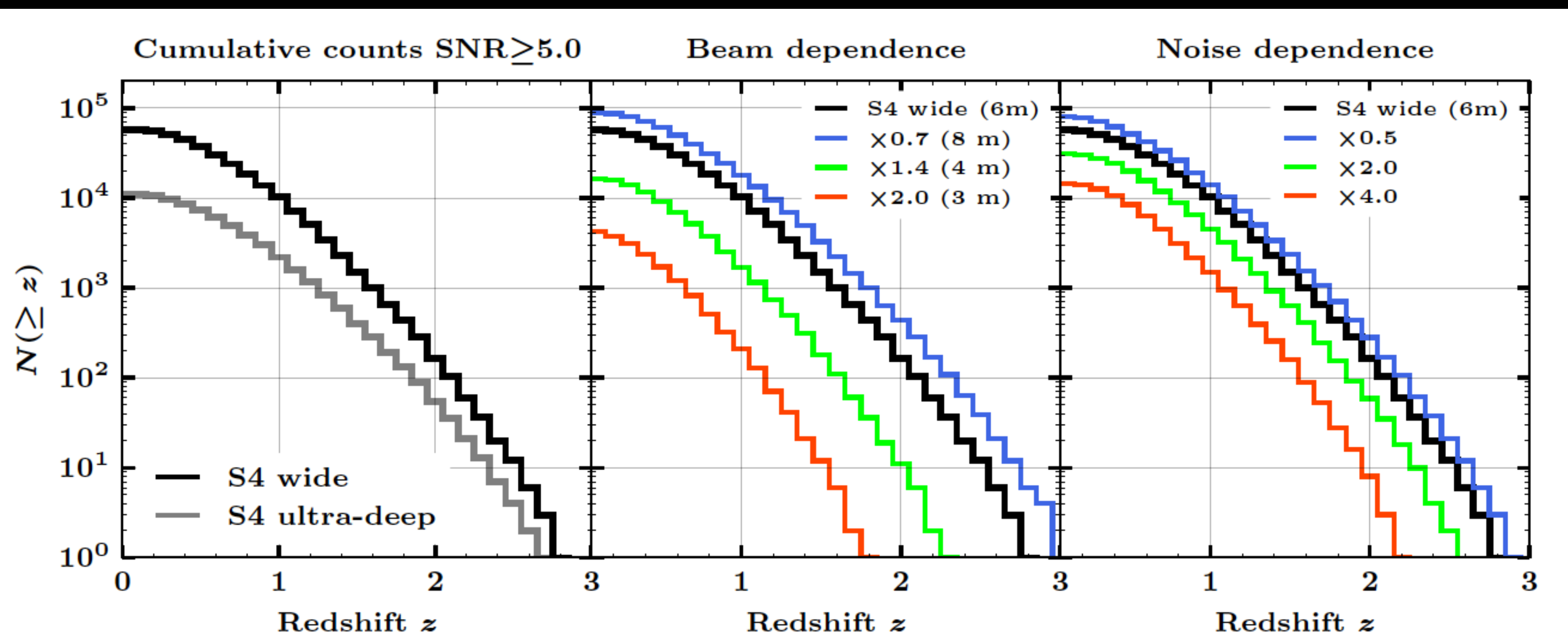
To assess the options for the distribution of detectors, we employed an end-to-end simulation-based optimization framework based on that used in Ref. [49]. We focused on temperature-based observables as metrics for optimization: the tSZ power spectrum, kSZ power spectrum, reconstructed CMB lensing power spectrum via the TT quadratic estimator (as a proxy for CMB "halo lensing," which is TT-dominated), and the CMB TT power spectrum (this is already well-measured, but included for completeness). Due to the current lack of knowledge regarding small-scale polarized foregrounds, and the expected stronger need for multifrequency coverage for tSZ and kSZ observables, we did not consider the reconstructed CMB lensing power spectrum from polarization data in this optimization.

