Microwave Kinetic Inductance Detectors for optical and near-IR astronomy

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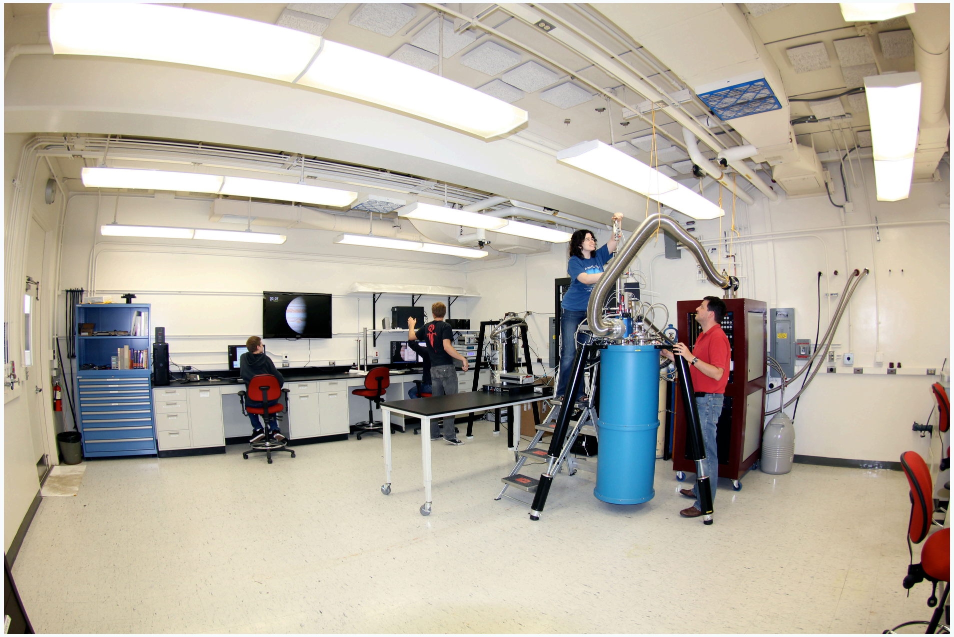
MKIDs Team



The Optical/UV MKID Team:

UCSB: Ben Mazin, Sean McHugh, Danica Marsden, Seth Meeker, Julian van Eyken

Oxford: Kieran O'Brien

JPL: Bruce Bumble, Rick LeDuc

Fermilab: Chris Stoughton

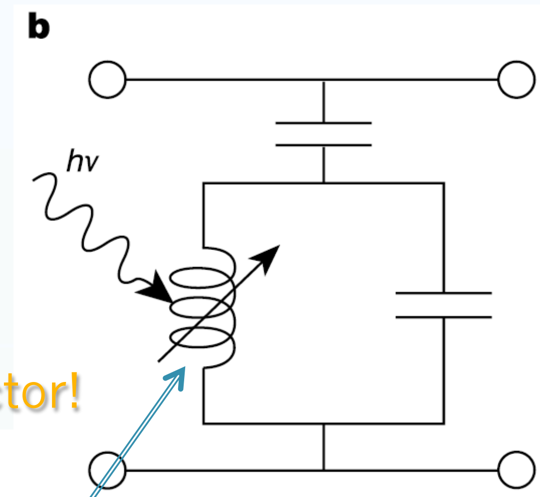
Caltech: Jonas Zmuidzinas, Sunil Golwala, David Moore

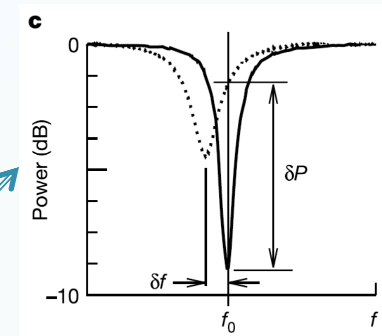
Outline of talk

- What are Microwave Kinetic Inductance Detectors (MKIDs)?
- Status of technology
- ARCONS
- Palomar commissioning and Science run
- Future Instrumentation
  - Giga-z

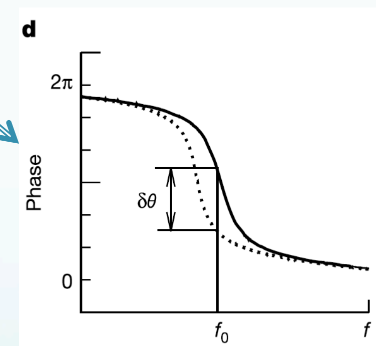
Microwave Kinetic Inductance Detectors

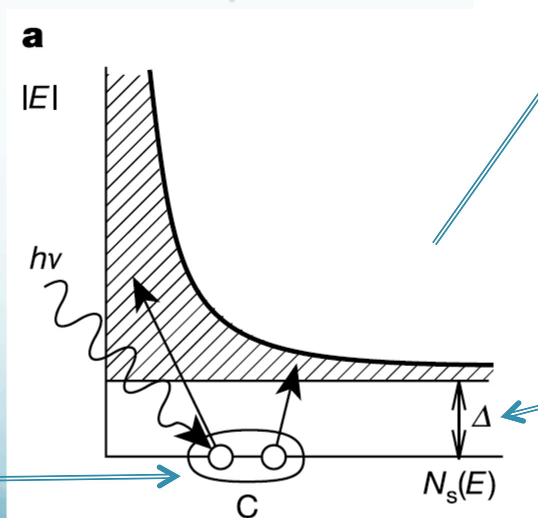
MKID Equivalent Circuit





Inductor is a Superconductor!





Cooper Pair

Energy Gap

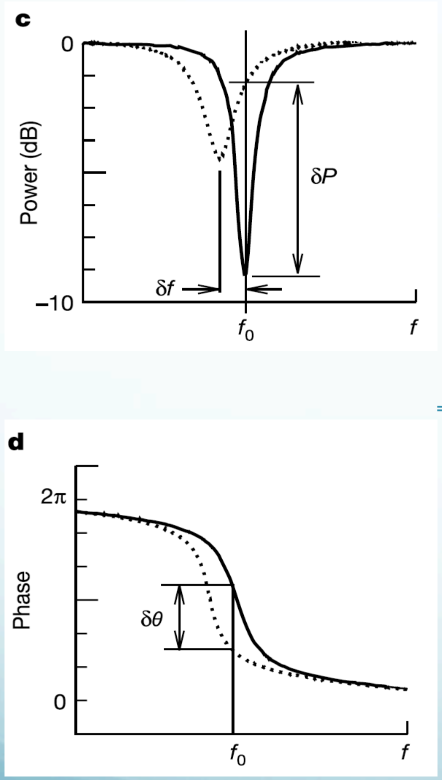
Silicon – 1.10000 eV

Aluminum – 0.00018 eV

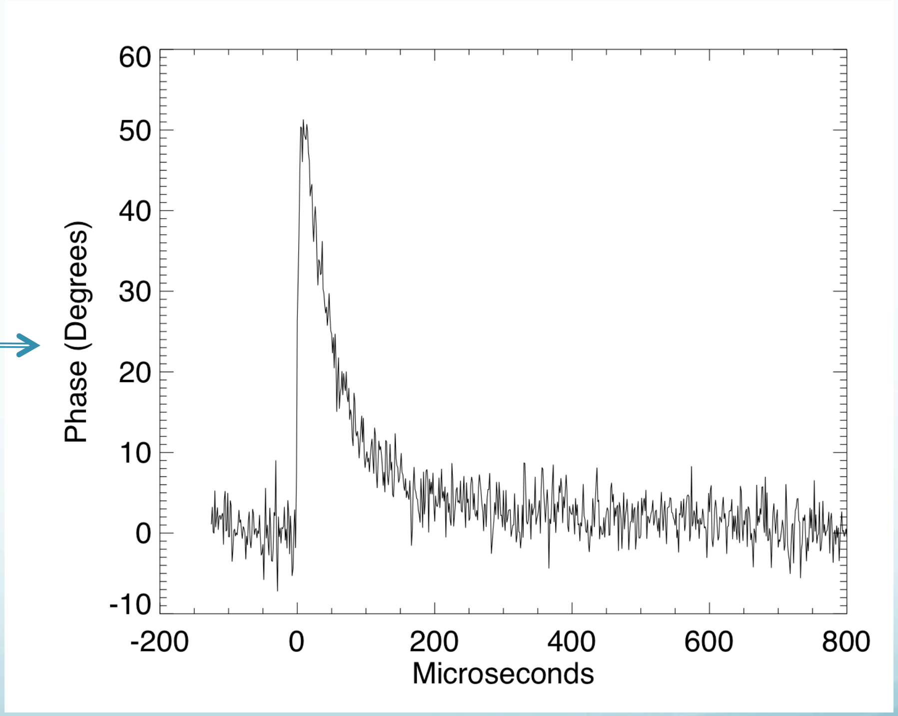
Energy resolution:

