Some Aspects of Optical Photon Detection

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(Princeton, 19 Nov 2013)

How many fundamentally different ways have astronomers used to detect optical photons?

How many more remain to be discovered or exploited?

Classification

(Rieke, Detection of Light 1996)

Three basic detection mechanisms by which photons produce an electrical response that can be amplified and interpreted:

1. photon detectors which respond directly to individual photons: an absorbed photon releases one or more charge carriers that may:
   - lead to a chemical change: photography, the eye
   - modulate the electric current in the material: photoconductors (intrinsic and extrinsic), photodiodes, [fluorescence/phosphorescence], [superconductors]
   - move directly to an output amplifier: photoemissive detectors

2. thermal detectors (bolometers): these absorb photons and thermalise their energy, changing the electrical properties of the detector and modulating the current: important at infrared, sub-mm, and X-ray

3. coherent detectors: these respond to the electric field strength of the signal, preserving phase information of the incoming photons:
   - they operate by interference of the electrical field of the incident photon with the electric field of a coherent local oscillator
   - mainly used in the radio and sub-mm, and also in the infrared

Considerations

Detectors are characterised by, amongst others:

- quantum efficiency: the fraction of the incoming signal detected
- noise: in the ideal case determined by photon statistics, but usually other contributions
- linearity: the degree to which the output signal is proportional to the incoming signal
- dynamic range: the range of signal intensity over which output reflects input
- number and size of pixels: determining the resolution and imaging field
- time response: the minimum time to distinguish changes in photon arrival rate
- spectral response: the total wavelength range over which the detector is sensitive
- spectral resolution: the wavelength range over which photons can be distinguished
- others (in principle): spin angular momentum (polarisation), orbital angular momentum

Photoemission

- the physical process in which a photon is absorbed by a material and, if sufficiently energetic, ejects an electron

- observed by Hertz (1887), and described through the absorption of quantised energy (photons) by Einstein (1905)

- if the emitted electron can be captured, the process can be used to detect light

- photoemissive detectors use electric or magnetic fields (or both) to accelerate the electron into an amplifier, allowing detection as a current or even as an individual particle (photon counting)

- semiconductors are used (rather than metals) because of their lower reflectivity

- practical devices: electron multipliers, image intensifiers, microchannel plates

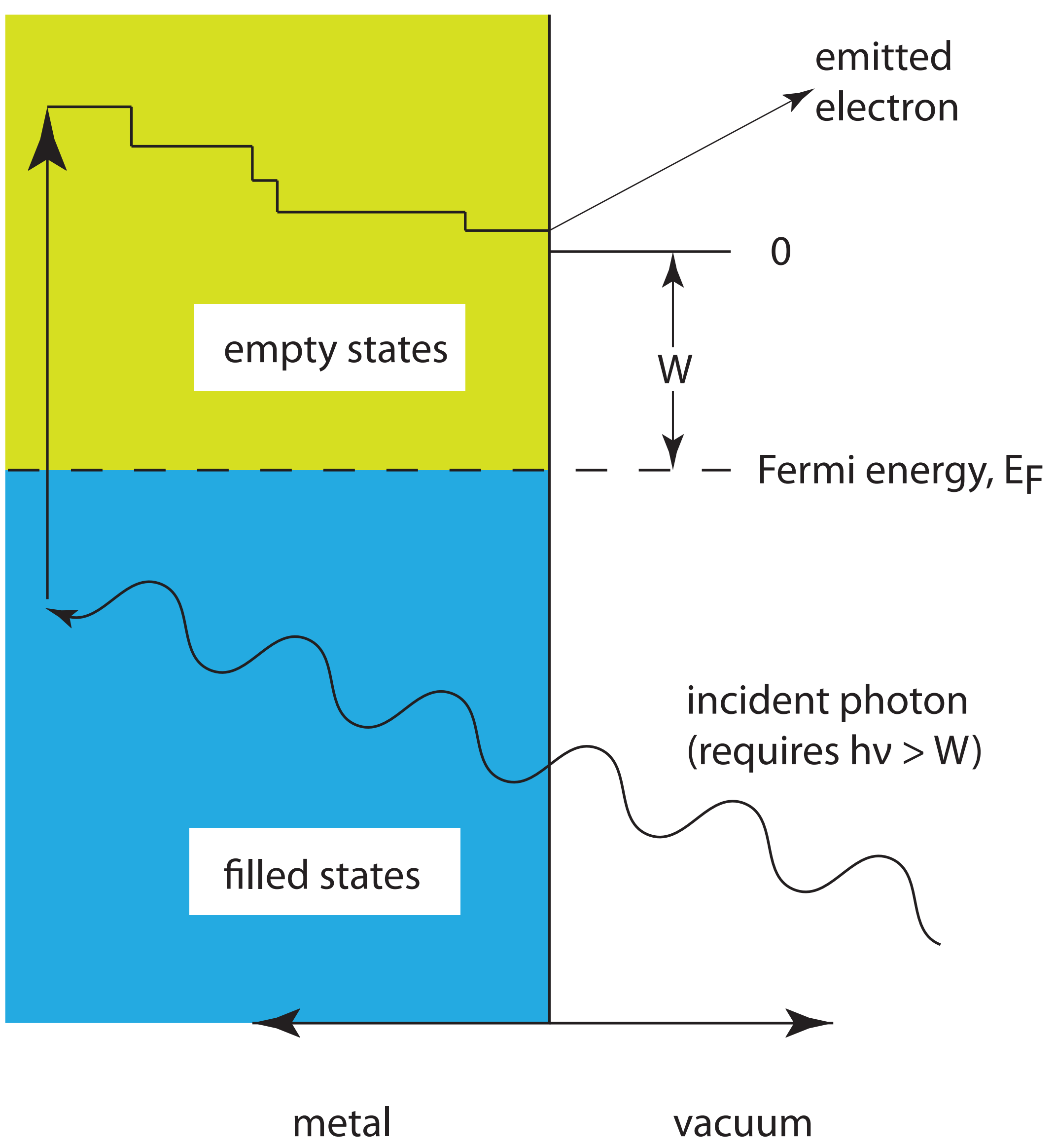
- advantages:
  - capable of very high time resolution (ns)
  - sensitive detector areas of several cm^2
  - moderate QE ~10−30%, particularly in visible/ultraviolet
  - can count individual photons at (very) low photon arrival rates

Qualitative Description

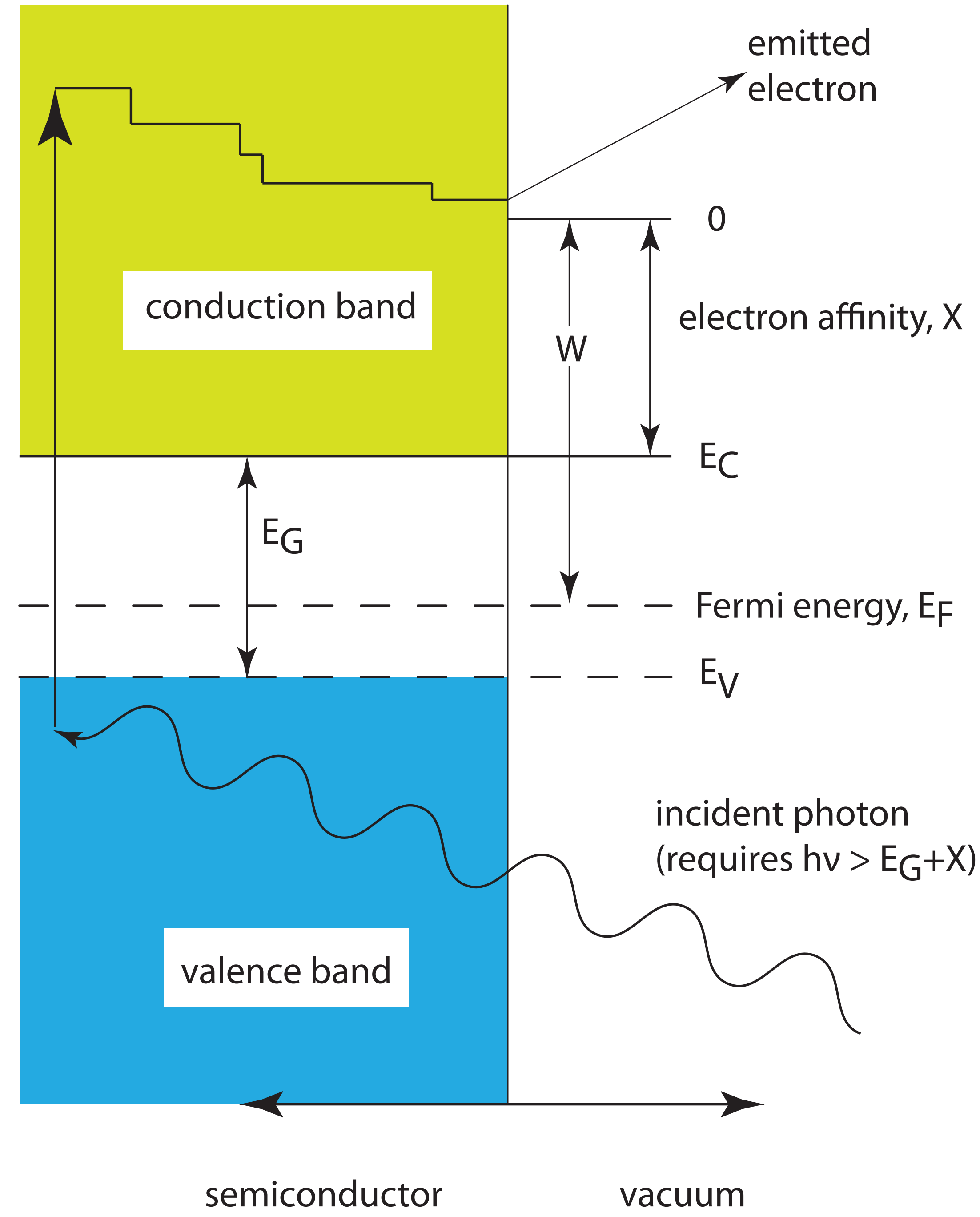
- Photoemission from a <u>metal</u>:
  - if a photon with $h\nu > W$ (the work function, difference between Fermi level and minimum escape energy) is absorbed, it can raise an e^- into the conduction band
  - as the ('hot') electron diffuses in the material, it loses energy ('thermalises')
  - if it reaches the metal surface with $E>0$ it has a reasonable probability of escaping into the vacuum (as described by the theory of the photoelectric effect)
  - the high reflectivity of metals implies a very low QE

- <u>Semiconductors</u> are used as photoemitters because of their lower reflectivity
  - more complex physics, involving affinity, diffusion length and absorption coefficient
  - multilayer photocathodes are used to enhance the emission of low-energy (red or near-infrared) photons by modifying the energy band structure at their interface
  - other mechanisms can release (unwanted) electrons, resulting in dark current; at room temperature, dark current is dominated by thermally-excited electrons (reduced by cooling, or restricting the detector area), but also by cosmic rays
  - a wide variety of photocathodes have been developed which vary in their spectral response and thermal noise properties, e.g. S-1 (Ag-O-Cs, the first compound photocathode material, developed in 1929), GaAs, Cs-Te, S-11, S-20, etc

Energy band diagrams: metals and semiconductors



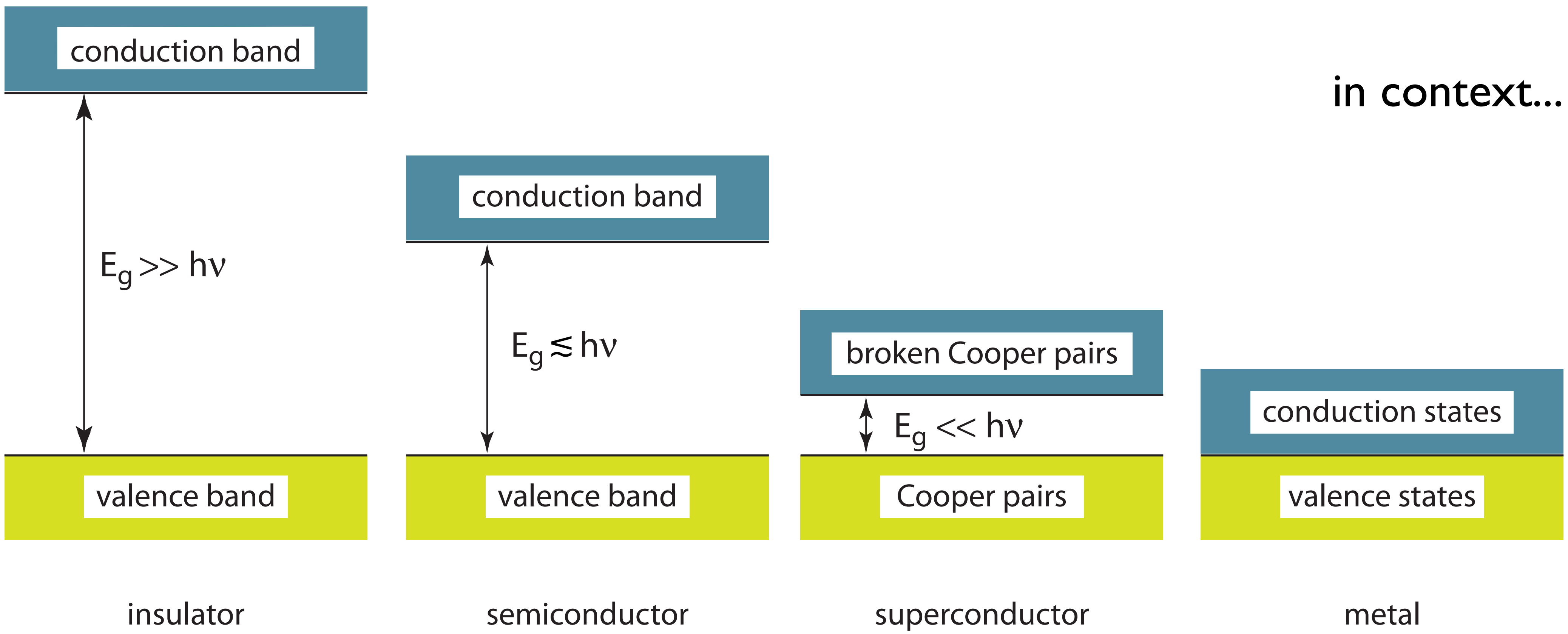
Photoelectric effect in a metal
(energy band diagram)