The most important conclusion from this optimization is that the CMB-S4 LAT reference configuration (2 LF tubes, 12 MF tubes, 5 UHF tubes) used throughout this work is sufficiently near-optimal to serve as an excellent choice. In nearly all cases, it performed within 5–10% of the maximum S/N found in the optimization; the only exceptions to this were in measurements of the kSZ power spectrum with tSZ or CIB deprojection, where the reference configuration was within 15–20% of the maximal S/N found in the optimization. While future refinements of the detector allocation across frequency may be performed, particularly with updated CIB modeling to inform the high-frequency optimization, the flowdown presented here justifies the reference distribution that has been used throughout this document.

Measurement Requirements

We'll take Deep & Wide High-Resolution survey as an example

Angular Resolution: Examined impact of variation of aperture size away from reference design 6m



Measurement Requirements

We'll take Deep & Wide High-Resolution survey as an example

Deep & Wide High-Resolution
- Total Map Weight
- Map Area
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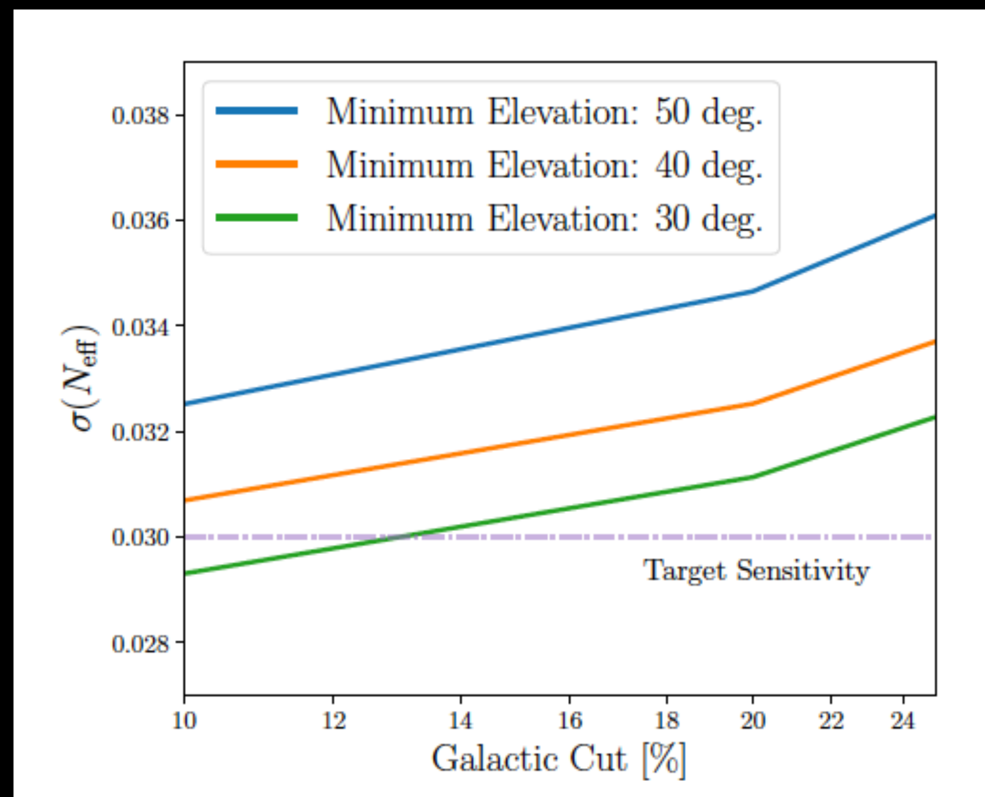
Total map weight: With the given frequency distribution, angular resolution, and amount of sky we can access, we made these forecasts:



Conclusion: we need at least the total weight (and angular resolution and sky area) of the reference design to make our Neff goal

Measurement Requirements

We'll take Deep & Wide High-Resolution survey as an example

Deep & Wide
High-Resolution
- Total Map Weight
- Map Area
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decays in ~few days

