Instrumentation developments for Dark Energy

Juan Estrada - Fermilab

Instrumentation Frontier

"The main goal of the instrumentation frontier is to study the long-term instrumentation needs for the various frontiers: What technology development and innovation program, guided by the science questions, is needed for the decade after next! We kindly ask the various conveners to make this an integral part of their discussions in the parallel sessions and include it in the summary at the end of the workshop."

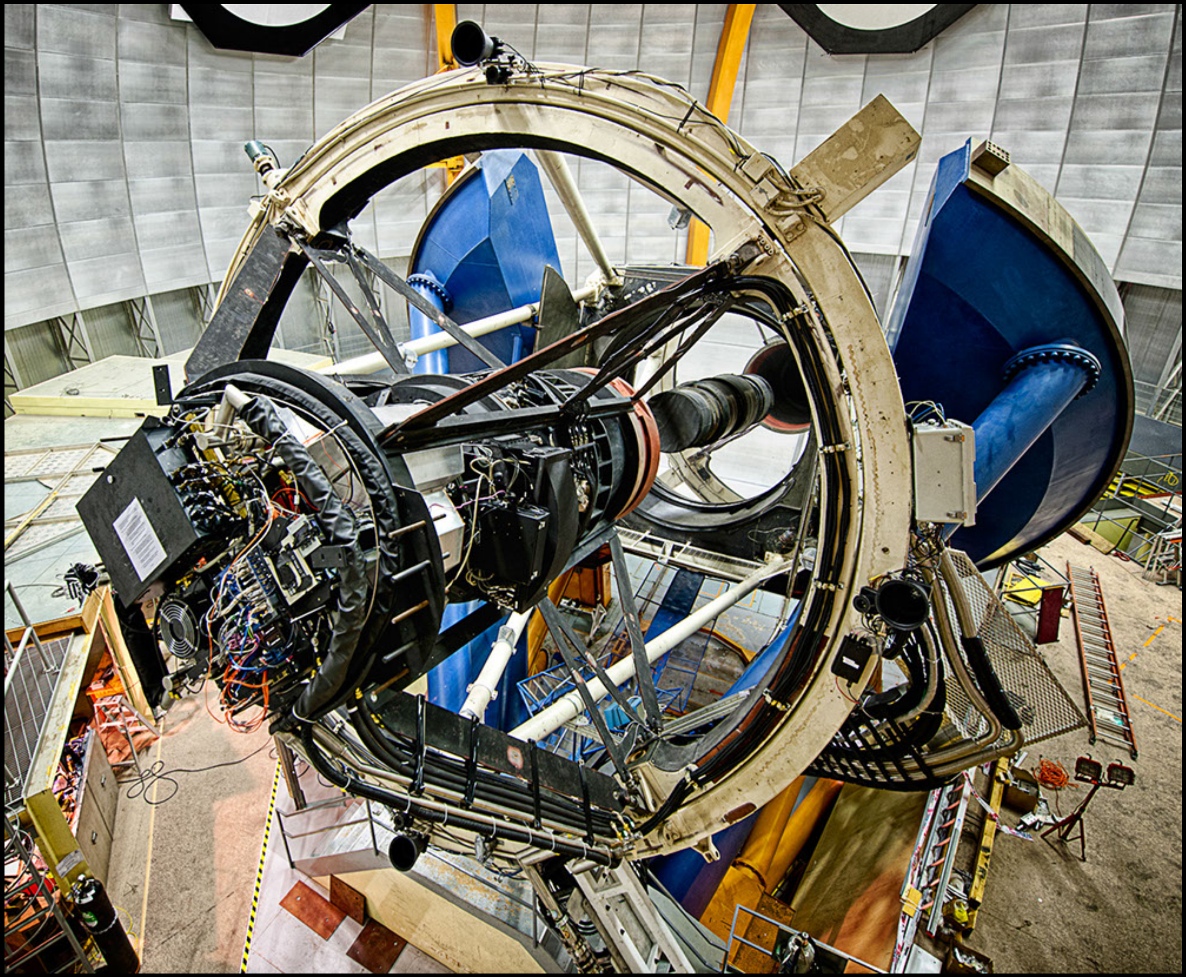
So far:
We had a meeting at Argonne in January and started organizing around physics topics. Unfortunately, this was at the same time of the DES, DESpec and DESC meetings.

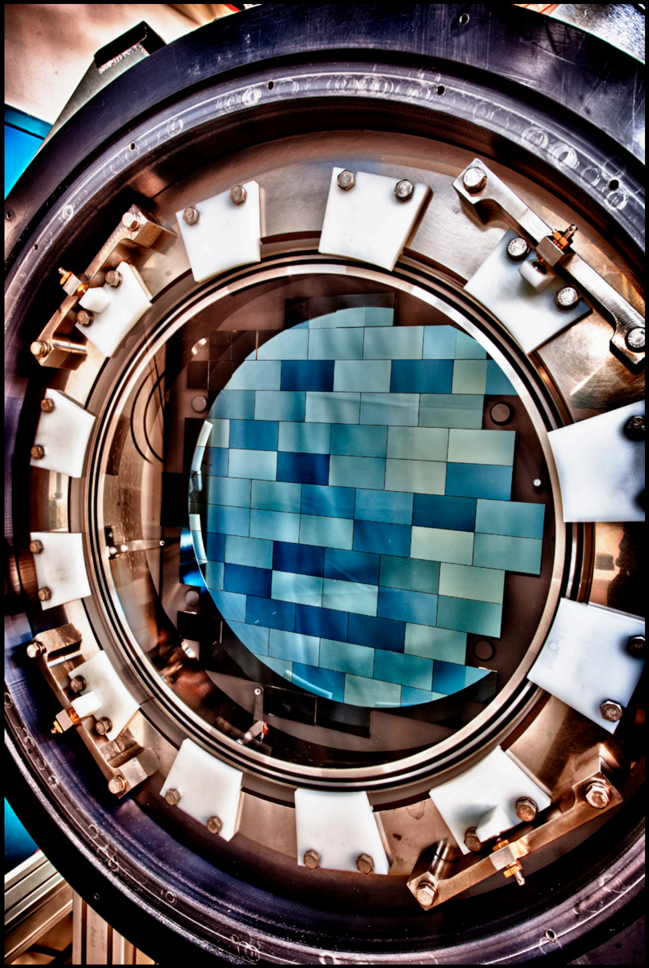
In the case of Dark Energy we are considering what instrumentation developments are needed after LSST.

If you have ideas please contact:
Gaston Gutierrez (gaston@fnal.gov) writing the first draft for instrumentation for DE
Juan Estrada (estrada@fnal.gov) liaison between Cosmic Frontier and Instrument. Frontier

