X-RAY TELESCOPES AND DETECTORS

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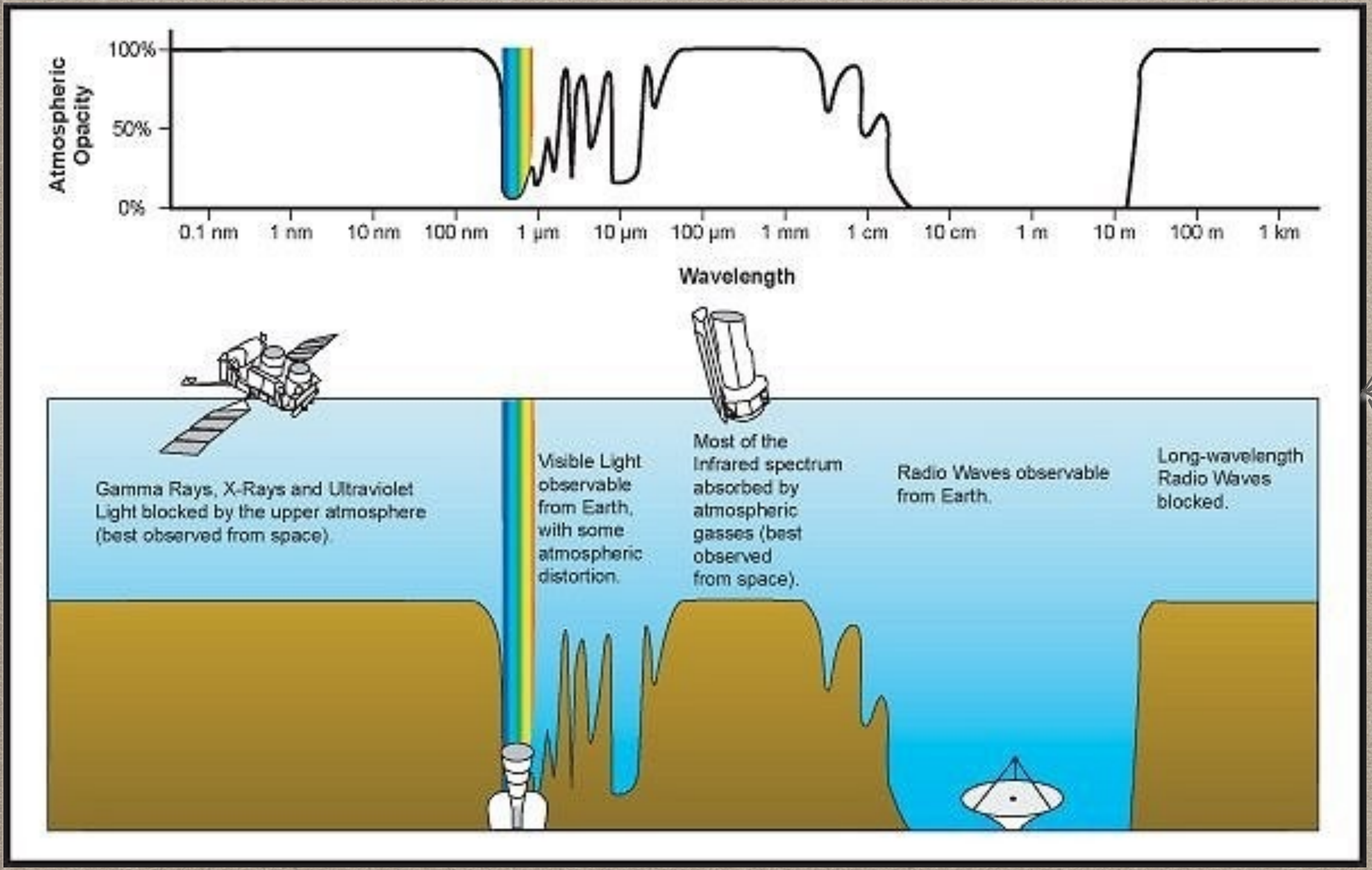
WHY SATELLITES?

(Courtesy LCOGT)



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

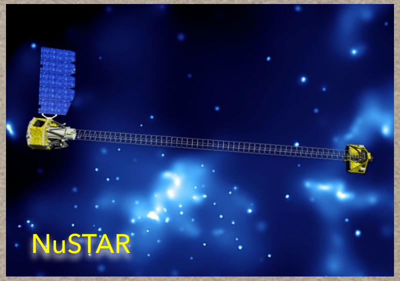
Visible Light observable from Earth, with some atmospheric distortion.

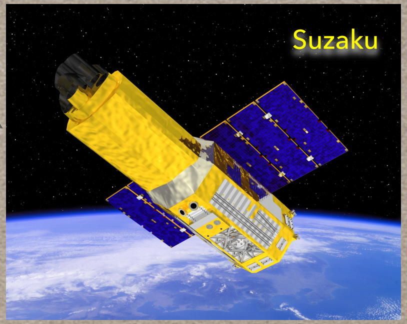
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

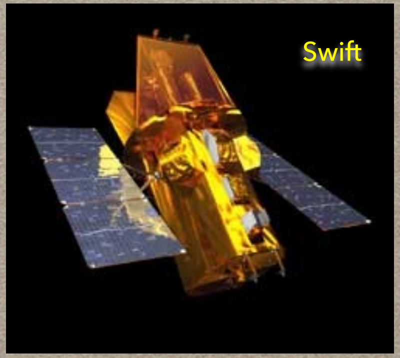
Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.

[… and why so many?]







OUTLINE

- How do we “focus” X-rays?
- How do we detect X-rays?
- Which quantities characterise the instrument performances (and must be *calibrated*)?

[No “gratings” in this lecture. More in the lecture by A.Ibarra tomorrow]

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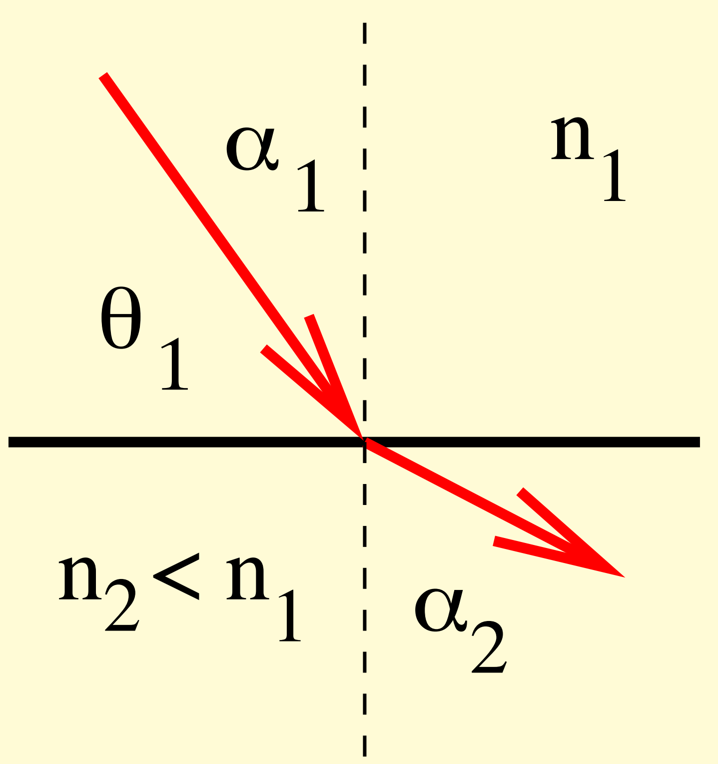
TOTAL REFLECTION



Snell's law: $$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{n_2}{n_1} = n$$

Total reflection: $\alpha_2 = 90^\circ \Rightarrow \theta_c \equiv \pi/2 - \alpha_{1,c} = n$ **[1]**

Maxwell relation: $$n = \sqrt{\epsilon\mu}$$

Metals: **[2]**

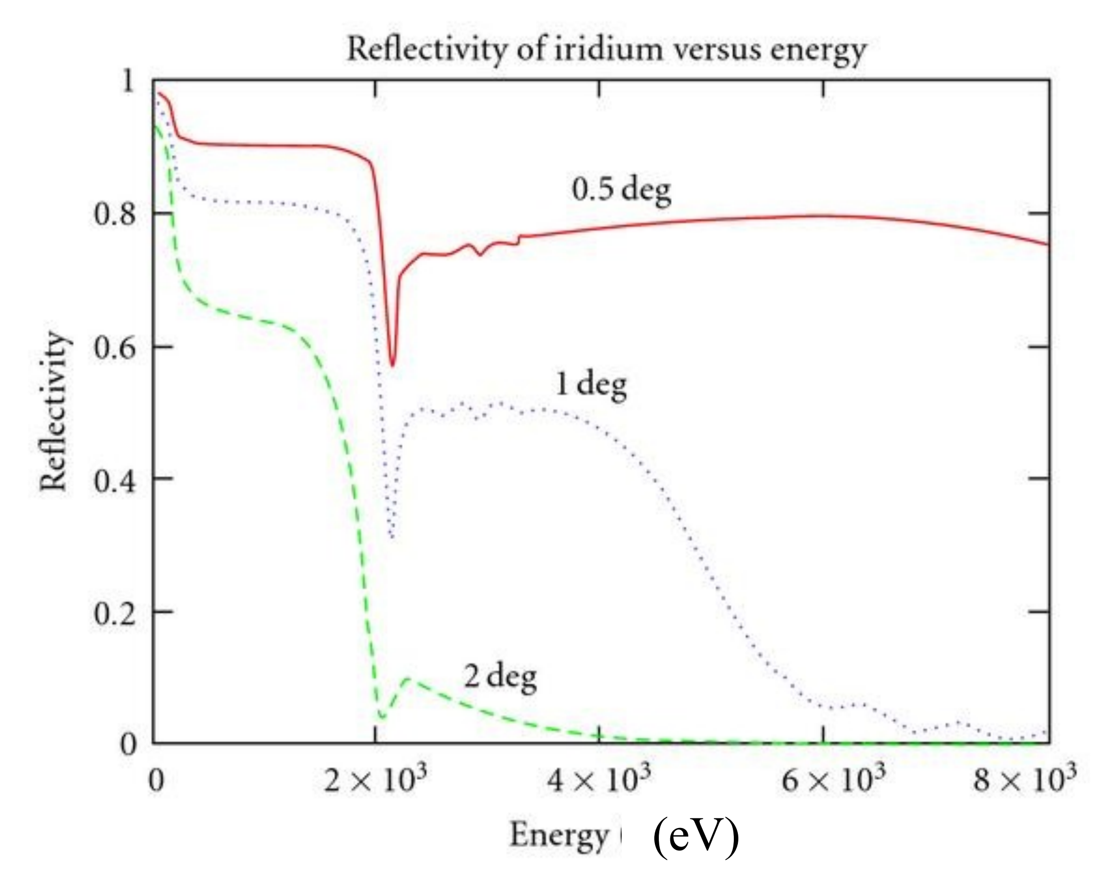
$$n = \sqrt{1 - \frac{nZr_\mathrm{e}}{\pi}\lambda^2} \sim 1 - \frac{nZr_\mathrm{e}}{2\pi}\lambda^2 = 1 - \frac{\rho}{(Z/A)m_\mathrm{u}}\frac{r_\mathrm{e}}{2\pi}\lambda^2 =: 1 - \delta$$

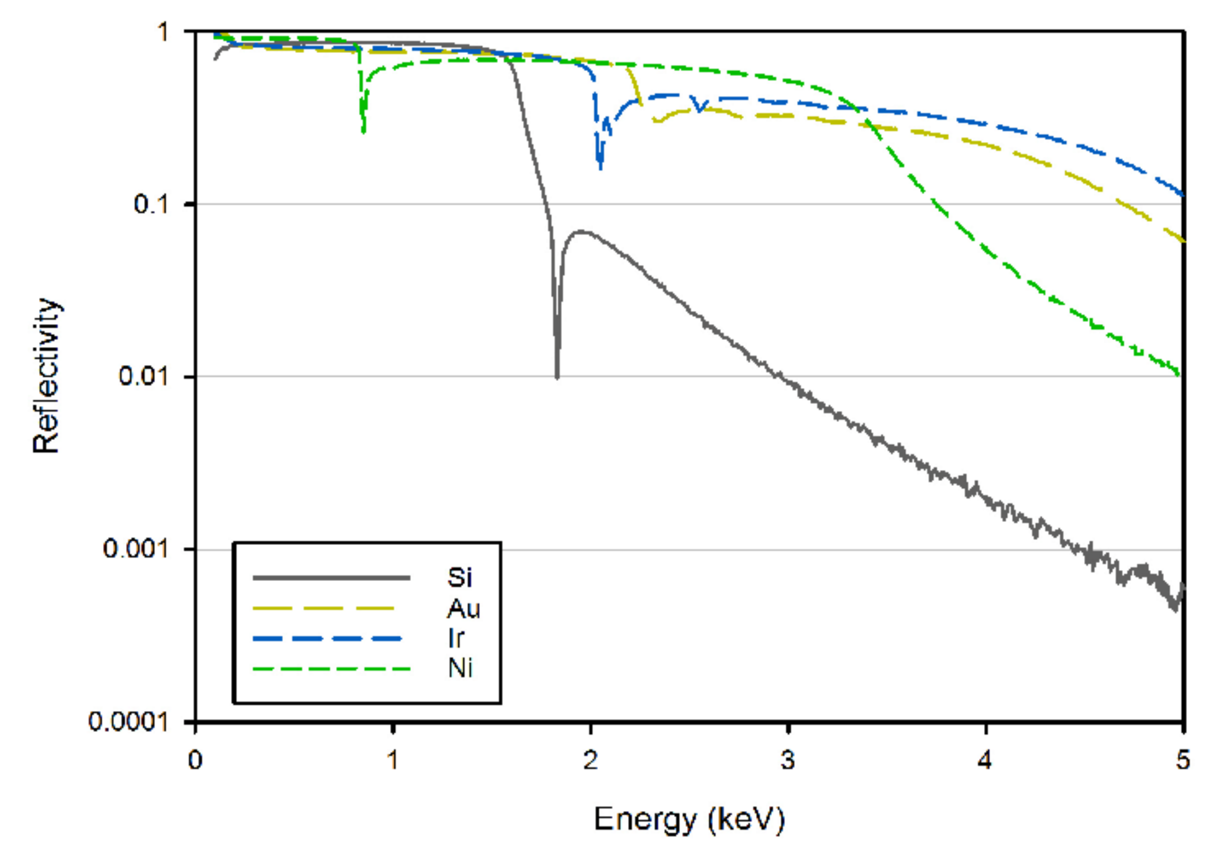
Equating [1] & [2], and after Taylor expansion

$$\theta_\mathrm{c} = \sqrt{2\delta} = 5.6' \left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)^{1/2} \frac{\lambda}{1\,\mathrm{nm}}$$

(full derivation in Kalemci & Wilms, `http://pulsar.sternwarte.uni-erlangen.de/black-hole/2ndschool/talks/Wilms_xrays.pdf`)

GRAZING INCIDENCE REQUIRED





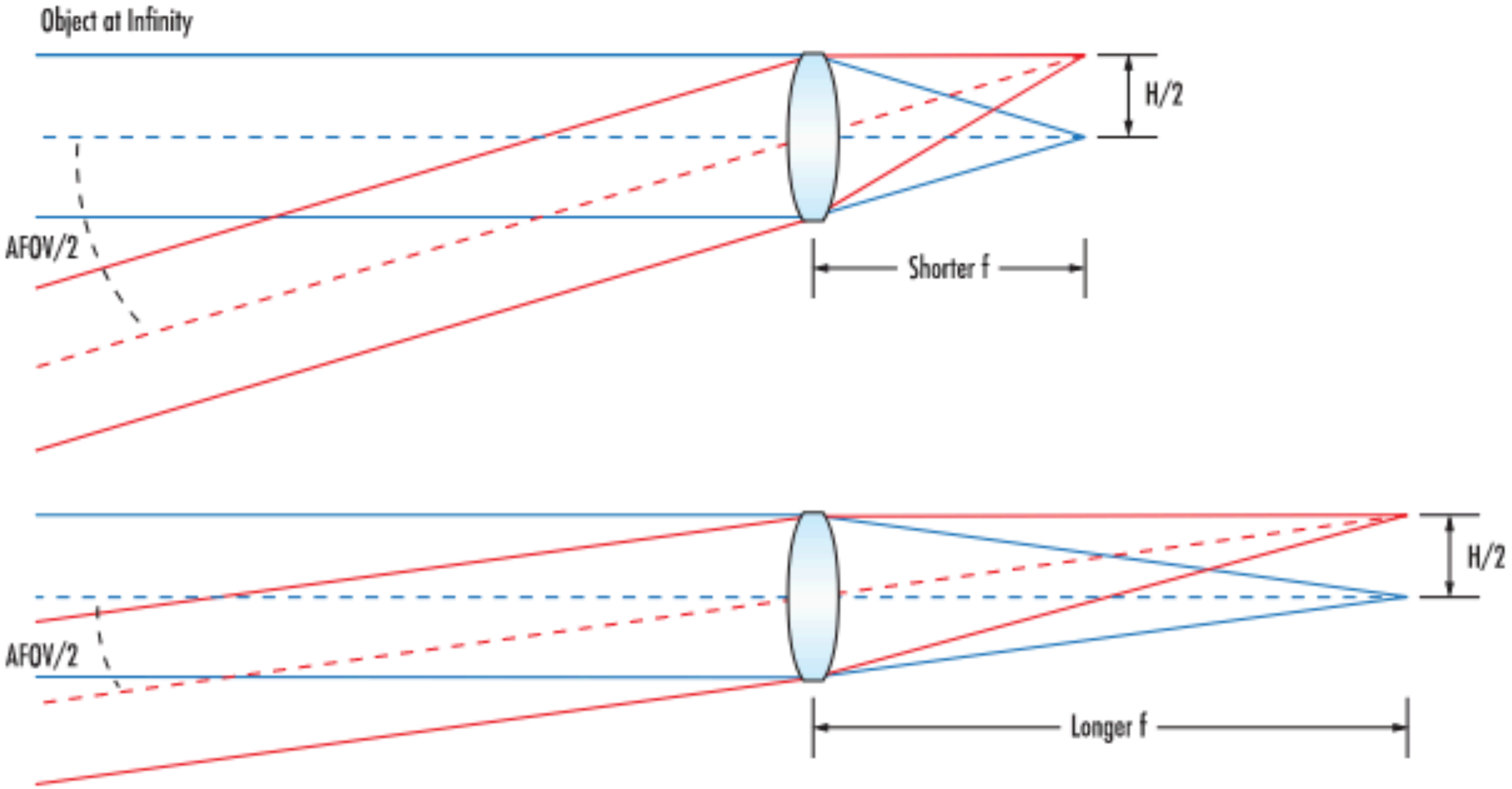
Focusing higher energies requires longer focal lengths (smaller grazing incidence angles)

