Scintillation Camera

Mi-Ae Park
Oct. 27, 2016

- RSNA/AAPM Physics Module 17.5 (Phys0309)
https://www.rsna.org/RSNA/AAPM_Online_Physics_Modules_.aspx
- Review of Radiologic Physics, W. Huda.
- The Essential Physics of Medical Imaging by Bushberg at al.
- Physics in Nuclear medicine, 3rd ed. by Cherry et al.

17.5. Scintillation Camera

17.5.1. Clinical Purpose
17.5.2. Camera Design;
Crystal Parameters, Spatial Localization, Energy Discrimination
17.5.3. Collimator Characteristics;
Sensitivity, Resolution, Energy
17.5.4. Collimators;
Parallel-Hole, Pinhole, Specialized

Scintillation camera = Gamma Camera
➔ Anger Camera (invented by Hal O. Anger)

1. Decreasing the hole size of parallel hole collimator likely to _____ sensitivity and _____ spatial resolution.
    a. increases, improves
    b. decreases, improves
    c. decreases, degrades
    d. increases, improves

2. The function of scintillation detector in gamma-ray imaging is ___________.
    a. To absorb as much gamma radiation as possible
    b. To convert the gamma radiation to visible light
    c. To transfer the visible light to the PMTs
    d. To detect radiation coming from the patient
    e. All of the above

3. What does photomultiplier tube (PMT) detect?
    a. High energy gamma ray
    b. Low energy gamma ray
    c. Visible light
    d. Electron
    e. Positron

4. Which type of collimator is best for thyroid imaging in clinic?
    a. Parallel hole collimator
    b. Pinhole collimator
    c. Conversing hole collimator
    d. Diverging hole collimator

5. What will results from using a thicker scintillation detector?
    I. Increase sensitivity
    II. Improve spatial resolution
    III. Decrease sensitivity
    IV. Degrade spatial resolution
    V. No effect in image quality

        a. I, II
        b. I, IV
        c. II, III
        d. II, IV
        e. V

6. A 10 kBq of Tc-99m was imaged for 10sec using a gamma camera equipped with a low-energy high-resolution parallel hole collimator. Approximately how many gamma rays will arrive to NaI(Tl) detector?
   a. 1
   b. 10
   c. 100
   d. 1000

7. From Q6, how many gamma rays will be detected by the scintillation detector?
   a. 1
   b. 10
   c. 100
   d. 1000

8. A point source containing Tc-99m was placed at 10cm from the surface of a parallel hole collimator. During a 1min acquisition, total 1,000 gamma rays were detected by a gamma camera. If the point source is now moved close to the camera and placed at 5cm from the collimator, how many gamma rays are detected for 1min?
   a. 250
   b. 1,000
   c. 2,000
   d. 4,000

9. Using a low energy collimator for a high energy radionuclide ___"

   a. allows faster scans
   b. reduces the sensitivity of the detector
   c. causes the image to be inverted
   d. increases the field of view but minifies the image
   e. results in septal penetration

10. For NaI(Tl) detector, low energy gamma emitter yields better spatial resolution than high energy gamma. (True / False)

11. Hole septa used for Ga-67 imaging is thicker than that for Tc-99m imaging. (True / False)

12. Tc-99m imaging with 20% energy window uses the energy range between 120 and 140 keV. (True / False)

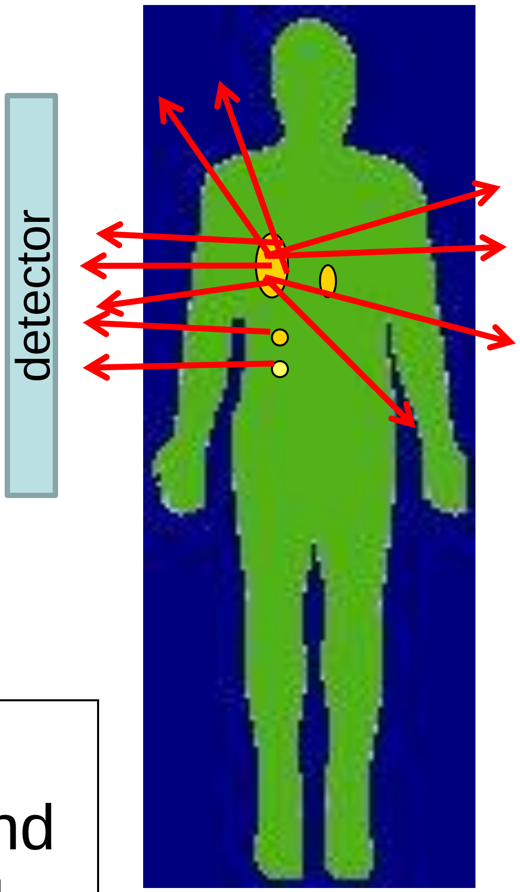
13. Increasing hole length of a parallel hole collimator likely increases sensitivity (True / False)

14. Increasing hole length of a parallel hole collimator likely improves spatial resolution (True / False)

17.5.1 - Clinical Purpose

The purpose of nuclear medicine imaging is to map physiologic processes in vivo

- Find tracer compounds that we can label with radioactive substances
- Then we image the radioactivity distribution with a Gamma camera



The quality of a NM image is determined
by the performance of the imaging device and
by the properties of the radiopharmaceutical

General purpose systems

Dual-Head gamma camera

Triple-Head gamma camera

Detector size ~ 30 – 50 cm

Dedicated systems

Cardiac system

brain system

Breast-Specific Gamma Imaging (BSGI)

Gamma emitting radionuclides for NM imaging

- Must be able to pass through the body
- Must be detectable

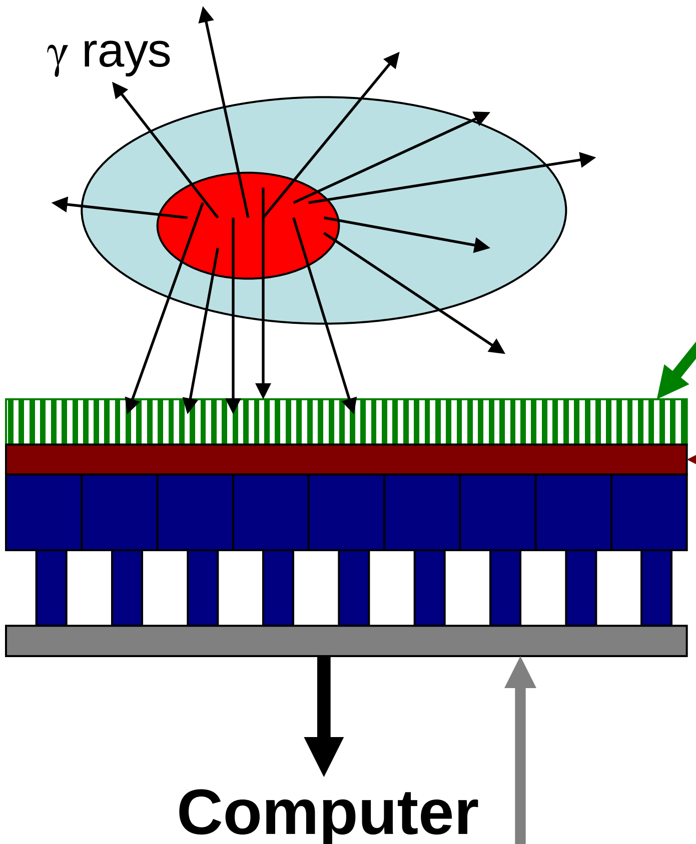
Radionuclide	Energy (keV)	tracers
Tc-99m	140	16
Tl-201	71, 167, 135	1
In-111	245, 171	5
Ga-67	184, 300	1
I-123	159	3
I-131	364	2
Xe-133	81	1

Workhorse of NM

80-85% of all NM imaging procedures

Energy range
70 ~ 360 keV

17.5.2 - Camera Design



Collimator Define the direction of the detected γ rays. Major component affecting resolution and efficiency.

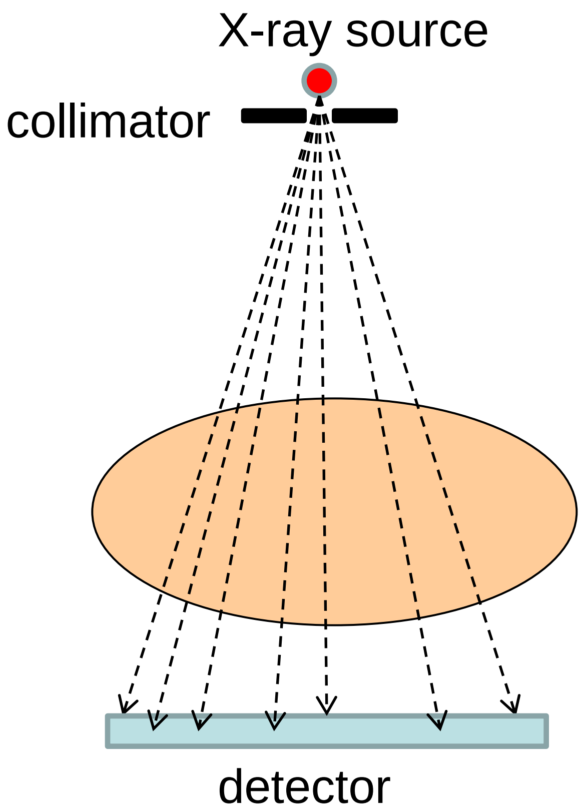
scintillation crystal γ ray detector. Emits light photons after deposition of high energy γ rays.

Photomultiplier tube (PMT) Each tube converts a light signal to an electrical signal and amplifies it.

Preamplifier, Positioning circuit & pulse height analyzer
Determines the location of each scintillation event.
Rejects non-photopeak events.