area	Physics goal	tech in use	limitations	new technologies	
					Paolo Privitera
UHECR	identify sources and composition of UHECR study strong interactions at ~100 TeV CM energies	water cherenkov tanks Fluorecence telescopes	aperture e/mu separation xmax resolution	1) radio detection 2) UV telescope from space	
UHEnu	neutrinos are the only UHE messenger beyond local universe study weak interactions at ~100 TeV CM energies	optical cherenkov (ICECUBE)	limit in rate, not scalable	3) detection of coherent RF pulses (Askaryan)	Peter Gorham
Dark Energy	obtain spectroscopic information for LSST galaxies	mutifiber spectrograph with CCDs	not easily scalable to cover 50,000 gals.per square.deg	4) MKIDs	Gaston Gutierrez
Gamma Rays	indirect DM detection Axion like particle searches Lorentz invanriance	water tanks for air showers	limited energy reach and sensitivity	5) large area, fast, low noise + cheap photosensors 6) Water based scintillators 7) distributed DAQ with radio communication 8) relative timing better than 1nsec	Amanda Weinstein
		cherenkov telescopes	limited energy reach and sensitivity	10) large array of telescopes (CTA) 11) Fast ADCs 12) high resolution with FOV compact camera	
Directional DM	measure sideral anysotropy in nuclear recoils	Nuclear emulsions	can it be made practical?	13) columnar recombination detector	David Nygren
		Low pressure TPC	tension between increased mass and track range no scalable		
Light DM	detection of low mass DM from 1 GeV to 10GeV mass	low noise Ge detectors cryogenic Detectors	energy threshold, noise, nuclear recoil calibration	14)low noise CCD Si Detectors 15) cryogenic detectors with Luke gain	Matt Pyle, Javier Tiffenber
	detection of low mass DM from 1 MeV to 1GeV mass			15)single electron-hole detectors in Noble gas TPC 16)single electron-hole detectors in semiconductor 17)single photon in detection in cryogenic detector	
DM observatory	measurements on the wimp particles after discovery	assuming we have the G3 detectors	mass vs cross section degeneracy hard to overcome astrophysical uncertainties neutrino background	18)develop program with multiple nuclear targets	Andrew Sonnenschein
CMB		Satellites	small size telescope. High coast, long lead time	19) multimode detectors 20) engineered radiation coupling 21) microcalorimeter readout techniques	Stephan Meyer
		Ballon	telescope size limited, focal plane size limited		
		Ground	Sensitivity limited by atmosphere		
Axions					Jonghee Yoo
Spacetime structure	measure macroscopic quantum properties of geometry			holometer	Craig Hogan

Organizing along this matrix with each topic producing a ~1 page paper. Eventually we will invert things and write papers about the technologies… many overlaps.

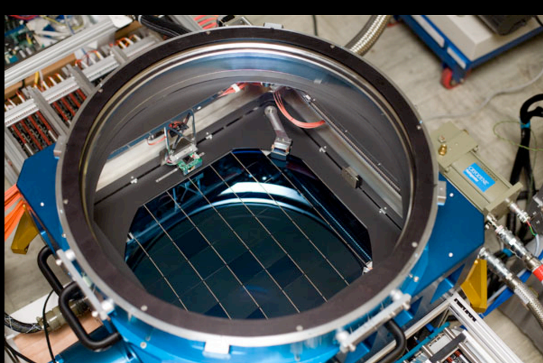




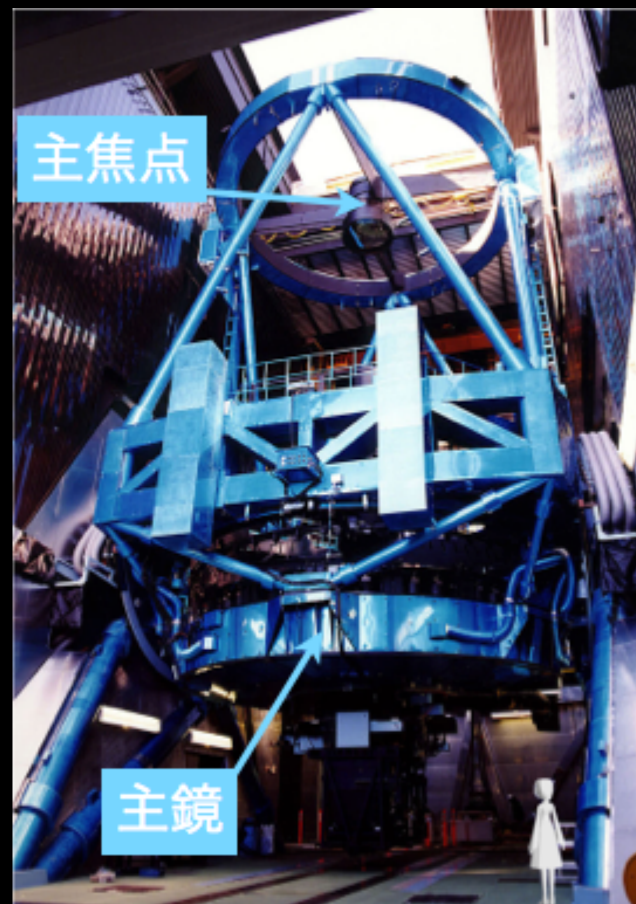
We all know our favorite instrument for Dark Energy…
Dark Energy Camera

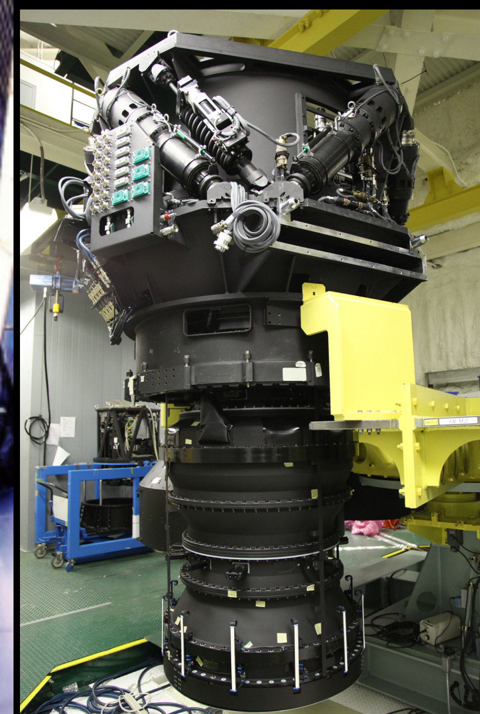
Other current instruments

Pan-STARRS
1.4 Gpix camera
3 more to be built
3deg FOV



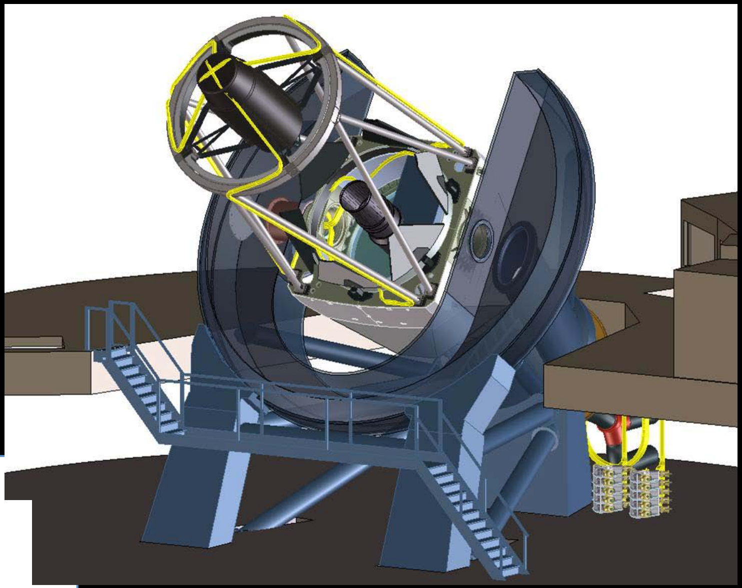
Hyper-Suprime-CAM @ subaru
8.2 m telescope, 870 Mpixel 1.5deg FOV