(Gorenstein, 2010, X-ray Optics and Instrumentation, 2010, 109740)

(Abbasian Motlagh, Mehdi & Rastegarzadeh, Gohar, 2020)

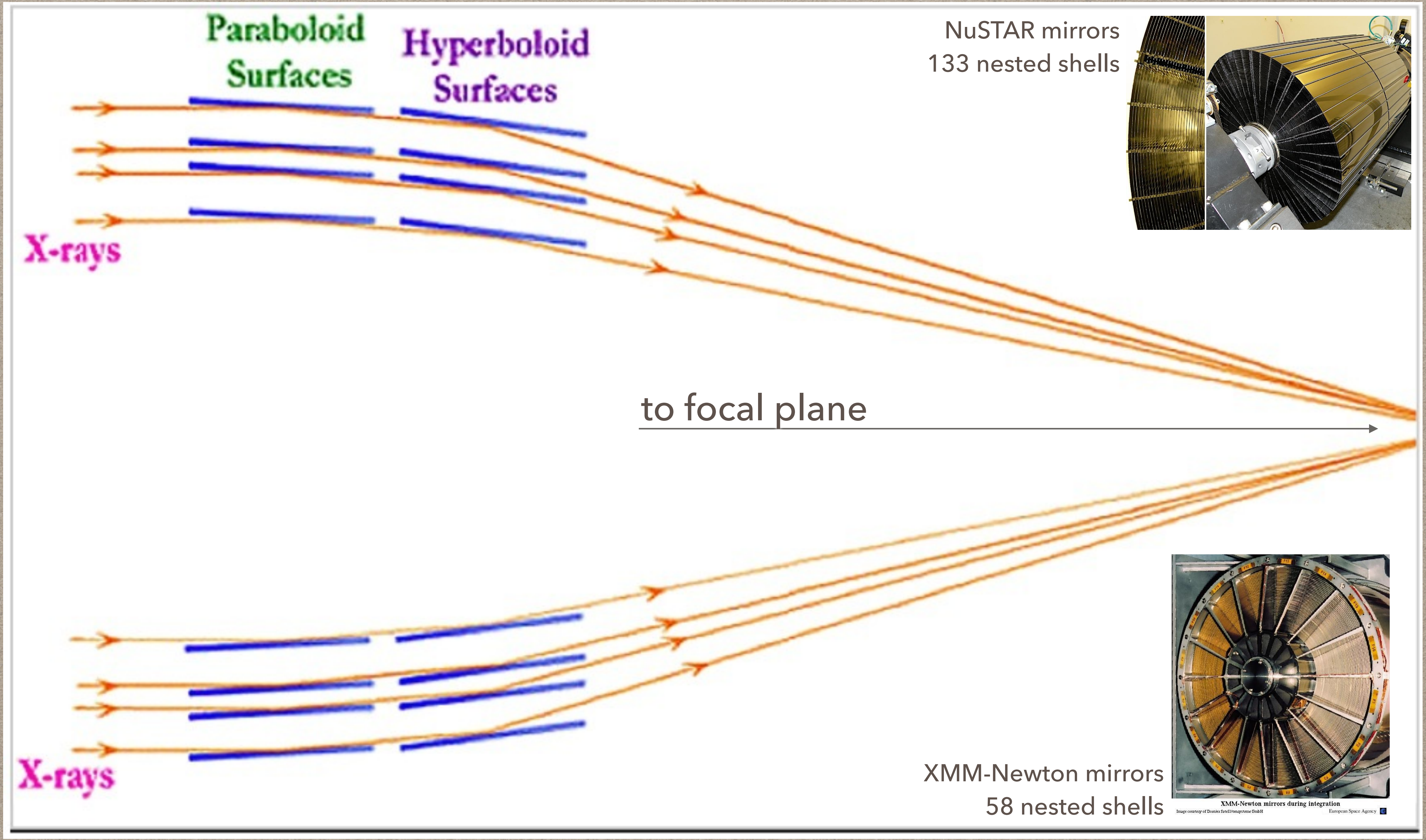
RELATION BETWEEN FOCAL LENGTH AND FIELD-OF-VIEW

$$\mathrm{AFOV} = 2 \times \tan^{-1}\left(\frac{H}{2f}\right)$$



(Hollows & James, `https://www.edmundoptics.eu/knowledge-center/application-notes/imaging/understanding-focal-length-and-field-of-view/`)

WOLTER I GEOMETRY



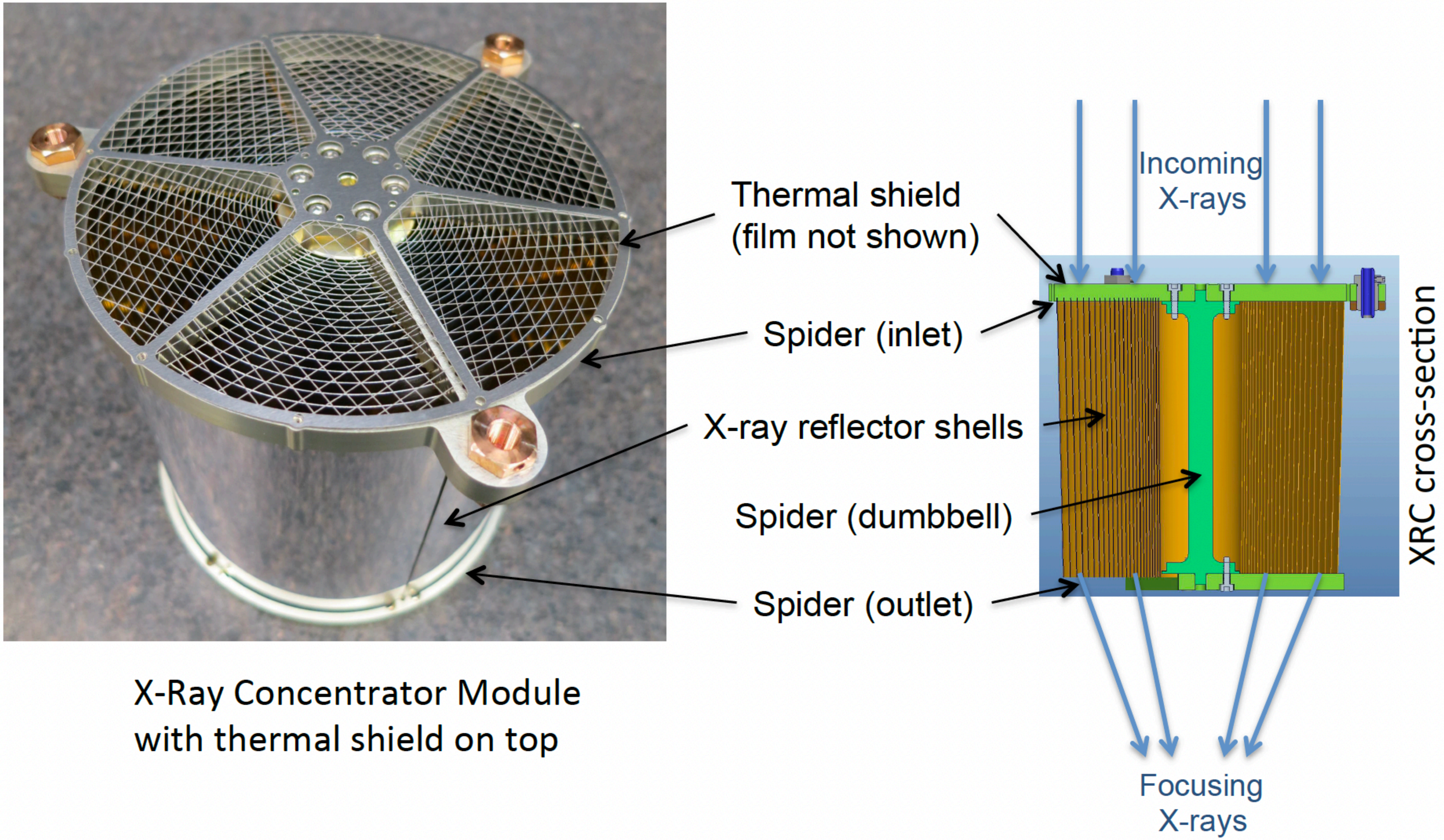
NuSTAR mirrors
133 nested shells

to focal plane

XMM-Newton mirrors
58 nested shells

(from a review by Gorenstein, 2010, X-ray Optics and Instrumentation, 2010, 109740; original paper by Wolter, 1952, Ann.Phys, 10, 94 & 256)

NICER CONCENTRATORS

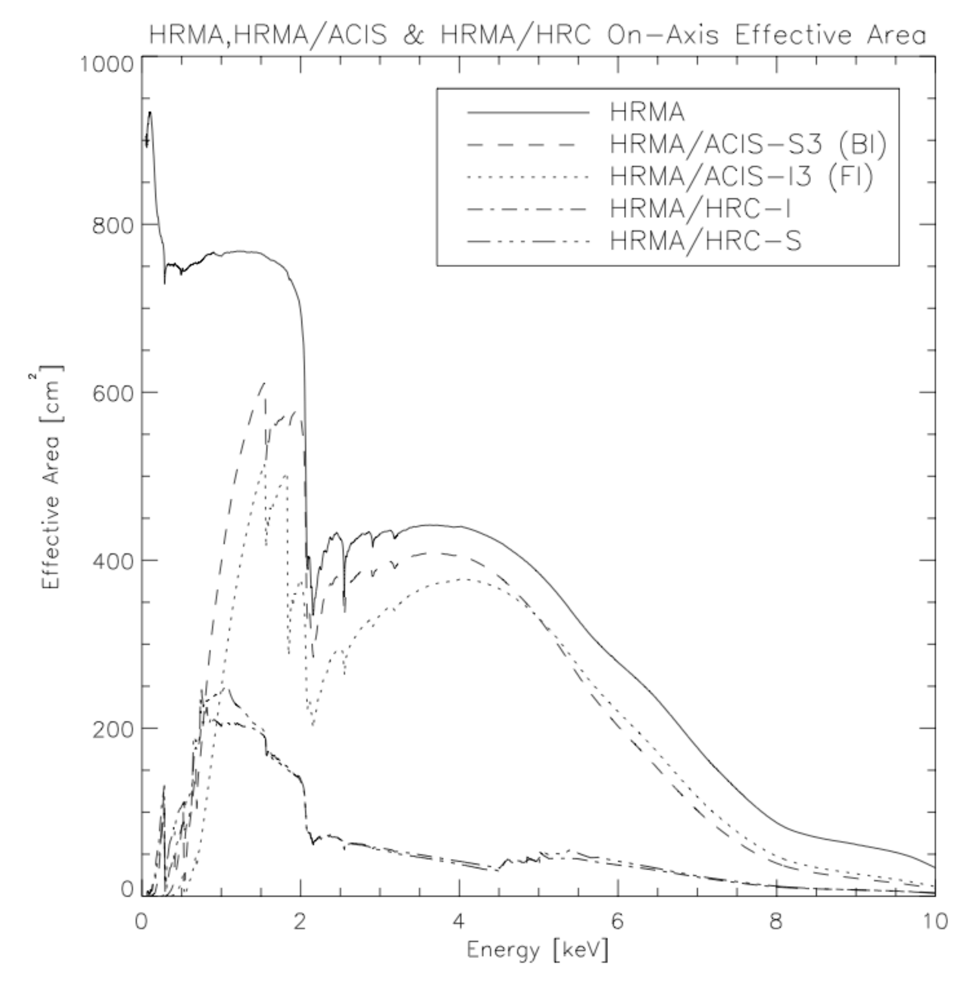


X-Ray Concentrator Module with thermal shield on top

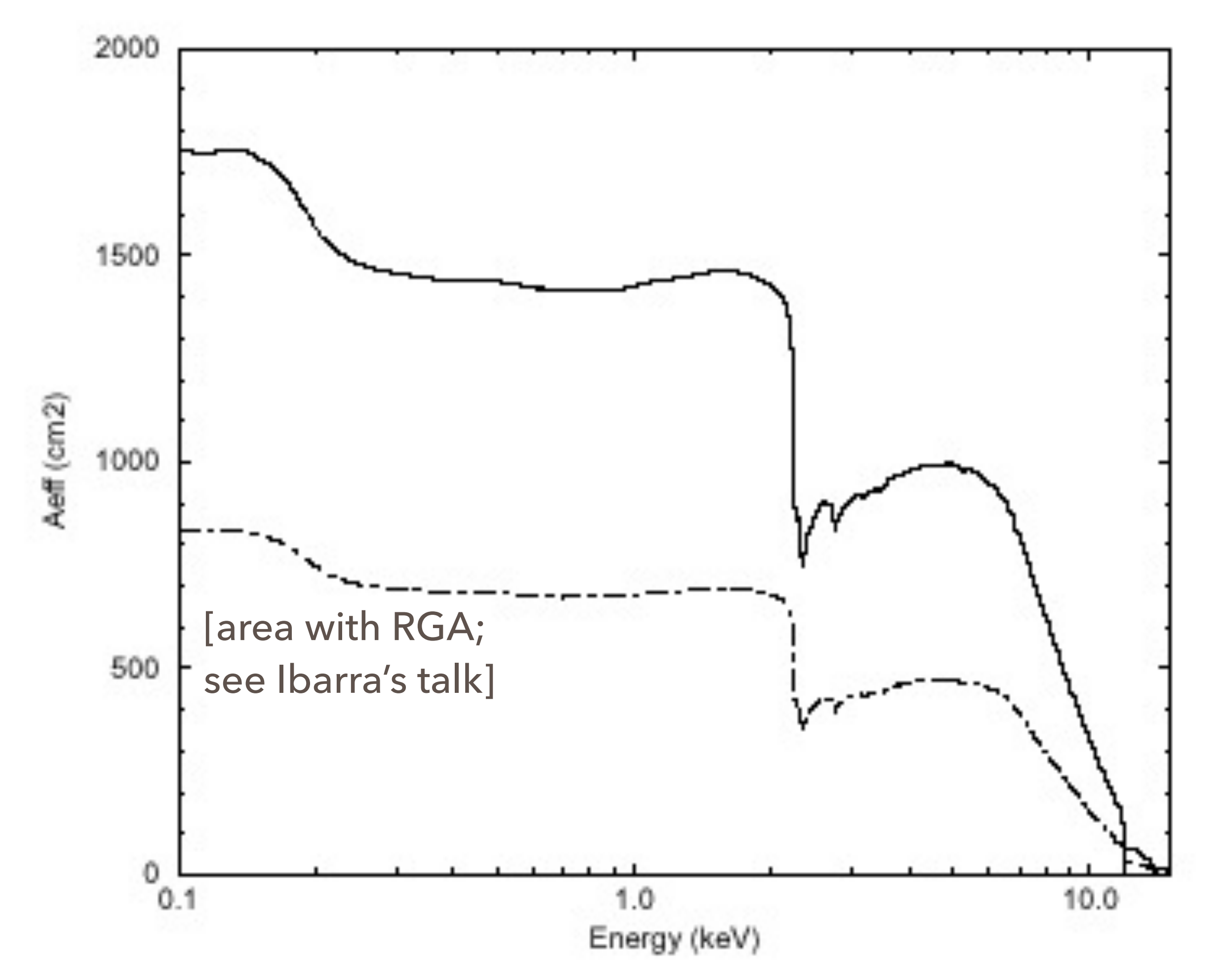
(Okajima et al., 2016, SPIE, 99054X)

