Microwave kinetic inductance detectors for Dark Energy.

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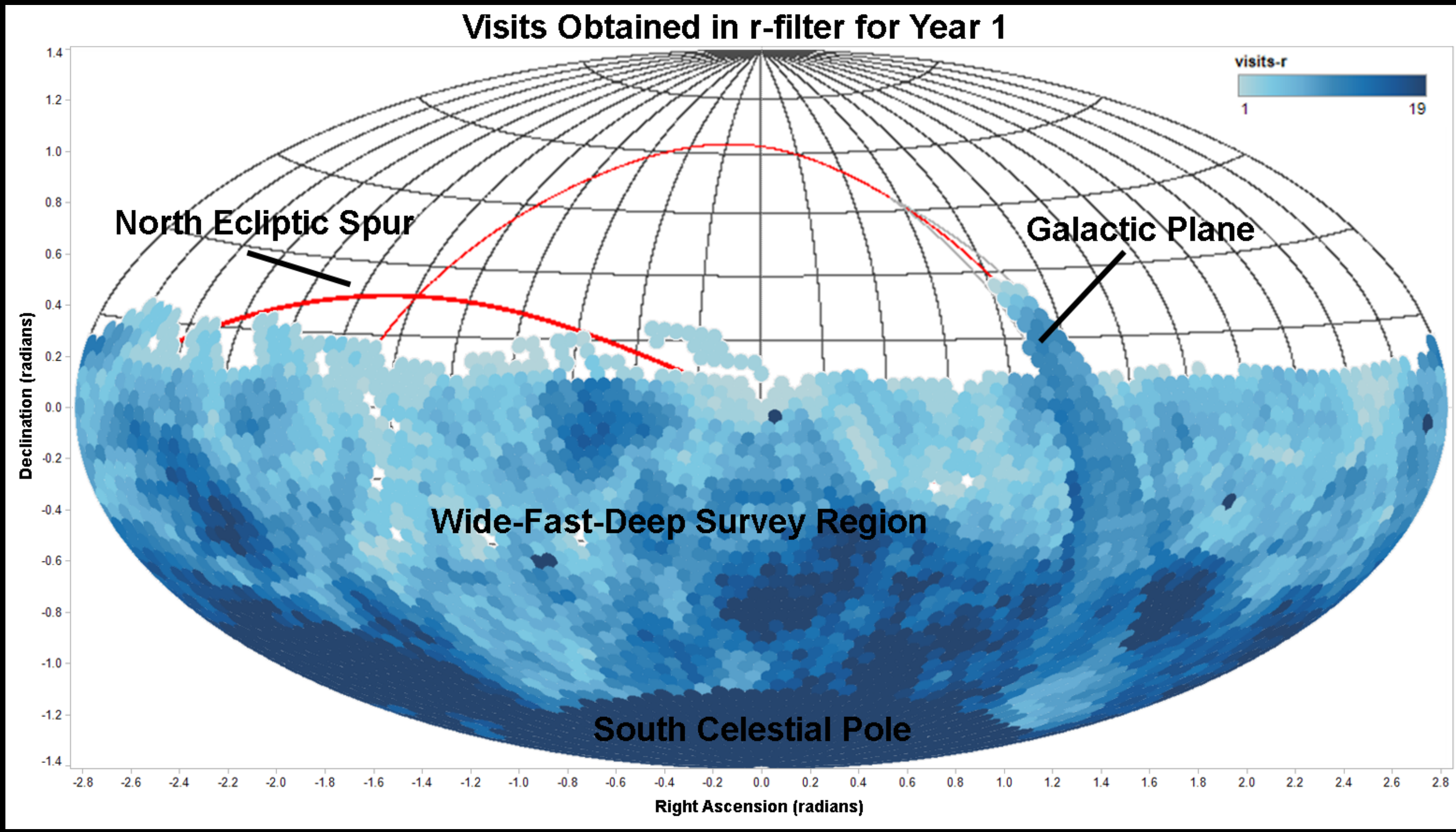
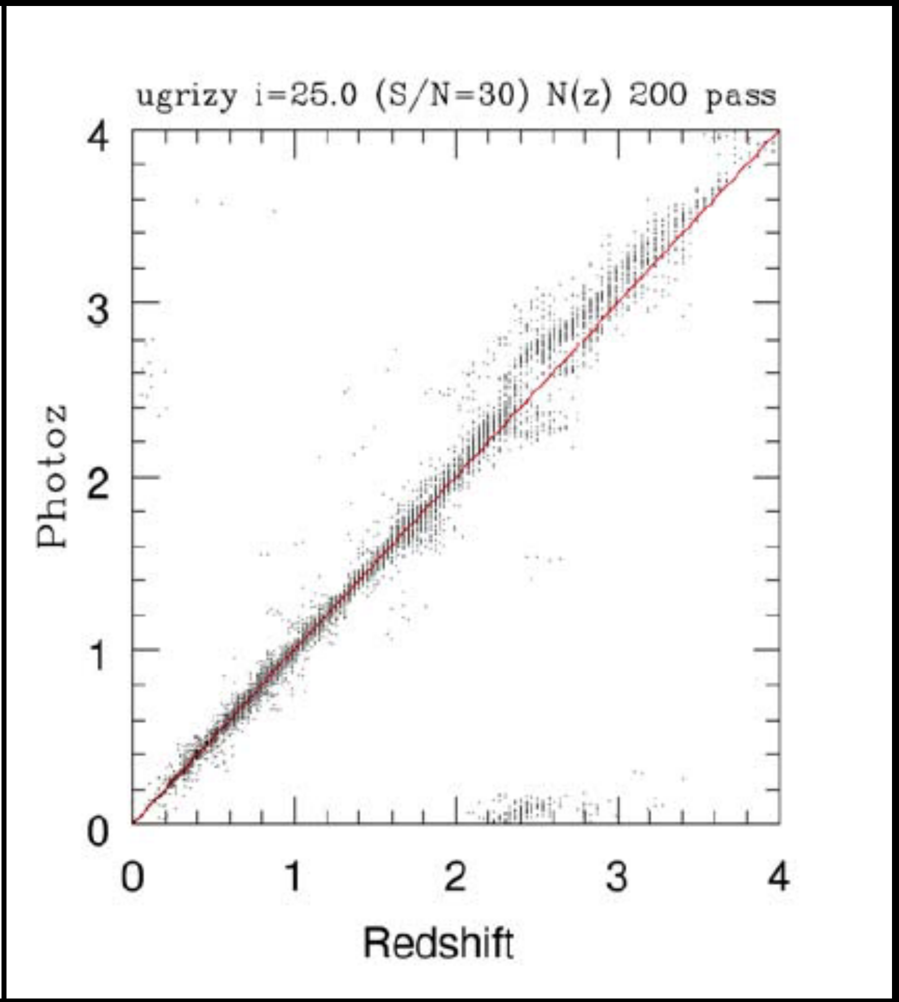
Were are we going to be after LSST?



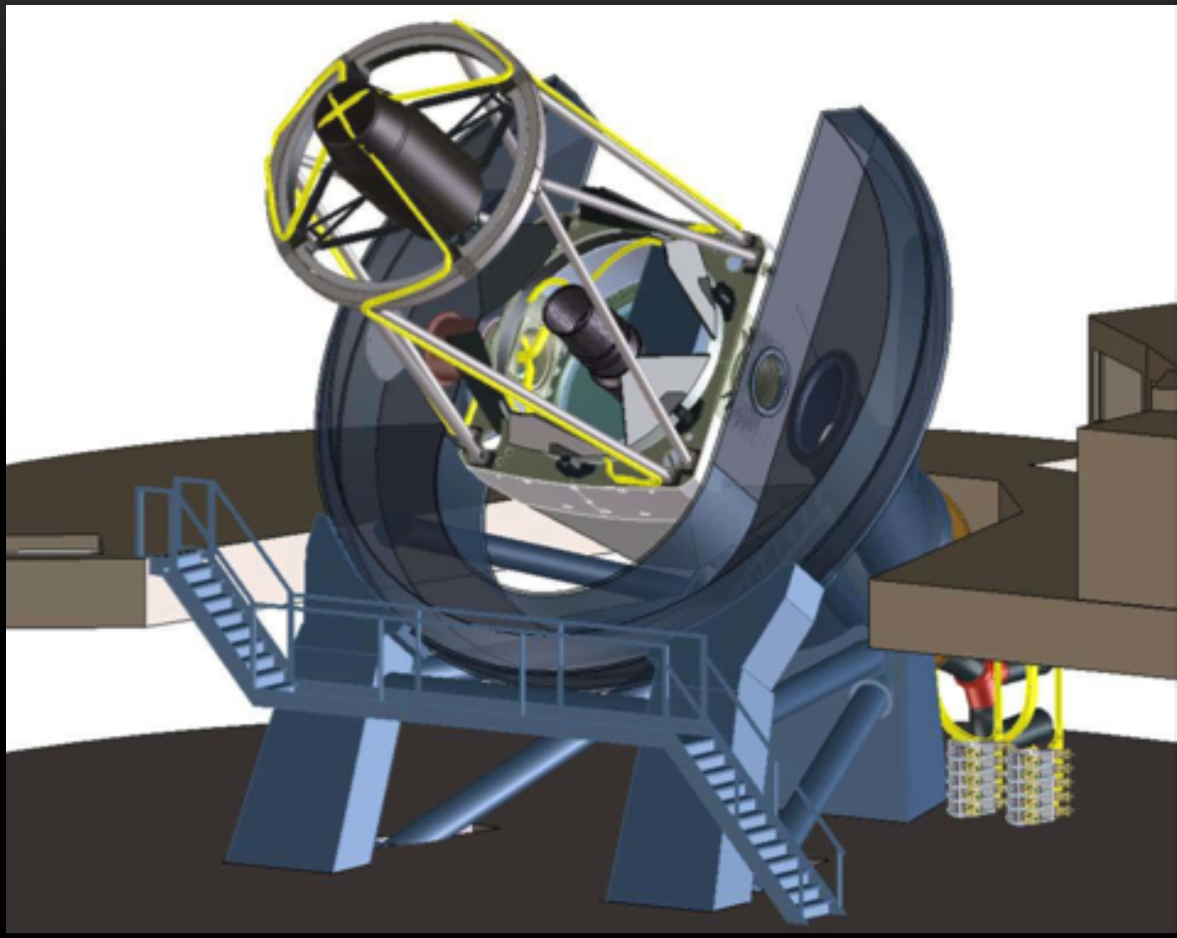


LSST will produce photometric data for 20,000 sq-deg to magnitude 27. Redshift will be estimated from the colors of the objects.

We will never have enough spectroscopic instruments to follow up all these observations using current technology.

DARK ENERGY SPECTROSCOPIC INSTRUMENT (DESI)

- 4 m telescope in Arizona
- 5000 fiber, 3 arm spectrograph,
- R~4000
- Spectra for 1800 objects/deg^2 (~10% of available galaxies)
- Magnitude limit ~22.5, z~3.5
- Will cover 14,000 deg^2 in 3 years
- 20 M galaxies, 0.6 M QSO

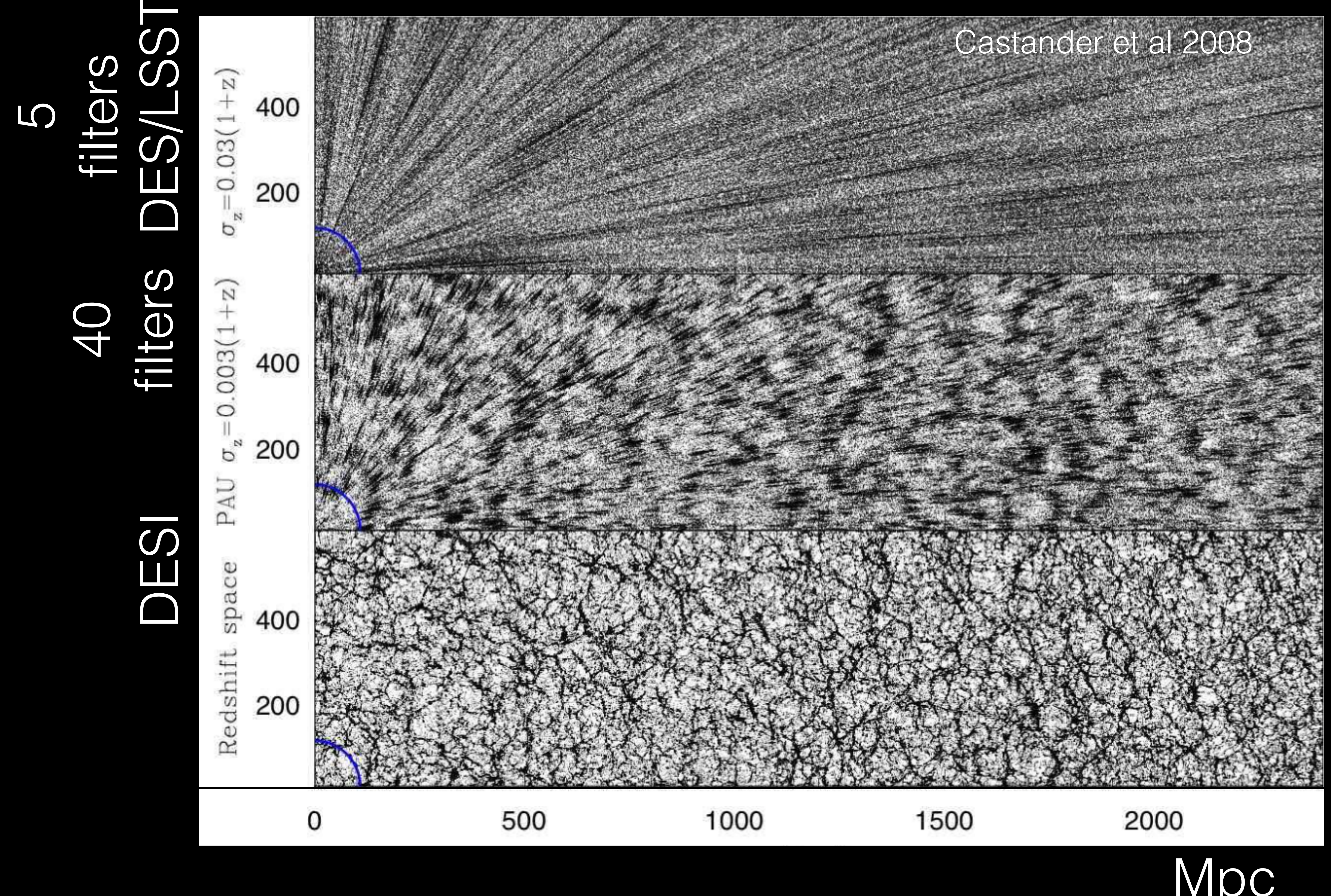


Starting construction in soon…

This technology is not enough to address the need.

NOT enough!

Good news: Low Resolution Spectroscopy cal help a lot



Low resolution could get us a lot of information

Low Resolution Spectroscopy

Gastanaga et al 2011

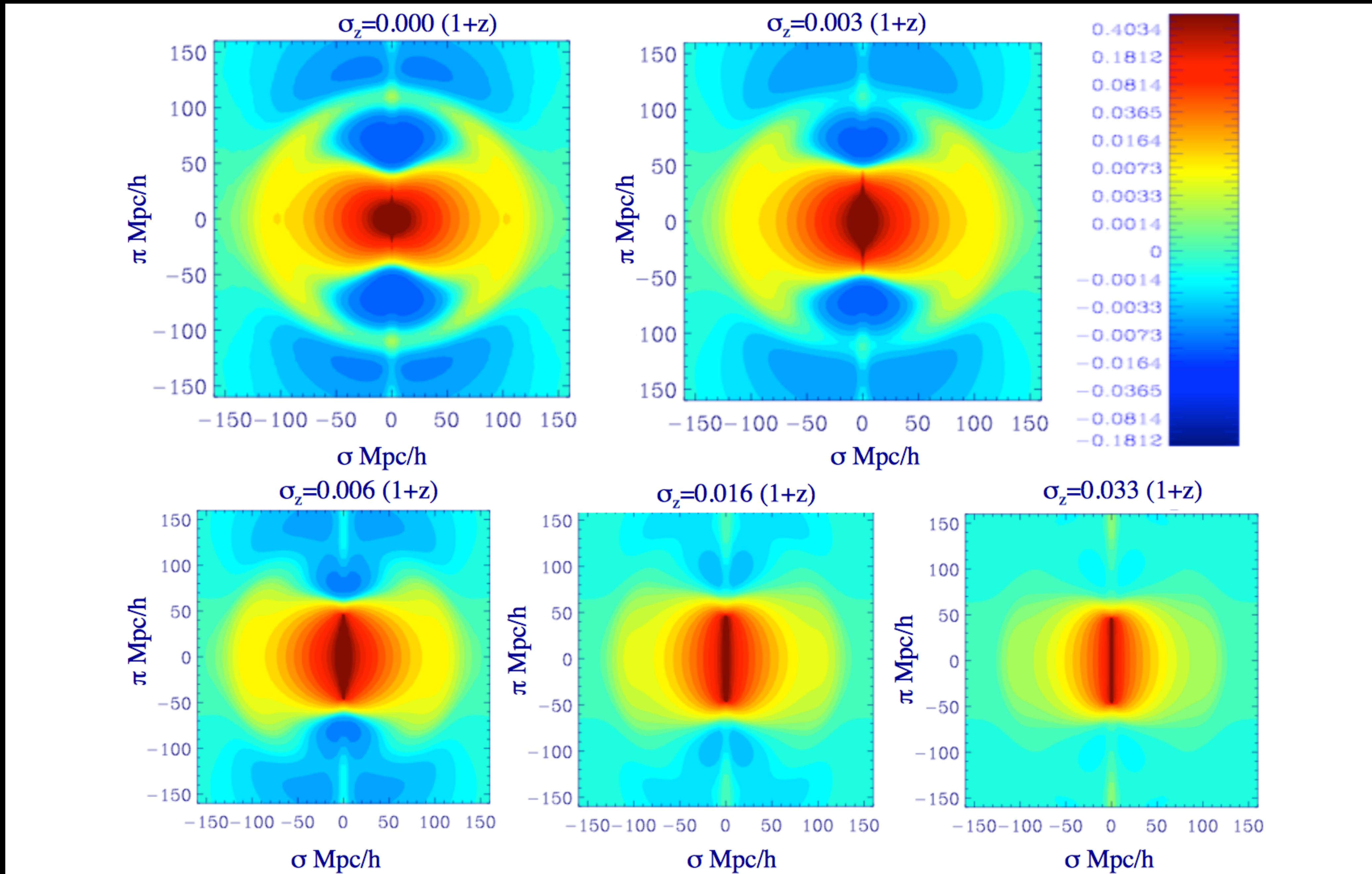


Figure 2. Top left panel shows the $\xi(\pi,\sigma)$ correlation in the Kaiser model with no photo-z error, i.e. $\sigma_z = 0$ (from Gaztañaga, Cabré & Hui 2009). The correlation is clearly squashed in the radial direction with a region of negative correlation (in blue) between $\pi = 50 - 100$ Mpc/h. Top right panel shows the same model but with a photo-z degradation of $\sigma_z = 0.003(1+z)$, corresponding to the PAU Survey. The difference is small and is mostly confined to small radial scales. Bottom panels show how the results are degraded as we increase σ_z to 0.006 (left), 0.016 (center) and 0.033 (right panel). As the photo-z increases the radial squashing disappears, turning instead into a radial elongation. Note also how the region of negative correlation vanishes as we increase the photo-z error.