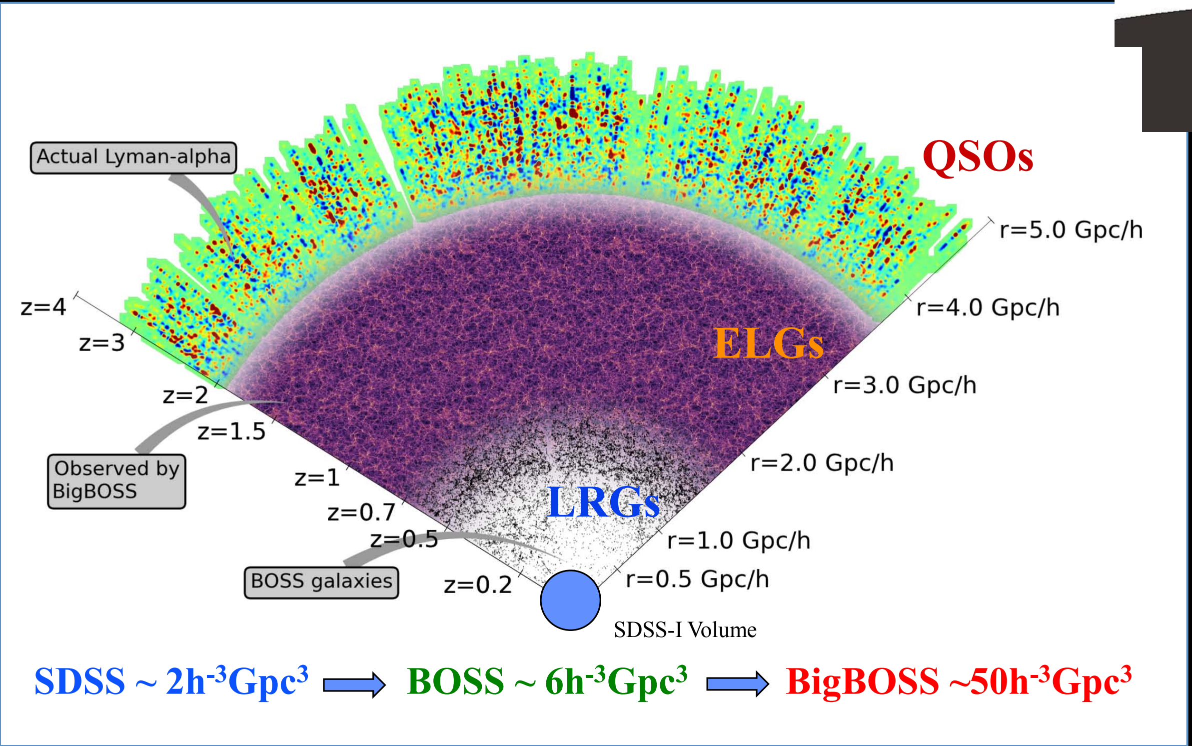




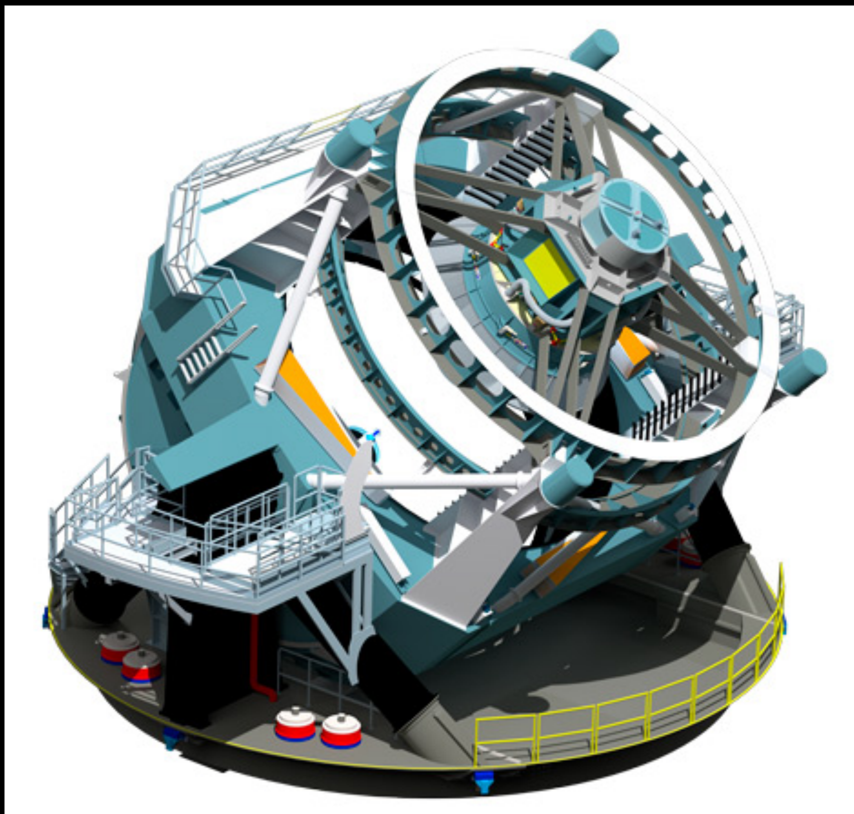
Near future: MS-DESI

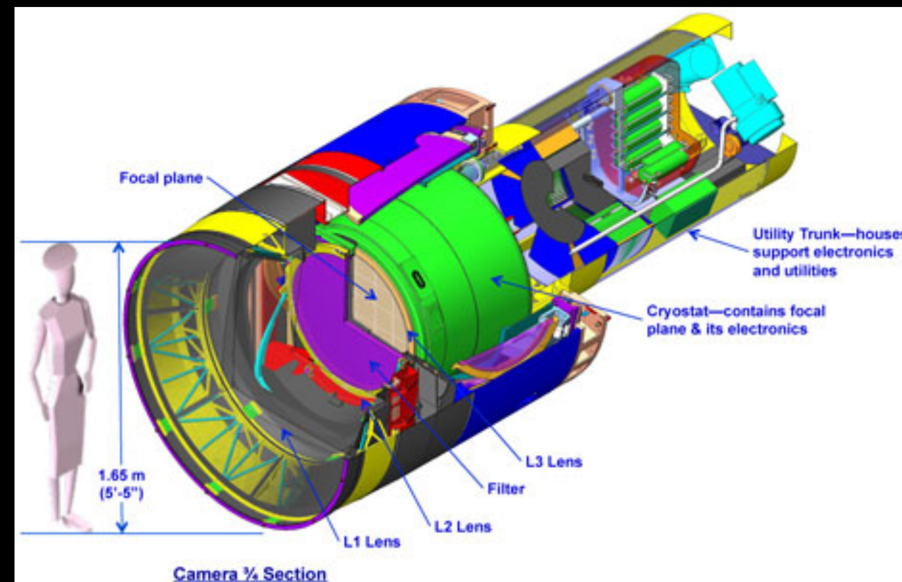
1. 4 m telescope
2. 5000 fiber, 3 arm spectrograph, R~4000
3. Spectra for 1800 objects/deg^2 (~10% of available galaxies)
4. Magnitude limit ~22.5, z~3.5
5. Will cover 14,000 deg^2 in 3 years
6. 20 M galaxies, 0.6 M QSO





What is next?

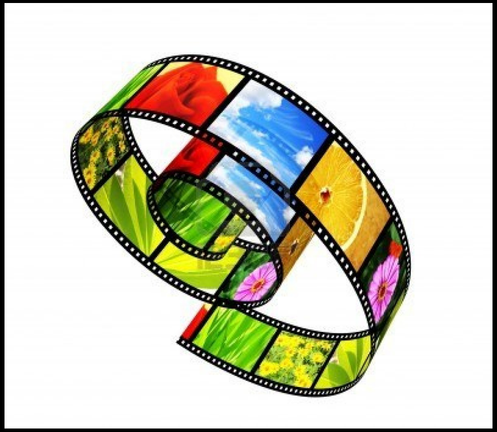




Faster and larger. Operations to start in 2021.
8.2m dedicated telescope, 3.2 Gpix camera, 3.5 deg field of view. HUGE!!!

What we really want?