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

Phase-shift of probe signal



Typical Single Photon Event



Energy resolving detector

Energy Gap

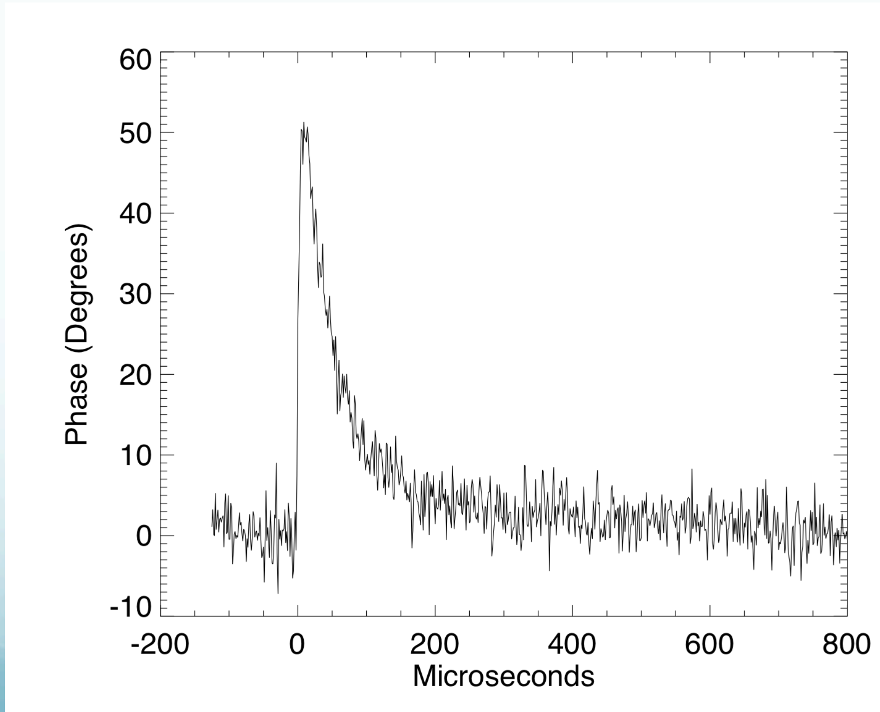
Silicon – 1.10000 eV

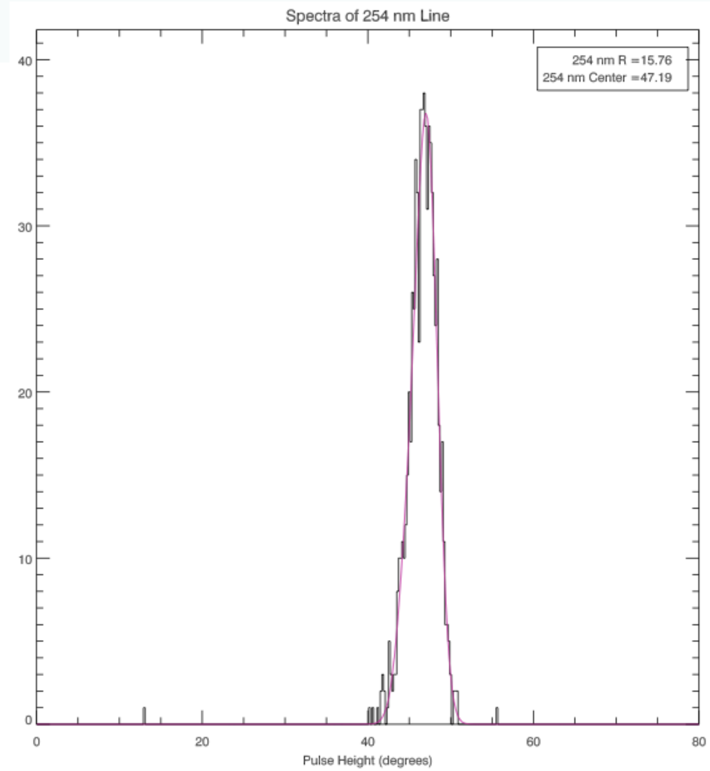
Aluminum – 0.00018 eV

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

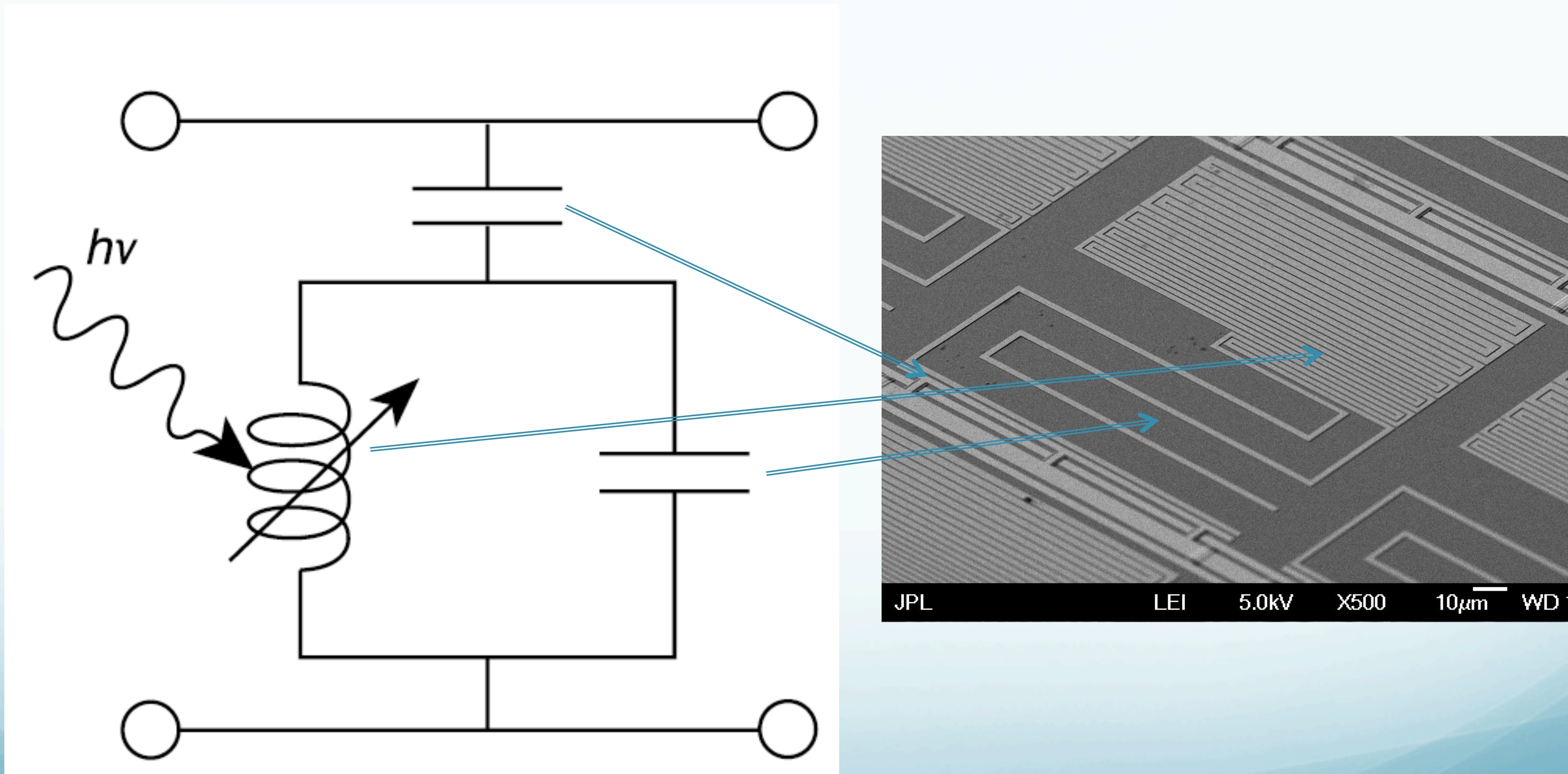
Distribution of Photon Events

$h\nu$ = 4.9eV, R <~ 100 for η ~1

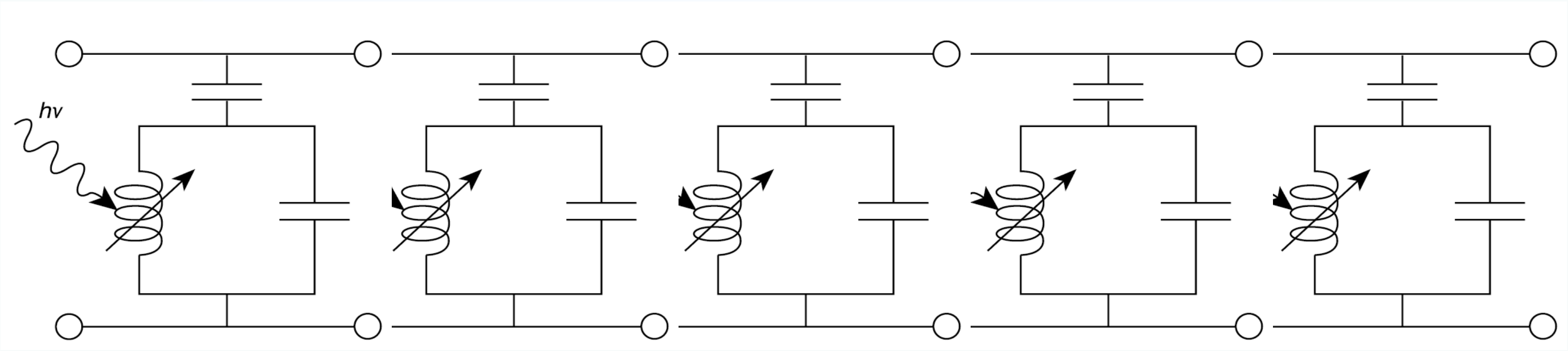


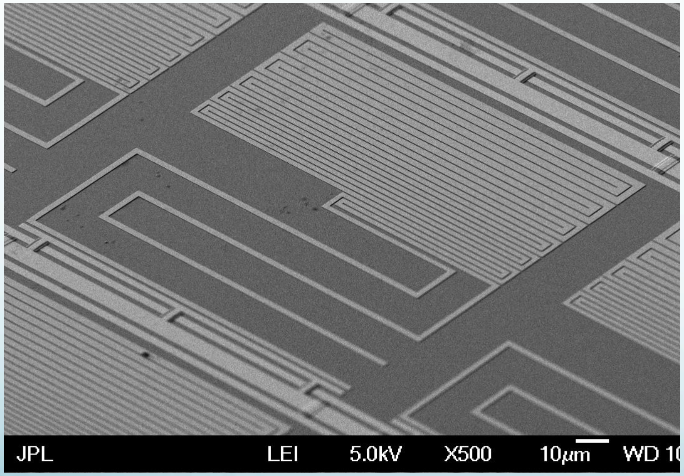


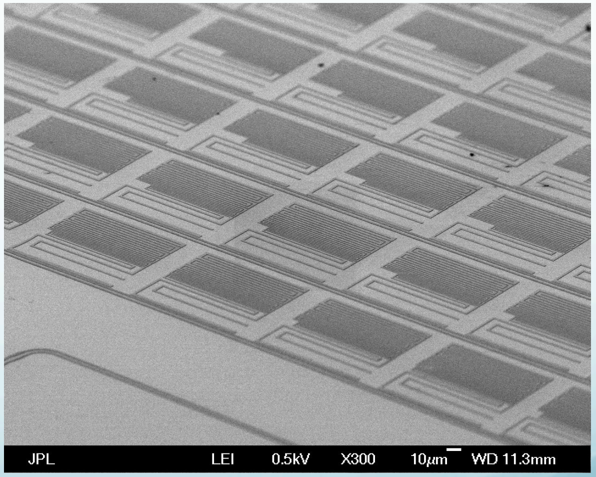
Lumped element pixels



Arrays of MKIDs



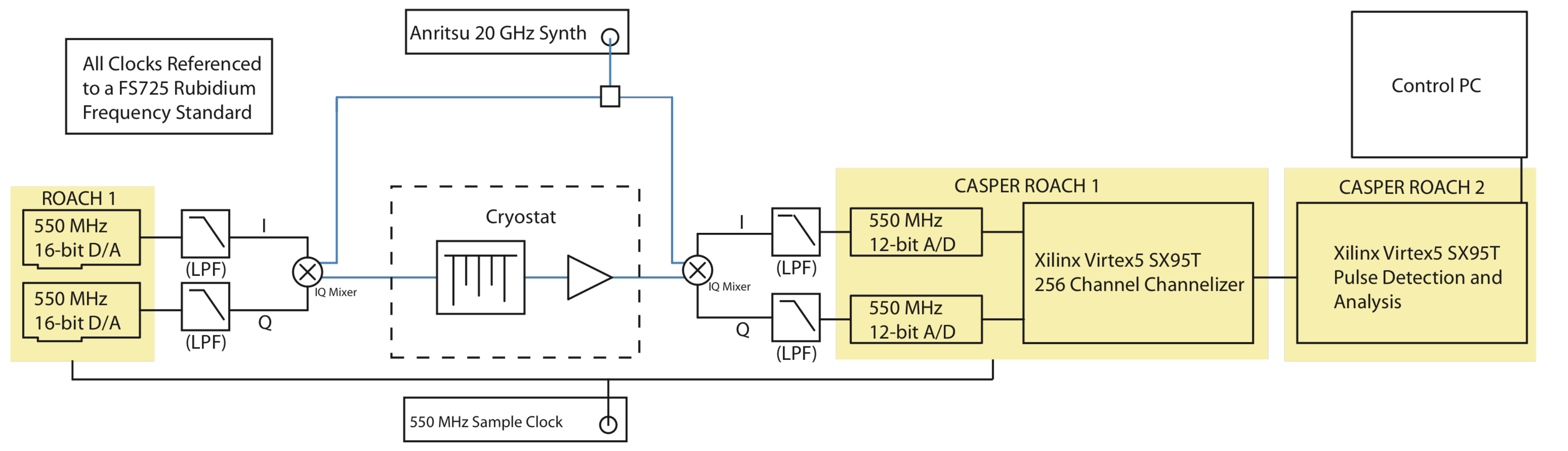




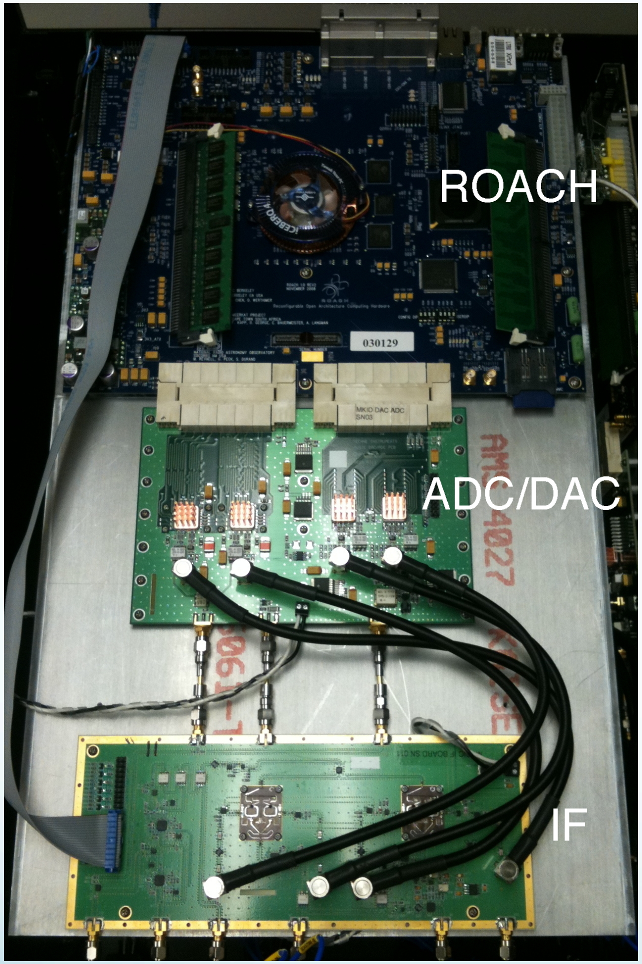
Digital MKID Readout

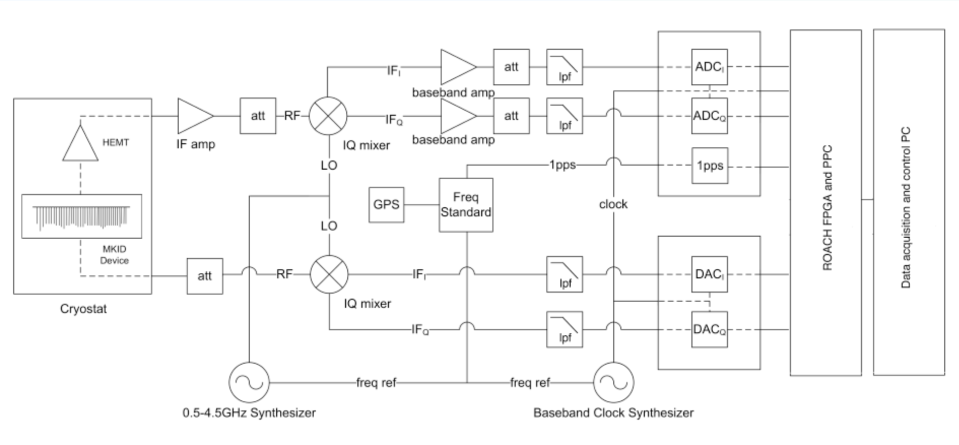
Software Defined Radio (SDR) Overview

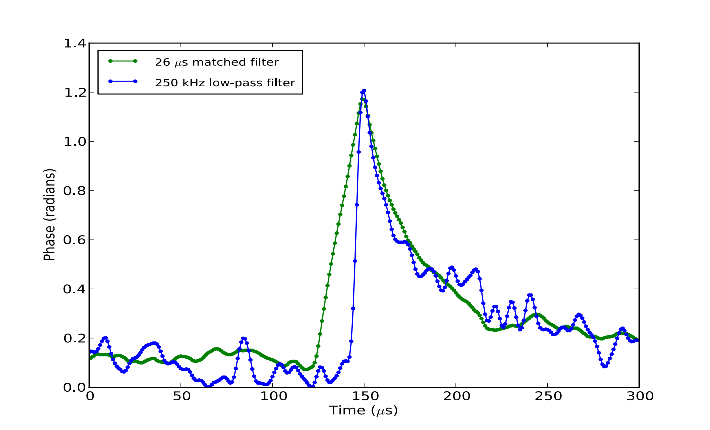
- Leverages massive industry investment in ADCs/FPGAs