CHANDRA AND XMM-NEWTON MIRRORS - LIMITED TO <10 KEV

Chandra optics
(the solid line is the mirror area)



XMM-Newton optics



[area with RGA;
see Ibarra's talk]

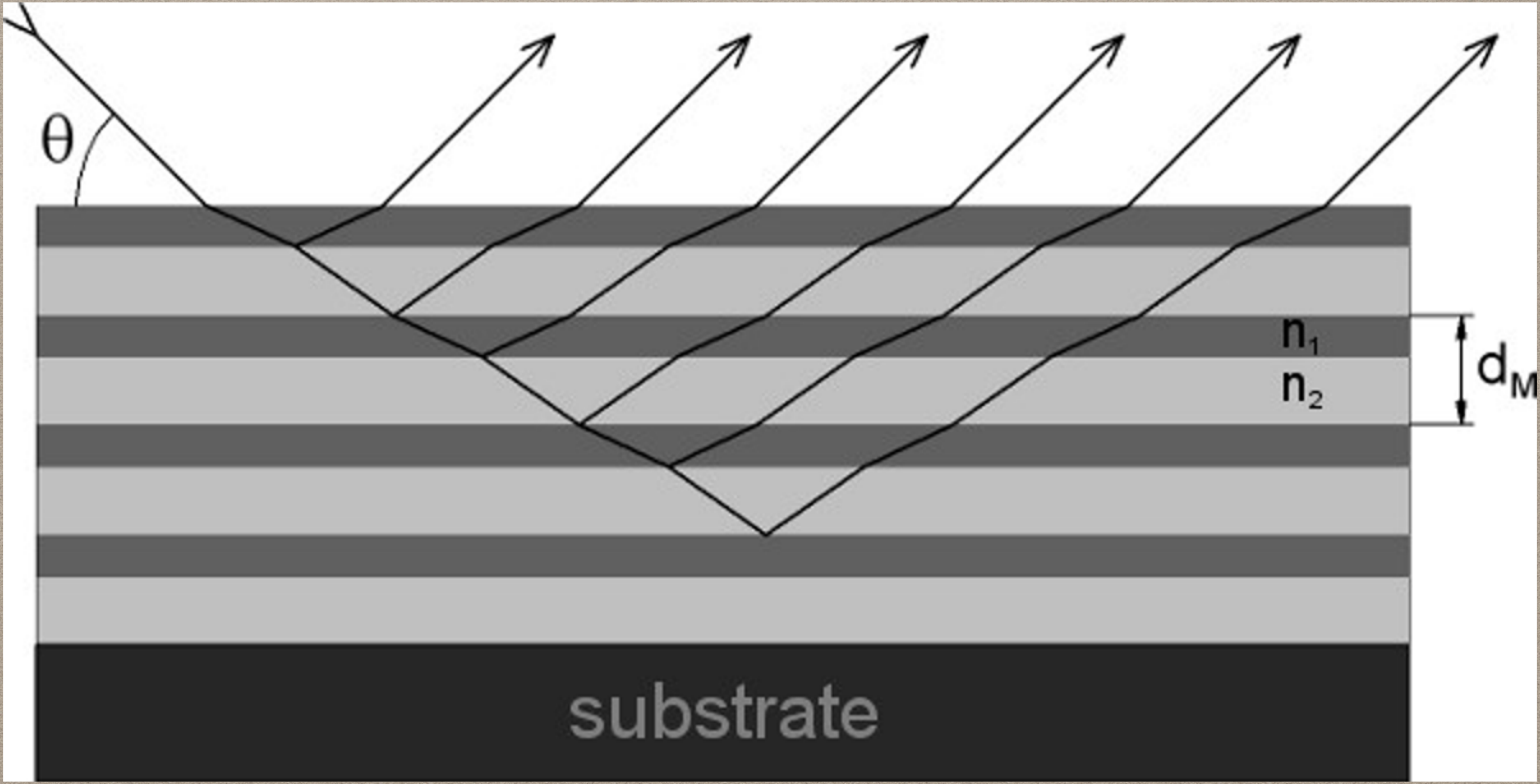
They die out miserably at 10 keV!

(Chandra POG, `http://cxc.harvard.edu/proposer/POG/`)

(`http://xmm.esac.esa.int/external/xmm_user_support/documentation/technical/Mirrors/index.shtml`)

CAN WE FOCUS ABOVE 10 KEV?

Multiple layers of reflecting, high density contrast materials can act as a crystal lattice and yield constructive interference, enhancing reflectivity

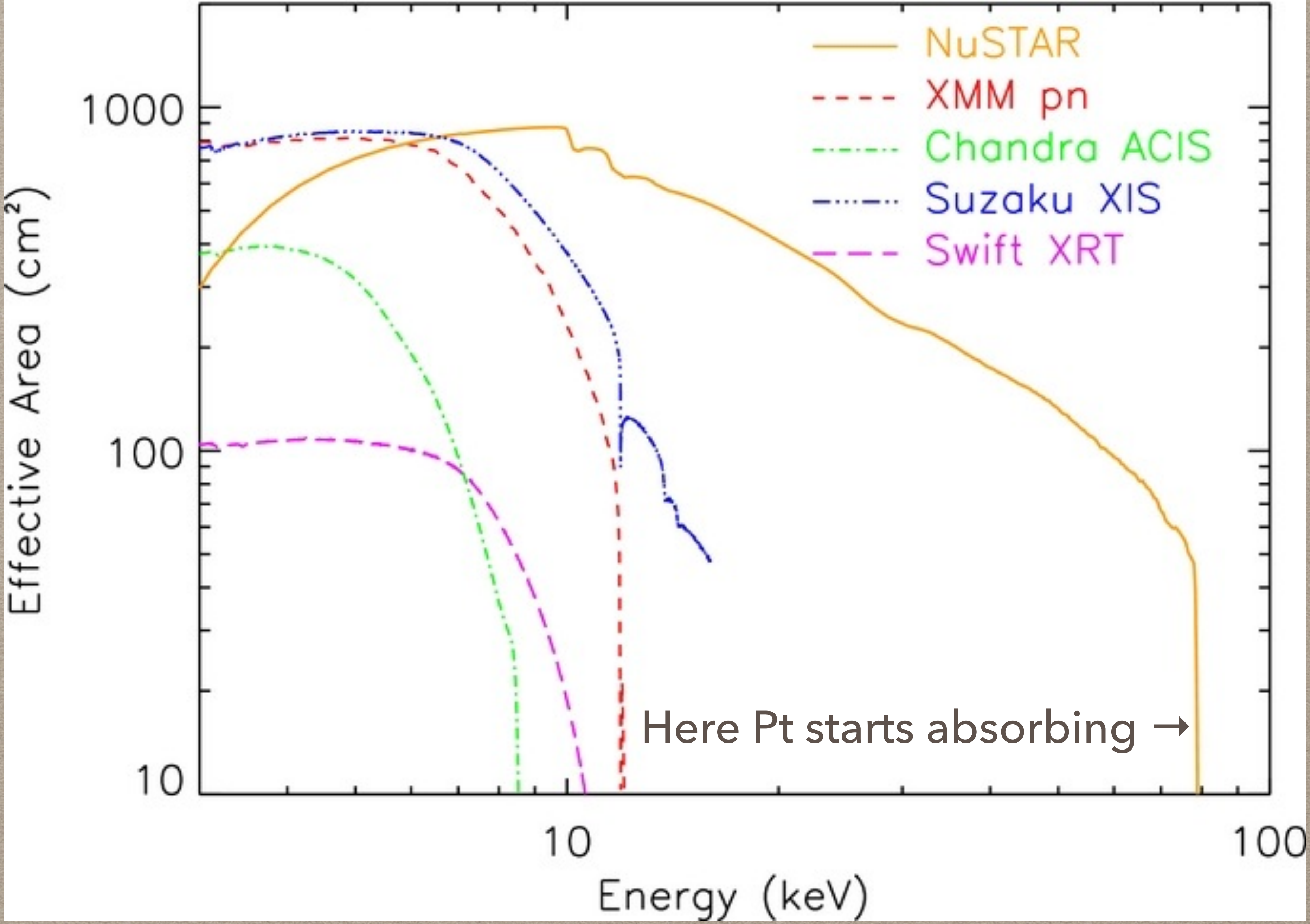


(Credit: M. Dadina INAF)

FOCUSING OPTICS >10 KEV

- NuSTAR carries the **first operational focusing optics above 10 keV**

- 200 pairs of Pt/Sc & W/Si coating layers



Here Pt starts absorbing →

(Harrison et al., 2013, ApJ, 770, 103)

OUTLINE

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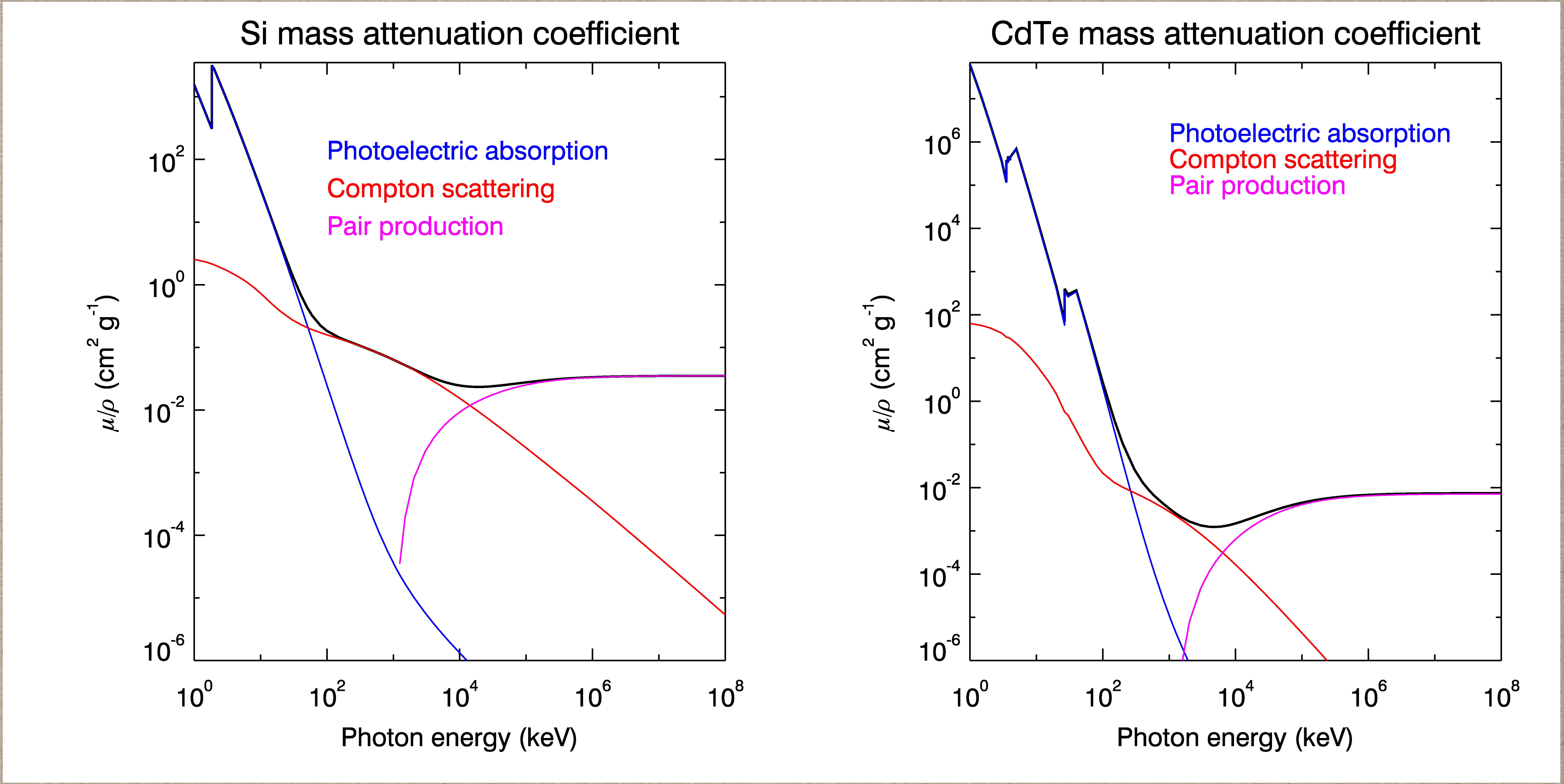
PHOTON-MATTER INTERACTION

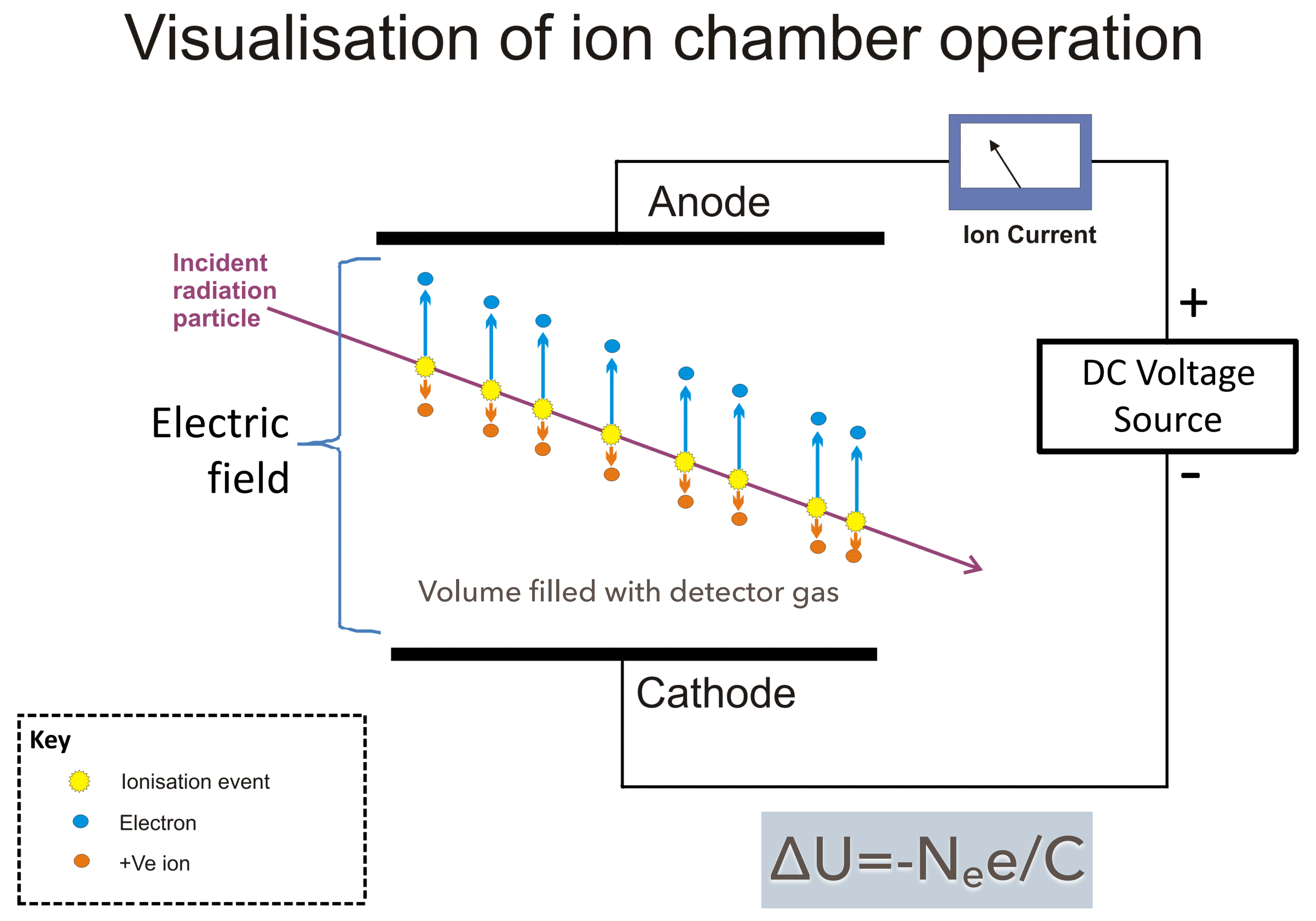


μ/ρ: linear attenuation coefficient.

