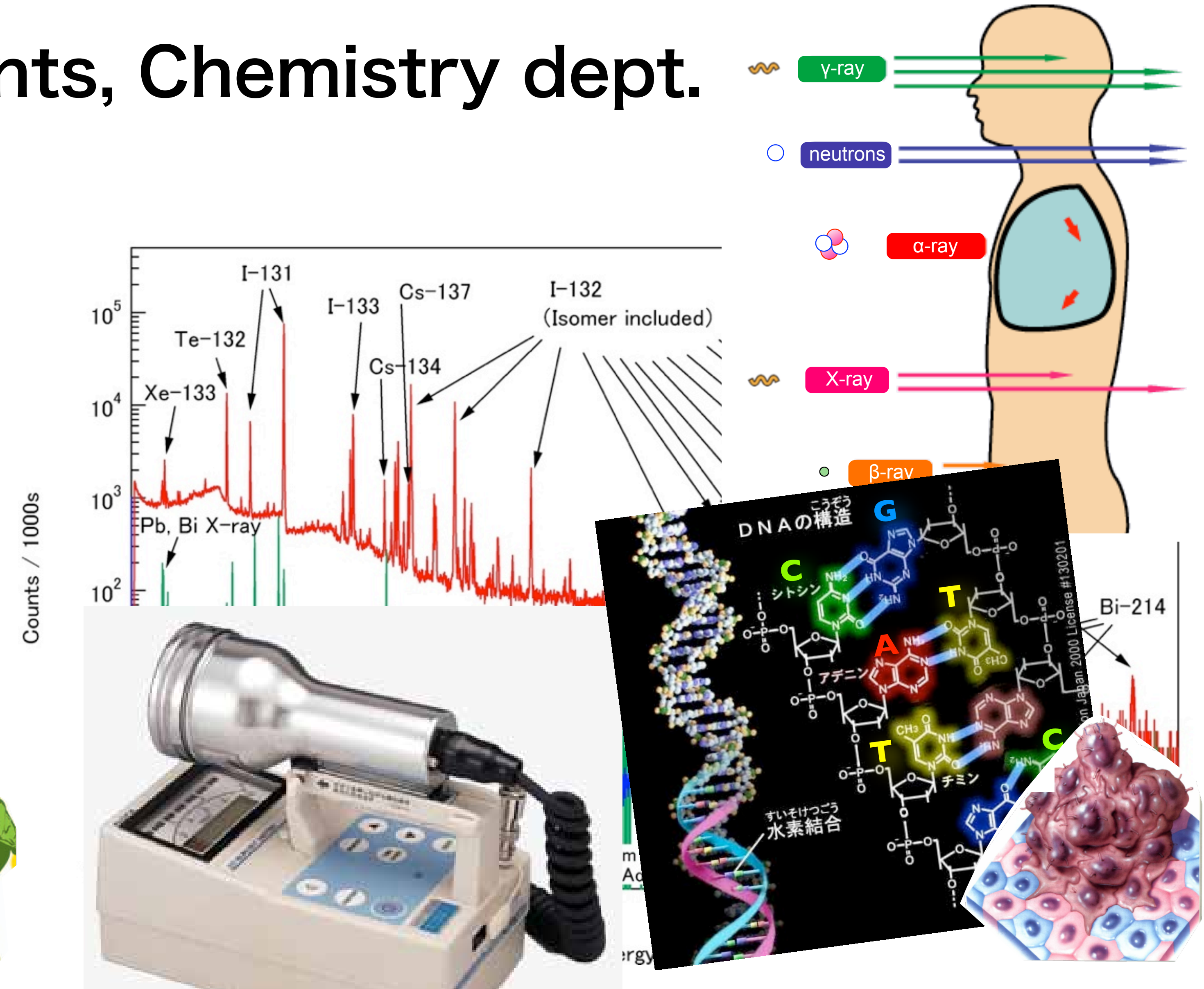
Lecture for 3rd-year students, Chemistry dept.

Radio-chemistry
放射化学



Wed. 7th June 2017

7th lecture

Radiation detection & measurement
Biological effects of radiation

鳥居 寛之 (Hiroyuki A. **TORII**)
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Radation detection & measurement

measurement of
ambient dose rate & surface contamination

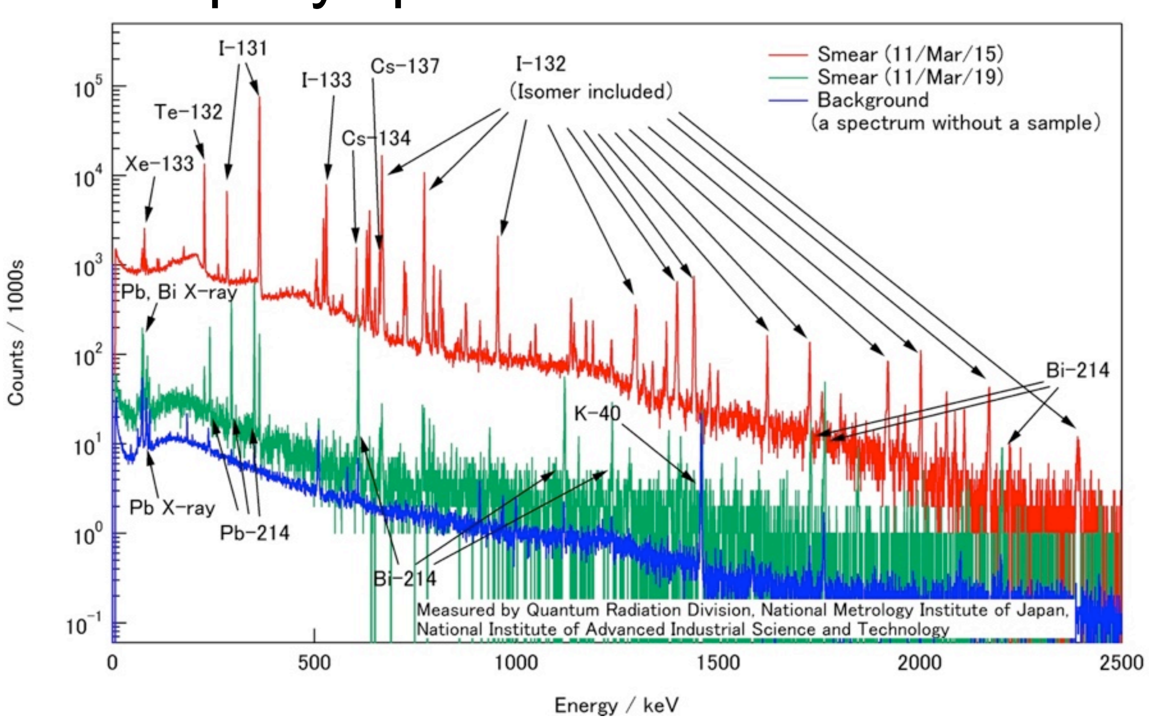
β (γ)　　γ

counting (cps = counts per second)

表面汚染検査計（例：GM サーベイメータ）空間線量計（例：NaI(Tℓ)サーベイメータ）

energy analysis (ID of nuclide)

γ-ray spectrum of a Ge detector



Ionization of gas

ionization chamber, G-M tube

Scintillator + PMT (photomultiplier)

NaI, CsI, plastic scinti., ZnS

Semiconductor detectors

Ge, Si(Li)

detectors

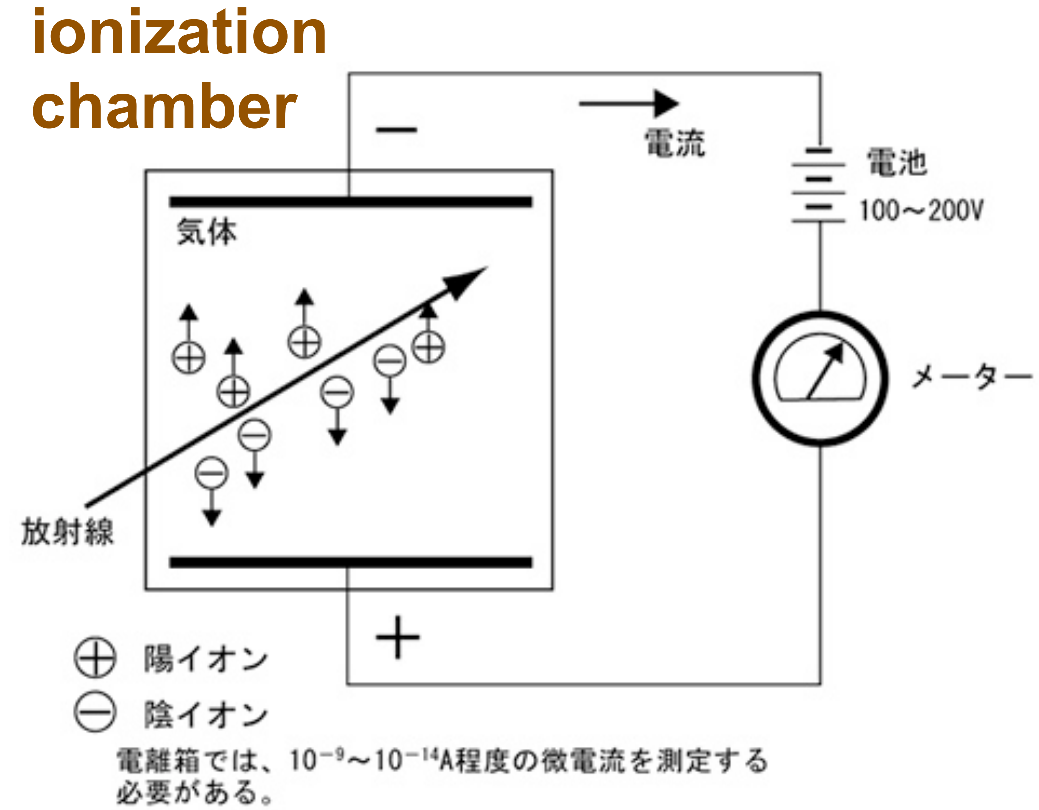
measurement
for **samples**

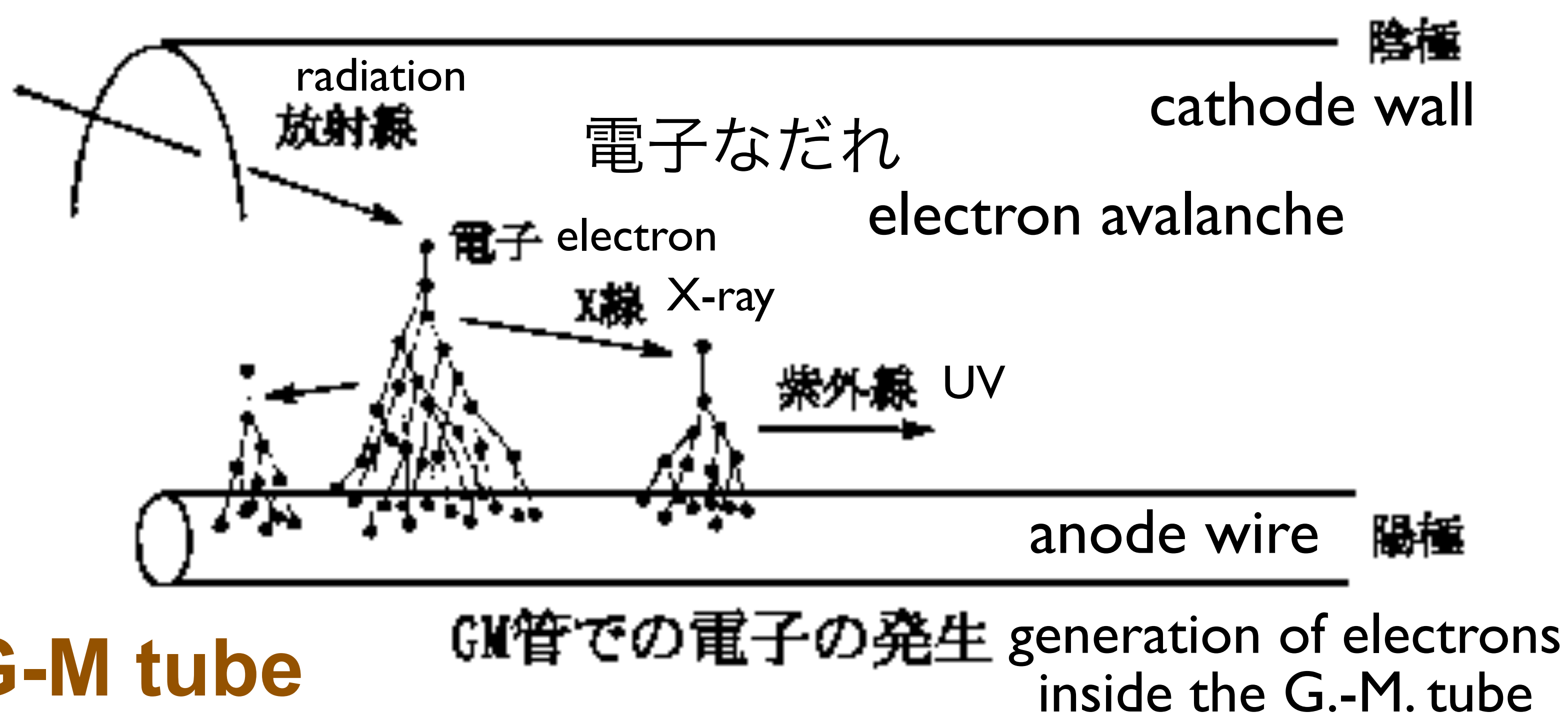
γ

食品検査用ゲルマニウム検出器
(Ge detector for food samples)