Collimator

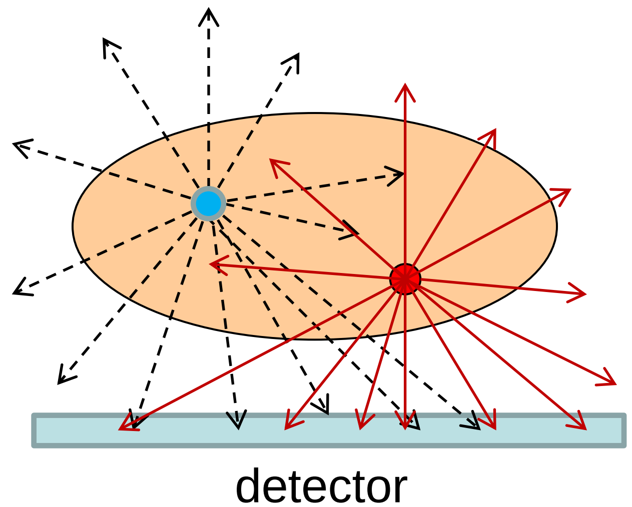
Transmission imaging



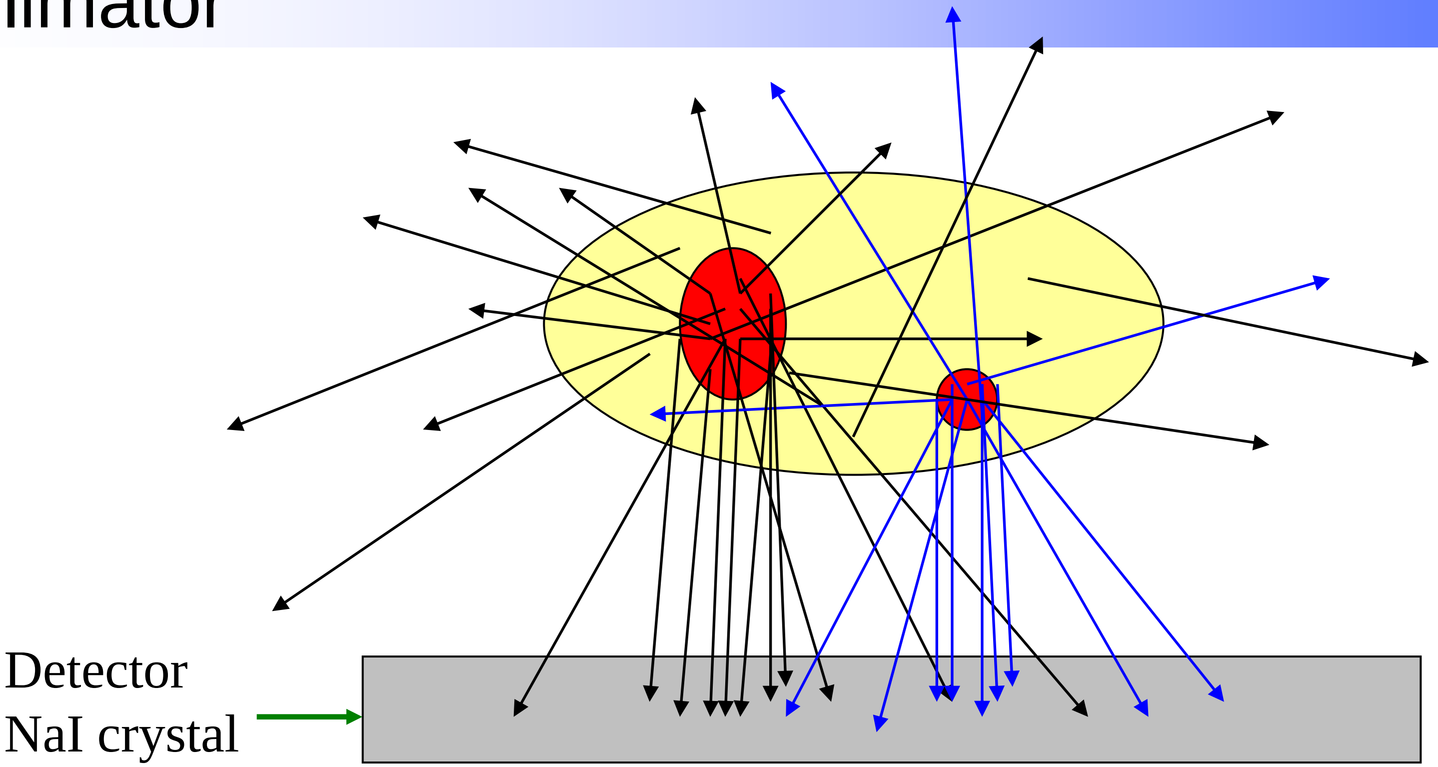
Primary photons travel known paths diverging radially from the focal spot

Emission imaging using a gamma camera

Photons in each volume element of a patient are emitted isotropically (equally in all directions)

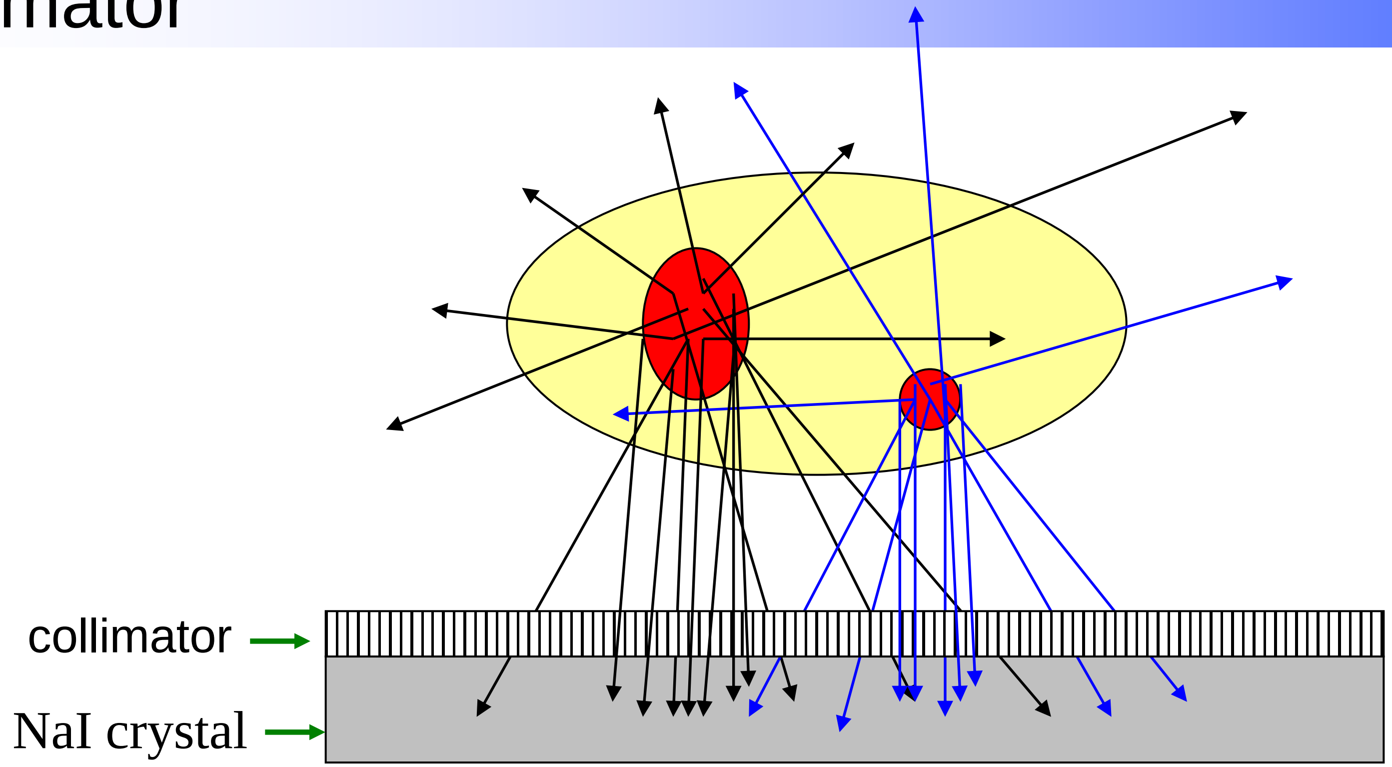


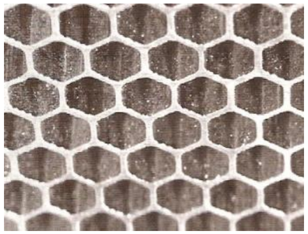
Collimator



- Gamma rays are emitted to any direction in space.
- The detected gamma rays can come from any location in the body

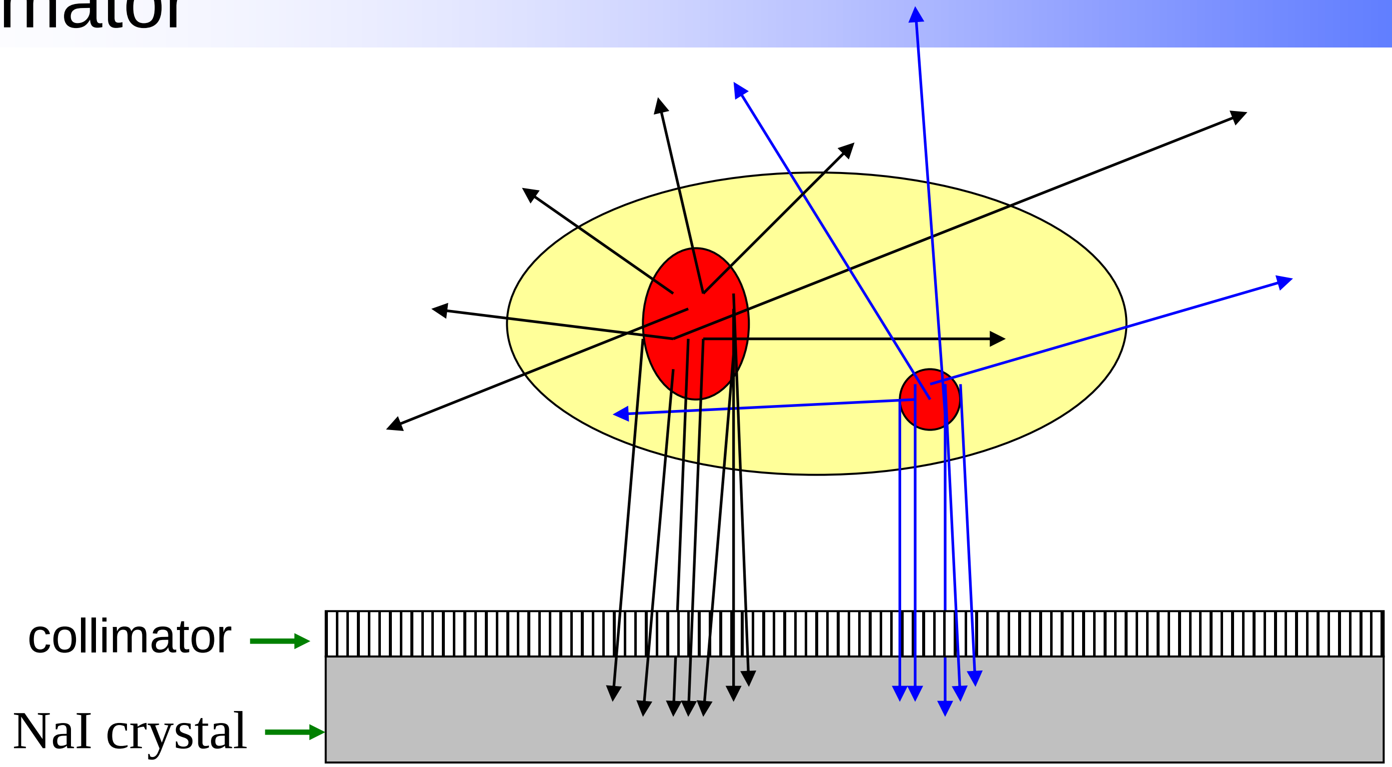
Collimator

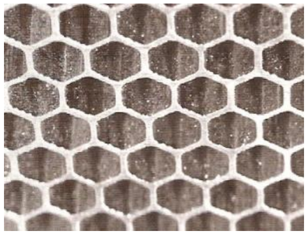




- Gamma rays are emitted to any direction in space.
- The detected gamma rays can come from any location in the body

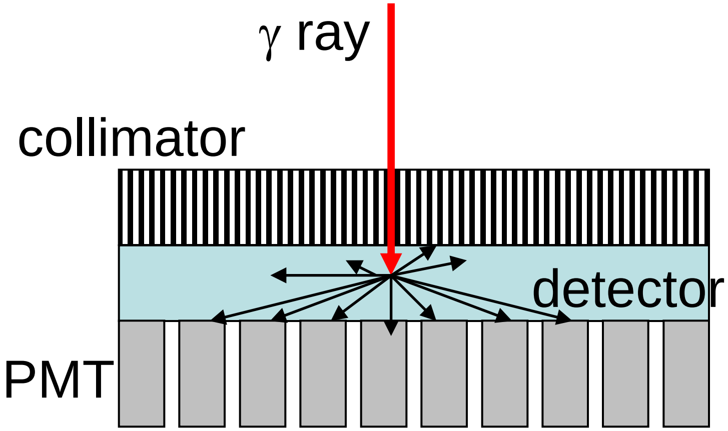
Collimator





- The collimator allows those gamma rays traveling along certain directions to reach the detector (only a few out of 10,000 for parallel collimation).
- The collimator establishes a one-to one correspondence between locations on the detector and those within the organ.

Scintillation Crystal



1. The gamma ray photon interacts with the scintillation detector through the Photoelectric Effect or Compton Scattering primarily with the iodide ions of the crystal. → This interaction releases an electron .

2. The electrons interact with the crystal lattice to produce **light** in a process known as **scintillation.**

3. A flash of light trigger nearby photomultipliers tube (PMT)

Scintillation crystal (detector) converts the gamma ray to visible light!