- Generate frequency comb and up-convert to frequency of interest
- Pass through MKID and amplify
- Down-convert and Digitize
- "Channelize" signals in a powerful FPGA
- Process pulses (optical/UV/X-ray) or just output time stream (sub-mm)



SDR Readout



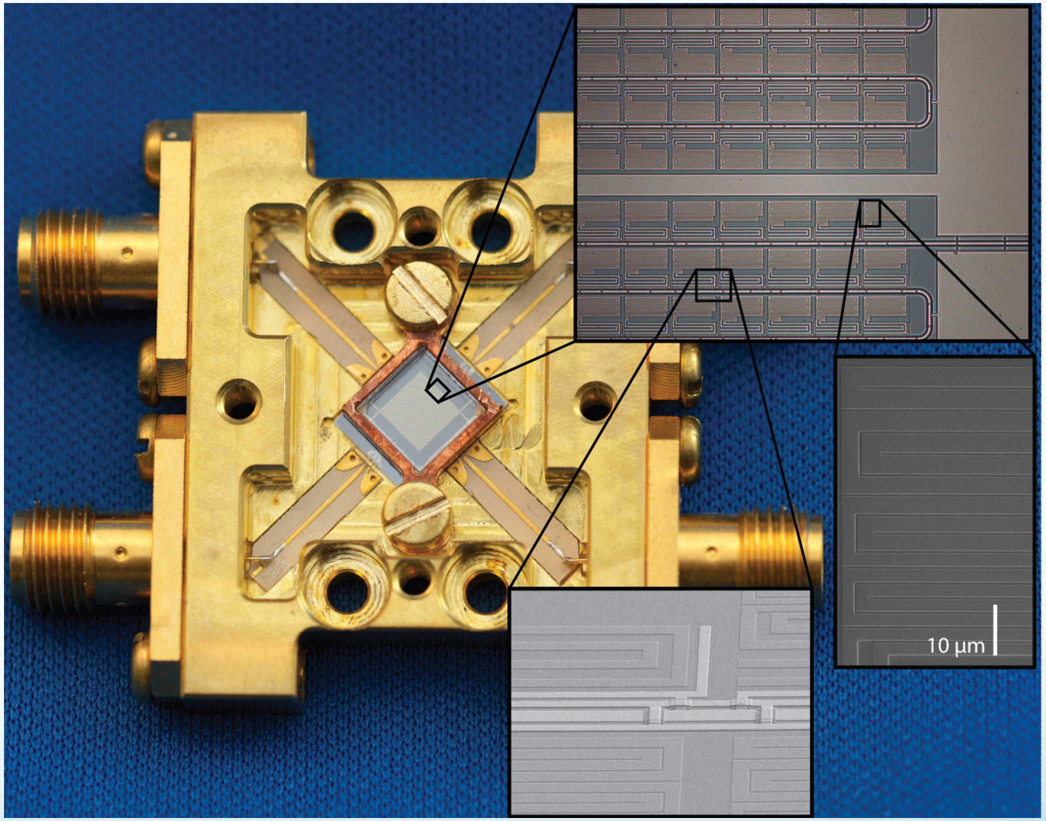




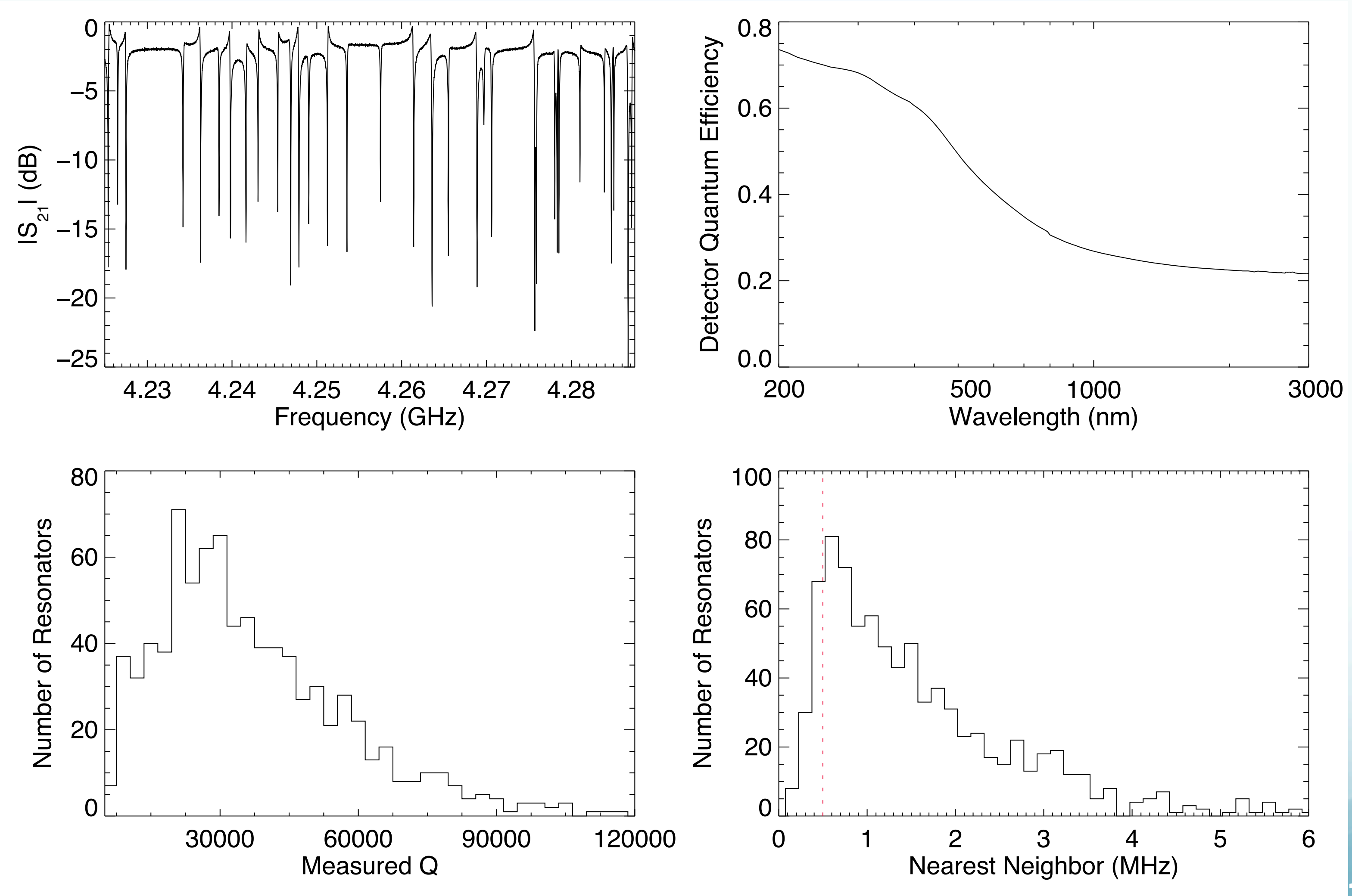
ROACH Based readout cost ~$20/pixel, ROACH2 system being deployed now which has several times the resources for the same cost.

The first science array

- 1024 pixel array (15x larger than any previous STJ/TES array)
- 2 feedlines with 512 resonators/feedline
- Designed to have 2MHz spacing between resonators
- Resonators close in frequency are far apart in space
- 839 resonators found in wide sweep (82%)
- 669 pixels accessible by read-out (4x512MHz)
- 65% of total array



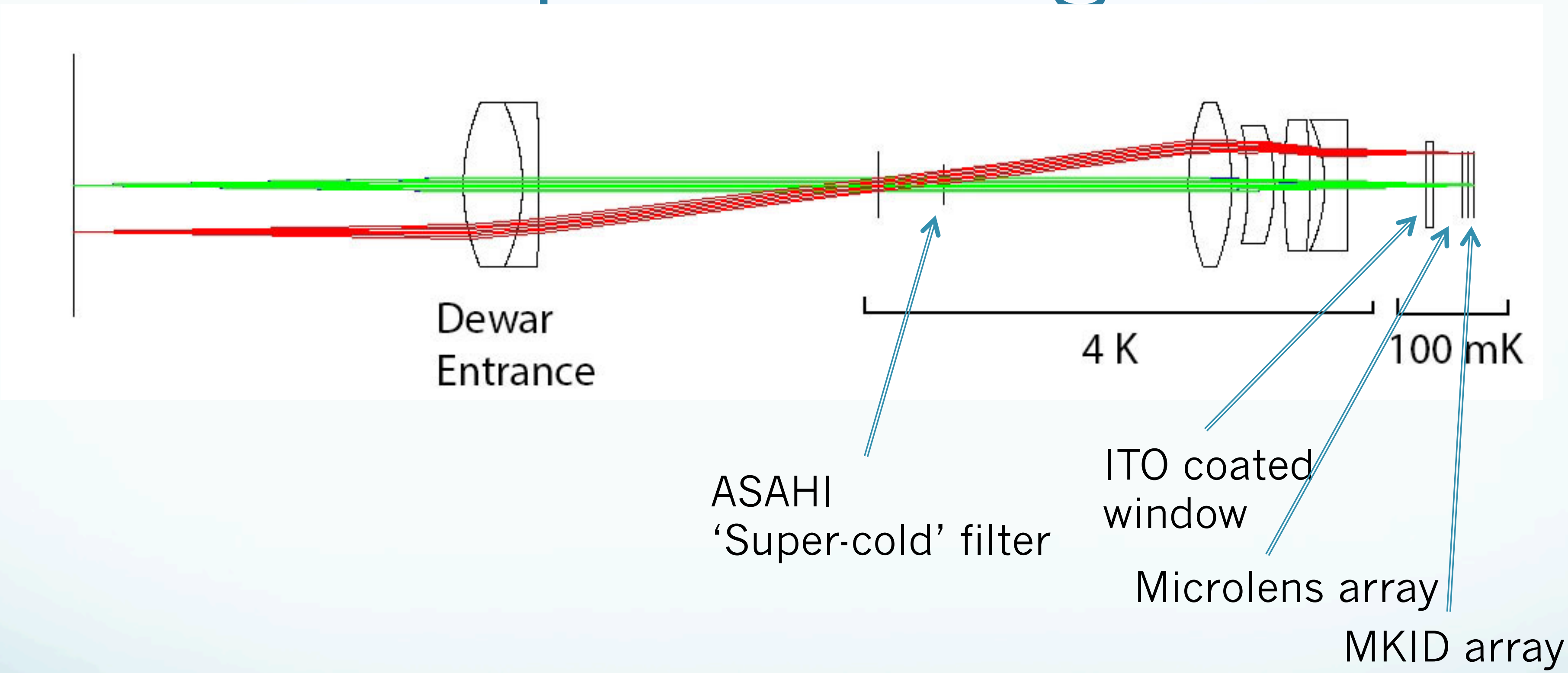
SCI-2B Uniformity



ARCONS (2011)