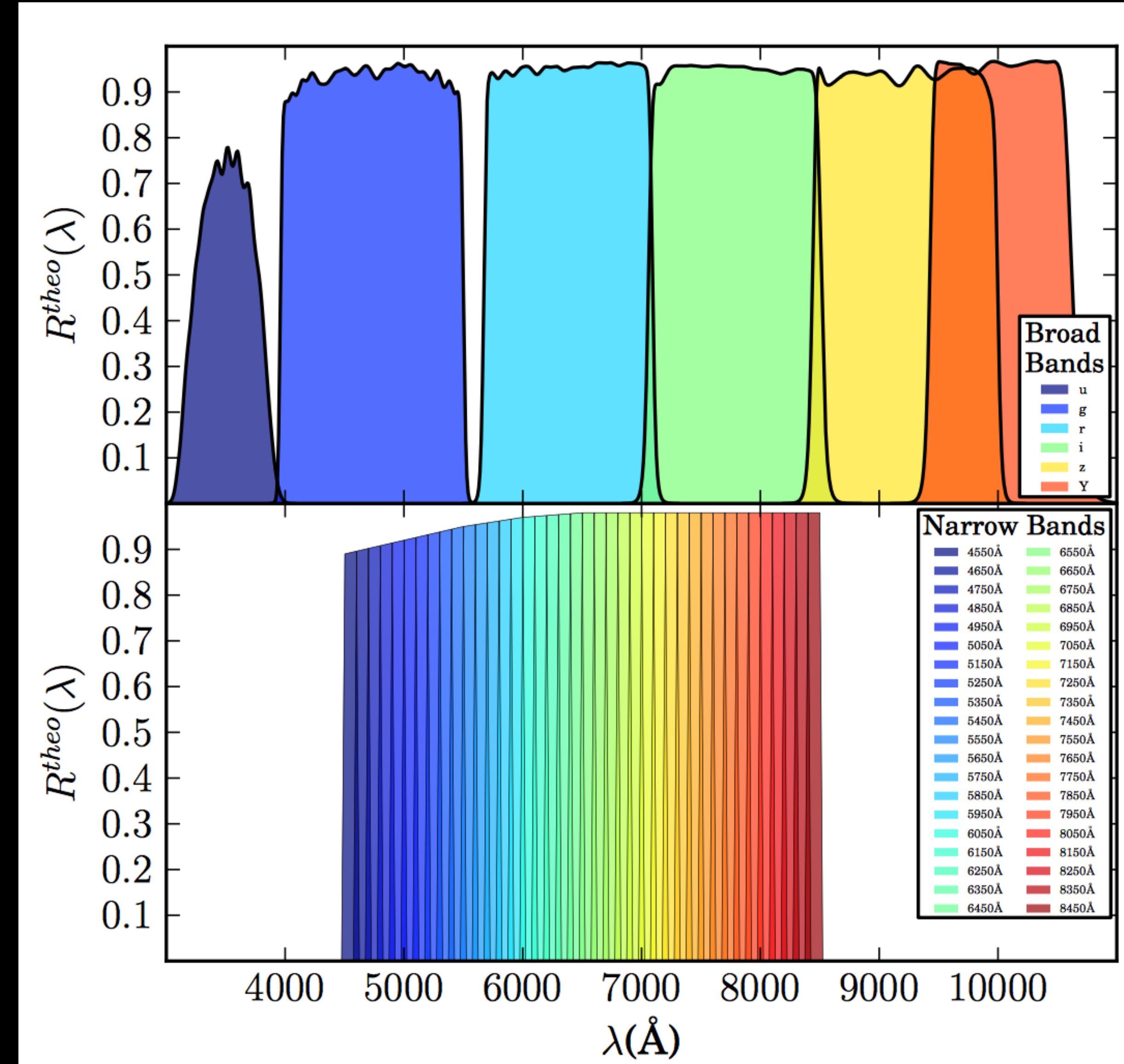
Low resolution could get us a lot of information

PAU http://www.pausurvey.org/

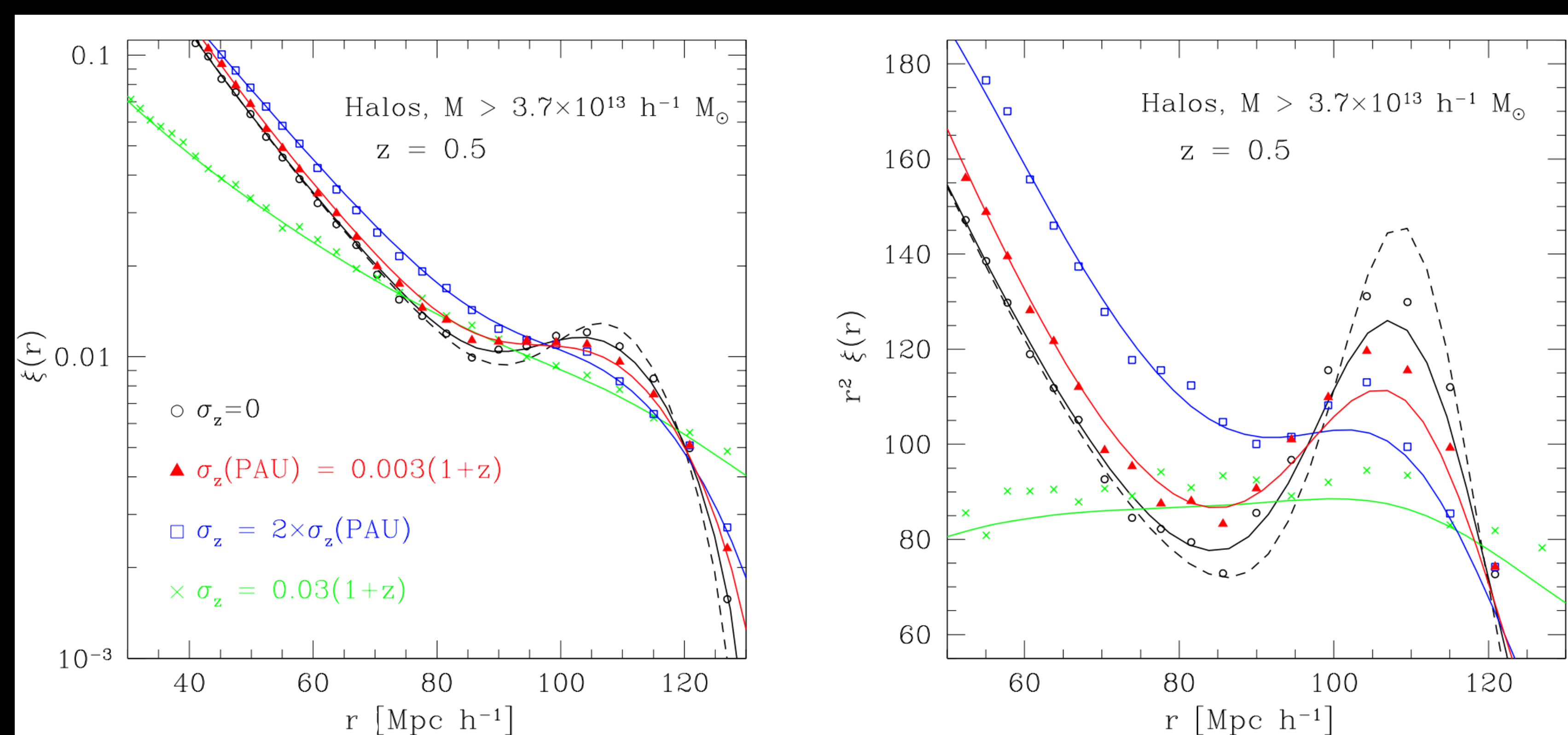
Physics of the Accelerating Universe

This project takes does photometry in 40 filter. It is starting to operate now. The point is **a lot of cosmology could be done with low resolution spectroscopy**

The issue is that if you use 40 filters, you are discarding 39/40 of the photons on each observation. A DES like survey would take 40 years instead of 5.



Example of potential of BAO measurement with 10 times better photo-z. Castander et al 2008.

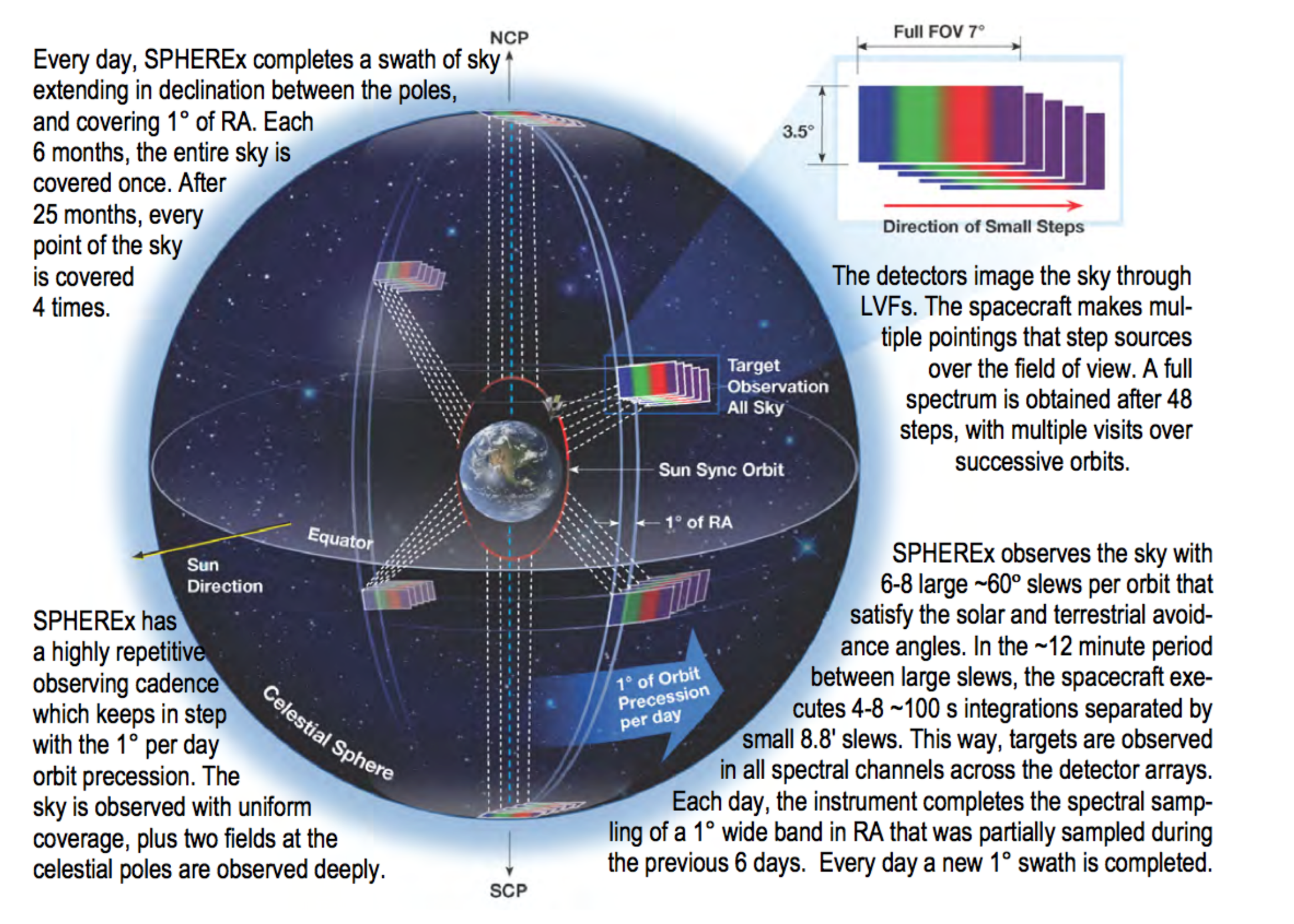


Cosmology with the SPHEREX All-Sky Spectral Survey

Olivier Doré, Jamie Bock, Matthew Ashby, Peter Capak, Asantha Cooray, Roland de Putter, Tim Eifler, Nicolas Flagey, Yan Gong, Salman Habib, Katrin Heitmann, Chris Hirata, Woong-Seob Jeong, Raj Katti, Phil Korngut, Elisabeth Krause, Dae-Hee Lee, Daniel Masters, Phil Mauskopf, Gary Melnick, Bertrand Mennesson, Hien Nguyen, Karin Öberg, Anthony Pullen, Alvise Raccanelli, Roger Smith, Yong-Seon Song, Volker Tolls, Steve Unwin, Tejaswi Venumadhav, Marco Viero, Mike Werner, Mike Zemcov

(Submitted on 16 Dec 2014 (v1), last revised 25 Mar 2015 (this version, v3))

SPHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer) (this http URL) is a proposed all-sky spectroscopic survey satellite designed to address all three science goals in NASA's Astrophysics Division: probe the origin and destiny of our Universe; explore whether planets around other stars could harbor life; and explore the origin and evolution of galaxies. SPHEREx will scan a series of Linear Variable Filters systematically across the entire sky. The SPHEREx data set will contain R=40 spectra fir $0.75< \lambda <4.1\mu m$ and R=150 spectra for $4.1< \lambda <4.8\mu m$ for every 6.2 arc second pixel over the entire-sky. In this paper, we detail the extra-galactic and cosmological studies SPHEREx will enable and present detailed systematic effect evaluations. We also outline the Ice and Galaxy Evolution Investigations.



Parameter	Value
Telescope Effective Aperture	20 cm
Pixel Size	6.2" × 6.2"
Field of View	$2 \times (3.5° \times 7.0°)$; dichroic
Spectrometer Resolving Power and Wavelength Coverage	R=41.5; λ=0.75-4.1μm R=150; λ=4.1-4.8 μm
Arrays	2 x Hawaii-2RG 2.5 μm 2 x Hawaii-2RG 5.3 μm
Point Source Sensitivity	18.5 AB mag (5σ) on average per frequency element with 300% margin
Cooling	All-Passive
2.5 μm Array and Optics Temperature	80K with 700% margin on total heat load
5.3 μm Array Temperature	55K with 450% margin on total heat load
Payload Mass	68.1 kg (current best estimate + 31% contingency)

TABLE I: SPHEREx Key Instrument Parameters.

Low spectral resolution, big fixes, all sky!

Another low resolution spectroscopy example : PRIMUS

failure rate in redshift measurements with low-res spectra

TABLE 1
PRIMUS Redshift Confidence Classes

Class	$\sigma_{\delta z/(1+z)}$	Outliers[a]	Sample Fraction[b]
4	0.005	7.85	49.2
3	0.022	5.32	21.6
2	0.050	5.06	29.2

[a] Fraction of objects with known redshifts deviating more than 5σ from agreement.
[b] Fraction of PRIMUS primary galaxies which received the specified class designation.

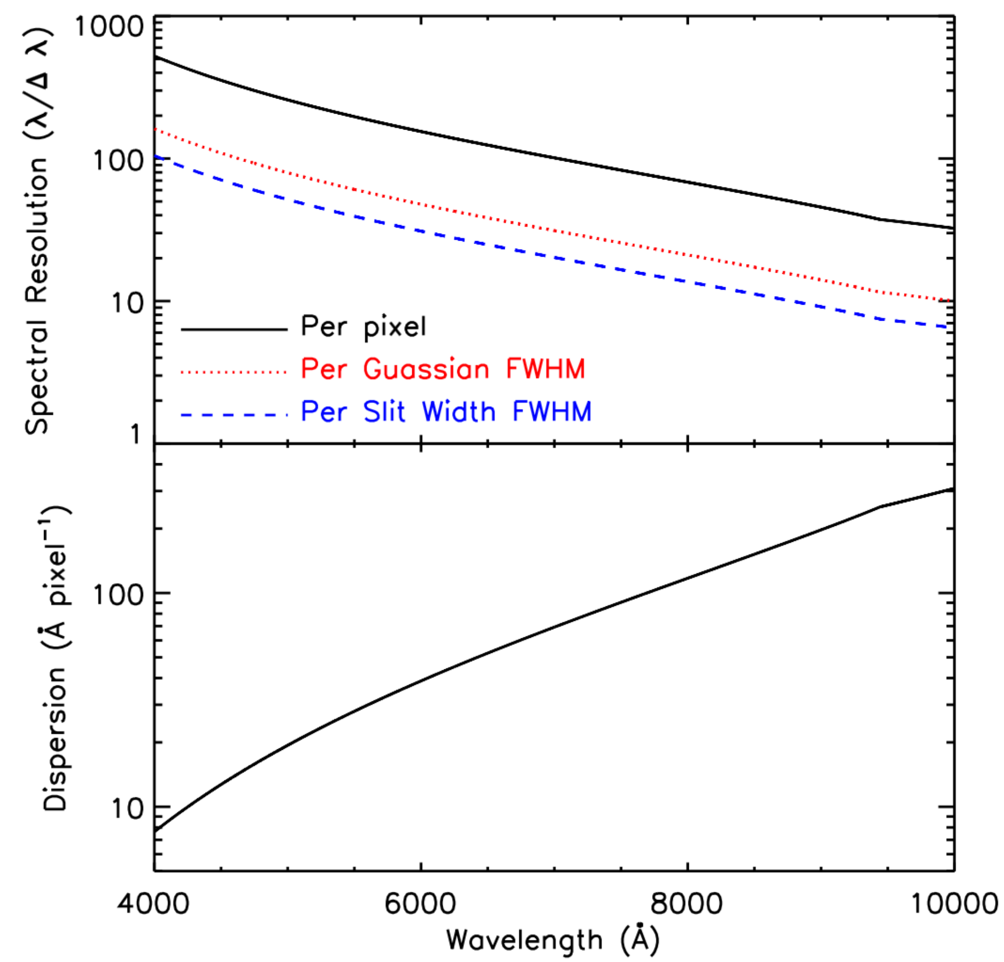


Fig. 2.— Resolution and dispersion of the PRIMUS prism versus wavelength. The resolution and dispersion generated by the low dispersion prism is a strong function of the wavelength with increased resolution in the blue but low resolution at $9000\AA - 1\mu m$. The low resolution allows us to observe the full optical spectrum of a target galaxy on only ~150 pixels on the detector and up to ~3000 galaxies on a single mask.