Scintillation Crystal

Gamma ray detector,

- Must have good detection efficiency
- Nearly all nuclear imaging devices in routine clinical use utilize Thallium doped Sodium Iodide, NaI (Tl),
- NaI (Tl) is the detector of choice for radionuclides with γ ray emissions in the energy range, 70-360 keV
- a solid inorganic scintillator
- Typical detector thickness : ~ 0.95 cm (3/8 inch)
- Large area crystal with a field of view ~ 53 x 39 cm

Detection efficiency

1cm NaI (Tl) detector,

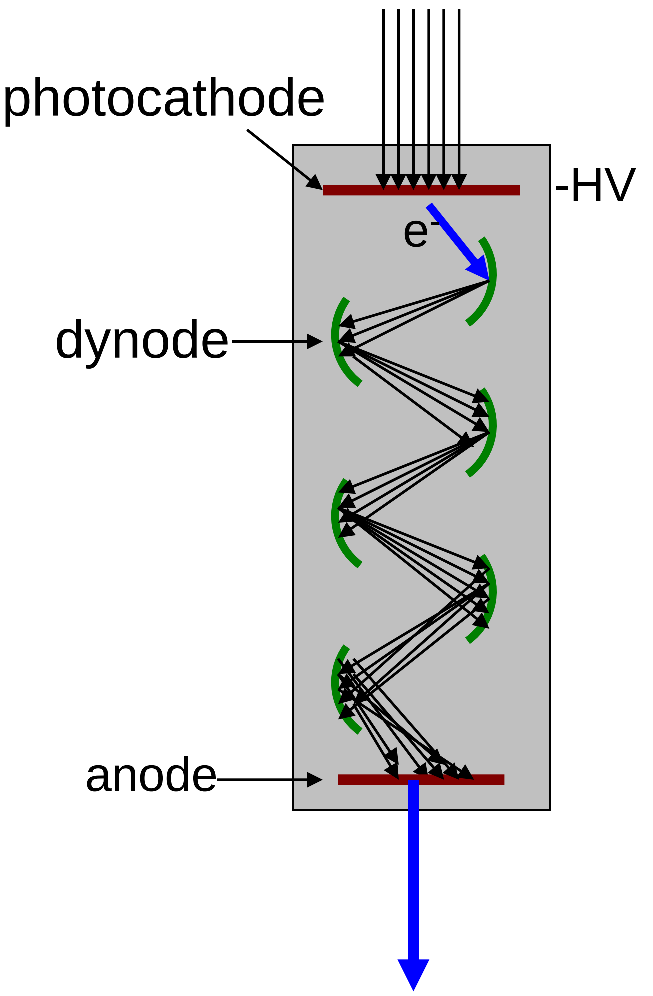
Energy (keV)	Percentage absorbed (%)
100	100
140	90
200	50
300	20
511	5

New detectors.

Small field of view camera using CZT (Cadmium zinc telluride, CdZnTe) semiconductor detectors had been developed.

(dedicated cardiac or breast imaging system)

Photomultiplier tube (PMT)

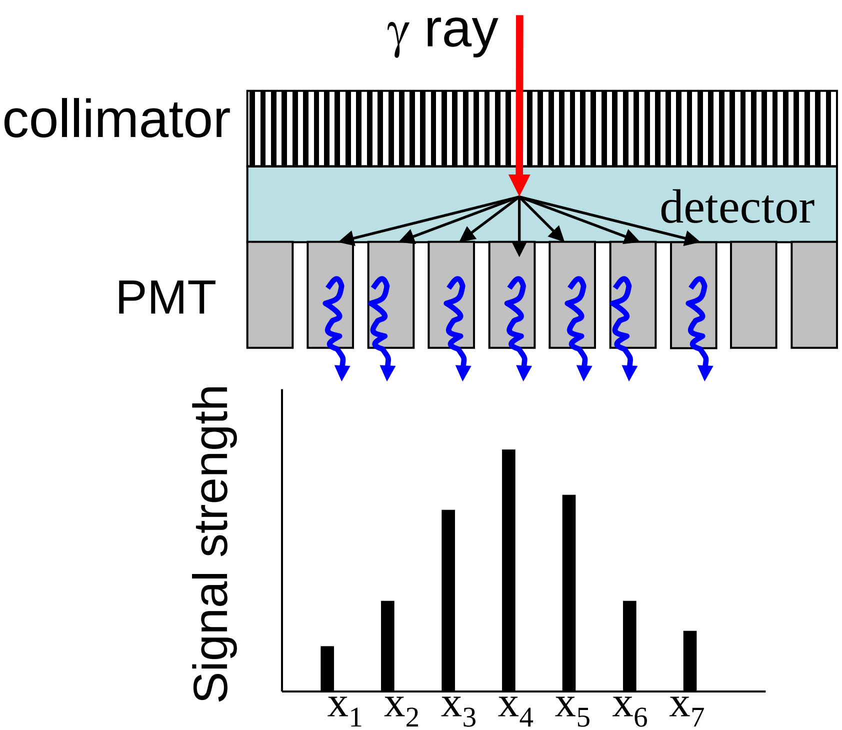


Electric current pulse to electronics board for positioning and summing circuits

PMT turns those visible light photons into an electrical signal

1. photocathode will emit electrons by photoelectric effect, after absorbing light photons.
2. The electron multiplier (amplifier), called a dynode, emits several secondary electrons for each incident electron. ~10 - 14 multiplication steps (number of dynodes).
3. Total electrons ~ (#electron amplified)$^{\#dynode}$
4. For each electron liberated from the photocathode, ~10^6 electrons reach the anode, depending on the number of dynodes

Spatial Localization

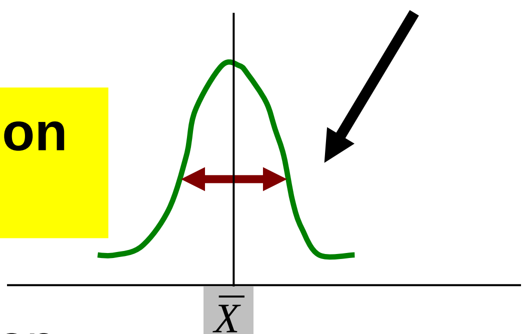


Weighted sum for positioning the primary interaction

$$\hat{X} = \frac{\sum_{i=1}^{7} x_i S_i}{\sum_{i=1}^{7} S_i}$$

This allows the position circuits to determine where each scintillation event occurred in the detector crystal.

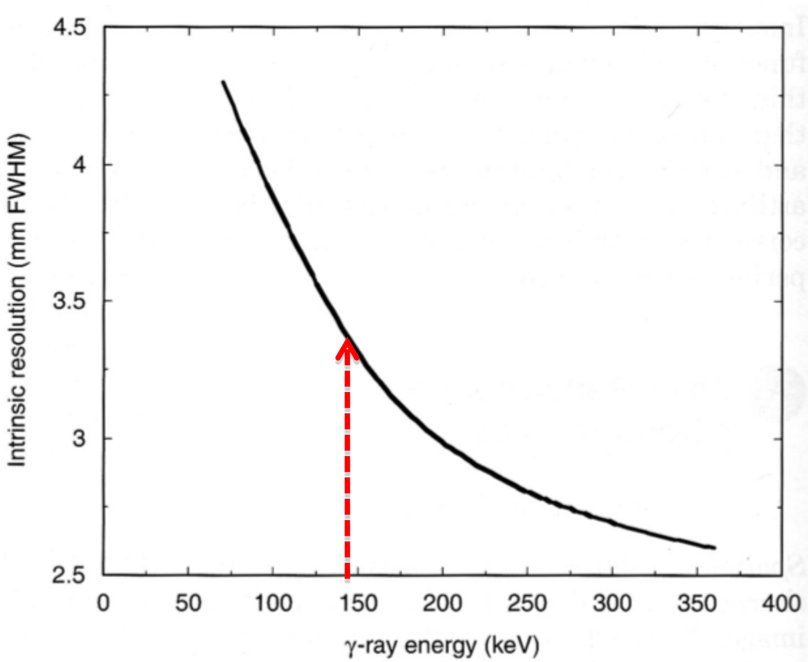
intrinsic resolution (FWHM)



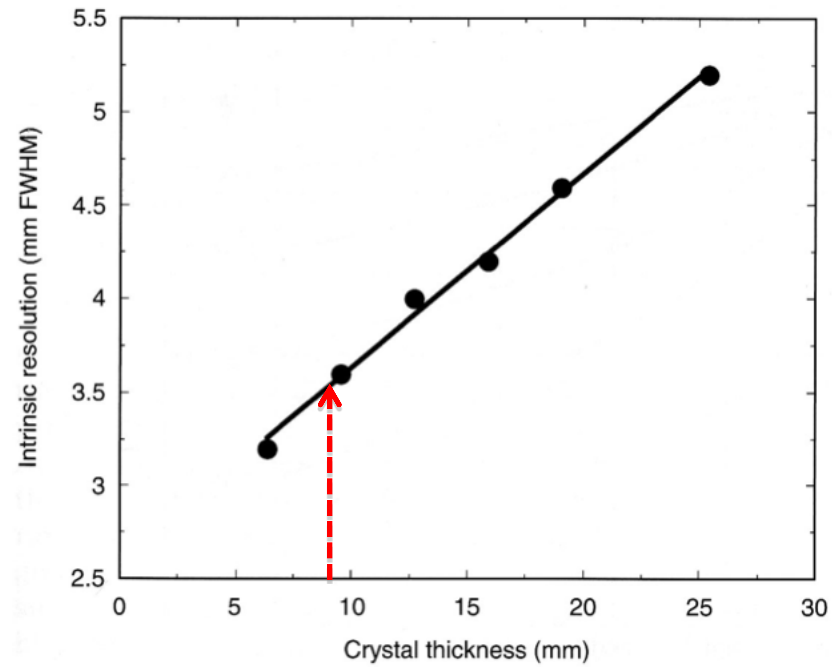
Error in the calculation of the position

Intrinsic spatial resolution

Number of scintillation light photon is roughly proportional to E.
At low E ➔ less photons → statistical fluctuation → blurring



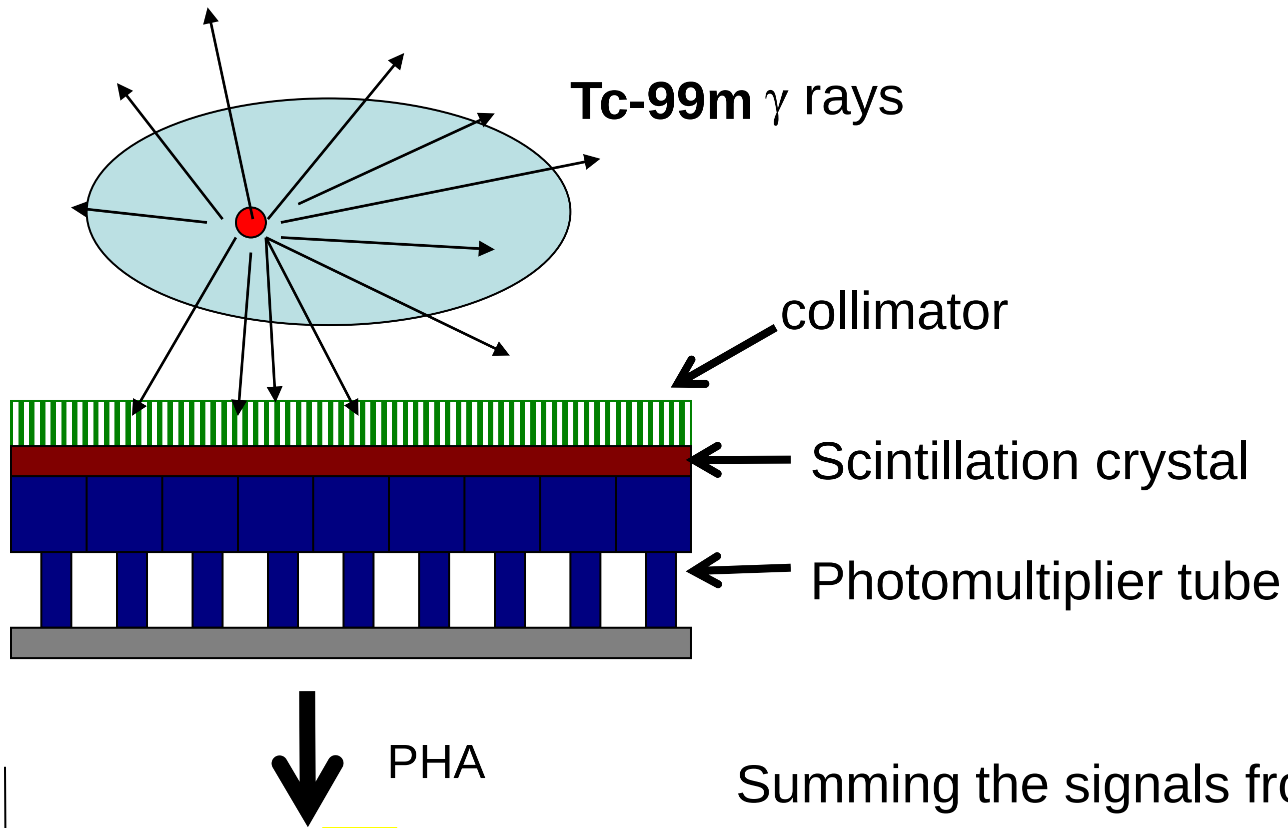
Thicker crystal →
greater spreading of light