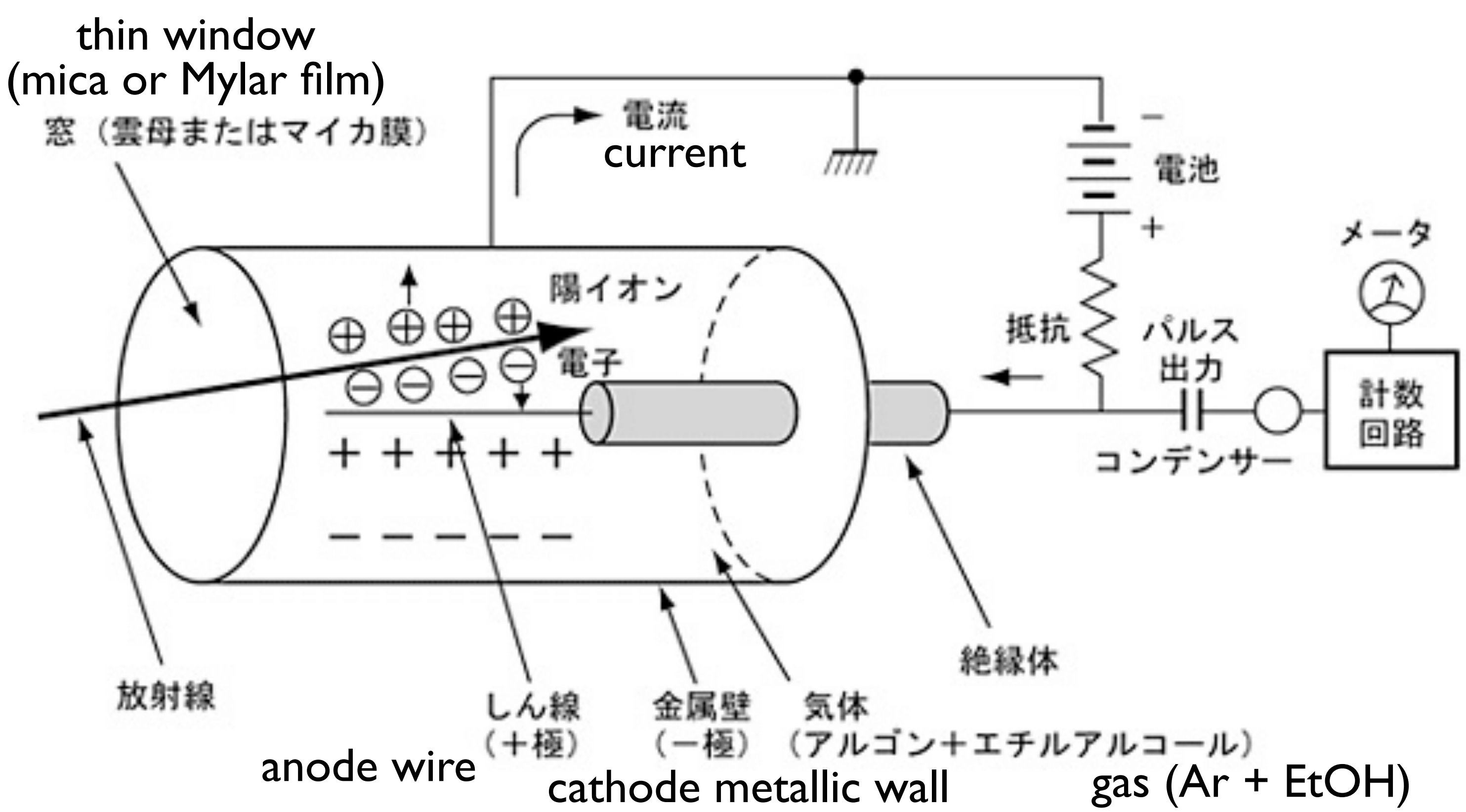
Radiation detection using **ionization of gas**

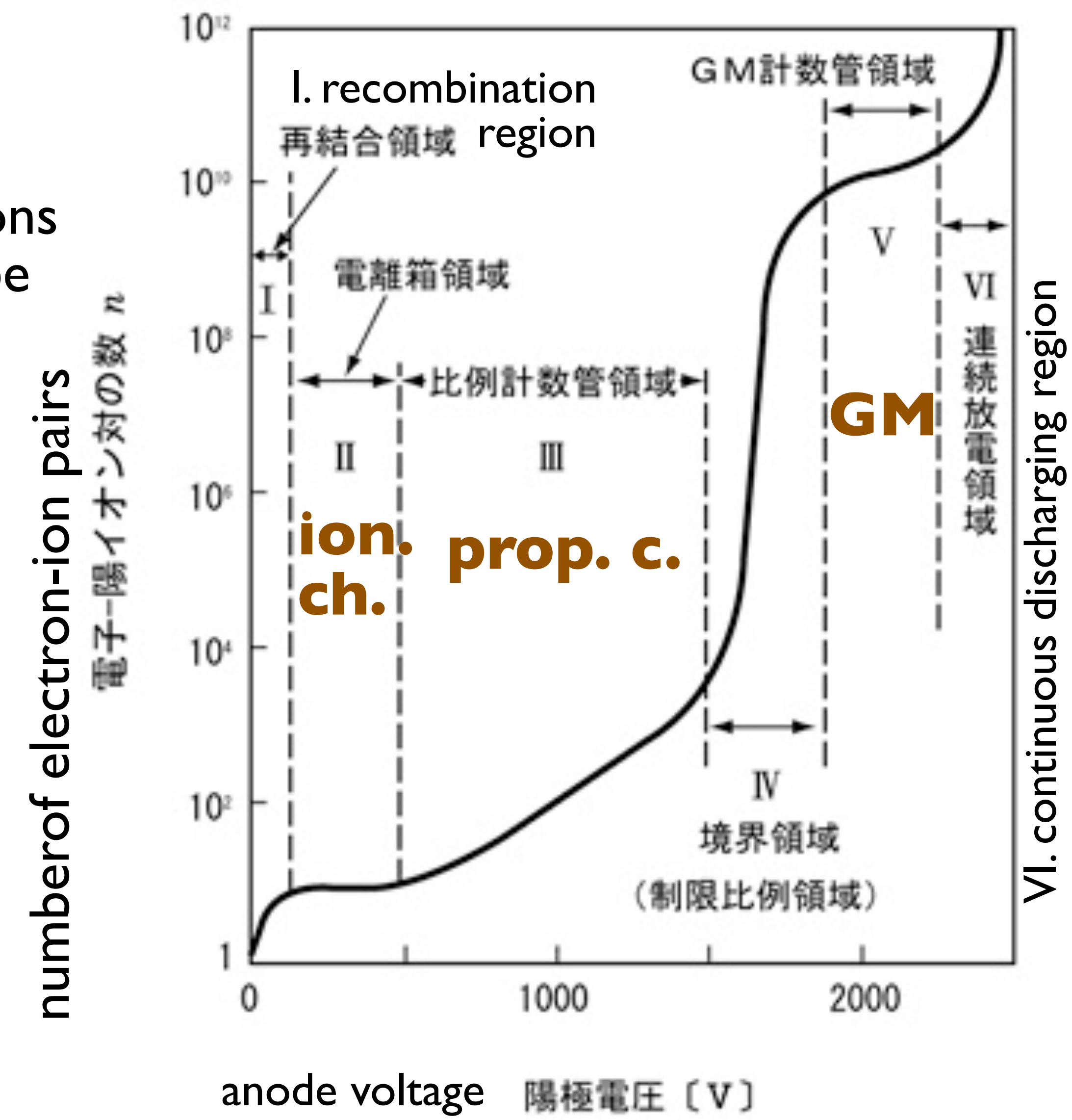
ionization chamber 電離箱
proportional counter 比例計数管
Geiger-Müller tube GM管





G-M tube





fluorescence of materials by irradiation or radiation

Scintillators

Plastic scintillator
& light guide

Inorganic : NaI (Tl), CsI (Tl) (γ-ray, X-ray)

BGO, GSO etc. (γ-ray, X-ray)

$Bi_4Ge_3O_{12}$ Gd_2SiO_5

ZnS (Ag) (α-ray)

BaF_2

Organic : plastic scintillator (electron beam) (charged particles)

e.g. PPO, POPOP / polystylene

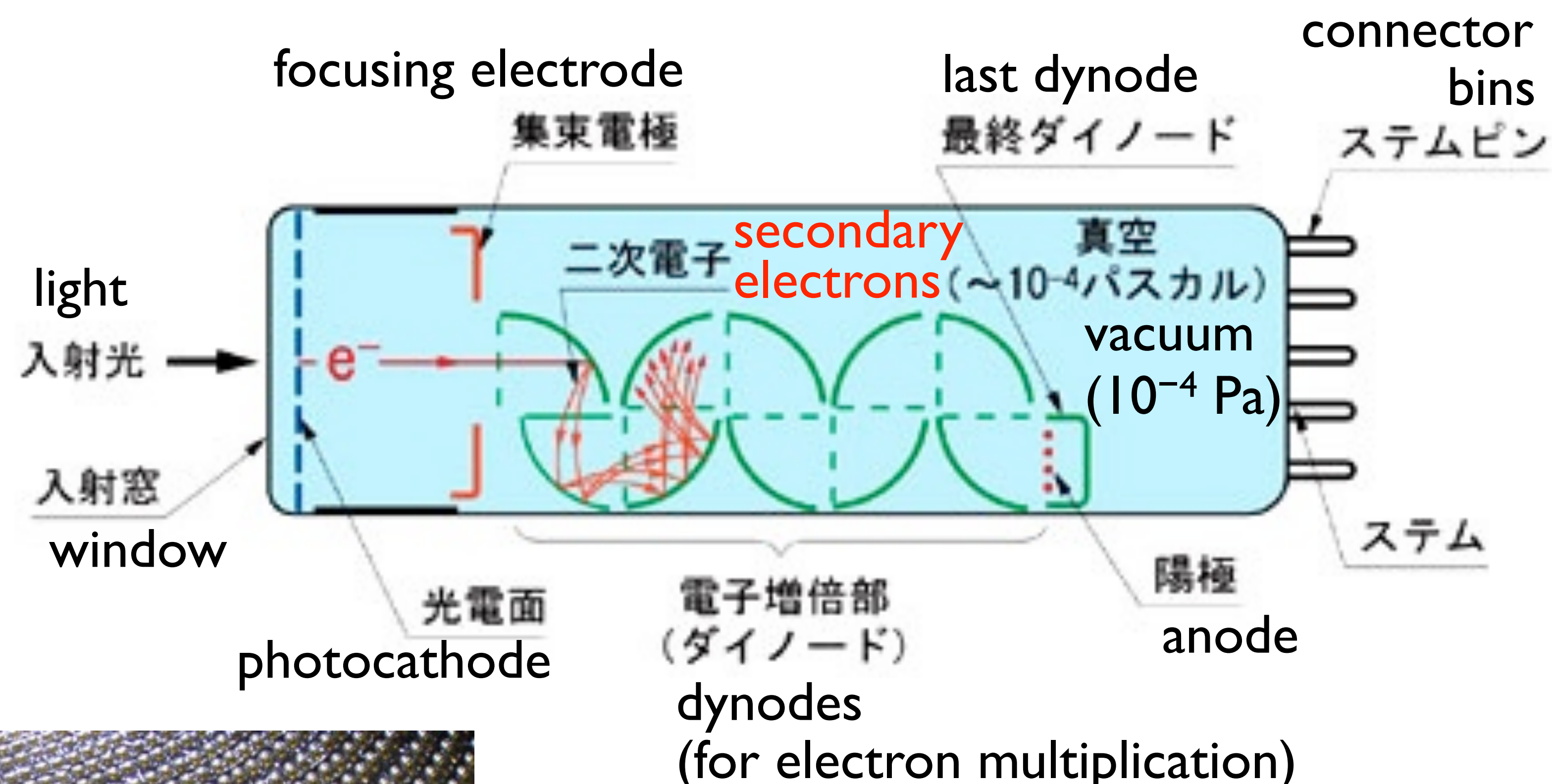
liquid scintillator (β-ray)