This is data, not simulation. Primus with R~100 gets in real 5% failure rate in the best 50% sample, and 8% failure in the rest.

the Baade I 6.5m telescope at Las Campanas, PRIMUS spectroscopically measures galaxy redshifts in much less time than would be required with more traditional high-resolution spectroscopic techniques ($\sim 10,000$ galaxies per night) and reaches depths of $i \sim 23$ in one hour. PRIMUS redshifts have typical precision of $\sigma_z/(1+z) = 0.005$. PRIMUS spectroscopy focuses on fields with existing optical imaging for target selection and emphasizes areas with existing high-quality multiwavelength imaging from *GALEX*, *Spitzer*, *Chandra*, and *XMM-Newton*. The

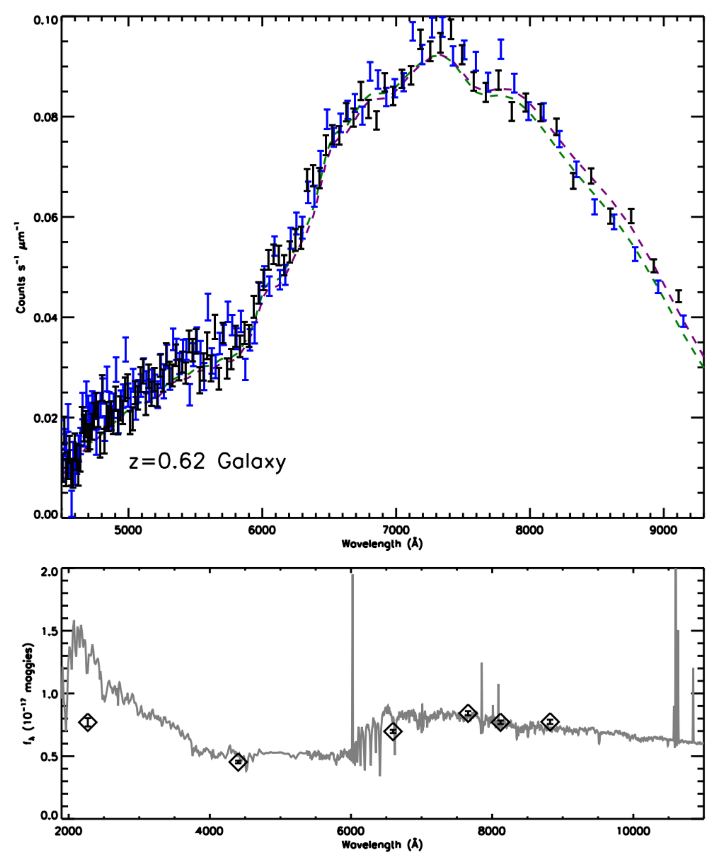


FIG. 17.— Example of a PRIMUS fit to an object identified as a $z = 0.62$ galaxy. The top panel shows the observed PRIMUS spectrum from both slit A (black) and slit B (blue). The dashed line shows the best-fitting model convolved to PRIMUS resolution. In the bottom panel, the grey line shows the full-resolution best-fitting galaxy model. The data points with errorbars mark the broadband UV and optical photometry available for the object.

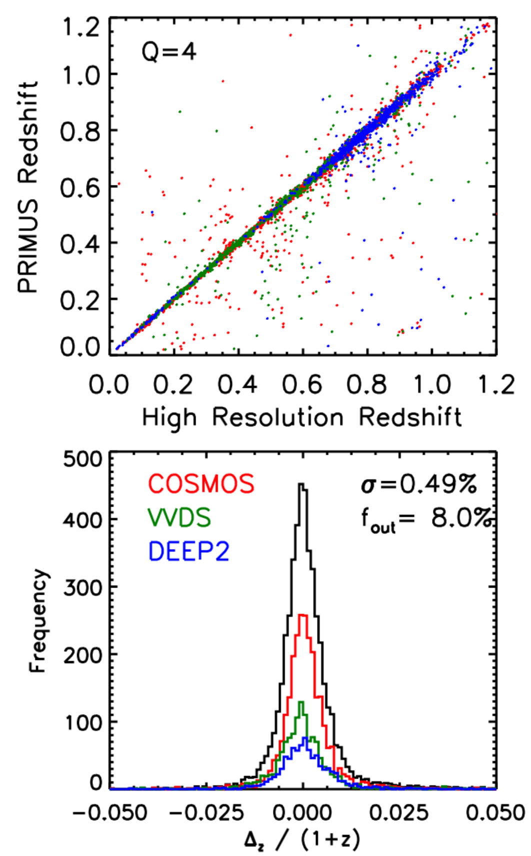
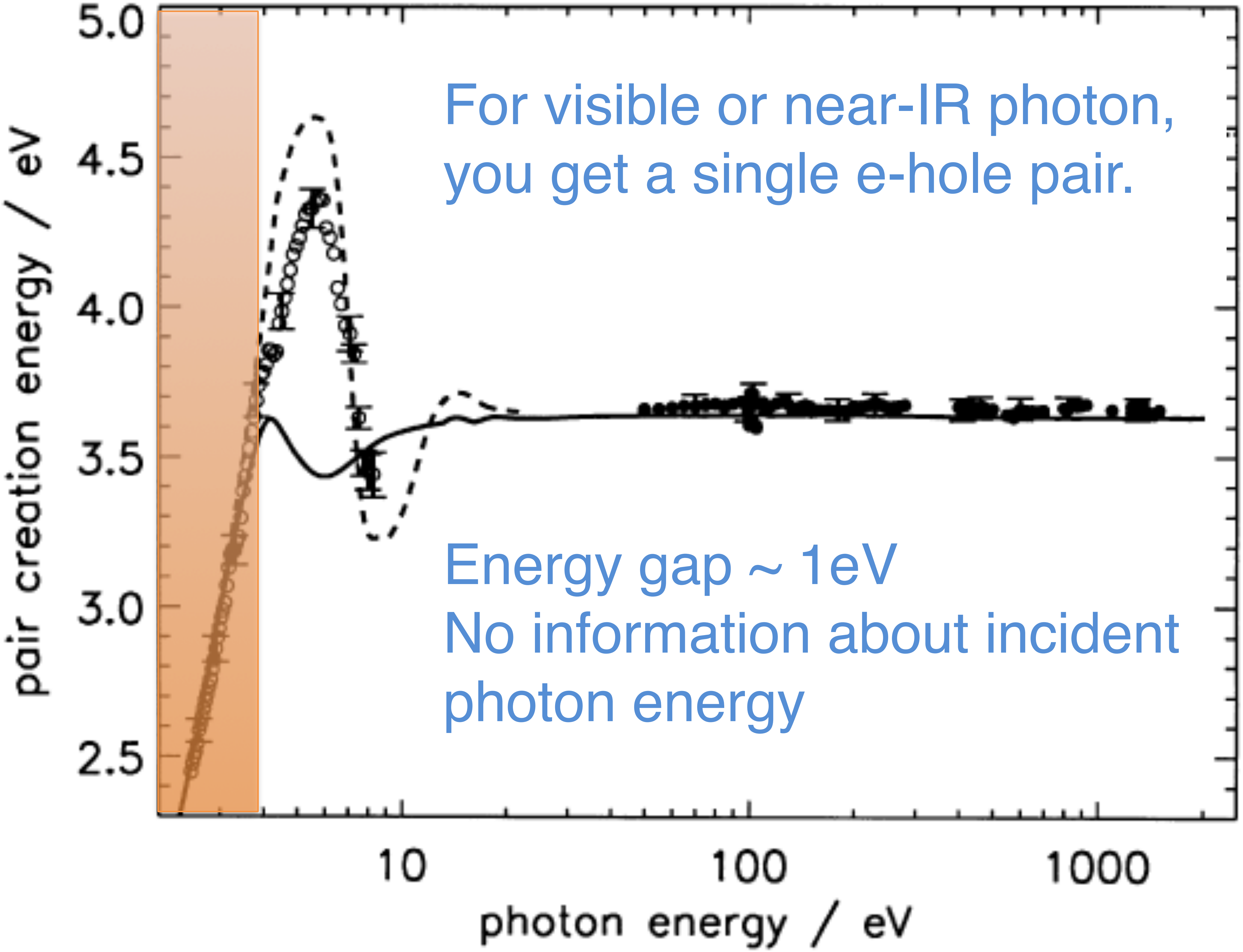


FIG. 20.— Comparison of PRIMUS redshift with redshifts obtained from higher-resolution spectroscopy from COSMOS, DEEP2, and VVDS for $Q = 4$ quality rating. The bottom panel shows the histogram of the difference between the PRIMUS and high-resolution redshift for each survey as well as the full comparison sample. Overall, we find a $\sim 0.5\%$ dispersion between PRIMUS and the high-resolution sample with $\sim 8\%$ of the galaxies falling more than 5σ from agreement.

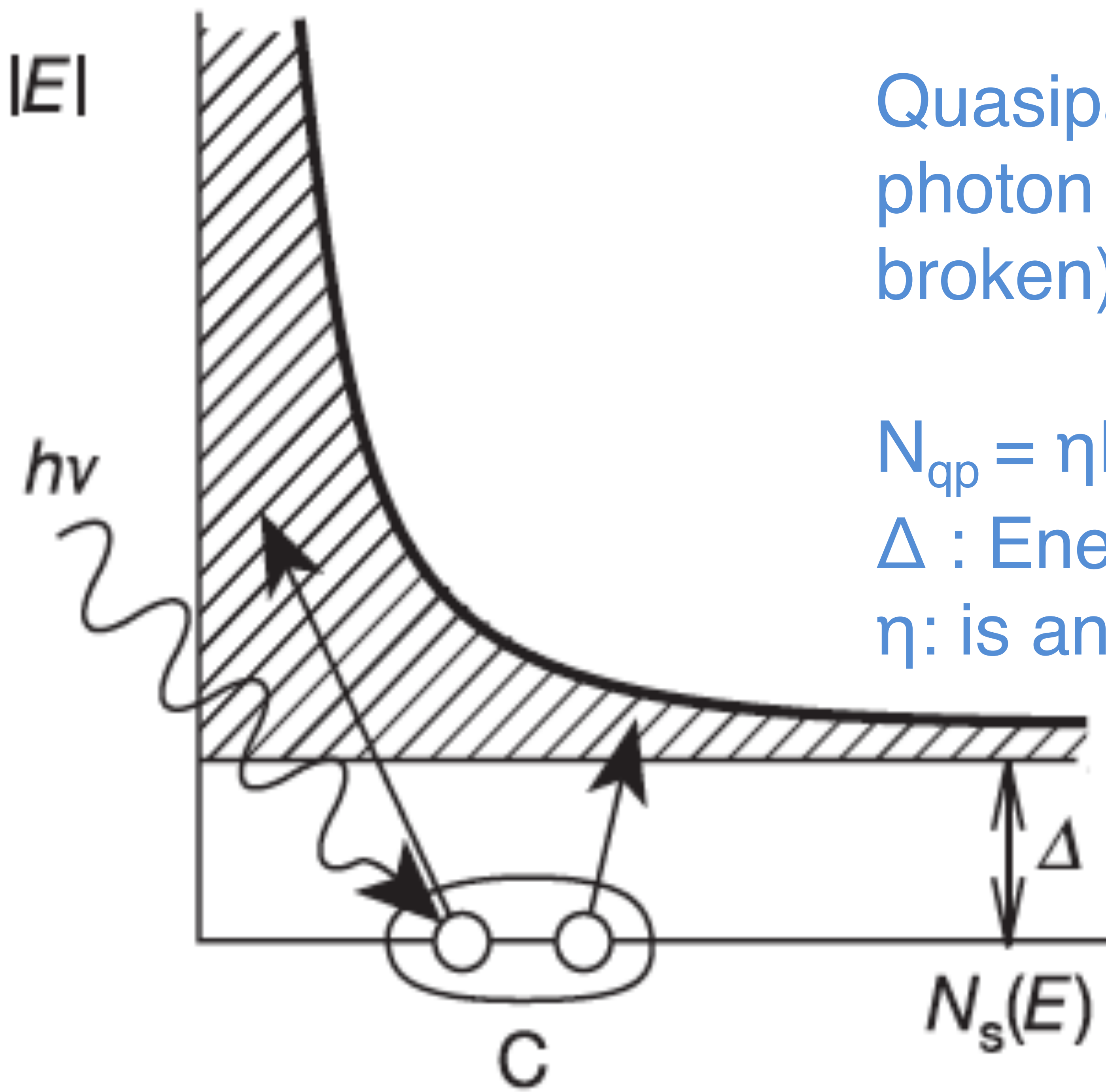
High statistics low-resolution spectroscopy is a tool that we want for after LSST?

Microwave Kinetic Inductance Detectors could be a technology for high volume low resolution spectroscopy without filters.

limitation of Si semiconductor detectors…



superconductors overcome this limitation



Quasiparticles are created when a photon hits a SC (Cooper pairs broken)

$N_{qp} = \eta h\nu/\Delta$

Δ : Energy gap ~ 0.001 eV

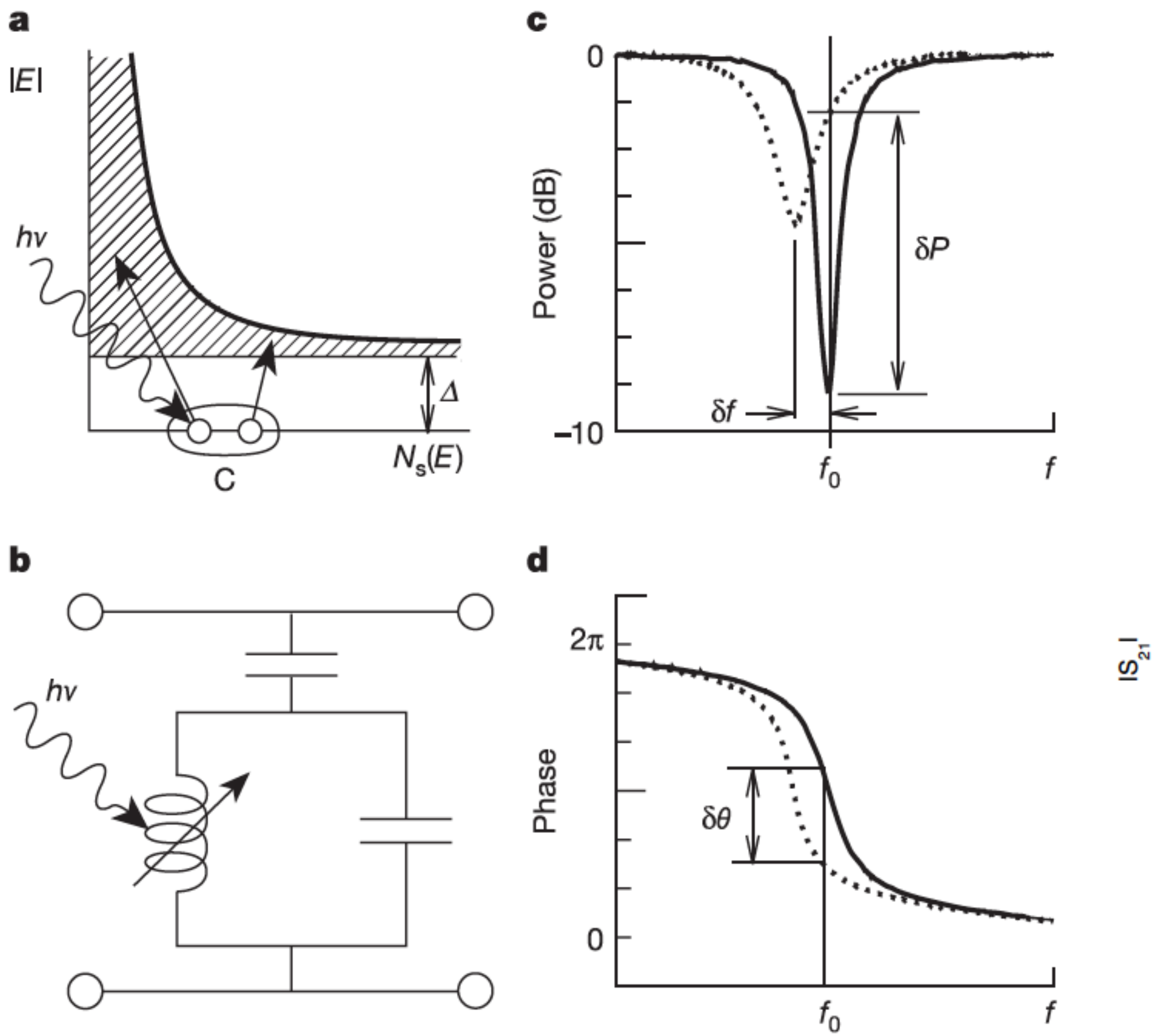
η: is an efficiency ~ 0.6

	Niobium $T_c = 9.25$ K $\Delta = 1.4$ meV	Tantalum $T_c = 4.47$ K $\Delta = .68$ meV	Aluminum $T_c = 1.175$ K $\Delta = .18$ meV	Titanium $T_c = 0.4$ K $\Delta = .06$ meV	Hafnium $T_c = 0.128$ K $\Delta = .02$ meV
IR (0.62 eV)	15	22	42	73	126
Optical (3.1 eV)	34	48	94	163	282
UV (10.3 eV)	61	88	171	297	514
X-ray (6 keV)	1500	2140	4000	7200	12500

Table 3.2: Energy resolution $R = E/\Delta E$ limits for different superconducting absorbers for photon counting detectors. These calculations were done with an IR wavelength of 2 μm, optical wavelength of .4 μm, UV wavelength of .12 μm, and X-ray energy of 6 keV.