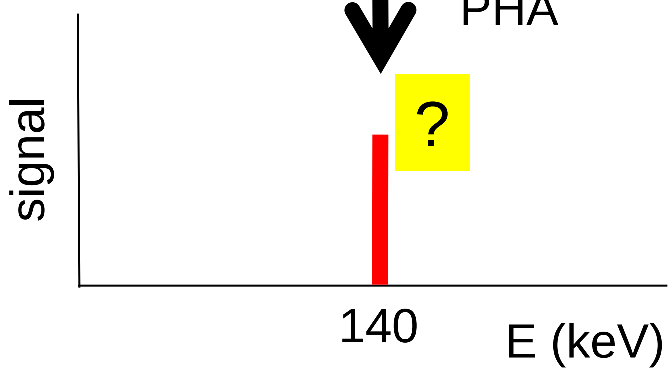


Intrinsic resolution for a large field of view gamma camera, ~ 3.5 mm FWHM at 140 keV (Tc-99m). (**3/8in=9.5mm thick NaI**)

Cherry, p. 228-229

Pulse-height analyzer : Energy Discrimination





Summing the signals from the individual PMT & produce an energy signal

→ proportional to total energy deposited in the crystal

→ Send to energy discrimination circuit

Individual events are analyzed for energy by pulse-height analyzer circuit

Energy Discrimination

Compton scattering process : photon gives some energy to electrons

- change direction with reduced energy
- Position information has been lost

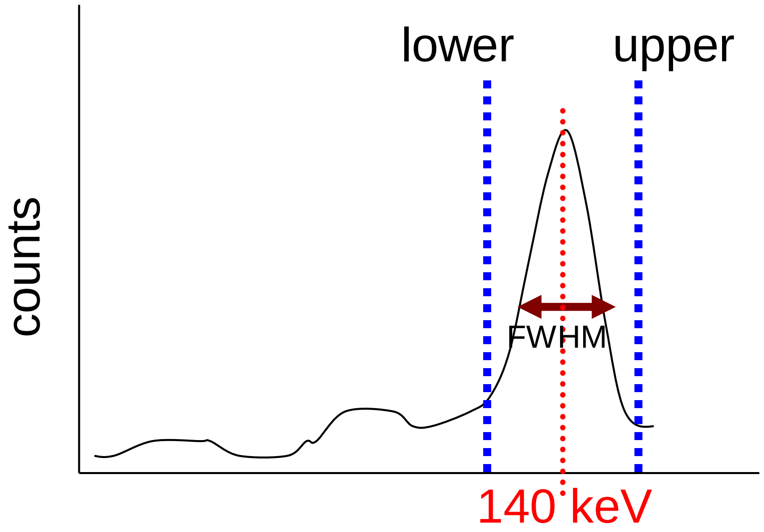
→ contribute to noise and reduce contrast

→ Need to get rid of these scattered photons from our final dataset

Scattered photons have reduced energy compared to original emission energy!

➔ set gamma camera to only accept events that deposit energy close to the photopeak energy

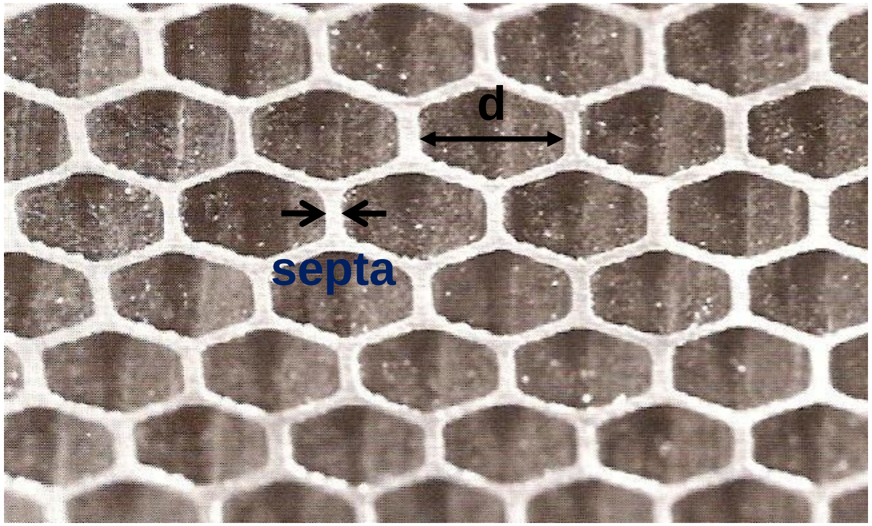
➔ Energy resolution ~10% (ability to determine the energy of a photon event)



Typical window for Tc-99m is 15-20%

Collimator

- Made of gamma ray absorbing material, usually lead or tungsten
- Round, square, hexagonal hole shape
- Collimator selection requires consideration of the imaged object's location and size, energy of gamma rays, and desired resolution and sensitivity.
- Usually more than 99.95 % of incident γ rays are absorbed (not detected!!!).

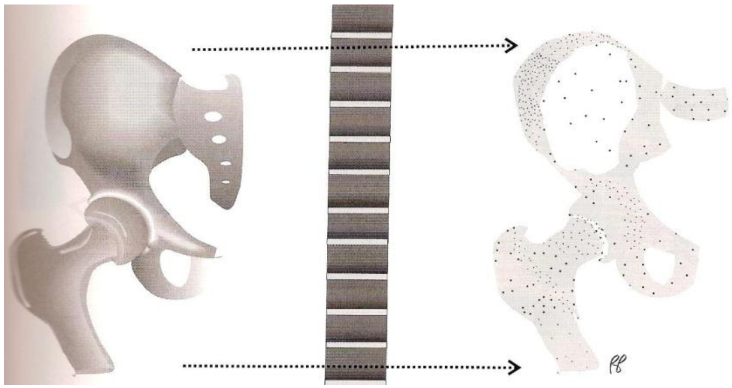


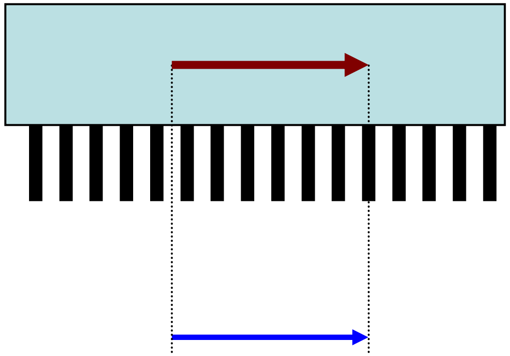
Cherry, p. 220 Fig.13-8

Half value layer (HVL) of lead for 140 keV (Tc-99m) ~ 0.3 mm

Types of Collimators

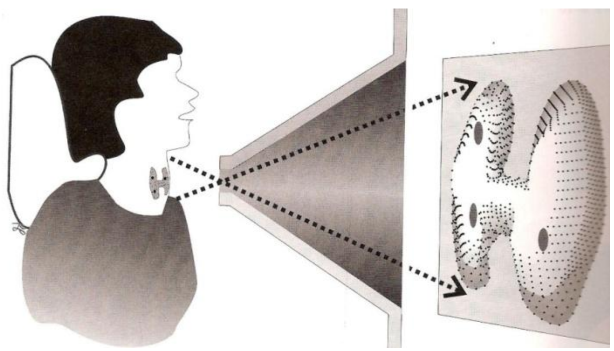
Parallel-hole collimator

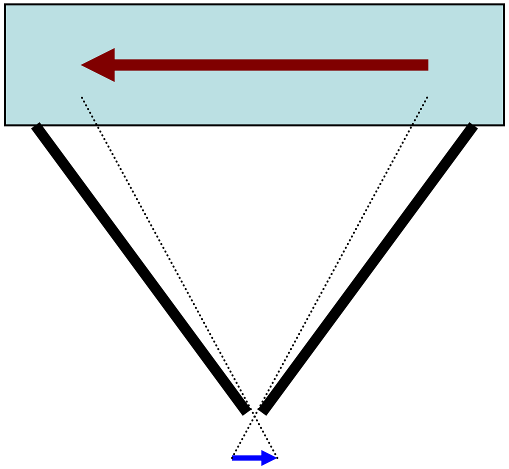




Workhorse collimator
Image size = object size

Pinhole collimator



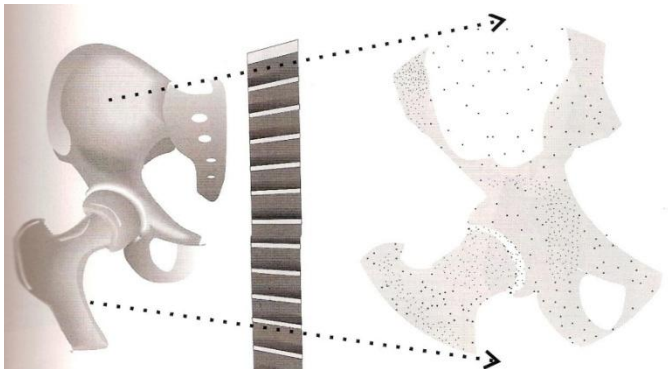


Inverted and magnified images. For small organs, thyroid, joint, pediatric imaging.

Powsner, p. 89-90.