- The Array Camera for Optical and Near-IR Spectrophotometry
- 1024 pixel MKID array (70% active pixels)
- TiN lumped element pixels
- Lens coupled
- 100mK cryogen-free ADR
- 0.23”/pixel plate scale
- 0.38-1.1 μm passband
- 2000 cts/pixel/sec limit
- Energy resolutuion R=10-20 at 400nm

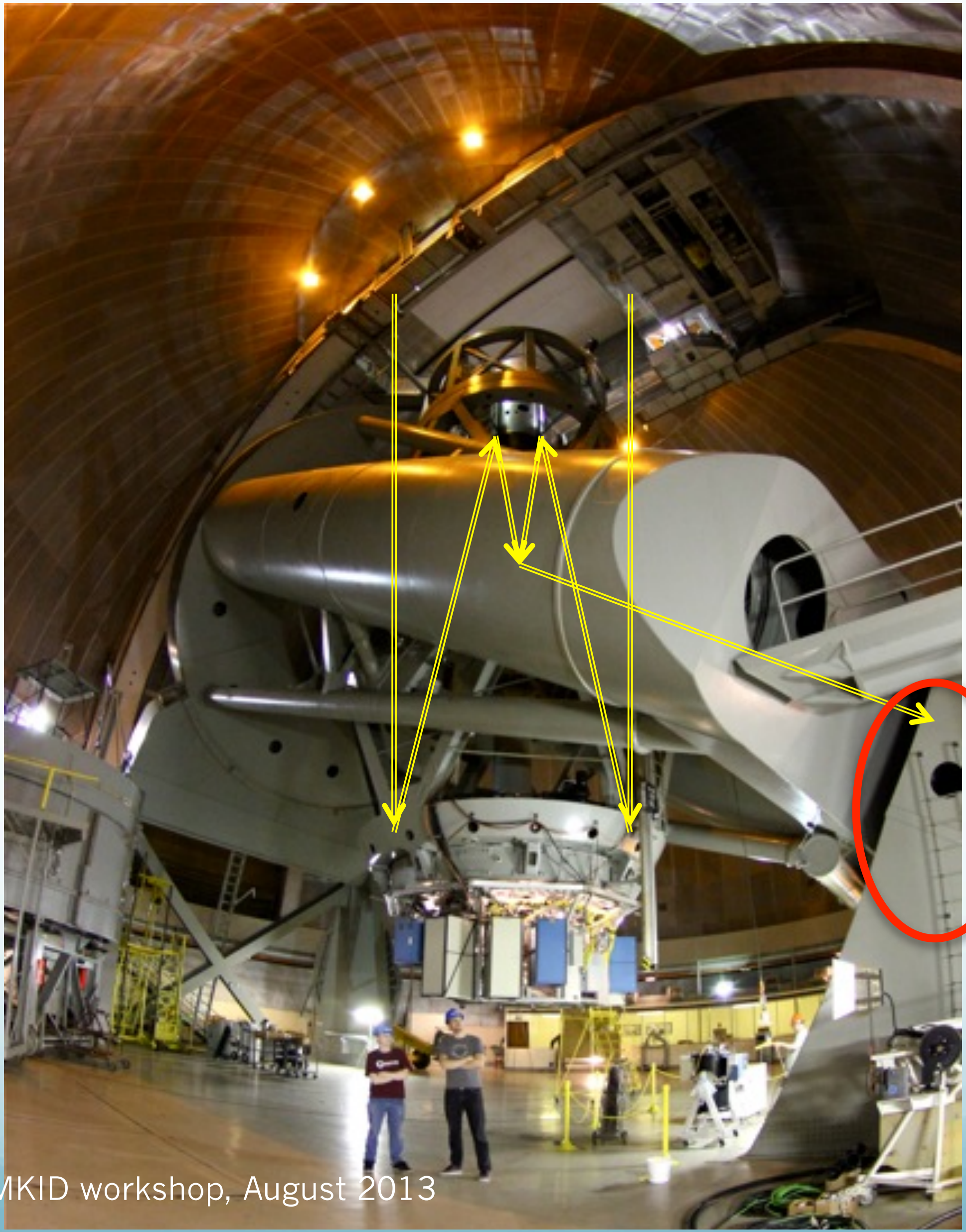
Optical design



Simple optical design comprising off-the-shelf components, designed to block as much thermal infrared as possible.

First MKIDs on sky!