All these instruments are based on Charge Coupled Devices (CCDs). These work like a digital film. “Expose and readout(develop)”

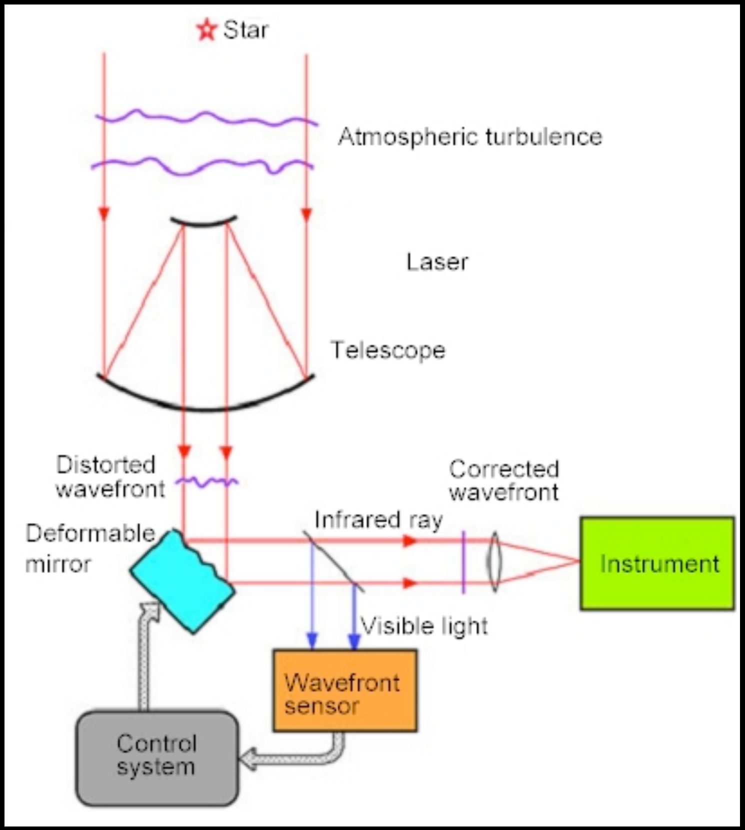


What would be the ideal sensor for these instruments:

1) perfect detection efficiency
2) zero noise (photon counting)
3) very fast (arrival time for each photon) - Atmosphere
4) measure energy for each photon – Spectral info

Will describe two technologies beyond CCDs that get us closer…

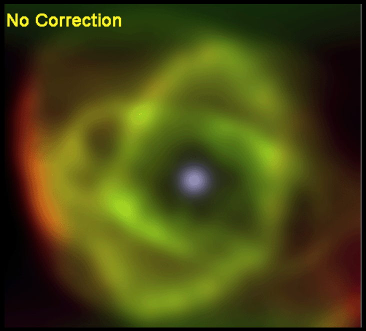
Why is timing important in wide field imager?

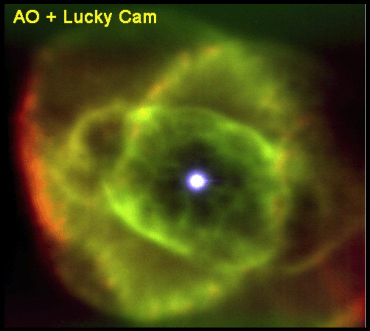


In narrow field imaging on adaptive optics is used to correct for atmospheric turbulence.

For wide fields of view this does not work because turbulence effect changes along the field.

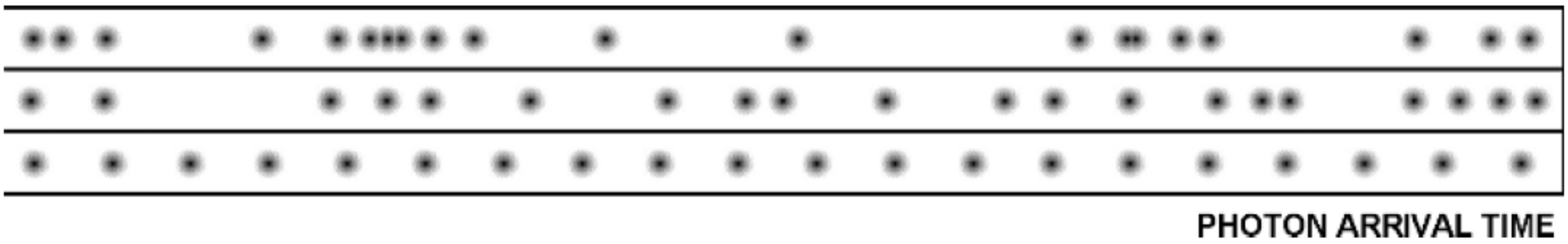
A detector with msec time resolution would allow atmospheric corrections offline.





http://www.ast.cam.ac.uk/research/lucky

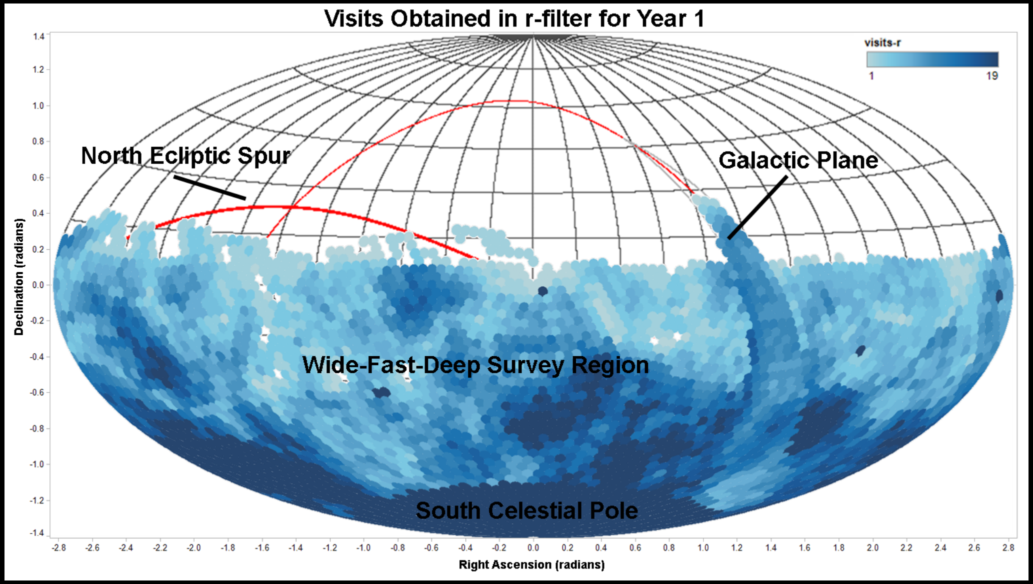
Why else timing?

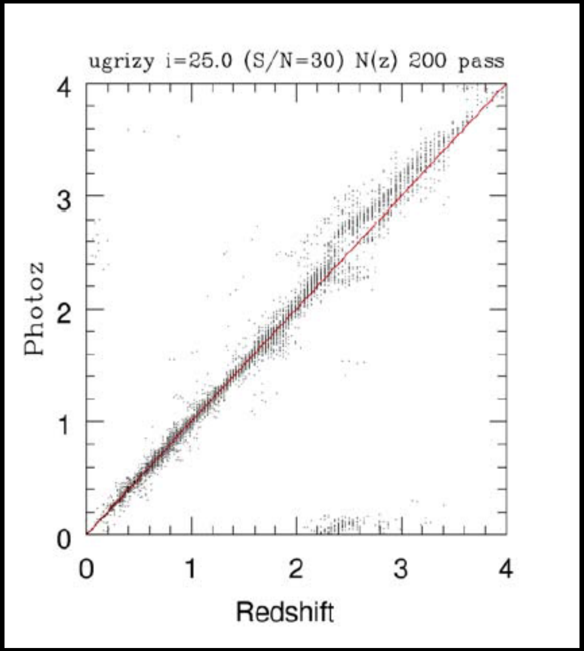


… this is pushing it a bit, but photon arrival times have information about spectral properties of the source. This does not really work yet in optical astronomy because 1e-15 sec resolutions are needed.

However, we could be getting much closer now with detectors with hi QE and psec timing.