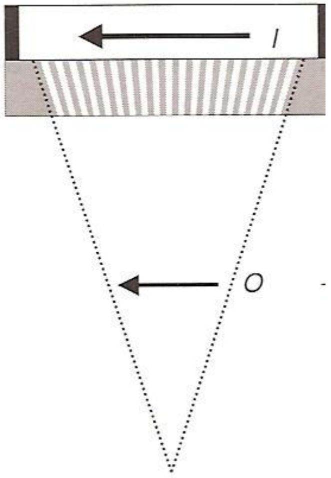
Types of Collimators

Converging collimator

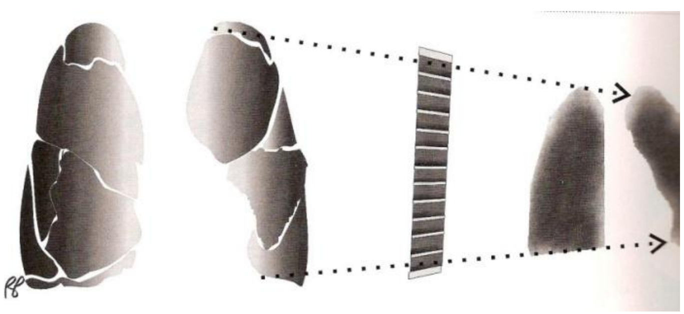


Magnified image

Imaging small or medium size organs with a large detector

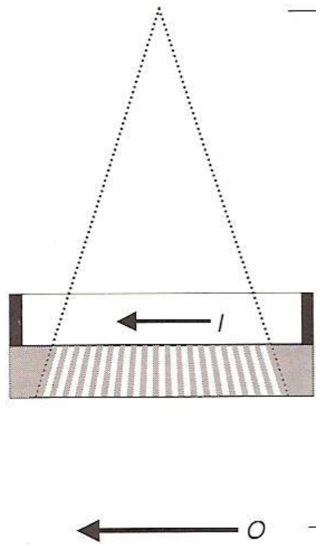


Diverging collimator

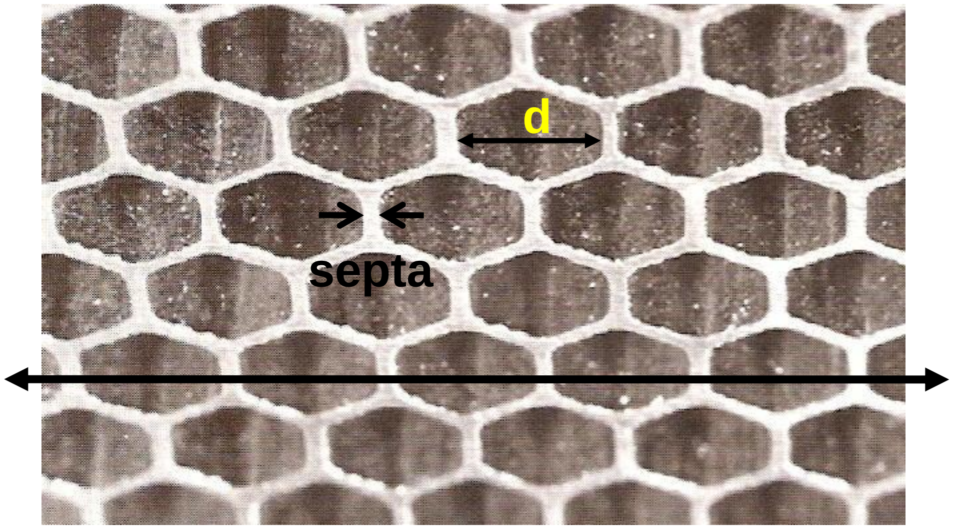


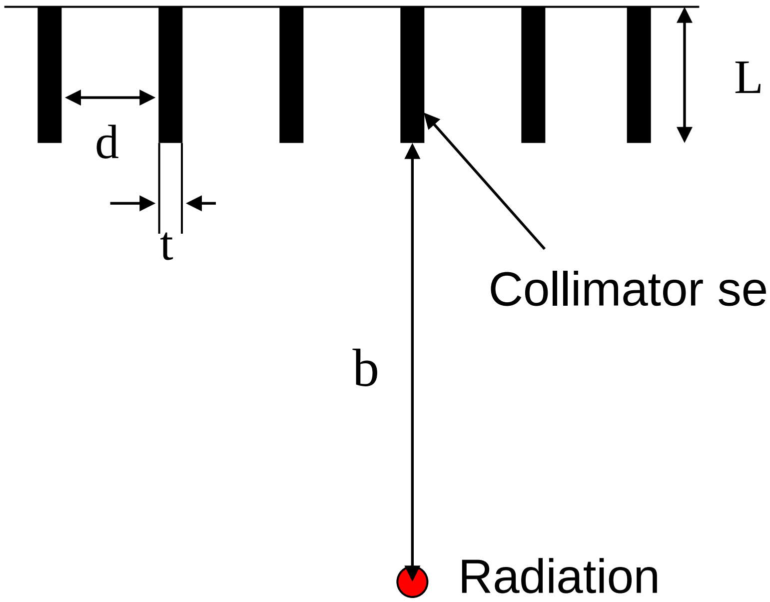
Minified image

Imaging large organ with smaller detector



Parallel-hole Collimator





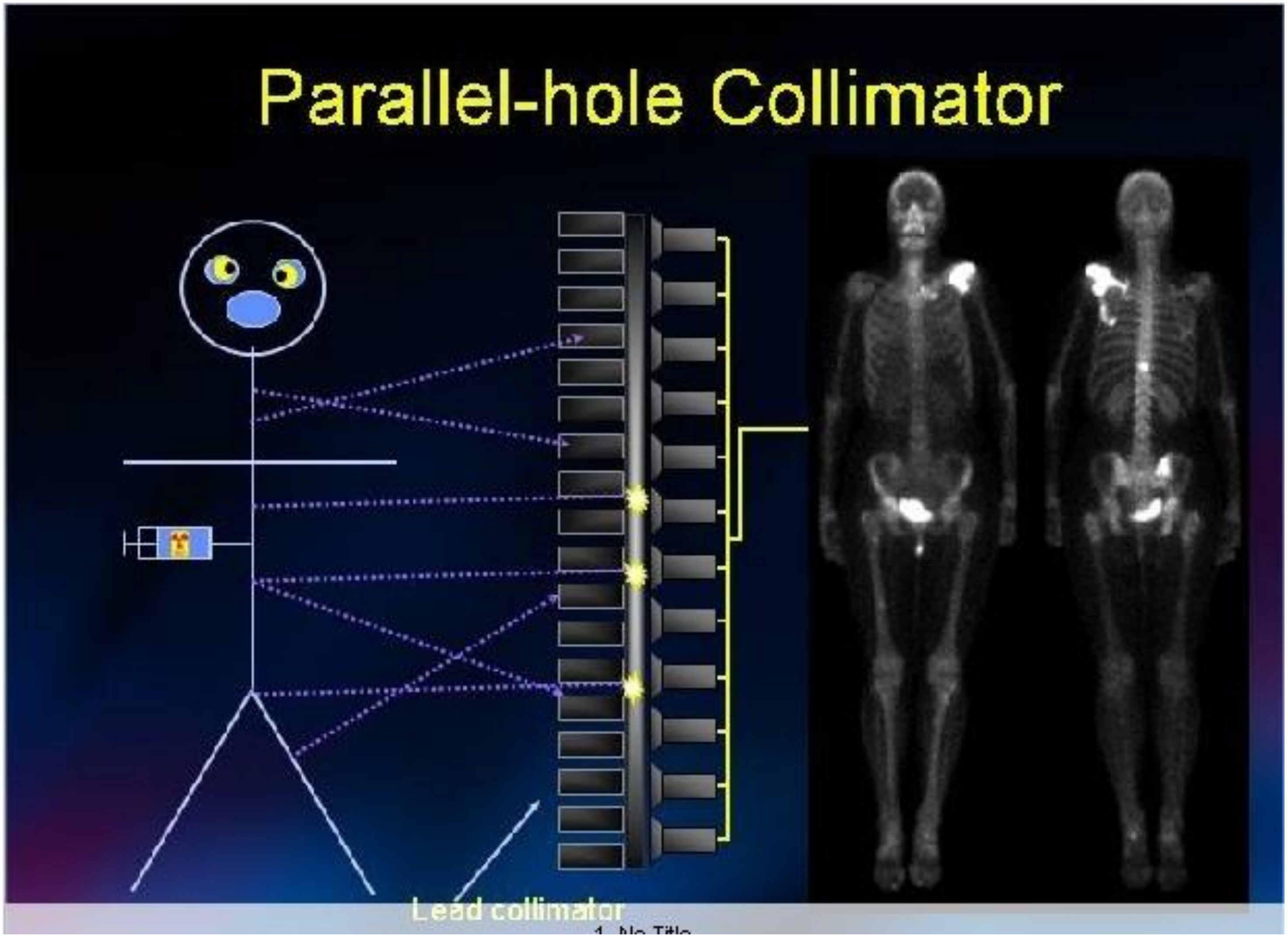
Three adjustable parameters

L : hole length (2 - 4 cm)
d : hole diameter (1 - 3 mm)
t : septal thickness (0.1 – 0.3 mm)

➡ All contribute to image quality

b: distance from the collimator to the source

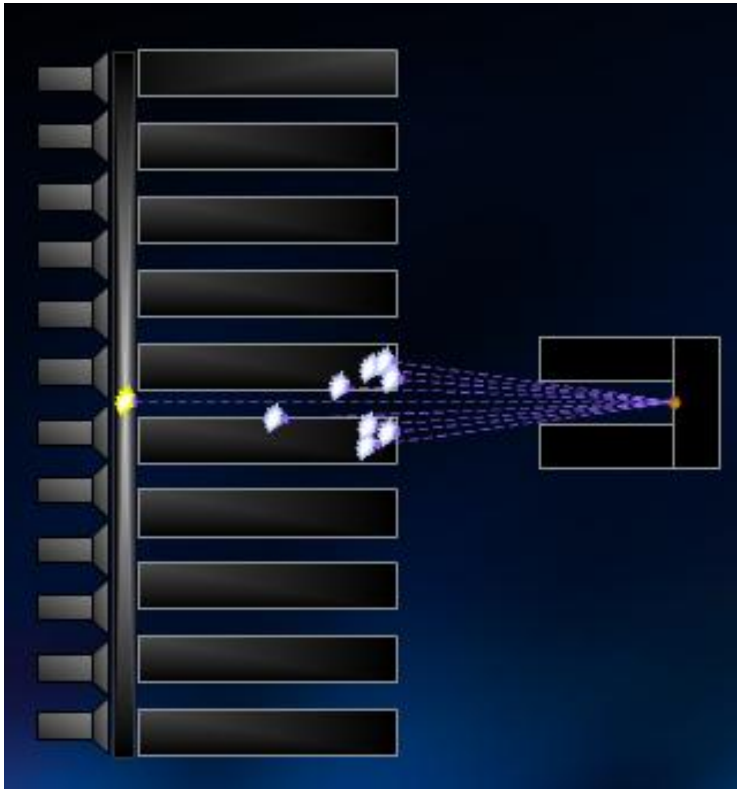
17.5.3 - Collimator Characteristics



dual-head gamma camera, AP planar bone scan

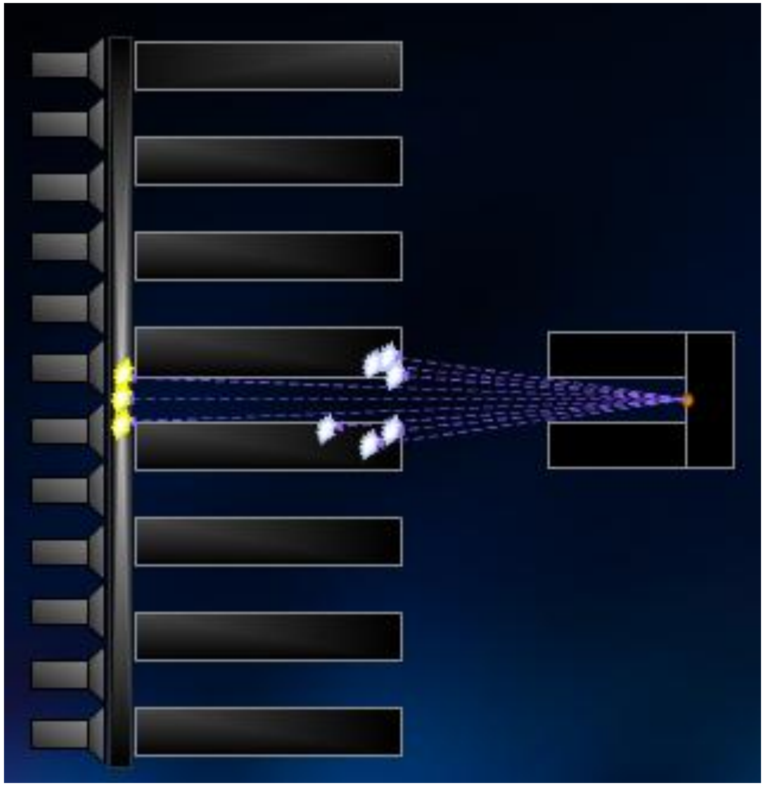
Collimator Characteristics : Hole diameter

Small hole diameter



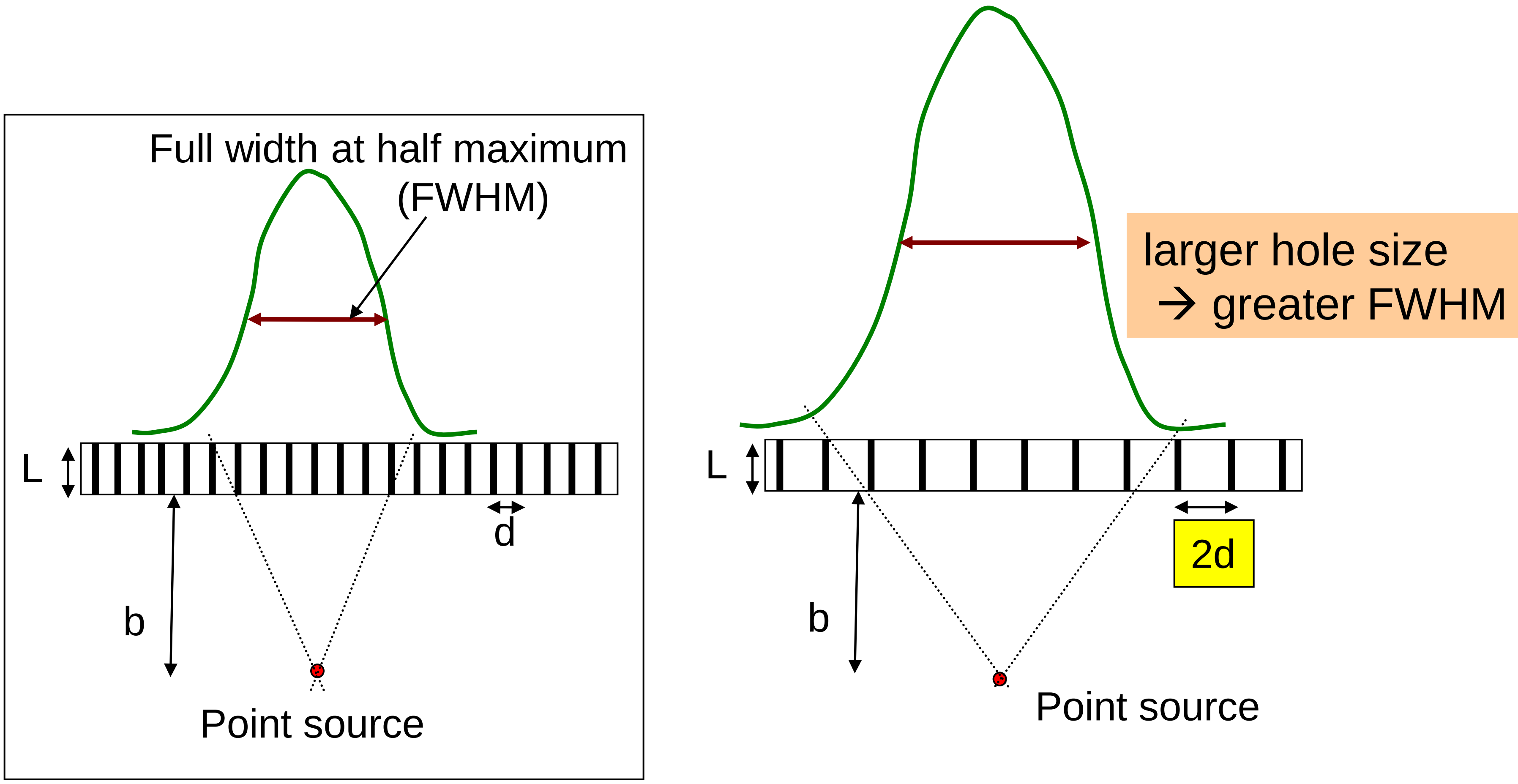
Better spatial resolution
Low sensitivity