Photoelectric effect in a semi-conductor
(energy band diagram)

Semiconductors

Semiconductors



Many/most detectors now depend on semiconductors:

- electrical conductivity is dramatically altered by absorption of an optical/UV photon (~1-4 eV):
  - metals: have a high electrical conductivity which is only insignificantly modified
  - insulators: which need far more energy to excite electrical changes
- additionally, adding small amounts of impurities further modifies their electrical properties
- semiconductors: the elements Si and Ge, and many compounds (spanning column IVa)

Semiconductors: intrinsic and extrinsic

Column	Semiconductor	Band gap (eV)
IV	Ge	0.67
	Si	1.11
	SiC	2.86
III-IV	AlAs	2.16
	GaAs	1.43
	GaSb	0.70
	InSb	0.18
II-VI	CdTe	1.58
	ZnSe	2.70
I-VII	AgBr	2.81
	AgCl	3.33
IV-VI	PbS	0.37

- elemental semiconductors: Si and Ge (bandgaps corresponds to 1.1μm and 1.8μm respectively)
- many compounds are semiconductors
- typically diatomic molecule symmetrically spanning column IVa in the periodic table

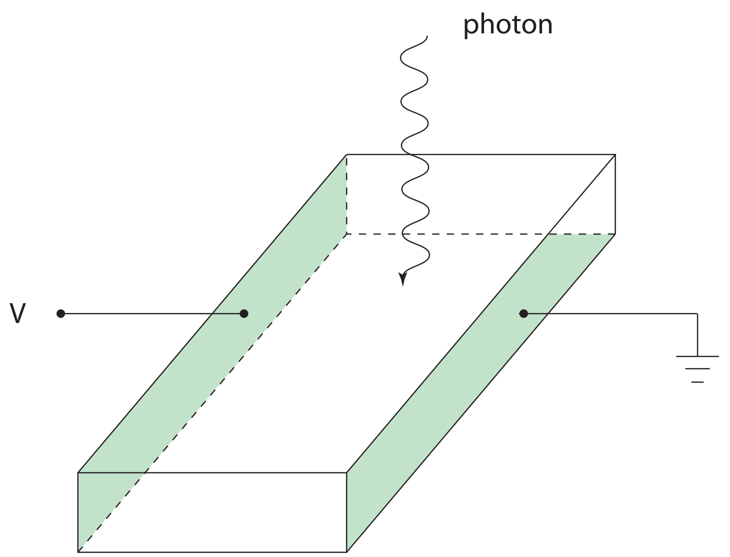
Bandgap engineering (e.g. HgCdTe):

- bandgap can be altered by changing proportions
- CdTe has E_g = 1.55eV, HgTe is metallic with E_g~0
- the bandgap of $Hg_{1-x}Cd_xTe$ then varies monotonically with x between these values
- response can be engineered to 25μm (with caveats)

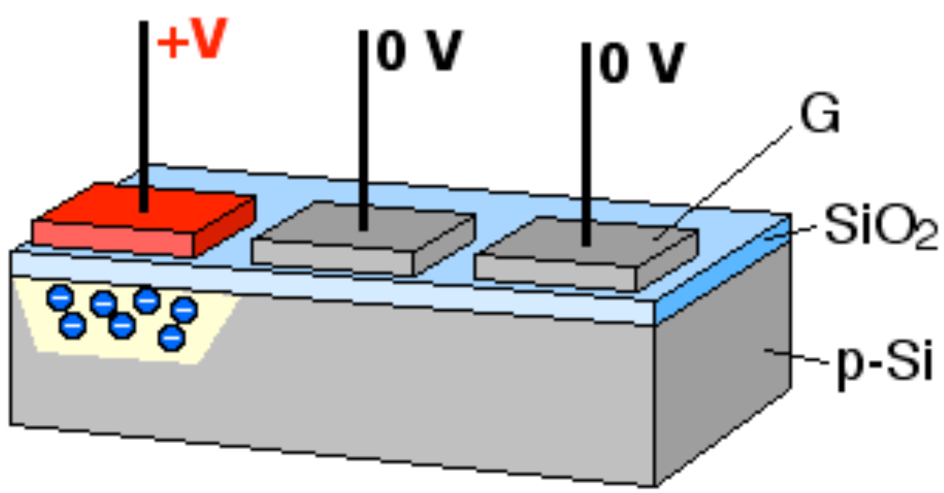
Some nomenclature:

- pure semiconductors are termed <u>intrinsic</u>
- adding impurities (p/n doping) can further modify their electrical properties: termed <u>extrinsic</u>
- impurities, as well as crystal defects, can also act as <u>traps</u> (if e^- is potentially subsequently released by thermal excitation) or <u>recombination centres.</u> Both inhibit the smooth movement of charge in CCD arrays, and lead to 'charge transfer inefficiency' (CTI)
- other variants: (avalanche) photodiodes, stressed detectors, BIBs, Schottky diodes, heterojunctions, quantum wells, L3 CCDs, ...

Basic Operation



- shown here with transverse contacts; can also be built with transparent contacts on front face, through which photons are received
- the detector region has few free charge carriers, and hence high resistance; an electric field is maintained across it (bias voltage)
- photons with E>hν free charges and a resulting current across the device
- large arrays are the basis of the CCD camera: free charges are collected in potential wells, then (at the end of the exposure) passed from one electrode to another by a (typically) 3-phase readout voltage
- charges are moved along columns to one edge of the array, then along the edge to an output amplifier



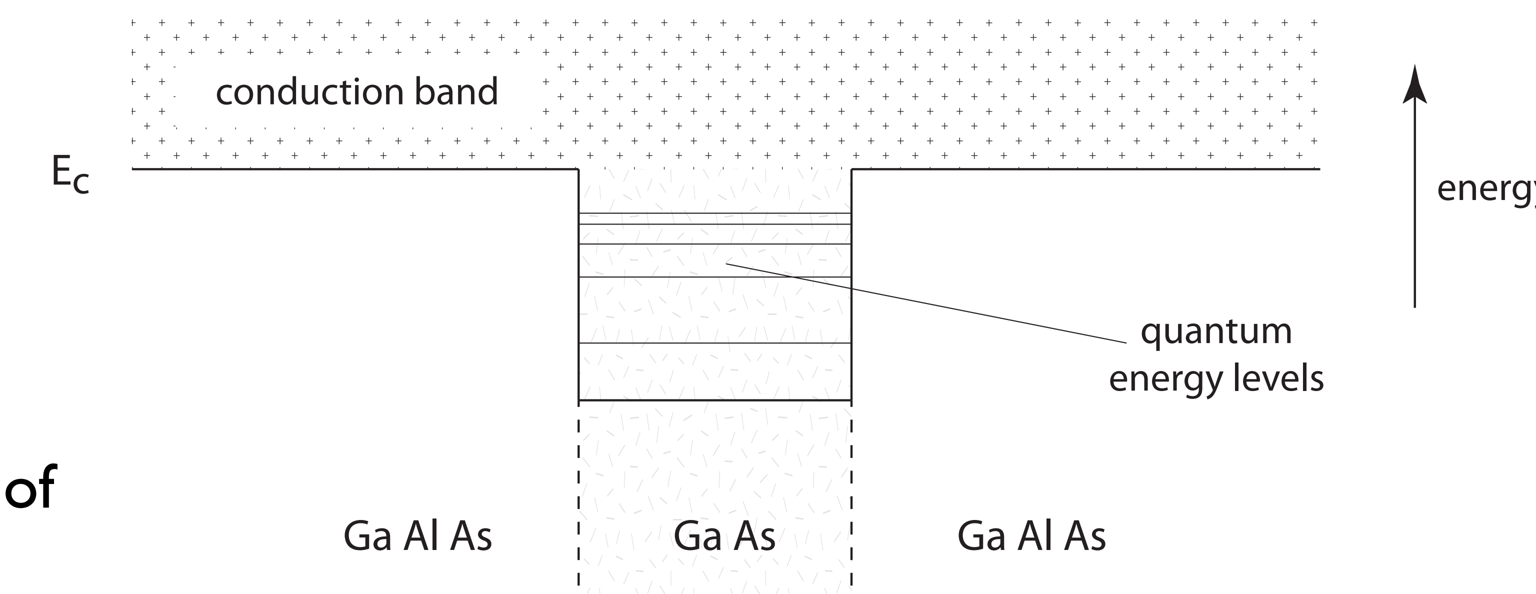
Some variants of extrinsic photoconductors:

- <u>stressed detectors</u>: the crystal structure is stressed, and less energy is required to break the atomic bonds. e.g. diamond lattice crystals (stressed along [100]), GeGa response extends from 115μm to 200μm
- <u>blocked impurity band</u> (BIB): separate detector layers are used to optimise the electrical response (low conductivity demands low doping) and optical response (heavy doping) separately

Photodiodes

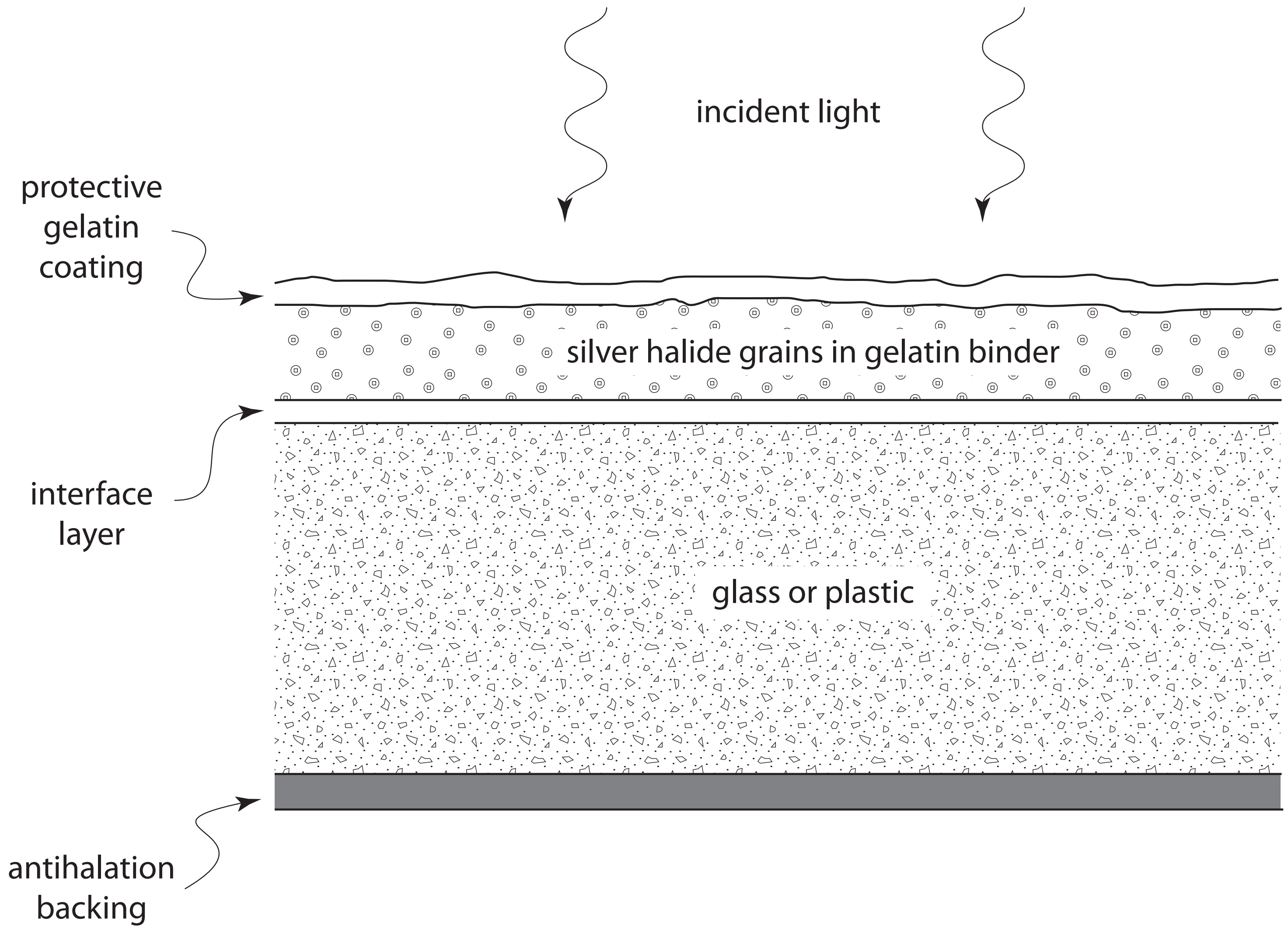
- based on a junction between two oppositely doped zones in an intrinsic semiconductor (Si or Ge)
- the adjacent zones create a region depleted of charge carriers, hence high resistivity, permitting high sensitivity even at room temperature
  - if photon absorption occurs in or near the junction's depletion region, carriers are swept from the junction by the built-in field of the depletion region (holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced)
  - the common, traditional solar cell used to generate electrical solar power is a large area photodiode
- Schottky diode: a junction between a semiconductor and metal → asymmetric barrier which acts as a diode