Cadence: Sole driver is the GRB afterglows goal

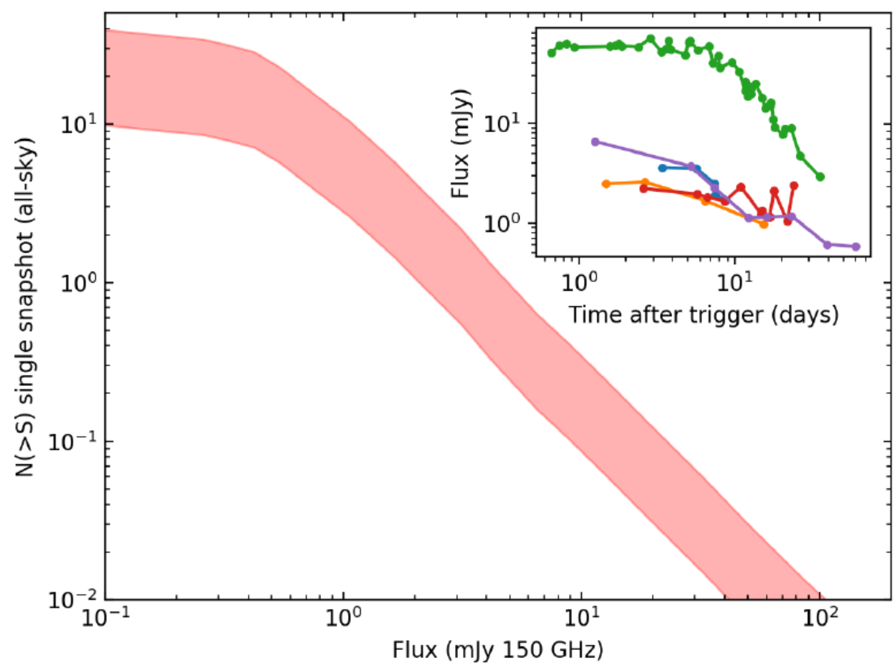

Figure 81. *Projections for 150-GHz transient source counts from Metzger et al. (2015) [468]. Shown are the total number of on-axis long gamma-ray bursts that are expected to be visible in the entire sky at any one time as a function of flux at 150 GHz. The width of the band schematically represents the uncertainty in this estimate. The inset shows some mm-wave follow-up observations of long gamma-ray bursts [494], showing typical variations on time scales of several days.*

Measurement Requirements

We'll take Deep & Wide High-Resolution survey as an example

Deep & Wide High-Resolution

- Total Map Weight
- Map Area
- Frequency Distribution
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- Cadence