Large hole diameter



Worse spatial resolution
High sensitivity

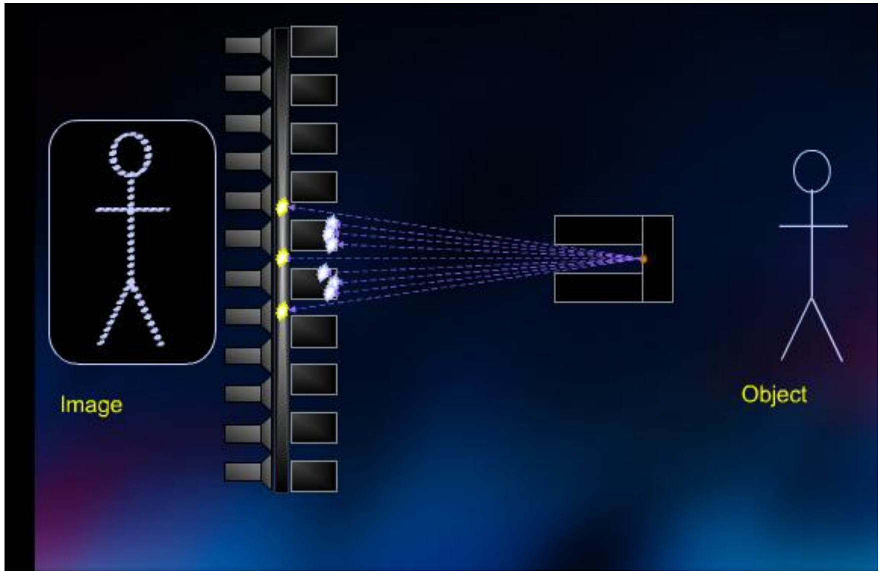
Collimator Characteristics : Hole diameter



Projected radiation profile (point-spread function)

Collimator Characteristics : Septal length (hole length)

Short septa



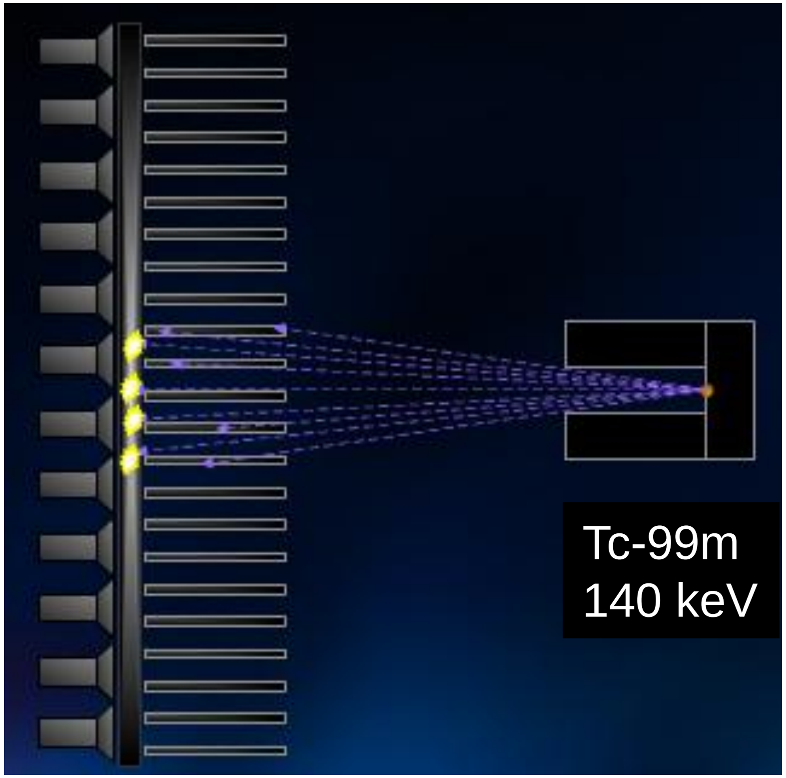
long septa

Low spatial resolution
high sensitivity

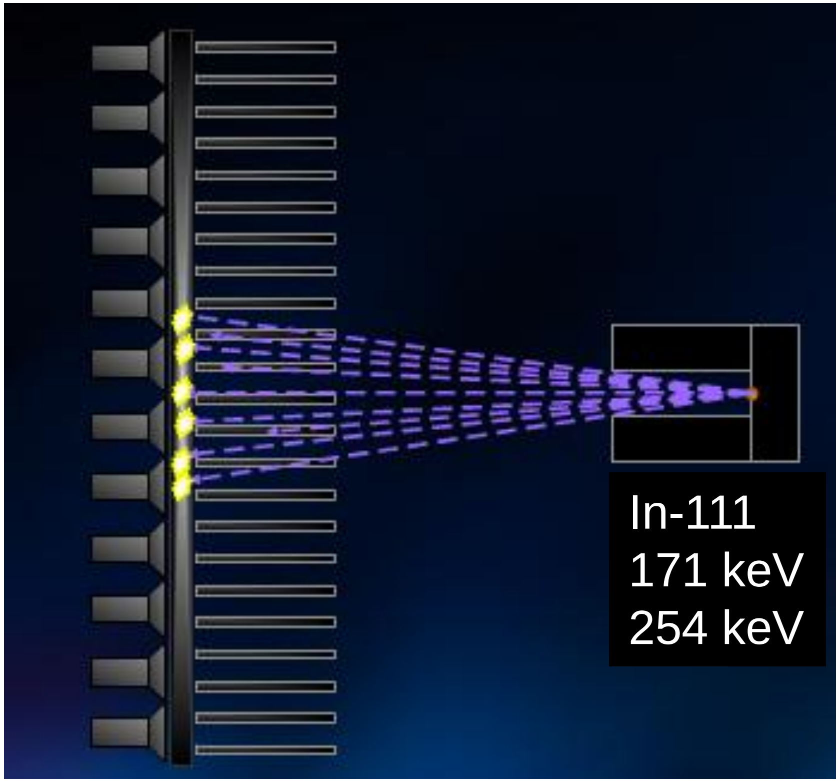
high spatial resolution
Low sensitivity

Collimator Characteristics : Septal thickness

Low energy, Tc99m



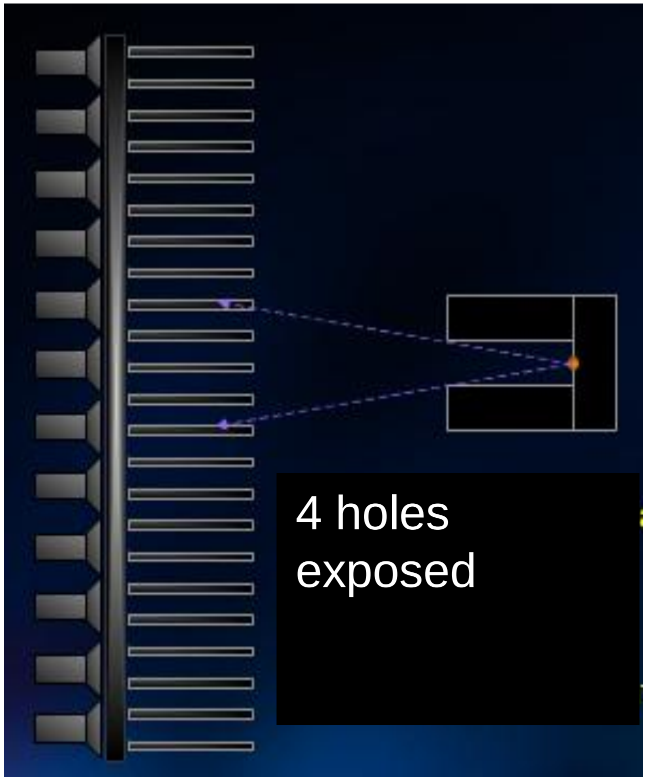
Medium energy, In-111



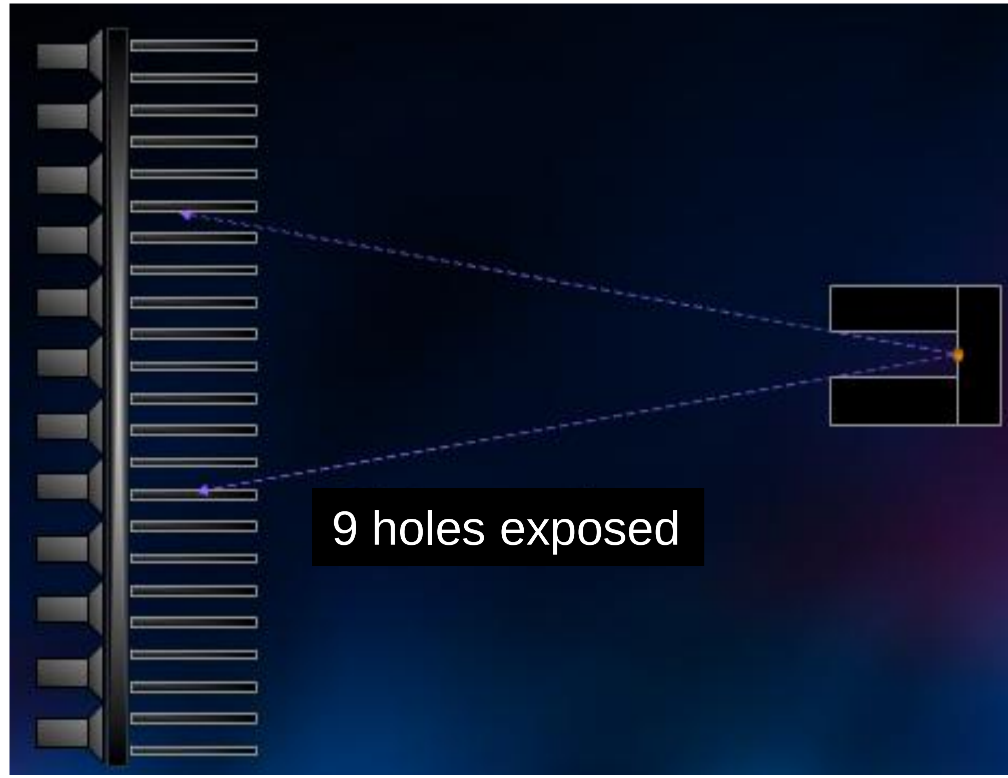
septal penetration : degrade spatial resolution
Thicker septa is used for medium and high energy gamma rays