Probability for a photon to be absorbed per unit distance and density

(data from NIST)

IONISATION CHAMBER



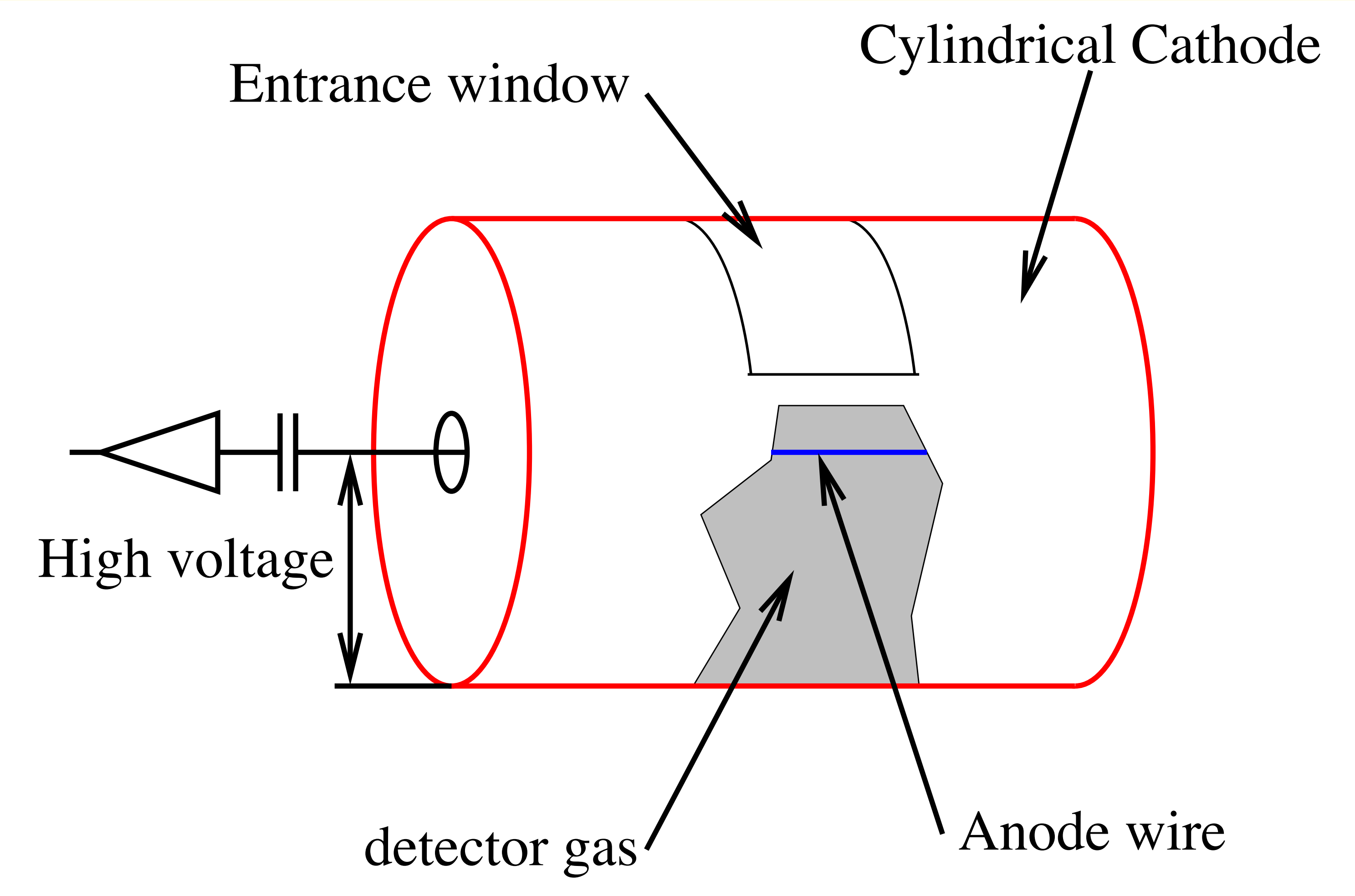
$$\Delta U = -N_e e/C$$

(Source: Wikipedia)

PROPORTIONAL COUNTERS

Problem: primary ionisation produces weak signals (≃ a few mV)

Solution: **multiply the charge detected at anode**



Solution: amplify charge

Close to Anodewire:

$$E(r) = V/(r \ln(b/a) \qquad (10)$$

(b radius of cathode, a radius of anode)

$\Longrightarrow$ Strong acceleration of ionized particles

$\Longrightarrow$ Collisional ionization of gas

$\Longrightarrow$ cascade!

Measured voltage:

$$\Delta U = -\frac{eN}{C} \cdot A \qquad (11)$$

where A: amplification factor (typically: $A = 10^4 \dots 10^6$).

Since $A \sim$ const.: Voltage pulse $\propto N$, and therefore Voltage pulse $\propto$ detected X-ray energy!

and therefore: "proportional counter"

(Courtesy Kalemci & Wilms, `http://pulsar.sternwarte.uni-erlangen.de/black-hole/2ndschool/talks/Wilms_xrays.pdf`)

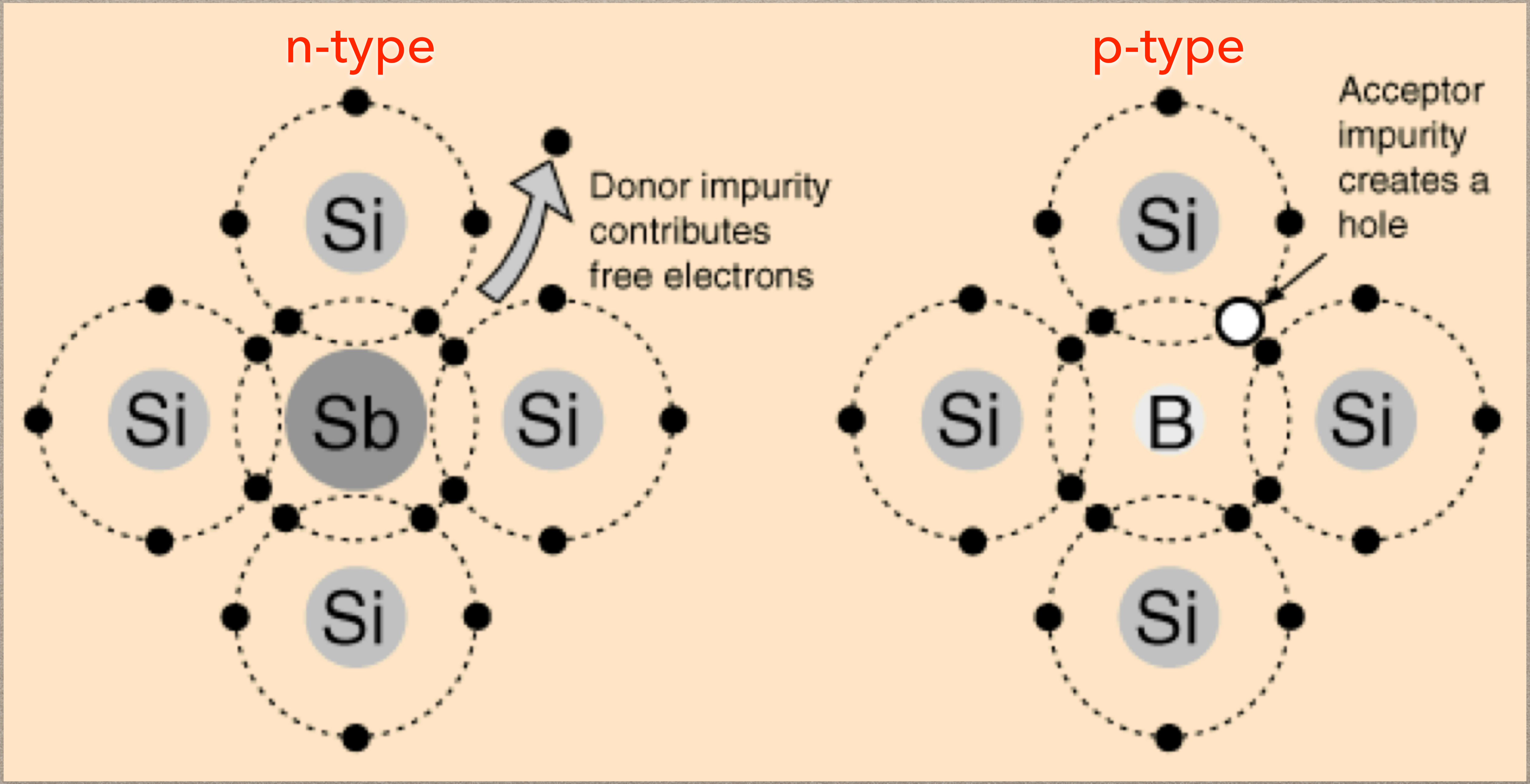
CCDS

- Array of electrostatically-linked ("coupled") capacitors
- Photons interacts in a semiconductor (Si) layer via photoelectric absorption, and produce an electron-hole pair "cloud"
  - temperature dependence
    {number of e^-}$\simeq${X-ray photon energy}/3.7 (eV/e^-)
- Electrons are collected in pixels through an electric field
- Pixels can transfer charge to a neighbouring pixels via modulated potential
- The transferred "cloud" is eventually read by an amplifier

We know how to create an e^- cloud. Problem: **how to prevent it from recombining immediately with the corresponding holes?**

DOPED SEMI-CONDUCTORS

- Small gap between valence and conduction band (≃1.1 eV for Si)
- Even a small number of impurities increases conductivity

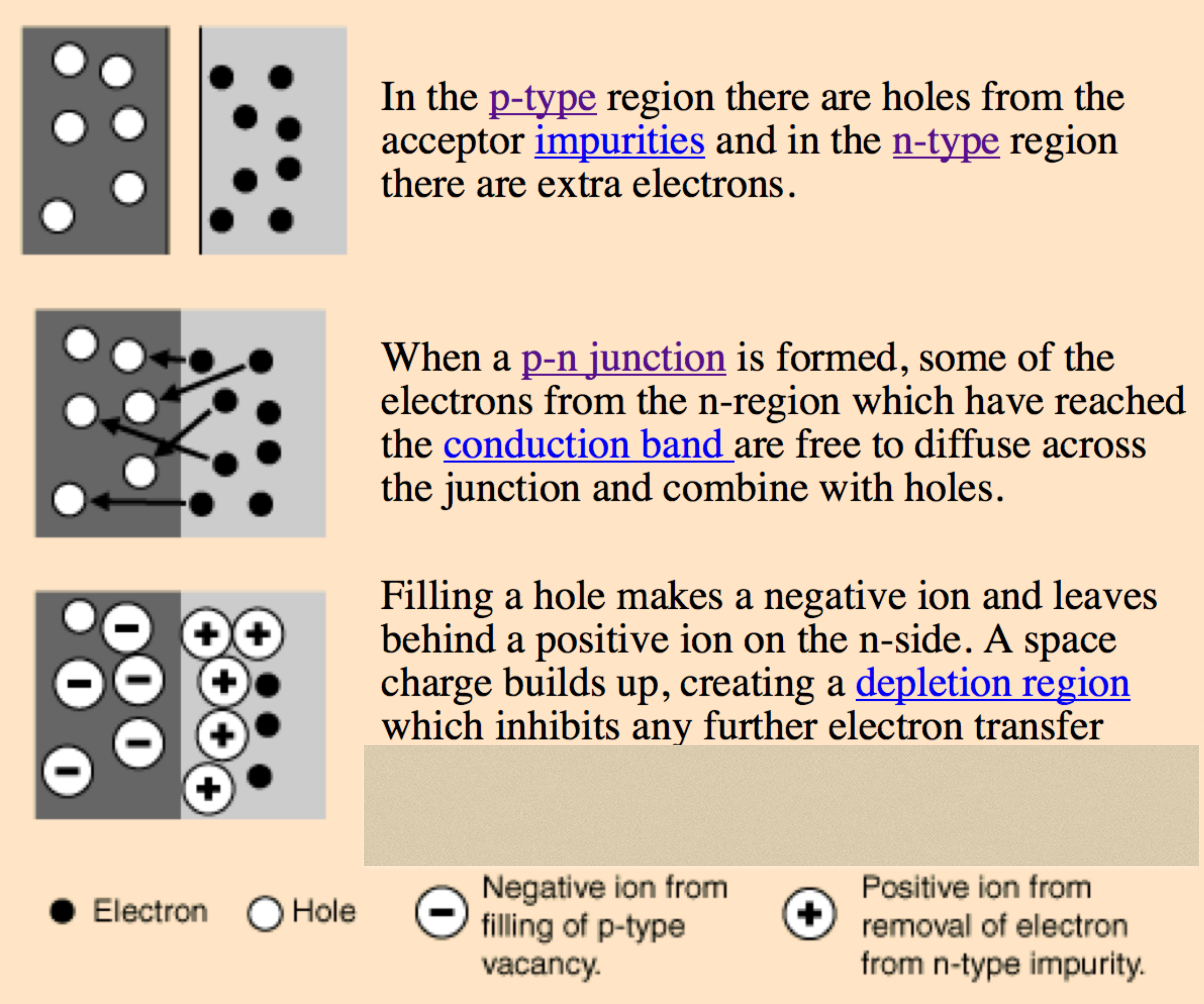


Donor impurity contributes free electrons

Acceptor impurity creates a hole

(material extracted from `http://hyperphysics.phy-astr.gsu.edu`)

PN JUNCTION



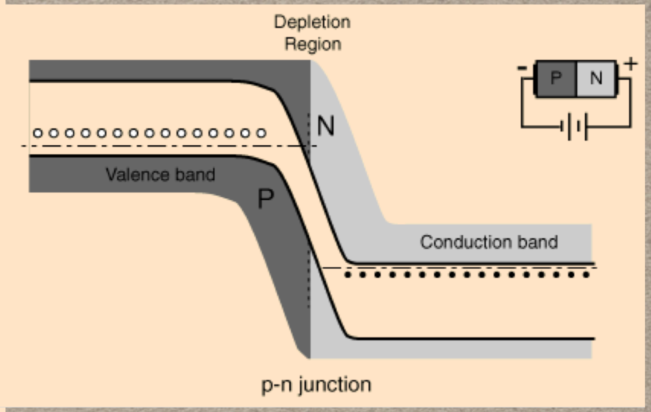
In the p-type region there are holes from the acceptor impurities and in the n-type region there are extra electrons.

When a p-n junction is formed, some of the electrons from the n-region which have reached the conduction band are free to diffuse across the junction and combine with holes.

Filling a hole makes a negative ion and leaves behind a positive ion on the n-side. A space charge builds up, creating a depletion region which inhibits any further electron transfer

● Electron ○ Hole ⊖ Negative ion from filling of p-type vacancy. ⊕ Positive ion from removal of electron from n-type impurity.

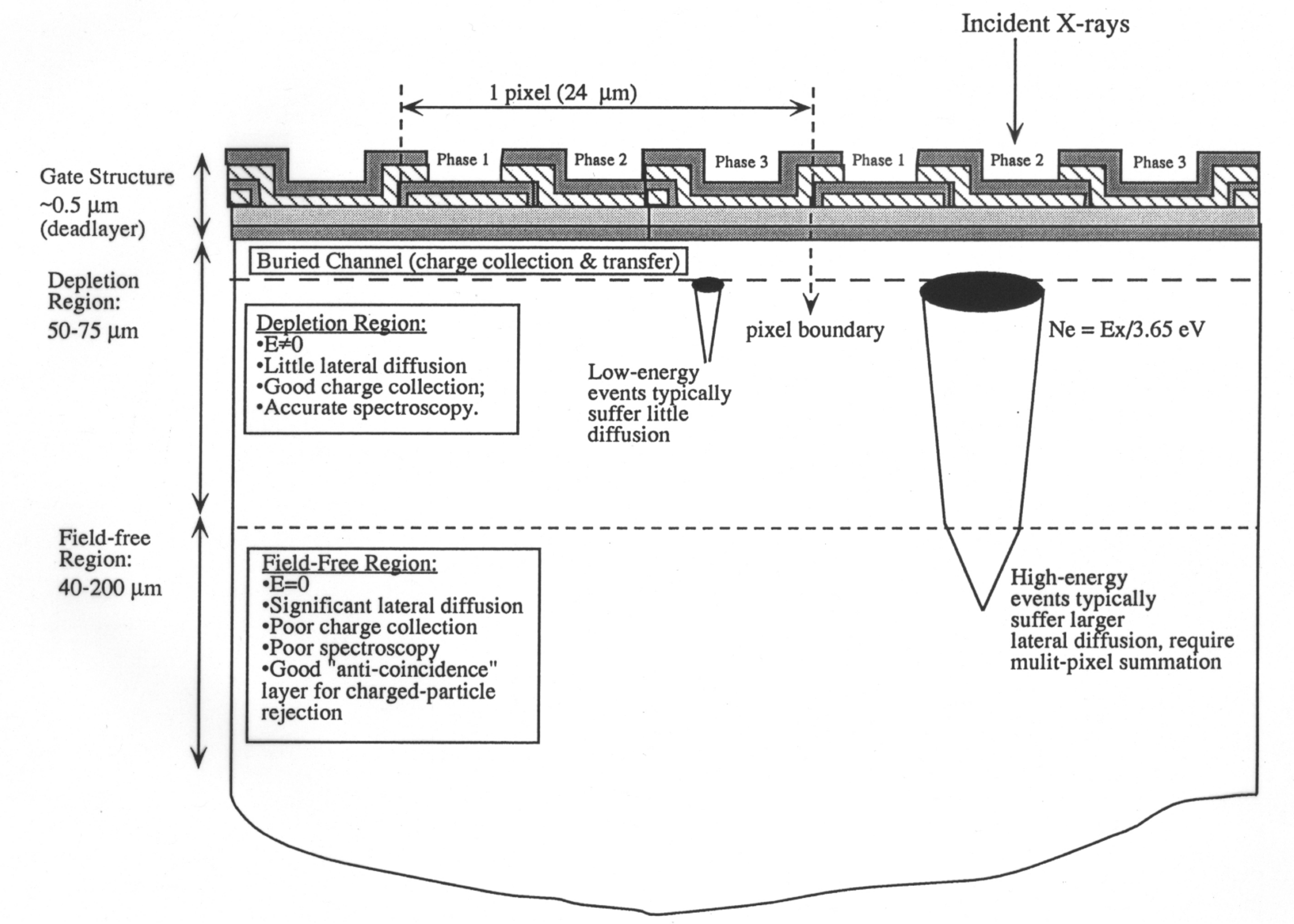
- Charge formed in the depletion layer cannot diffuse further
- A "reverse bias" increases the potential gap and size



- this "depletion layer is where all the action occurs (the e$^-$ cloud forms)

(material extracted from `http://hyperphysics.phy-astr.gsu.edu`)

CCD STRUCTURE (*CHANDRA*/ACIS)



Depletion Region:
- E≠0
- Little lateral diffusion
- Good charge collection;
- Accurate spectroscopy.