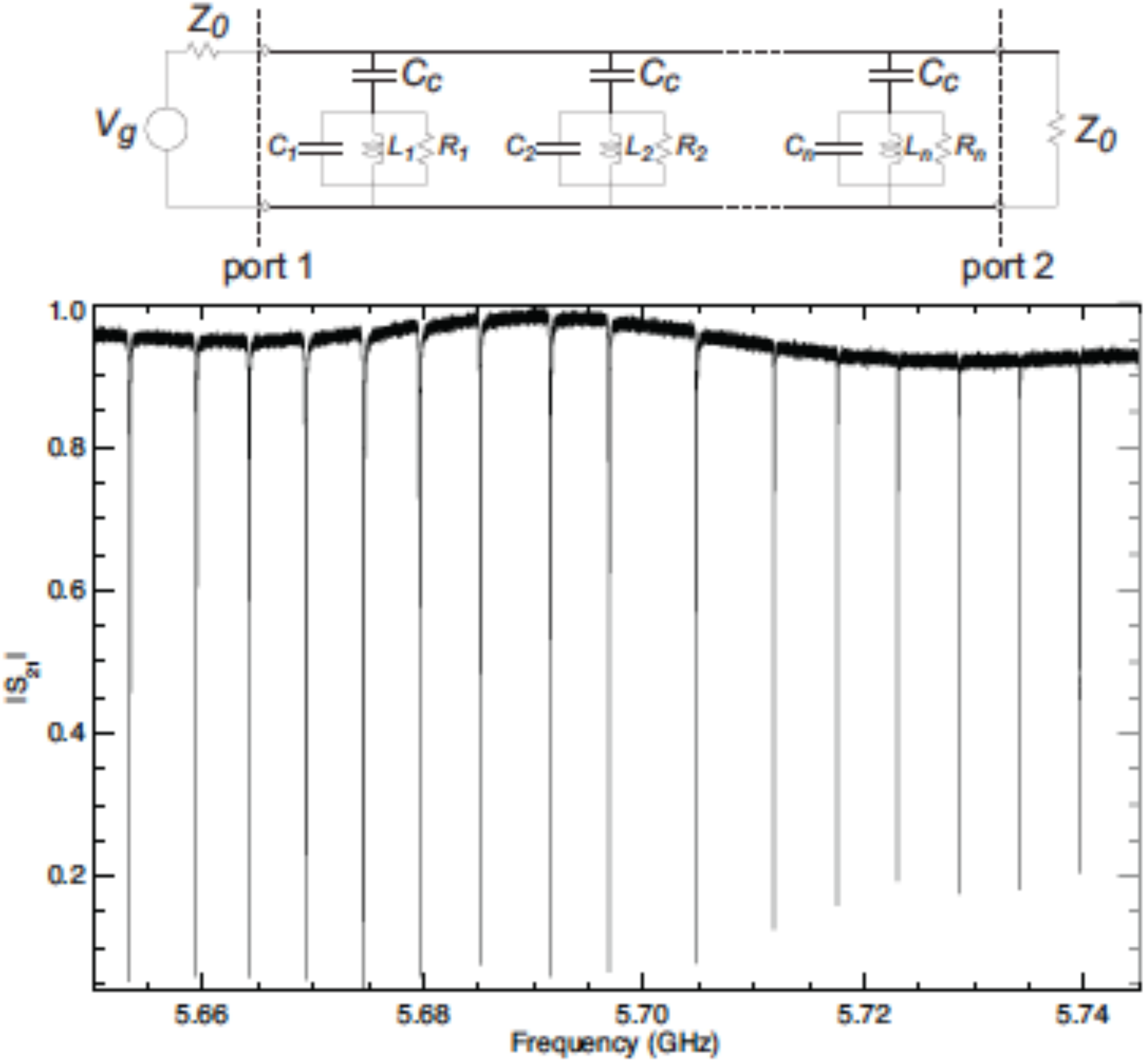
Number of quasiparticles is proportional to photon energy!
~5000 quasiparticles for a visible photon

Microwave Kinetic Inductance Detectors

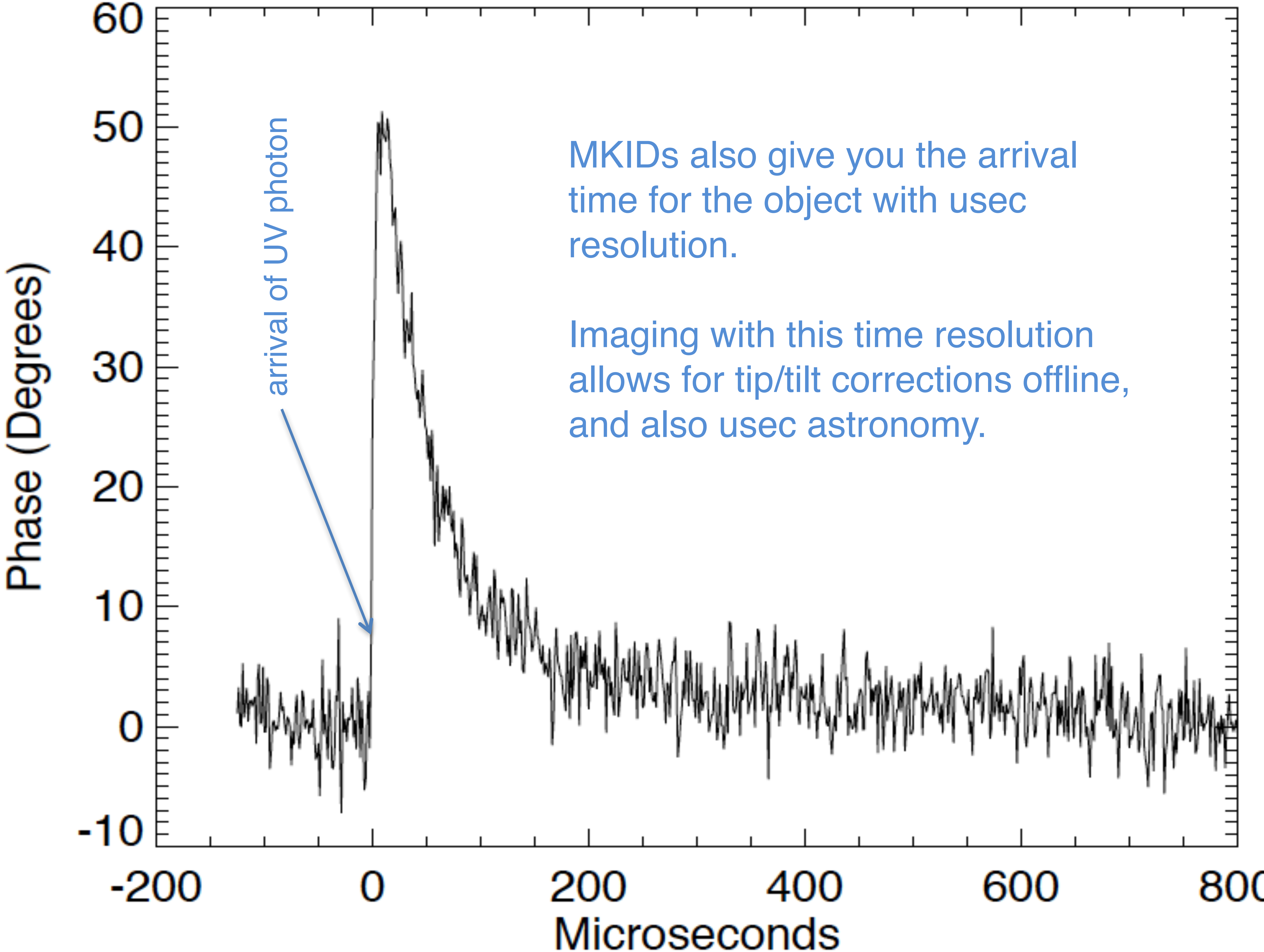


Superconductor sensors with "easy" frequency multiplexing

Each pixel is tuned to a different frequency. Photons each a pixel and move the resonance for that pixel. Digital FM radio.



Large array of superconducting detectors are NOW possible.



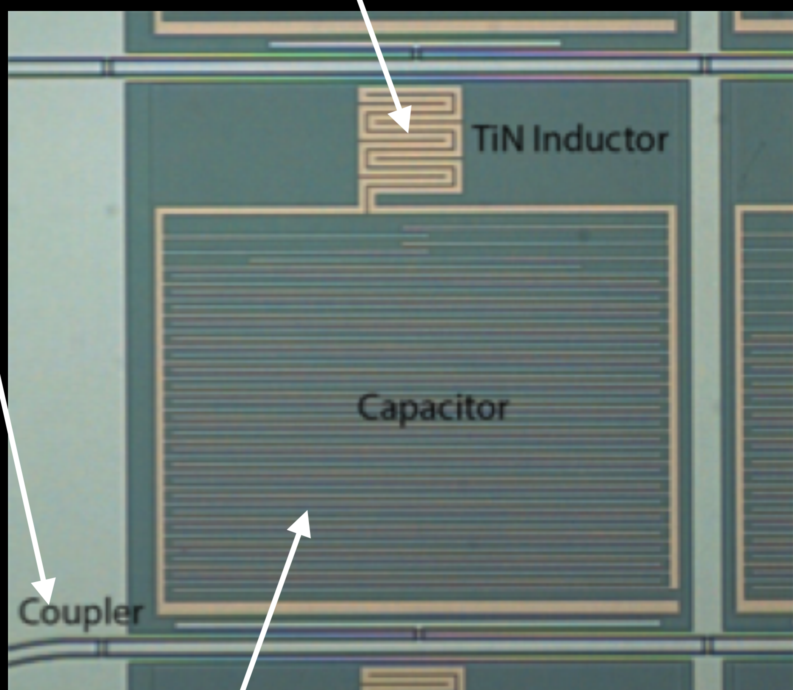
MKIDs also give you the arrival time for the object with usec resolution.

Imaging with this time resolution allows for tip/tilt corrections offline, and also usec astronomy.

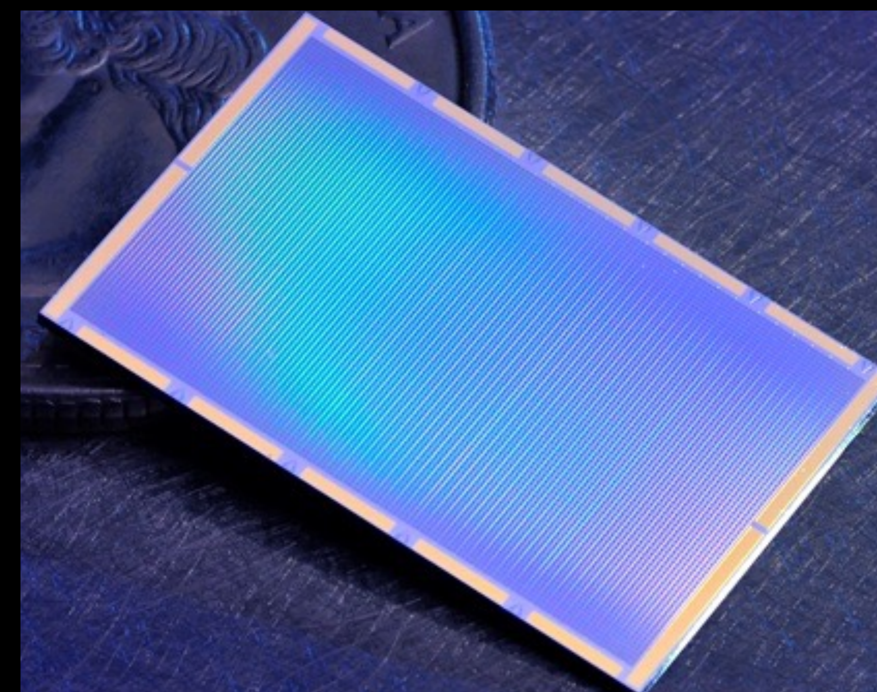
MKID pixel- designed by B.Mazin (UCSB)

RF feedline

inductor
(need microlens)

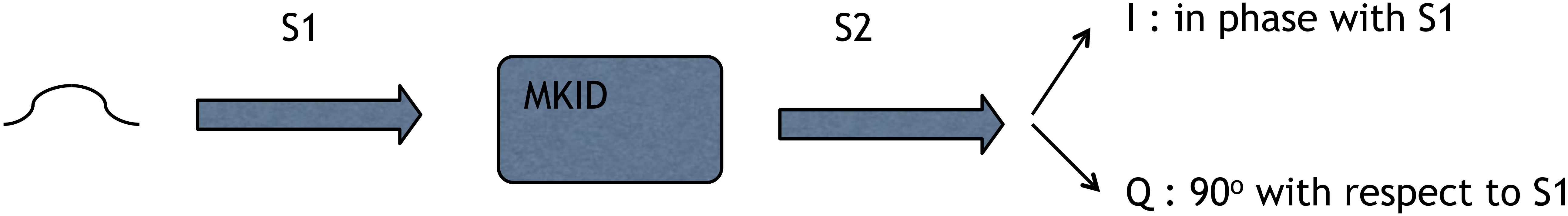


capacitor



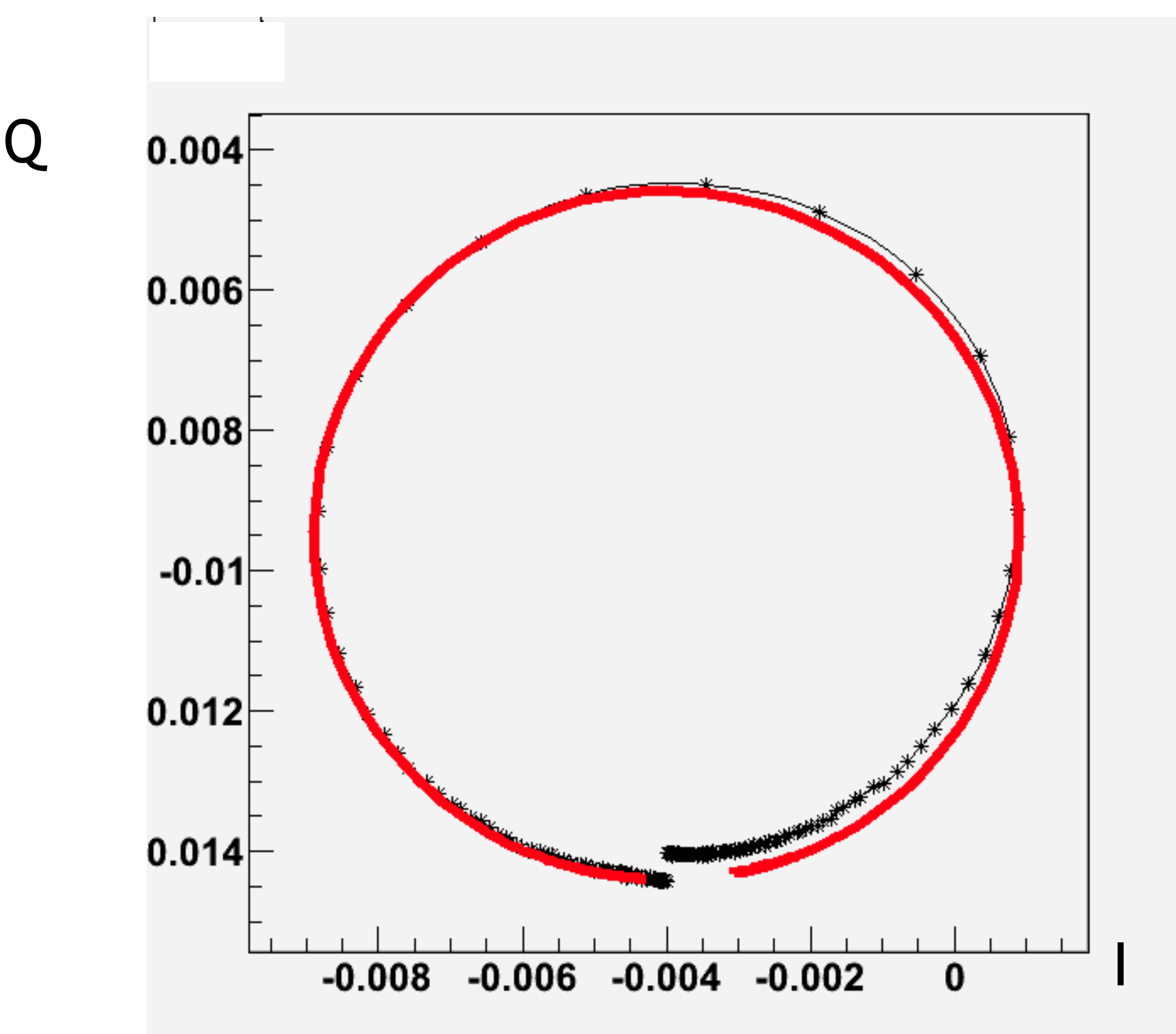
10k pixels in a sensor
4-8 GHz

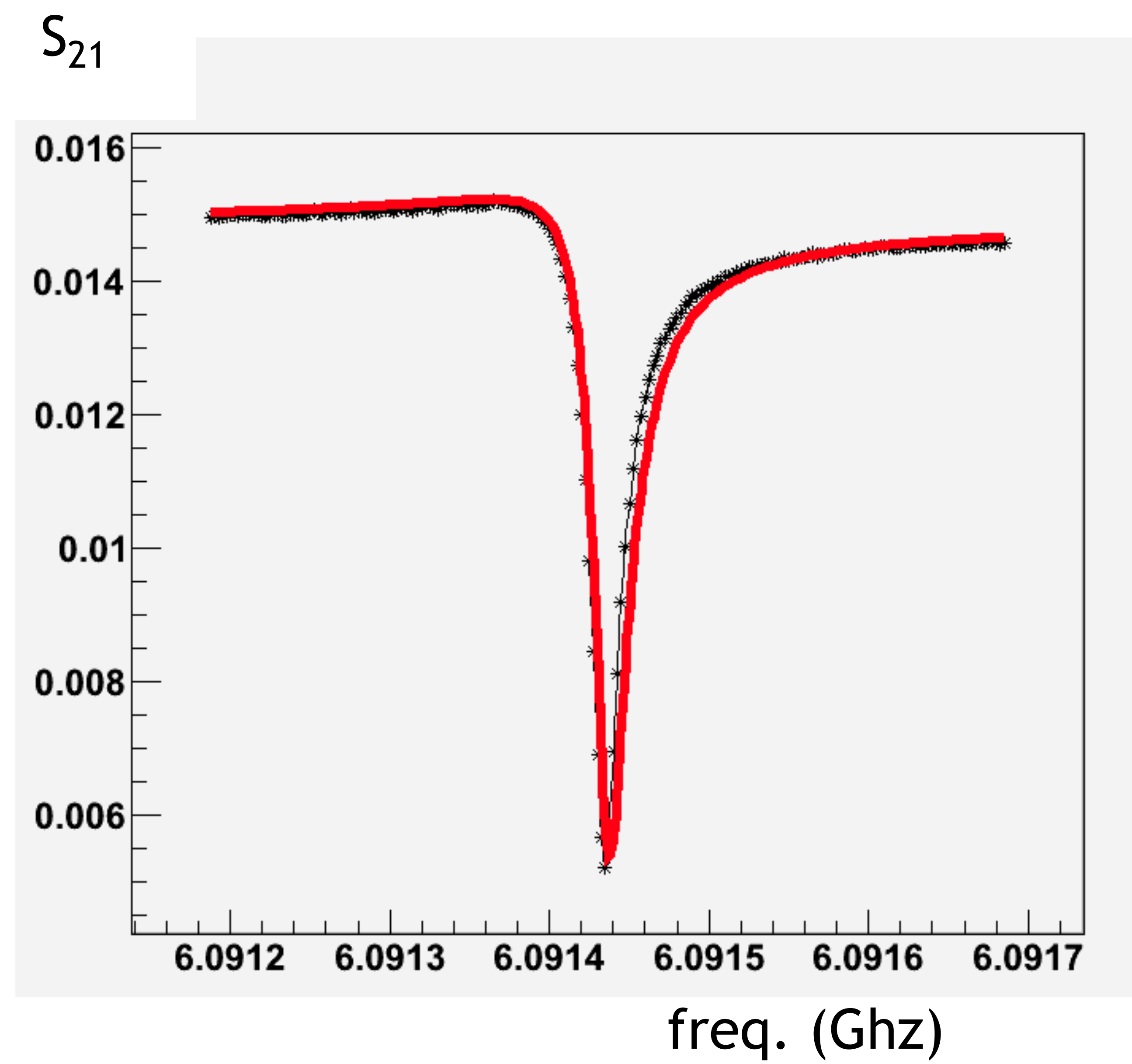
Current performance R=E/ΔE~10, the sensors should be able to achieve R~100. Lot’s of R&D still needed. DAQ is a big challenge.