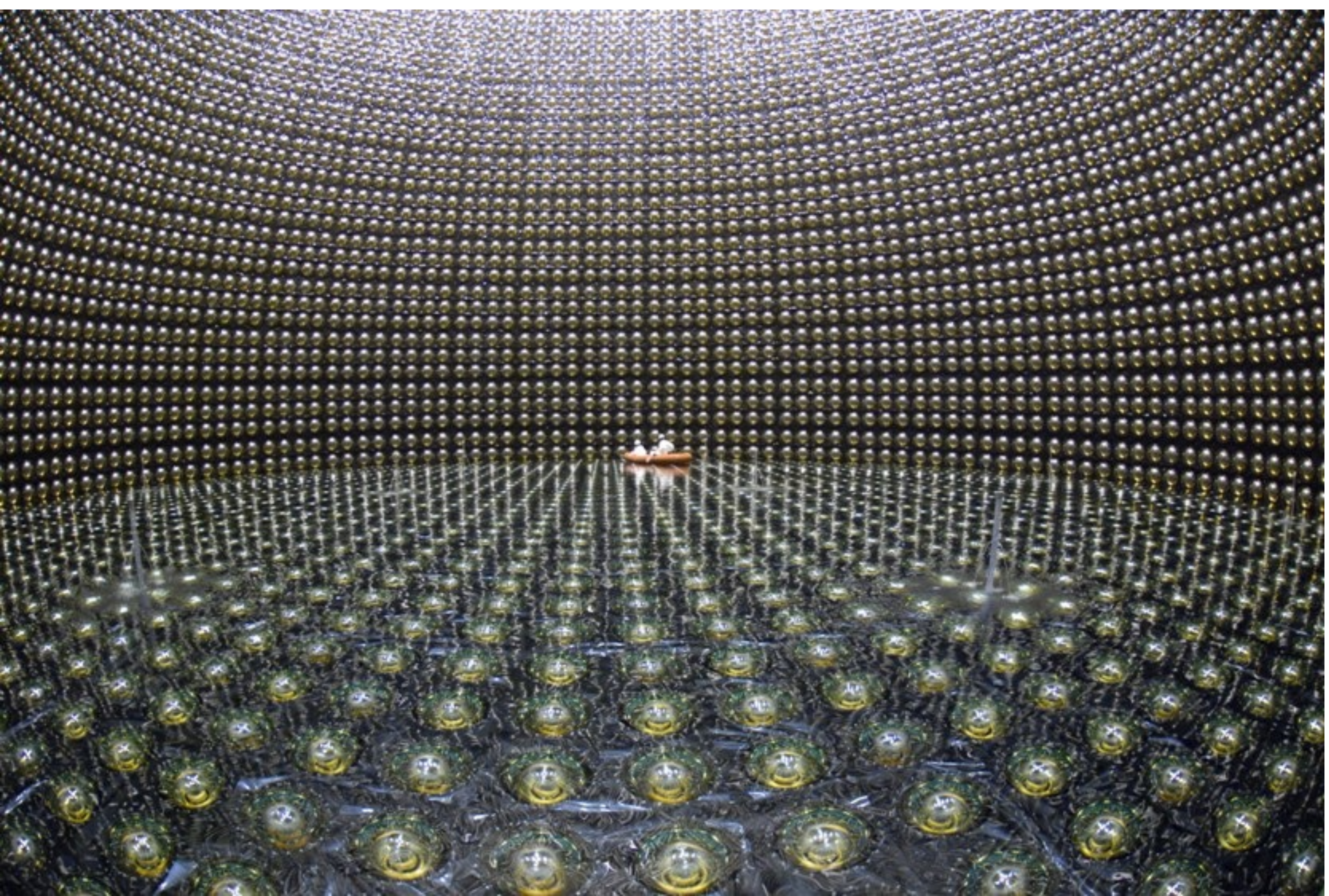
e.g. p-terphenyl / toluene, xylene

liquid scintillation counter

electric pulse : timing : time of particle passage
: pulse height : energy

Photomultiplier tube (PMT) 光電子増倍管





light ⇒ photoelectric effect
⇒ electron multiplication
⇒ current

Combination with a Scintillator

radiation
⇒ excitation of molecules
⇒ fluorescence
light ⇒ PMT

Measurement of radiation

Counting (cps = counts per second)

Survey meters 【ambient dose rate】

β (γ) / γ

G-M tube

β (γ) / γ

ionization chamber

γ

CsI (Tl)

NaI (Tl)

β (γ)

50–100% for β

< a few % for γ

γ

【surface contamination】

β (γ)

G-M tube

Ionization of gas

Scintillation

(radiation-induced fluorescence)

α

ZnS (Ag)

Measurement of radiation

Semiconductor detectors

例：Si(Li) detector (X-ray)

Ge detector (high energy resolution)

(γ-ray, X-ray)

radiation ⇒ ionization

⇒ electron-hole pair ⇒ charge measured

electric pulse : pulse height ⇔ energy

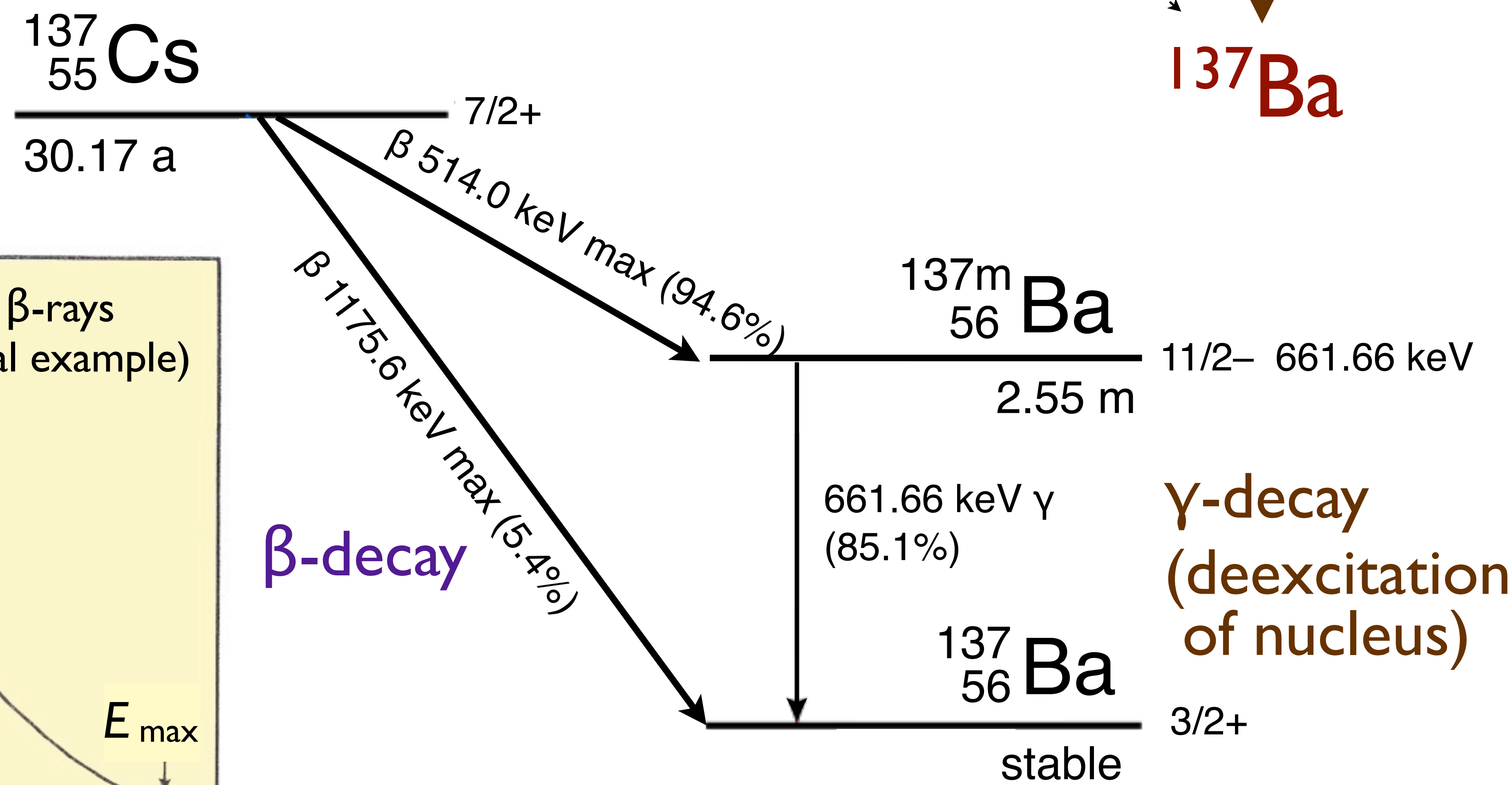
energy analysis (ID of nuclide)

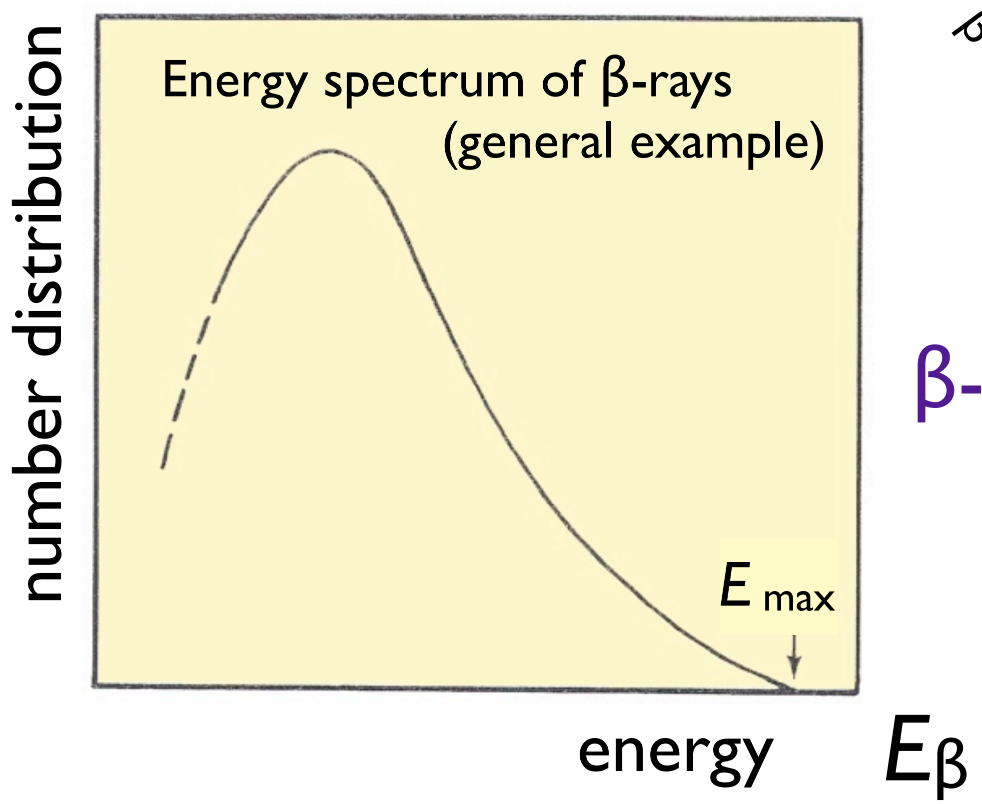
Measurement for **samples**

γ ゲルマニウム検出器 (Ge detector)

食品検査用ゲルマニウム検出器
(Ge detector for food samples)

$$^{137}\mathrm{I} \xrightarrow{24\ \mathrm{s}} {}^{137}\mathrm{Xe} \xrightarrow{3.8\ \mathrm{min}} {}^{137}\mathrm{Cs} \xrightarrow{30\ \mathrm{yr}} {}^{137m}\mathrm{Ba} \xrightarrow{2.5\ \mathrm{min}} {}^{137}\mathrm{Ba}$$