Low-energy events typically suffer little diffusion

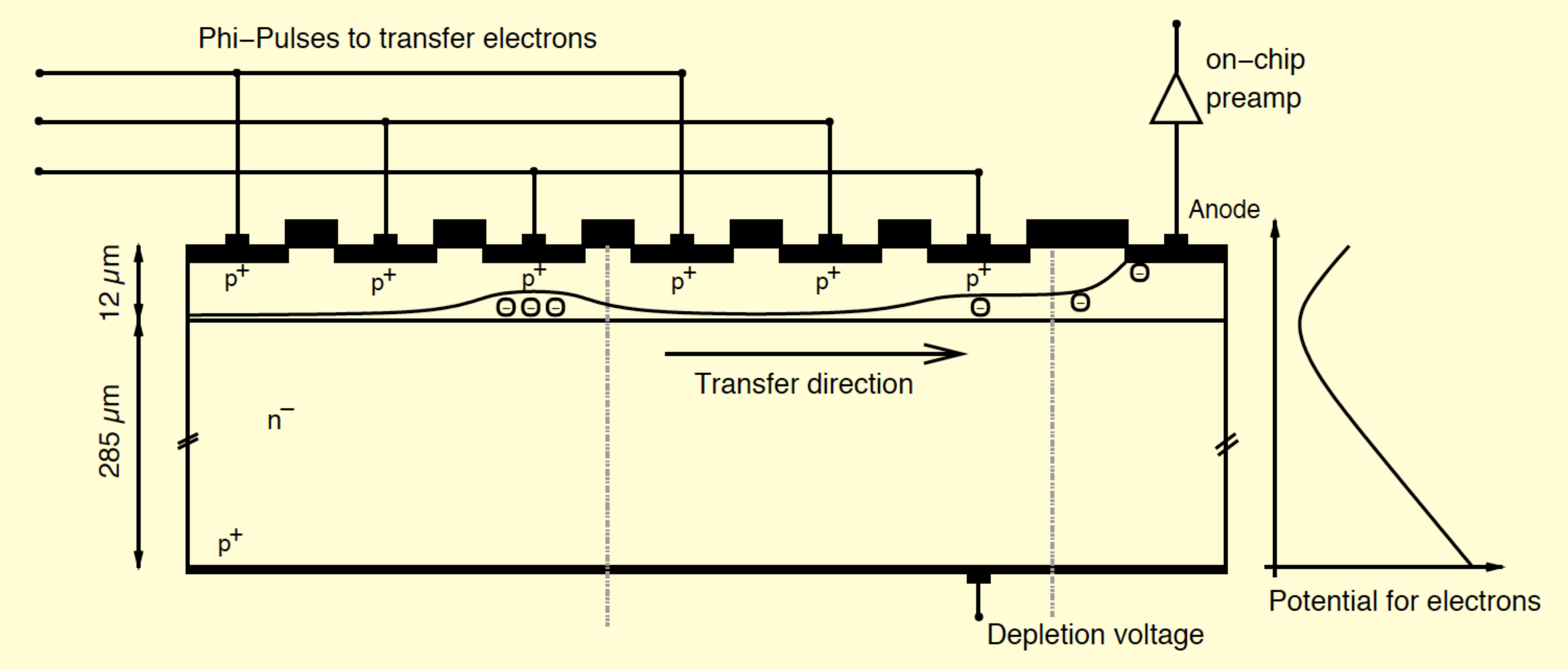
Field-Free Region:
- E=0
- Significant lateral diffusion
- Poor charge collection
- Poor spectroscopy
- Good "anti-coincidence" layer for charged-particle rejection

High-energy events typically suffer larger lateral diffusion, require mulit-pixel summation

(Lecture on CCD by C.Grant at the NASA 2007 X-ray Astronomy School: `http://heasarc.gsfc.nasa.gov/docs/xrayschool-2007/grant_ccds.pdf`)

CCD CHARGE TRANSFER (EPIC-PN)

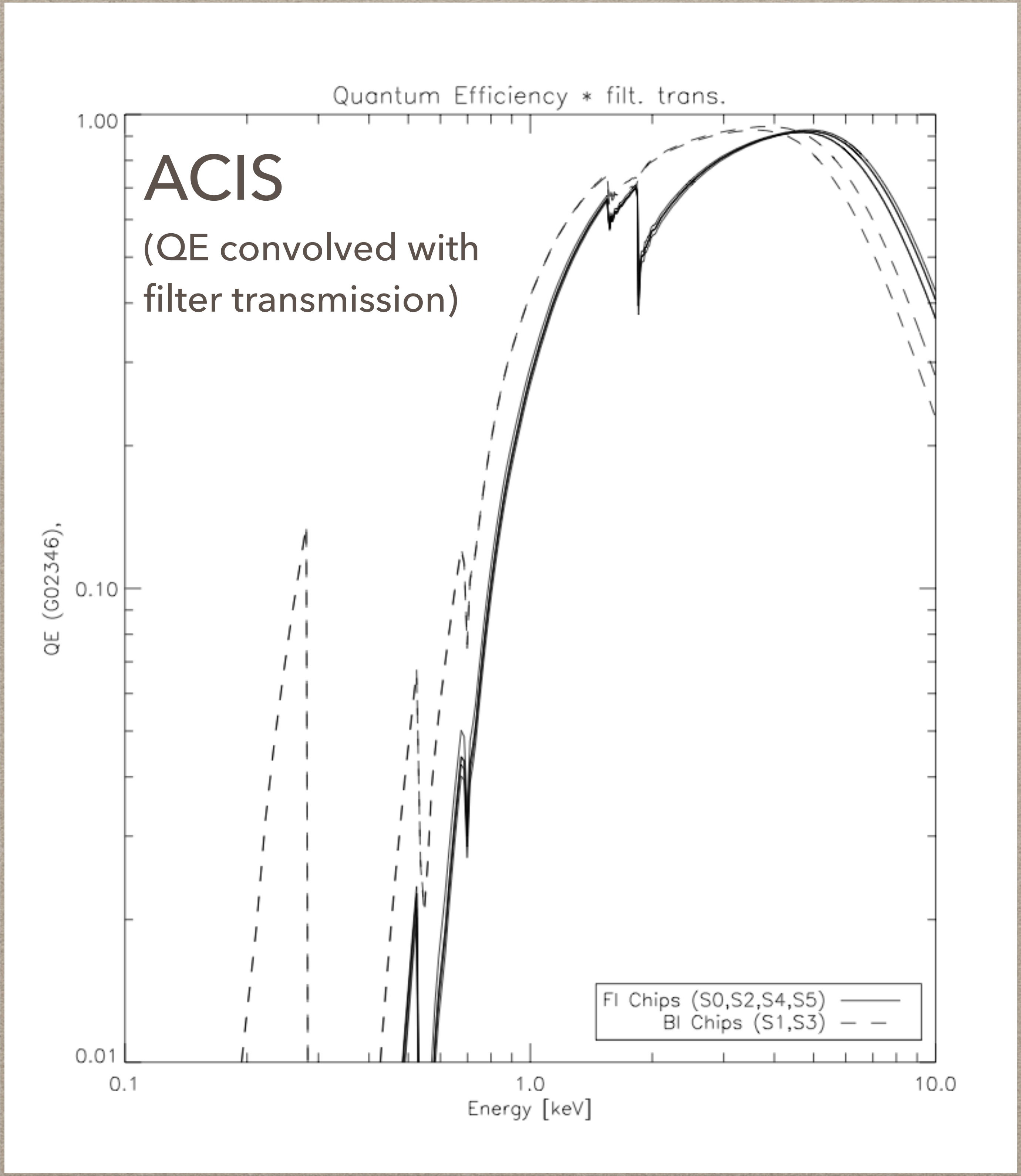
EPIC-pn is **back-illuminated** to avoid gate absorption.



In the transfer process, charge may be lost: this **Charge Transfer Inefficiency** is the main source of uncertainty in the energy reconstruction

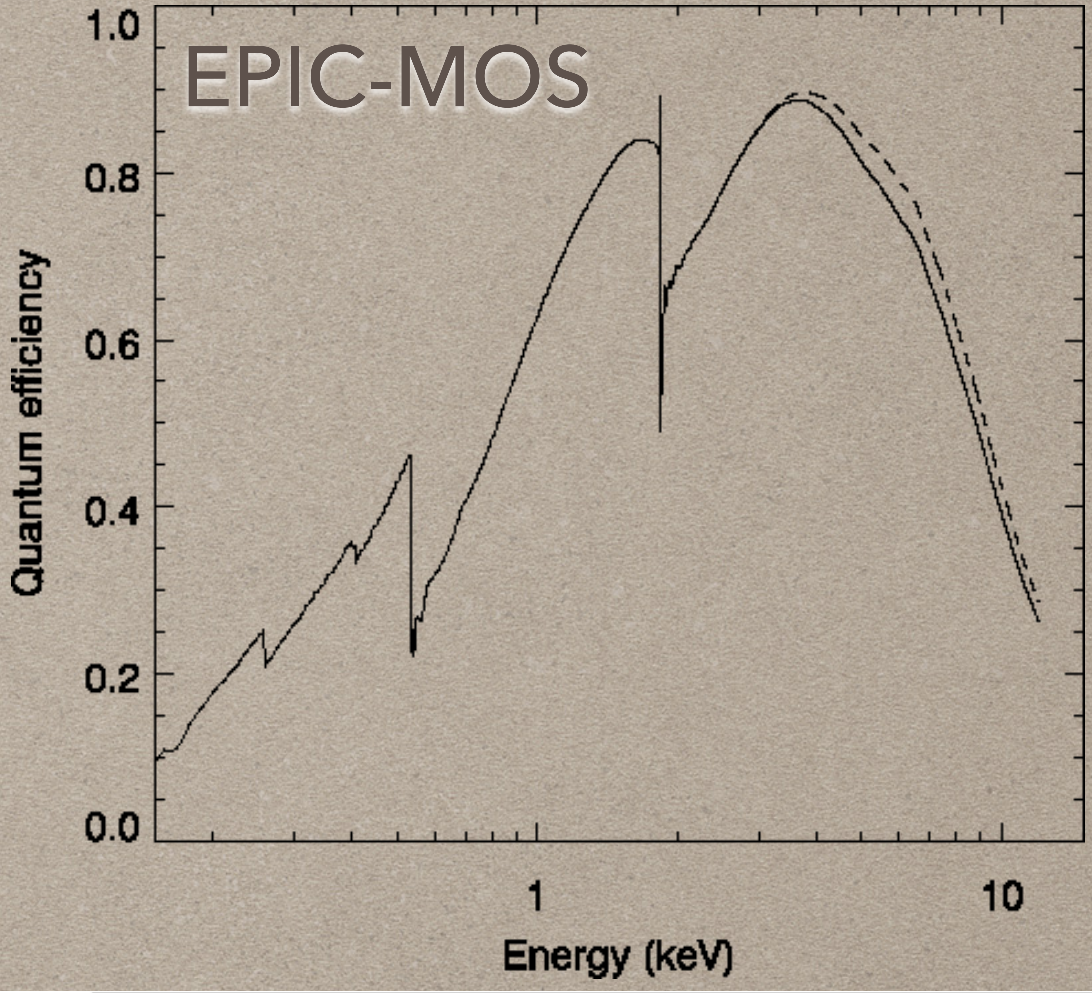
(Courtesy Kalemci & Wilms, `http://pulsar.sternwarte.uni-erlangen.de/black-hole/2ndschool/talks/Wilms_xrays.pdf`)

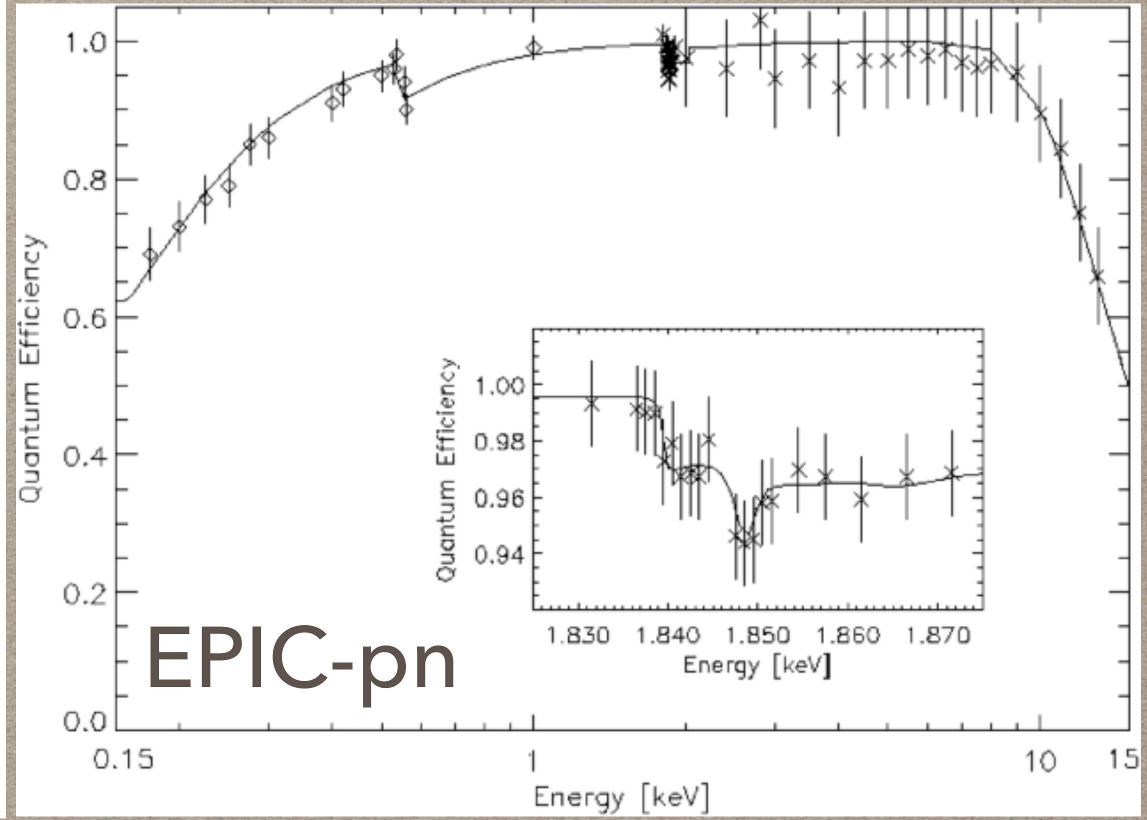
BI VS. FI CCDS


ACIS

(QE convolved with filter transmission)

(from the Chandra POG: `http://cxc.cfa.harvard.edu/proposer/POG/`)