Collimator Characteristics : collimator-object distance

Closer to the collimator



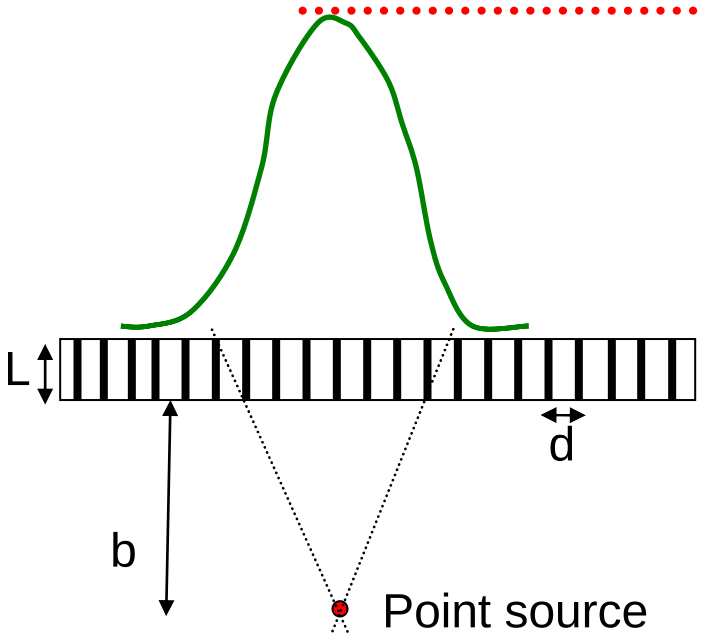
Far from the collimator

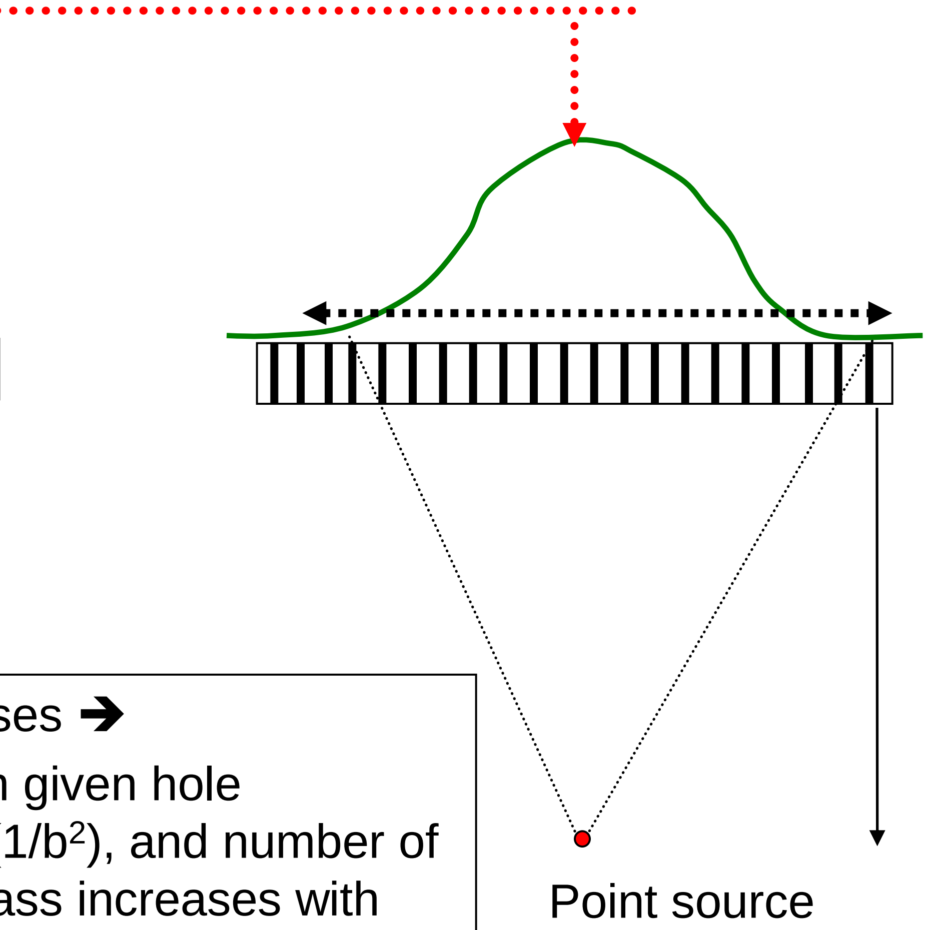


High resolution

low resolution

Collimator Characteristics : collimator-object distance



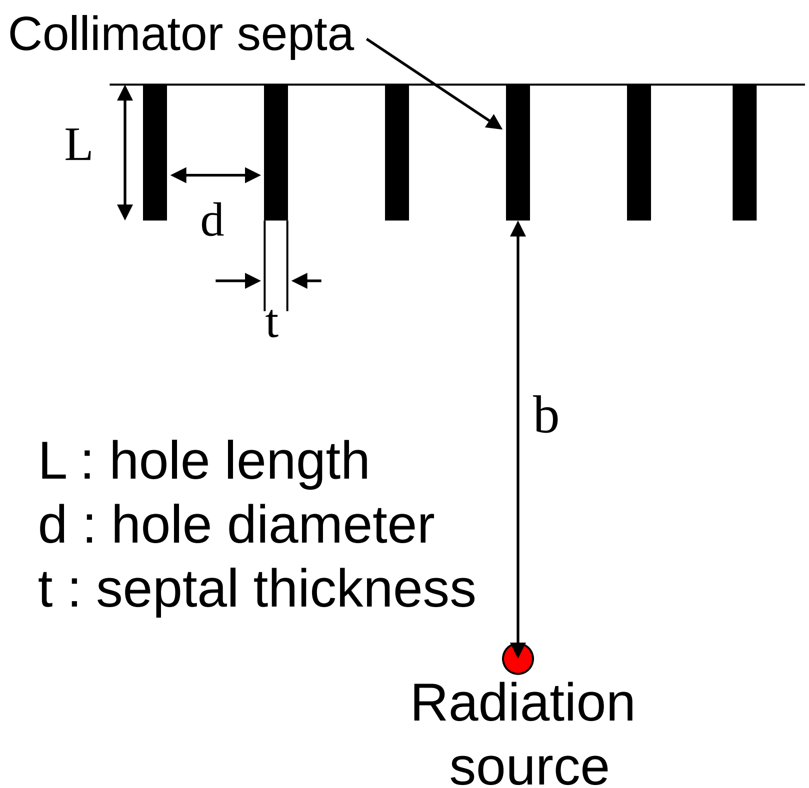


collimator-to-object distance increases ➔

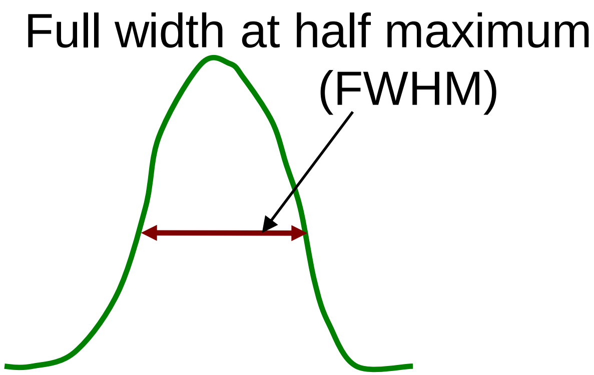
Number of photons passing through given hole decreases with square of distance ($1/b^2$), and number of holes through which photons can pass increases with square of distance (b^2).

Efficiency of a parallel-hole collimator is constant over the collimator-to-object distances

Collimator resolution



L : hole length
d : hole diameter
t : septal thickness



Full width at half maximum (FWHM) of the radiation profile from a point or line source projected by the collimator onto the detector

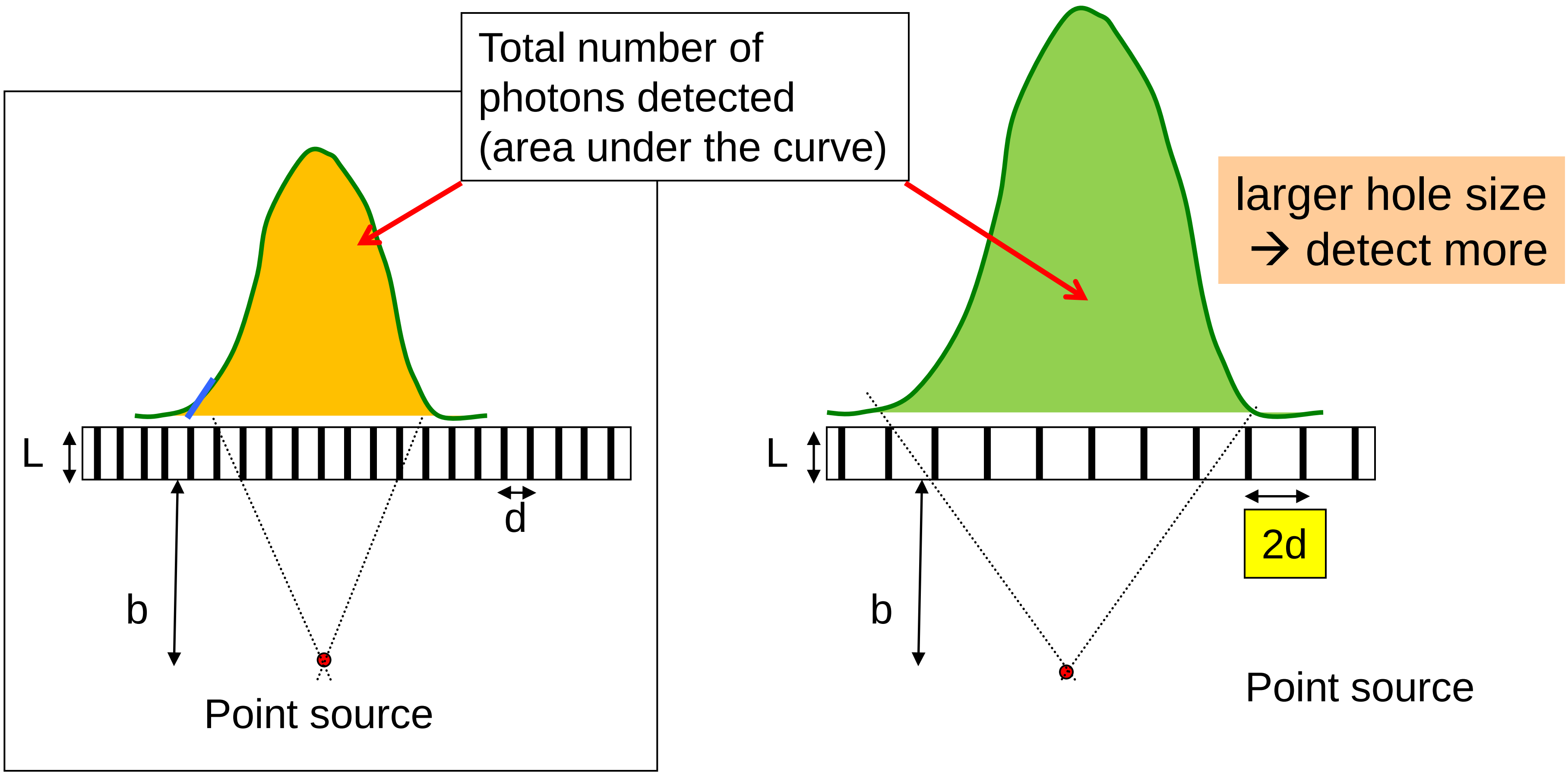
$$R_{coll} \approx \frac{d(L+b)}{L}$$

Example : Collimator parameters, d=0.25cm, L=2.5cm, t=0.03cm

a. Source at b=2cm, R ≈ 0.25 (2.5+2)/2.5 = 0.45 cm
b. Source at b=10cm, R ≈ 0.25 (2.5+10)/2.5 = 1.25 cm

Improvement in resolution means smaller R_{coll}

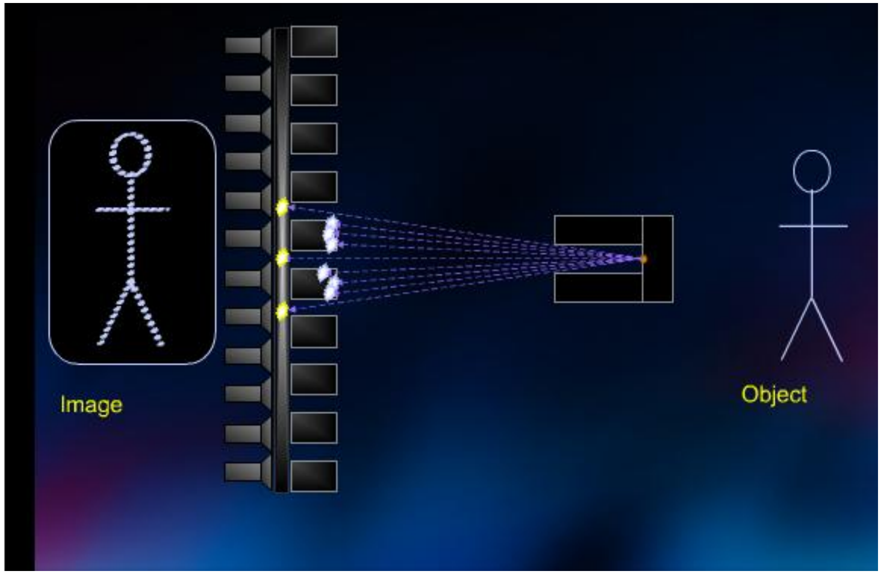
Collimator Characteristics : Geometric sensitivity