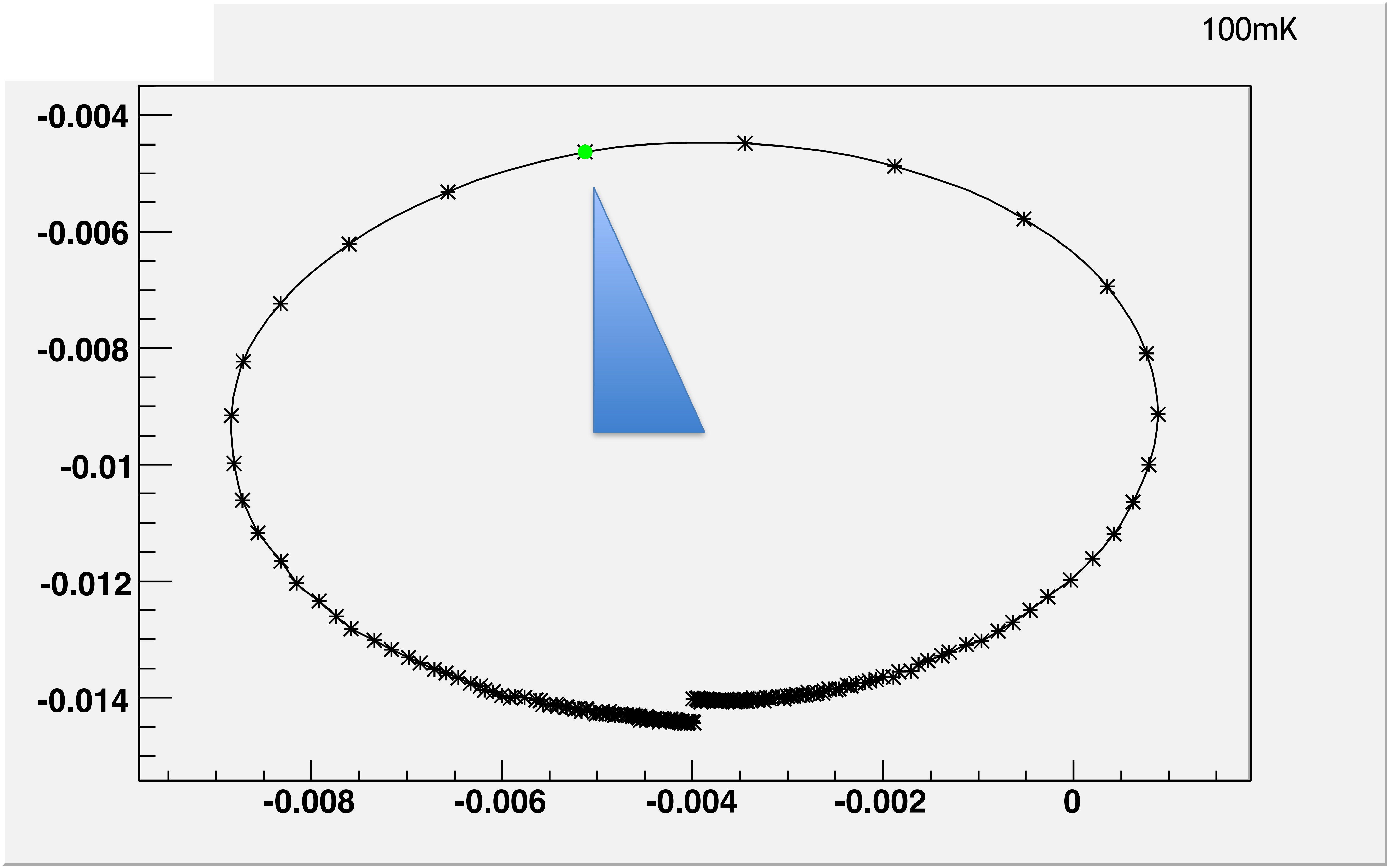
Q & I measured relative to S1

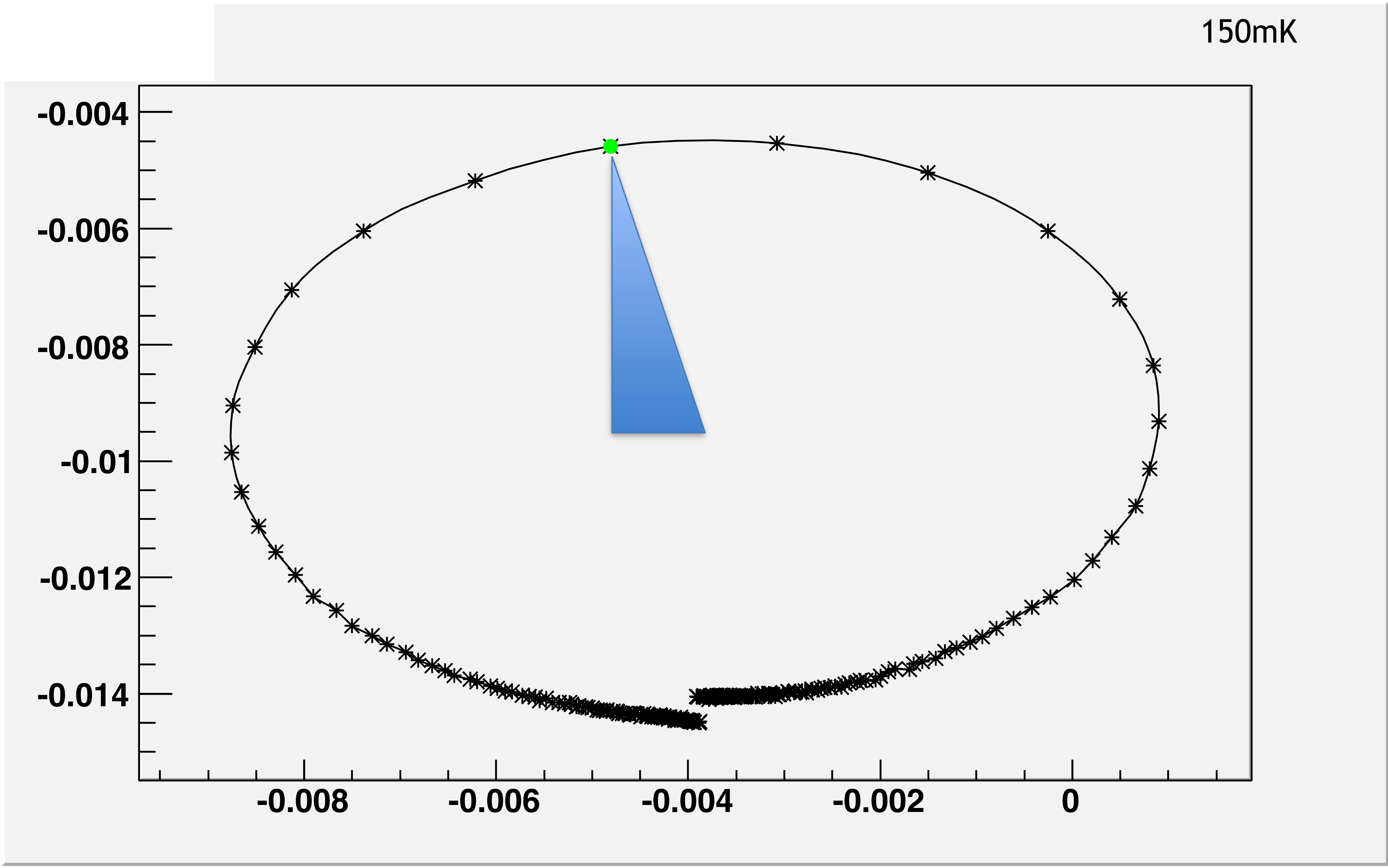
S_{21} is the sum in quadrature of Q & I





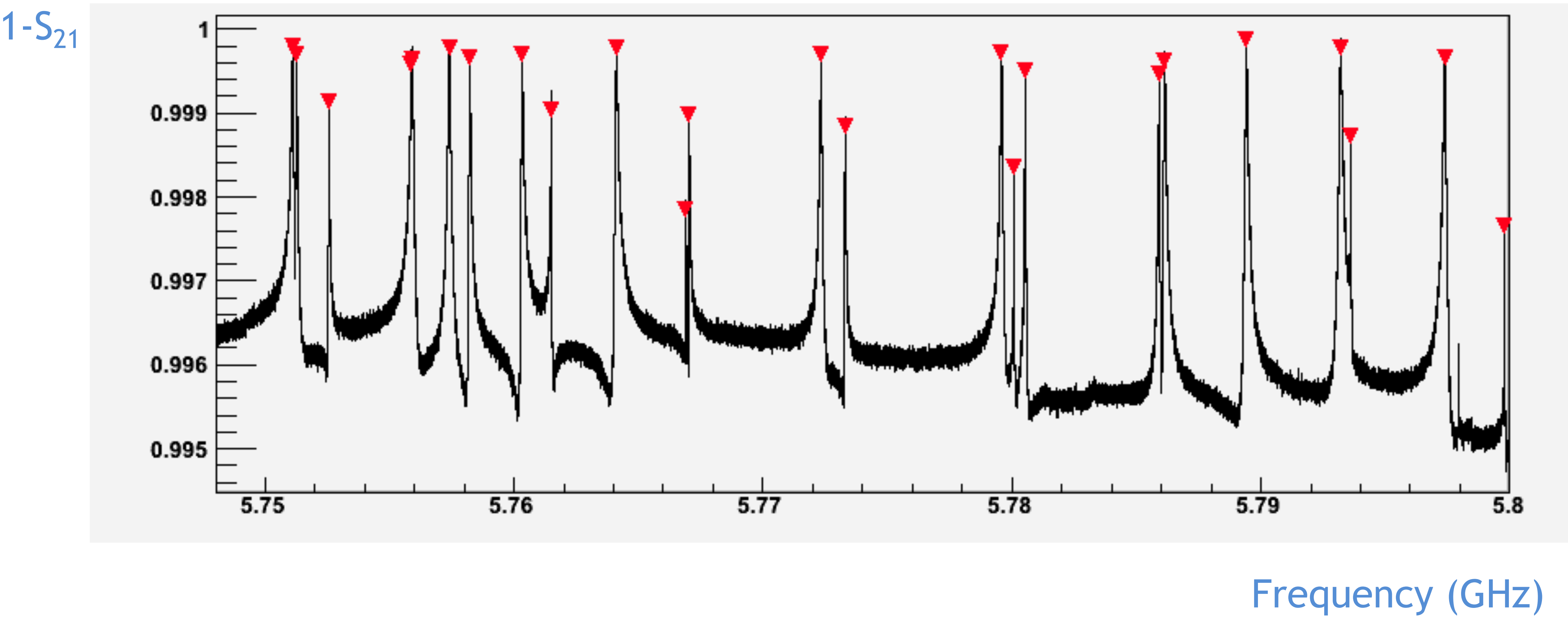
Pixel 1: Q=187k , f0=6.09143 Ghz


100mK
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.008
-0.006
-0.004
-0.002
0


150mK
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.008
-0.006
-0.004
-0.002
0

There is still a lot of work to do

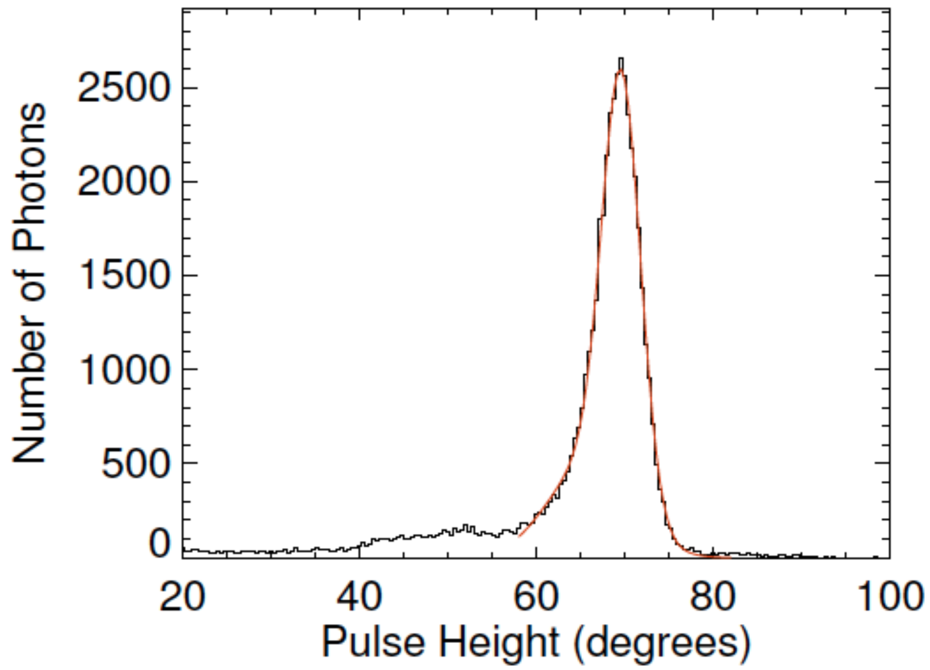
- Pixel overlap
- Pixel non-uniformity (Q)
- Pixel spacing