EPIC-MOS

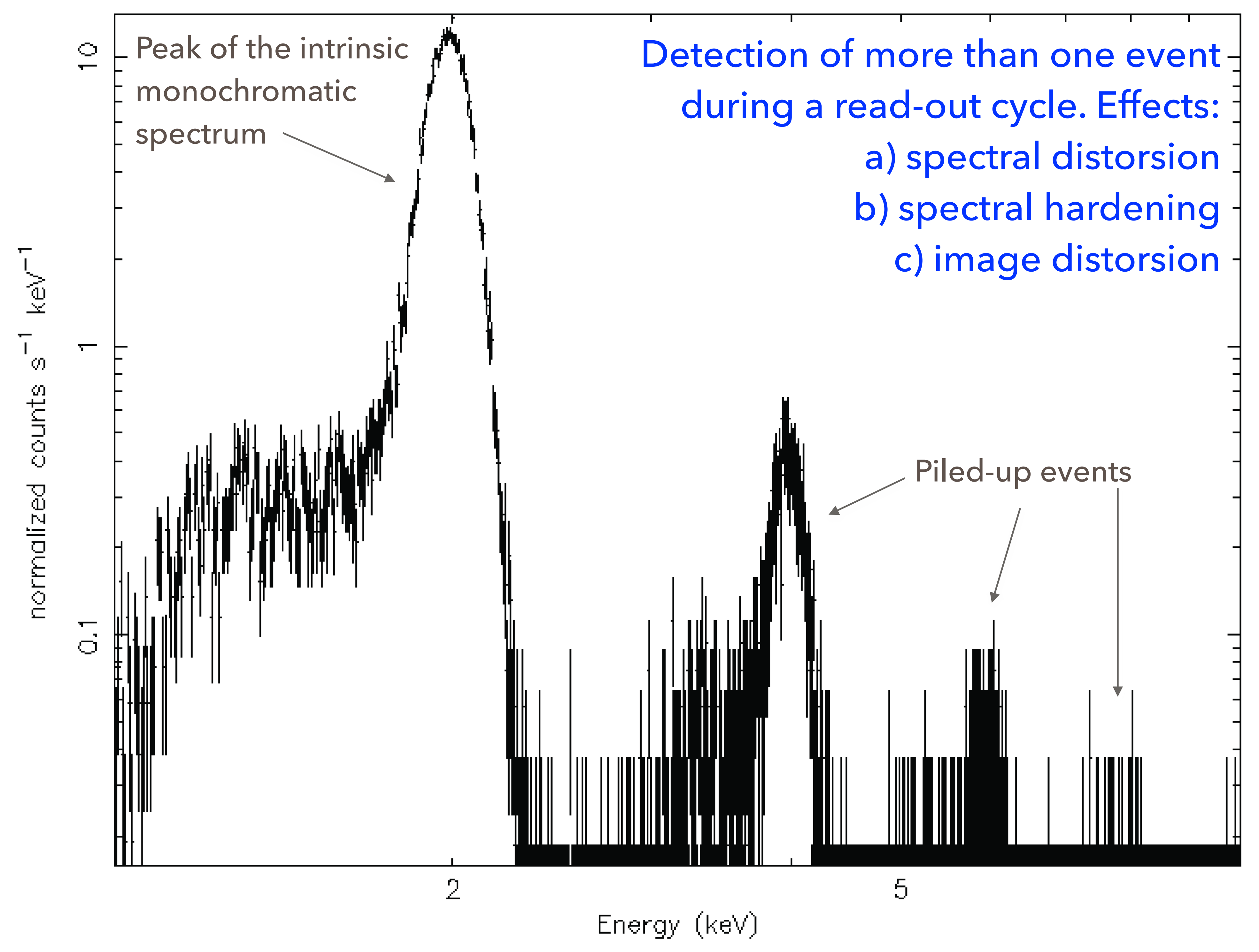

EPIC-pn

(Strüder et al., 2001, A&A, 365, L18; Turner et al., 2001, A&A, 365, L27)

PILE-UP

Seminal papers on pile-up:

- Ballet, 1999, A&AS, 135, 371
- Davis, 2001, ApJ, 562, 575



Peak of the intrinsic monochromatic spectrum

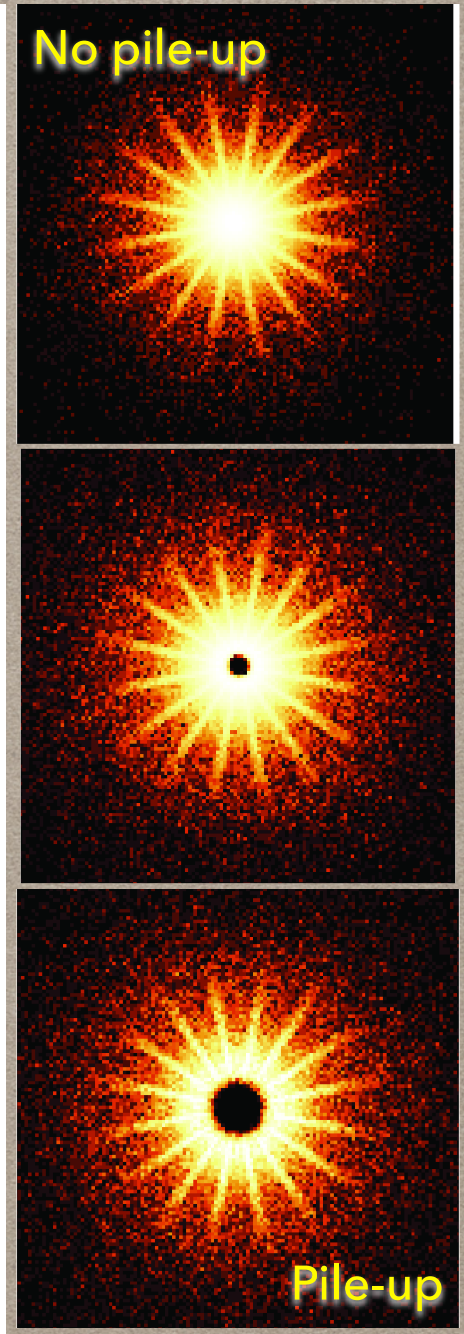
Detection of more than one event during a read-out cycle. Effects:

a) spectral distortion

b) spectral hardening

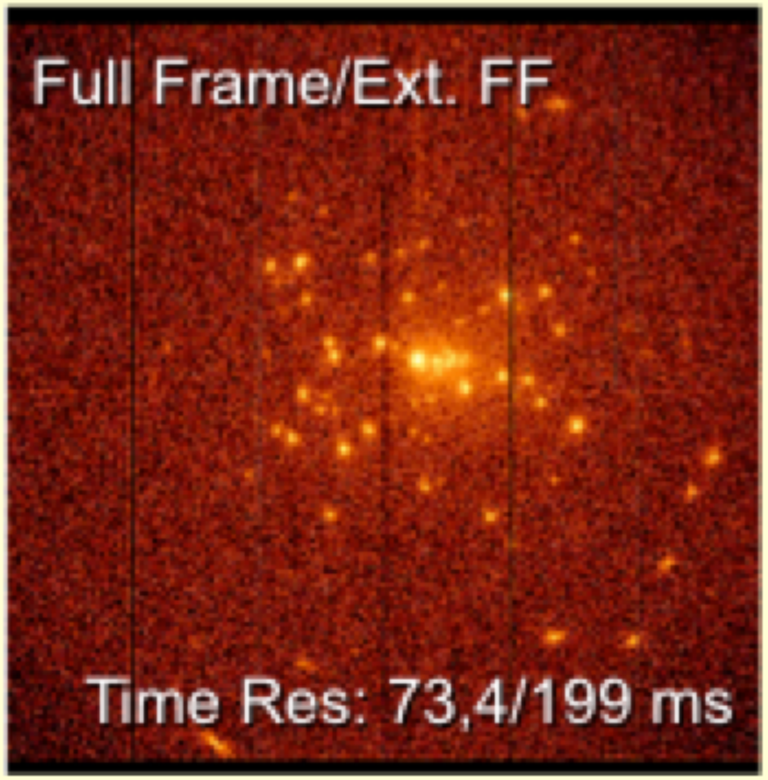
c) image distortion

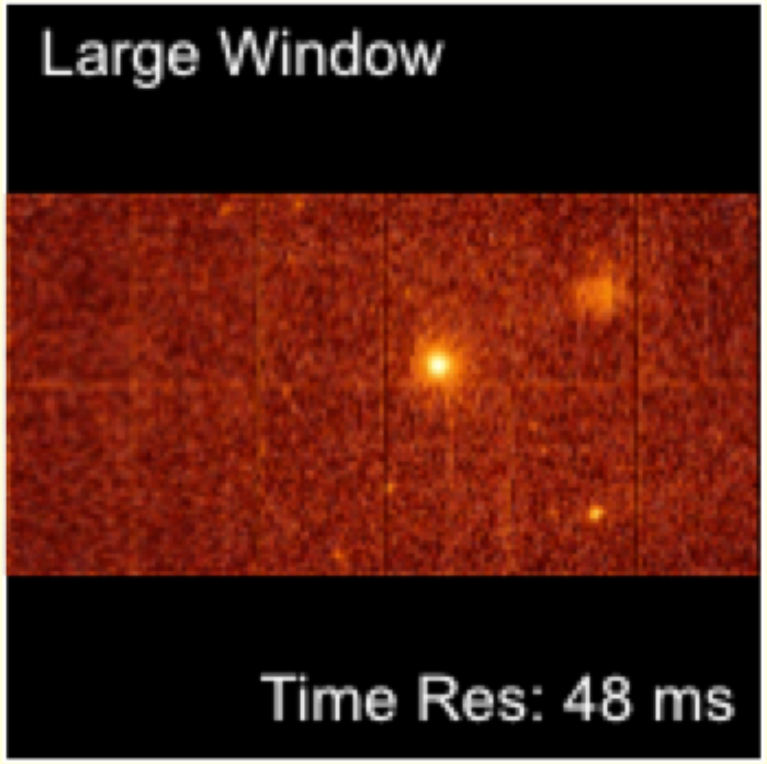
Piled-up events

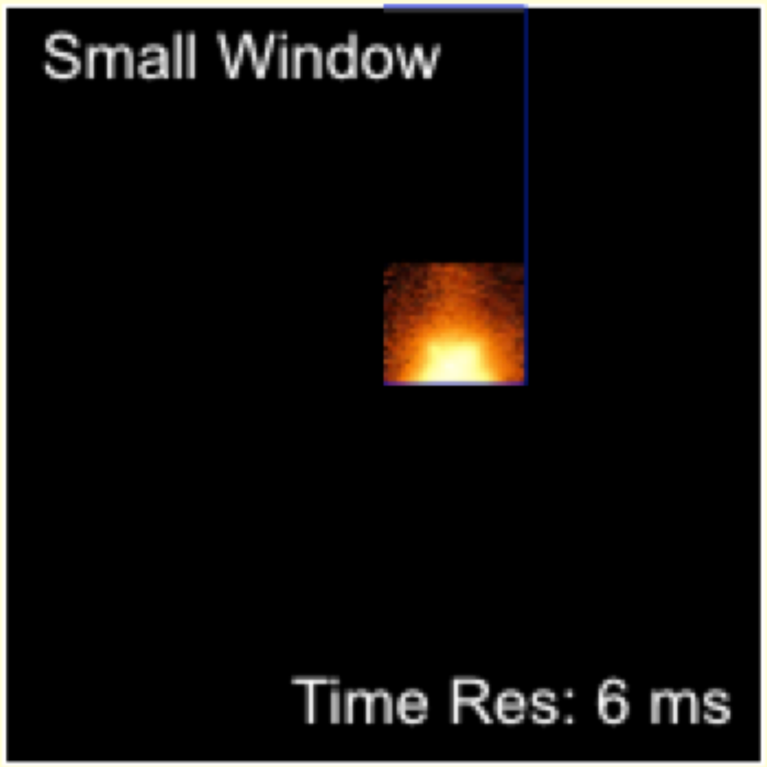


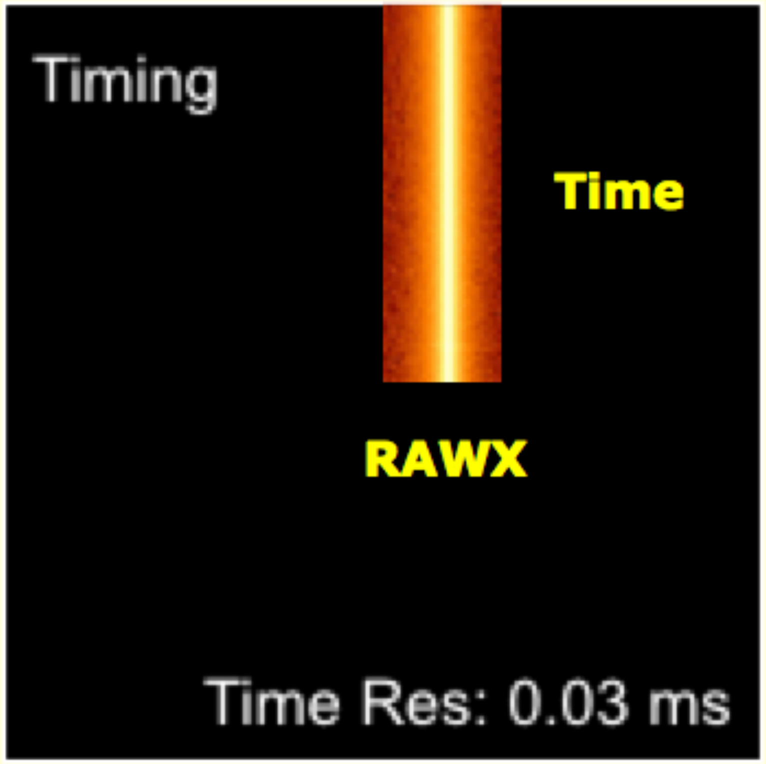
(Jethwa et al., 2015, A&A,)