Spectral information





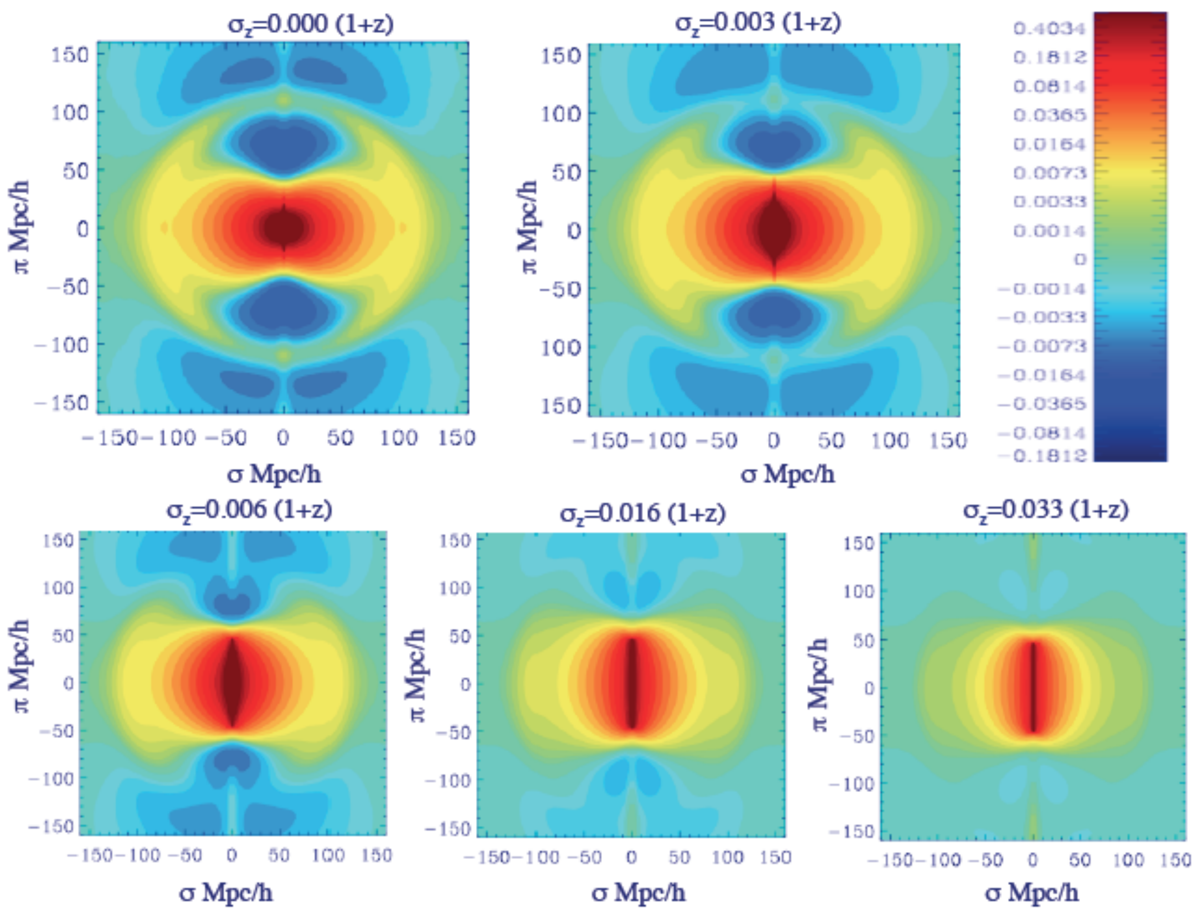
LSST will produce photometric data for 20,000 sq-deg to magnitude 27. Redshift will be estimated from the colors of the objects.

First priority for Astro-2010 decadal report

The cosmological measurements would be much improved with spectroscopic information for these objects.

Cosmological information lost due to photo-z error

Hi-res spectrum



Multi filter imaging

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.

Gastanaga et al, Monthly Notices of the Royal Astronomical Society, Volume 422, Issue 4, pp. 2904-2930.

Technology 1: MKIDs

MKID: new detectors

Semiconductor (CCDs)

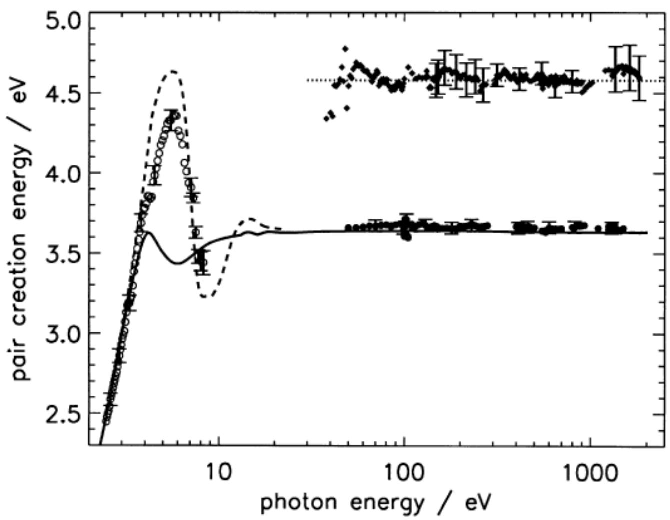


Fig. 5. Mean energy W required for creating an electron-hole pair determined from s_r and s: for silicon in the soft X-ray region [14] (closed circles) and UV and VUV region [21] (open circles) and for GaAsP in the soft X-ray region (diamonds). Typical experimental uncertainties are indicated. For silicon, calculations from Ref. [14] are shown as solid line and dashed line (see text). The points indicate the mean value of 4.58 eV for GaAsP.

Superconductor

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

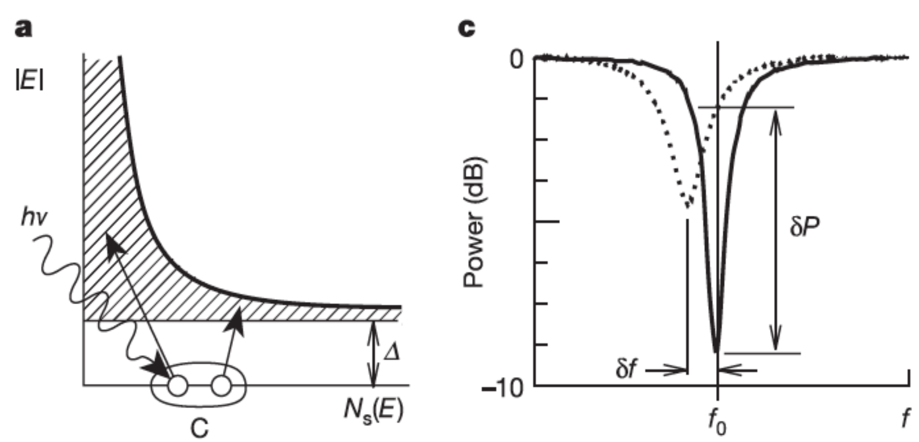
Δ : gap parameter of the superconductor

η: is an efficiency factor (about 0.6)

Δ is meV instead of eV (this is why we like them!)