From obs strat used for forecasting

From obs strat Reijo found that delivers desired cadence + uniform coverage

Cadence: Sole driver is the GRB afterglows goal

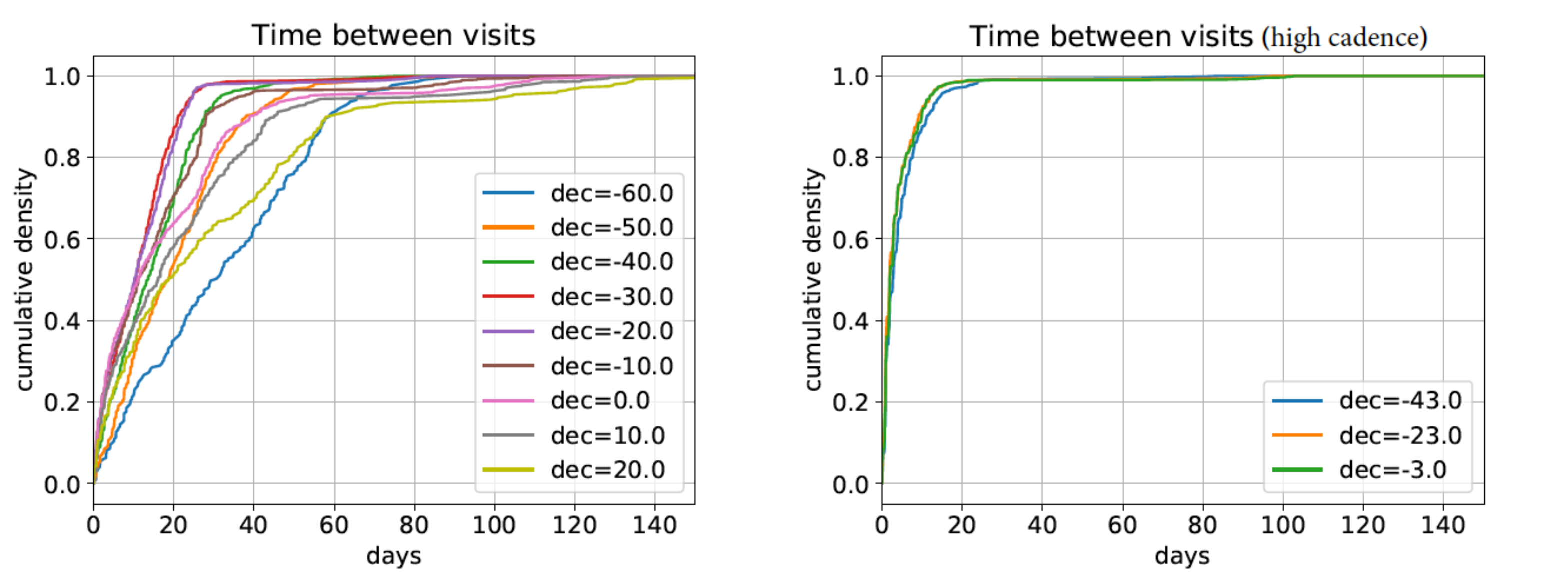

Figure 82. *Cumulative fraction of time between visits for the deep and wide field, split by declination. Left panel shows the default scan strategy assumed for calculating noise curves for the reference design: right panel shows results for a scan strategy with a high cadence that results in comparable overall survey performance. The ultra-deep field is expected to revisit every location daily in the reference design.*

Deep & Wide High-Resolution
- Total Map Weight
- Map Area
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To do list for our December 2020 Baseline document

- Actually optimize the frequency distribution
  - Similar to DSR or will we actually flow down from galaxy cluster goal?
- Demonstrate survey can deliver Neff goal with
  - better modeling of galactic foregrounds
  - an observing strategy that achieves desired cadence
  - some margin built in? should we adjust requirement to 0.033? do we have a goal and a requirement (with goal more ambitious)?
  - demonstration that elmin = 30 degrees is ok (noise models good? nonlinear detector response OK?). go to lower elmin?
  - demonstrated capability to measure beams sufficiently well
- Couple optimizations (e.g., ang. resolution and total weight) with cost models? How do we get these?
- Set requirements on systematic errors ==> requires input from technical side (a low-dimensional parameterization)

Example: DESI CD-1 Requirements Document (available on CMB-S4 wiki)