β-ray (continuous spectrum)

$$n \rightarrow p + e + \bar{\nu}_e$$

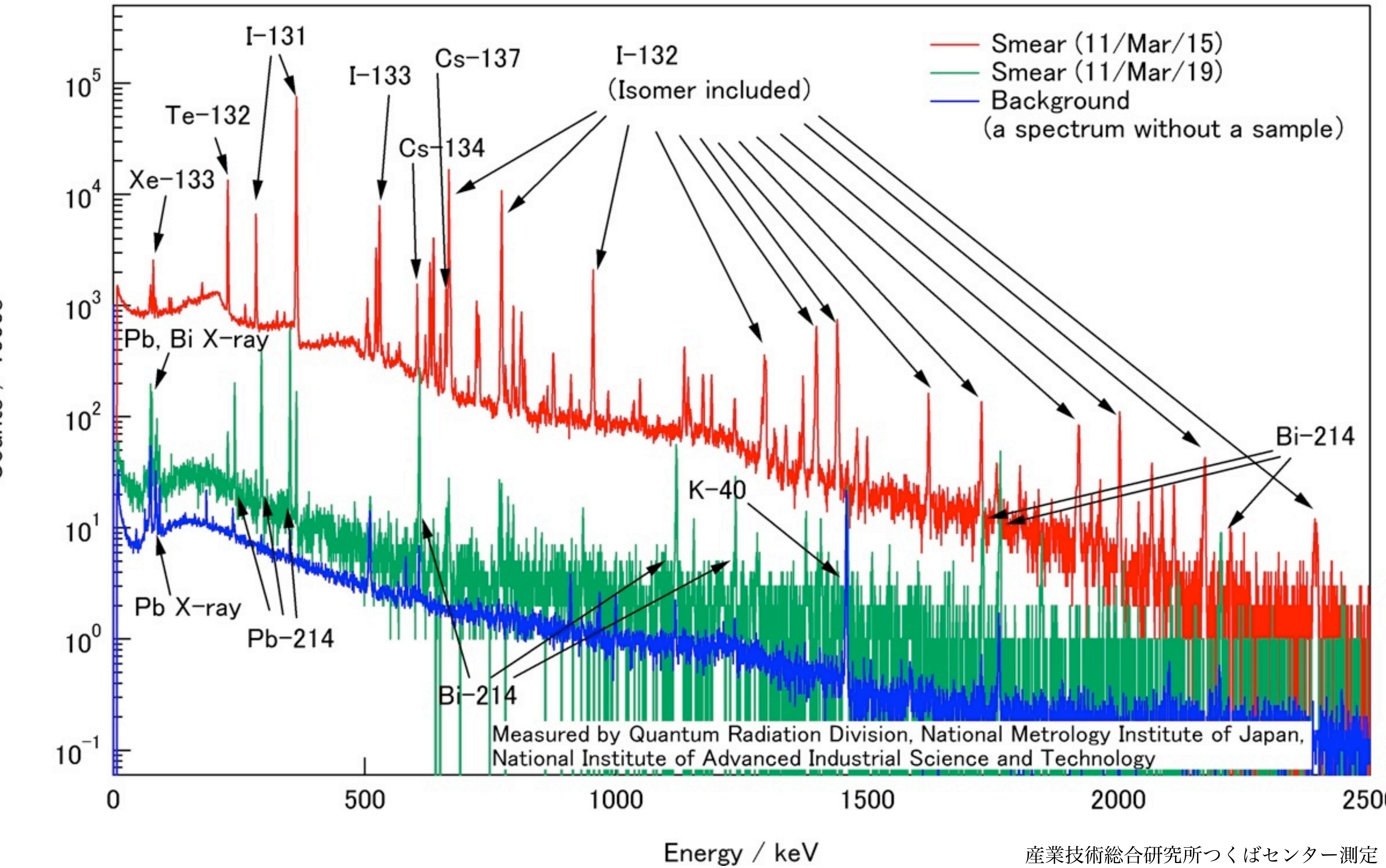
(β)

$$^{A}_{Z}N^{*} \rightarrow {}^{A}_{Z}N + \gamma$$

γ-ray (fixed energy)

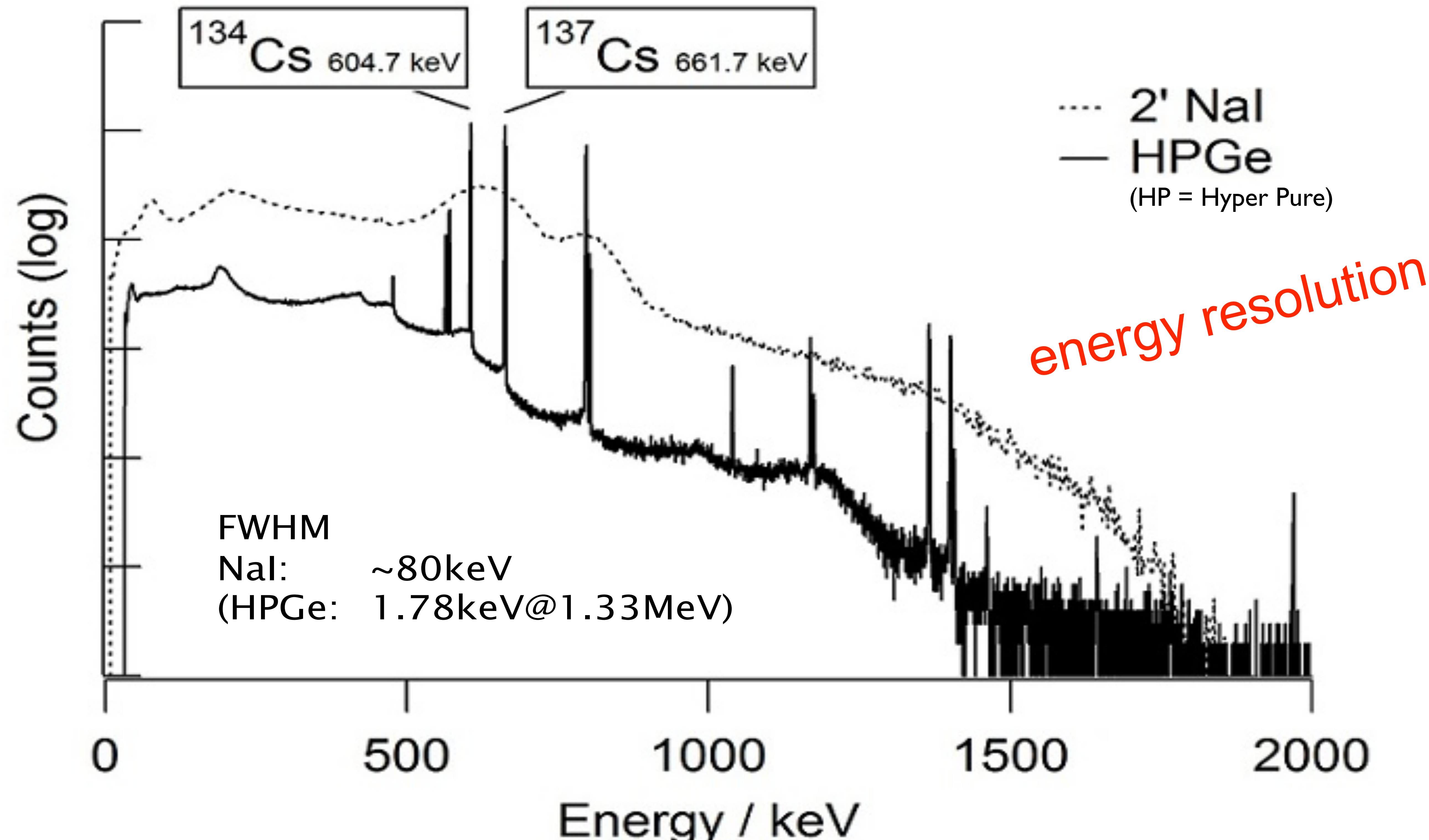
Energy analysis (identification of nulide)

γ-ray spectrum of a Ge detector

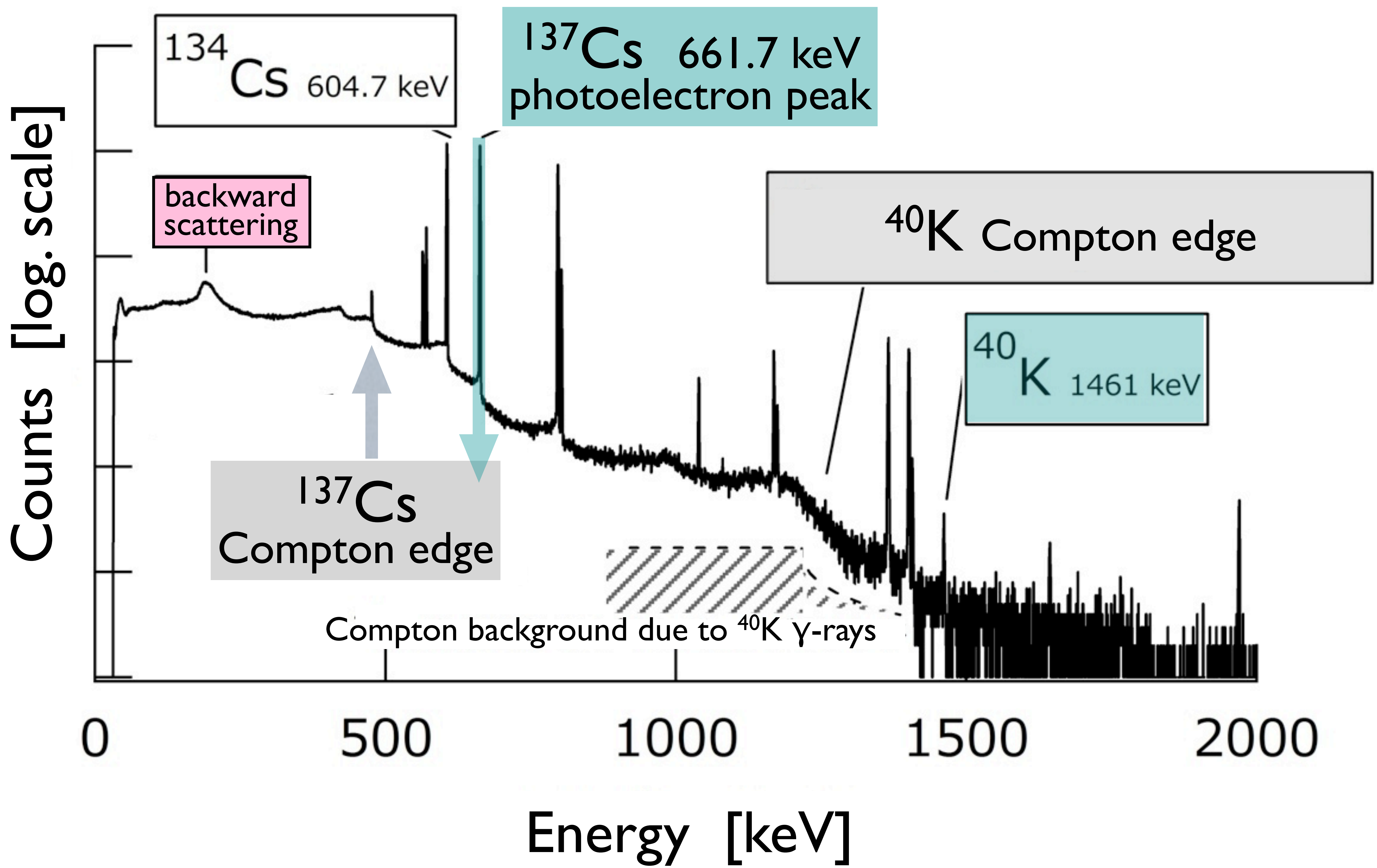


産業技術総合研究所つくばセンター測定

Comparison of γ-ray spectra : NaI (scintillator) vs. Ge (semiconductor)