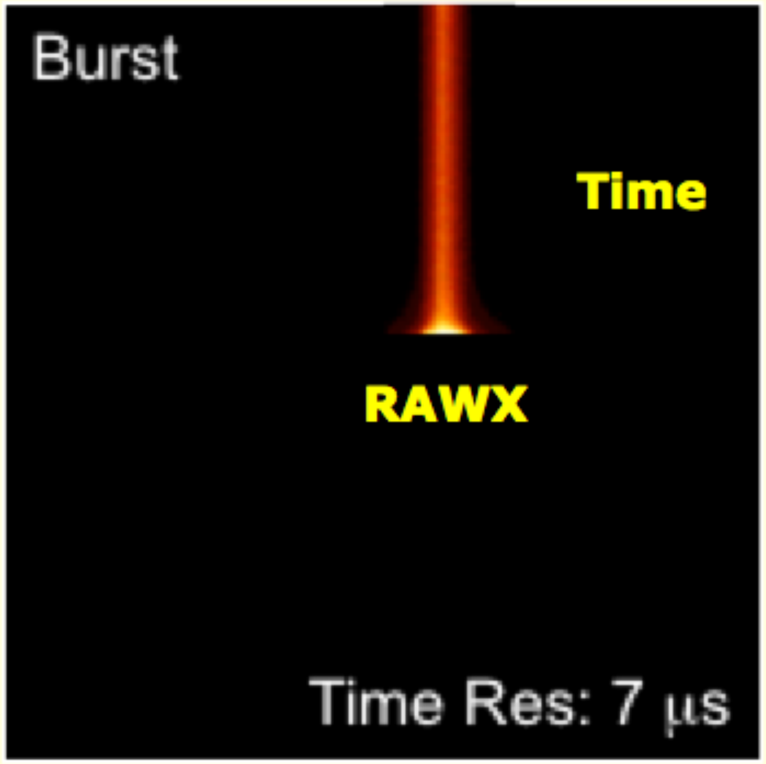
PN operating modes



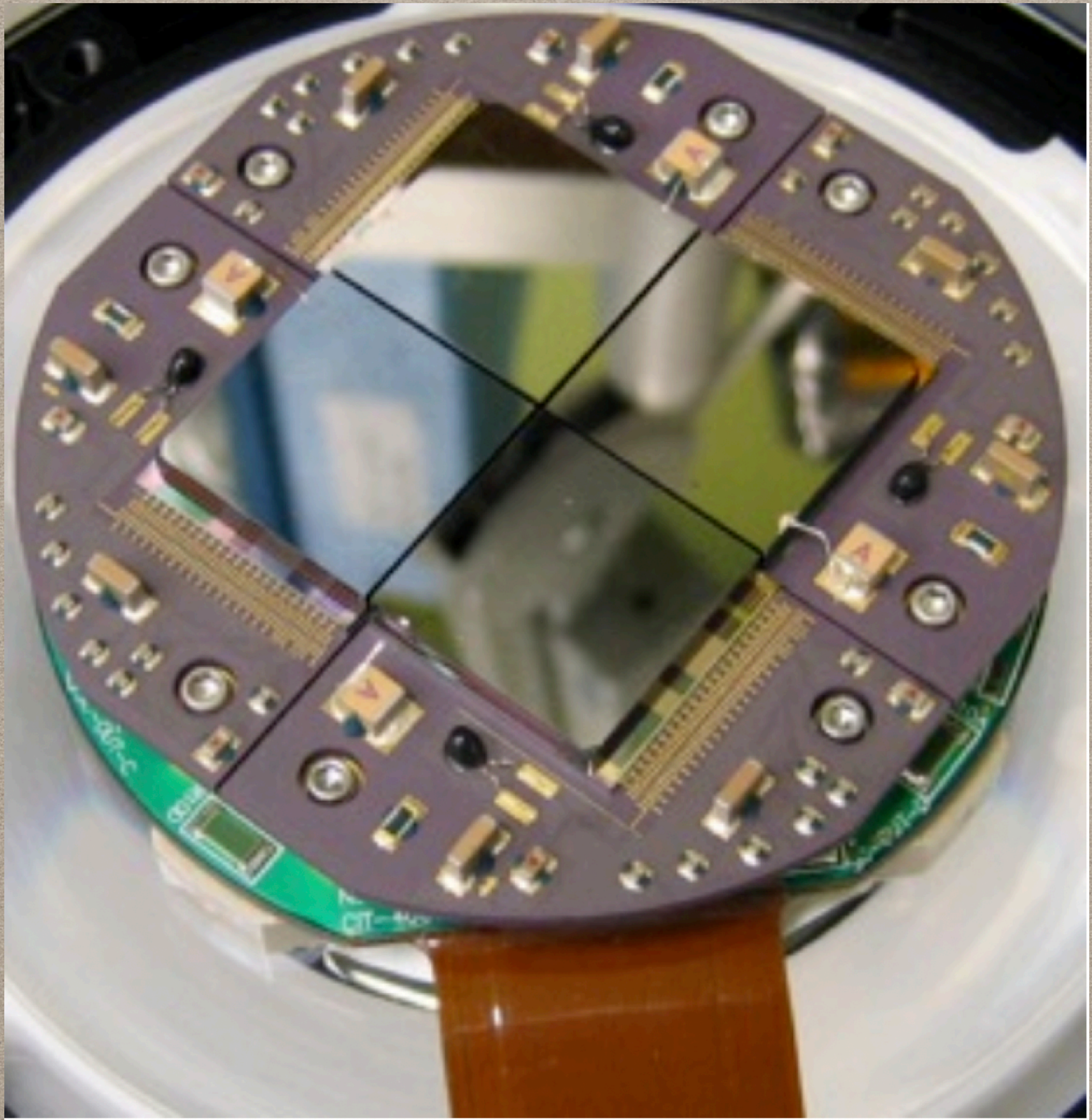








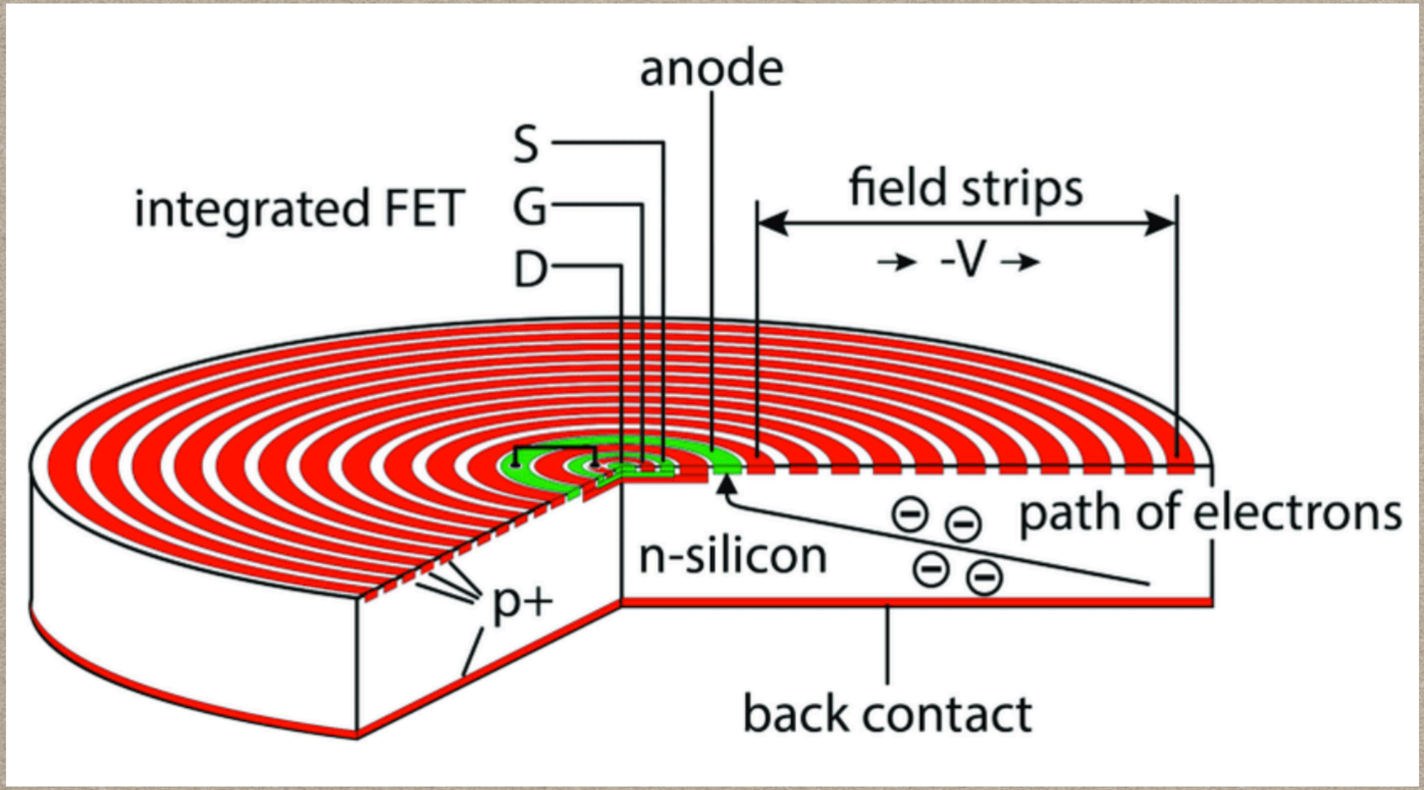
NUSTAR DETECTORS



- NuSTAR detectors are solid-state, optimised for the detection of high(er) energy photons
- Array of Cadmium-Zinc-Telluride crystals
- 4 detectors, 1024 pixels each

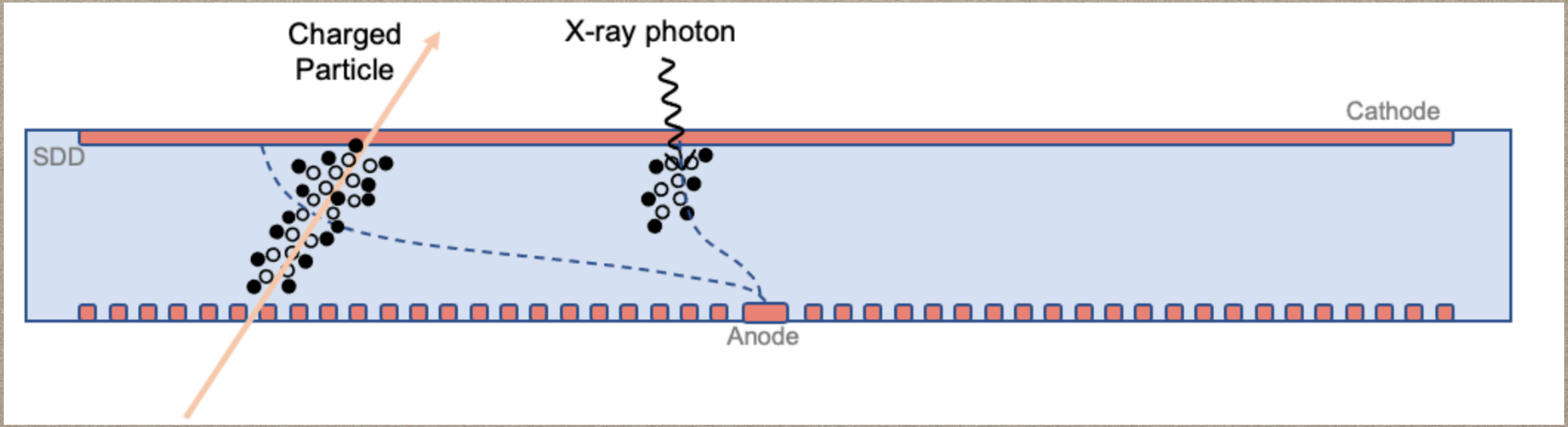
(Rana et al., 2016, SPIE, 7435 743503-1)

NICER DETECTORS



NICER detectors are **Silicon Drift Detectors**

Basically, a set 56 single-pixel coupled to each concentrator)



(https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/)

OUTLINE

- How do we “focus” X-rays?
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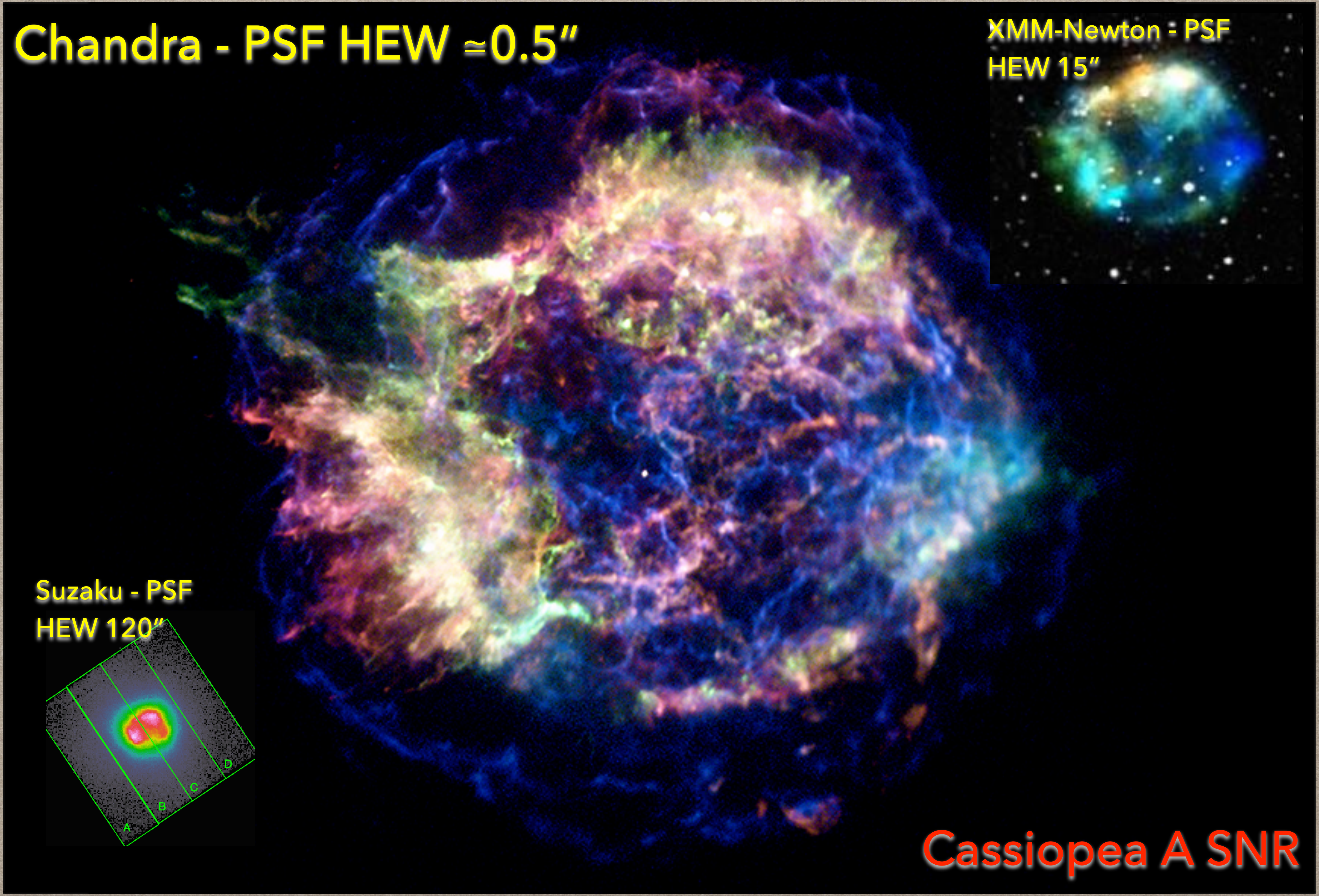
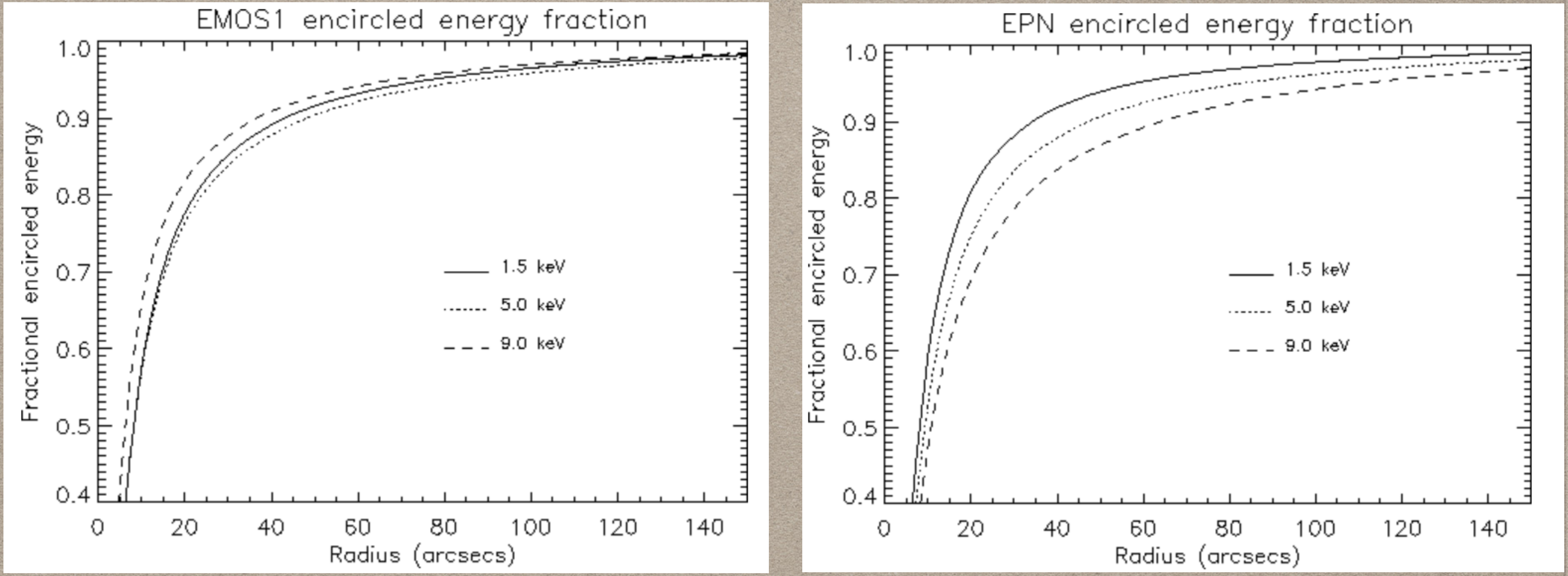
POINT SPREAD FUNCTION (PSF)



(Chandra: Page et al., 2011, Ph.Rev.Lett, 106, 081101; Suzaku: Maeda et al., 2009, PASJ, 61, 1217; XMM-Newton: from the image gallery)