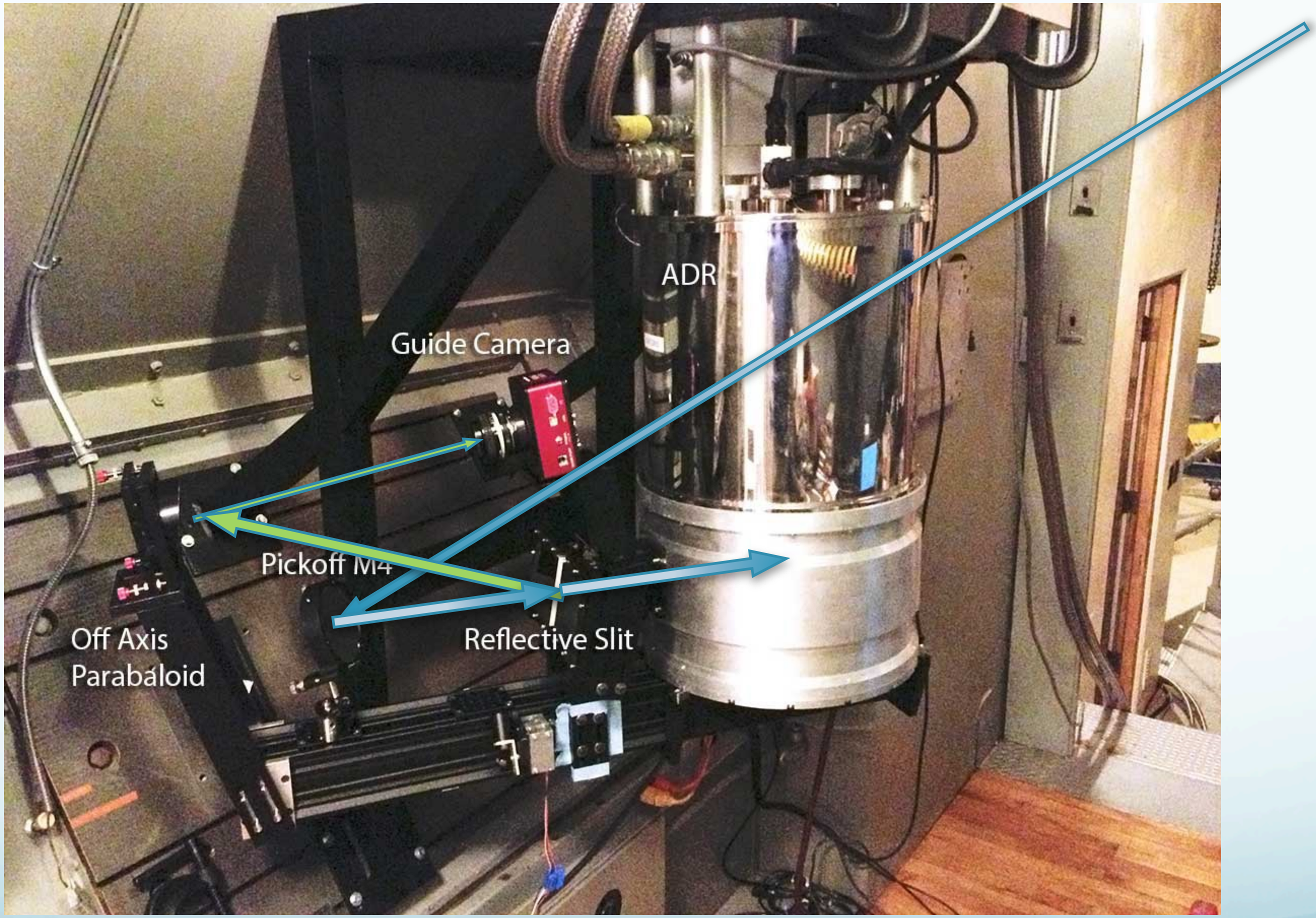
Some photos



ARCONS

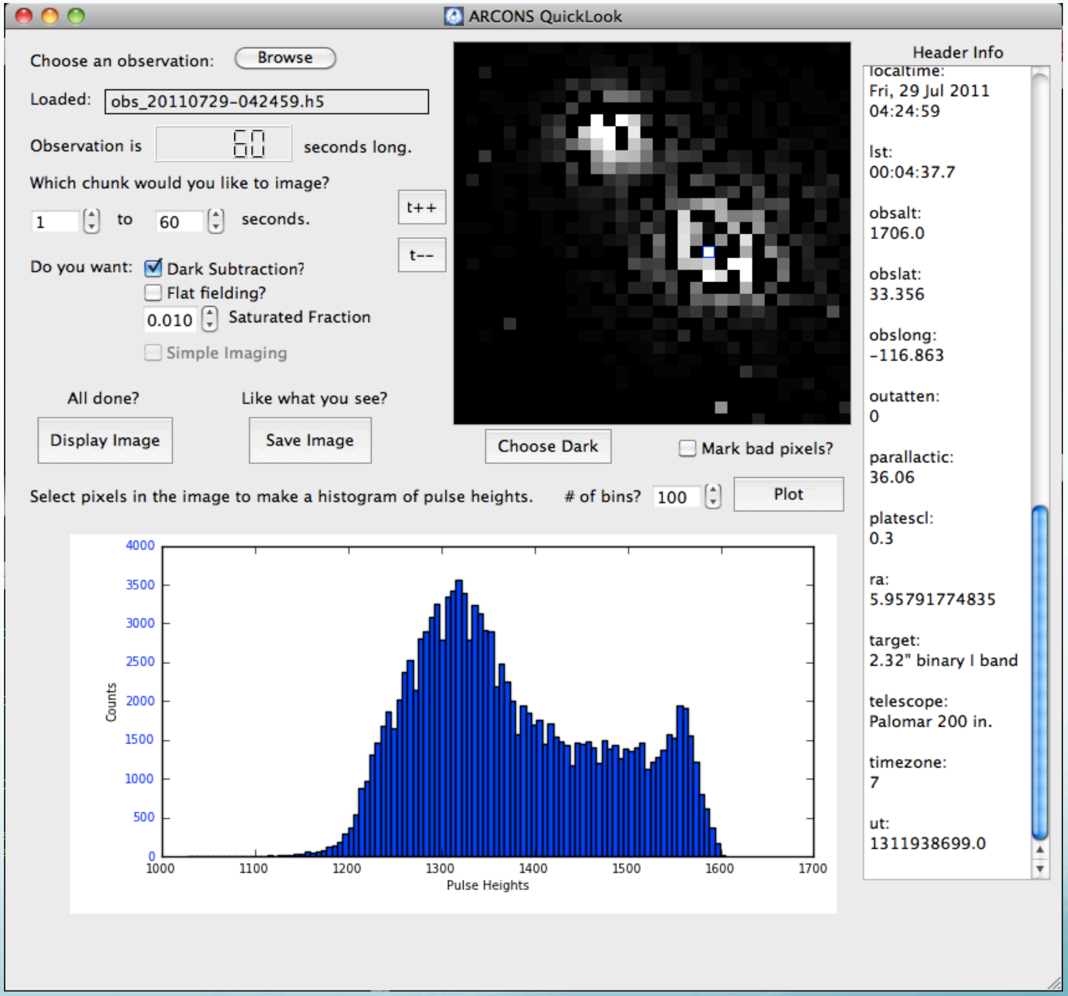
Installation

Optical layout

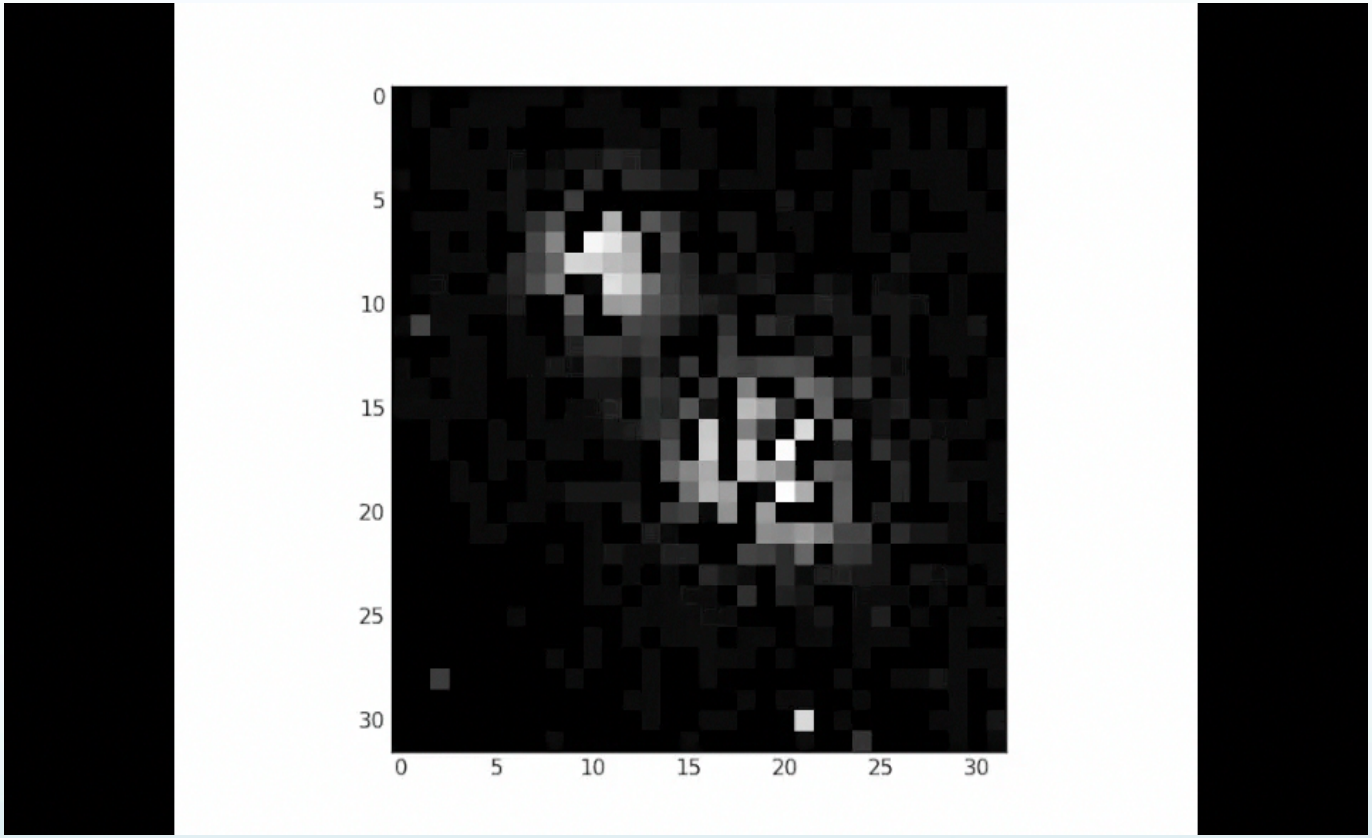


First light!

- 2.32" separation visual binary



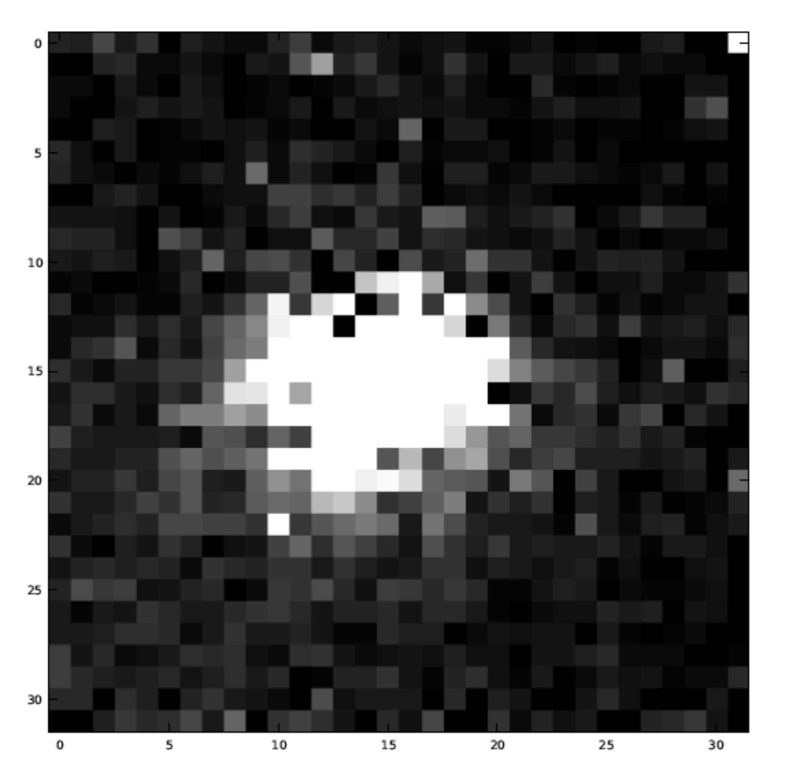
First light: the movie!



Courtesy: Seth Meeker

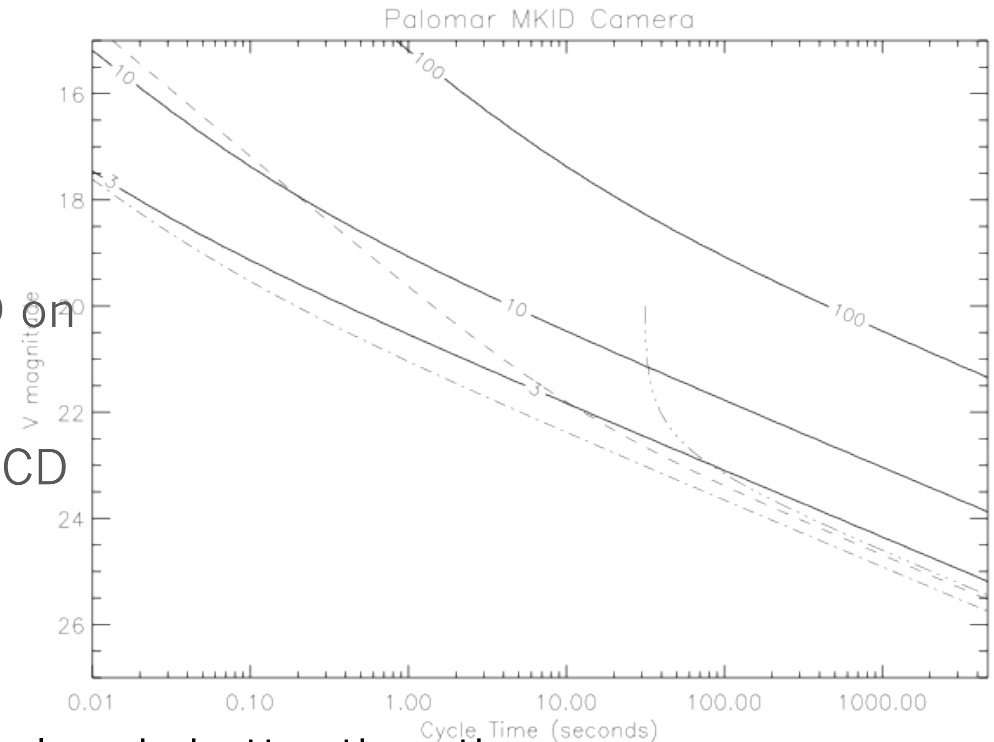
Results

- ‘Dithered’ reconstruction of 3 offset exposures of PG1633+099A
- m_v = 15.26 standard star
- 20 second integration
- $I_{cousins}$ filter
- S/N ~ 80
- Limit of m_I ~ 22.5 for 10-sigma in 1 hr



Sensitivity

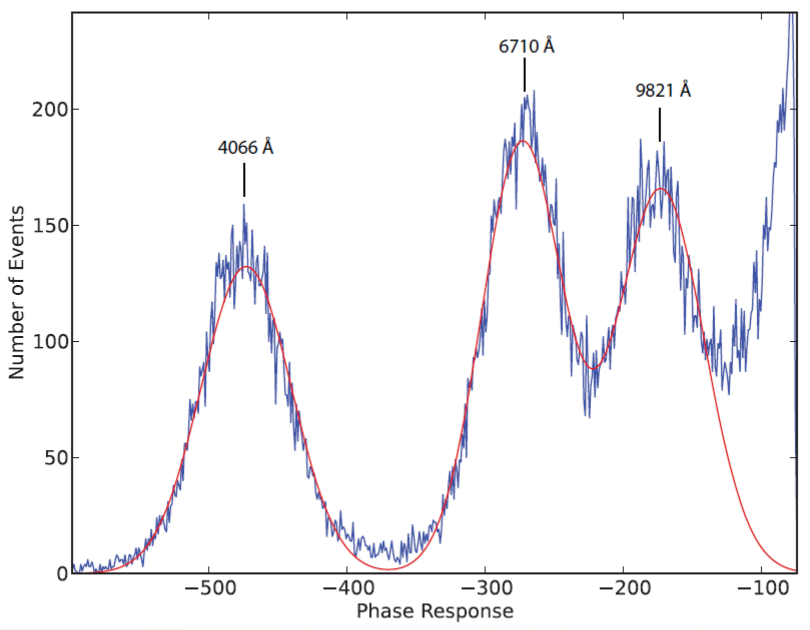
- m_v=23 for 10-sigma in 1hr
- m_v=25 for 3-sigma in 1hr
- 3 dot-dash - conventional CCD on an 8-m telescope (FORS/VLT)
- Dashed line - frame transfer CCD on an 8-m telescope (ULTRACAM/VLT)



Short duration observations are already better than those on a large telescope

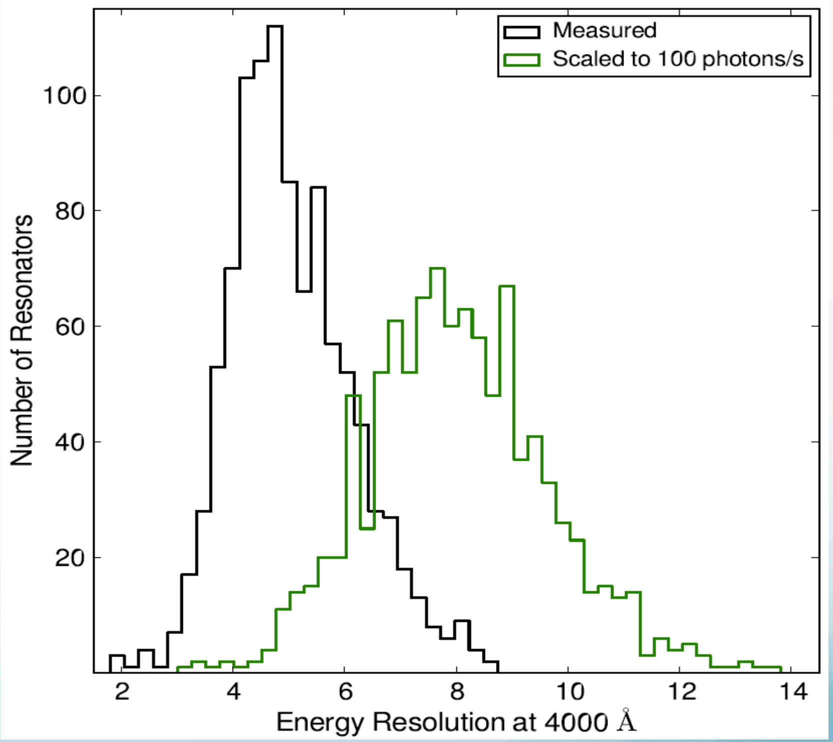
Spectral response

- Currently far from 'Fano' limit.