For Al Δ= 0.18 meV

Microwave Kinetic Inductance Detector



1e- / red photon

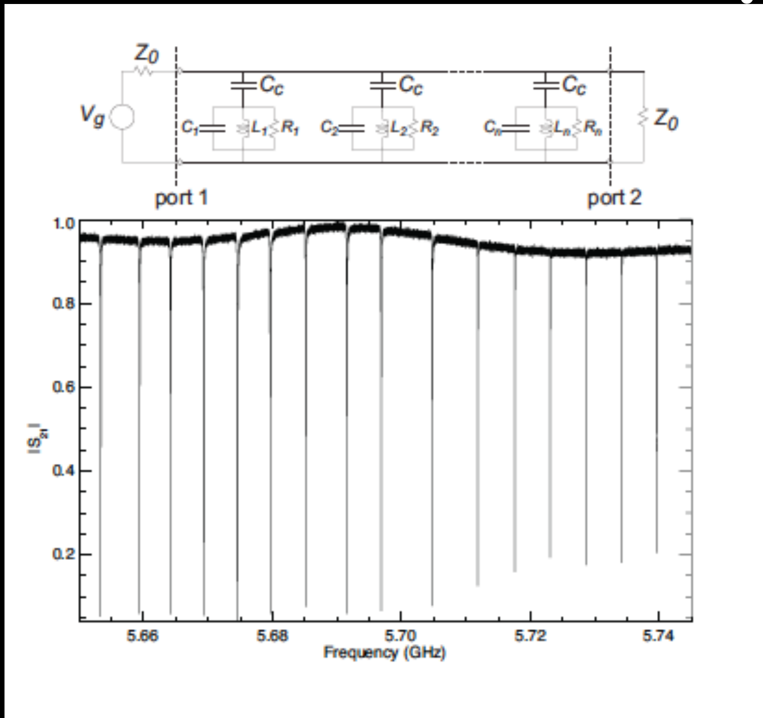
No energy information

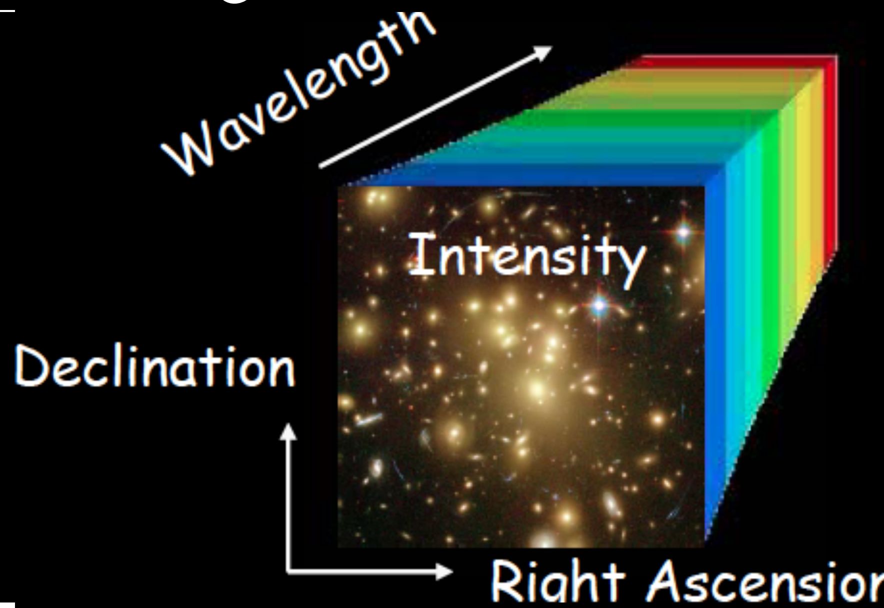
5000 qp / red photon

Energy resolution

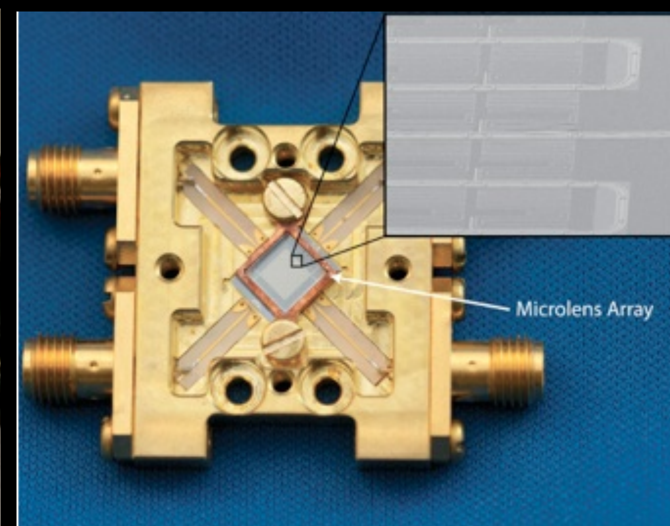
MKIDs multiplexing

3D information + timing





Optical MKIDs developed by UCSB and tested in a small astronomical instrument 1k pixels in 2011, “2k” pixels in 2012.



operating temperature = 100 mK

MKIDs - Future

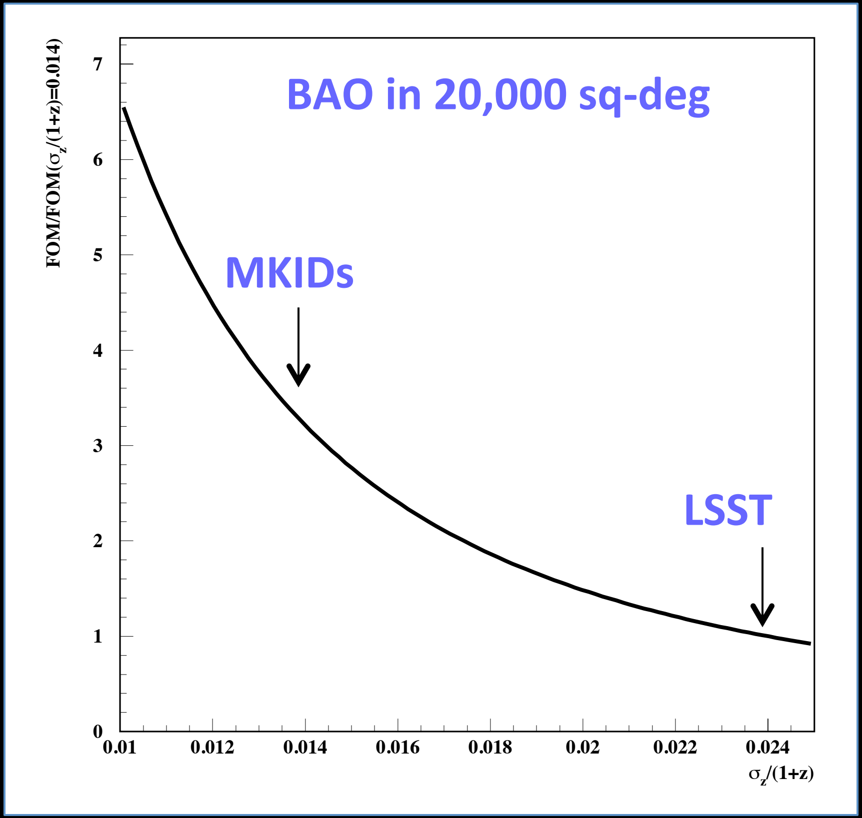
Yung et al 2010

MKIDs low resolution spectrograph (R~100) with ~100,000 channels could be used as a survey instrument to follow up LSST objects on a 4m telescope.

At least a factor of 20 more channels than any other planned spectroscopic instrument.

For cosmology you can do a lot with low resolution spectroscopy! Follow up of LSST objects with MKIDs could give a factor of ~4 improvement in FOM!

MNRAS, Volume 409, Issue 2, pp. 737-749



A group lead by UCSB is proposing the Giga-Z instrument to do this.
There is a long way before we can built anything like this, at FNAL we are starting an R&D effort to build a ~50kpix imager with MKIDs for SOAR 4m telescope.

Towards a large MKIDs instrument

The plan is to develop technology to enable large MKIDs instruments for cosmology, there are three aspects that limit the growth and we can contribute on all of them:

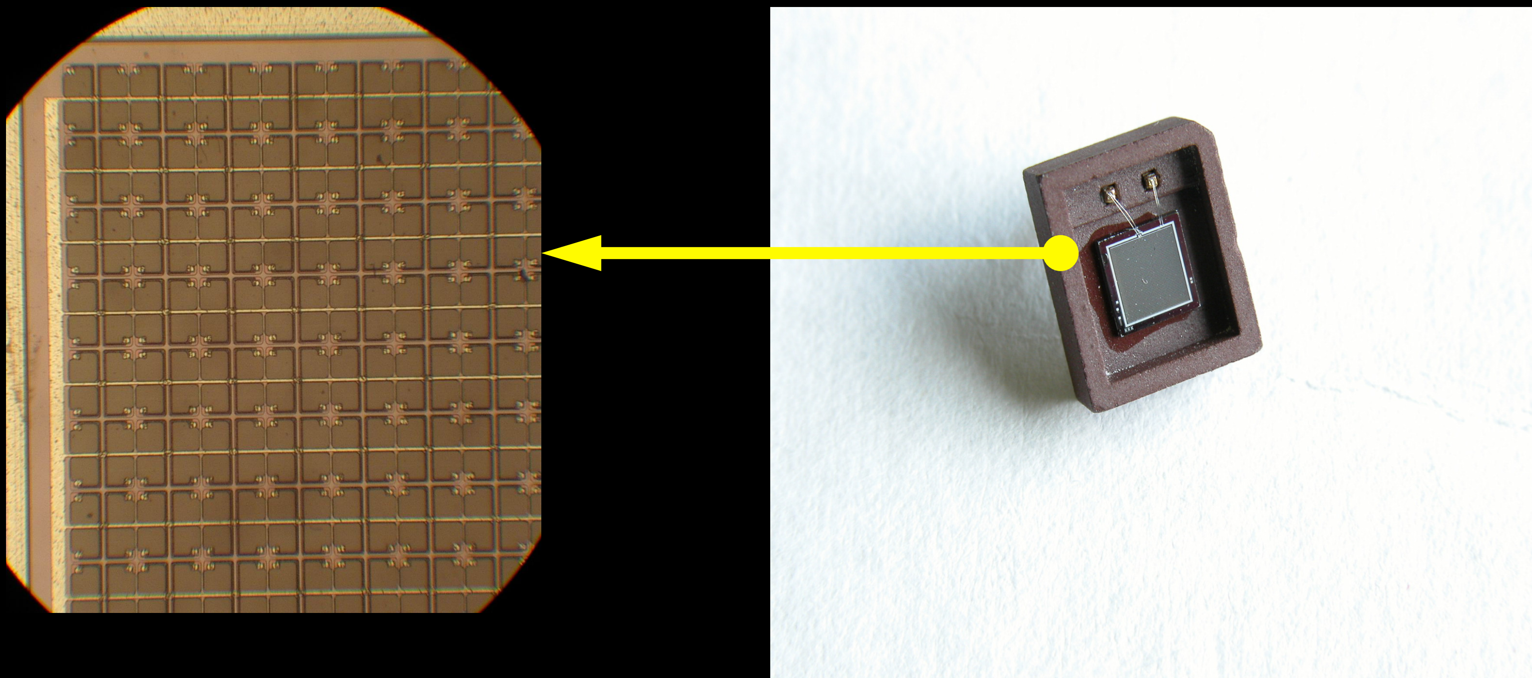
- Number of channels per feed line is currently limited to digital signal processing and ADC speed.
  FNAL has important expertise on microwave digital signal processing from low-level RF control for accelerators.
- MKID packaging is not mechanically or thermally viable for a large array.
  FNAL has large expertise in building cryogenic packages for focal plane detectors and dark matter detectors.
- MKID DAQ :2 TBytes/sec (100 parallel 20 GSPS 8 bit ADC).
  Data rates on the scale of a particle physics experiment. High throughput DAQ is part of our expertise.

Collaborators:
UCSB will continue working on the sensors (R) (B.Mazin
Argonne developing MKIDs for X-rays, we plan to benefit from the local collaboration (A.Miceli)
SOAR 4m telescope team interested in a sky test (S. Heathcote)

The involvement of FNAL will accelerate this development. It aligns very well with our scientific expertise, our technical skills and the national priorities in cosmology (LSST).

Technology 2: SiPMs

SiPM : no noise + 10psec timing

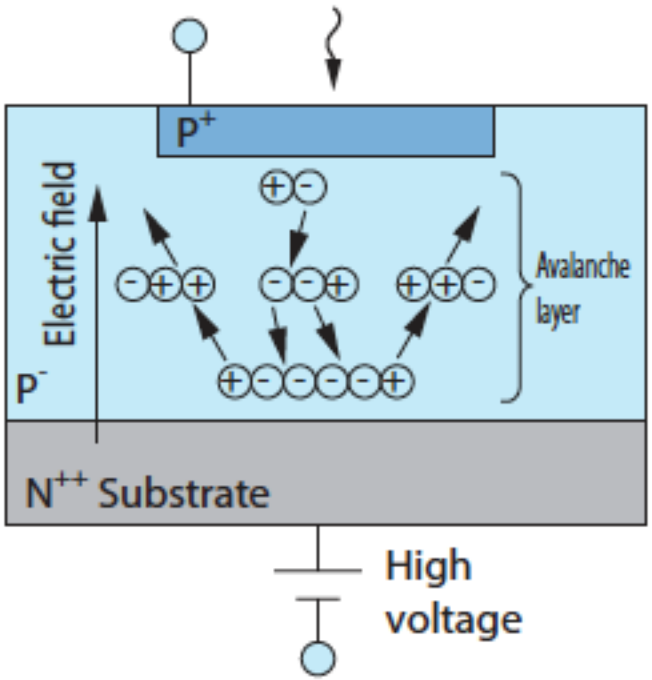


Single photon detectors with very high time resolution.

SiPMs are arrays of GM-APD. Each APD is about 25um x 25um and the are making arrays of 1mm x 1mm .

SiPM: array of Avalanche Photodiodes

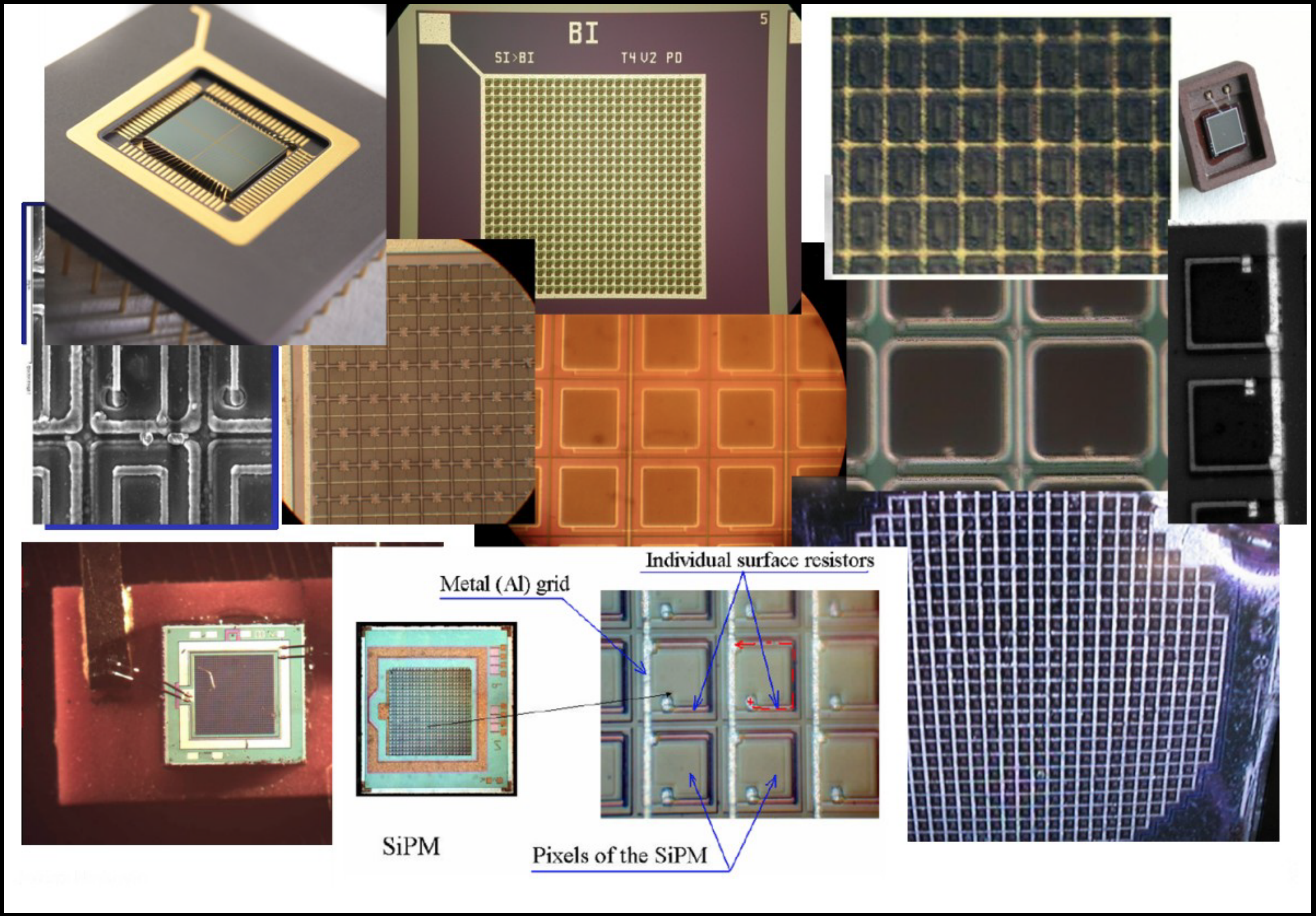
Operating principle example of APD



Generated carriers produce new electron-hole pairs while being accelerated by high electric field. Ionization

Newly generated carriers are also accelerated to produce further electron-hole pairs, and this process repeats itself. Avalanche multiplication

Gain proportional to the applied reverse bias voltage can be obtained.