- heterojunction: uses different semiconductors with similar crystal structures, e.g. GaAs and $Al_xGa_{1-x}As$
- discontinuity of the conduction band leads to trapping between the layers of AlGaAS+GaAs+AlGaAs: this is the quantum well detector



Photography

Photography: the concept



- the active detectors are the silver halide grains (AgBr, AgCl..)
- the grains are suspended in a gelatin 'binder', and coated onto glass or plastic (mylar) for stability
- back reflections blocked by an anti-halation coating that absorbs light passing through

Advantages:

- huge 'pixel array': 8x10 inch plates may have 10^{12} grains (~ 10^9 pixels)
- inexpensive, and (potentially) stable storage over long periods of time

Disadvantages:

- low QE (~1%), poor linearity, limited dynamic range

Photography: outline physics

- photography is based on chemical changes initiated by the creation of a conduction electron when a photon is absorbed in certain kinds of semiconductor
- these changes are amplified by post-exposure chemical processing
- invented and developed via a long series of experiments (before solid state physics understood)
- explained by Gurney-Mott hypothesis, with some details remaining controversial
- various photographic materials have been discovered, but those based on silver halide 'grains' (tiny crystals) are particularly sensitive
- halogens (halides): fluorine (F), chlorine (Cl), bromine (Br), iodine (I) [and astatine, At], the name given (1840s) to the 4 elements that produce 'sea-salt' like compounds with metals
- photography based on AgBr, AgCl, or AgBrI
- now explained in terms common to other types of solid state detector (semiconductor):
  - photons strike a grain, excite the atoms, and raise an electron to the conduction band
  - this triggers a chain of events resulting in a small silver speck (development centre) in the grain
  - during chemical development, the development centres act as catalysts that blacken the entire grain through the reduction of Ag ions to Ag atoms
  - to stop undeveloped grains from further blackening over time, the process is stopped by 'fixing' (i.e. dissolving and washing away any residual silver halide)
  - photographic detection is binary: either a grain receives enough photons to develop, or it does not: this leads to limited dynamic range; can be extended by introducing multiple types and sizes of grain

Photography: Outline Physics

The Gurney−Mott hypothesis (after Ronald Gurney & Nevill Mott, Nobel Prize 1977) invokes a two-stage mechanism, essentially based on semi-conductors:

(1) a photon is absorbed within the silver halide gelatin, releasing a mobile electron and a positive hole; these mobile defects diffuse to trapping sites (sensitivity centers) within the volume or on the surface of the grain

$$h\nu + Br^- \rightarrow Br + e^-$$

(2) a trapped (negatively charged) electron is neutralized by an interstitial (positively charged) silver ion, which combines with the electron to form a silver atom:

$$e^- + Ag^+ \leftrightarrows Ag$$

the silver atom can act as a trap for a second electron:

$$Ag + e^- \rightarrow Ag^-$$

the process repeats, causing the silver speck to grow as exposure to light continues:

$$Ag^- + Ag^+ \rightarrow Ag_2$$

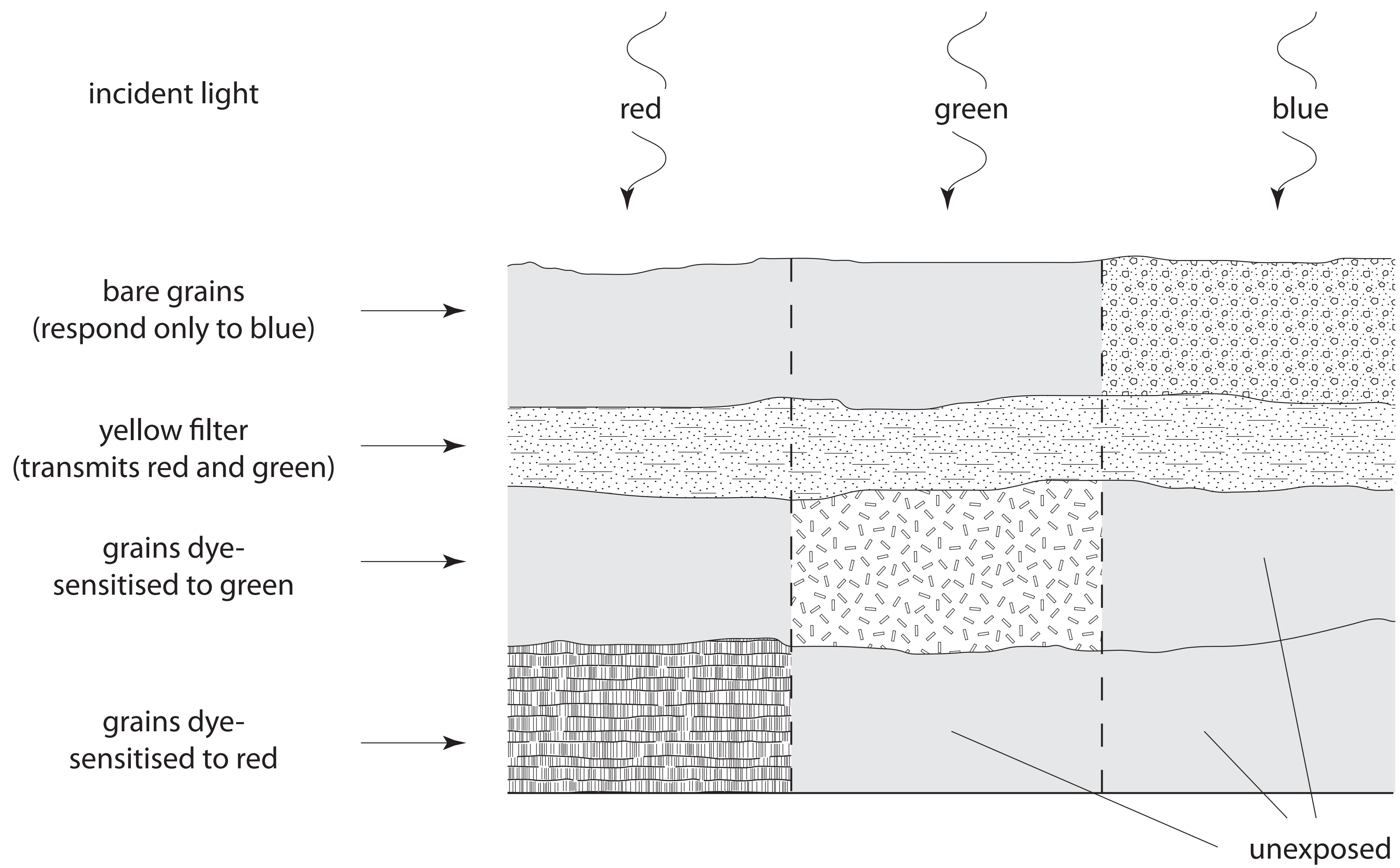
if this development centre reaches a critical size (3 or 4 Ag atoms) the grain becomes developable by catalysing the reducing of Ag^+ to Ag_2 by chemical processing

Photography: energetics

- for AgBr the bandgap (ΔE valence-conduction band) is 2.81 eV, or hν = 440 nm
- hence, the intrinsic spectral sensitivity of photographic emulsions is limited to the blue
- towards the ultraviolet, the gelatin absorbs light, cutting off below λ<300 nm
- extension redwards is by 'dye sensitisation': a red (or green) absorbing dye is adsorbed onto the silver halide grains

- only the grain surface takes part in the initial photon detection
- there are different explanations of the basic physics: e.g. the photon creates a conduction electron in the dye, which is transferred into the conduction band of the halide crystal

- colour photography is then based on a depthwise superposition of various emulsions



The Eye

Rhodopsin: the basis of all visual systems

Rhodopsin:

- a biological pigment of the retina
- a photoreactive chromophore (the part of a molecule responsible for its colour)
- responsible for the formation of the photoreceptor cells and the first events in the perception of light
- consists of a protein part (opsin) and a reversibly covalently bound cofactor (retinal)
- rhodopsin of the rods most strongly absorbs green-blue light and therefore appears reddish-purple
- it is responsible for monochromatic vision in the dark

Opsin:

- a bundle of seven transmembrane helices connected to each other by protein loops
- it binds retinal which is located in a central pocket on the seventh helix at a lysine residue
- other closely-related opsins differ in a few amino acids and in the wavelengths they absorb most strongly
- humans have four different other opsins besides rhodopsin:
    - the photopsins are found in the different types of the cone cells, and are the basis of color vision
    - absorption maxima for yellowish-green (photopsin I), green (photopsin II), and bluish-violet (photopsin III) light
    - the remaining opsin (melanopsin) is found in photosensitive ganglion cells and absorbs blue light most strongly

Retinal:

- produced in the retina from Vitamin A, from dietary beta-carotene
- molecular formula $C_{20}H_{28}O$
- IUPAC designation: (2E,4E,6E,8E)-3,7-dimethyl-9-(2,6,6-trimethylcyclohexen-1-yl)nona-2,4,6,8-tetraenal
- mammals use retinal exclusively as the opsin chromophore
- other groups of animals additionally use four chromophores closely related to retinal

Photoisomerisation of retinal

Vision begins with the photo-isomerisation of retinal:

- when the 11-cis-retinal chromophore absorbs a photon it isomerises from the 11-cis state to the all-trans state
- the absorbance spectrum of the chromophore depends on interactions with the opsin protein to which it is bound
- different opsins produce different absorbance spectra
- isomerisation induces a conformational change (bleaching) in opsin
- this continues with metarhodopsin II, which activates the associated G protein transducin
- triggers a second messenger cascade

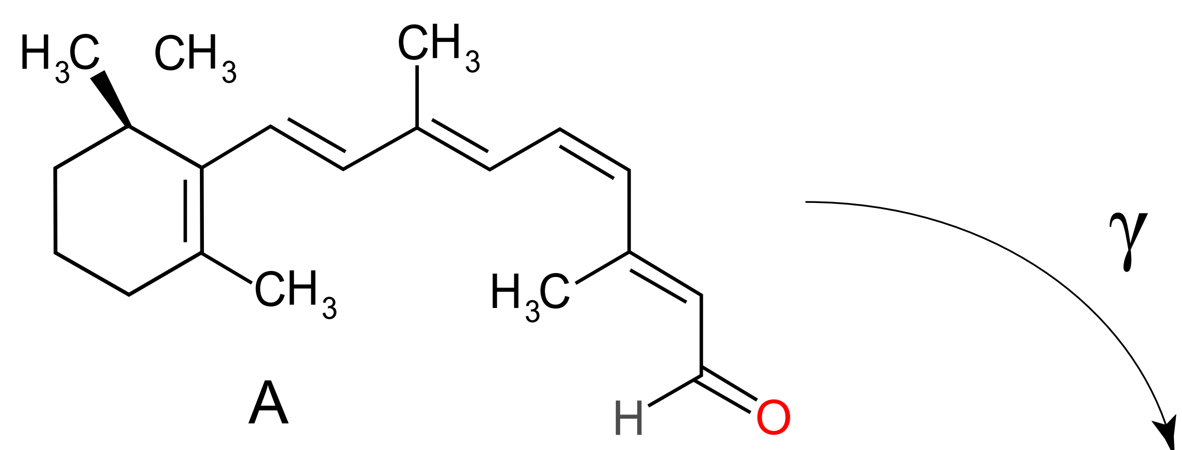
The structure of rhodopsin has been studied via x-ray crystallography:

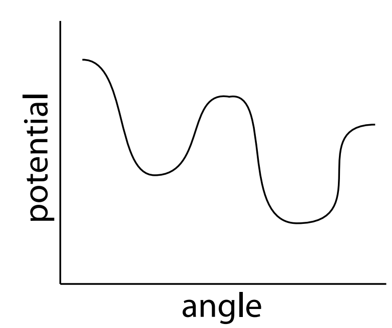
- the photoisomerisation dynamics has been investigated with time-resolved IR/UV/visual spectroscopy
- the first photoproduct (photorhodopsin) forms within 200 fsec after irradiation (one of the fastest chemical reactions)
- its is followed within a psec by a second photoproduct called bathorhodopsin with distorted all-trans bonds
- the visual cycle is a circular enzymatic pathway, which regenerates 11-cis-retinal

