HTRA Instrumentation I

Phil Charles (Univ. of Southampton)

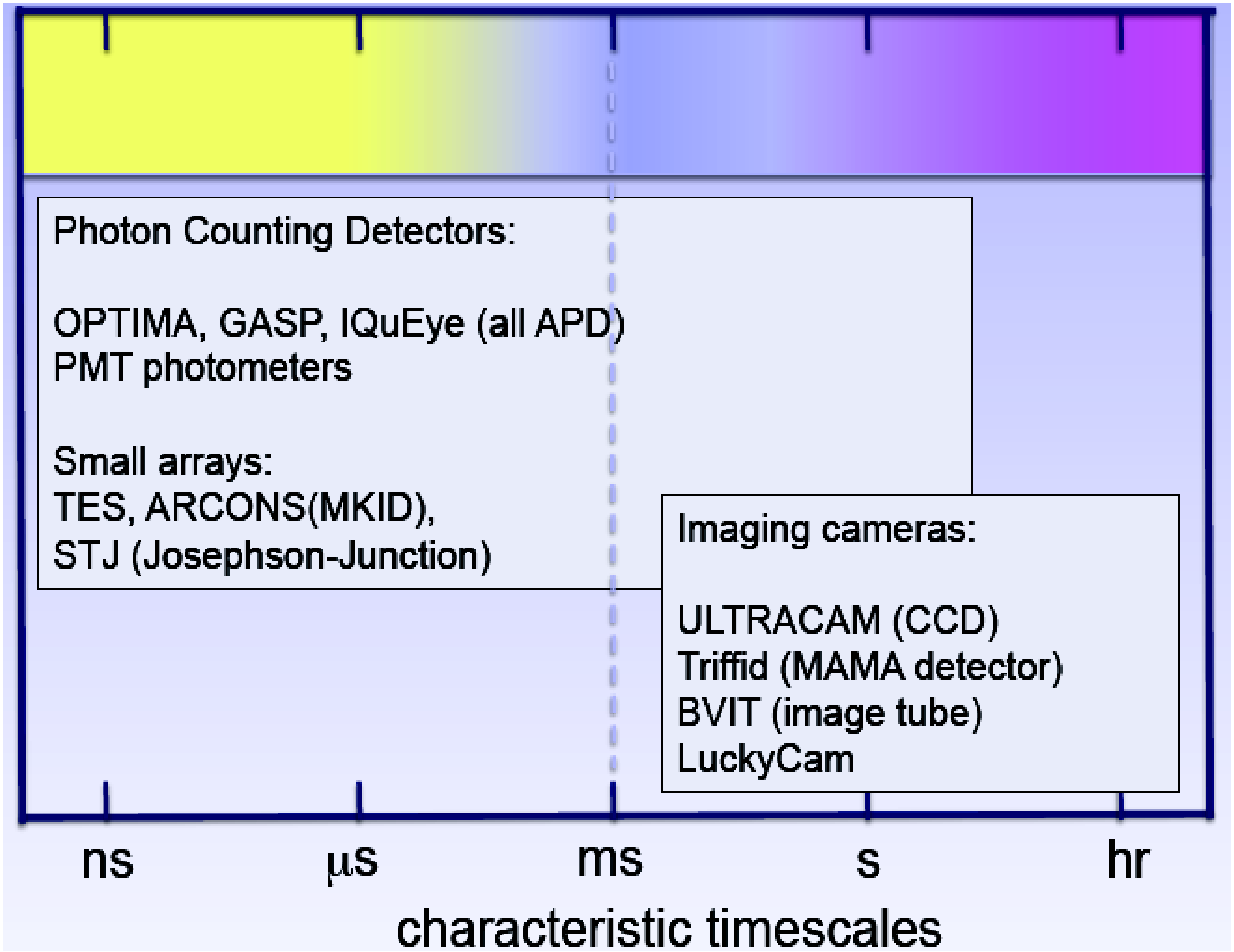
Lecture 3: HTRA future developments/new technologies

X-rays:
- AXTAR, LOFT
- XEUS/Athena
- Lobster concept

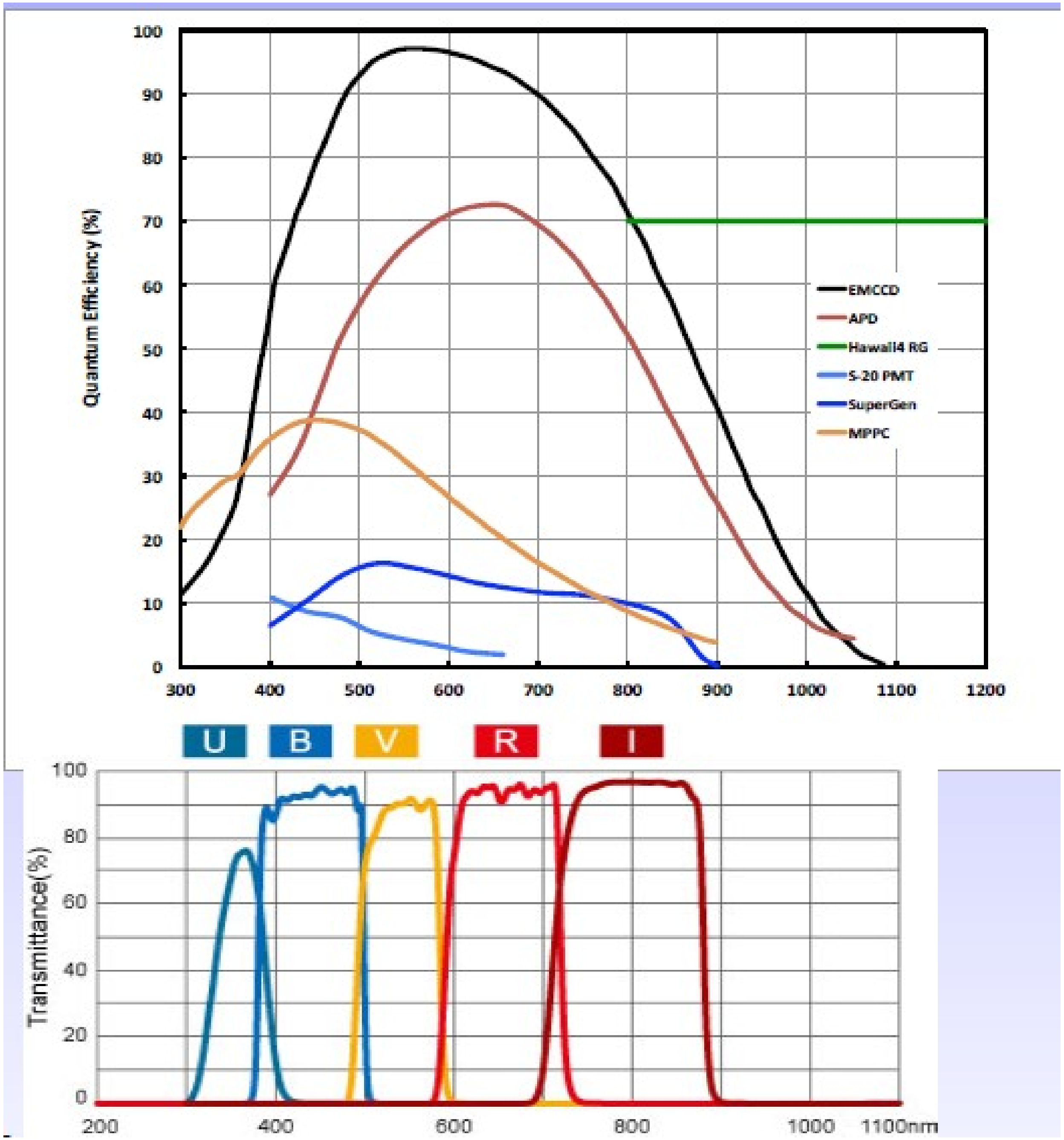
Visible/IR:
- MKIDS, STJs

Ultra-fast detectors

Techniques and instruments:

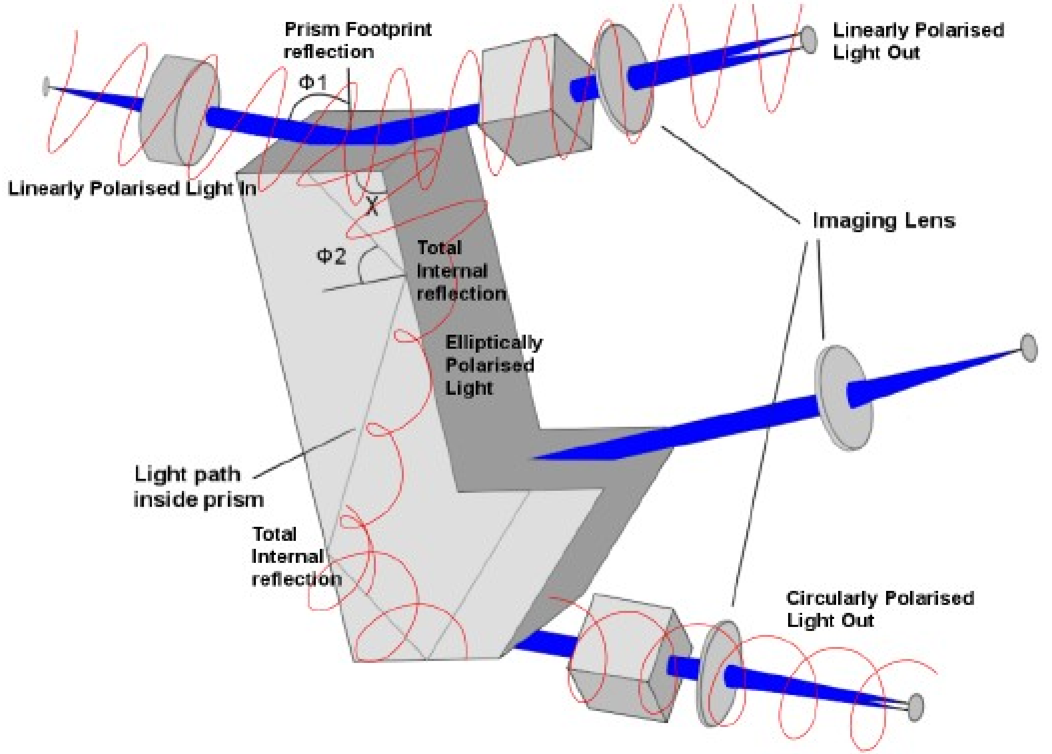


Kanbach 2014



Kanbach 2014

GASP – Galway Astronomical Stokes Polarimeter

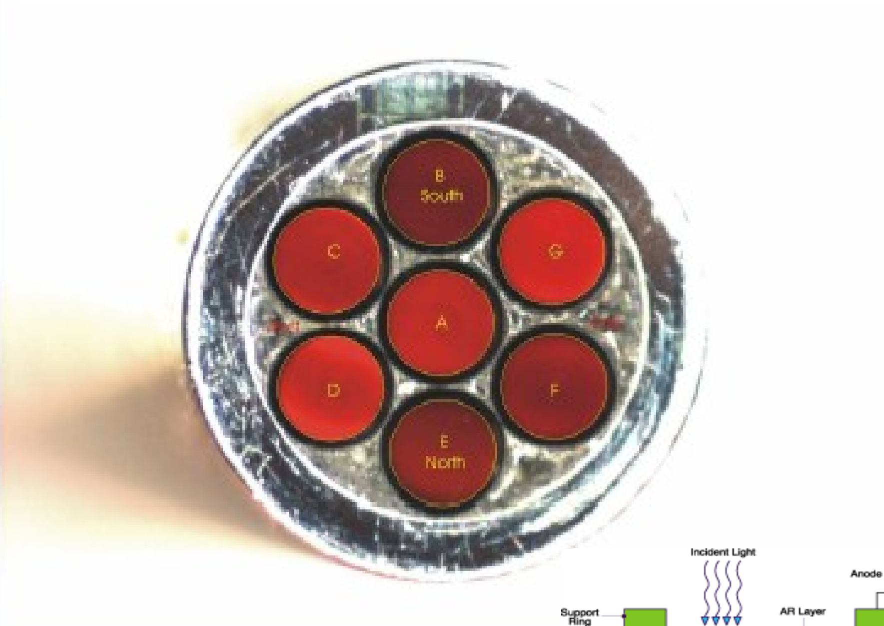


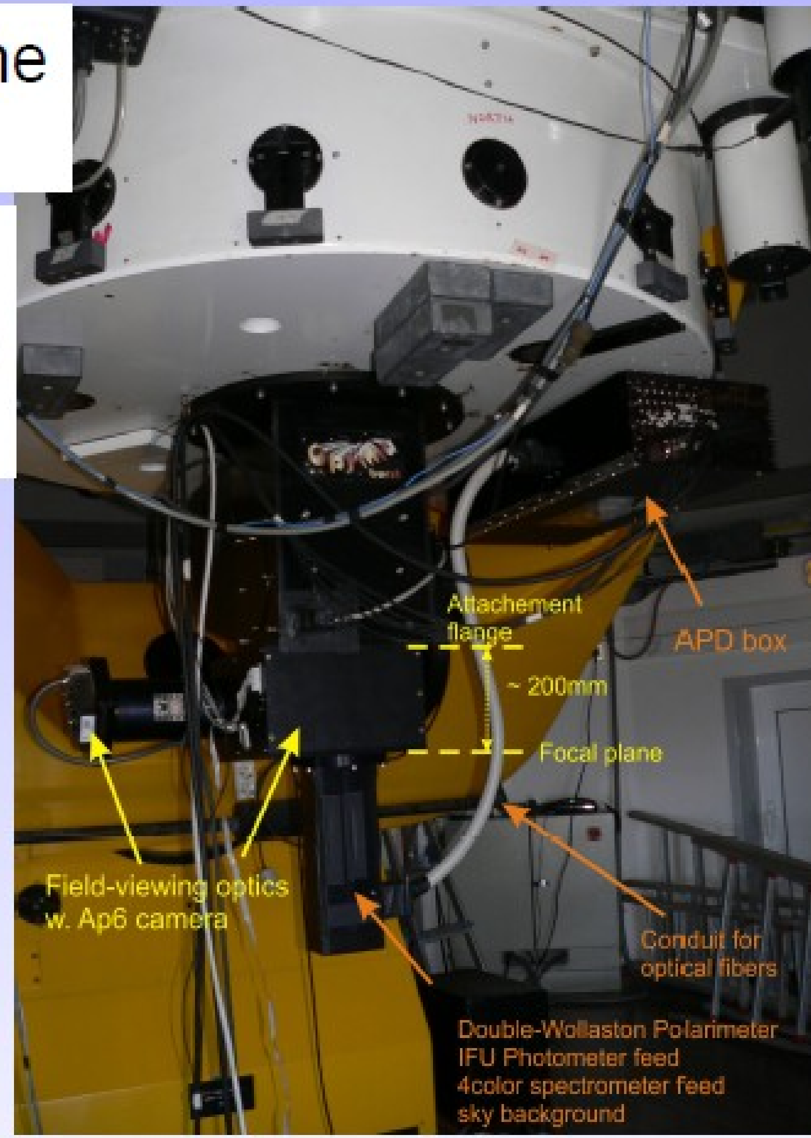
See Shearer, Sheehan papers on its operation with L3CCDs and APDs (for highest time resolution pulsar work)

Kanbach's OPTIMA photon-counting system

OPTIMA at the SKO 1.3m

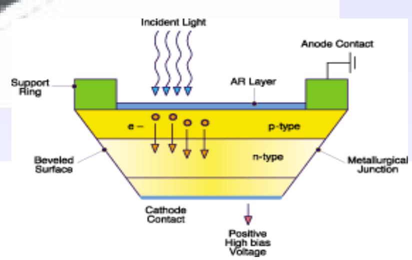
Small array of fibre apertures (dia. 300 μm each) connected to APD photon counters