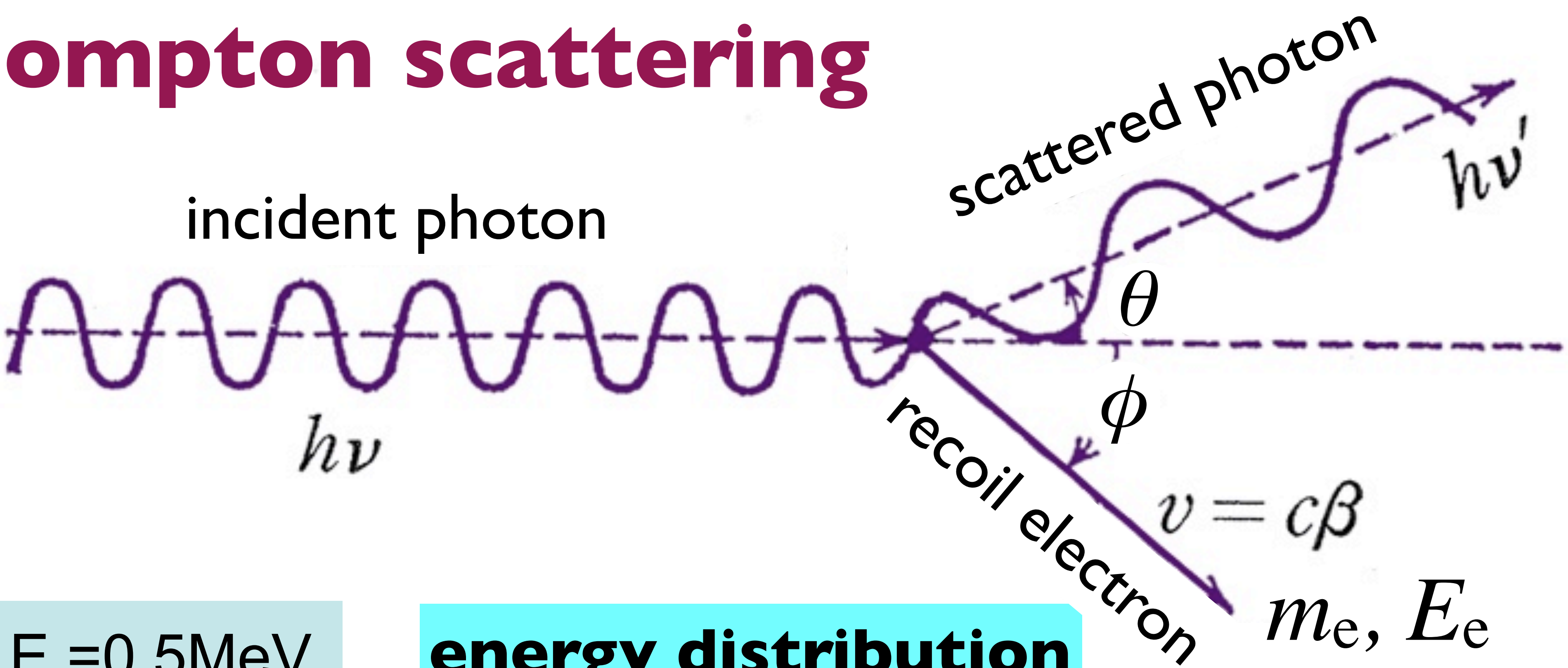


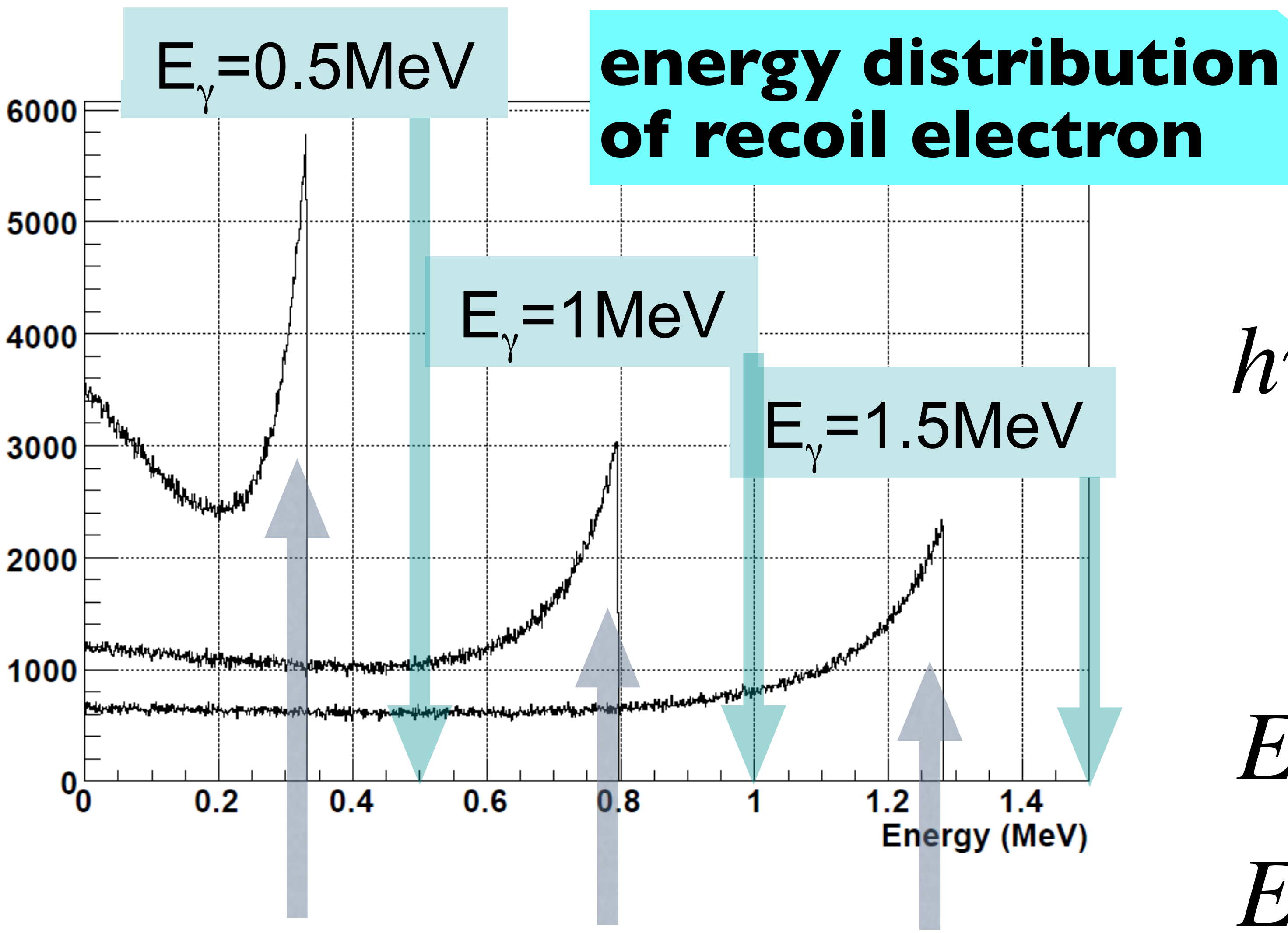
（東京大学教養学部 小豆川勝見先生のスライドより借用）



^{134}Cs 604.7 keV
^{137}Cs 661.7 keV photoelectron peak
backward scattering
^{40}K Compton edge
^{40}K 1461 keV
^{137}Cs Compton edge
Compton background due to ^{40}K γ-rays
Counts [log. scale]
0
500
1000
1500
2000
Energy [keV]

Compton scattering





Compton edges

$$m_e c^2 = 511 \text{ keV}$$

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_e c^2}(1 - \cos\theta)}$$

$$E_\gamma = h\nu$$

$$E_e = h\nu - h\nu'$$

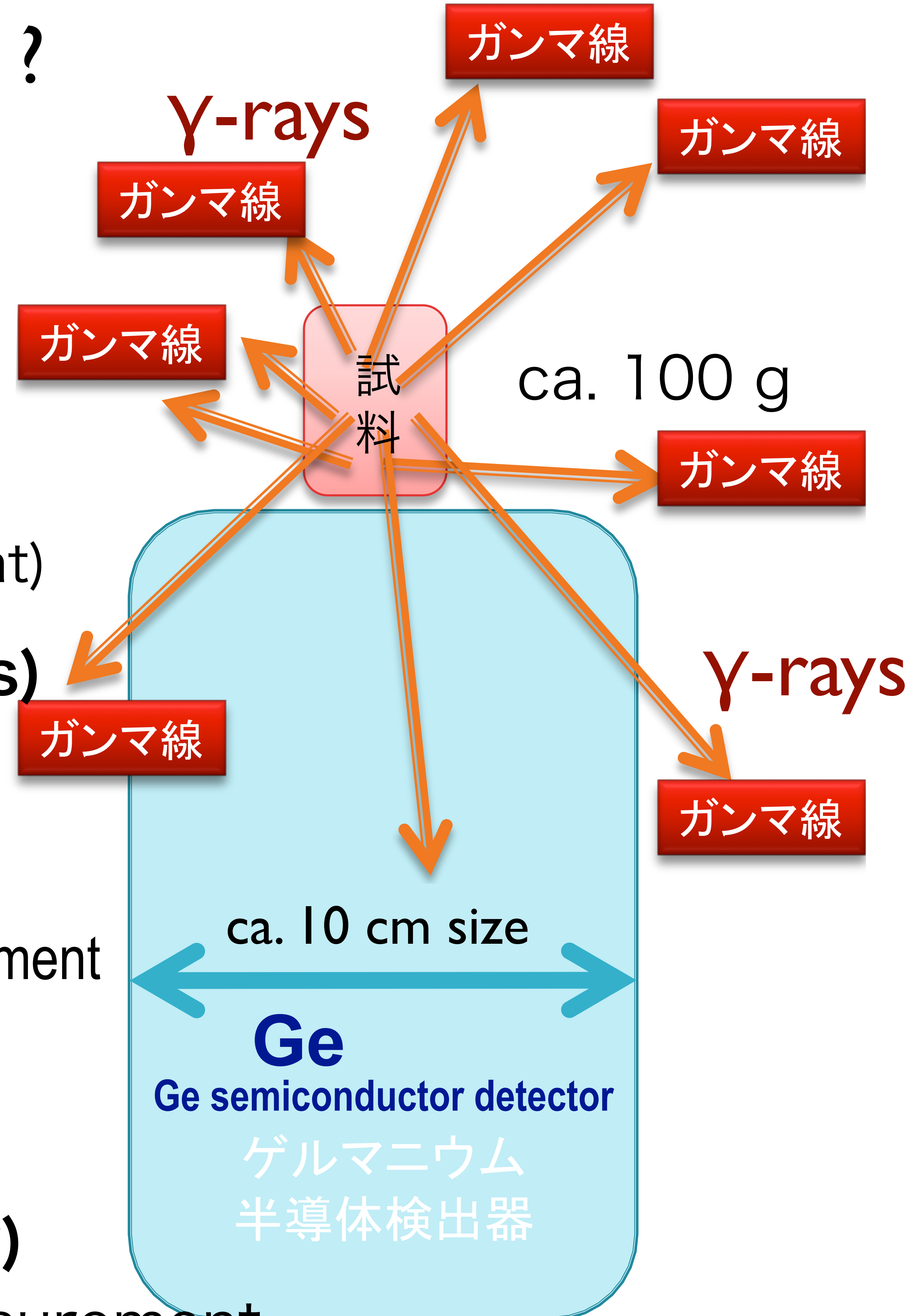
How to measure food samples ?

100 Bq/kg = 10 Bq / 100 g

Detection efficiency around 1%.
(solid angle coverage × eff. of Ge)

^{134}Cs / ^{137}Cs = 1 / 1 (radioactivity)
(soon after the Fukushima NPP accident)

regulation value = 100 Bq/kg (Cs)
0.05 cps / 100 g (1 count / 20 s)
each for ^{134}Cs / ^{137}Cs



(図の提供：東京大学教養学部 小豆川勝見先生)

Measurement under **low-background** environment
(Shielding of radiation)

long measurement time (> 1 h)
(to reduce **statistical uncertainty)**
high **detection limit** for short measurement.
⇒ **N.D.** (Not Detected = **不検出**) ≠ 0 Bq (not exist = 不存在)

Measurement results of 10 samples (detailed expression)

No.	試料	採取場所		^{134}Cs(Bq/kg)	^{137}Cs(Bq/kg)
1	畑の土	練馬区内	soil	ND(5.56)	14.1±2.17
2	ジャガイモ	練馬区内	potato	4.58±0.55(0.23)	7.16±0.86(2.33)
3	培養土	練馬区内	soil	5.95±1.43(5.82)	9.35±1.89(6.78)
4	梅	練馬区内	plum	ND(2σ)(3.98)	ND(2σ)(4.04)
5	干し椎茸	群馬産	shiitake	ND(26.6)	ND(29.4)
6	路傍の土	練馬区内	soil	4110±20.9(24.6)	6330±38.7(21.6)
7	生椎茸	富山産	shiitake	ND(5.65)	ND(5.73)
8	カツオ	？	katsuo fish	ND(4.12)	ND(5.32)
9	田圃の土	練馬区内	soil	185±11.6(37.5)	298±19.4(33.5)
10	ブルーベリー	練馬区内	blueberry	1.42±0.29(1.01)	ND(2σ)(1.38)

Complete check of rice produced in Fukushima

over regulation limit **(100 Bq/kg)**

0 ／10 250 000 sacks (2016)

0 ／10 500 000 sacks (2015)

2 ／10 770 000 sacks (2014)

28／11 000 000 sacks (2013)

71／10 340 000 sacks (2012)