- Typical histogram of pulse heights from calibration source

- Histogram of resolution of individual resonators (pixels)

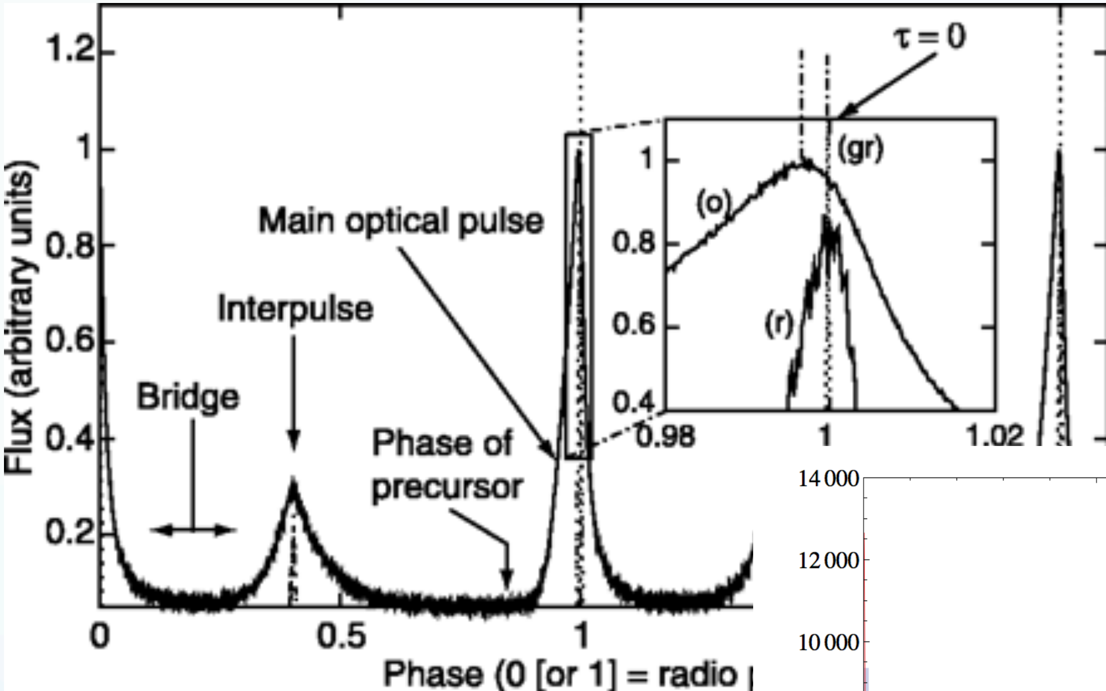


Science demonstration targets

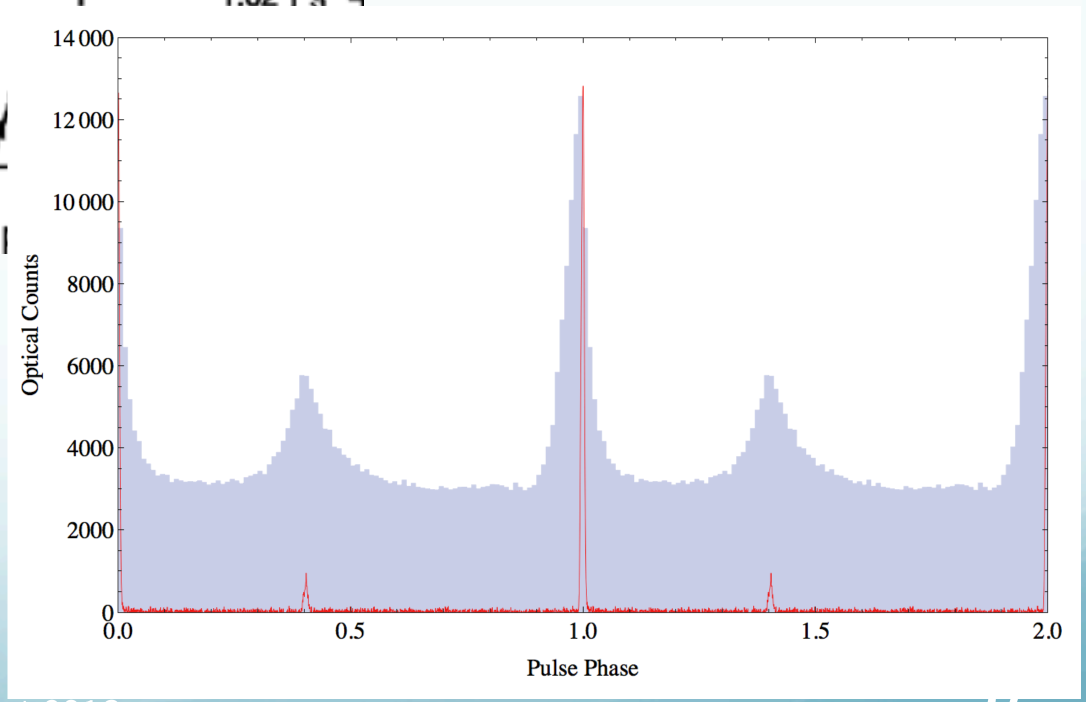
(or ‘what we hoped to do!’)

Object	Description	Key fact	Goal
NN Serpentis	Post common-envelope binary	0.13008017141(17) day period	Determine system parameters
PTF11jfm, PTF11hzx, PTF11htj	Supernovae from PTF survey		Demonstrate object classification
Einstein’s cross	Strongly lensed galaxy		Spectroscopically identify components
SDSS J0022+1431, SDSS J2321-0939, VBDS220339925, VBDS220265418, QSO 2308+098, QSO 1745+163	Quasars	Known redshift	Demonstrate spectroscopic redshift determination
V404 Cygnus	Quiescent blackhole LMXB	$9M_{sun}$ Blackhole	Determine spectrum of flaring
V407 Vulpeculae	Double degenerate accreting binary	9-min orbital period	Measure phase-resolved spectrum
NLTT 11748	Detached double degenerate binary	Eclipsing	
Crab Pulsar	Pulsar	33msec pulsar	Determine spin resolved spectrum

Run 2 - Crab Pulsar



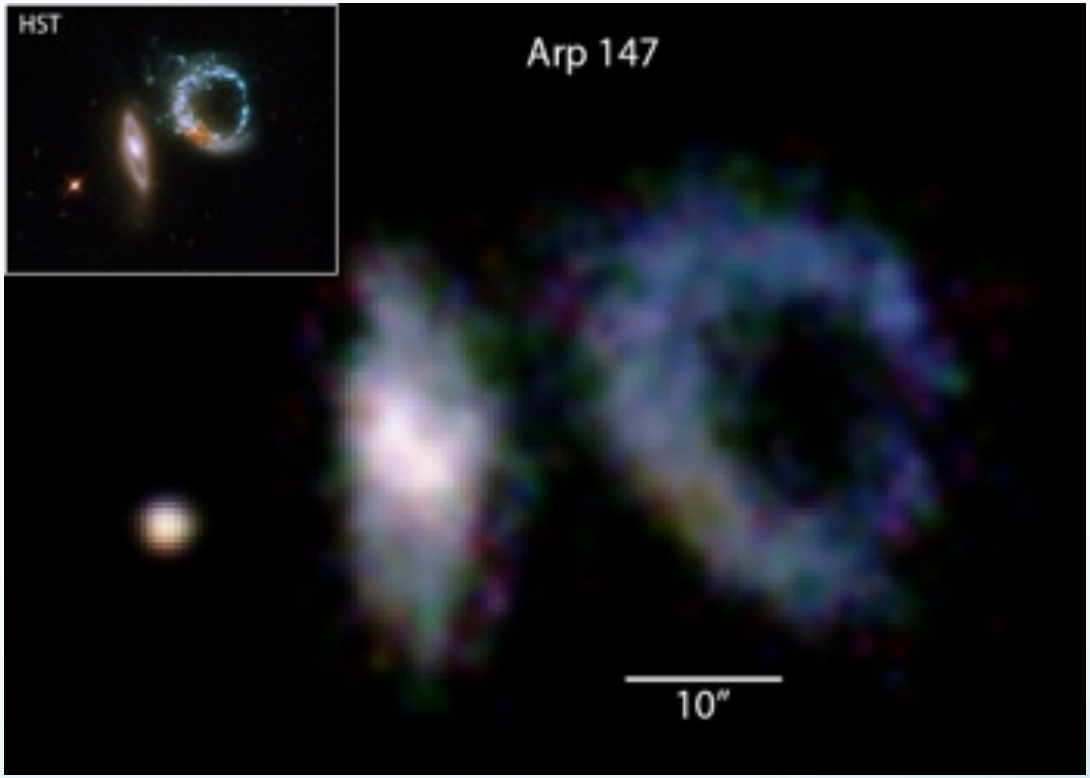
Pulse profile measured with ARCONS



Archival pulse profile for Crab (Shearer 2003)

Run 2 - ARP 147

- Mosaic of 36 x 1 minute pointings.
- False colour image made from spectral information from each pixel



Summary of status of ARCONS

	July 2011	Sept 2012	
Pixels	1024	2024	
Quality	82%	80%	
QE	20-60%	20-60%	
R (spectral resolution)	'5'	8	
Time resolution	10^{-6} secs	10^{-6} secs	
# MKID instruments	1	1	

Detectors for astronomy

	sensitivity	Noise	Time resolution	Energy resolution	Array size	Cost/unit
Eyes	Poor	Good	msec	Poor	Good	Free
Photographic plates	Fair	Poor	minutes	none	Good	Moderate
Photomultipliers	Fair	Good	msec	none	Poor	High
CCDs	Excellent	Good	seconds	none	Excellent	Moderate
CMOS	Excellent	Fair	seconds	none	Excellent	Moderate
APD	Fair	Good	msec	none	Poor	High
STJ	Fair	Excellent	μ sec	Fair	Poor	High
TES	Fair	Excellent	μ sec	Fair	Poor	High
MKIDs	Fair	Excellent	μ sec	Fair	Fair	Moderate

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APD	Fair	Good	msec	none	Poor	High
STJ	Fair	Excellent	μ sec	Fair	Poor	High
TES	Fair	Excellent	μ sec	Fair	Poor	High
MKIDs (2020)	Excellent	Excellent	μ sec	Fair	Good	Moderate

Summary of status of ARCONS

	July 2011	Sept 2012	~ 2017
Pixels	1024	2024	10^4 - 10^5
Quality	82%		>99%
QE	20-60%	20-60%	80-100%
R (spectral resolution)	'5'	8	30
Time resolution	10^{-6} secs	10^{-6} secs	10^{-6} secs
# MKID instruments	1	1	???

Instrument concepts

Classification of transients	Accretion onto compact objects	Dark matter/ energy	Exoplanets
High throughput, low spectral resolution Integral Field Spectroscopy	High time resolution and high spectral resolution single-object spectroscopy	Highly multiplexed, low spectral resolution spectroscopy	Photon-counting IFS for coronographic planet finder
ARCONS-10K	KIDSPEC	Mega-Z/Giga-z	Darkness

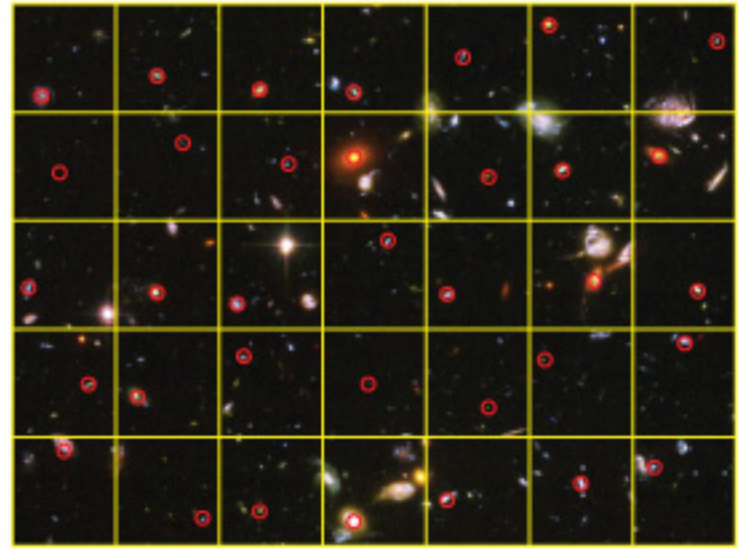
Instrument concepts

Classification of transients	Accretion onto compact objects	Dark matter/ energy	Exoplanets
High throughput, low spectral resolution Integral Field Spectroscopy	High time resolution and high spectral resolution single-object spectroscopy	Highly multiplexed, low spectral resolution spectroscopy	Photon-counting IFS for coronographic planet finder
ARCONS-10K	KIDSPEC	Mega-Z/Giga-z	Darkness

Era of surveys

- Current large surveys (eg. COSMOS) combine large area imaging in a few (5-10) filters with spectroscopy of a small fraction of the sample
- Photometric redshifts are used to constrain clustering
- Some surveys using multiple narrow band filters, very expensive in terms of telescope time
- Too time consuming/expensive to perform spectroscopy of more than a subset of objects detected

Giga-z



Marsden, Mazin, O'Brien & Hirata, 2013, ApJ, in press

- Redshift machine
- Pre-cut mask covers 1deg FOV
- Array of 100,000 MKIDs
- R~30 spectra for ~80,000 objects per telescope pointing
- Grid of 10"x10" macro-pixel (individual 'patrol fields')
- Each patrol field mapped onto a single MKID

The survey

- Limiting magnitude: m_I = 25 in 15mins
- Survey using 800 nights of
  4-m telescope time
- Survey of LSST catalog sources yields redshifts of > 2 billion objects