1
2
3

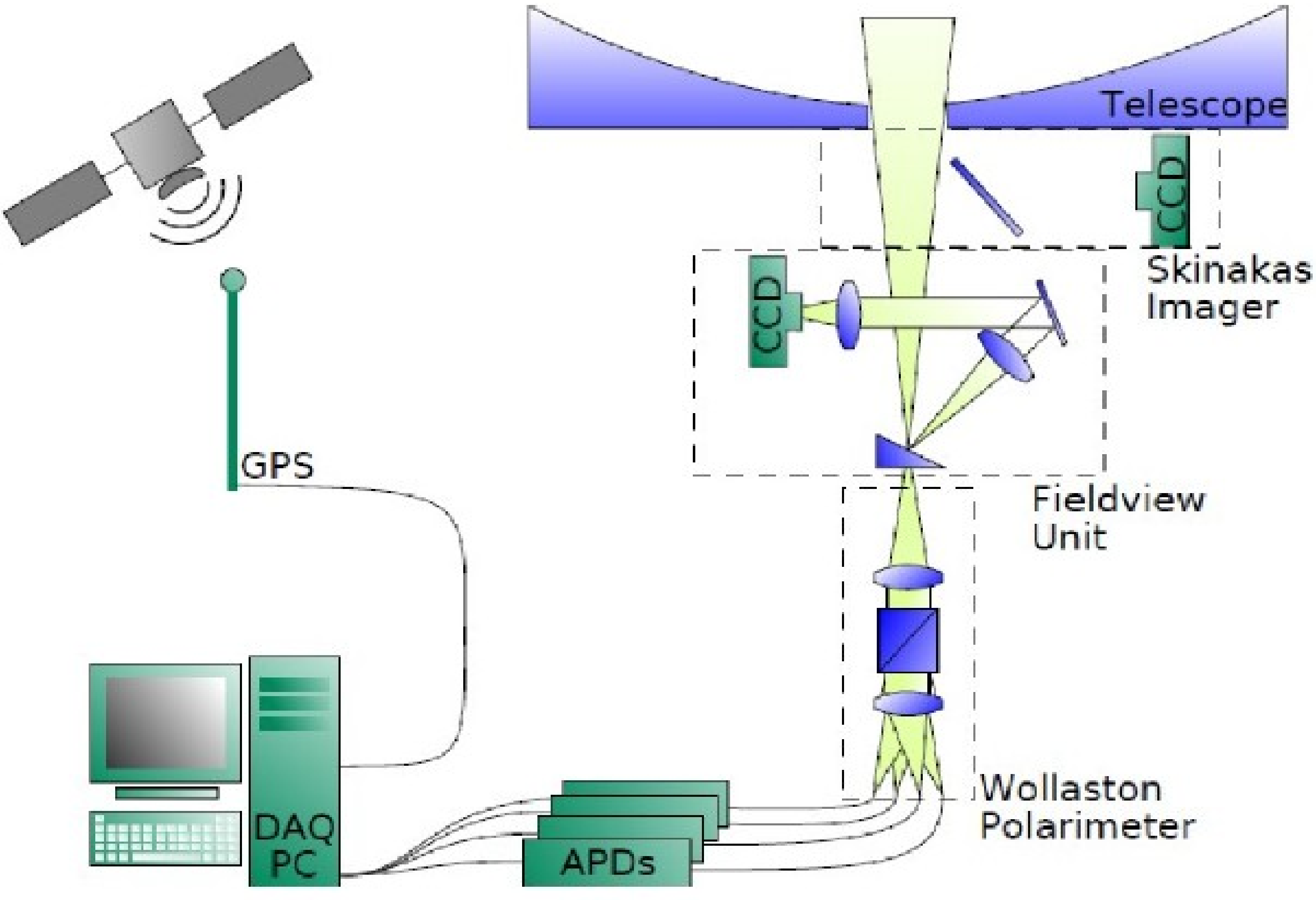
Large reverse bias (~2kV)
→ avalanche amplification
of photoelectrons



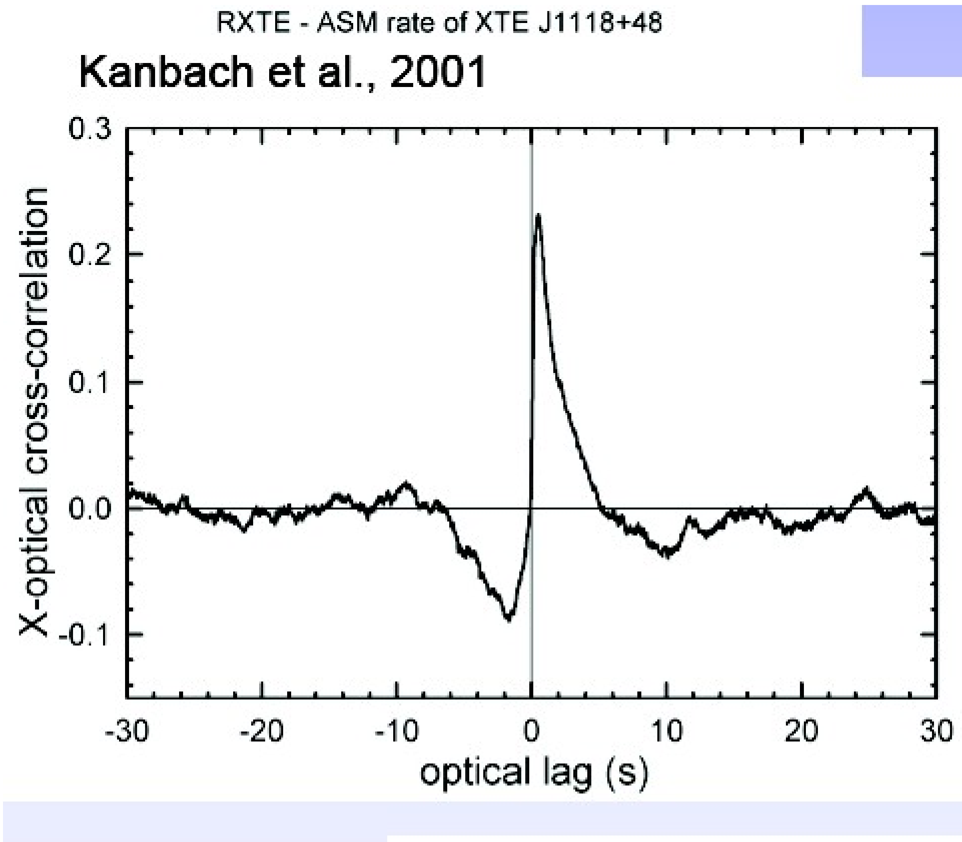
Row 1 Row 3 Row 4

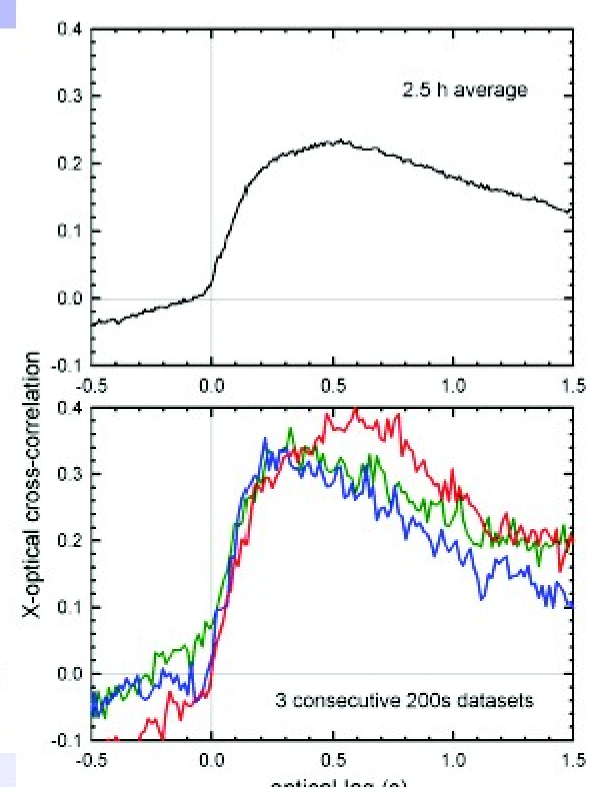
see http://www.mpe.mpg.de/OPTIMA

OPTIMA schematic:



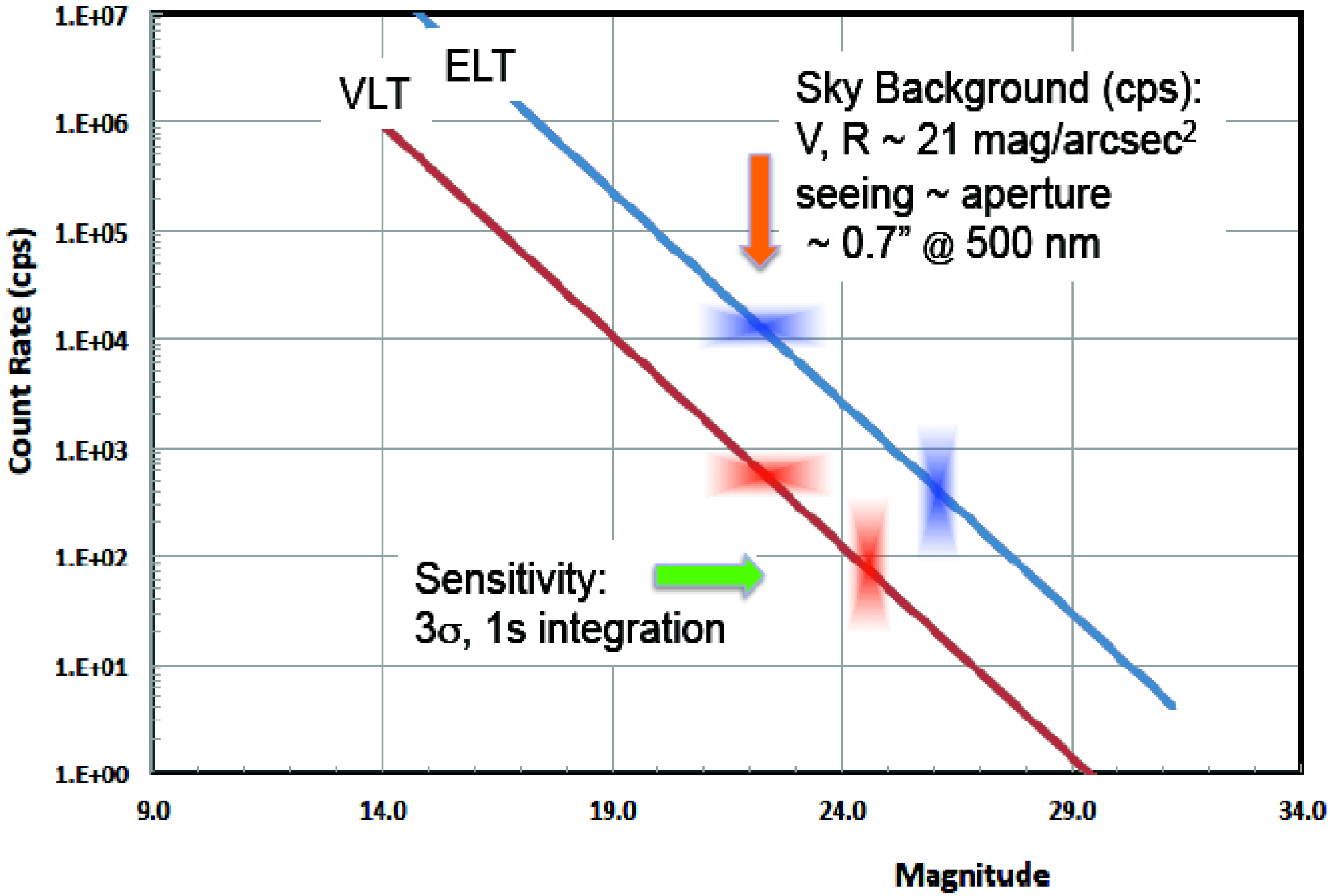
Jets/outflows in LMXB BHXRBs (OPTIMA)

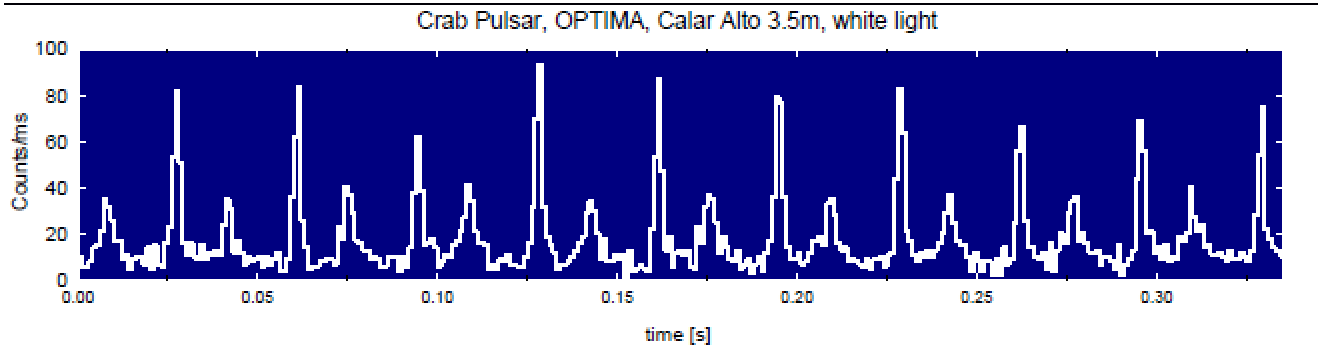




- Note optical precedes X-ray
- No X-ray reprocessing, but genuine jet emission
- Optical response within 30ms

Scale OPTIMA rates to VLT (8m; f/13.4) and e-ELT (39m; f/17/5)

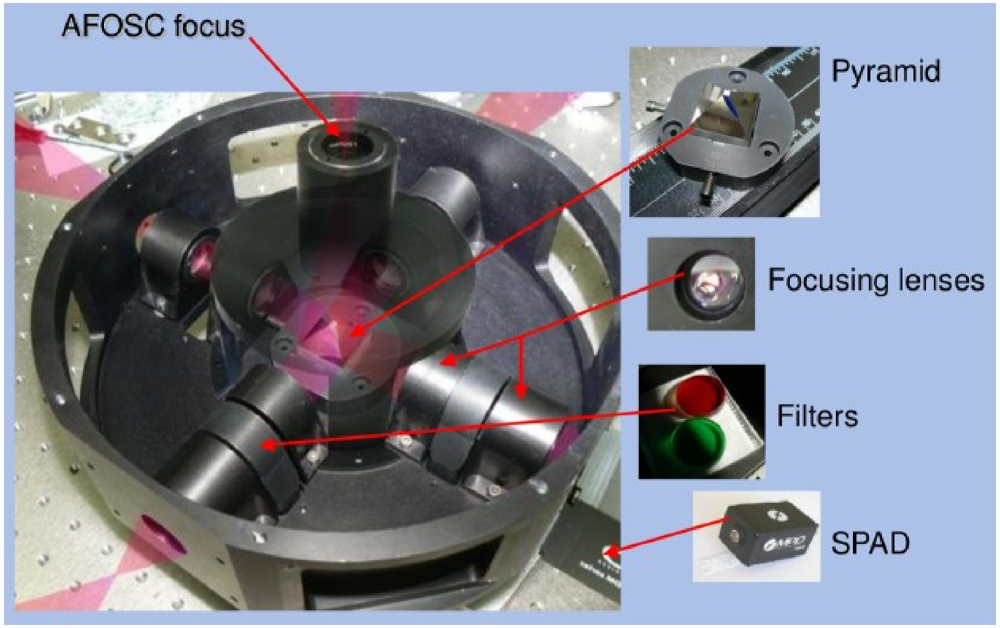


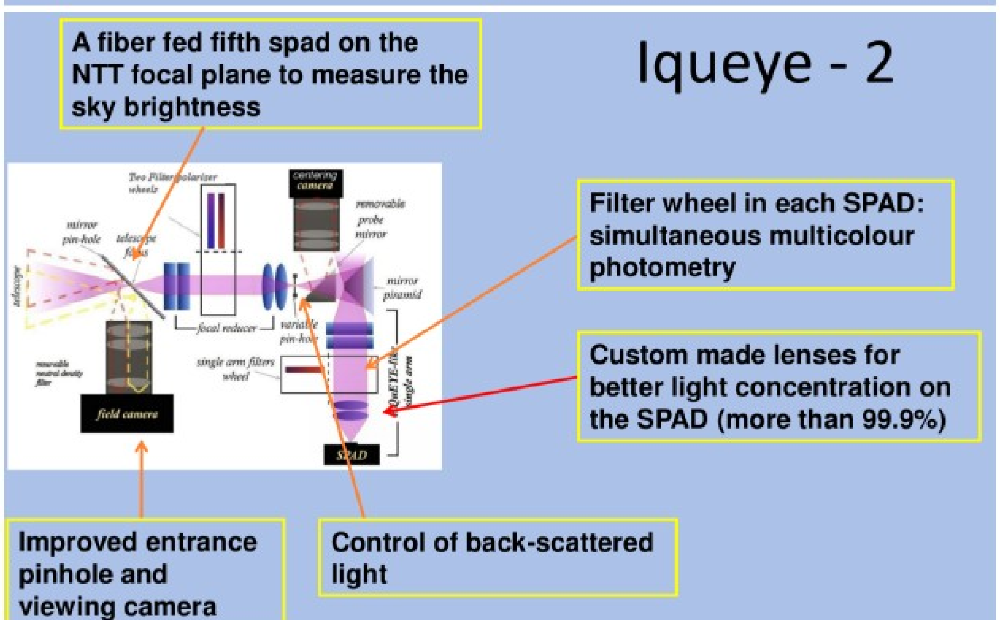


		Time-Scale Now	Time Scale ELT era
Stellar flares and pulsations		Seconds/ minutes	10-100ms
Stellar Surface Oscillations	White Dwarfs Neutron Stars	1-1000 μs -	1-1000 μs 0.1 μs
Close Binary Systems accretion & turbulence	Tomography Eclipse in/egress Disk flickering Correlations (e.g. X & optical)	100ms++ 10ms+ 10ms 50ms	10ms+ < 1ms < 1ms < 1ms
Pulsars	Magnetospheric Thermal	1 μs- 100ms	ns ms
AGN		Minutes	Seconds