Many companies are now making this. They are not thinking in astronomy yet...

SiPMs for astronomy

Step 1: using commercial technology we are planning build an array of 1000 SiPM 1mm x 1mm pixels. Cryogenic package (cooling of sensors with electronics outside cryostat) and show that this can be used for imaging

> measure imaging capabilities
> timing performance for atmospheric corrections
> Fourier spectroscopy?

We hope this will start in 2013.

SiPMs for astronomy

Step 2:

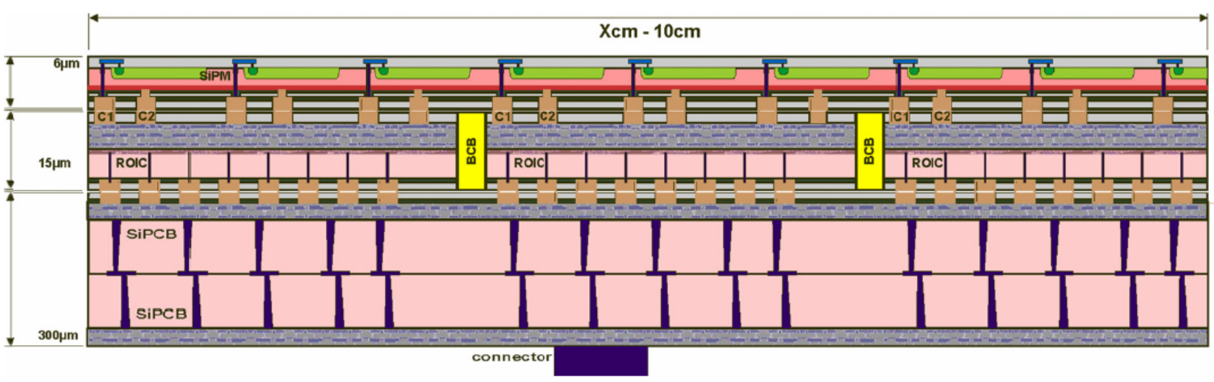


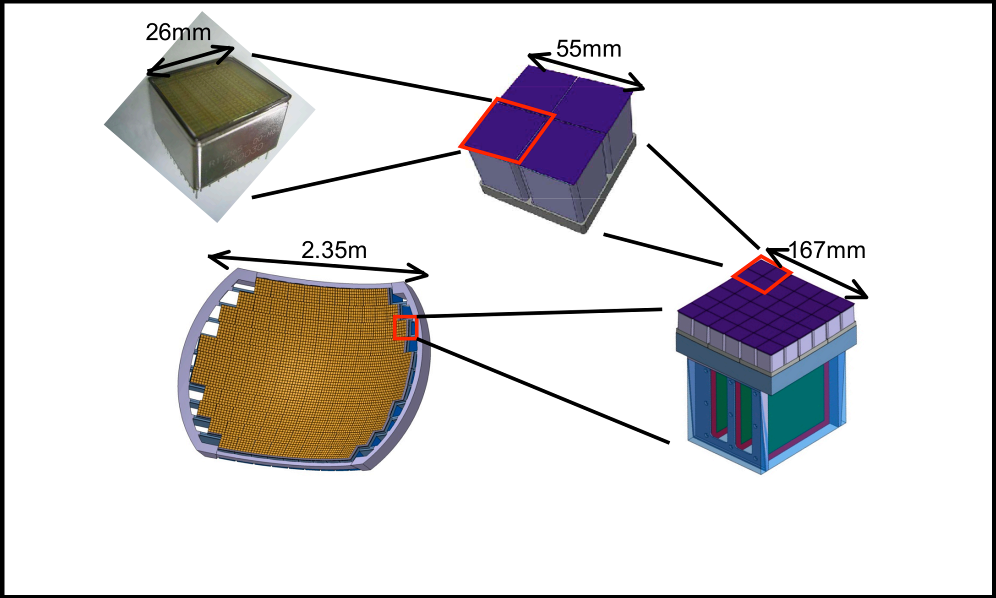
Figure 16. Final implementation of a 3DDigSiPM – large area device exploiting the SiPCB technology.

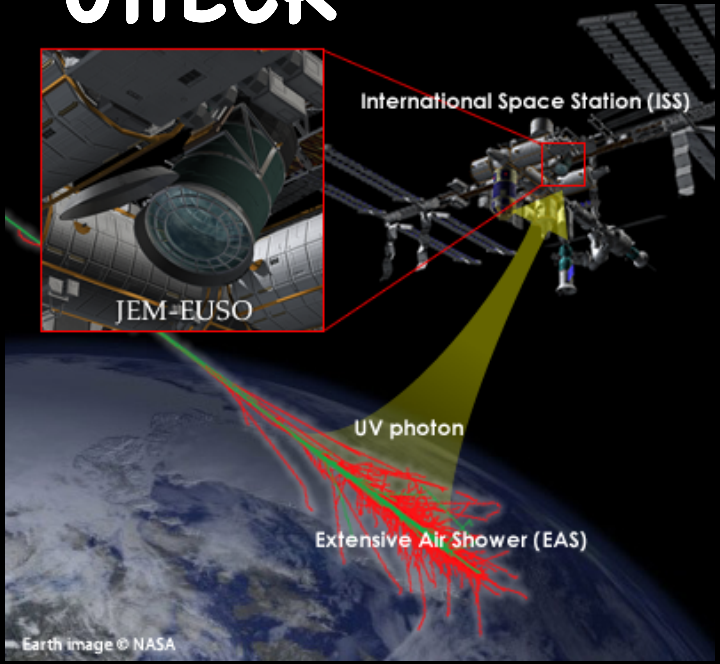
[EC Proposa by G. Deptuch]

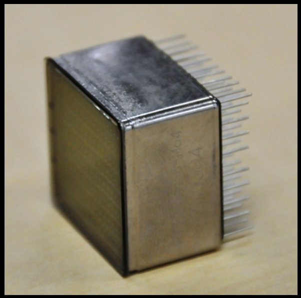
3D asic design: integrate the electronics with the SiPM and get access to each APD independently. FNAL recently submitted a proposal to DOE for the development of this fully digital imager.

Phillips is doing something that is getting close. It has integrated digital summing electronics to their SiPMs, but for the moment is still summing because that it what sells in the medical industry.

Synergy with UHECR







This could also be a solution for the JEM-EUSO focal plane, replacing MultiAnode-PMTs. Other groups are already considering focal planes for gamma-ray telescopes with SiPMs.

Conclusion

- If you are working on technology innovations to enable your DE science, please get in contact with us (gaston@fnal.gov, estrada@fnal.gov) to be included in the instrumentation document.

- Keep an eye on MKIDs as a tool for wide field low resolution spectroscopy.
- Keep an eye on SiPMs as a new detector for astronomical imaging pushing opening a new window for high time resolution.

“New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained”

Freeman Dyson

thanks