Evaluation of internal exposure

Measurement of radioactivity in the body by WBC

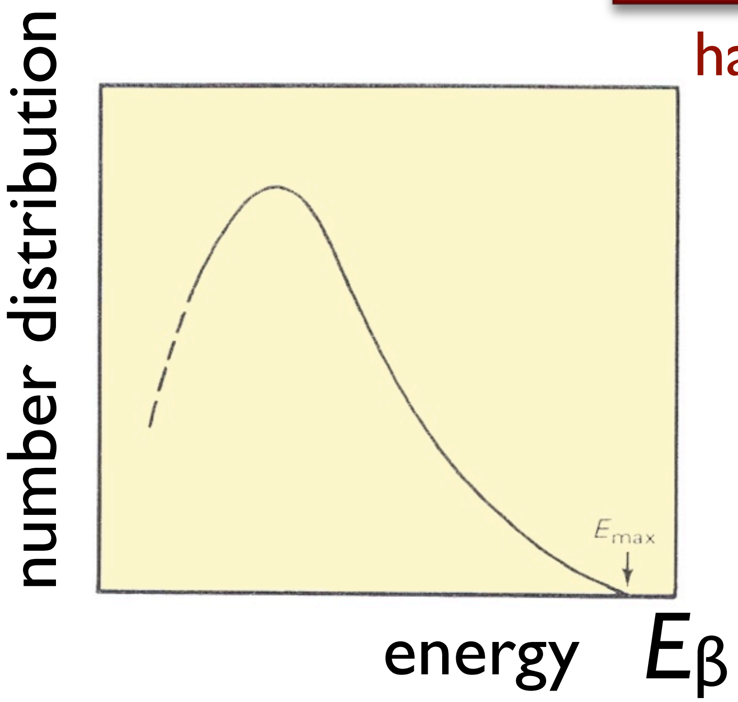
Whole
Body
Counter

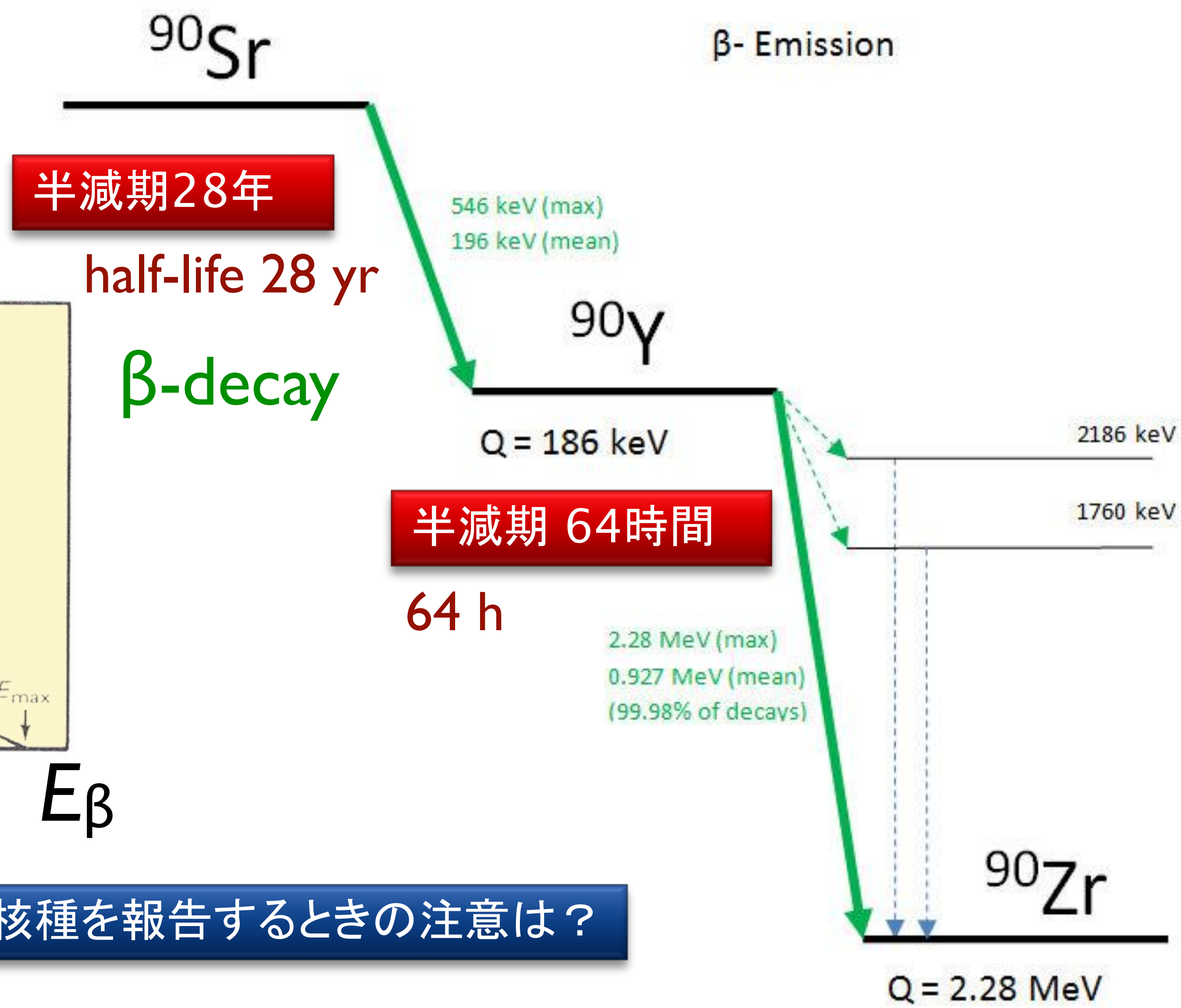
（東京大学教養学部 小豆川勝見先生のスライドより借用・一部壊変）

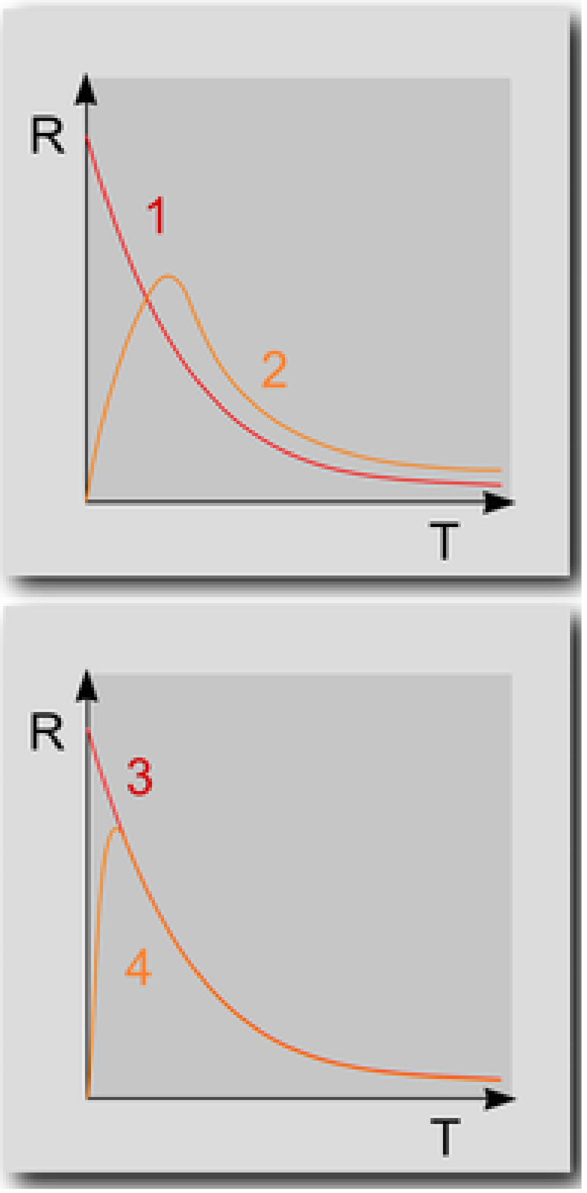
ID of β-decay nuclides (without any γ-ray emission)

Chemical separation required

例：^{89,90}Sr







核種を報告するときの注意は？

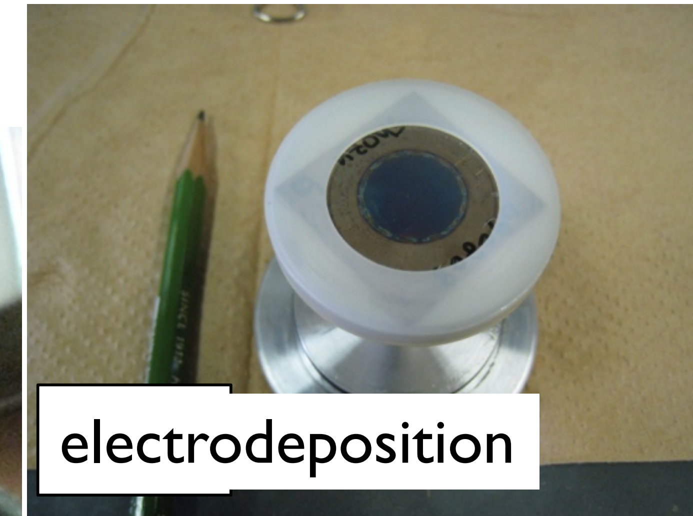
（東京大学教養学部 小豆川勝見先生のスライドより借用）

ID of α-decay nuclides

U, Th, Pu, Am, Cm…

- alpha spectrometry

238, 239, 241Pu


electrodeposition


chemical separation 1


chemical separation 2

Analysis requires really a lot of work.
chemical separation of the targeted element → refinement → electrodeposition → alpha-ray measurement

Dosimeters (personal / environment monitoring)

Fricke dosimeter フリッケ線量計

Fe^{2+} + radiation → Fe^{3+}, absorbance measurement

thermoluminescence dosimeter (TLD) 熱ルミネッセンス線量計

Fluorite or other crystal + radiation → (heating) → fluorescence

蛍石

Electrons / holes are captured in lattice defects.

glass badge (RPL: radio-photoluminescence) 蛍光ガラス線量計

Ag^{+}-activated Phosphate Glass + radiation → (UV) → fluorescence

$Ag^{+} \rightarrow Ag^{0}, Ag^{++}$ production of color centers

ガラス線量計

glass dosimeter : cobalt glass → color center (colored)

OSL Luxel badge ®

optically stimulated luminescence (OSL) badge

光刺激ルミネッセンス線量計

ポケット線量計

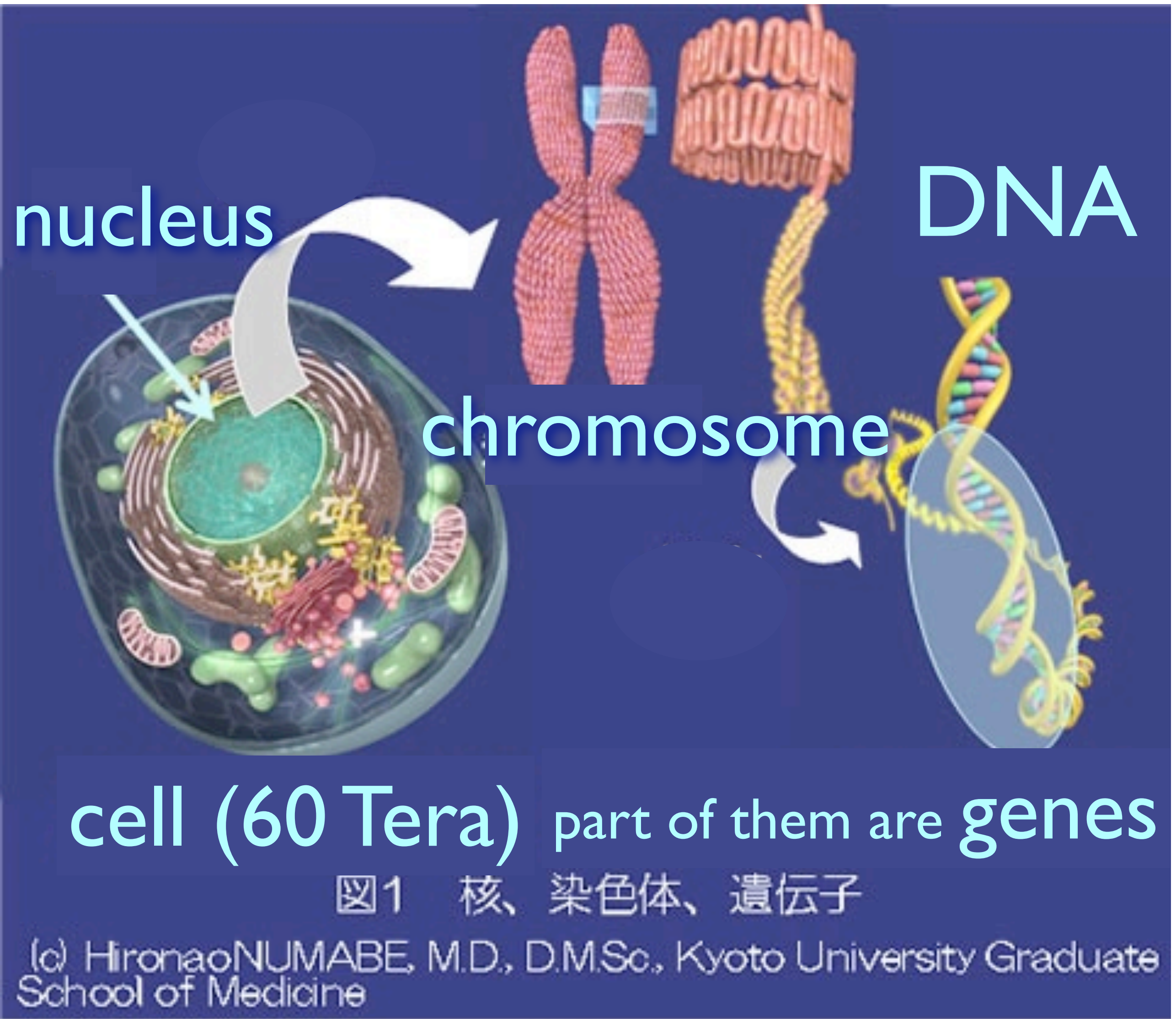
pocket dosimeter : ioniz. chamber / semiconductor detector