Shearer 2010: HTRA White Paper: science timescales

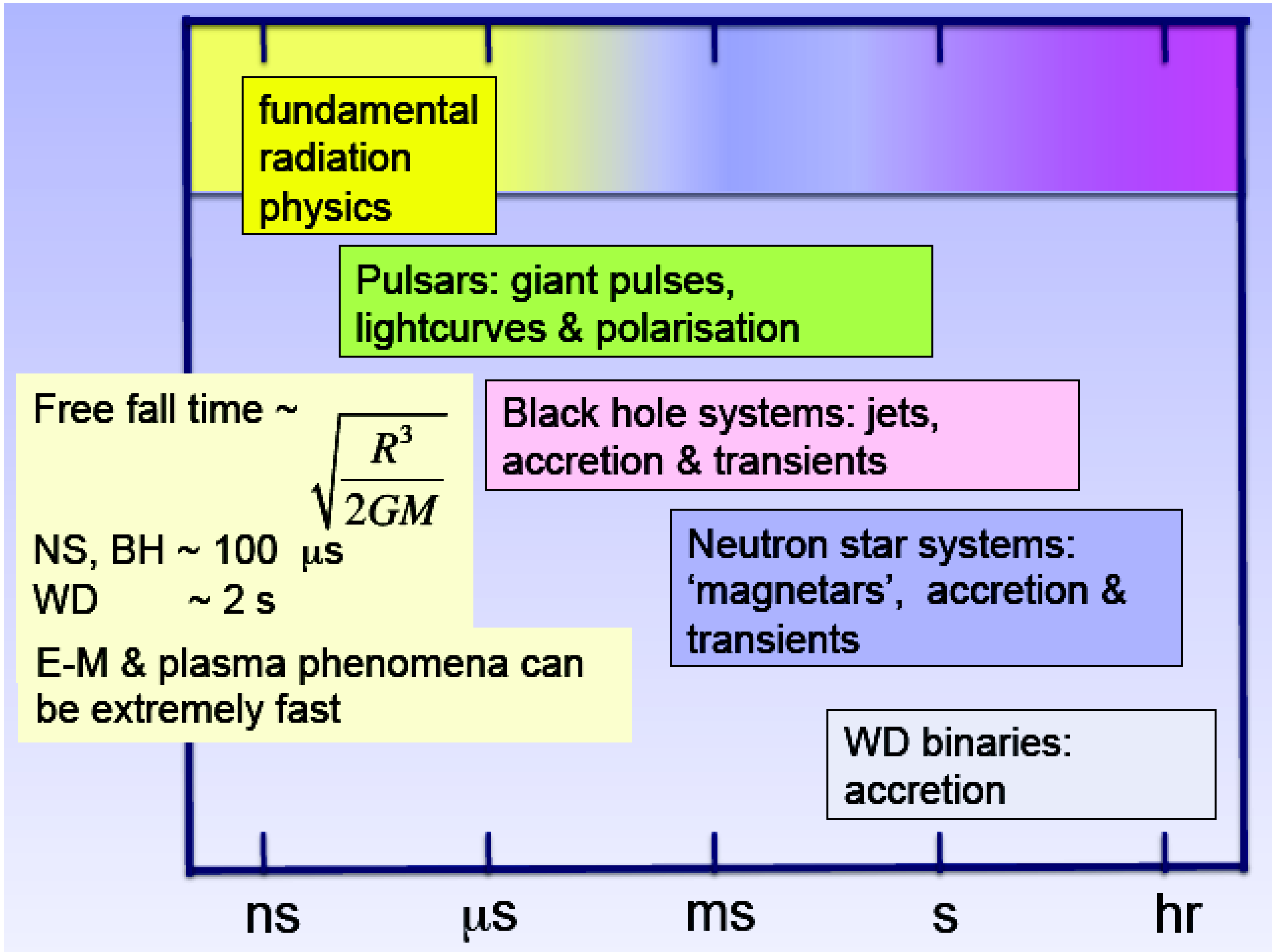
AQuEYE and IQuEYE





Barbieri (Padova)

Pushing to the shortest timescales:



Photons per Rotation for known optical pulsars

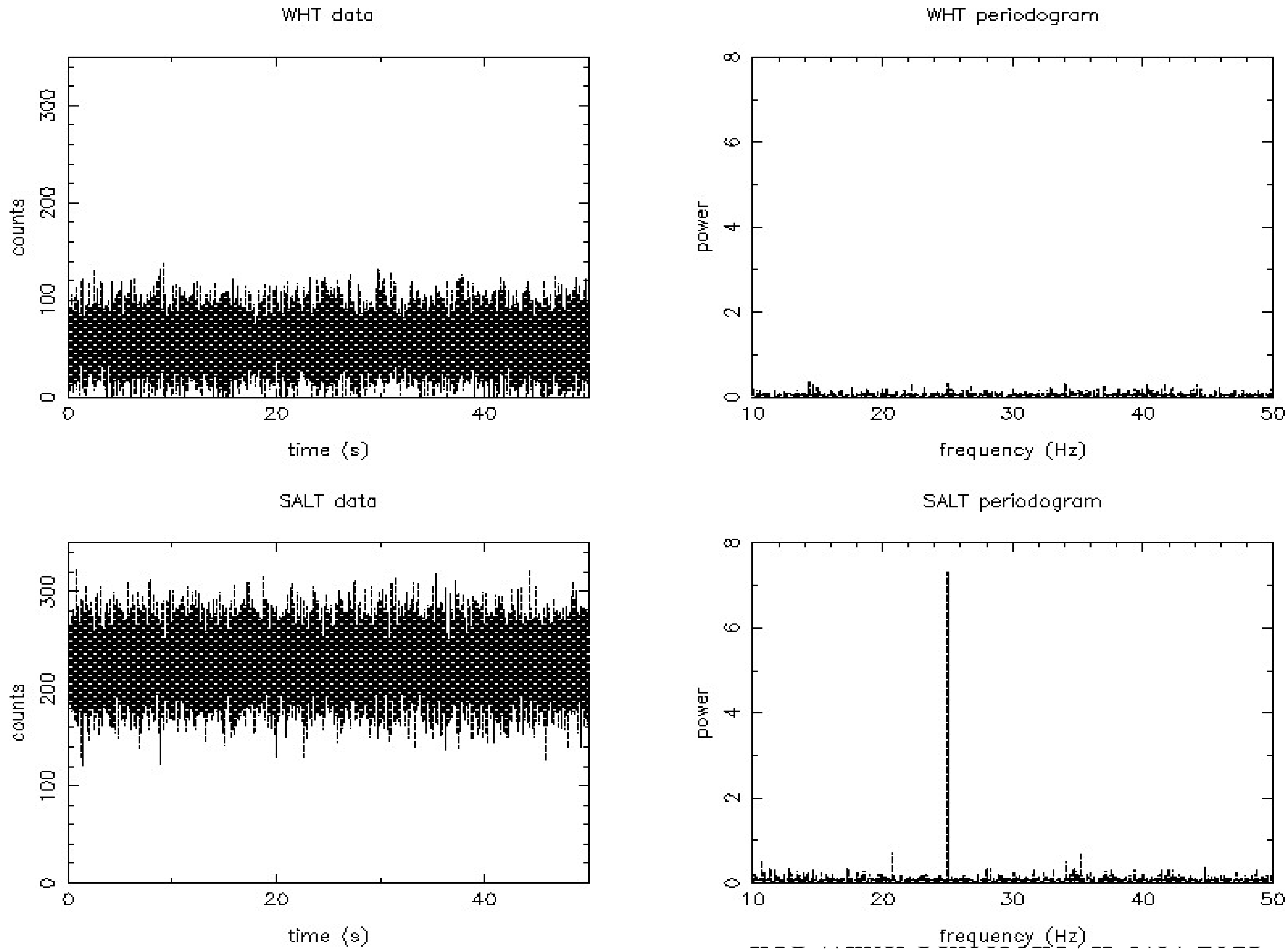
(updating Shearer, 2009)

Pulsar	Period (ms)	Mag (B,V)	VLT	ELT	
Crab	33	16.5	3000	63000	cts/rot
PSR0540-69	50	23	13	300	cts/rot
Vela	89	24	10	200	cts/rot
PSR0656+14	385	25.5	11	230	cts/rot
Geminga	237	26	4	90	cts/rot
Crab in M31		29.6	1	15	cts/s

Typical sky background m_{Sky} ~ 21 / □"

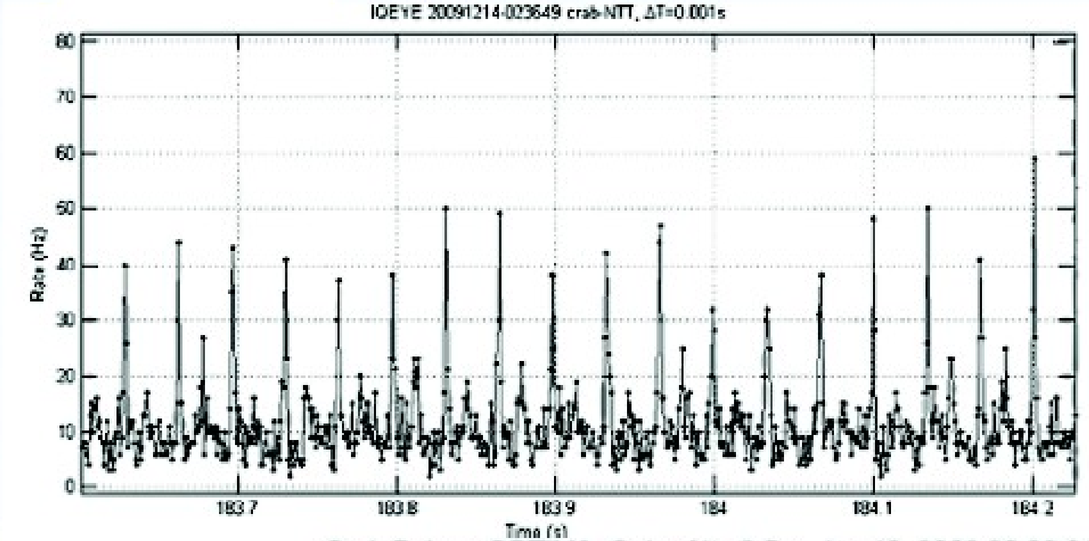
	VLT	ELT	
in aperture ≈ seeing (0.7")	600	15000	cts/s
small aperture (0.3")	120	2400	cts/s

N.B. note difference of *detecting* pulsations versus *resolving* them



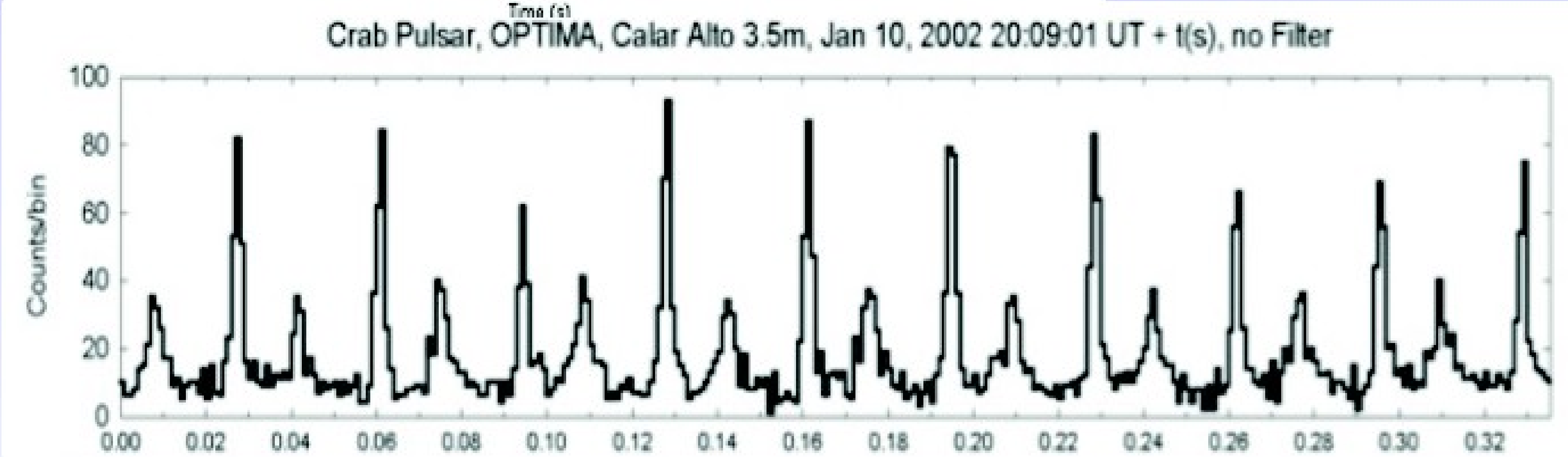
Crab single rotations with current telescopes

1ms binning



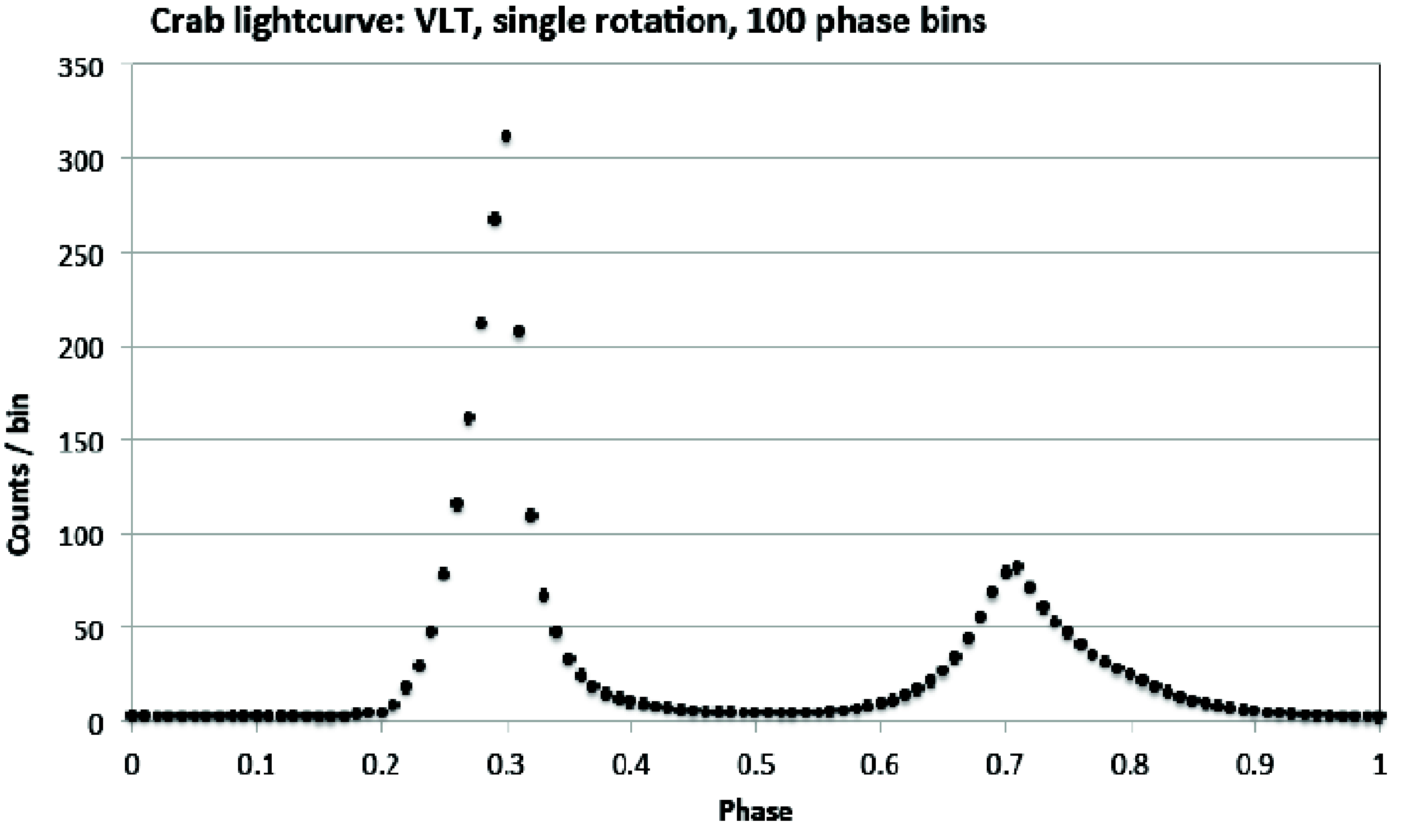
IquEYE @ 3.6m NTT
(Barbieri et al., 2012)

OPTIMA @ 3.5m CAHA
(Kanbach et al., 2008)