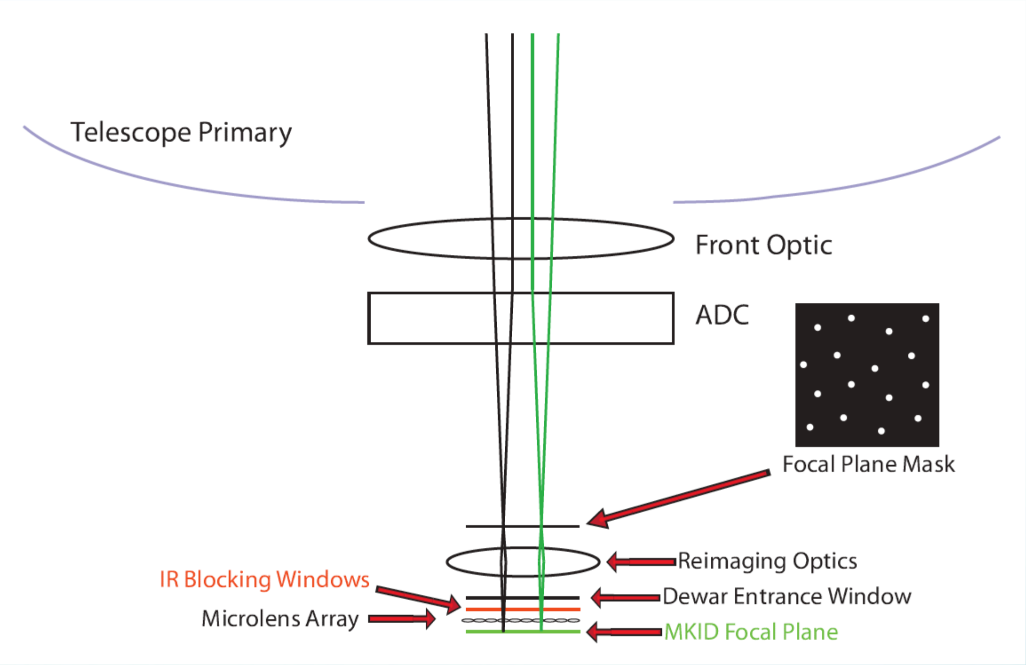
Comparison to other existing/planned surveys

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	$\sim 20\%$
	~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	$\sim 19\%$
	224,000,000	20,000	$i_{AB} \lesssim 22.5$	$R_{423} = 30$	0.01	0.3%

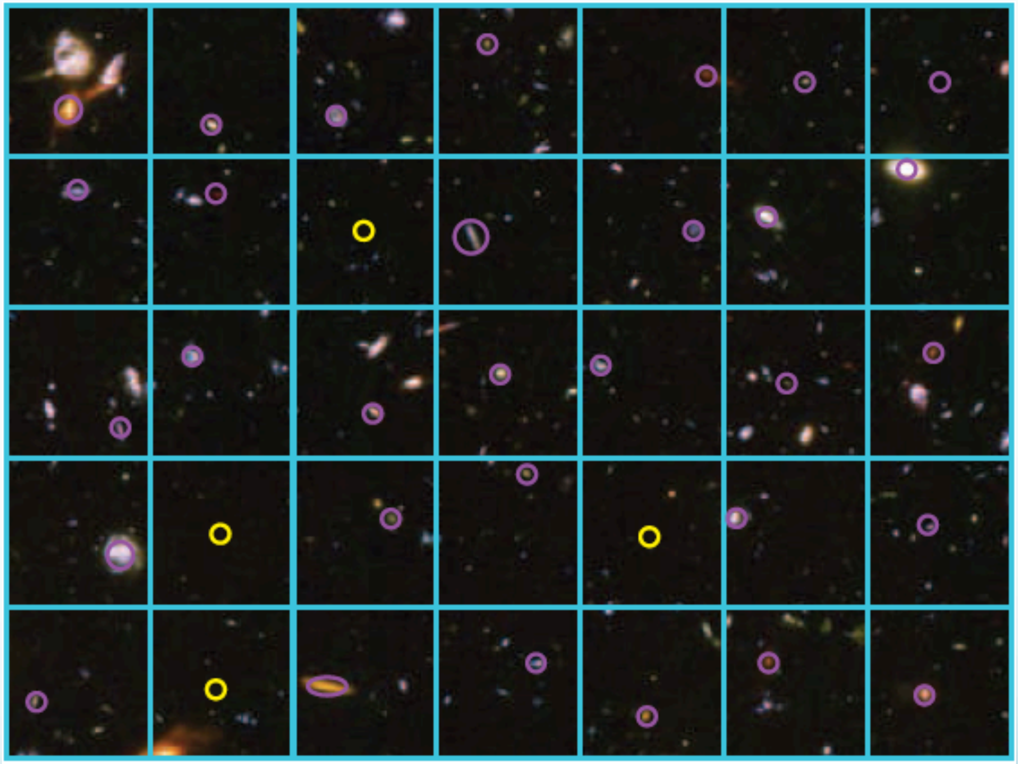
Schematic design

- Simple design
- Atmospheric Dispersion Corrector to minimize aperture and hence sky flux
- Focal plane mask pre-cut using input catalogue
- Mask are warm to enable easy operation. Thermal background from masks is limit in near-IR
- Re-imaging optics to could be combined with the micro-lens array



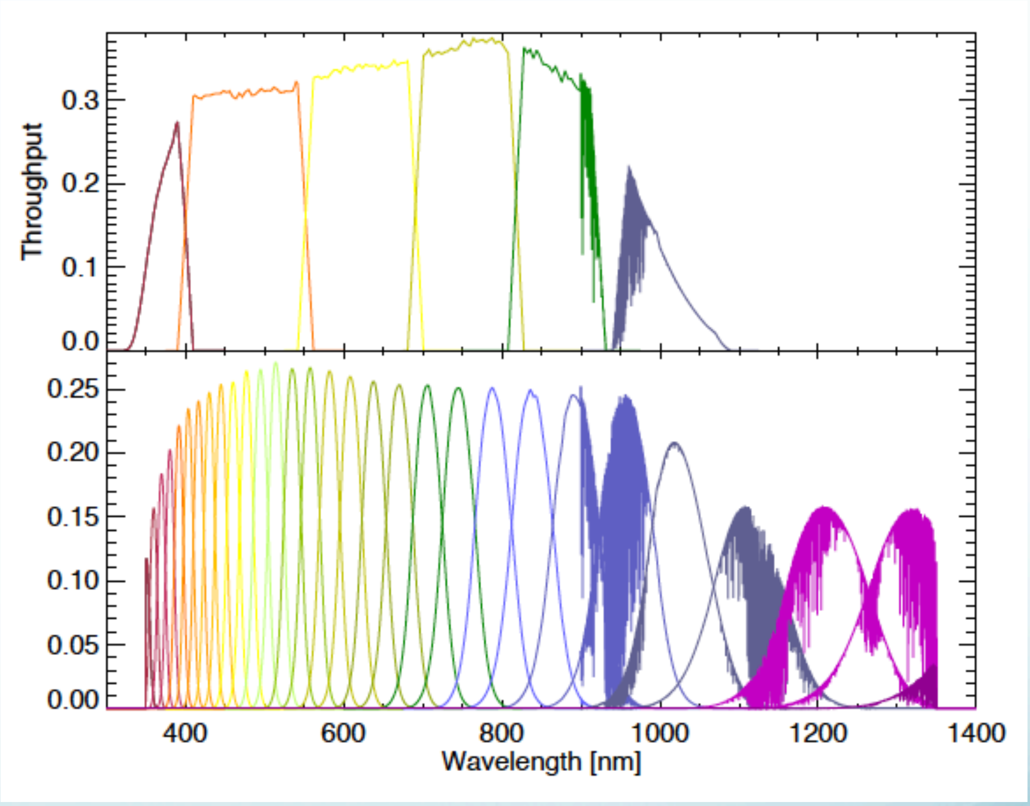
Masks

- Each mask subdivided into small patrol fields
- Each patrol field is 10x10" on sky
- Each patrol field is re-imaged onto a single MKID using a lens-let array.
- Empty fields are used as sky measurements or spectrophotometric calibrators
- 20,000 masks over duration of survey, ~25/night
- Could use algorithm to optimize footprint of each mask

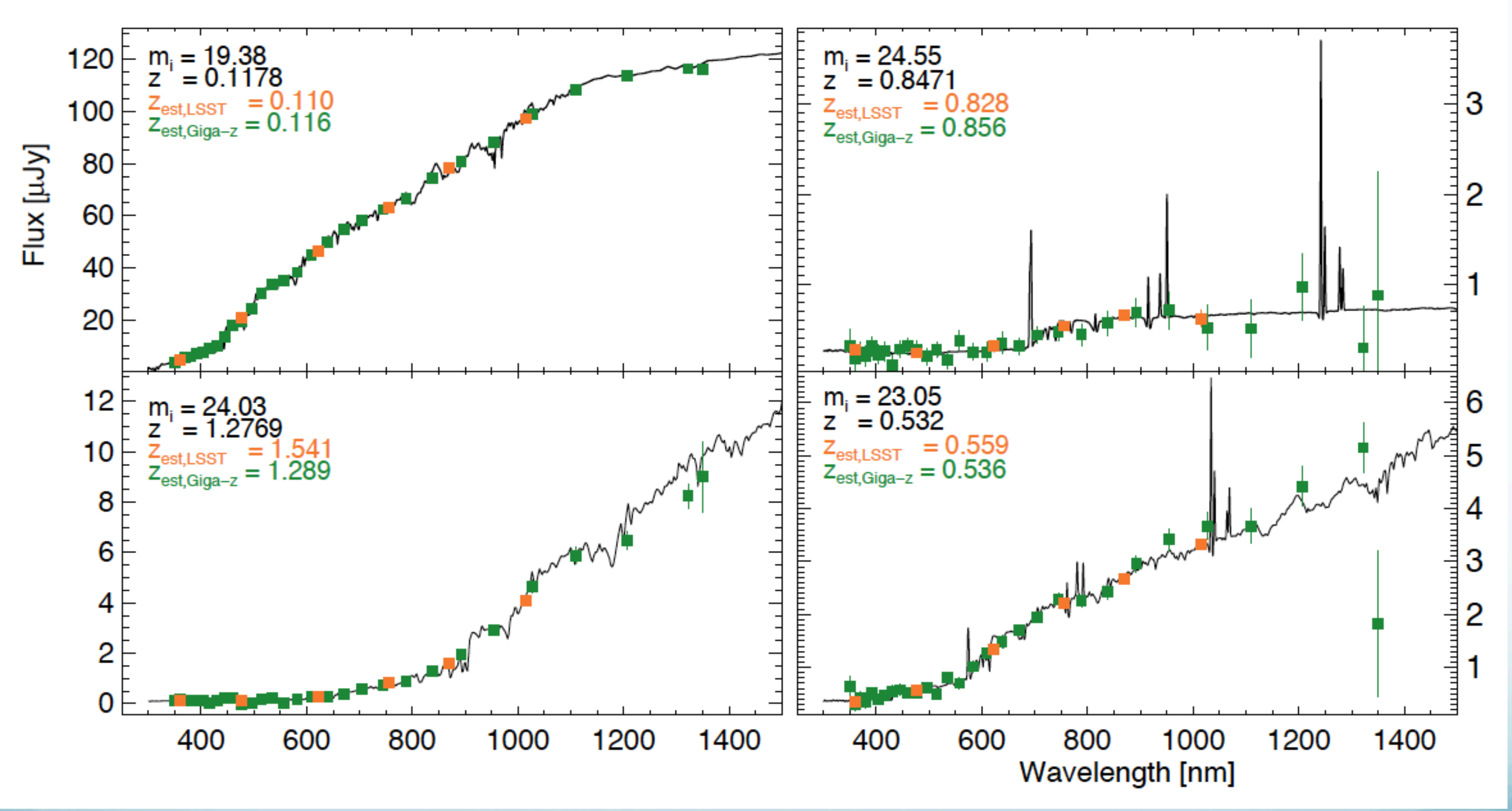


Spectral coverage

- Pseudo-filters are constructed in software to enable easy implementation of a photo-z code (EAZY)
- Spectra from actual giga-z observations will be treated like any other spectra.
- Addition of IR wavelengths greatly improves catastrophic failure rate
- All 'filters' are taken at the same time, under the same conditions, unlike LSST, which will combine data from many different epochs taken under potentially very different atmospheric conditions