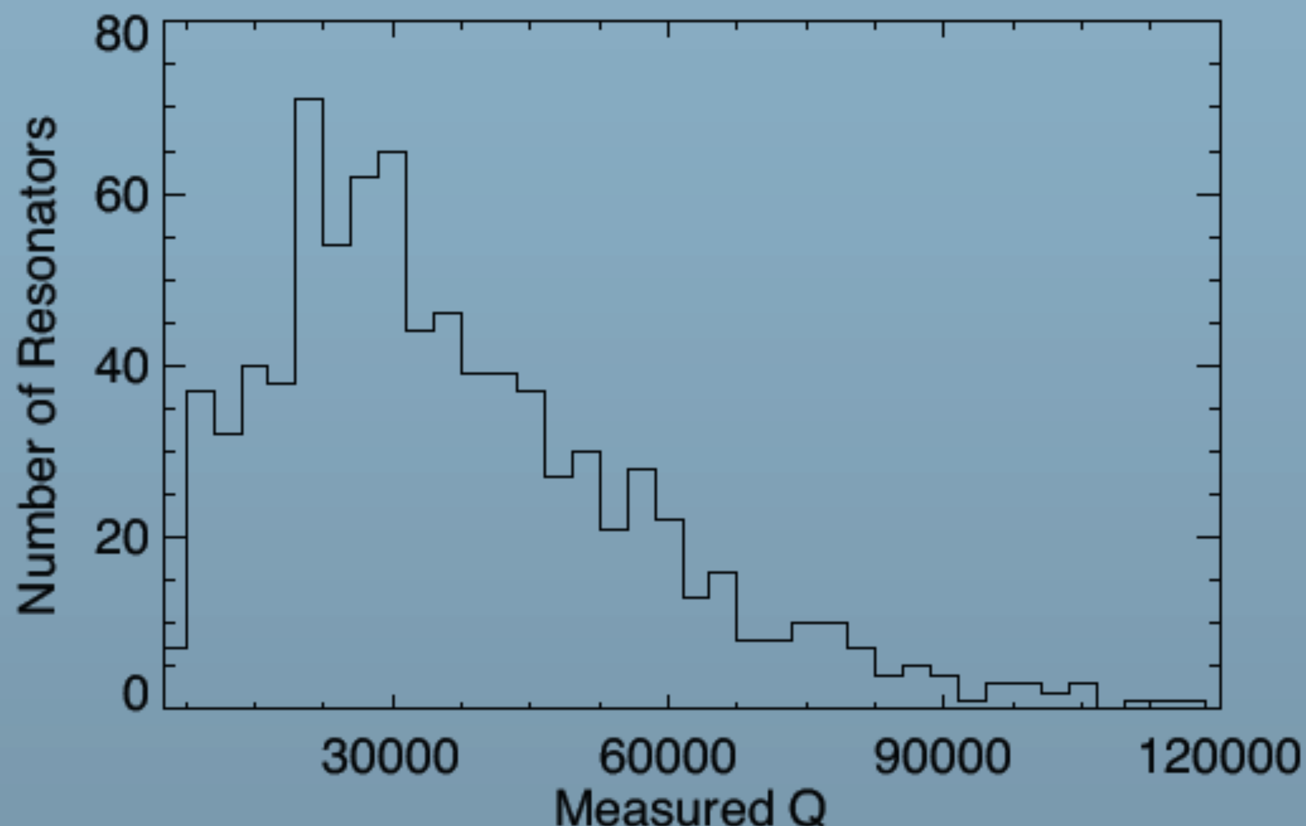


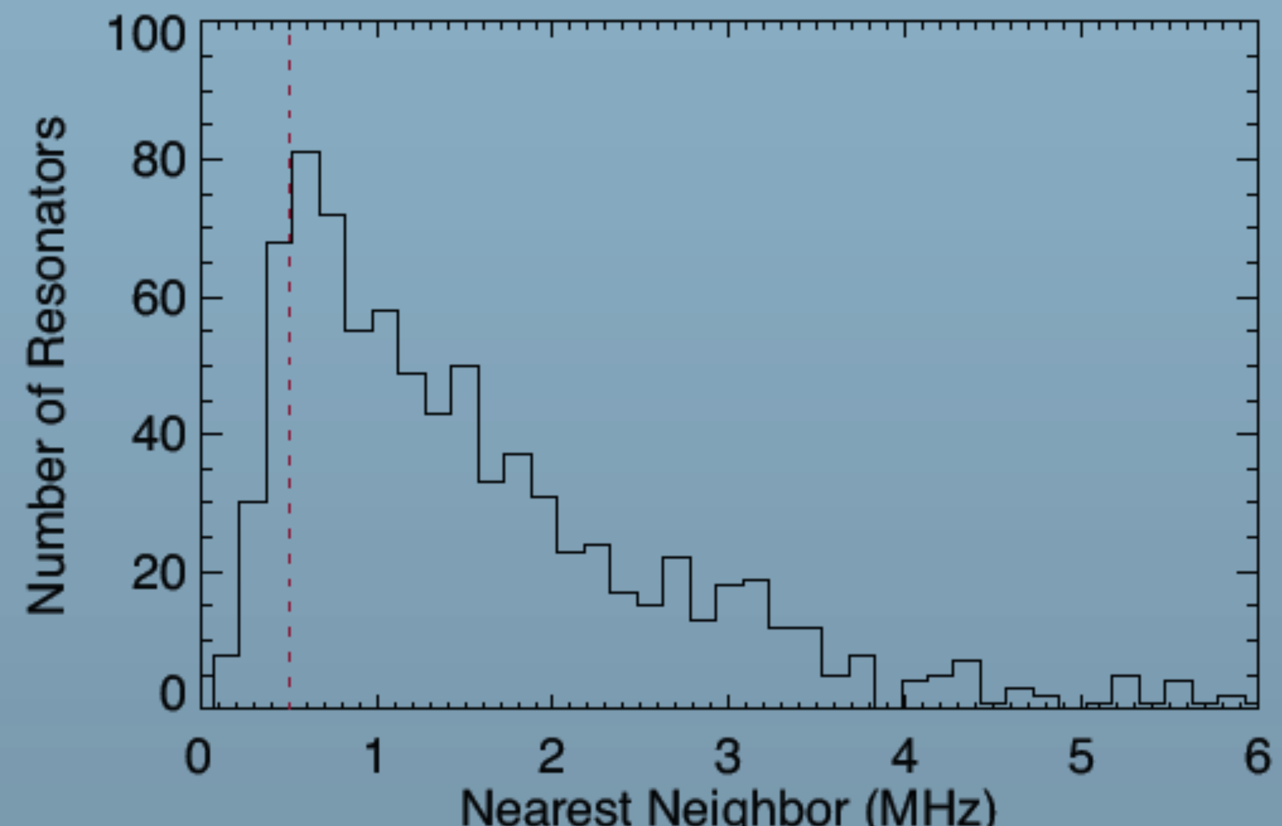
R= E/δE = 16 @250nm

Theoretical limit for the MKIDs is R=180… there is still ways to go.

Q is not always the same.







Mazin at al 2013.(arXiv:1306.4674)

yield issues

Figure 10. The results of beam mapping the ARCONS array. Pixels with good locations are shown in white. Vignetting is apparent at the bottom right side of the array. The overall pixel yield in this engineering-grade array is ~70%.

rate issues

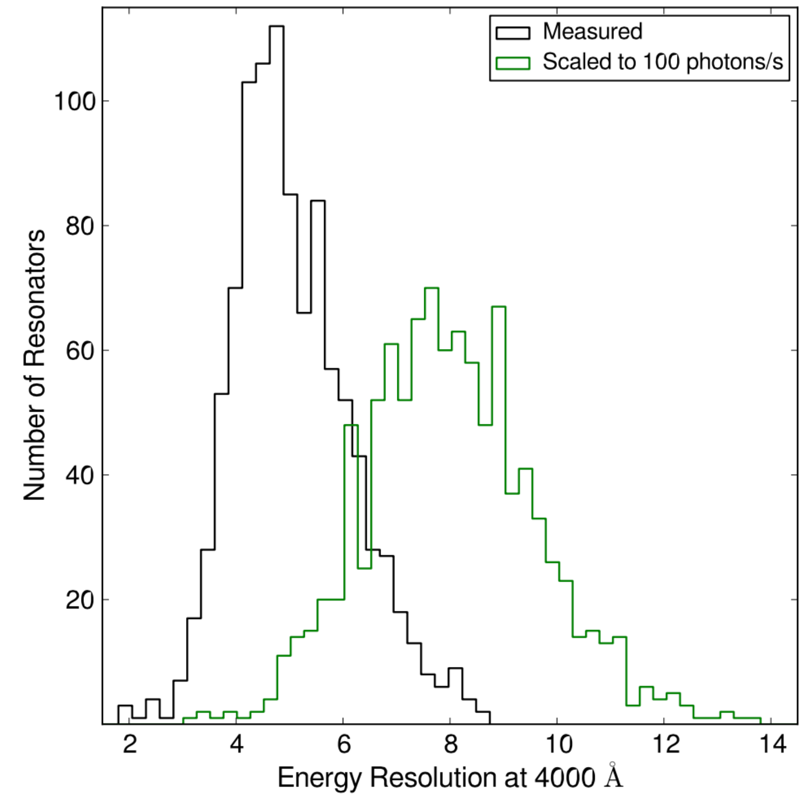
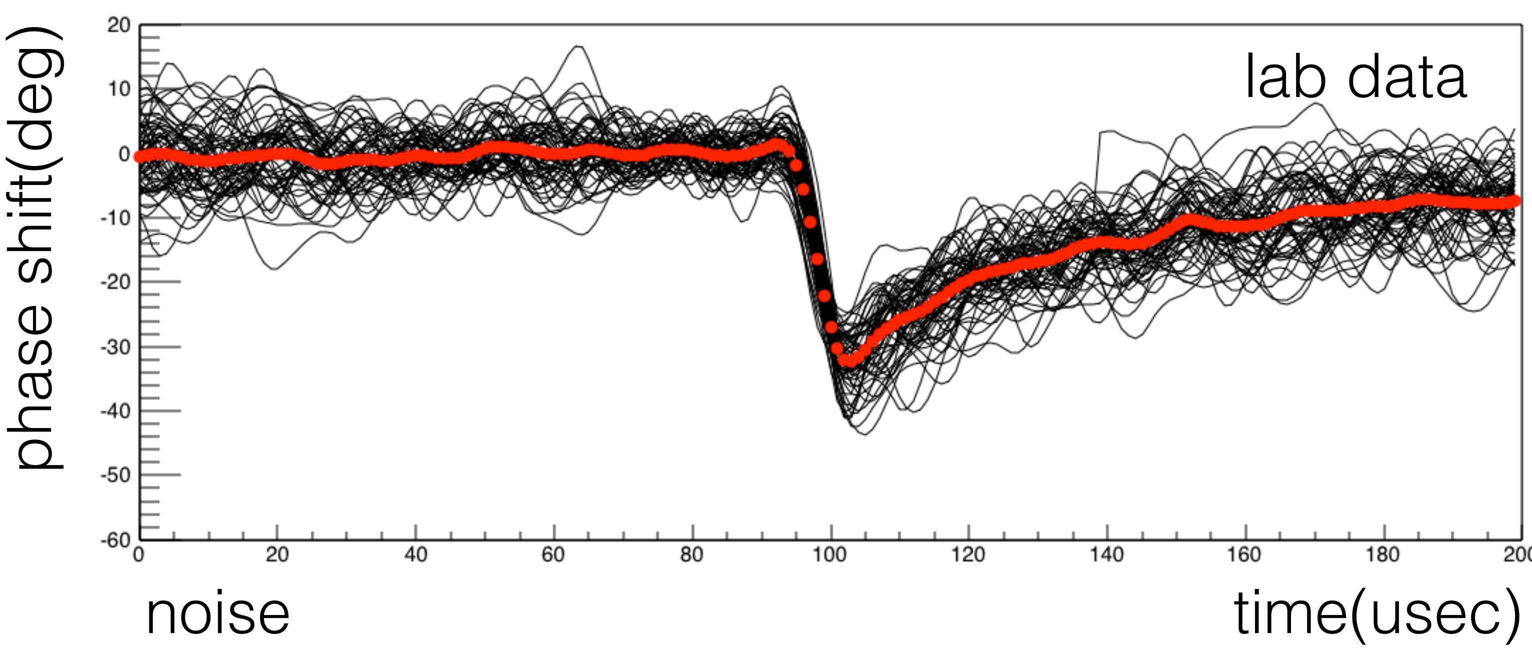


Figure 11. A histogram of spectral resolution of one feedline from the array. The black line shows the energy resolution from calibration files taken at Palomar with a high count rate of ~1000 cts/sec. The green curve shows the projected energy resolution we expect to recover at the nominal sky count rate of 100 cts/sec by scaling the black data by the expected degradation in spectral resolution with count rate, the red curve in Figure 13. The other feedline is very similar.



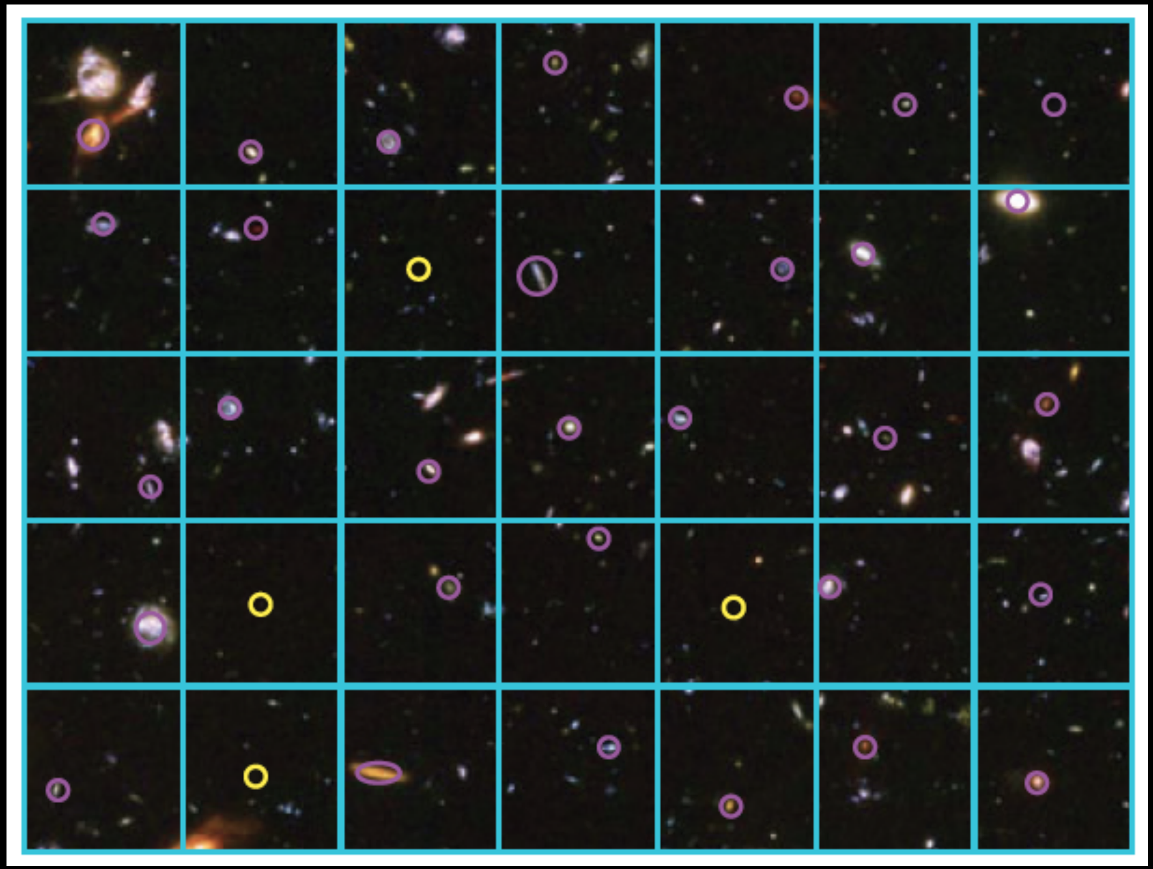
the UCSB group has done huge progress. Now we need to invest more resources to make then viable for Dark Energy.

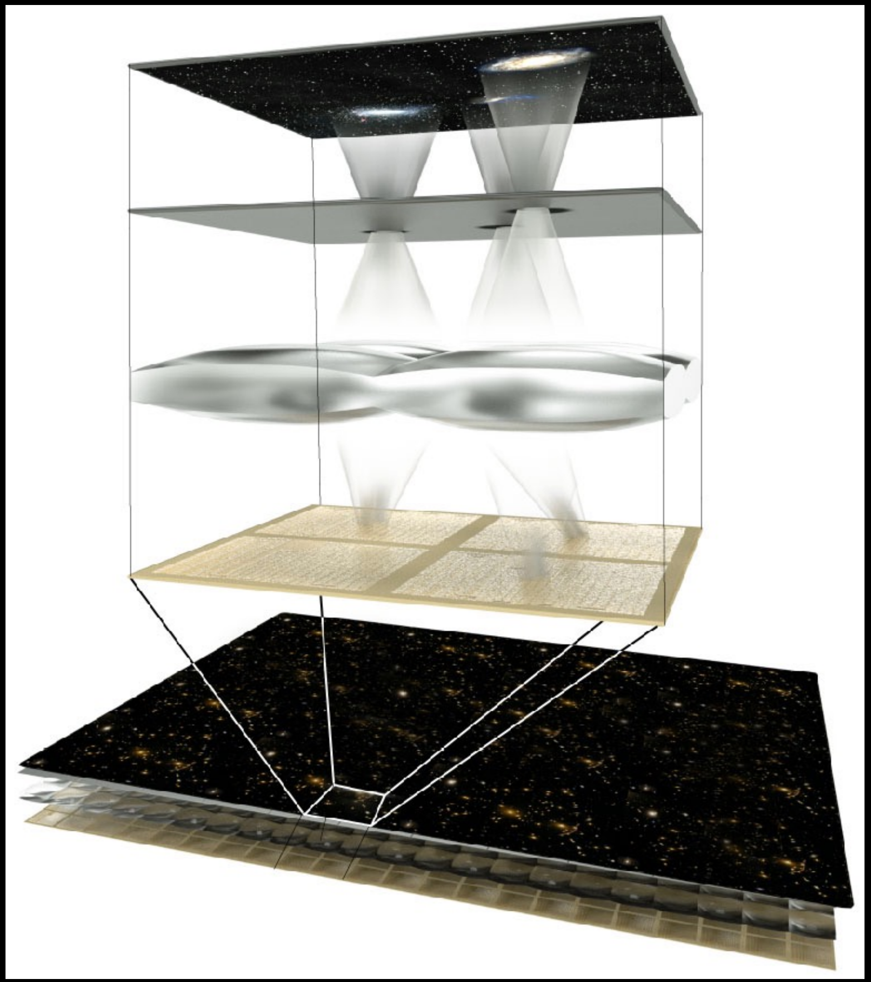
Recognized by P5 as a technology that could dramatically leverage investments.

Candidates for the Small Projects Portfolio can dramatically leverage investments in DESI and LSST. With Integral Field Spectrographs, the large samples of both nearby and distant supernovae found by, *e.g.*, DES and LSST can be studied in detail to make supernova-based measurements as precise as the complementary DESI BAO measurements. With focused spectroscopic follow-up of the LSST galaxies, the galaxy-based measurements from LSST can be calibrated much more precisely. Proposals to develop novel Microwave Kinetic Inductance Detectors would allow the billions of galaxies found by LSST to be used for wider field/lower resolution RSD. Novel probes to search for the new force introduced by explanations of acceleration that modify Einstein's theory of gravity were identified at Snowmass.

GigaZ/MegaZ : Photo-z machine

- Marsden et al 2013
- LOI ESO 2014 (Oxford,Fermilab,UCSB)





Make large pixels, and use mask to select a galaxy for each pixel. **100,000 spectroscopic channels in 1 square deg. is possible (20x DESI). Resolution R~100.** White paper to Snowmass 2013. Large project after LSST. (See comment from P5)

Marsden et al 2013.

This paper discusses what is possible with an MKID base survey. Some aspects of the science with MKIDs after LSST are presented.

There is still a lot of work to do in this area.