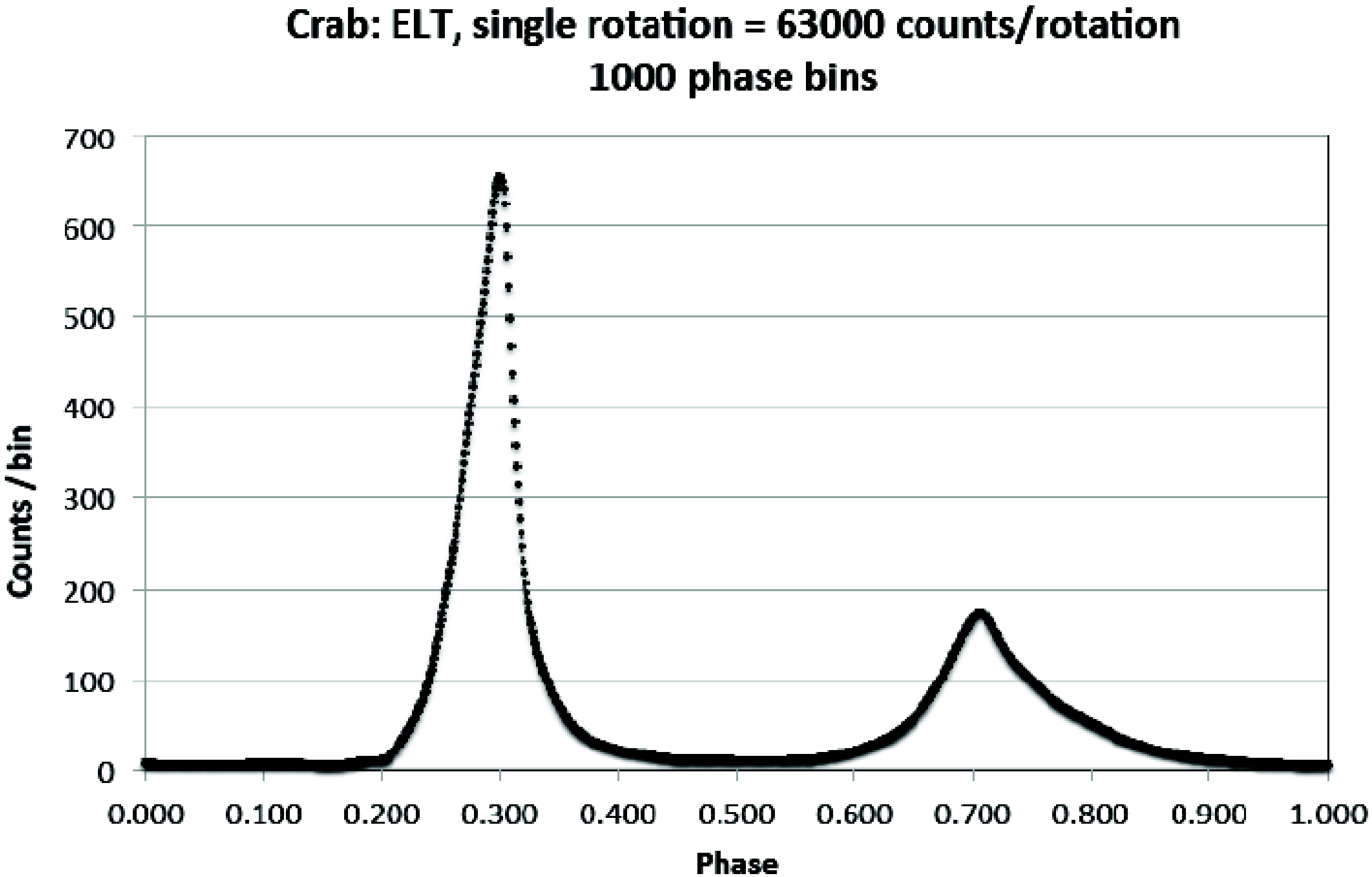


... the Crab with a 8m or 39m telescope?

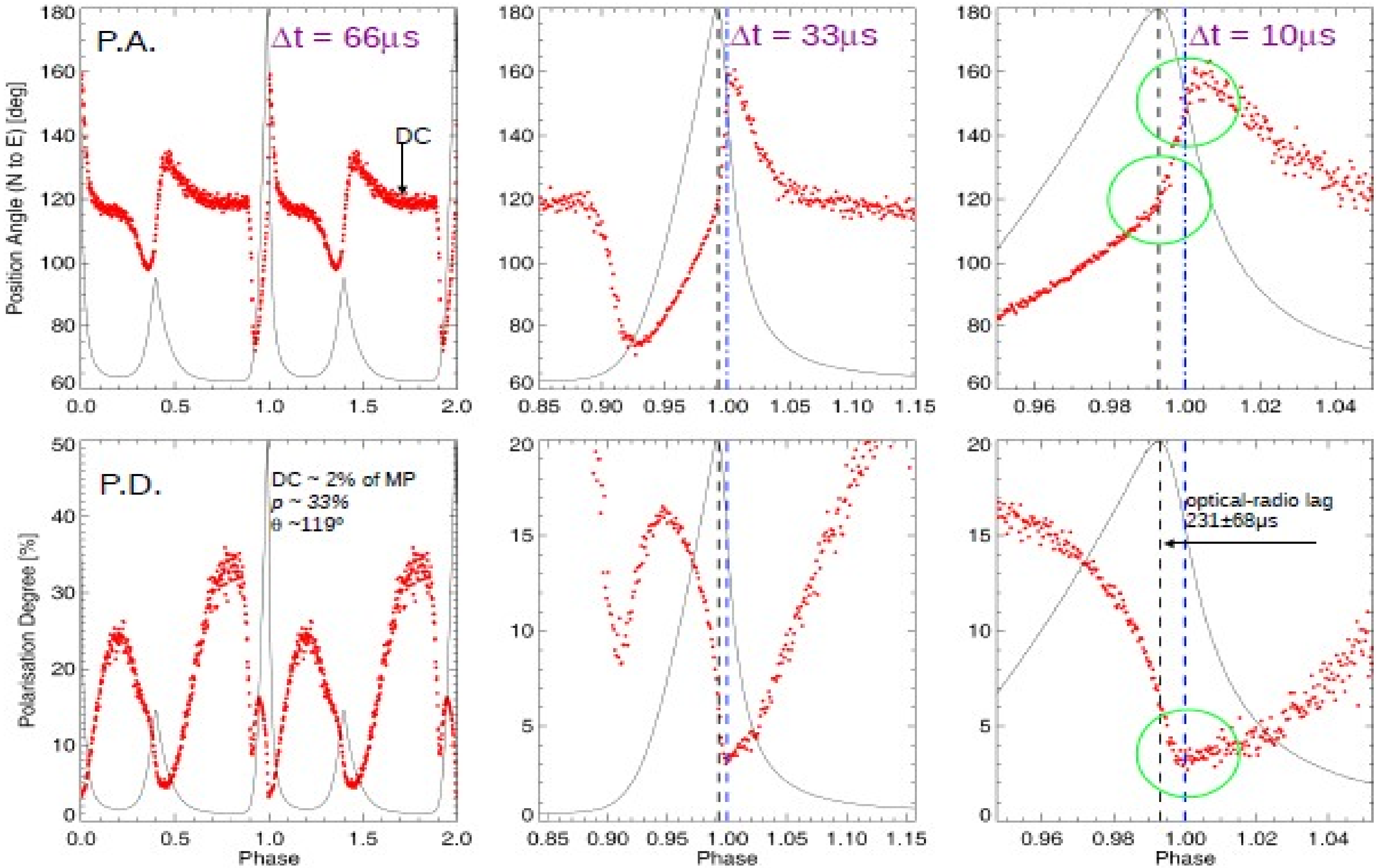
Synthetic light-curve at 300μs resolution (Zampieri+14)



And at 30μs resolution (Kanbach 2014)

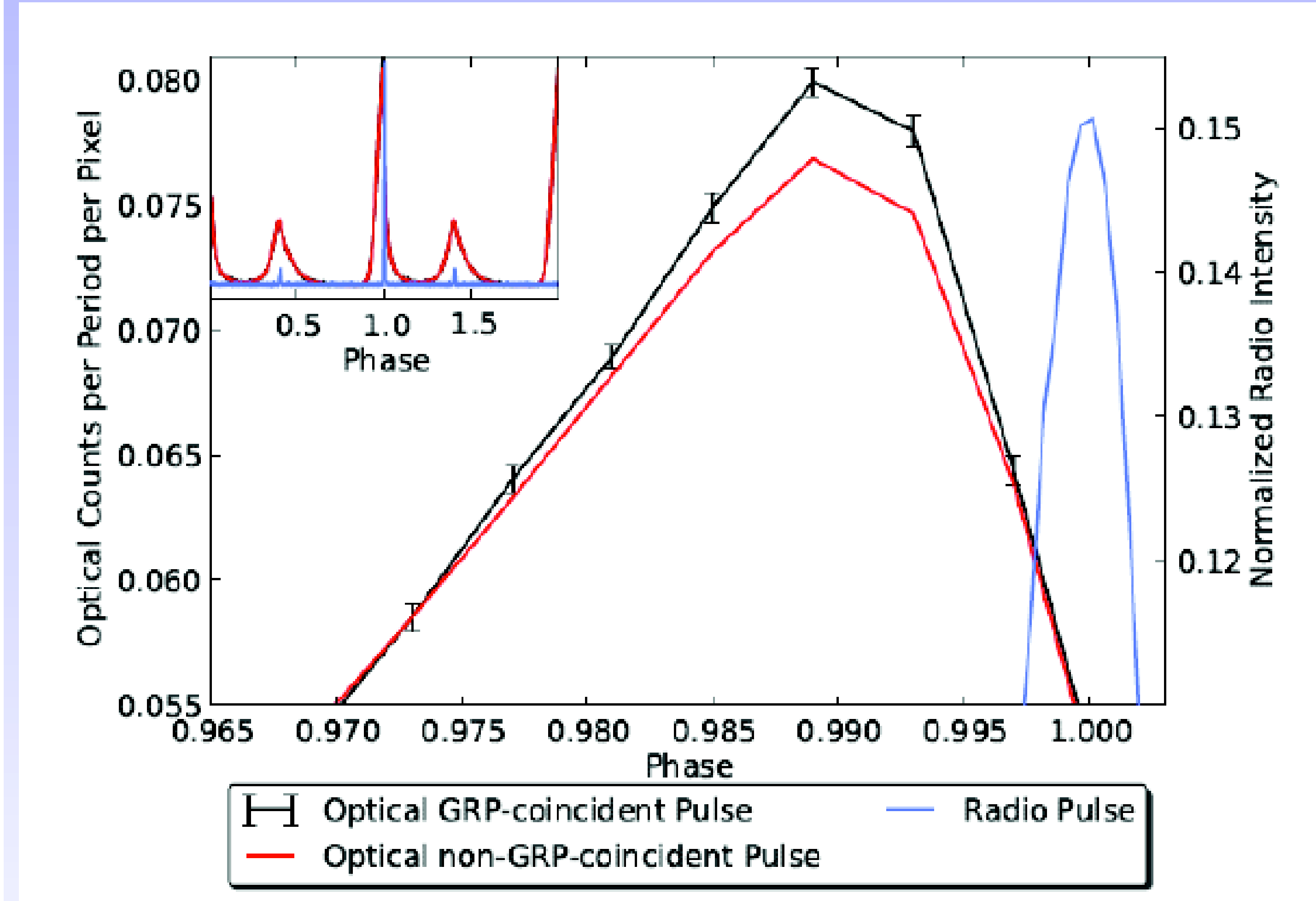


Optical polarisation from rotation to rotation
(Słowikowska+09; NOT 14h run)



Optical response to Giant Radio Pulses:

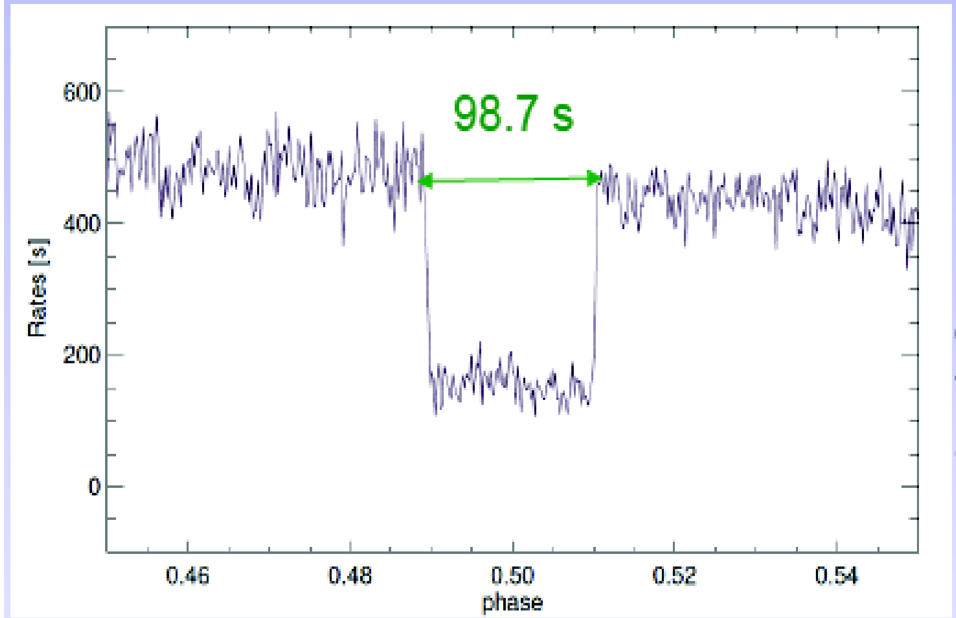
Strader et al., 2013 (ARCONS on 200" Hale Telescope) based on 7200 GRPs



Confirmation of Shearer+03; Collins+12

See Słowikowska+09

Binary eclipse measurements:



Example:
OPTIMA lightcurve (averaged)
RXS J1845+4831 (mag 18-19): New polar

extremely short orbital period of 79m 04s and eclipse duration of 98.7s (Rau et al., 2014 in prep.)

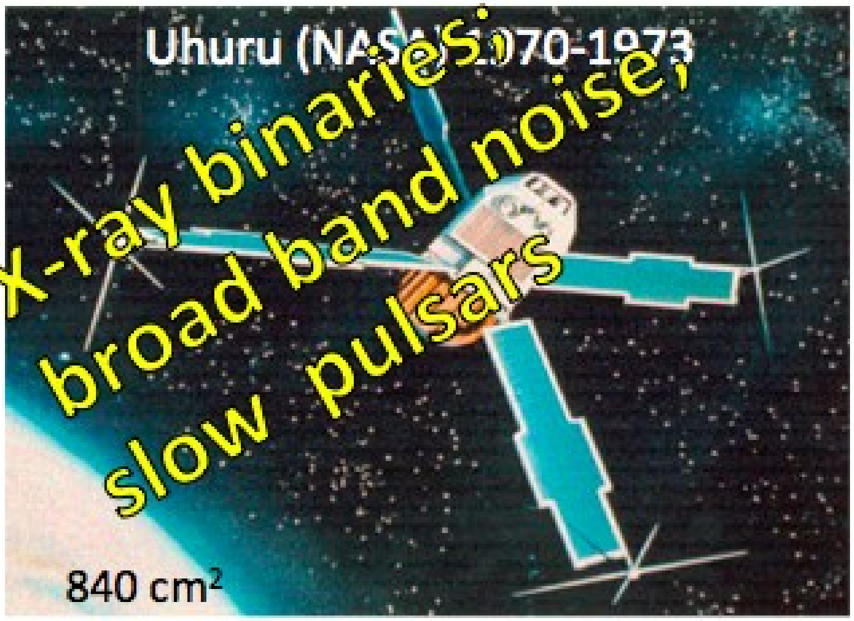
Goals:

with VLT/ELT (10^4 / $2x10^5$ cps):

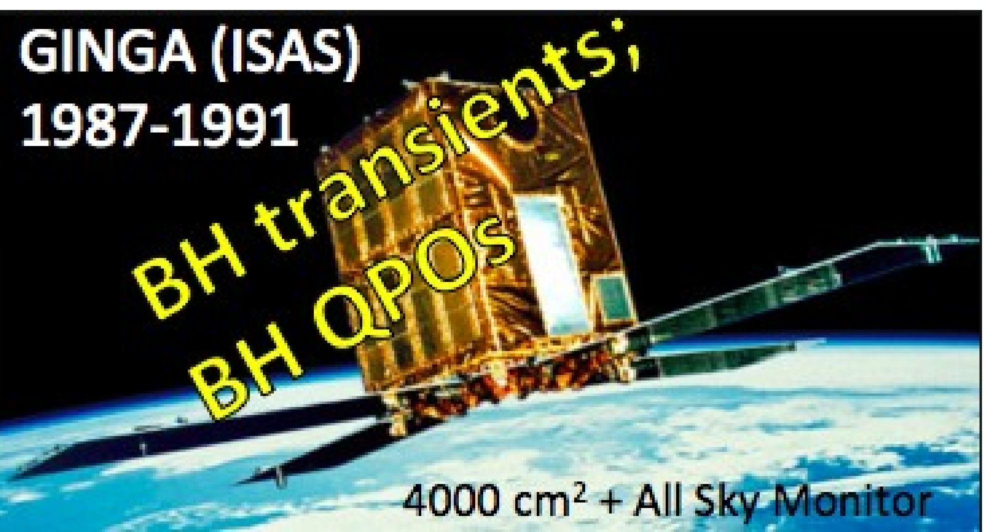
- several ms resolution
- spectroscopic / polarimetric resolution of ingress/egress