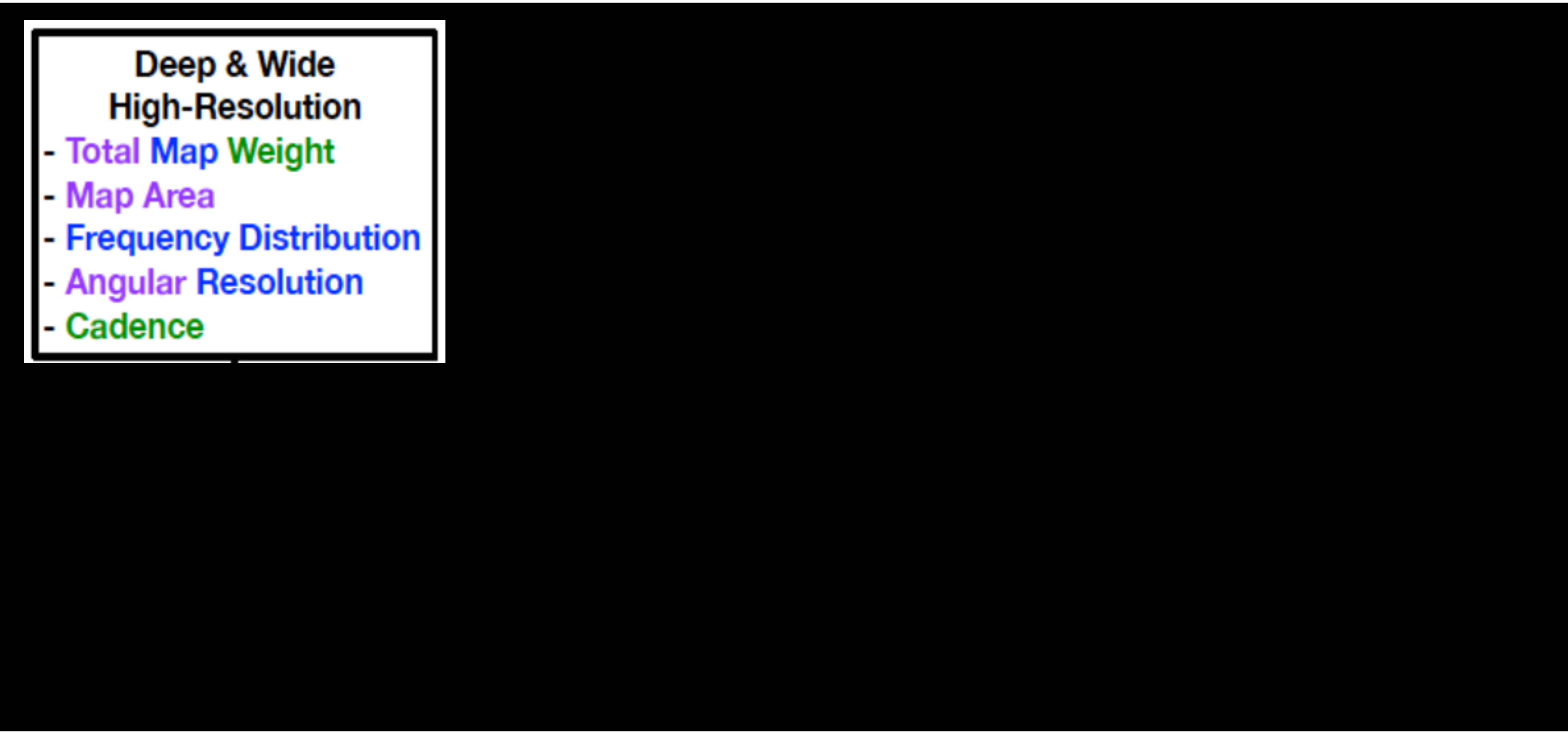
- Their document is only 19 pages with only 5 references!
- Their L1 goals all had to do with BAO. This was a simplification that greatly reduced the amount of flowdown work to be done, and even allowed them to avoid simulations.
- Sky available drove coverage to maximal which set their science goals (errors on D(z) and H(z)).
- They then flowed those science goals to measurement requirements and then technical requirements.

Thoughts on Schedule

- Early 2020: Define handful of instrument designs for simulation, define sky models, and make all choices about how to simulate.
- From now to June 2020: develop capabilities to analyze simulated maps, exercise them on Dec 2019 reference design and subsequent simulated maps
- June 2020: Perform analyses of baseline set of simulated maps.
- June to September 2020 From these analyses, and other relevant analyses, produce conclusions that are actionable regarding instrument design.
- September 2020: Settle on a final baseline design for simulation and analysis.

High-level Questions

- What is required for the baseline requirements document? What historical examples are useful as guides?
- Do we want to revisit any science goals?
  - Do we want to add a science goal, or alter an existing one, that will drive resolution of the ultra-deep high-resolution survey?
  - Should we set sigma(Neff) = 0.03 as a goal, and 0.033 as a requirement?
- What aspects of flowdown require spectral domain Fisher analyses? map-based sims? time-stream sims? Will we follow a hybrid approach of fast, more approximate methods, cross-checked in particular cases with more sophisticated simulations?
- How do we specify requirements on systematic errors in a map?
- How do we make sure our plan for science to measurement flowdown is useful for the measurement to technical flowdown?
- How do we structure the work to motivate people to get it done? What papers are worth writing based on the flowdown work.



Frequency (GHz)	30	40	95	145	220	270
Angular resolution (arcmin)	7.4	5.1	2.2	1.4	1.0	0.9
Total survey weight $(TT)/10^6$ [μK^2]	0.22	0.68	26.3	26.3	2.2	0.38
White noise level for TT (μK-arcmin)	21.8	12.4	2.0	2.0	6.9	16.7
White noise level E/B (μK-arcmin)	30.8	17.6	2.9	2.8	9.8	23.6

Table 2-3. *Deep and Wide Field map noise and angular resolution requirements.*