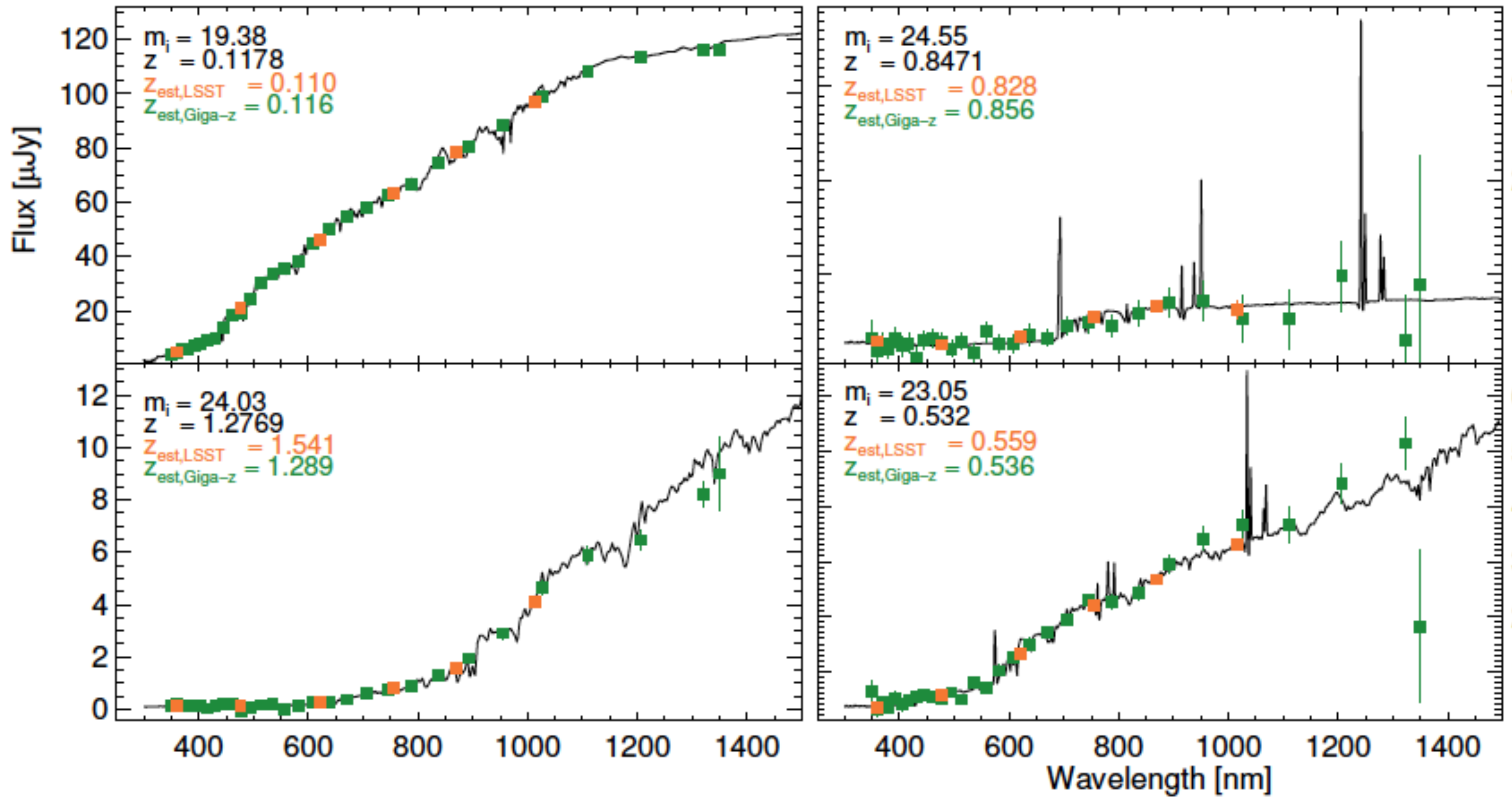
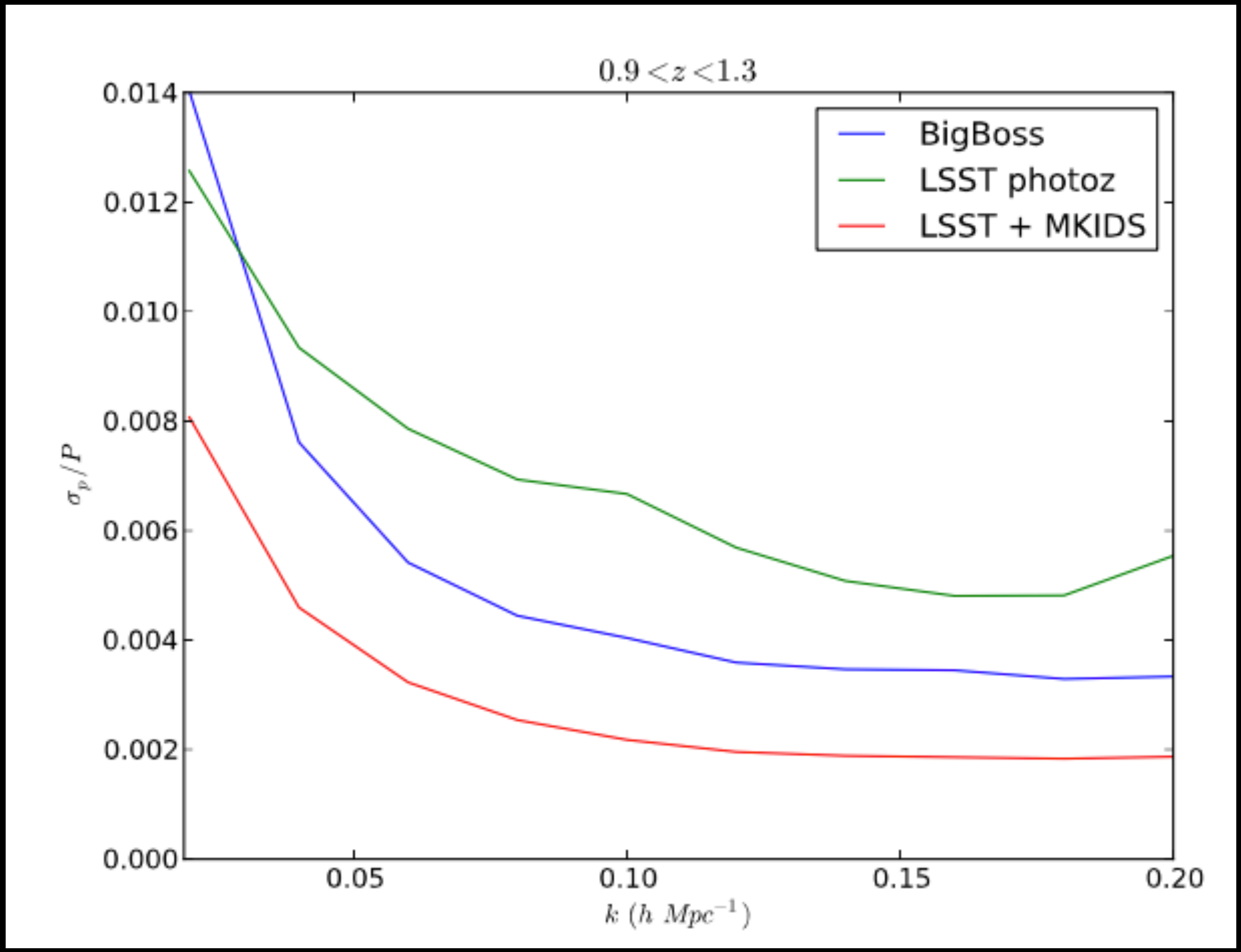


TABLE 4

A COMPARISON OF REDSHIFT RECOVERY STATISTICS BETWEEN MULTI-BAND PHOTOMETRY OR MULTI-OBJECT SPECTROSCOPY EXPERIMENTS, BOTH PAST AND PLANNED.

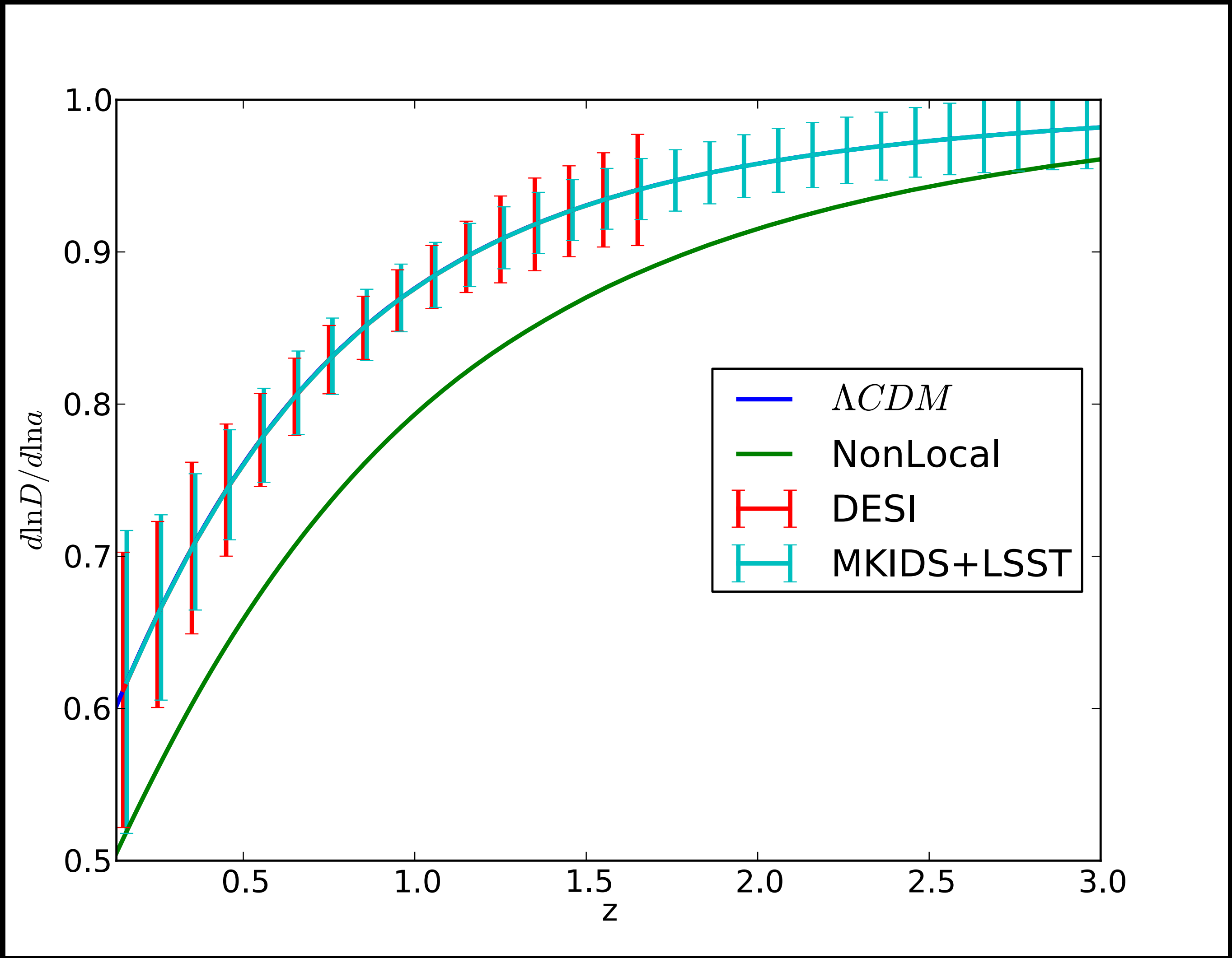
Experiment	N_{gals}	Area [deg^2]	Magnitude Limit	N_{filts}/Resolution	Scatter	Cat. Failure Rate
COMBO 17 [a]	~10,000	~0.25	$R < 24$	17	0.06	$\lesssim 5\%$
COSMOS [b]	~100,000	2	$i^+_{AB} \sim 24$	30	0.06	~20%
	~30,000	2	$i^+ < 22.5$	30	0.007	< 1%
CFHTLS - Deep [c]	244,701	4	$i'_{AB} < 24$	5	0.028	3.5%
CFHTLS - Wide [c]	592,891	35	$i'_{AB} < 22.5$	5	0.036	2.8%
PRIMUS [d]	120,000	9.1	$i_{AB} \sim 23.5$	$R_{423} \sim 90$	~ 0.005	~2%
WiggleZ [e]	238,000	1,000	$20 < r < 22.5$	$R_{423} = 845$	$\lesssim 0.001$	$\lesssim 30\%$
Alhambra [f]	500,000	4	$I \leq 25$	23	0.03	...
BOSS [g]	1,500,000	10,000	$i_{AB} \leq 19.9$	$R_{423} \sim 1600$	$\lesssim 0.005$	~2%
DES [h]	300,000,000	5,000	$r_{AB} \lesssim 24$	5	0.1	...
EUCLID [i]	2,000,000,000	15,000	Y,J,K $\lesssim 24$	3+	$\lesssim 0.05$	$\lesssim 10\%$
	50,000,000	15,000	$H_\alpha \geq$ 3e-16 erg/s/cm^2	$R_{1\mu m} \sim 250$	$\lesssim 0.001$	< 20%
LSST [j]	3,000,000,000	20,000	$i_{AB} \lesssim 26.5$	6	$\lesssim 0.05$	$\lesssim 10\%$
Giga-z	2,000,000,000	20,000	$i_{AB} \lesssim 25.0$	$R_{423} = 30$	0.03	~19%
	224,000,000	20,000	$i_{AB} \lesssim 22.5$	$R_{423} = 30$	0.01	0.3%

plots from Scott Dodelson



How well could we measure the power spectrum if we reduce the redshift error in LSST from 0.1 to 0.01. From R~5 (5 filters) to R~50 (MKIDs)?

GR versus non-local gravity. The logarithmic derivative of the growth function as a function of redshift; this is directly measured in spectroscopic surveys capable of probing redshift space distortions. (arXiv:1310.4329)



Challenges for this technology

- Sensor performance: need to improve R, closer to theory limit

- Number of channels per feed line is currently limited to digital signal processing and ADC speed.

- MKID packaging is not mechanically or thermally viable for a large array.

- MKID DAQ: Data rates on the scale of a particle physics experiment.

UCSB, Oxford and Fermilab interested in developing large instruments with MKIDs. The current plan includes building an instrument at FNAL to be installed at SOAR to address these challenges. Ongoing tests at Palomar. Also Darkness, a Coronograph developed by UCSB.

Current status:

Tests done now: UCSB, Caltech, FNAL, Oxford, JPL September/October 2014

- Palomar 200” ARCONS array with latest wafer
- Hot pixels and “cosmic ray” noise greatly reduced
- > 75% pixels working; R = 5
- Targets Observed:
  - 1SWASP J000205 (W Uma with reference star)
  - J0303 magnet wd eclipsed by M-dwarf
  - PSR J0337 (triple system)
  - Supernova PSN234416 + host galaxy image/spectroscopy
  - Ring nebula, NGC6751
  - X2 ULX in core of M82

The ARCONS Camera

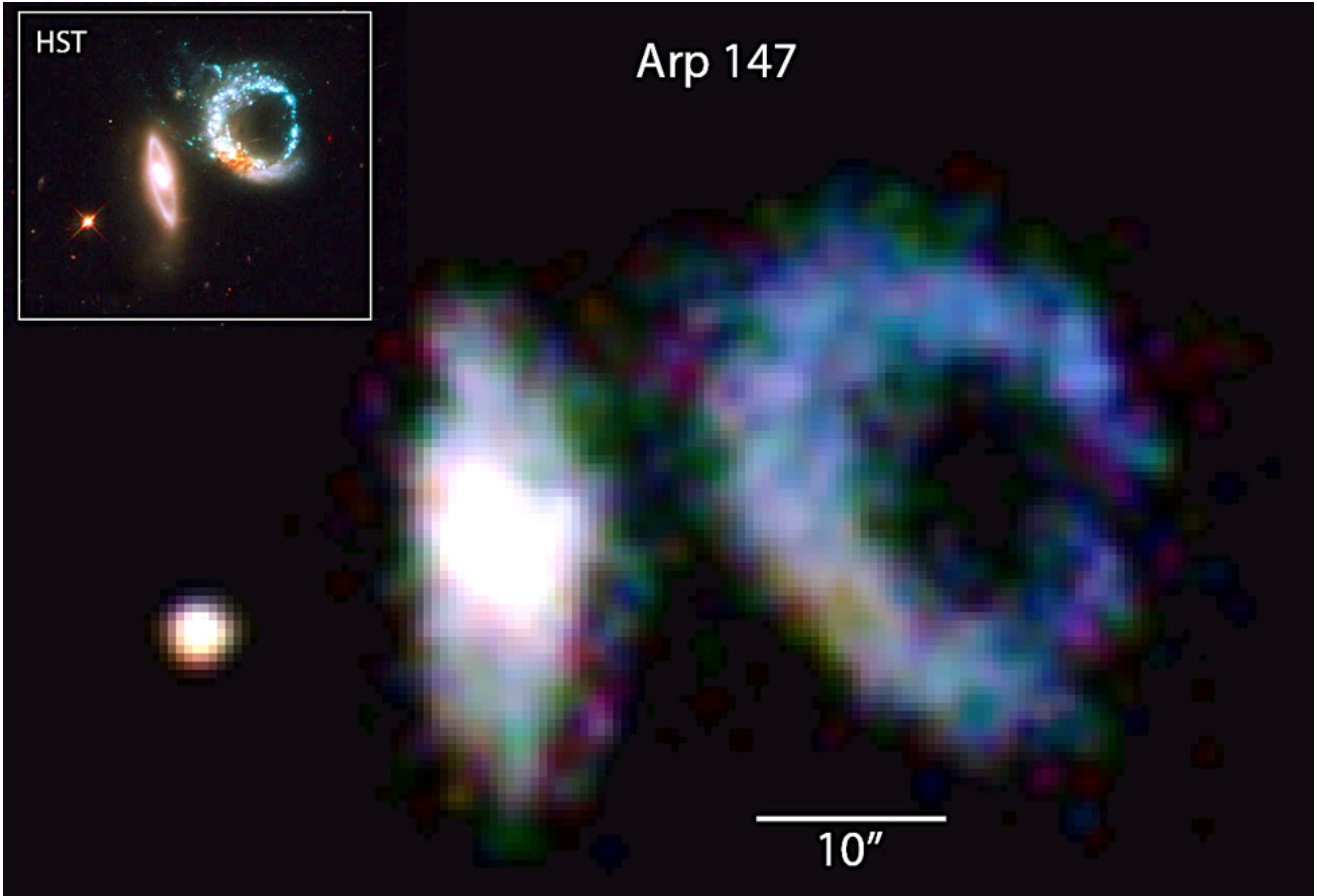
44x46 pixels
Lick and Palomar
30 nights
observing

First Papers:

Excess Optical Enhancement Observed with ARCONS for Early Crab Giant Pulses Strader et al. 2013 (ApJL)

Direct Detection of SDSS J0926+3624 Orbital Expansion with ARCONS Szypryt et al. 2013 (MNRAS)

… not dark energy yet.