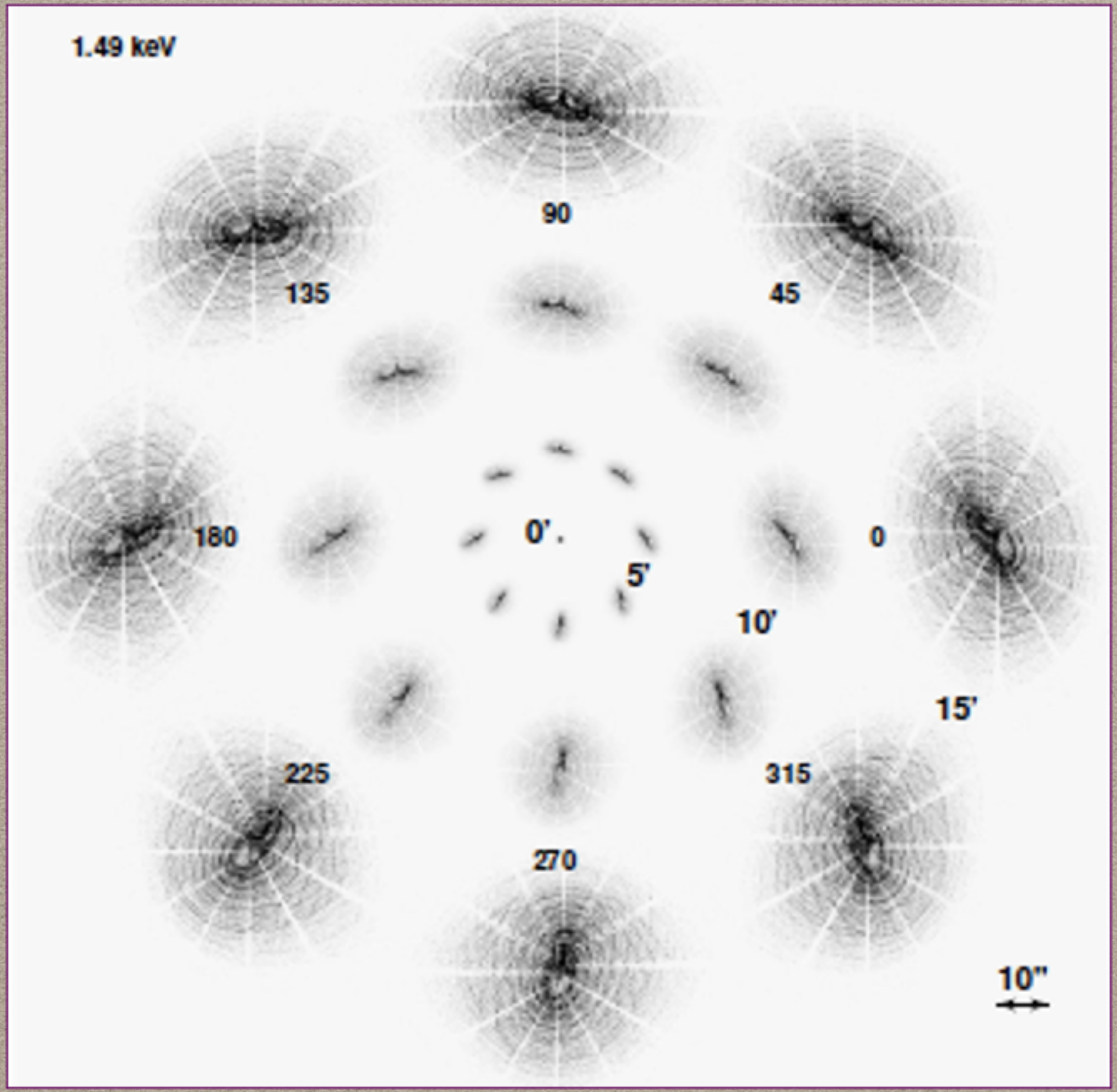
ENCIRCLED ENERGY FRACTION



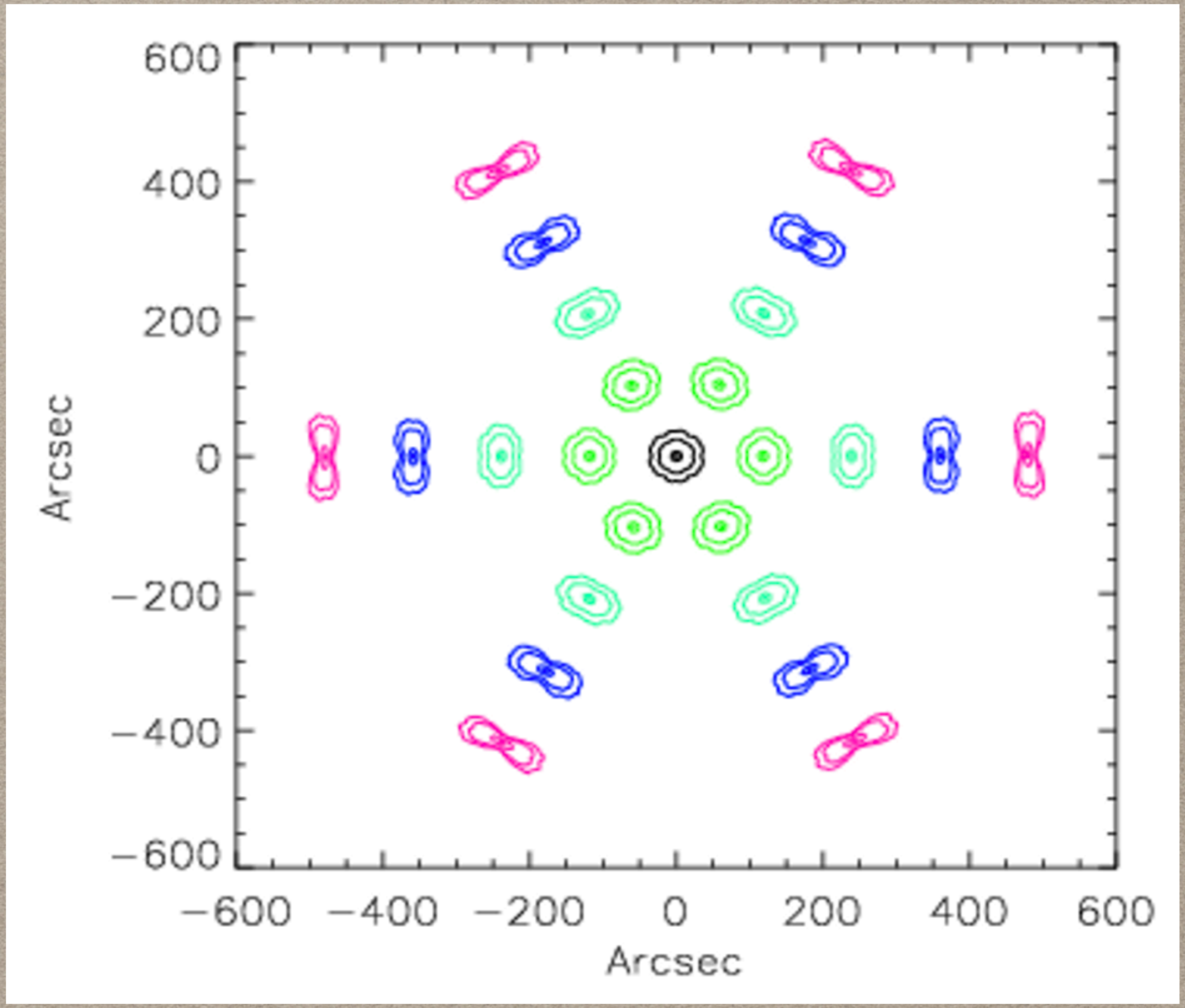
Alternative convenient way to represent the PSF in 1 dimension

(XMM-Newton User's Handbook: `http://xmm.esac.esa.int/external/xmm_user_support/documentation/uhb/XMM_UHB.html`)

IMAGE QUALITY QUICKLY DEGRADES OFF-AXIS



Chandra



NuSTAR

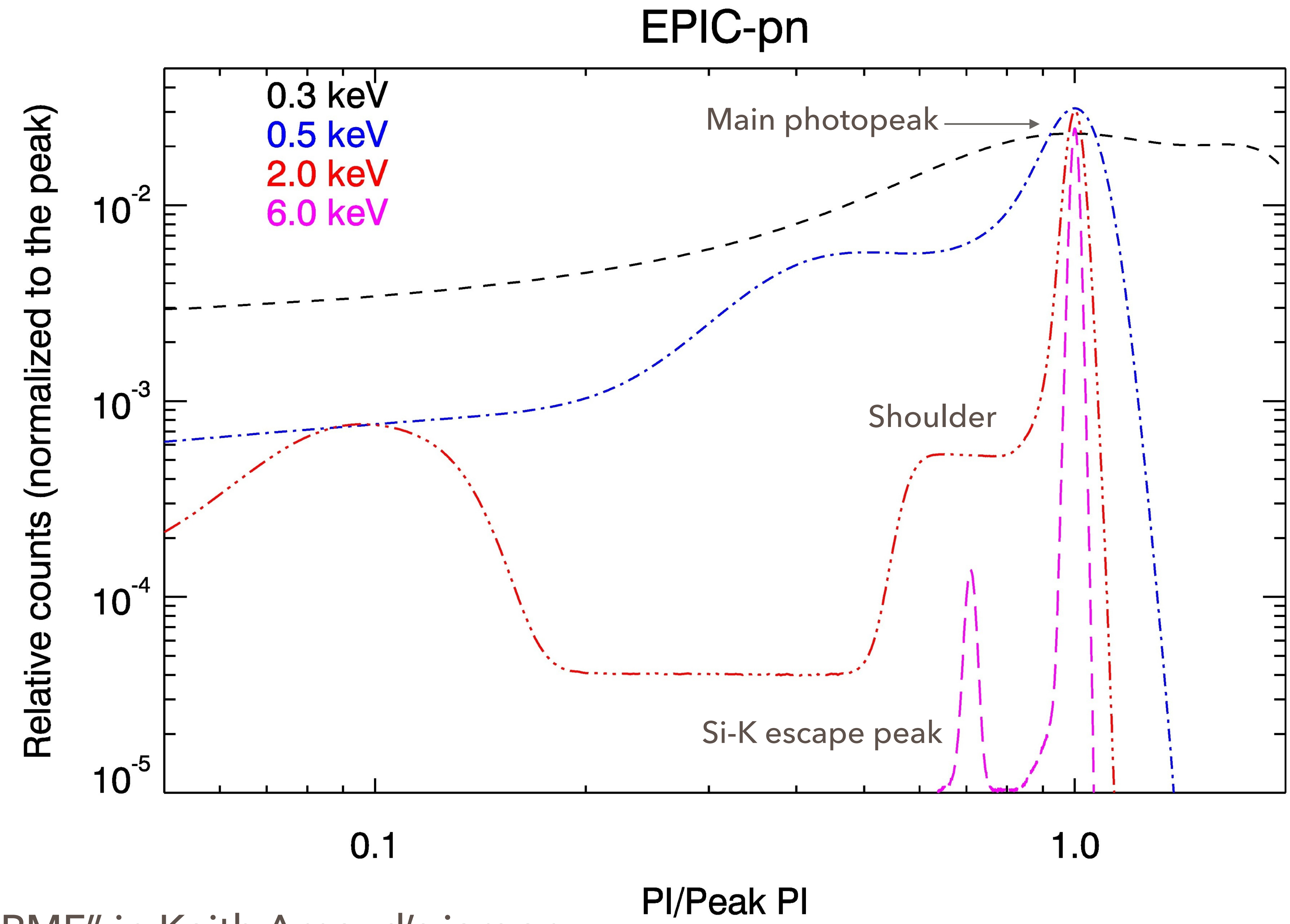
ENERGY RESOLUTION

- The energy resolution (ΔE) is the width - in energy space - of an input monochromatic signal
- Primarily driven by the Poissonian statistics (N discrete electron-ion or electron-hole pairs!) ⇒ $\Delta E \propto \sqrt{N} \propto \sqrt{E}$
- Slight correlation due to amplifying discharge yields a smaller variance than Poissonian ⇒ Fano Factor (F)

Energy required to create a pair

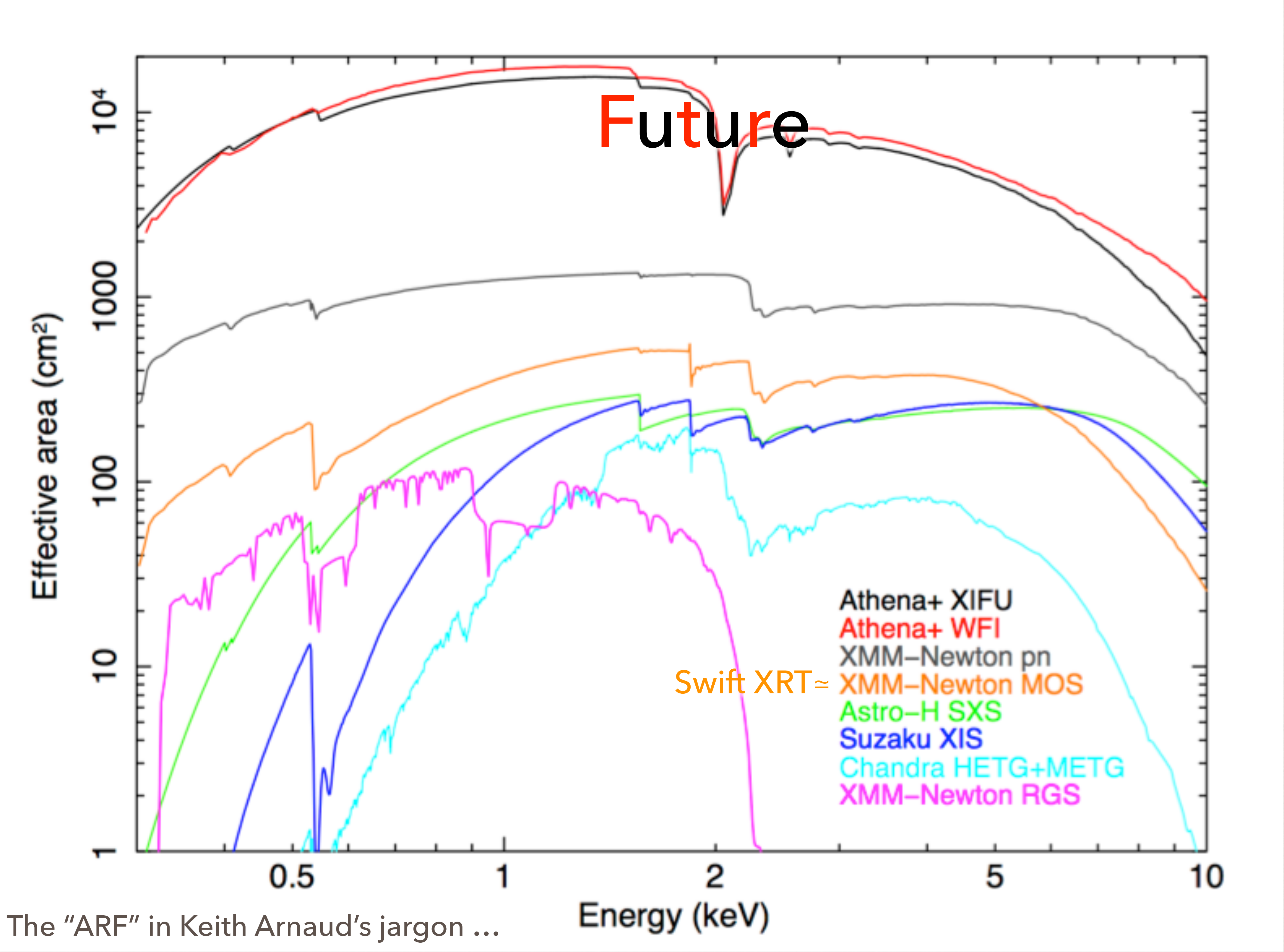
- In gas detectors: $$\frac{\Delta E}{E} = 2.35\left(\frac{W\,(F+A)}{E}\right)^{1/2}$$ F~0.2, ΔE(6 keV)~14%
- In CCDs: $$\frac{\Delta E}{E} = 2.355\sqrt{\frac{3.65\,\mathrm{eV}\cdot F}{E}}$$ F~0.1, ΔE(6 keV)~3%

ENERGY REDISTRIBUTION



The "RMF" in Keith Arnaud's jargon …

EFFECTIVE AREA

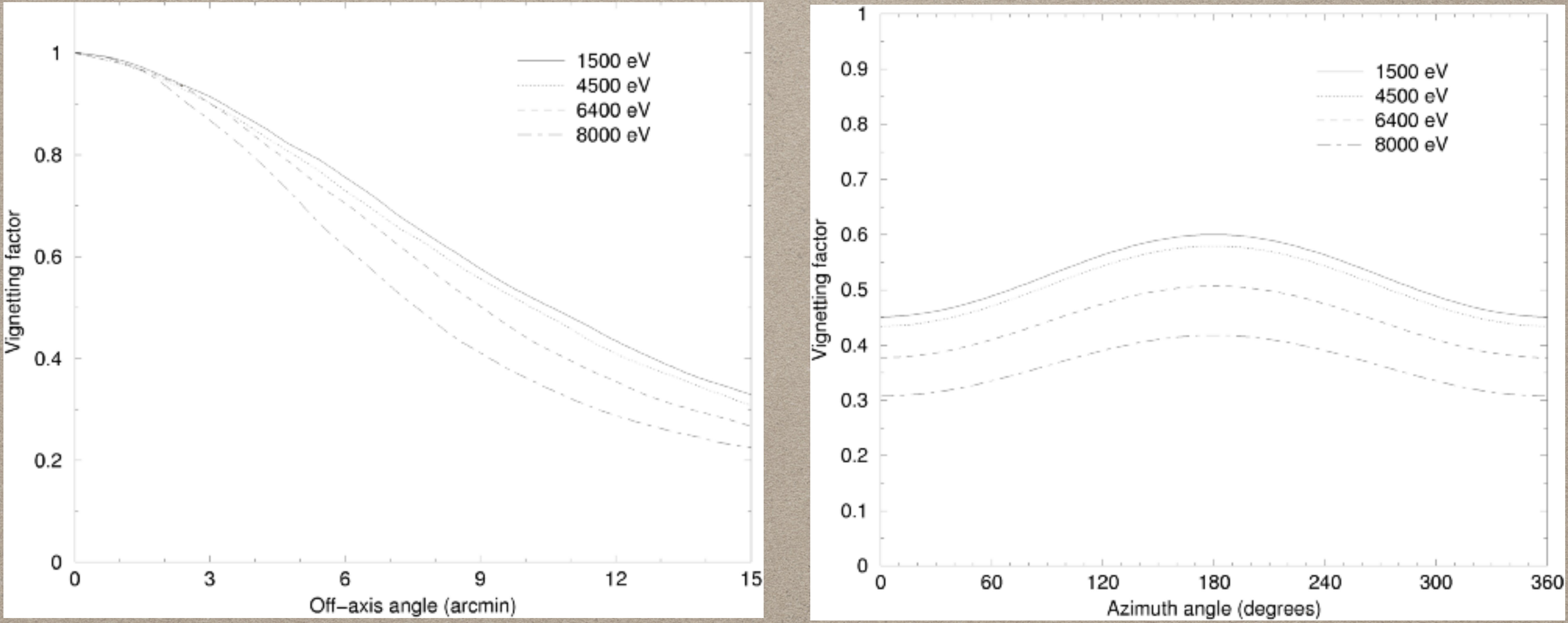


The "ARF" in Keith Arnaud's jargon …

(Courtesy ATHENA Science Team)

VIGNETTING

XMM-Newton vignetting curves



Shadowing effect changes dramatically the area off-axis!

(XMM-Newton User's Handbook: `http://xmm.esac.esa.int/external/xmm_user_support/documentation/uhb/XMM_UHB.html`)

SUMMARY

- Chandra: ACIS (CCD), [LH]HETG (gratings), HRC (MCP)
- INTEGRAL: JEM-X (PC),
- MAXI: GSC (PC), SSC (CCD)
- NuSTAR (focusing optics >10 keV, CdZnTe)
- Swift: XRT (CCD), BAT (CdZn Te)
- Suzaku: XIS (CCD), HXD (Phoswitch - scintillator)
- XMM-Newton: EPIC (CCD), RGS (gratings)