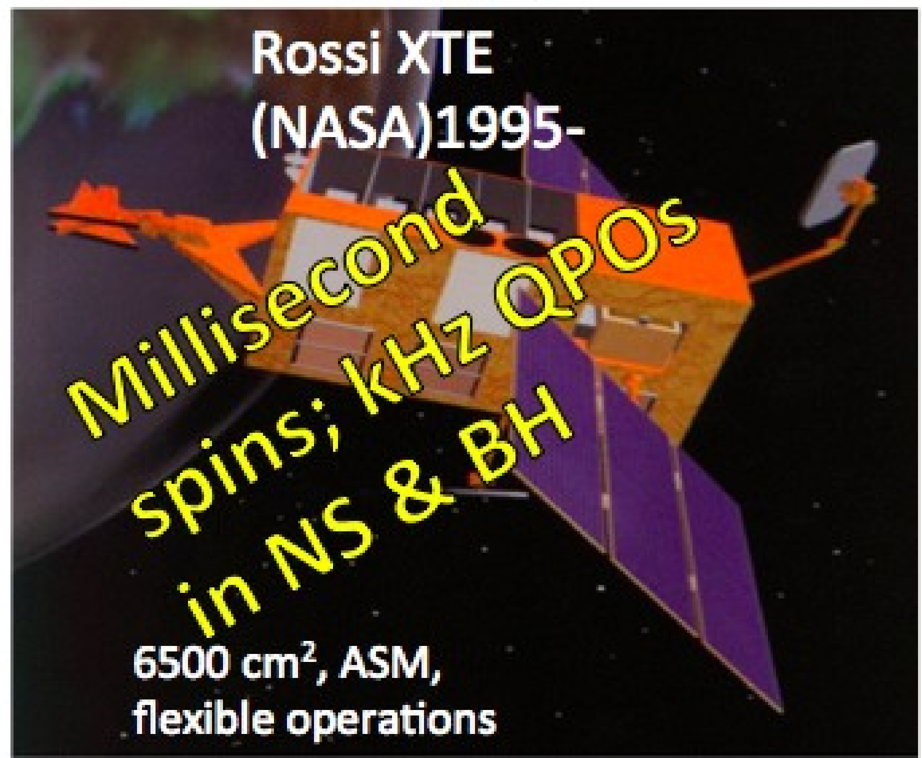
Kanbach 2014

X-ray developments


Uhuru (NASA) 1970-1973
X-ray binaries;
broad band noise;
slow pulsars
840 cm^2


EXOSAT (ESA)
1983-1986
NS QPOs
1600 cm^2
pointing


GINGA (ISAS)
1987-1991
BH transients;
BH QPOs
4000 cm^2 + All Sky Monitor


Rossi XTE
(NASA)1995-
Millisecond
spins; kHz QPOs
in NS & BH
6500 cm^2, ASM,
flexible operations

LOFT payload (Zane+13, MSSL, Leicester)

Large area detector (LAD):

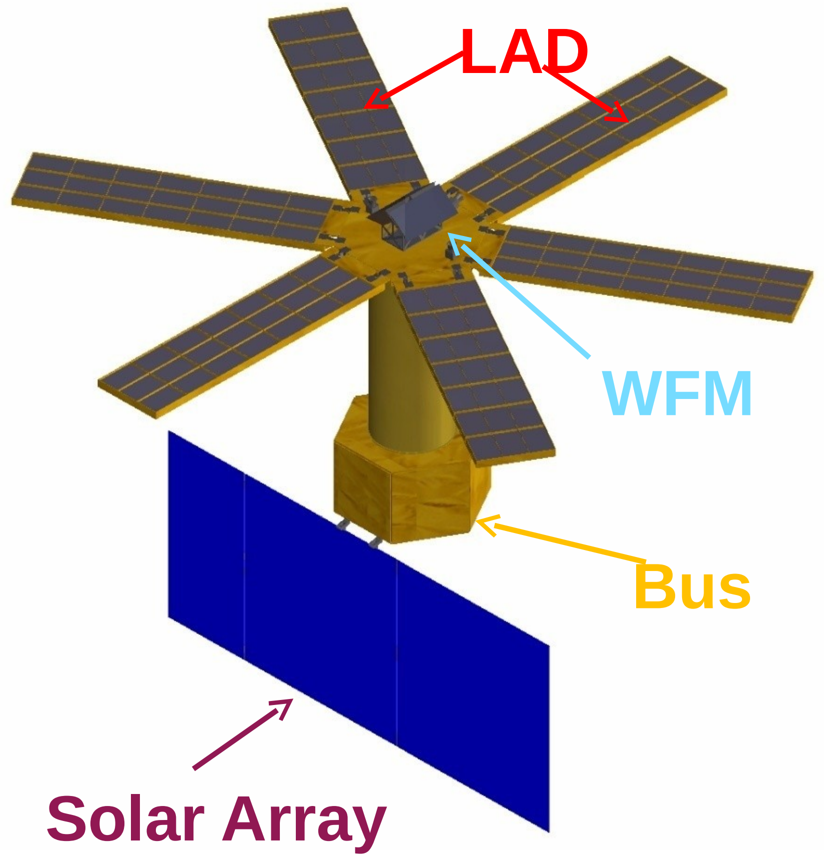
- 6 deployable panels
- $10 m^2$ collimated area,
- 2-30 keV, SSD+MCP,

- time res 10μs,
- ΔE ~ 260 eV @6keV

Wide field Monitor (WFM):

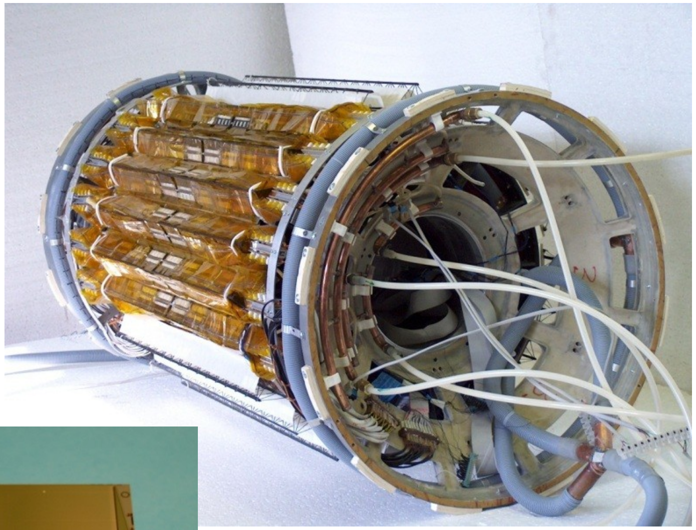
- coded mask detector
- 2-50 keV, 50% sky
- source localization 1'

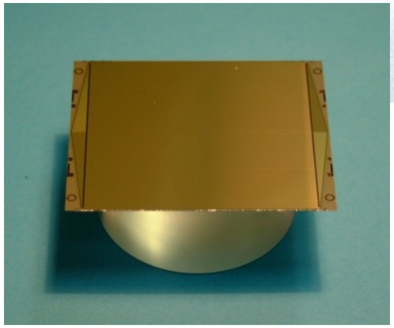
- identify bright transients



Large Area of Silicon Drift Detectors heritage of the Inner Tracking System of the ALICE experiment at LHC (CERN)

INFN Trieste → 1.5 m² of SDDs at LHC (~300 units), operating since 2011.





Thickness	450 µm
Monolithic Active Area	76 cm²
Low power requirement	(~60 W/m2)
Spectral resolution	260 eV FWHM
Drift time	<5 µs
Single-channel area	0.3 cm²

LAD has a mass per unit area ~30kg/m2

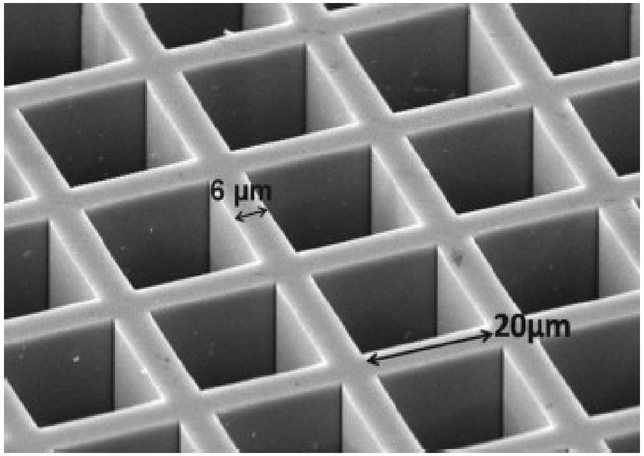
(the largest predecessor, RXTE/PCA, has >100kg/m2)

LAD Collimator

Built at Leicester SRC basing on Heritage BC MIXS-C

Capillary plate, High Pb content glass

MCP covered with Al filter



LOFT Large Area Detector

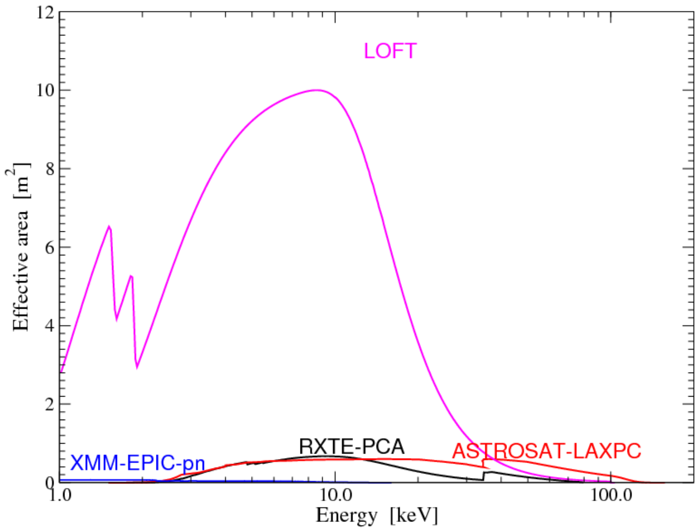
- Effective area 10 m^2 @ 8 keV
  - 0.25 10^6 c/s/Crab
  - 1σ timing feature becomes 20σ

    → detect QPOs in the time domain !

- 200-260 eV resolution
  - resolve relativistic Fe lines at huge S/N

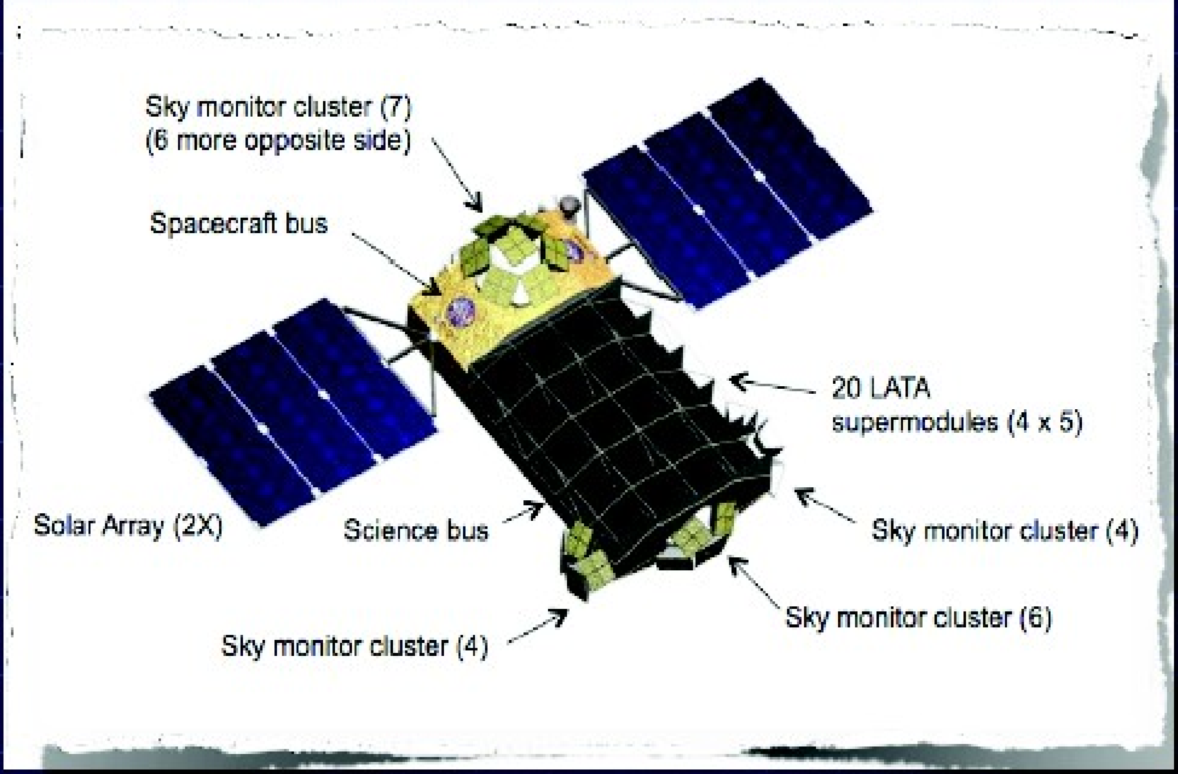
    → see line profile fluctuate at GR timescales !

  - See all [sub] msec spins
  - Routine neutron star seismology
  - Measure pulse profiles at enormous precision



AXTAR Basics

Collimated 1.8–80 keV X-ray timing and spectral mission with much larger area than RXTE

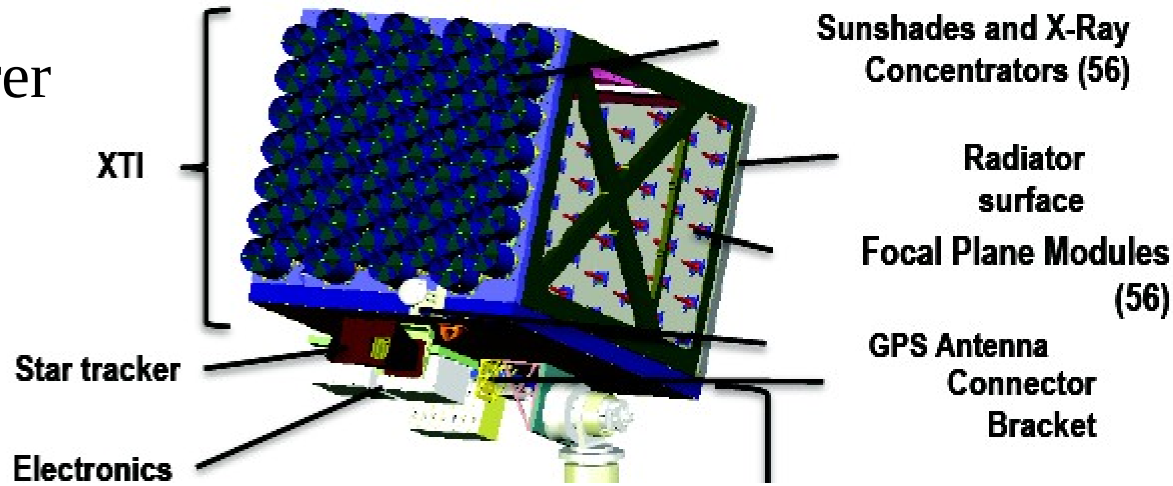


- **Large Area Timing Array (LATA)**
  - 3.2 m^2 effective area
  - <600 eV energy resolution
  - Low inclination LEO orbit
- **Sky Monitor (SM)**
  - Multiple coded-aperture cameras (40°x40° FOV each)
  - High duty cycle monitoring of sky
  - < 5 mCrab in 1 day
- **Flexible scheduling and rapid response**
  - Targets from GI program

Cost Category:
Small (<$400M, excluding launch)

cf. US proposal – Ray, Chakrabarty+14

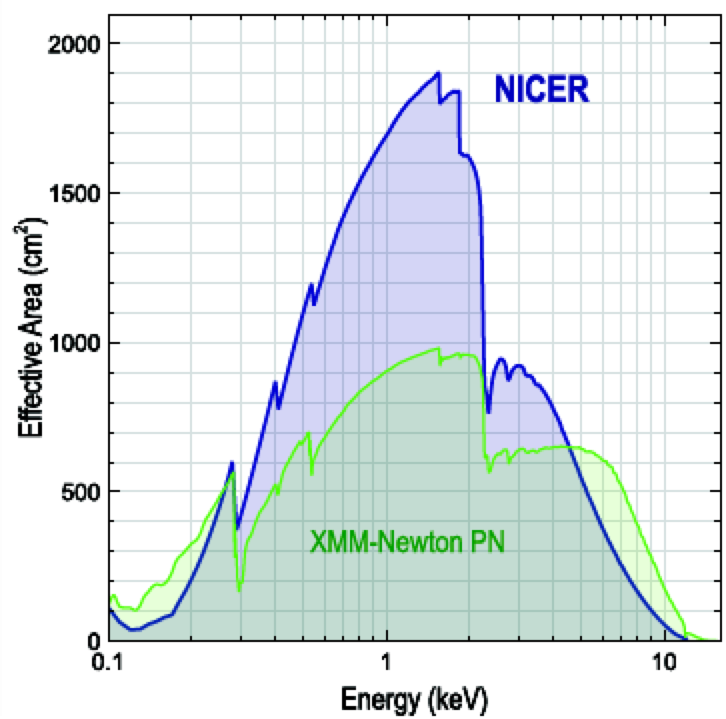
NICER – NASA Explorer



Attach to ISS in 2016!