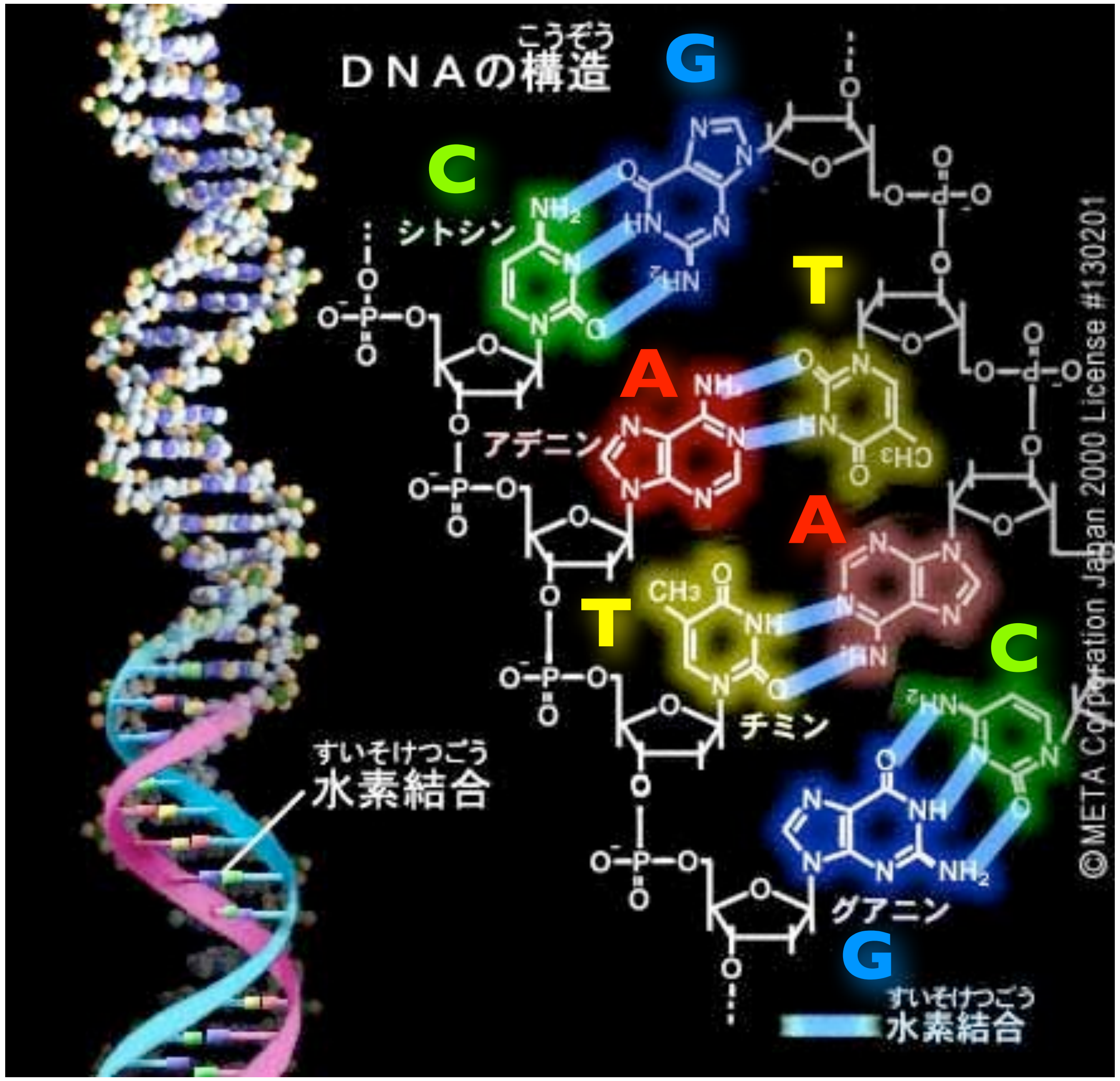
film badge フィルムバッジ : Silver halide film AgBr

Radiation biology

irradiation to cell nuclei

DNA

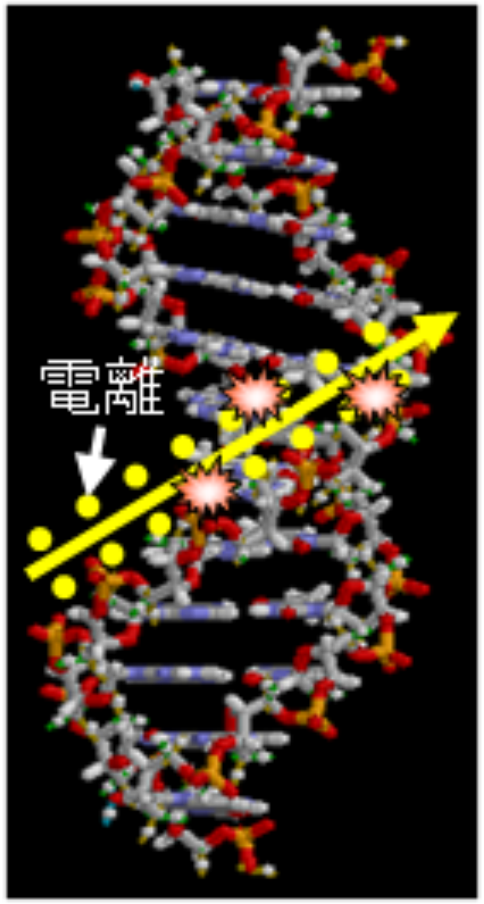




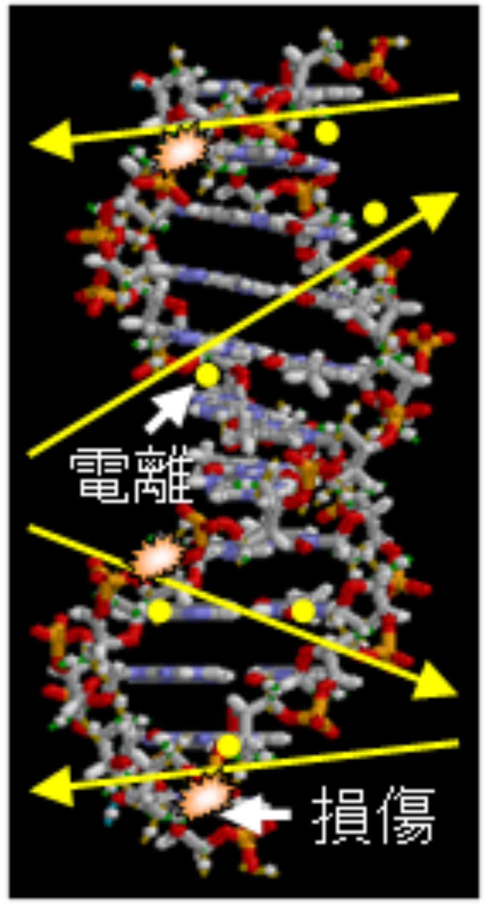
出典：IPA「教育用画像素材集サイト」 http://www2.edu.ipa.go.jp/gz/

DNA damages due to radiation

radicals (active oxygen)