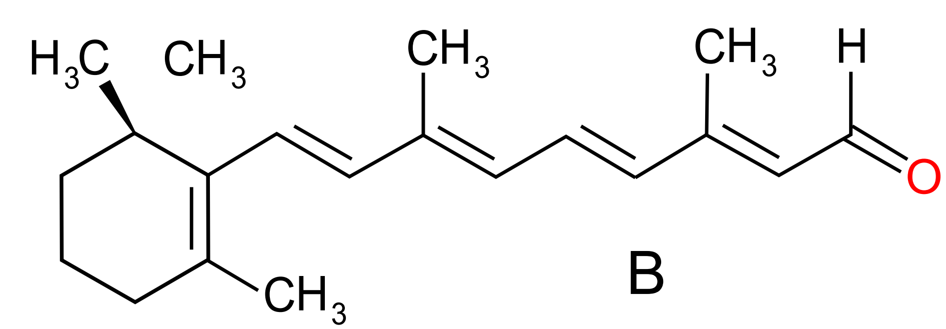
The eye is almost photon counting at low light levels

There are two subsequent pathways which switch according to illumination level: a linear path, and a logarithmic path (dark adaption)

Even Richard Dawkins considers the eye as *"dauntingly complex"*







Vision in other animals

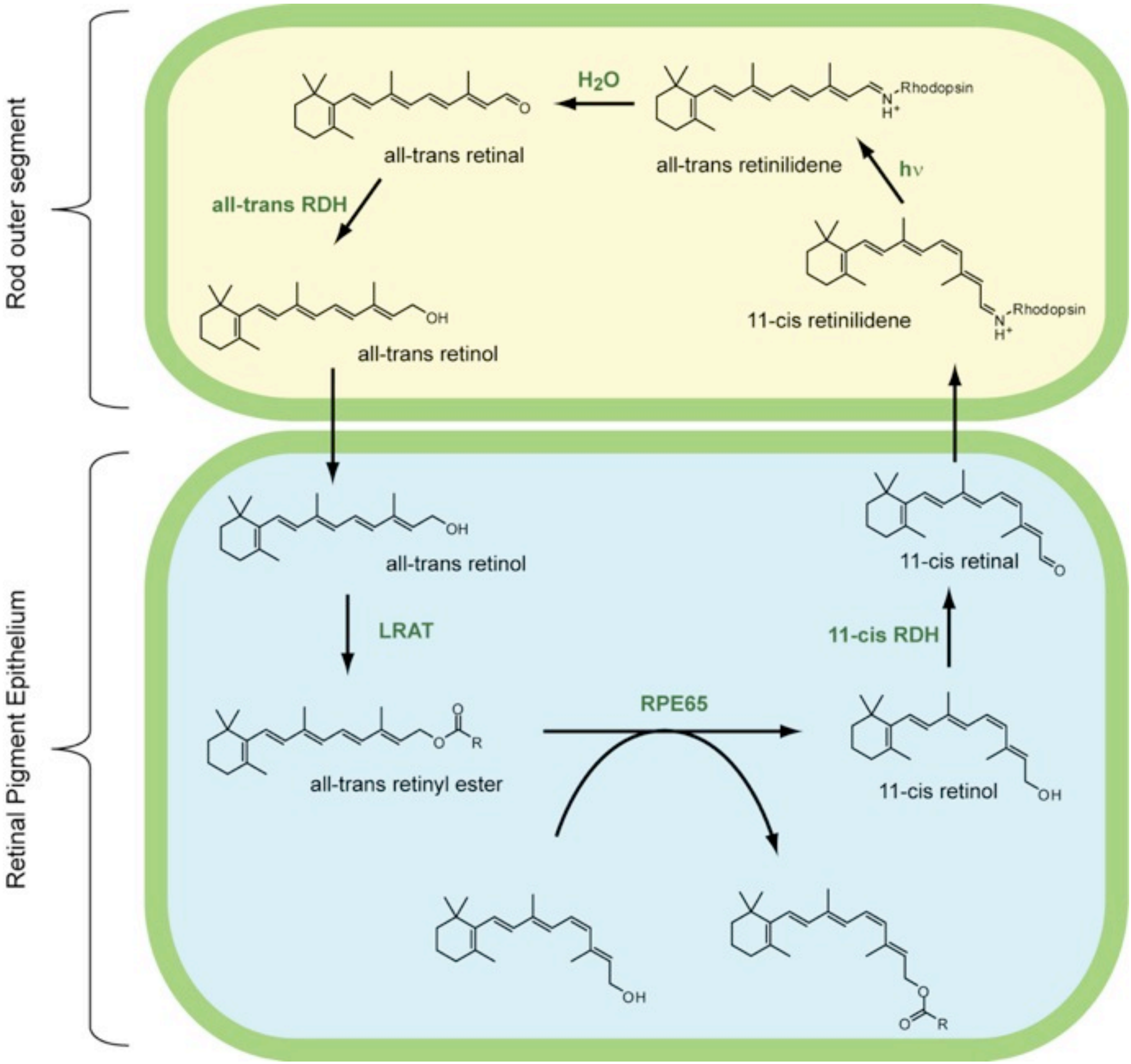
Chromatic vision:

- physiology of colour perception is complex...
- human-related primates: 3-colour receptors > trichromatic vision
- most mammals: dichromatic, specifically red-green colour blind
  (human trichromatic vision considered to have evolved with diurnal activity and eating fruit)
- bees: trichromatic, but ultraviolet/blue/green (not red) sensitive
- some butterflies are 5-colour
- birds: 4-colour, but pigeons may be pentachromatic
- the most complex systems: mantis shrimp with 12 spectral receptors
- many animals (and some cataract patients) can detect ultraviolet light
- dung beetles navigate by the Milky Way (Dacke+2013, Current Biology, and 2013 Ig Nobel...)

Polarisation:

- rhodopsin has a dipole axis ⇒ direction of maximum linearly polarised sensitivity
  - in humans, the rhodopsin molecular axes are randomly oriented (avoids sensory overload)
- compound insect eyes have rhodopsin arranged as star-like waveguides
  - polarisation sensitivity is maximal up (for navigation) and averaged down (limits confusion)
- humans have some sensitivity, which can be trained to detect polarised light:
  - discovered by von Haidinger (1795-1871): Haidinger's brush; explained by von Helmholtz)
  - reported by Minnaert (1993): *'I can see it particularly clearly in the twilight when I stare at the zenith'*

The visual cycle of mammalian rod cells...



included only to show that the entire pathway is bizarrely complex!

(Human) Vision

Vision is a remarkable process by which we are able to interpret an image from light the eyes receive from the objects around us. Although the process depends on the interplay of many different factors (including the optics of the eye, the isomerisation of retinal, nerve impulses, and the brain's ability to reconstruct the image), vision is <u>fundamentally based</u> on the change in the molecular orbitals of retinal that occurs when the molecule absorbs energy in the form of light

When visible light hits the chromophore (retinal):

- a p electron is promoted to a higher-energy orbital, allowing free rotation about the bond between carbon atom 11 and carbon atom 12 of the retinal molecule
- about half the time, this rotation leads to the isomerisation of retinal when the p electron returns to the lower-energy orbital
- when retinal isomerises, a conformational change in the protein opsin occurs. This initiates a cascade of biochemical reactions that result in the closing of Na+ channels in the cell membrane
- when the Na+ channels are closed, a large potential difference builds up across the plasma membrane; this is passed along to an adjoining nerve cell as an electrical impulse
- the nerve cell carries this impulse to the brain, where the visual information is interpreted

www.chemistry.wustl.edu/~edudev/LabTutorials/Vision/Vision.html

Superconducting Tunnel Junctions

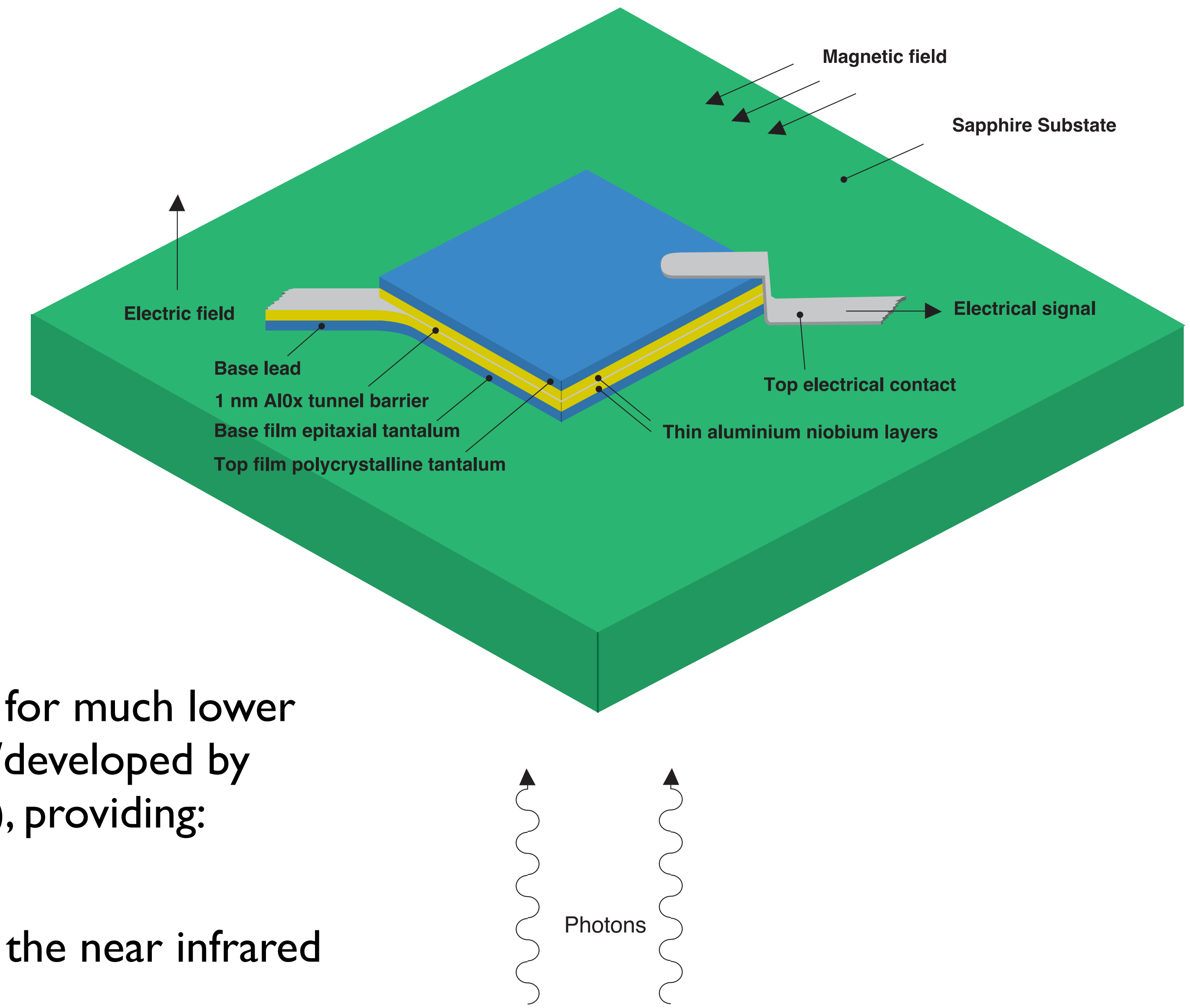
In Context

- superconducting imaging technology is widely used across ground and space mm, sub-mm, and far-infrared observatories:
  - both present: JCMT, APEX, IRAM, ALMA, Herschel
  - and future: CCAT-Chile, GLT-Greenland, SPICA, post-Planck PRISM

- various generic types:
  - TES: Transition Edge Sensors (bolometers)
  - CEB: Cold Electron Bolometers (related)
  - KID: Kinetic Inductance Detectors: large arrays
  - SIS mixers: Superconductor-Insulator-Semiconductor
  - HEB: Hot Electron Bolometers

Superconducting Tunnel Junctions (STJs)

- interest in superconducting junctions as X-ray time-resolved detectors developed in the 1980s
- STJs = superconductor−insulator−superconductor
- an X-ray absorbed in one of the films breaks a large number of bound 'Cooper pairs' (described by BCS theory)
- these quantum-mechanically tunnel through the insulator, and the resulting electron flow is detected as a current pulse
- with E(X-ray) ~ few keV, and energy gap Δ~1 meV gives a large number of electrons per photon



- realisation that the same principle could be applied for much lower energy photons, in the optical, was first announced/developed by Perryman et al (1993, Nuclear Inst Meth A325, 319), providing:
  - single photon counting
  - broad spectral response from the ultraviolet to the near infrared
  - arrival time information to ~1 μs
  - energy resolution (R=10-50)

- this led to the first experimental measurement of an individual optical photon energy, without using filters or spectroscopy (Peacock, Perryman et al, 1996, Nature, 381, 135)

STJs: some numbers

- the detector is operated at a small fraction of the critical temperature, ~ 0.1 T_{crit} (~1°K for Nb)
- tunneling is fast with respect to recombination
- at 400nm, $h\nu$ = 3eV, resulting in a number of tunneling electrons ~ 1100

Material	T_{crit} (K)	Δ (meV)
Nb	9.3	1.5
Ta	4.5	0.7
Al	1.2	0.2

A 10x12 pixel detector by the ESA Astrophysics Division (Peacock, Perryman et al) demonstrated:

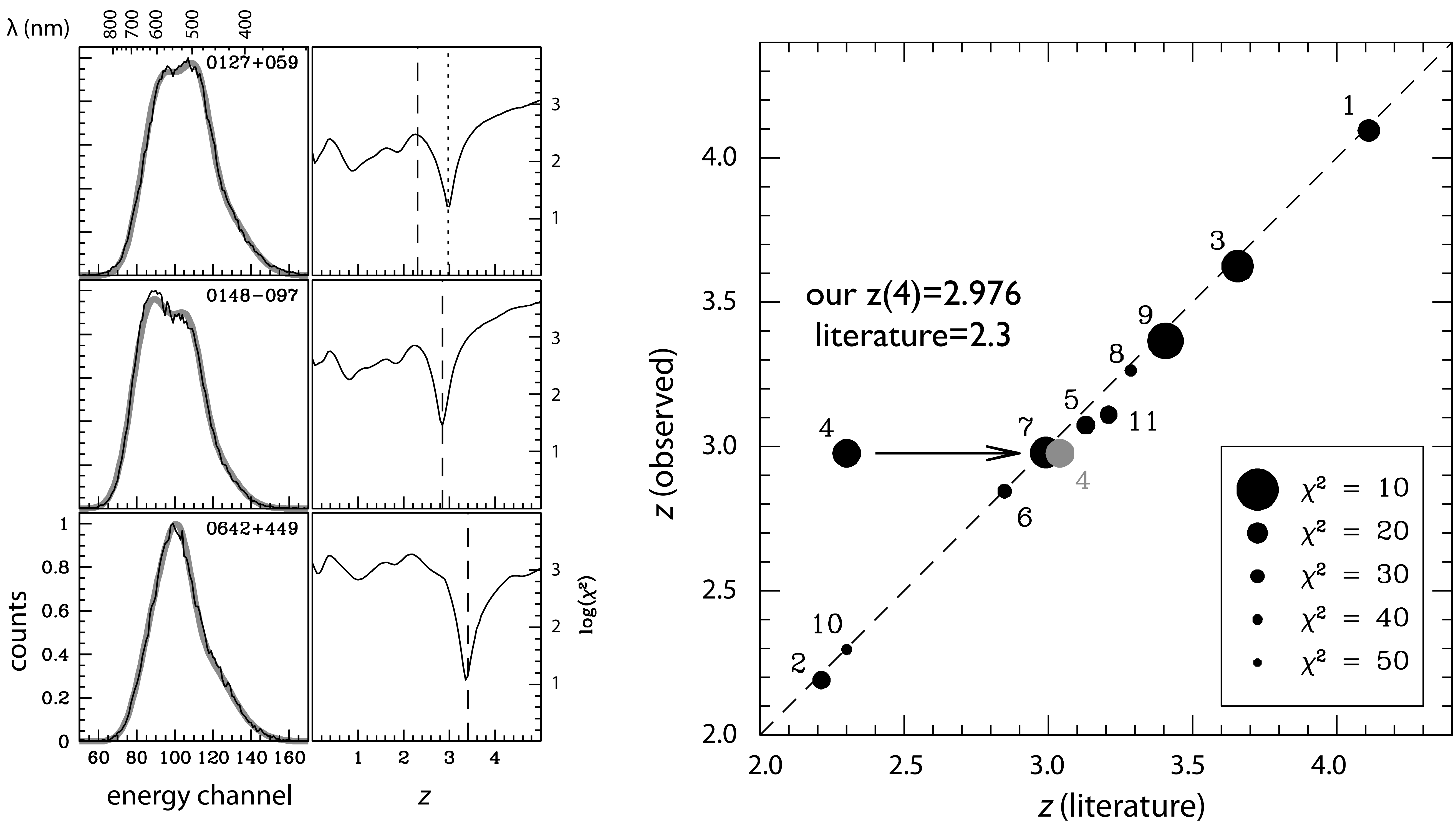
- single photon counting
- an intrinsic energy resolution of $\lambda/\Delta\lambda$~30 for Nb (extrapolates to $\Delta\lambda$~8 nm for Sn)
- a time resolution ~1 μs in the recorded photon arrival times
- a high quantum efficiency: theoretically can approach unity across UV to near IR
- spatial resolution

... with a range of scientific results including:

- 1999: Optical STJ observations of the Crab pulsar (Perryman et al)
- 2001: High-speed energy-resolved STJ photometry of the eclipsing binary UZ For (Perryman et al)
- 2002: Direct determination of quasar redshifts (de Bruijne et al) ***
- 2003: Temperature determination via STJ optical spectroscopy (Reynolds et al) ***
- 2003: A concept for a STJ-based spectrograph (Cropper et al)
- 2006: Absolute timing of the Crab Pulsar at optical wavelengths with STJs (Oosterbroek et al)

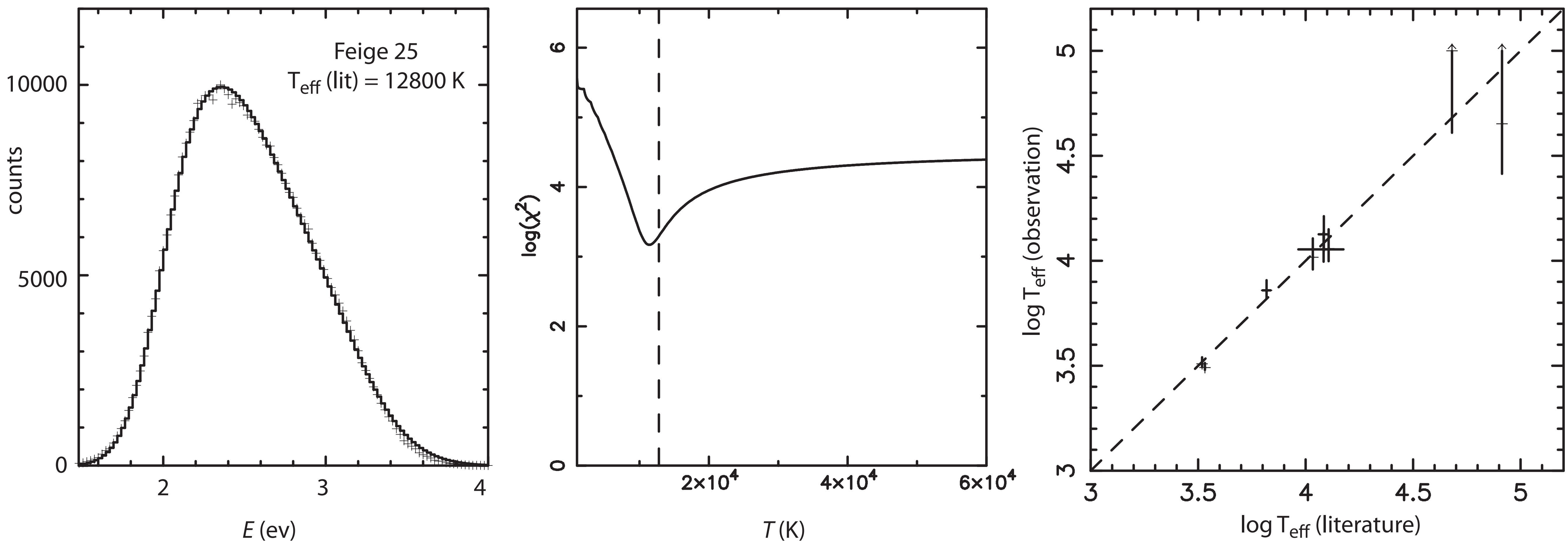
Example 1: determination of quasar redshifts

(de Bruijne et al 2002)



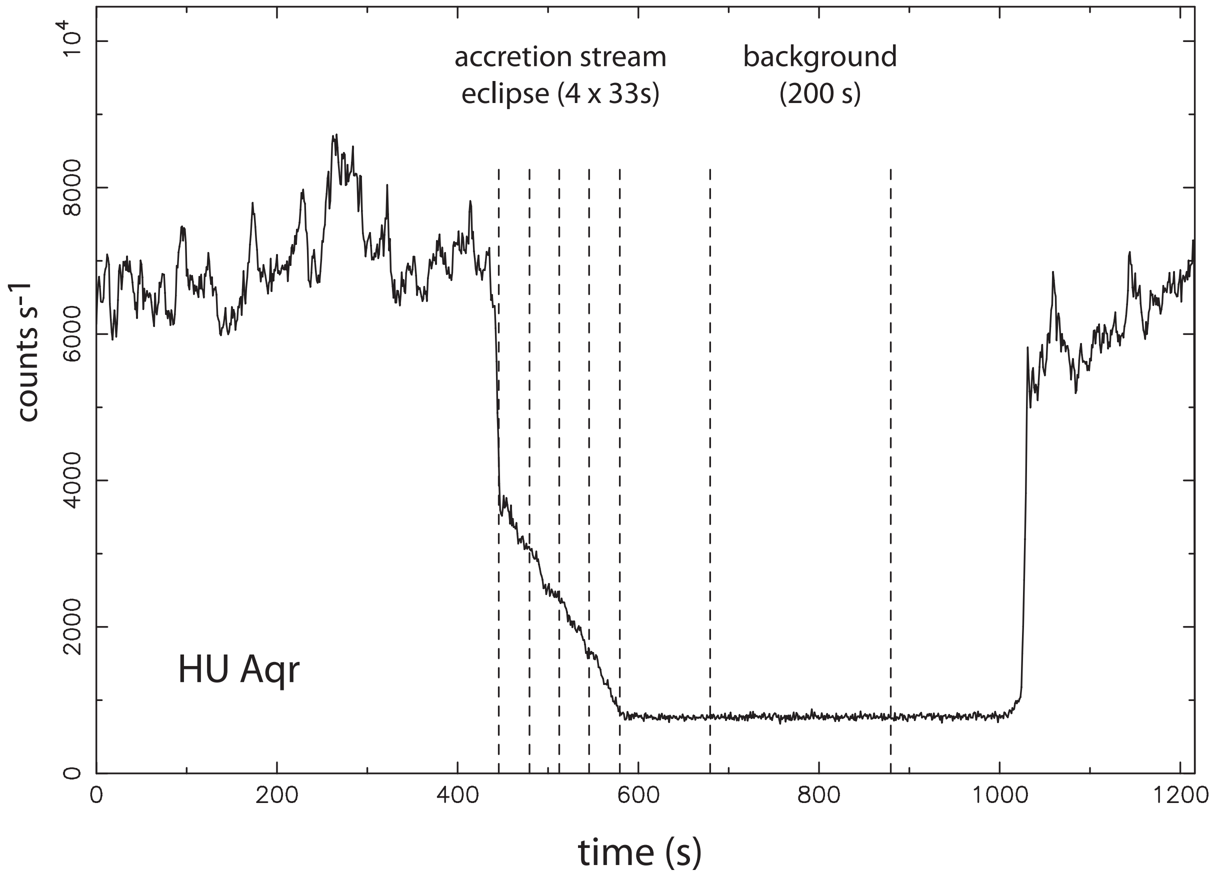
Example 2: determination of T_{eff}

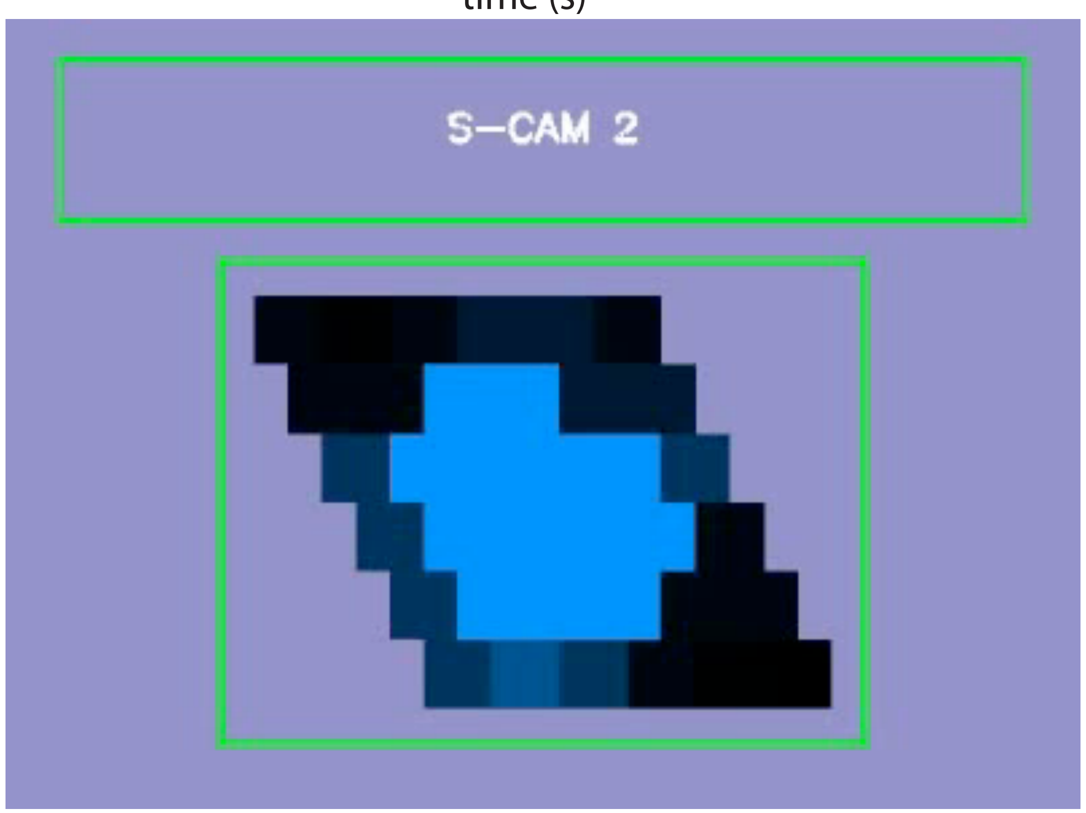
(Reynolds et al 2003)