Projected radiation profile (point-spread function)

Collimator Characteristics : Septal length

Short septa

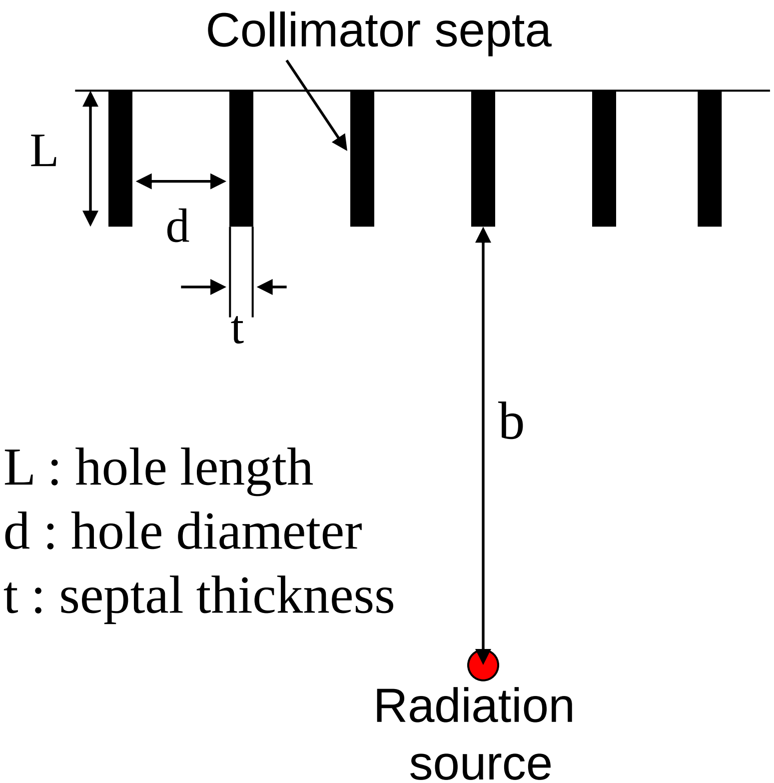


More photons

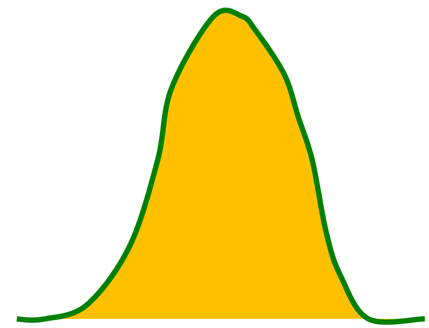
long septa

Less photons

Collimator geometric sensitivity



L : hole length
d : hole diameter
t : septal thickness



Geometric sensitivity (efficiency) is the fraction of γ rays passing through the collimator per γ rays emitted by the source

$$g_{coll} \approx K^2 \left(\frac{d}{L}\right)^2 \left[\frac{d^2}{(d+t)^2}\right]$$

No "b"

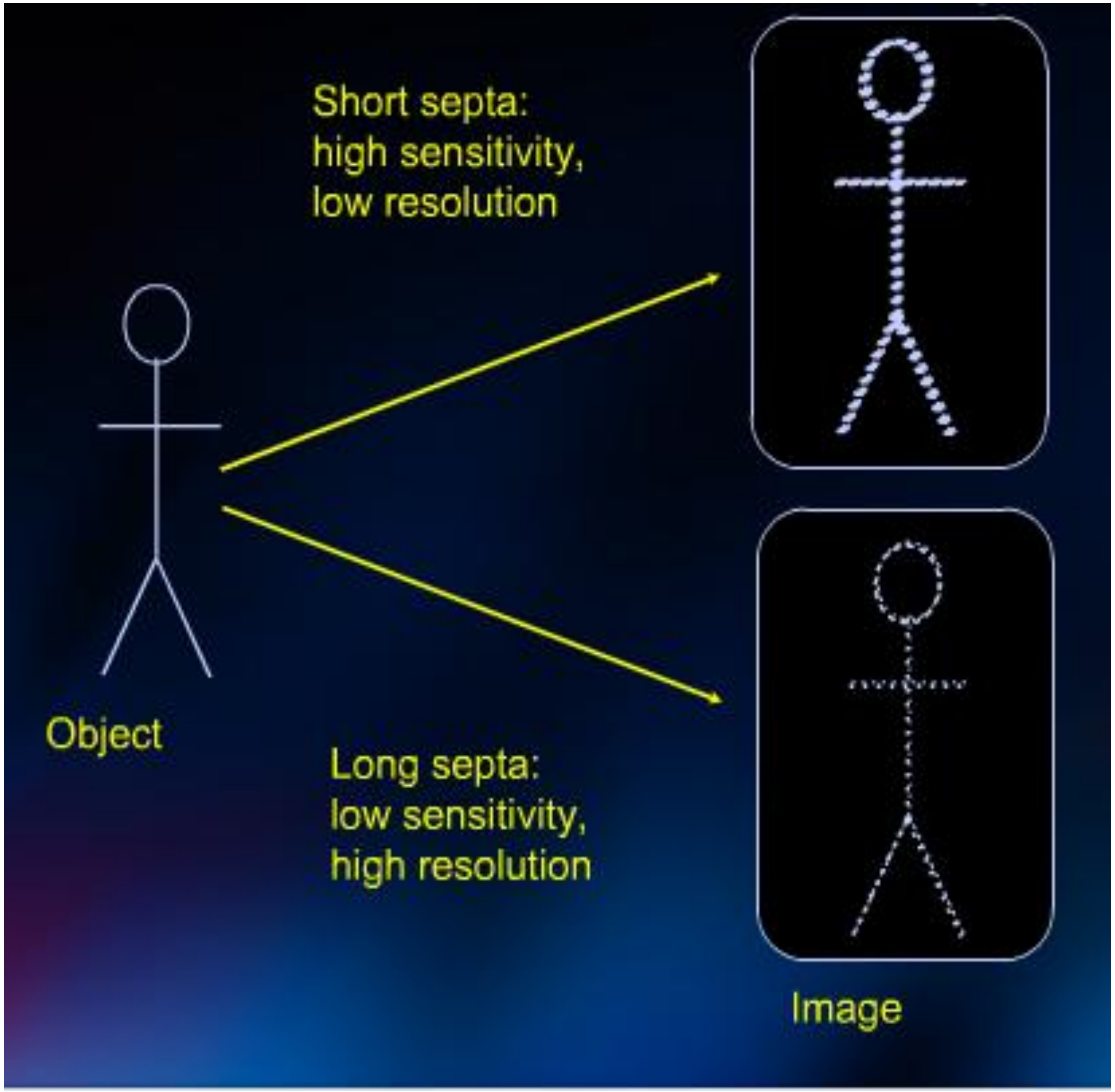
K~0.26 for hexagonal hole & array

<u>Example</u> : d=0.25cm, L=2.5cm, t=0.03cm, and a source at 10 cm.

$g \approx 0.26^2\ (0.25 / 2.5)^2\ [0.25 / (0.25+0.03)^2] = 5.4 \times 10^{-4}$

5 out of 10,000 photons are detected!!!

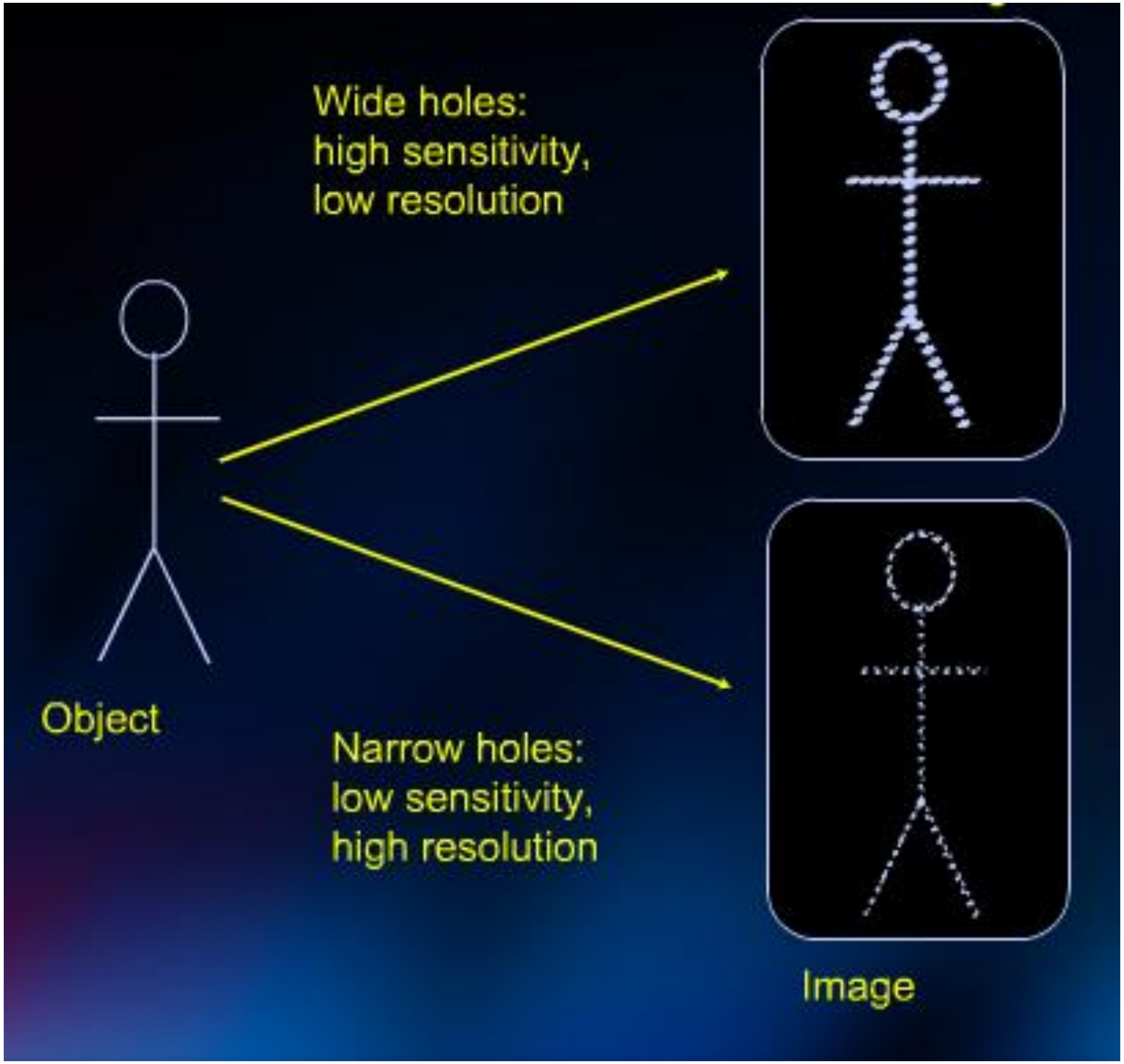
Resolution-Sensitivity trade-off : **hole (septa) length, L**



High counts
BUT not all in the right place

Counts are in the right place
BUT not many are detected

Resolution-Sensitivity trade-off : **hole diameter, d**



High counts
BUT not all in the right place

Counts are in the right place
BUT not many are detected

Summary of Collimator Characteristics

Collimator selection requires consideration of imaging object's location and size, energy of gamma rays, and desired resolution and sensitivity.

- Energy : low energy collimator (Tc-99m, Tl-201)
  medium energy collimator (Ga-67, In-111),
  high energy collimator (I-131)
  → Thicker septa to reduce septal penetration

- Resolution : Low-energy high resolution (LEHR)
  Low-energy Ultra-high resolution (LEUHR)

- Sensitivity : Medium- or Low-energy general-purpose collimator (MEGP, LEGP) → poor resolution, high sensitivity

System Resolution

System resolution determined the sharpness of images.

- intrinsic resolution
- Collimator resolution

$$R_{sys} = \sqrt{R_{\text{int}}^2 + R_{coll}^2}$$

<u>Example</u> R_{coll}=1.25cm (at 10cm from the collimator) and R_{int}=0.3cm

$$R_{sys} = \sqrt{R_{\text{int}}^2 + R_{coll}^2} = \sqrt{1.25^2 + 0.3^3} = 1.29cm$$

determined primarily by collimator resolution

1	b	8	b
2	e	9	e
3	c	10	F
4	b	11	T
5	b	12	F
6	b	13	F
7	b	14	T