- **Spectral band: 0.2–12 keV**
  - ***Well matched to neutron stars***
  - ***Overlaps RXTE and XMM-Newton***
- ** **Timing resolution: 100 nsec RMS absolute**
- **Energy resolution: 2% @ 6 keV**
- **Angular resolution: 6 arcmin (non-imaging FOV)**
- **Sensitivity, 5σ: 5.3 x 10^{-14} erg/s/cm^2**
  - ***0.5–10 keV in 10 ksec (Crab-like spectrum)***

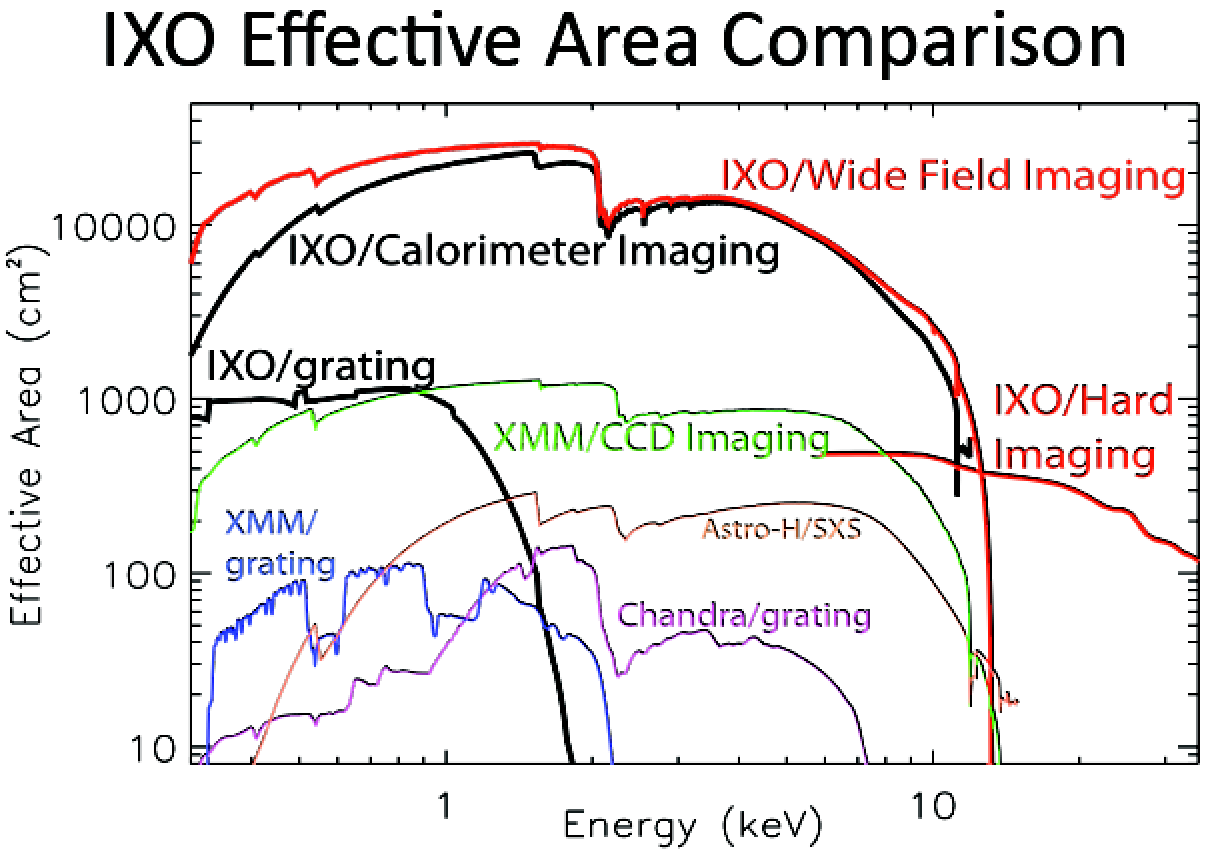
Uses SDDs (but << LOFT!)



LaMarr+14

Next generation X-ray imaging observatory
(i.e. successor to Chandra, XMM)

- Constellation-X (NASA) + XEUS (ESA) → IXO → Athena



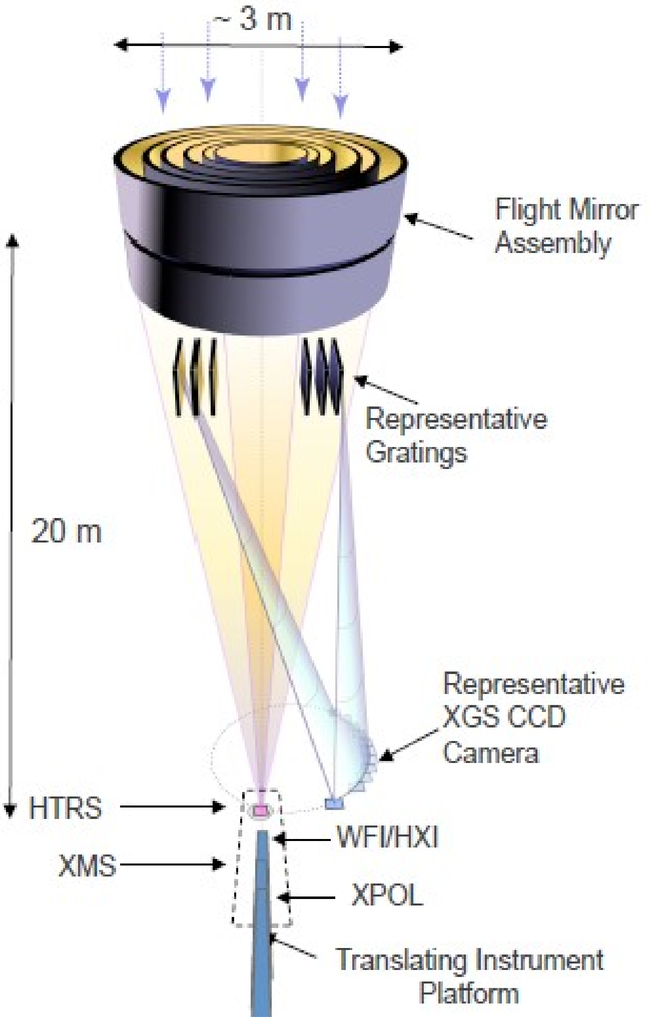
Instrument concepts (Parmar+10)

Optics

- Effective area 3 m² @ 1.25 keV, 0.65 m² at 6 keV with a goal of 1 m². 150 cm² (goal 350 cm²) at 30 keV
- 5 arc sec HEW spatial resolution with a 20 m focal length

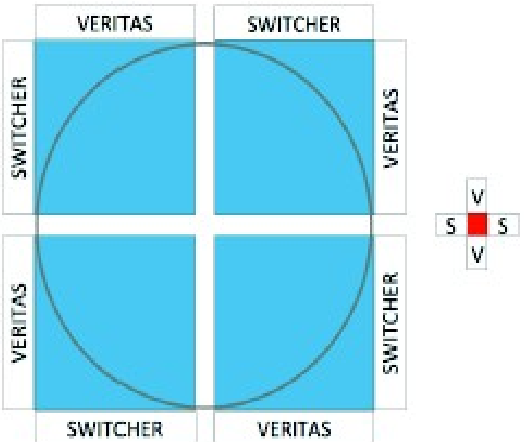
Instruments

- ➔ X-ray Microcalorimeter Spectrometer (XMS)
  - 0.3 to 7 keV with 2.5 eV over 2 arc min and 10 eV over 5 arc min FOV
- Wide Field Imager (WFI)/Hard X-ray Imager (HXI)
  - 0.1 to 15 keV with <150 eV & 18 arc min FOV
  - HXI extends band pass to 40 keV
- ➔ X-ray Grating Spectrometer (XGS)
  - Dispersive from 0.3 to 1 keV with R ~ 3000, 1000 cm² area with a goal of 3000 cm²
- X-ray Polarimeter (XPOL)
  - Gas Imaging Pixel Detector
- High Time Resolution Spectrometer (HTRS)
  - Bright source capability



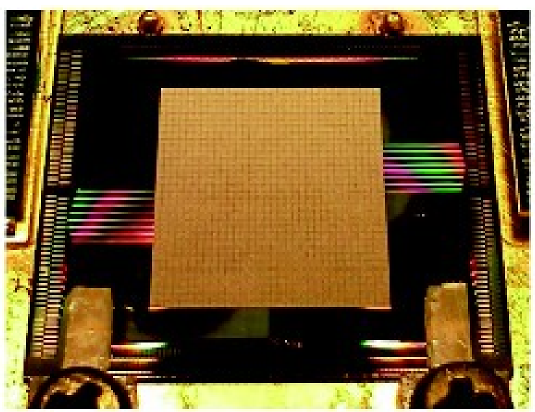
ATHENA INSTRUMENTS

Gimenez15



WFI based on Si DEPFET technology

- 100 micron pixels, 140 eV FWHM @ 6 keV
- 10 mCrab without pile-up
- Field of view up to 40 x 40 arcminutes
- Investigating a second (defocussed) FAST chip providing 1 Crab source brightness with 40 μs time resolution and only 1% pile up

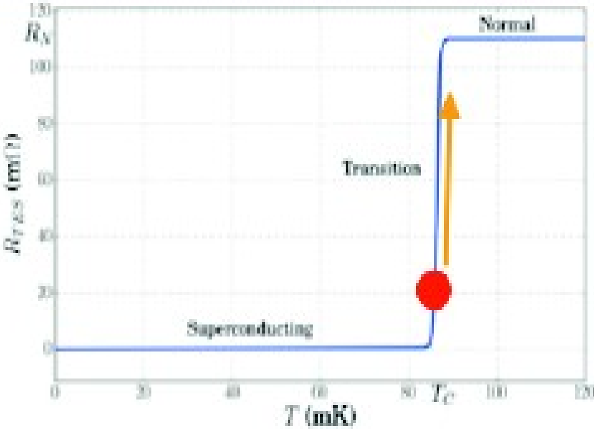


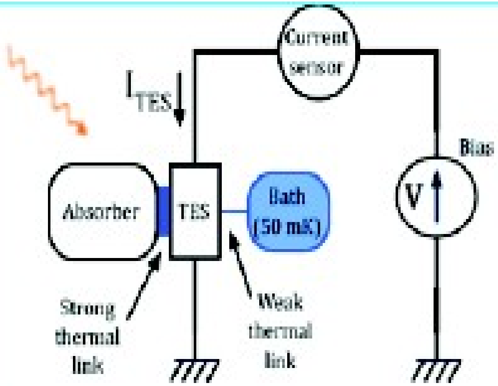
X-IFU based on TES microcalorimeter

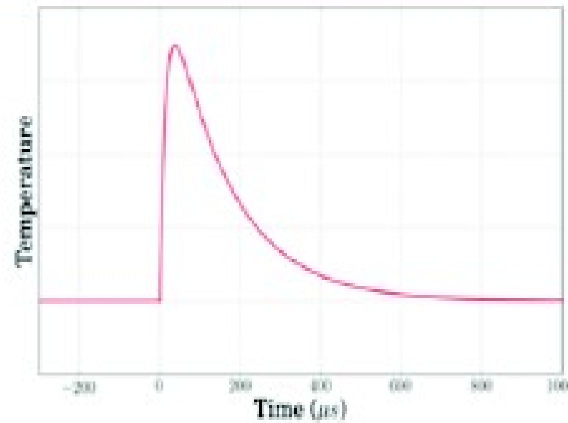
- 250 micron pixels, ~2 eV FWHM @ 6 keV
- Field of view 5 x 5 arcminutes (>32 x 32 array)
- Investigating optimised array with outer field having multiple pixels per TES readout
- US provision of sensor arrays and Japanese provision of part of the cooling chain baselined

Transition Edge Sensor (TES) detector

Barret+15

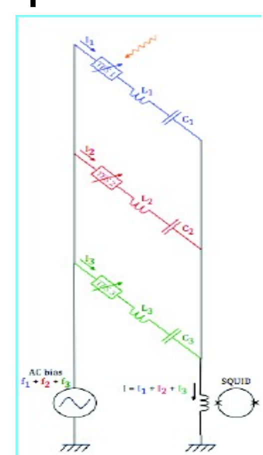






- Micro-calorimeter connected to 0.05K heat sink
- E of X-ray photon moves superconductor → normal conductor → R changes
- Target performance: ~2.5eV spectral resolution, ~5” spatial res.
- Each TES in array forms part of LCR circuit
- Frequency multiplexed read-out
- Via array of SQUID and low-noise amps

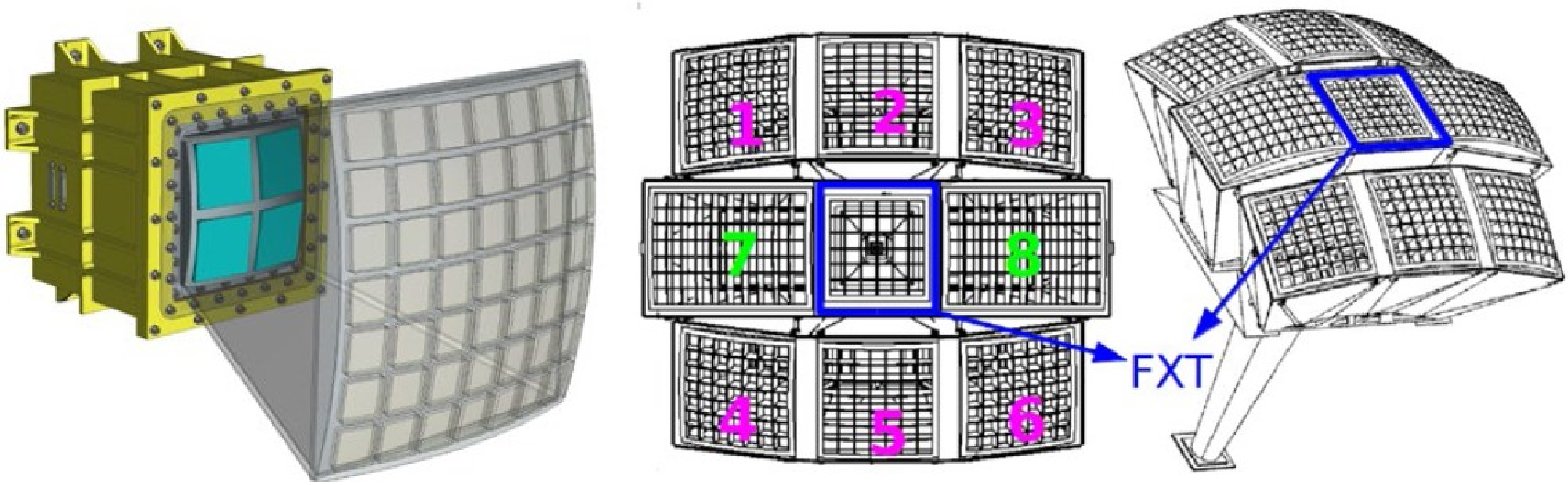
(Superconducting QUantum Interference Device)




Athena
L3 mission
Launch 2028

Still need wide-field monitoring of X-ray sky e.g. with Micro-Pore Optics (Chinese *Einstein Probe*) to improve by ~x10 over RXTE/ASM or MAXI

Willingale, Leicester



	WXT	FXT
Field-of-view	60°×60°	1°×1°
Focal length	375 mm	1400 mm
Energy band	0.5-4 keV	0.5-4 keV
Effective area	3 cm^2 (@0.7 keV, central focal spot)	60 cm^2 (@1 keV)
Angular resolution	<5′	<5′
Sensitivity (@1ks)	About $1x10^{-11}$ erg/s/cm^2	About $3x10^{-12}$ erg/s/cm^2
Timing resolution	100 μs	1 s
Energy resolution	~50% @ 4keV	~100 eV @ 1keV

Optical/NIR developments

Review of current HTRA instrumentation

Detector	Time Resolution	Quantum Efficiency	E/ΔE	No. of Pixels	Instrument
CCD	5ms+	90% +	-	$>> 10^6$	UltraCam[39]
EMCCD EMCCD	1ms+ 1ms+	15% + 15% +	- -	10^6 10^6	UltraSpec[39] GASP[40]
pn CCD	0.01 ms+	90% +	-	10^6	[41]
Active Pixel Detectors	a few μs	80% +	-	10^5	[42]
SPADs	ns+ ns+ 100ps	80% + 15% 50%+	- -	a few one[a] a few	Optima[43] GASP[40] Iqueye[44]
STJ TES MKID	ns+ ns+ ns+	90% + 90% + 90% +	5 20+ 500+	10s 10s 10s	SCAM[45] [46] [47]
Photo-Cathodes	ns+ 1ms	<30% 40%	- -	$1 - 10^6$ 10^6	Many wavefront sensor

Shearer et al., 2010, HTRA White Paper: HTRA in the ELT era

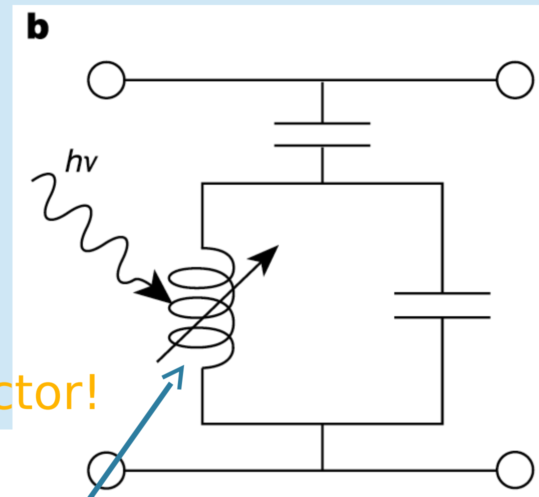
MKIDs: Microwave Kinetic Inductance Detectors for optical/NIR (from Kieran O'Brien + Mazin papers)

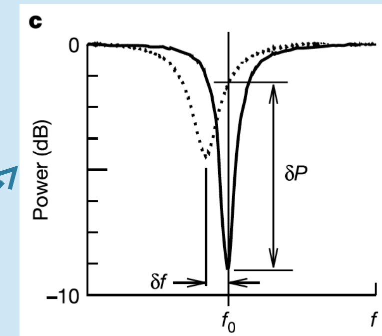
- What are Microwave Kinetic Inductance Detectors (MKIDs)?
- Advantage: Easy to multiplex (unlike STJs, TES)
- ARCONS
- O'Brien+15 Palomar commissioning and Science run
- Future Instrumentation

Microwave Kinetic Inductance Detectors

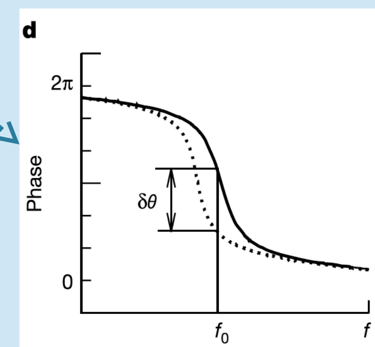
= extra inductance from stored KE in Cooper Pairs (based on Mattis-Bardeen theory from 1958)

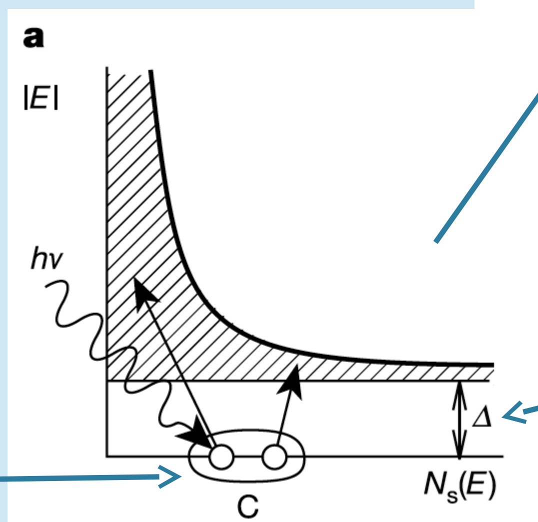
MKID Equivalent Circuit





Inductor is a Superconductor!