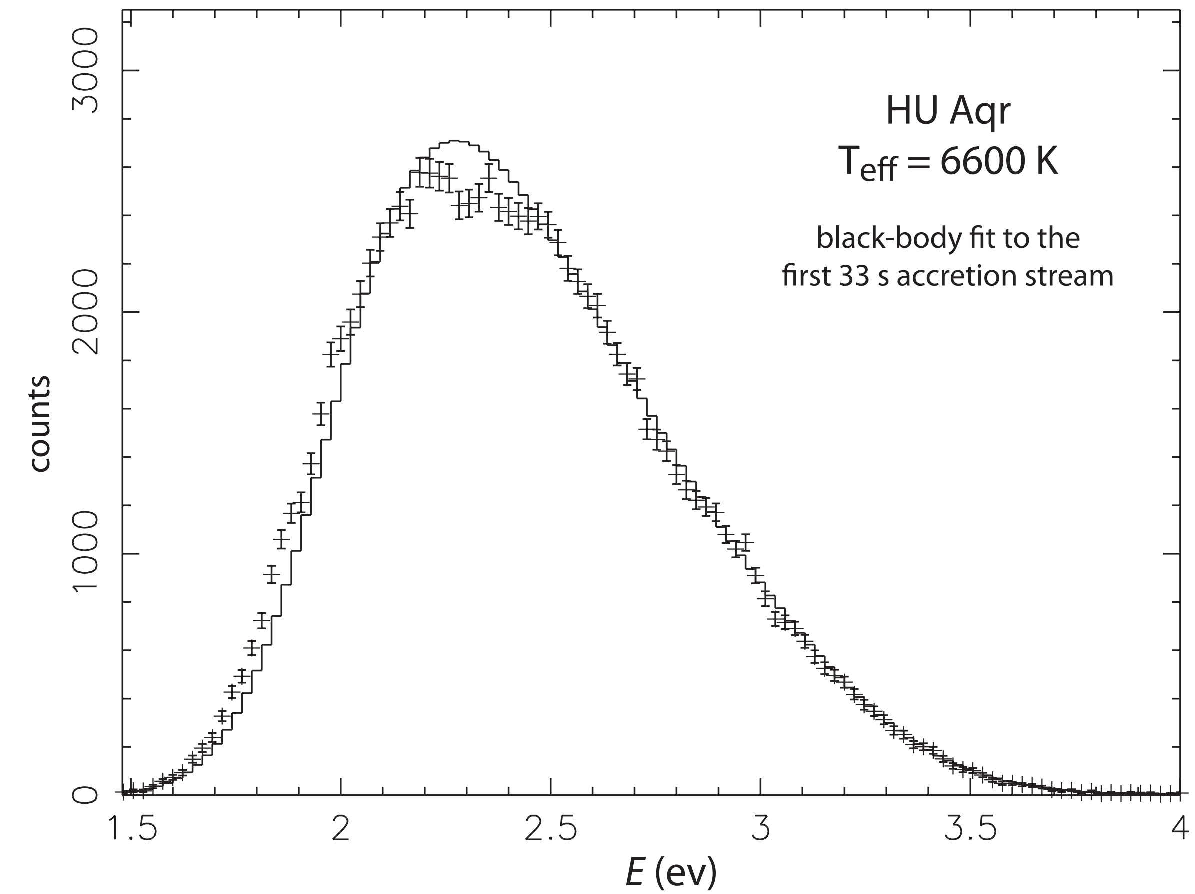


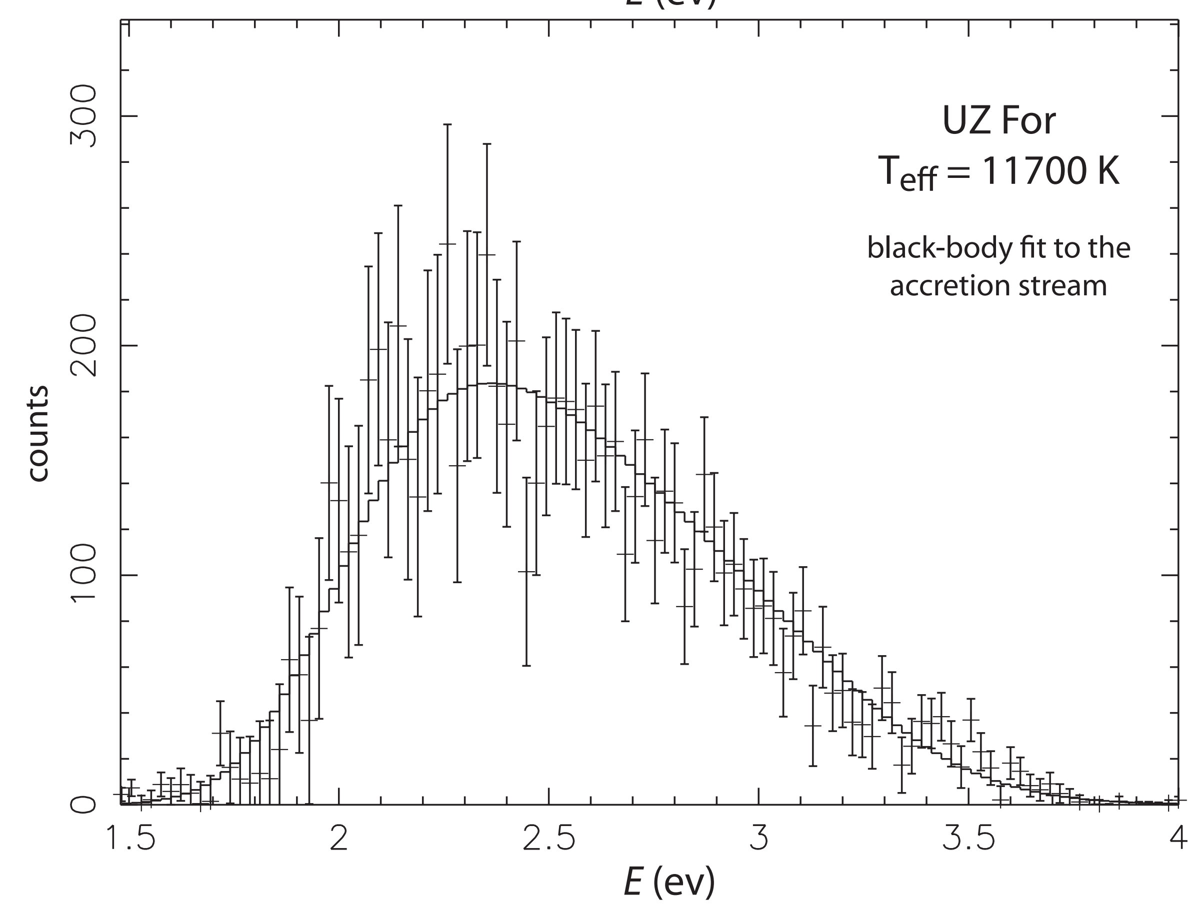
Example 3: time variability of magnetic CVs

(Reynolds et al 2003)









Related optical instrument developments...

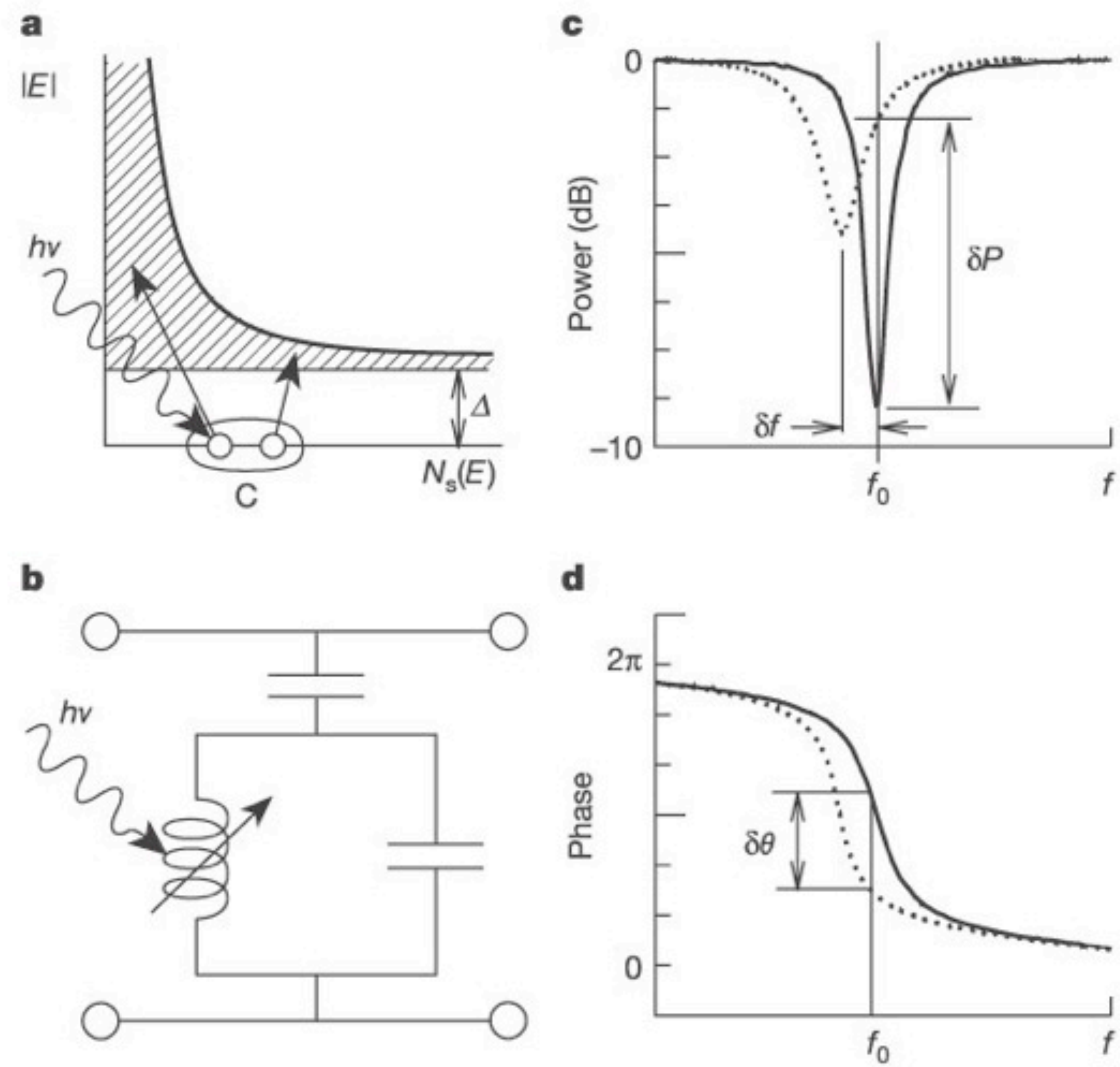
- Transition edge sensors/cameras:
  - large change in resistance accompanies the superconducting to normal transition
  - leads to a pulsed-decrease in the device current
  - current application in the optical: Romani et al (2008)
  - Crab observations at McDonald 2.7m: Romani et al (1999, 2001)
  - candidate for the X-ray microcalorimeter spectrometer on IXO
- MKIDS (Microwave Kinetic Inductance Detectors)
- QuantEYE (for E−ELT) and AquEYE (Asiago prototype)
  - probing us to ns timescales, using single photon APD arrays (Dravins 2006)
  - arrival times inform how the photon stream was created, or modified
  - Crab observations with AquEYE: Germana (2012)
- exploiting photon detection/properties more widely:
  - quantum information groups: qubits for quantum computing

MKIDs

- ARCONS at the Palomar 200-inch, 46x44 pixel (20" x 20") array
- R ~ 8 at 400 nm, wavelength: 400−1100 nm, Δt ~ 1 μs
- principles: Day et al 2003
- instrument: Mazin et al 2013

Principles:

- photon creates quasiparticles
- changes surface impedance through kinetic inductance (Mattis & Bardeen 1958)
- s/c is in a high-frequency resonance circuit
- photon absorption changes the resonator's phase and amplitude
- multiplexing by tuning each pixel to a different resonant frequency
- microwave probe signal: 0.1-20 GHz