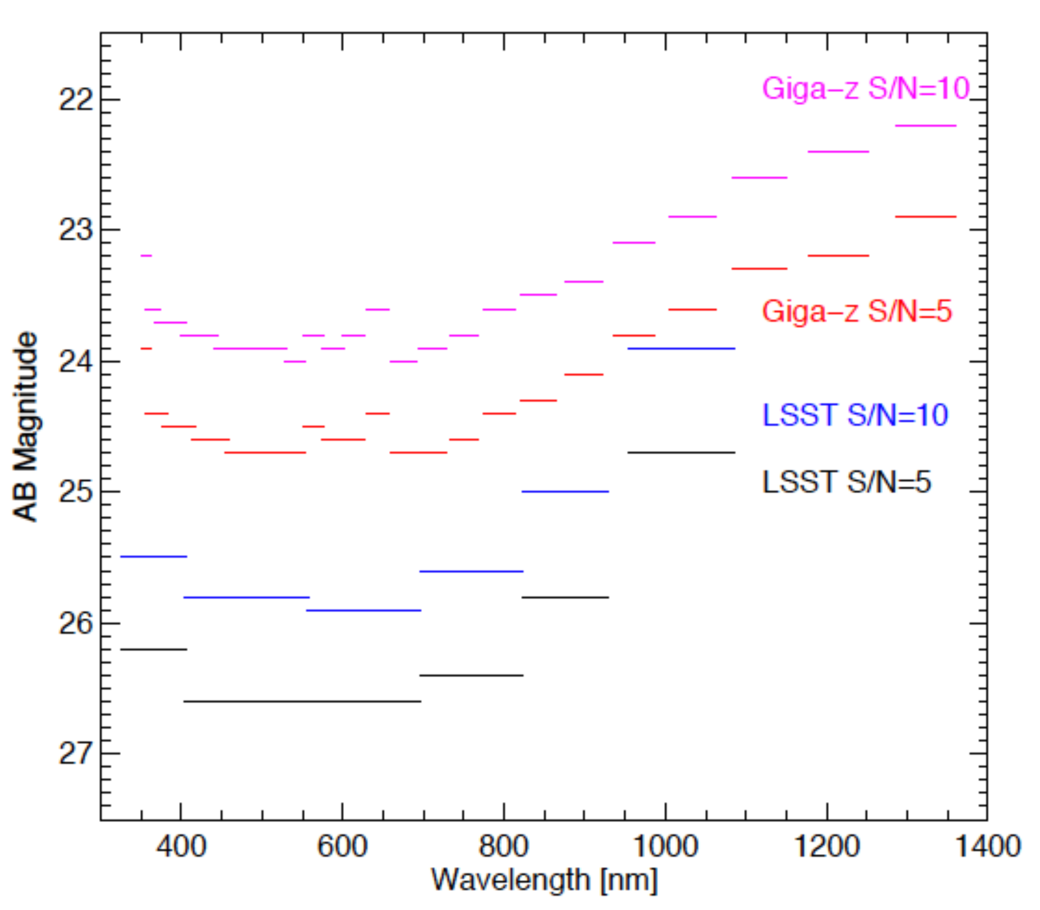


Sample galaxies

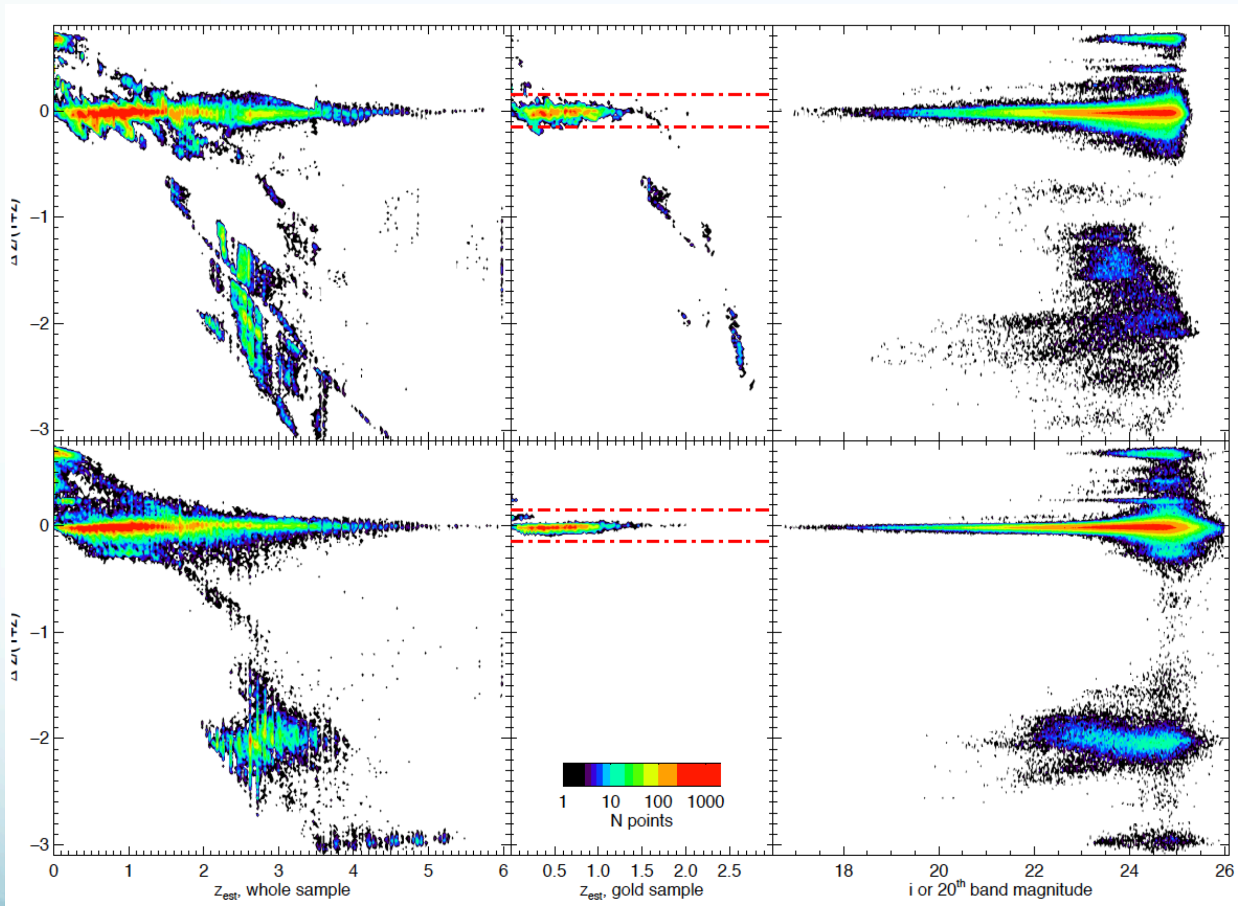


Deep survey

- Survey well suited to the LSST depth and sky coverage



Redshift determination accuracy



LSST

Giga-z

Impact of Giga-z survey

- Redshift accuracy
  - 0.03 for whole sample
  - 0.007 for 'gold sample'
- Improvement in cosmological parameters equivalent to adding an LSST-like survey in the North!
- Efficiently bridges a gap between broad-band photometry and low-resolution spectroscopy

TABLE 5
THE WL+CMB DARK ENERGY PARAMETER CONSTRAINTS. THE PRIMARY CMB IS FROM PLANCK, THE WEAK LENSING SHAPES FROM LSST, AND THE PHOTOMETRIC REDSHIFTS ARE FROM EITHER LSST OR GIGA-Z. RESULTS ARE SHOWN FOR ALL 5 INTRINSIC ALIGNMENT MODELS DESCRIBED IN THE TEXT, RANGING FROM I (VERY OPTIMISTIC) TO V (VERY PESSIMISTIC).

	$\sigma(w_p)$	$\sigma(w_a)$	$\sigma(\Delta_\gamma)$	$\sigma(\Omega_k)$
IA Model I				
LSST photo-z	0.0271	0.494	0.158	0.0246
Giga-z photo-z	0.0246	0.405	0.124	0.0200
IA Model II				
LSST photo-z	0.0373	0.671	0.204	0.0251
Giga-z photo-z	0.0341	0.562	0.157	0.0204
IA Model III				
LSST photo-z	0.0382	0.695	0.221	0.0252
Giga-z photo-z	0.0348	0.576	0.168	0.0205
IA Model IV				
LSST photo-z	0.0396	0.743	0.273	0.0258
Giga-z photo-z	0.0364	0.627	0.206	0.0211
IA Model V				
LSST photo-z	0.0503	1.053	0.330	0.0270
Giga-z photo-z	0.0450	0.912	0.279	0.0223

Mega-Z

Similar opto-mechanical concept as Giga-z

- 10,000 MKIDS
- 6x6" FOV for each MKID
  - samples unvignetted FOV of nasmyth focus
- 8-10m telescope (Keck, VLT)
- 1-hr integration/mask
  - Limiting magnitude i<26
- 20 night survey
- 1.2 million objects in 4 sq. degrees

Unique data-set bridging gap between photometric redshifts and the limiting magnitudes of 'classical' spectroscopic surveys

Summary

- MKIDs for optical/IR astronomy have been demonstrated on sky for the first time
- Challenges remain in increasing uniformity and responsivity of arrays
- Lots of effort currently on developing the pipeline for these large datasets, first science papers are being submitted
- Their unique scalability amongst energy sensitive detectors makes them an excellent candidate for future instrumentation
- Could transform astronomy in the same way as the transition from photographic plates to digital media

Instrument concepts

Classification of transients	**Accretion onto compact objects**	**Dark matter/ energy**	**Exoplanets**
High throughput, low spectral resolution Integral Field Spectroscopy	High time resolution and high spectral resolution single-object spectroscopy	Highly multiplexed, low spectral resolution spectroscopy	Photon-counting IFS for coronographic planet finder
ARCONS-10K	KIDSPEC	Mega-Z/Giga-z	Darkness

Classification of Transient sources

- Important step between discovery and follow-up
- PTF: 1.5Million candidates/night

  1000 ‘real’ sources

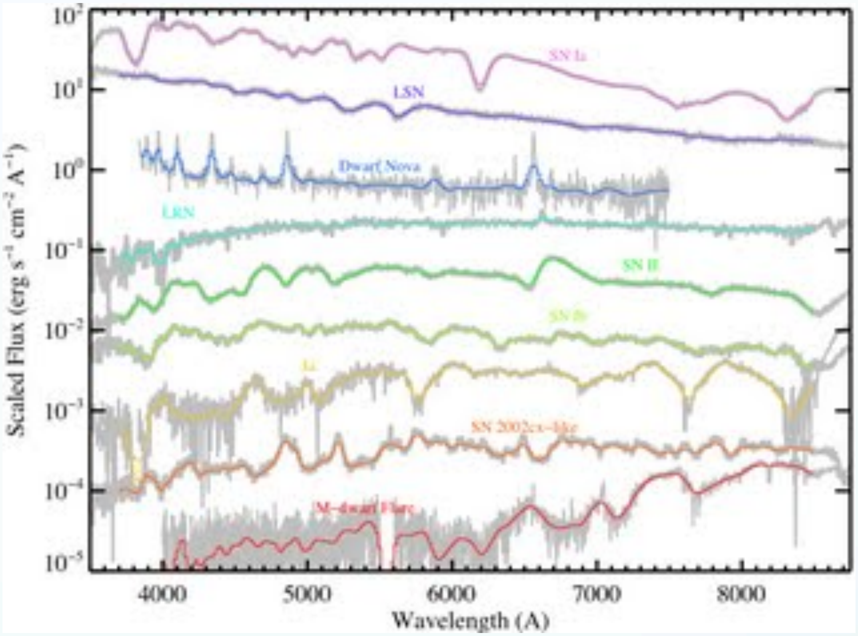
  300 variables

  10 SNe
- LSST: 100x volume of PTF

PTF: Josh Bloom
LSST: LSST science book

Classification spectrum of Transient sources

- Low resolution spectroscopy on small-medium sized telescopes is key
- Moderate (1'x1') field of view
- ARCONS-10K on a remotely controlled (/robotic) 2-m telescope(s) at a good site would give similar or better S/N with the addition of Y+J bands
- Additional variability information
- More efficient observing without need for fixed integration times



Source: Nick Konidaris, SED machine

- Classify large number of candidates to marshal 8-10m telescope follow-up. Optimize discovery potential of upcoming transient surveys

Instrument concepts

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Instrument characteristics

- Single object
- Medium spectral resolution (R > ~3000) to distinguish velocity components in the emission lines of Interacting Binary systems (and many other applications)
- Wide passband (0.35-2.4 μm) to capture as much of the SED of the object as possible simultaneously
- Good temporal resolution (< 0.1secs) to sample characteristic time-scales (frequencies of variability, light-travel times, orbital periods) in Interacting Binaries
- Low noise to avoid penalty of time resolution
- Optimizes collecting power of large telescopes, eg Keck, TMT

KIDspec

- Dual-arm (Vis+IR) spectrograph, with echelle grating in low order (<20) to achieve spectral resolution of 5-10,000
- Cross-disperser is replaced by energy resolution of MKIDs
- Photon counting detector allows for excellent background subtraction (a problem for eg. X-shooter/VLT)
- Combined with an image slicer, could give Integral-Field Spectroscopy as well.

See also, Cropper et al., 2003