Cooper Pair

Energy Gap

Silicon – 1.10000 eV

Aluminum – 0.00018 eV

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

Can work from 0.1-5μm

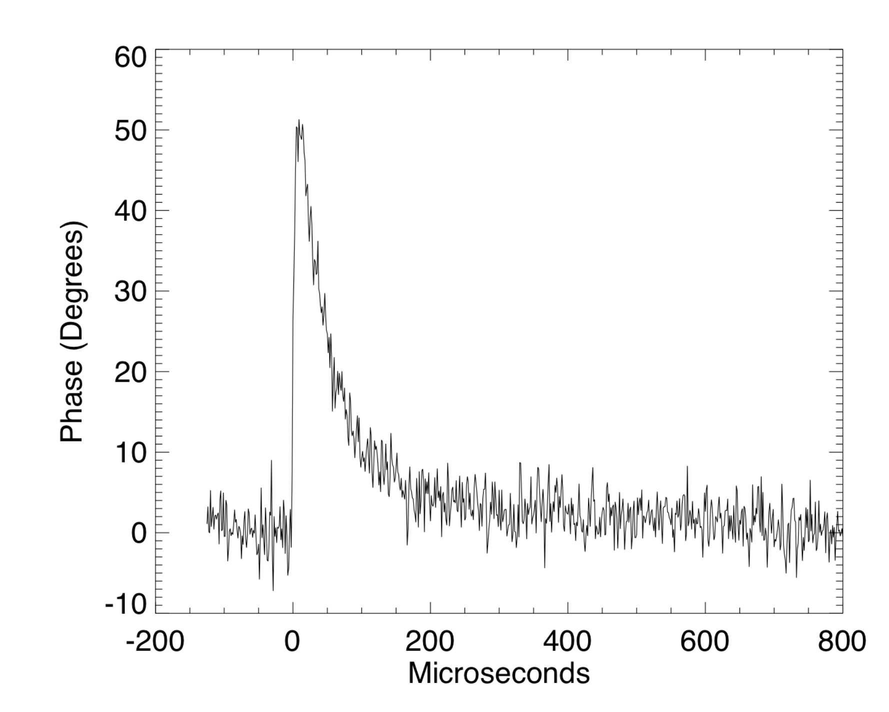
O'Brien+15

Energy resolving detector

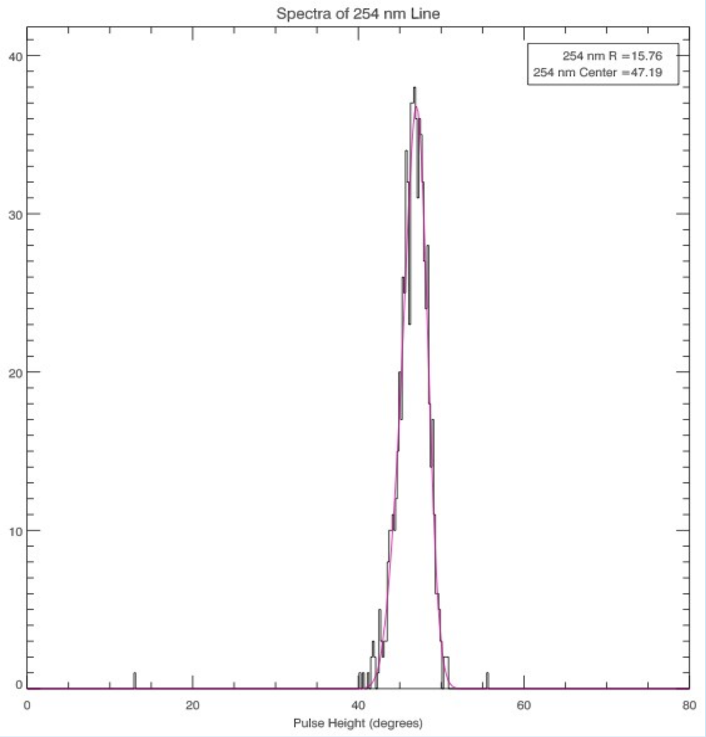
Energy Gap
Silicon – 1.10000 eV
Aluminum – 0.00018 eV

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

$h\nu$= 4.9eV, R <~ 100 for η~1

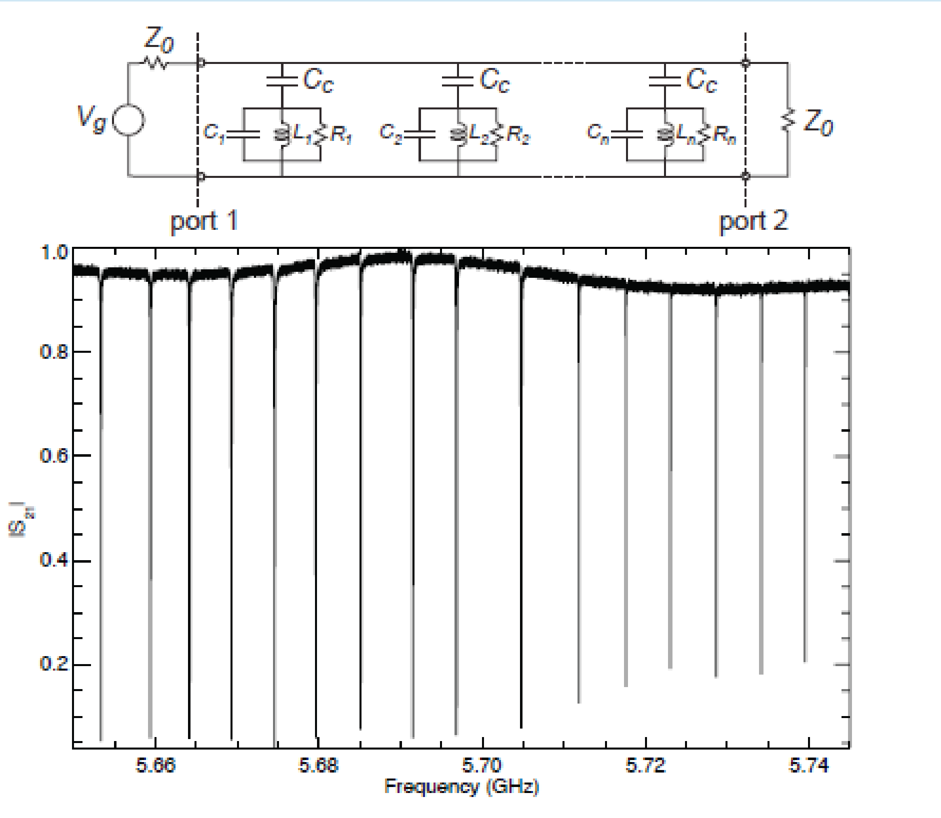


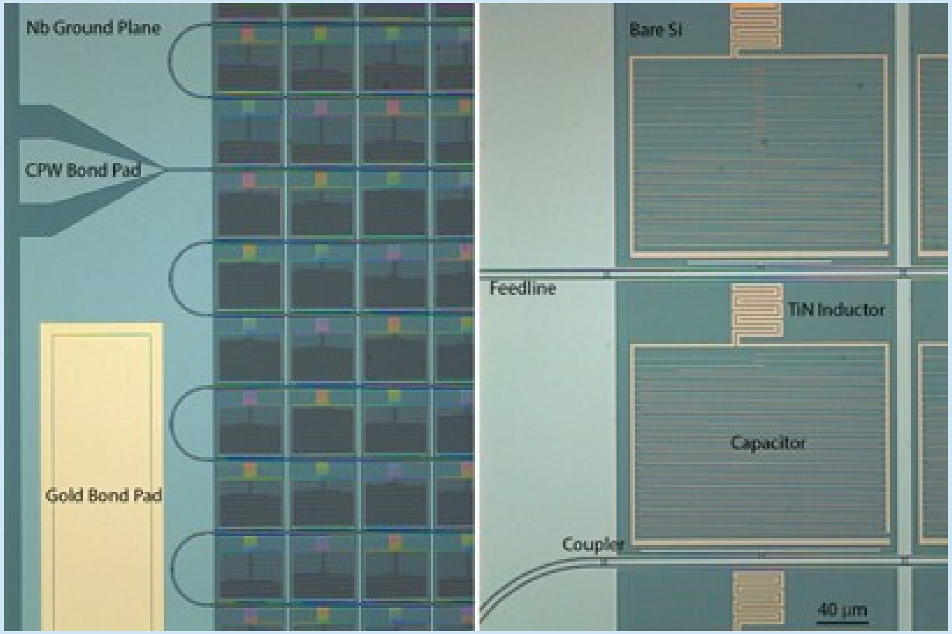
Single photon event



Distribution of photon events

Arrays of MKIDs





Each pixel tuned to different resonant frequency →
multiplexed readout with microwave probe signal 0.1-20 GHz

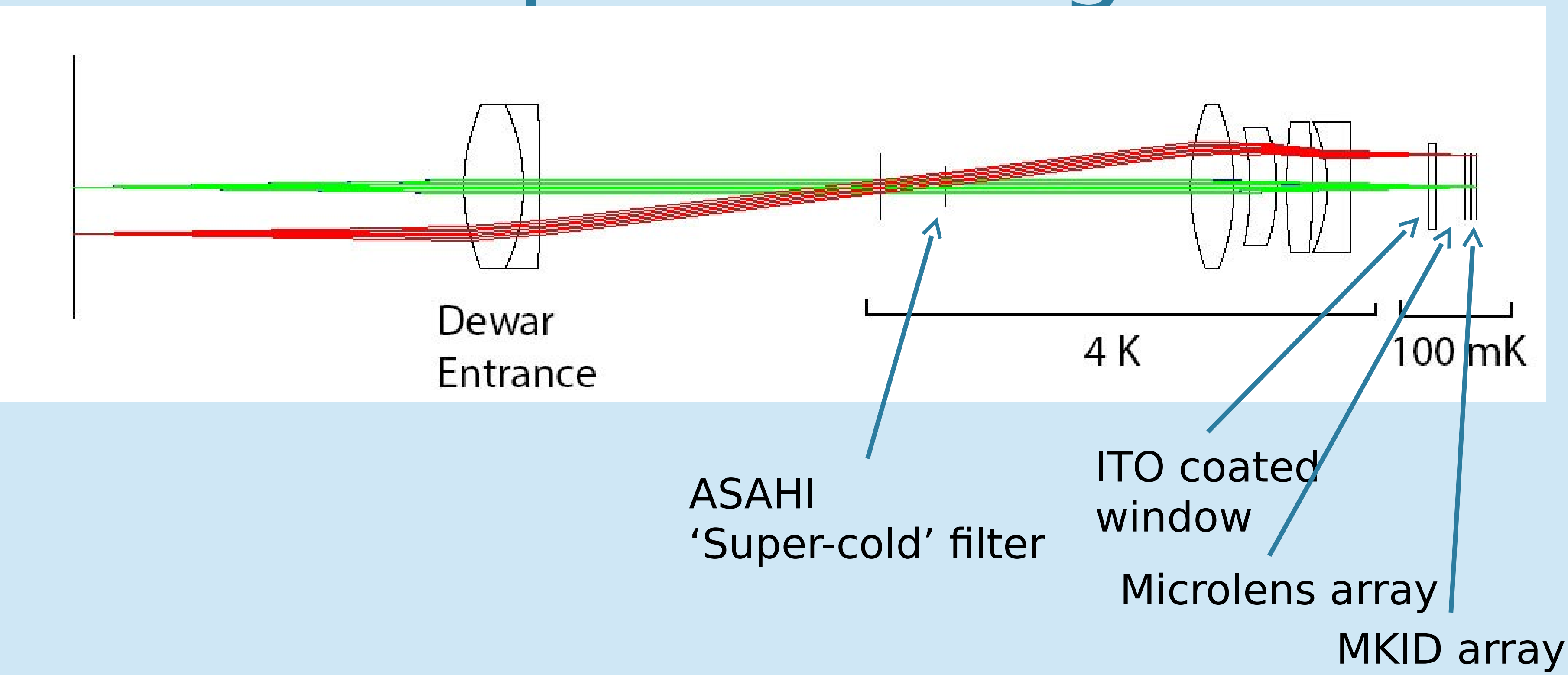
Mazin+13

ARCONS (2011)

- The Array Camera for Optical and Near-IR Spectrophotometry
- 1024 pixel MKID array (70% active pixels)
- TiN lumped element pixels
- Lens coupled 223μm pixels
- 100mK cryogen-free ADR
- 0.23”/pixel plate scale
- 0.38-1.1μm passband
- 2000 cts/pixel/sec limit
- Energy resolution R=10-20 at 400nm
- Time resolution $\sim 1\mu s$