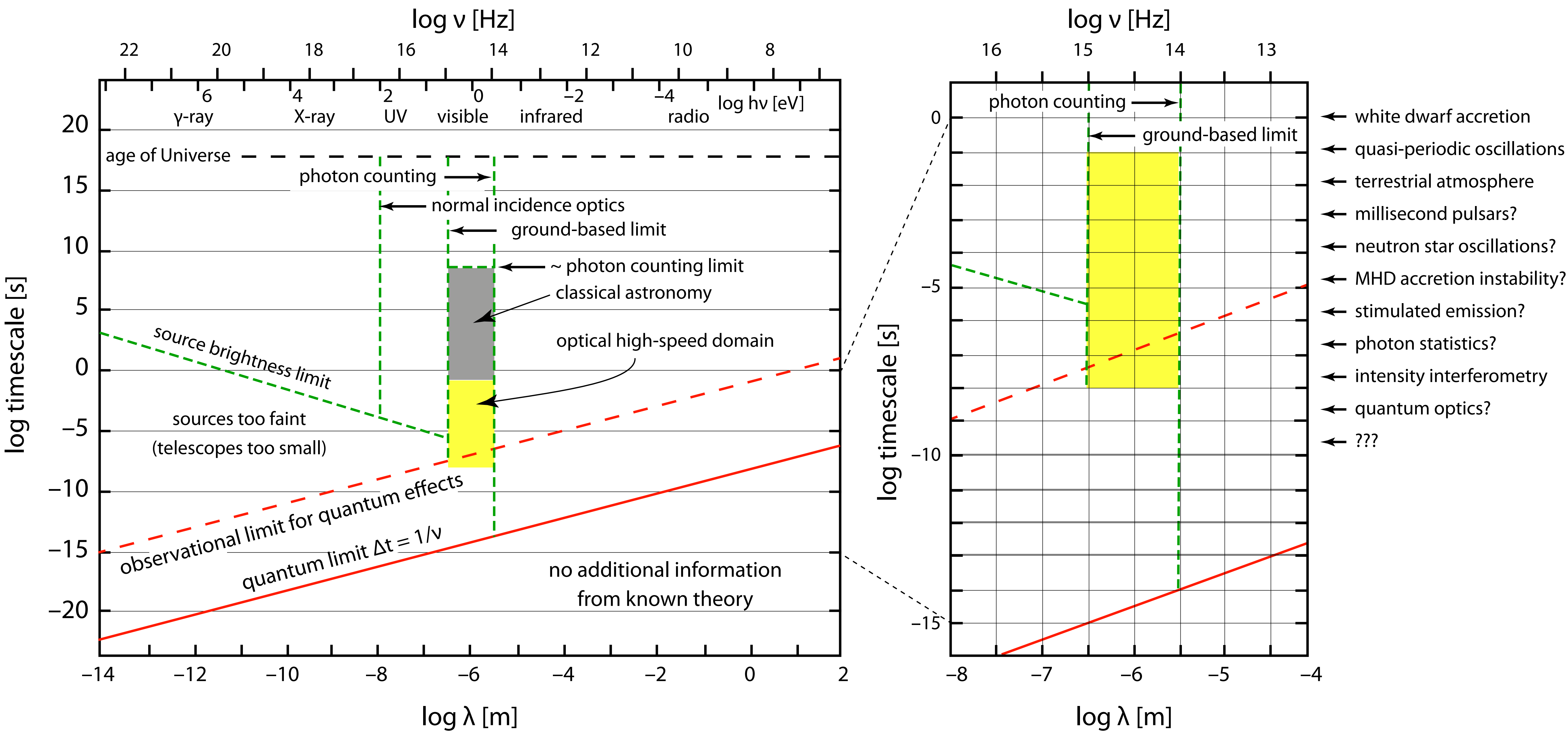


Science:

- Crab giant pulse observations: Strader et al (2013)
- orbital period changes in SDSS J0926: Szypryt et al (2013)

Time domain astrophysics...

Dravins (1994): ESO Messenger No. 78



- example physics:
    - coherent emission in fast radio bursts: Thornton et al (2013), Katz (2013):
    - *'the bursts do not correspond to any known astronomical phenomenon, but suggest that similarly fast phenomena may be observable at other frequencies'*

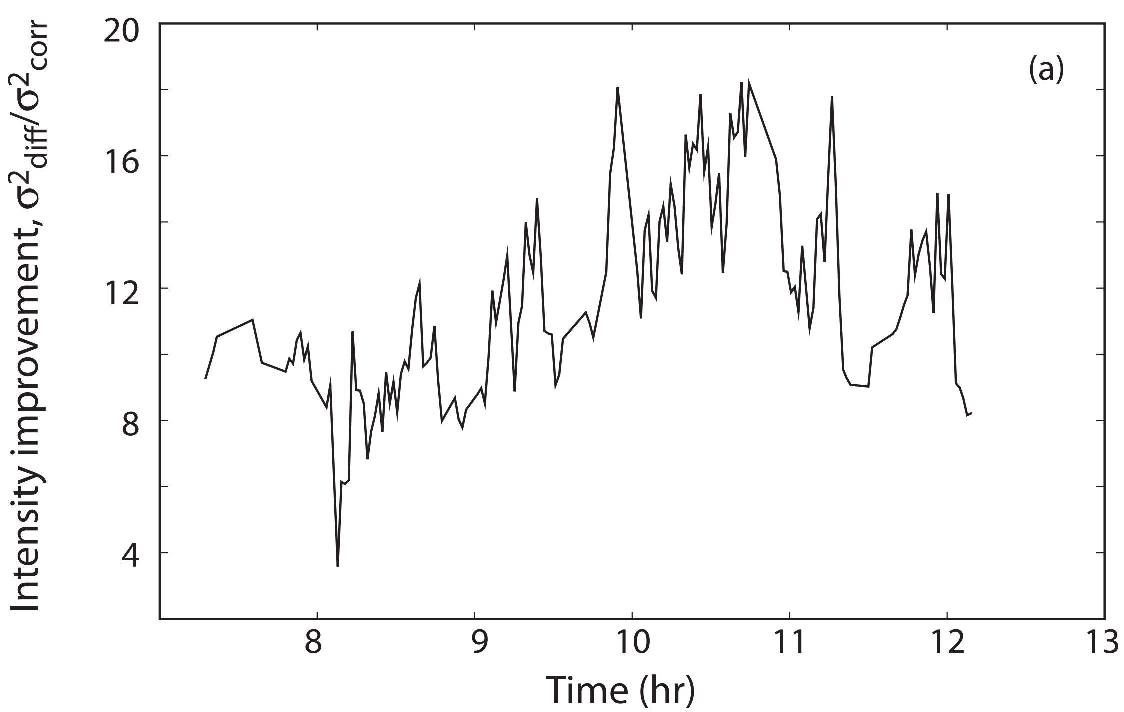
Atmospheric influence on exoplanet transits (1)

- CoRoT and Kepler exploit the better photometric capabilities above the atmosphere
- what are the limits from the ground? Details are complex, but they include:
  - atmospheric transparency variations: dry sites required; wavelengths optimised
  - atmospheric scintillation: dominates at dry sites; not assisted by differential photometry
  - detector granularity/red-noise: autoguiding, defocusing (Southworth+ 2010, Pont+ 2006)

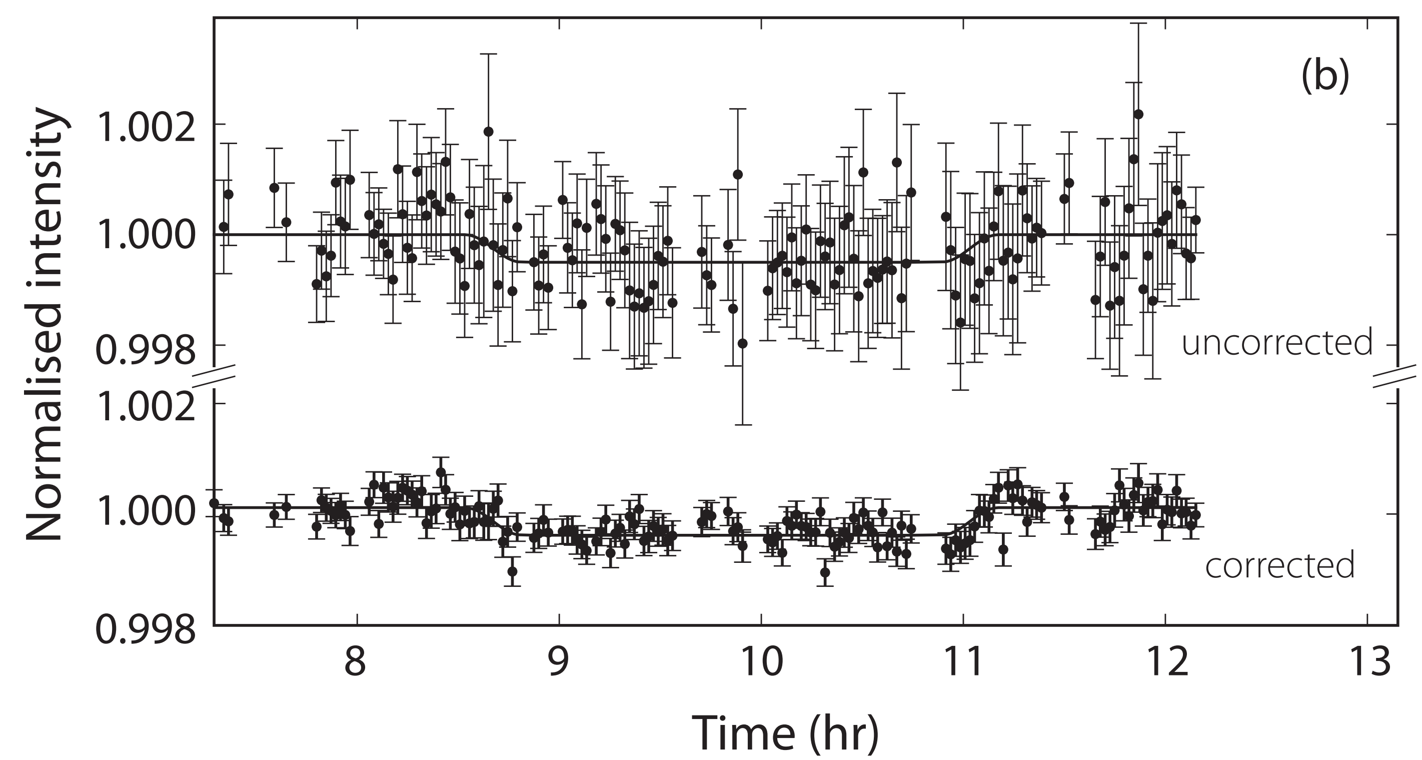
- Refractive index variations within the turbulent atmosphere introduce both:
  - <u>phase fluctuations (seeing)</u>
    - first-order effect (wavefront angle) responsible for 'seeing' and image motion (the change in the angle of the arriving wavefront degrades image resolution)
    - results from integrated effect of light propagating through the full atmospheric depth (although may be dominated by well-identified layers - near to ground [GLAO] or high up)
    - can be (partly) corrected using adaptive optics, and differential photometry
    - such efforts have been intensive and highly successful
  - <u>intensity fluctuations (scintillation)</u>
    - second-order effect (wavefront curvature) ⇒ space/time-varying intensity (twinkling)
    - arises from turbulent refocusing, therefore dominated by high-altitude turbulence (photons fall outside the pupil when they should have been collected, and vice versa)
    - intensity changes are unaffected by AO correction
    - high-altitude origin + small angular coherence scale results in *increased* scintillation noise for calibration wrt comparison star (Osborn+2011)

Atmospheric influence on exoplanet transits (2)

- conjugate-plane photometry proposed by Osborn et al (2011)
  - telescope pupil is conjugated to the dominant high-atmosphere turbulent layer (not ∞)
  - then apodising the pupil before calibration using a reference star
  - conceptually:
    - a mask blocks the light from outside of a slightly smaller 'high-altitude' entrance pupil
    - an oversize mirror collects the light that is sometimes refracted outside it
  - simulations suggest up to x30 improvement on variance, x10 from model observations



modeled improvement in intensity variance from telescope data (Osborne et al 2011)



simulated light curves of a secondary eclipse, with and without corrections: transit depth=0.05%, V=11, D=2m, Δt=30s

Resolving an exoplanet surface

- precursors:
  - TPF: detecting spectroscopic signatures: 6m x 3.5m coronagraph (TPF-C)
  - Life Finder to detect 7.6μm CH_4 would require (Woolf 2001):
    - 5 x 8m telescopes for a planet at 3.5 pc
    - 80 x 8m telescopes for a planet at 15 pc

- Planet Imager - for resolving an Earth at 10pc (Bender & Stebbins 1996):
  - 10x10 pixels: requires 20 x 10m telescopes over 200 km baseline
  - 100x100 pixels: requires 200 telescopes over 2000 km baseline, and t_{obs} = 10 yr

- solar gravitational lensing (??):
  - at >550 AU for the opaque sun (SETI): Eshleman 1979, Maccone 1993-2008
  - at > 25 AU for the 'transparent' sun (gravitational waves & neutrinos): Patla & Meniroff 2008

- superlenses (???):
  - diffraction: evanescent waves carry sub-λ resolution but decay exponentially
  - metamaterials with n<0 aim to enhance evanescent waves (Veselago 1968)
  - λ/6 resolution at 365nm reported (Fang et al 2005)
  - May & Jennetti (SPIE, 2004) postulated that evanescent waves reflected off a primary telescope mirror could be amplified to sharpen the focus below the diffraction limit

Linear, Spin, and Orbital Angular Momentum

An individual photon possesses:

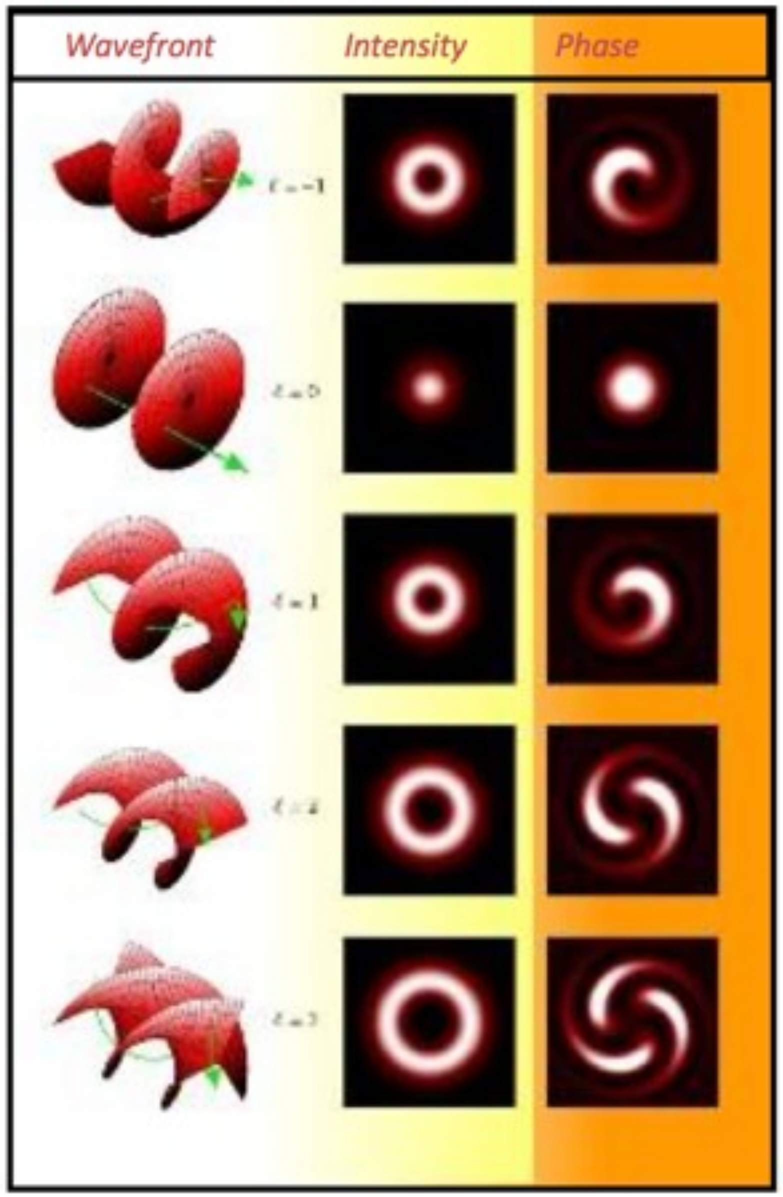
- energy: $h\nu$
- linear momentum: $h\nu/c$
- spin and orbital angular momentum (in both classical e-m and quantum theory):
  - spin angular momentum: associated with polarisation
  - OAM: associated with the azimuthal phase of the complex electric field (see next)
- spin/polarisation:
  - intrinsic spin (s=1): $\pm\hbar$ projected on the direction of propagation
  - $\pm\hbar$ (helicity) correspond to left/right circular polarisation
  - polarisation of a single photon described by a mixture of states
  - linear polarisation = superposition of states with equal probabilities
  - mechanical macroscopic measurement by Beth (1936) Phys Rev 50, 115
  - recent results e.g. Arita (St Andrews), Nature Comm (Aug 2013) demonstrate a micro-gyroscope (4 μm $CaCO_3$ sphere) spun up to 5 MHz
  - no discussions of single photon spin measurement for astronomy...

Orbital Angular Momentum: application

- Background:
  - Mandel & Wolf (Quantum Optics 1995, p488)
  - mathematical formulation: Allen et al (Phys Rev A, 1992)
- each photon of a beam with azimuthal phase dependence exp($il\varphi$) carries orbital angular momentum $l\hbar$ (= number of 'helicoidal twists' along a wavelength)
  - over the past 15 years, developed for classical and quantum communications
  - no limit on number of orthogonal states, and hence on $\log_2 l$ bits carried by a single photon
  - photon beams with l = 200 produced by Curtis et al (2002), see also Leach et al (2004)
  - photon orbital angular momentum can be transferred to small particles (He et al 1995)
  - can be measured at the level of an individual photon (Leach et al 2002, PhysRevLet)
  - astrophysical sources/effects might include (Harwit 2003):
    - maser beam + luminous sources (pulsar/quasar) passing through an inhomogeneous medium
    - angular momentum absorption by black holes (Teukolsky 1972, Mashhoon 1973, Tamburini et al 2011)
    - MACHOs?
    - probing of the CMB
    - SETI signal encoding: more information per photon compared with the radio (Tamburini 2012)
    - entangled photon pairs and ghost imaging: Sterkalov (JPL) 2013

Orbital Angular Momentum: coronagraphy

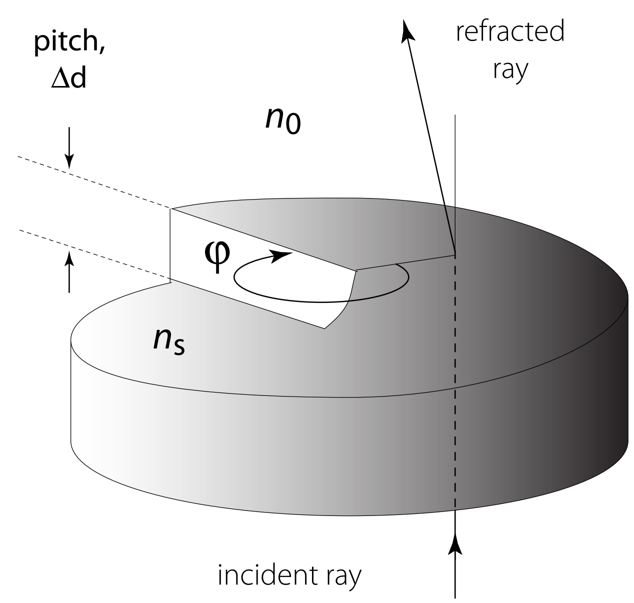
l = topological charge



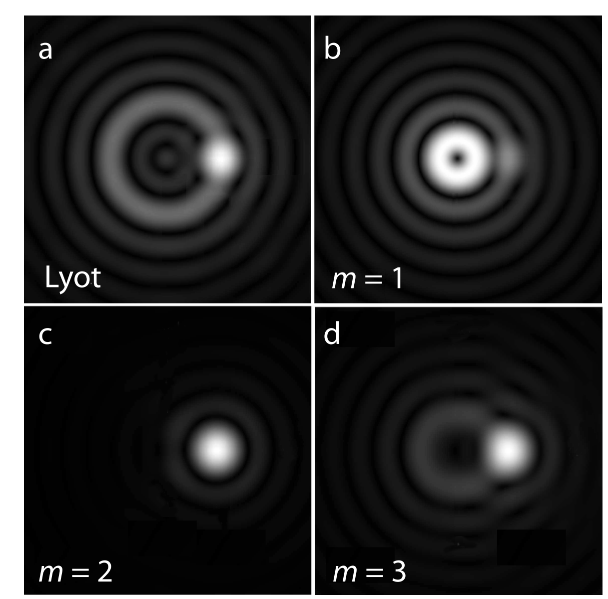
wavefront has helical shape, with *l* lobes disposed around *z*;
along the z-axis is a phase singularity (the optical vortex) where intensity = 0

- proposed for exoplanet coronagraphy as:
  - optical vortex coronagraph: Swartlander (2001), Foo et al (2005)
  - annular groove phase mask: Mawet et al (2005)
  - quantum coronagraphic mask: Tamburini et al (2006)

- astronomical tests: Swartlander+ 2008, Mawet et al (2010)
- 1.5-m sub-aperture of Hale: Serabyn et al (2010) observed the 3 planets around HR 8799, the innermost separated by 2λ/D
- sub-Rayleigh source detection, at 0.1λ/D: Mari+2012



a phase mask
(Swartlander 2006)



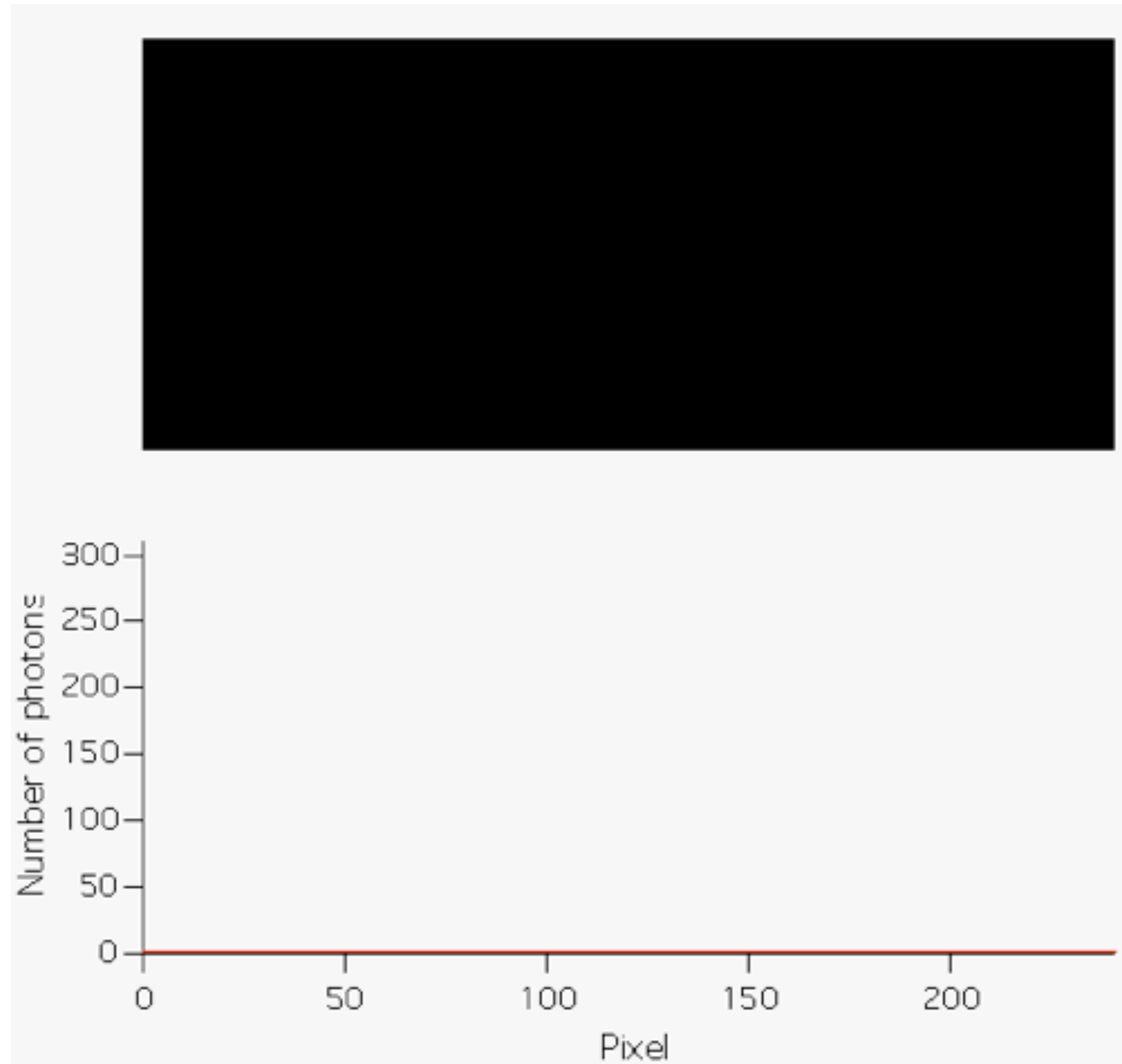
planet simulation: 100:1 at *l*=1
(Foo et al 2005)

Photon coherence length

- demonstration of wave-particle duality using Young's slits at a single photon level

- Hoy & Odeurs 2012 (Can. J. Phys.):
  - tutorial on wave-particle duality
  - calculating the photon wave-function requires "*specific advanced physics and mathematics which does not lead to a straightforward interpretation of concepts such as coherence length*"
  - simple model to derive space-time probability distribution function for observing a photon
  - related to photon coherence length

- Fong 2013 (arXiv):
  - proposes to measure photon coherence in continuum radiation
  - coherence time probes density, e.g.:
    - base of the solar photosphere
    - relative quasar redshifts
    - collisional broadening during CMB annihilation era



Jacques et al (2005)

...the pace of recent developments is
perhaps illustrated by...

“Photography remains the best detection method for many observations in the X-ray, ultraviolet, visible, and very near infrared”

(Rieke ‘Detection of Light’ 1996)

My conclusions...

improved ways of detecting optical photons await discovery

(cf recent work on STJ, TES, MKID)

improved ways of treating detected photons await development

(e.g. scintillation)

ways of detecting additional photon information await discovery

(t, $h\nu$, spin/helicity/polarisation, orbital angular momentum)

new physical information carried by photons await discovery

(black hole spin, CMB, SETI)

End