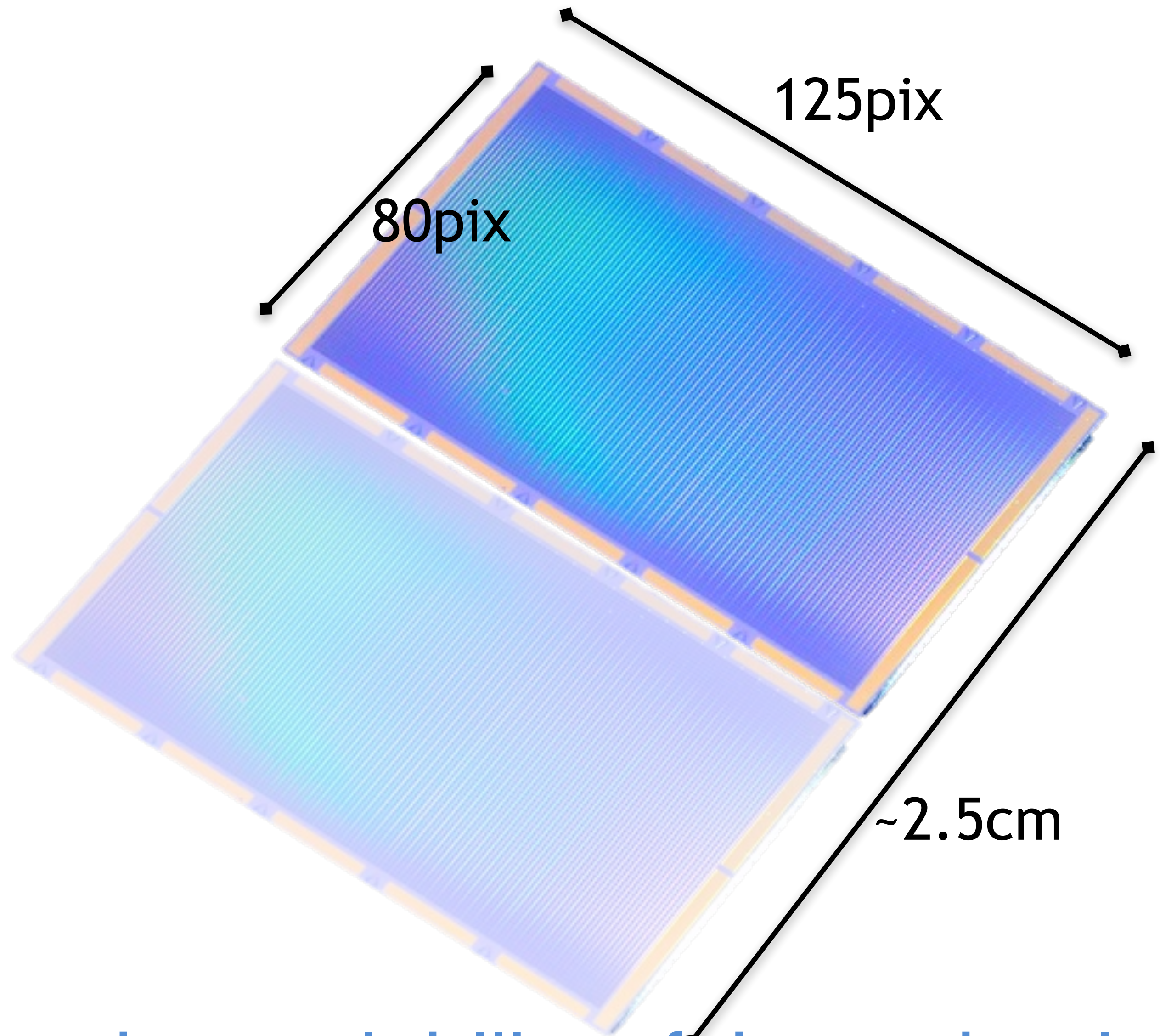
Arcons observation

10k R&D instrument for Dark Energy (for 4m SOAR telescope)

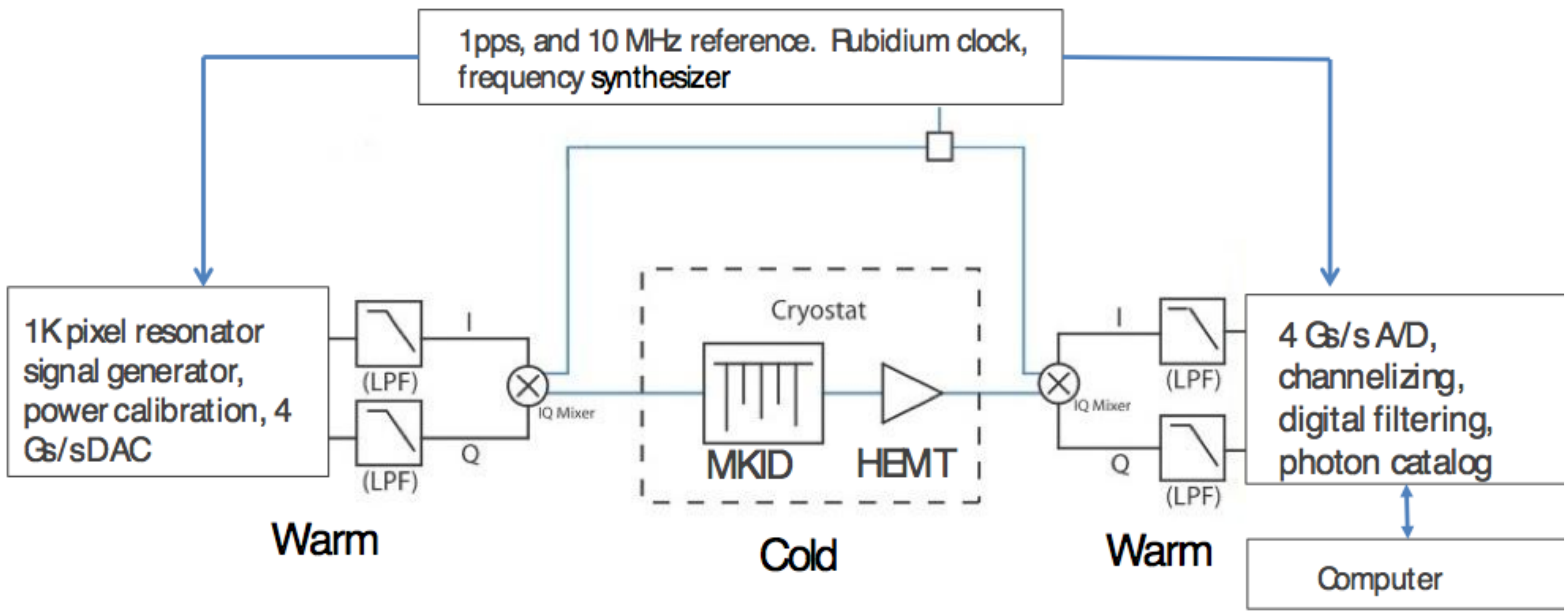
Baseline

- 10K pixels
- 0.3” pixel scale
- 80x125 pixels
- Band: 350-1350 nm
- R_{423}=30

- Maybe Mini-Mosaic with 2 sensors
- Scalable electronics
- Scalable packaging

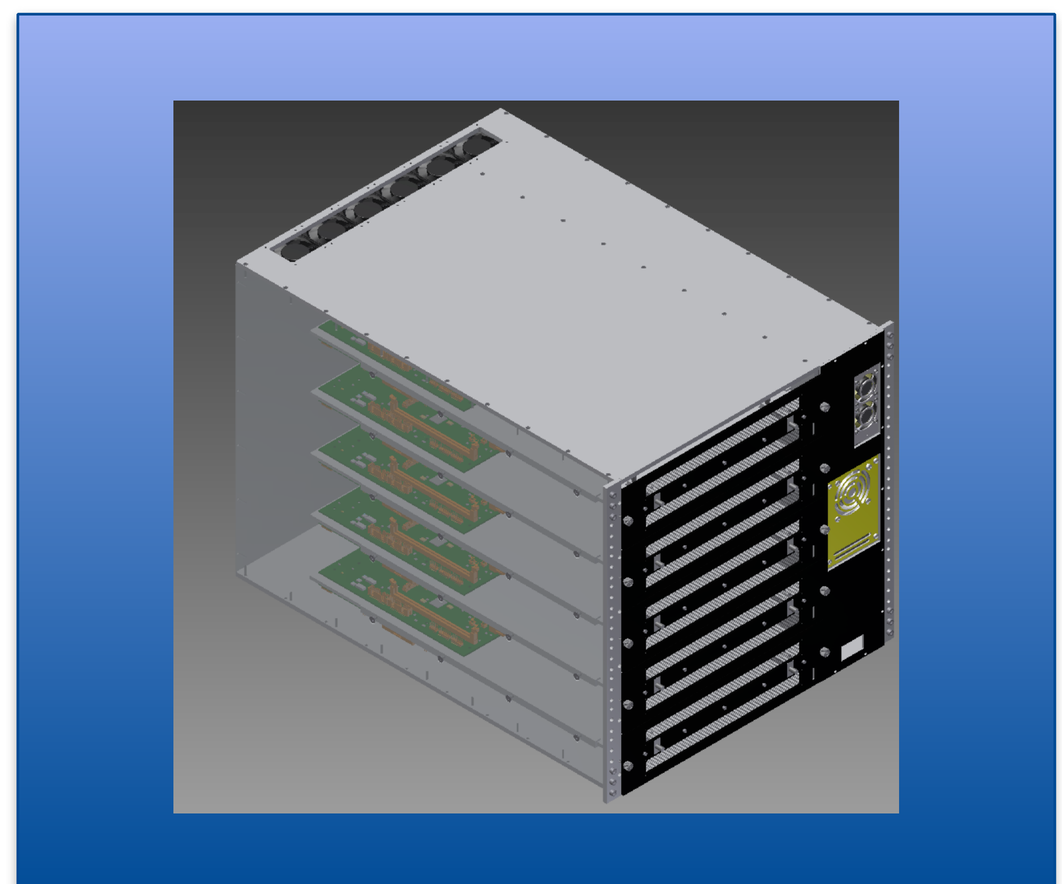


The main goal is to demonstrate the scalability of the technology. Baseline is one 10k array (2 would make it more fun!)



Critical: Scalable electronics being developed at FNAL and UCSB together.

DAQ crate concept. Each crate with 10 systems reads 10K pix.



Outlook

- Low-resolution spectroscopy with very large statistics possible with MKIDs.
- Need to work hard on detector R&D to develop the promising MKIDs technology.
- Science forecast of low resolution spectroscopic survey needs work.

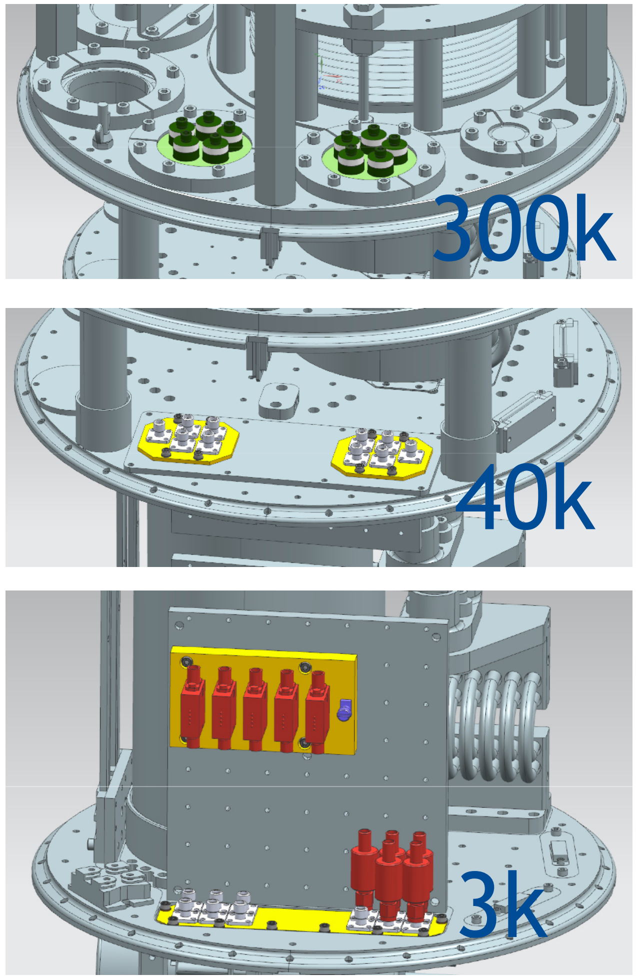
R&D steps

- HW R&D:
  - Frontend DAQ (Gustavo Cancelo, FNAL):
  Scalable 10k prototype currently in fabrication. need to keep support for this group if we want to have 100k readout system.
  - Backend DAQ : big deal (lots of data) room for contributions
  - sensor performance (Ben Mazin, UCSB):
  lot's of progress needed to get to R~80
  not enough people working on this right now

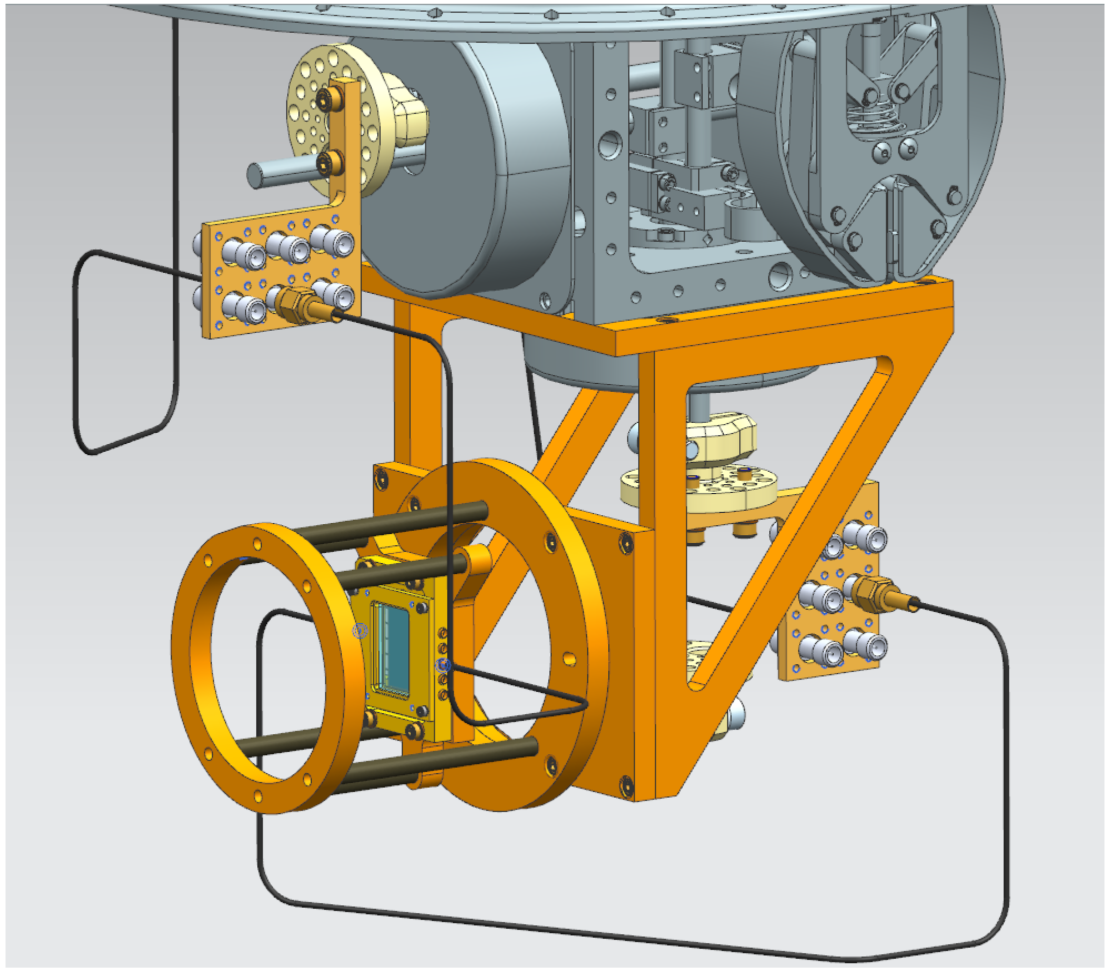
- Science Case for Low resolution spectroscopy in cosmology:
  - Need calculate scientific reach of a large MKID based survey:

Proposing two 2-day workshops to do this. Identify the areas where low-res can have an impact, forecast how this could be realized with MKIDs.

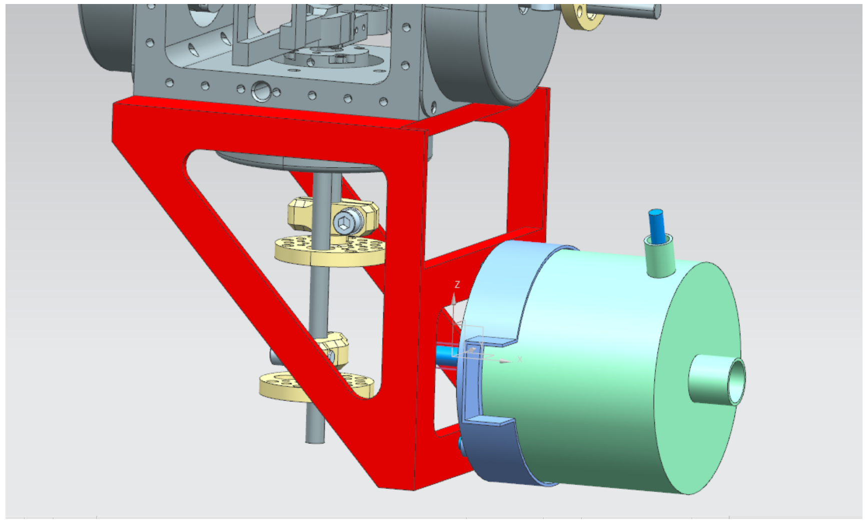
MKIDs instrument for SOAR



Cabling + cold electronics



Focal plane



Magnetic shield