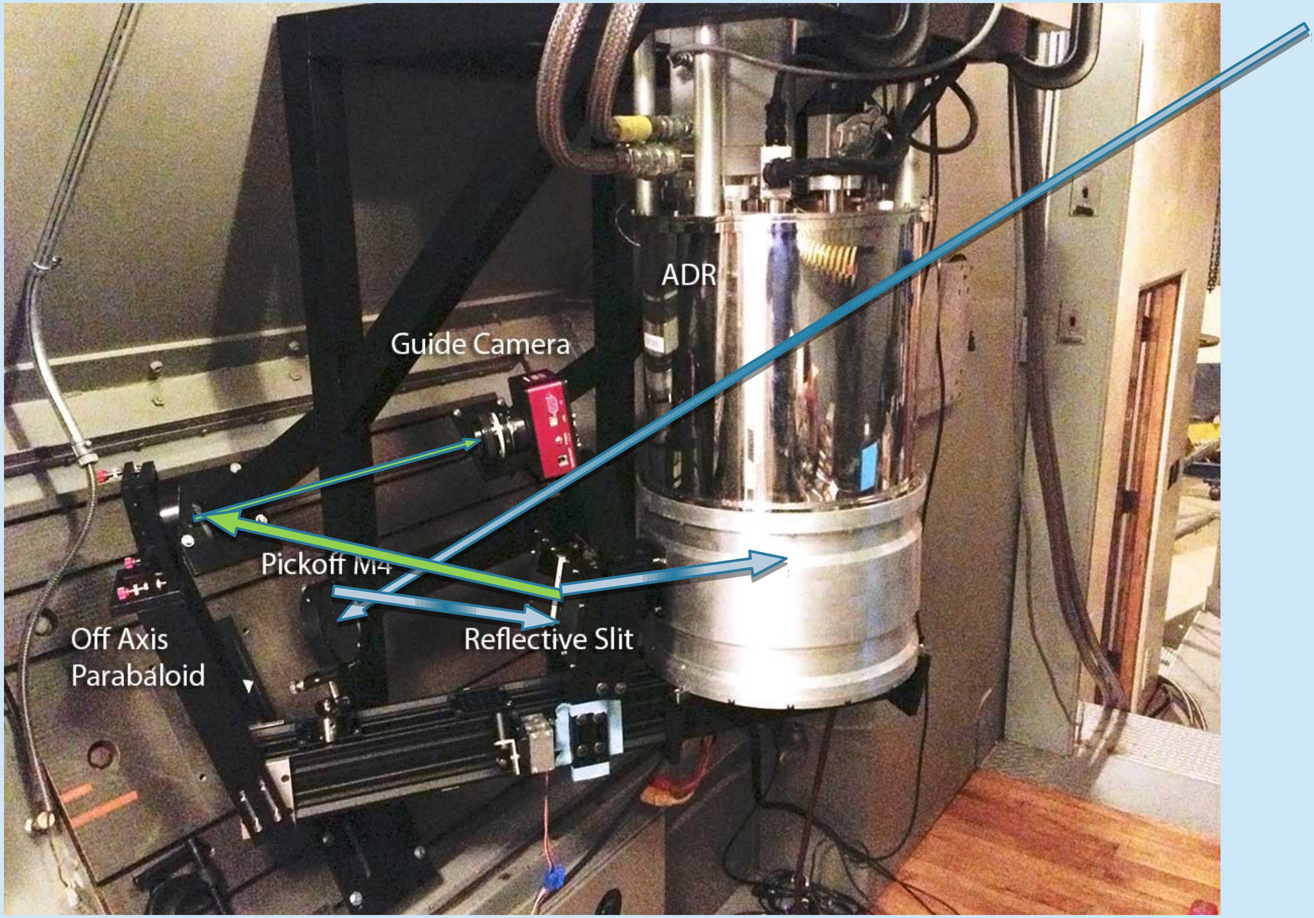
Mazin, et al. PASP, 123, 933

Optical design



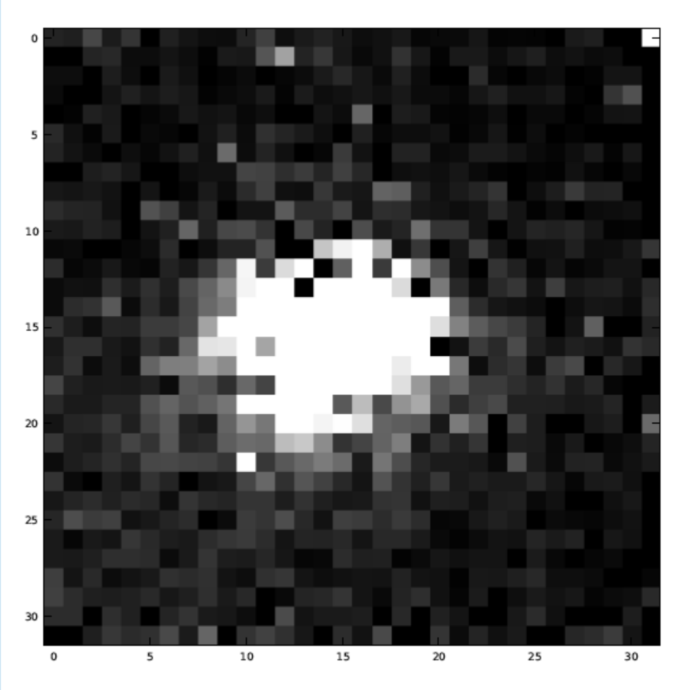
Simple optical design comprising off-the-shelf components, designed to block as much thermal infrared as possible.

Optical layout

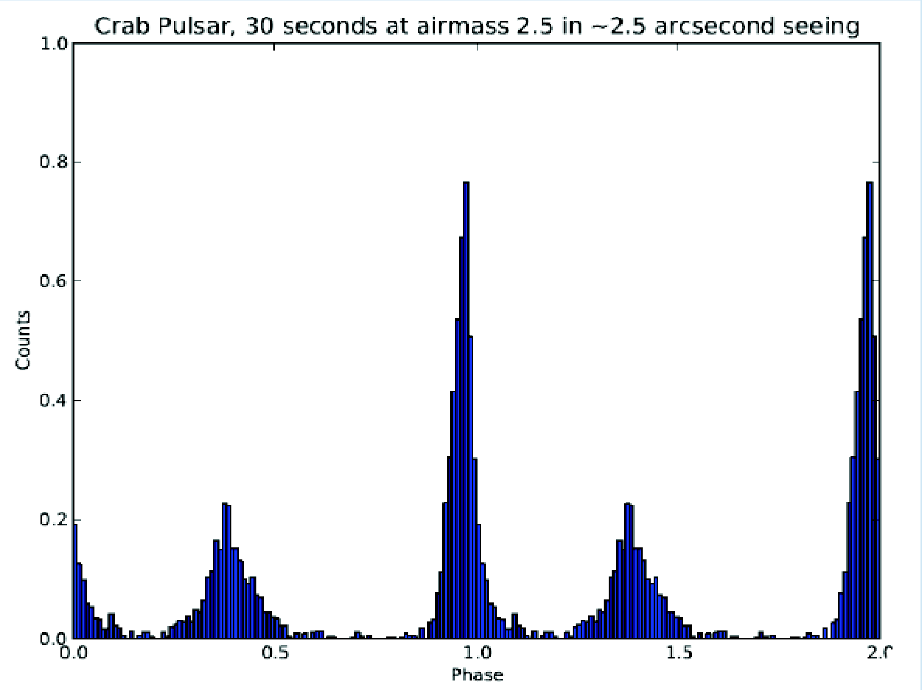


Results:

- ‘Dithered’ reconstruction of 3 offset exposures of PG1633+099A
- V = 15.3 standard star
- 20 second integration
- S/N ~ 80
- Limit of I ~ 22.5 for 10-sigma in 1 hr

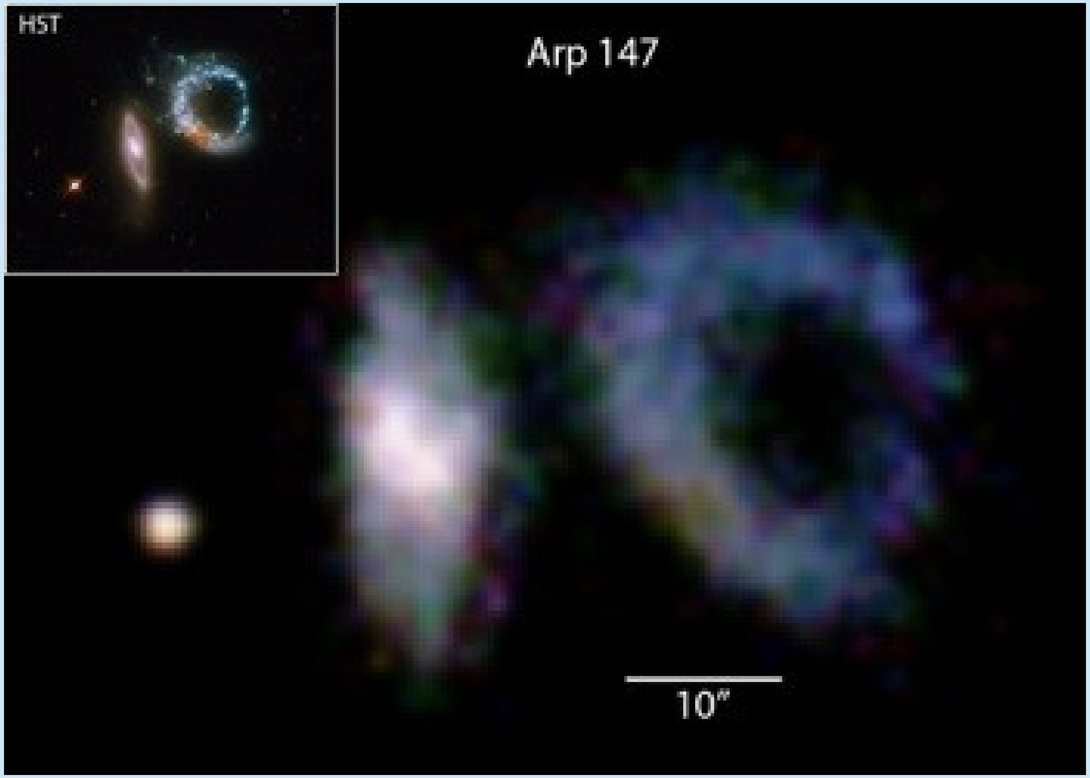


- Crab Pulsar:



Arp 147

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



Science results: see
Strader+ ApJL, 779, 12
Szypryt+ MNRAS, 439, 2765

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, MCPs	Fair	Good	<µsec	none	Poor	High
FT CCDs, EMCCDs	Excellent	Good	seconds	none	Excellent	Moderate
CMOS	Excellent	Fair	seconds	none	Excellent	Moderate
SPADs/Geiger-mode APD	Fair	Good	<µsec	none	Poor	High
STJ	Fair	Excellent	µsec	Fair	Poor	High
TES	Fair	Excellent	µsec	Fair	Poor	High
MKIDs	Fair	Excellent	µsec	Fair	Fair	Moderate

MKIDS Instrument Concepts

1.Classification of transients	2. Accretion onto compact objects	3. Dark matter /energy	4. 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

1. Classification of Transients

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

  1000 ‘real’ sources

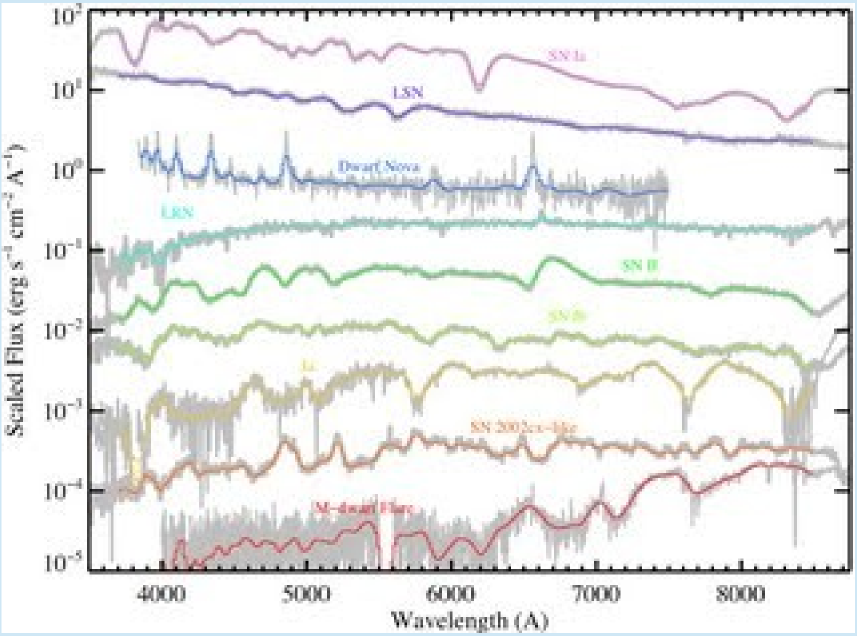
  300 variables

  10 SNe
- LSST: 100x volume of PTF

PTF: Josh Bloom
LSST: LSST science book

Classification spectra of transients

- 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

2. Accreting compact objects

- Single object
- Medium resolution (R > ~3000) to distinguish emission line velocity components (interacting binaries + ...)
- Wide passband (0.35-2.4μm) to capture full SED at same time
- Good temporal resolution (< 0.1s) to sample characteristic interacting binary time-scales
- Low noise to avoid penalty of time resolution
- Optimizes collecting power of large telescopes, eg VLT, ELT

KIDspec

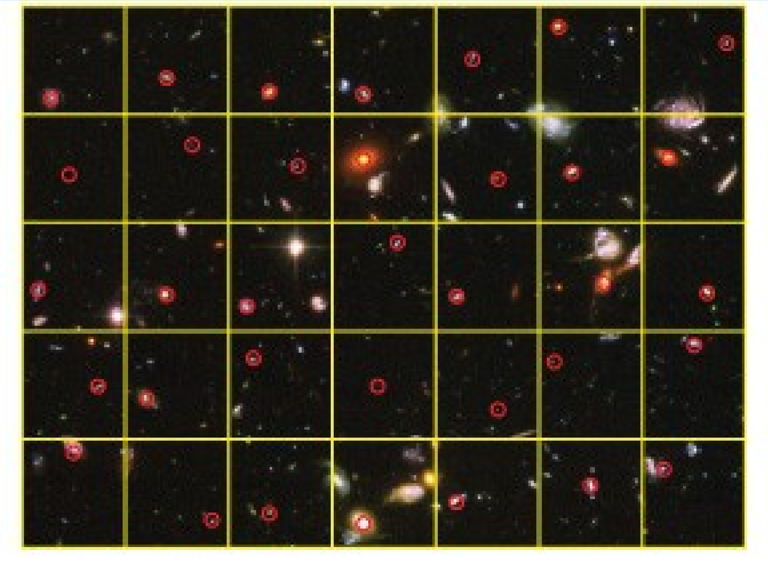
- Dual-arm (Vis+IR) spectrograph, with echelle grating in low order (<20) to achieve R~5-10,000
- Cross-disperser is replaced by energy resolution of MKIDs
- Photon counting detector allows for excellent background subtraction (a problem for e.g. X-shooter/VLT)
- Combined with image slicer → IFU Spectroscopy too

See also, Cropper et al., 2003

3. 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 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

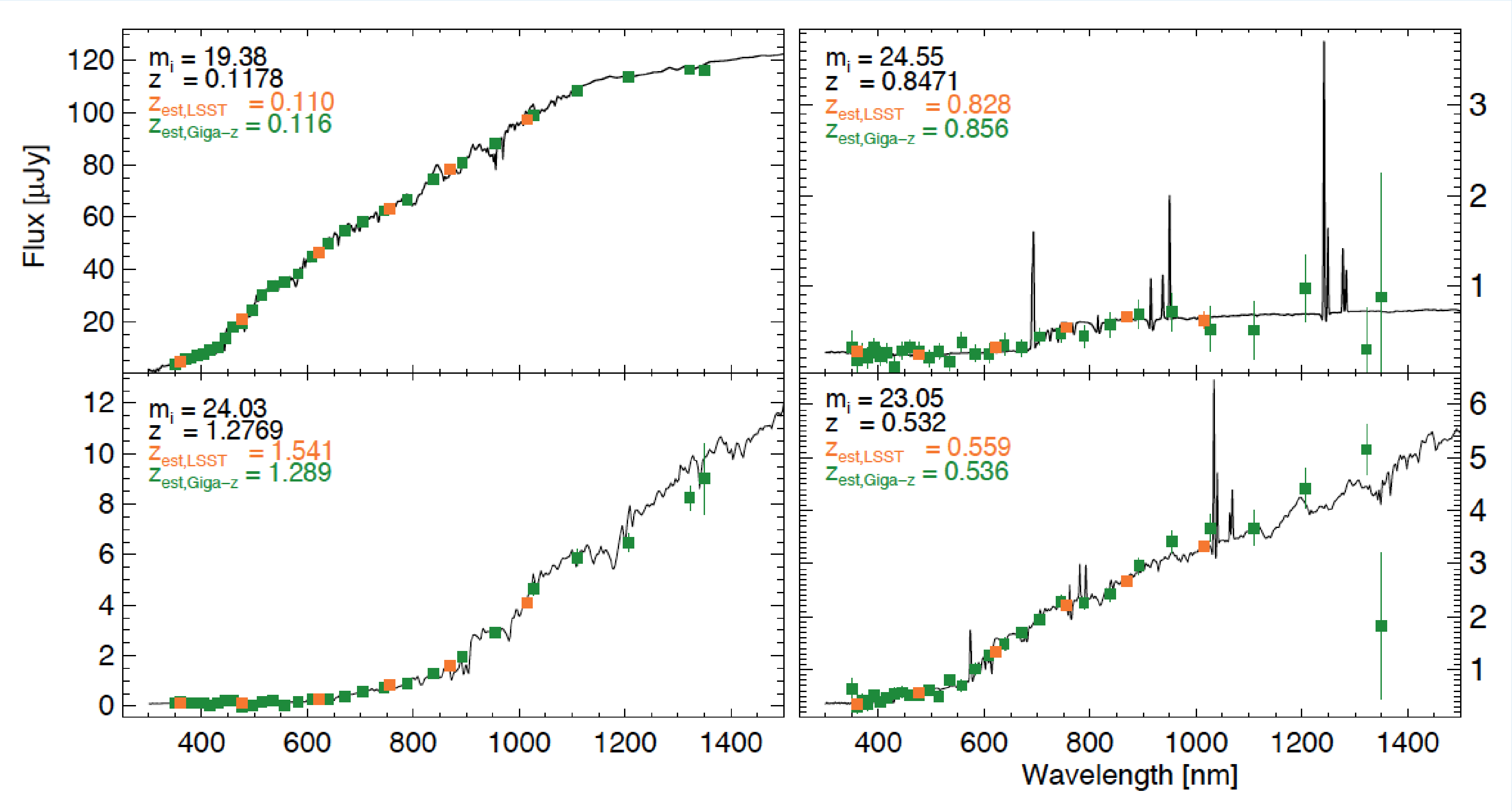
e.g. Giga-z



- 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
- Limiting magnitude: I = 25 in 15 mins
- Survey using 800 nights of 4-m telescope time → $2x10^9$ z

See Marsden+13, ApJ, 208, 8

Sample galaxies



- HTRA is key to understanding the most extreme astrophysical environments
- HTRA is demanding of detector technologies and their advances across all wavelengths
- Major developments in micro-calorimeter varieties, particularly TES (X-ray), MKIDs (opt/NIR)
- Next steps require large-scale multiplexing
- MKIDs not just for HTRA
  - broad passband + read-noise free → “perfect detector” for many applications
- MKIDs for optical/IR now successfully demonstrated on-sky, but challenges remain
- Key property: scalability amongst E-sensitive detectors → excellent candidate for future instrumentation
- Potential for astronomy similar to transition from photographic plates to CCDs!