重イオン
heavy ions



電子
electrons

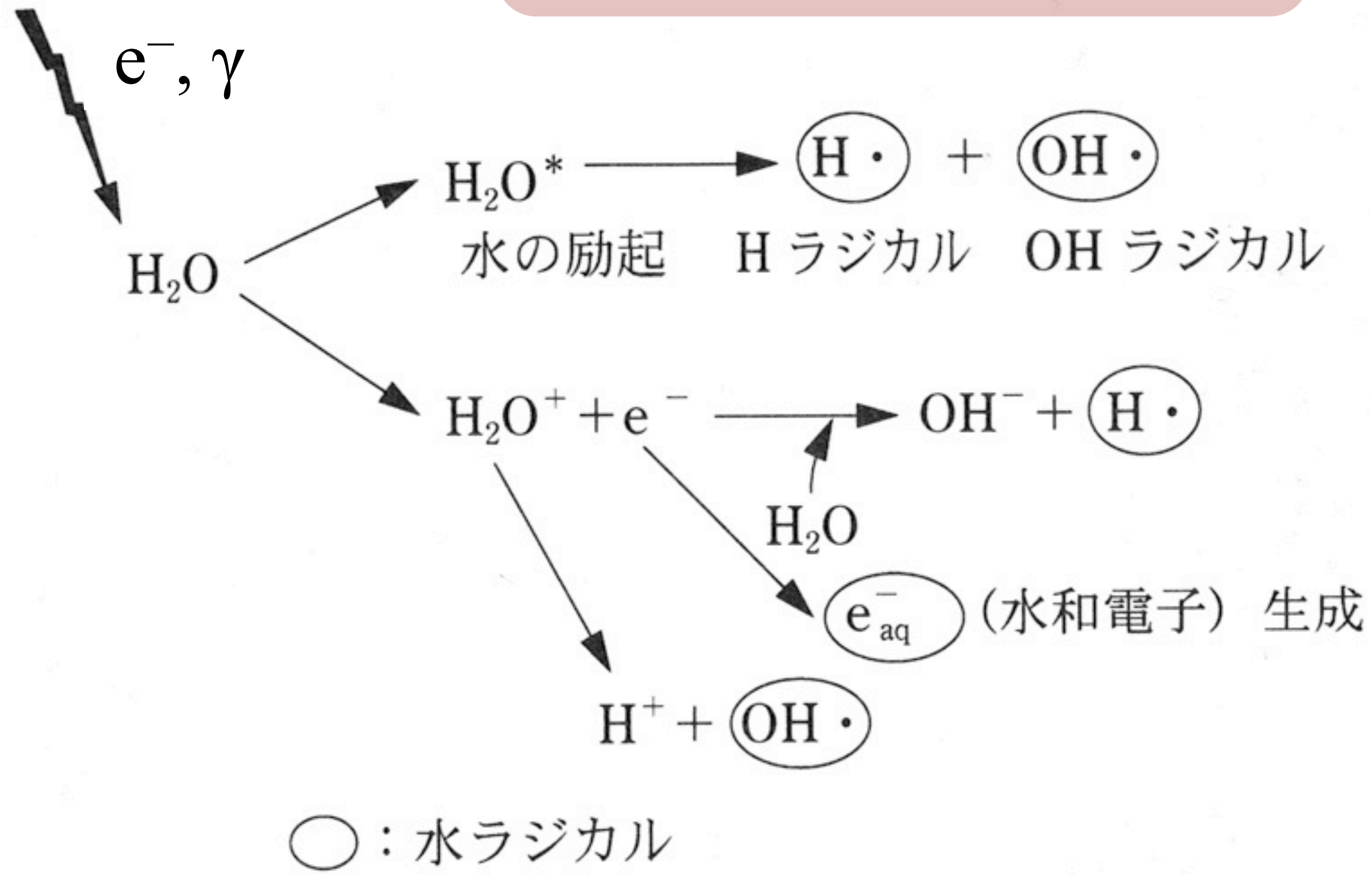


図 6・5　電離放射線による水分子の電離と励起の概略

（書籍「図解 放射性同位元素等取扱者必携」オーム社、より引用）

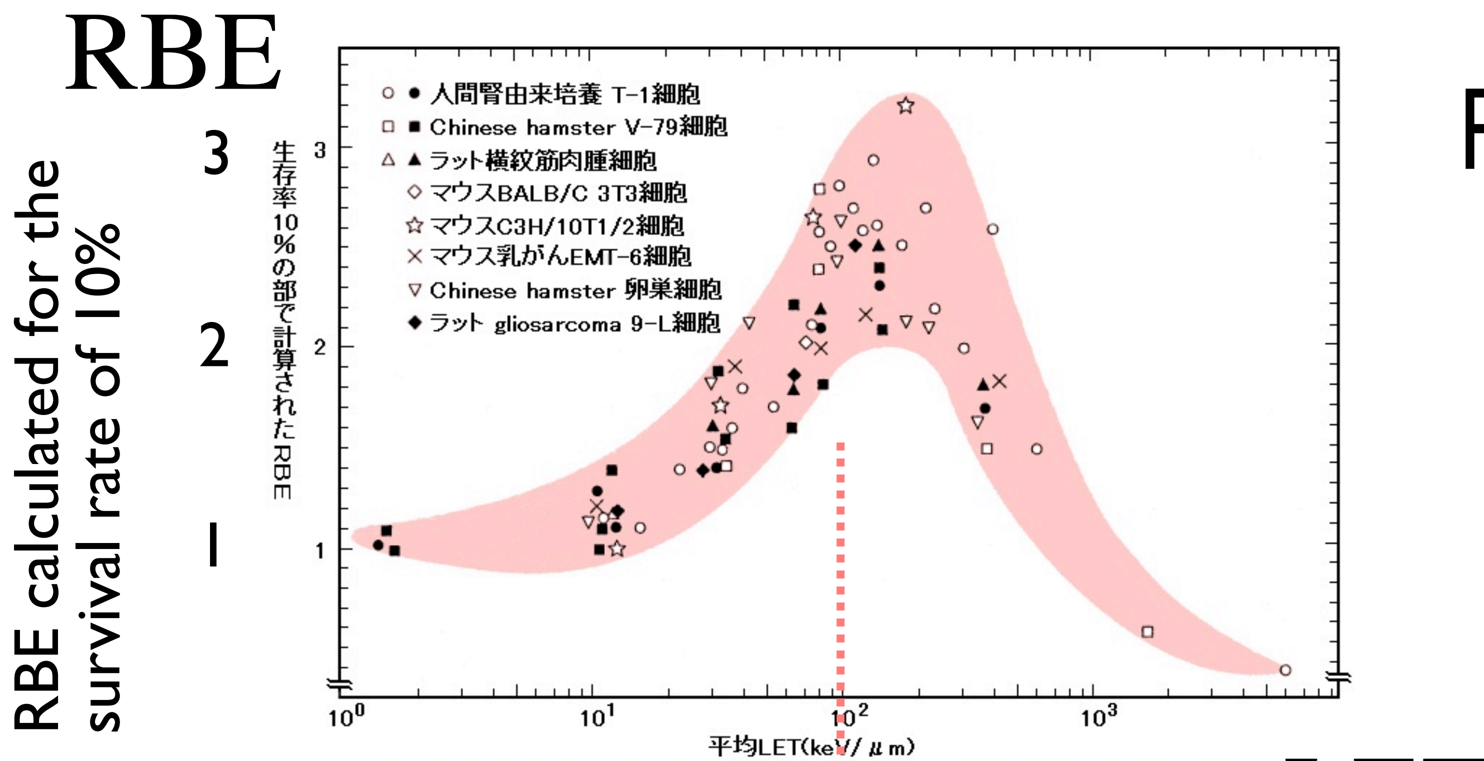
LET : Linear Energy Transfer

Direct effect : direct attack of charged particles to DNA molecules — **high-LET** radiation: **α-ray**

Indirect effect : attack to DNA molecules by radicals from ionization of water — **low-LET** radiation: **β-ray, γ-ray**

Relative Biological Effectiveness (RBE)

生物学的効果比

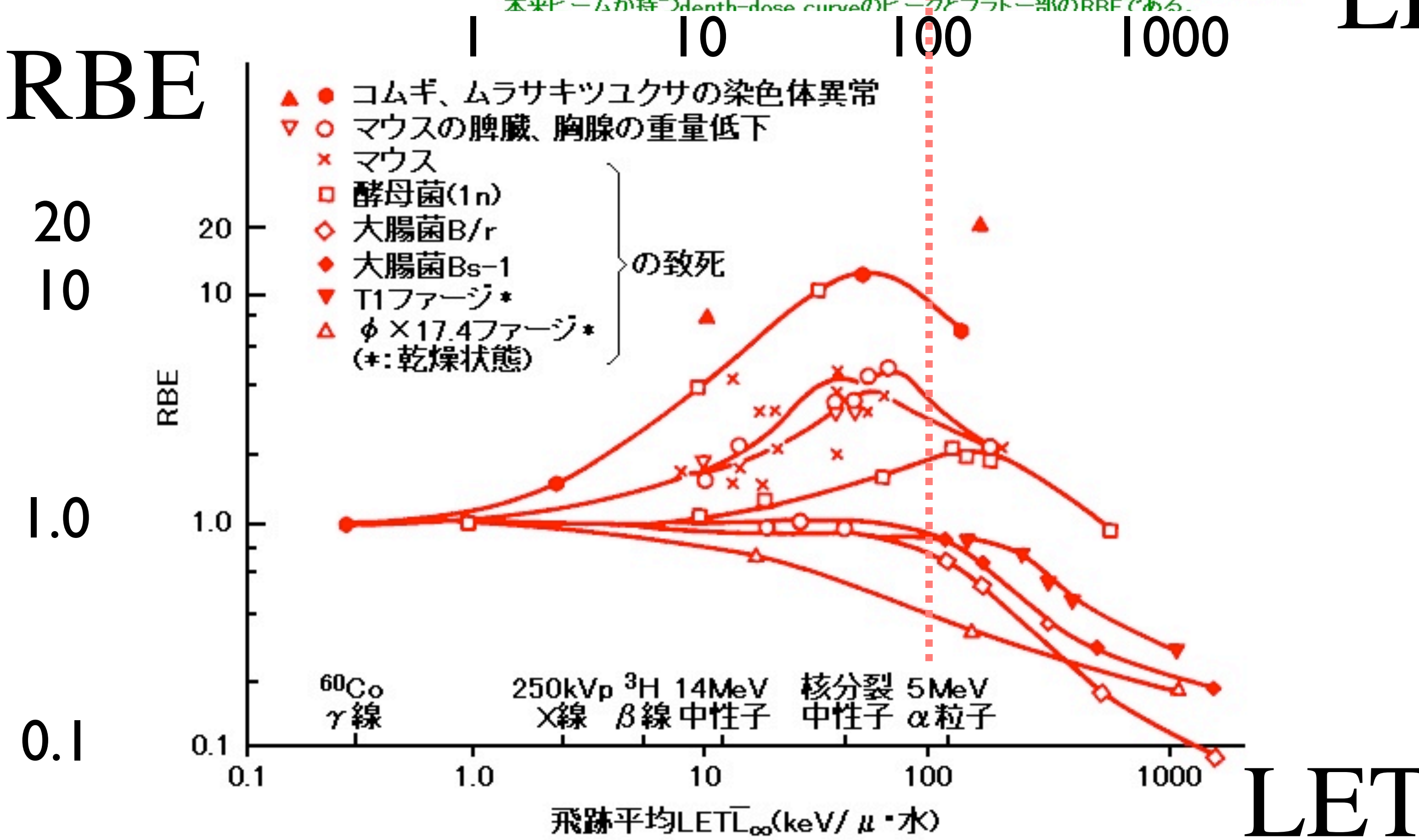


黒印はピーク幅を広げたときのピークとプラトー部のRBE、白印はピーク幅を広げず、本来ビームが持つdepth-dose curveのピークとプラトー部のRBEである。

linear energy transfer
（線エネルギー付与）

[keV/μm]

energy deposited to the matter per unit length along the trajectory of radiation



様々な生物反応(マウスの臓器の重量低下や致死、高等植物の染色体異常等)において、いずれも約80keV/μm付近のLET値をもつ放射線が最大のRBE値を示す。

図2 体細胞的効果に対する各種放射線のRBEとLETの関係

[出典]近藤 宗平:分子放射線生物学、東京大学出版会(1972年)、p.174

Relation between RBE and LET of different radiations for body-cell effects.

effective dose 実効線量 E [J / kg] = [Sv]

実効線量[Sv]

effective dose [Sv]

$$E = \sum_T w_T \times H_T = \sum_T w_T \times \left(\sum_R w_R \times D_{T,R} \right)$$

equivalent dose [Sv]
for a tissue T
組織 T における
等価線量[Sv]

組織 T における
平均吸収線量[Gy]

average **absorbed energy** [Gy]
for a tissue T

tissue weighting factor w_T for tissue T

器官・組織	tissue	組織加重係数:W_T	
生殖腺	gonads	0.20	0.08
骨髄(赤色)	bone-marrow (red)	0.12	0.12
結腸	colon	0.12	0.12
肺	lung	0.12	0.12
胃	stomach	0.12	0.12
膀胱	bladder	0.05	0.04
乳房	breast	0.05	0.12
肝臓	liver	0.05	0.04
食道	oesphagus	0.05	0.04
甲状腺	thyroid	0.05	0.04
皮膚	skin	0.01	0.01
骨表面	bone surface	0.01	0.01
脳	brain		0.01
唾液腺	salivary glands		0.01
残りの器官・組織※2	remaining tissues	0.05	0.12
合計(全身)		1.00	1.00

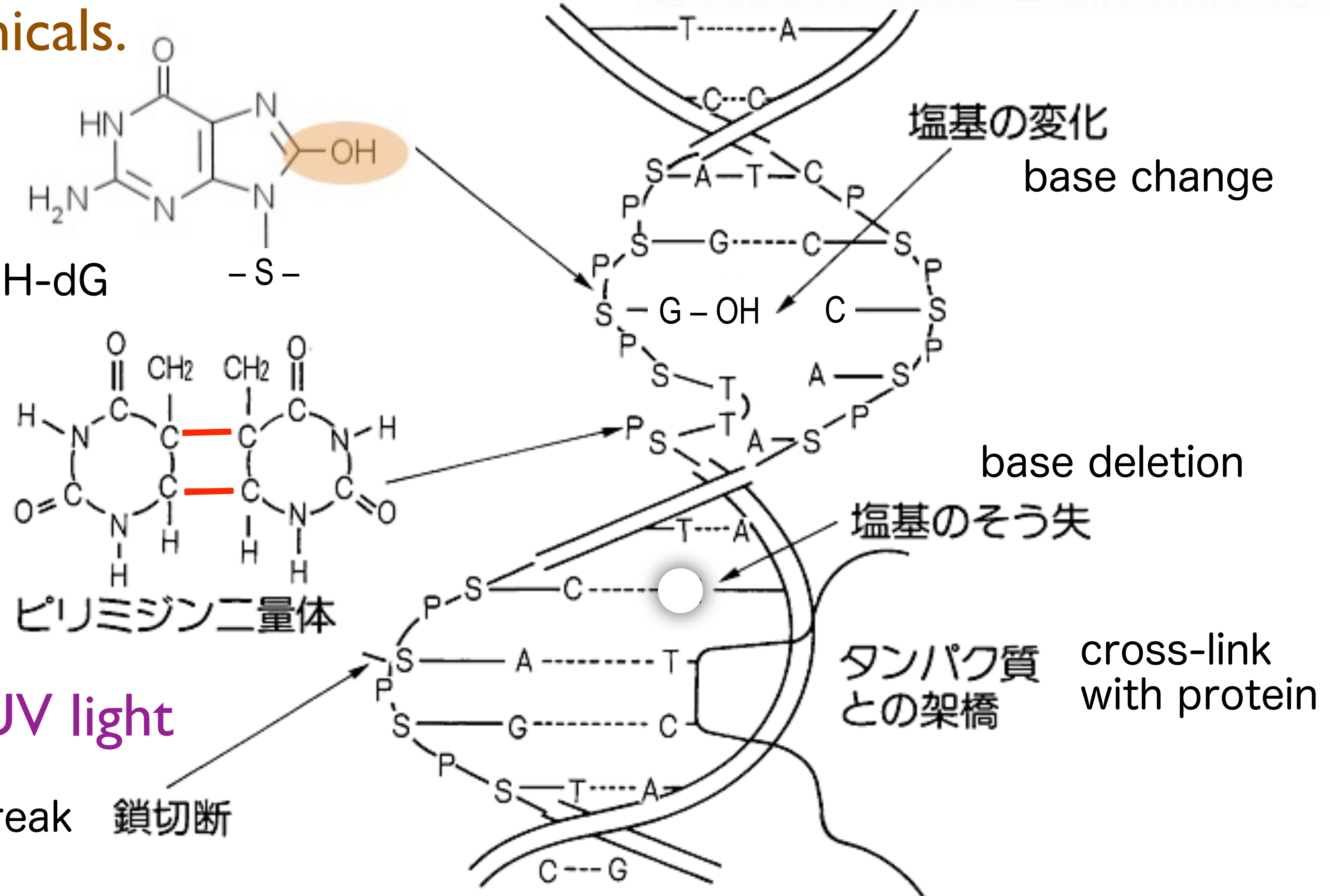
left in black : ICRP 1990
right in red : ICRP 2007

Natural DNA damages occur frequently.
e.g. 50 000 single strand breaks per cell per day !

表 5　増殖期のヒト細胞における DNA 損傷の自然発生率と放射線誘発率の比較[7]

傷の種類	自然の傷(/細胞/日)	X 線誘発の傷(/細胞/1 Sv)
塩基損傷	20,000	300
1 本鎖切断	50,000	1.000
2 本鎖切断	50(推定[2,19])	40

DNA damages are also induced by particular chemicals.



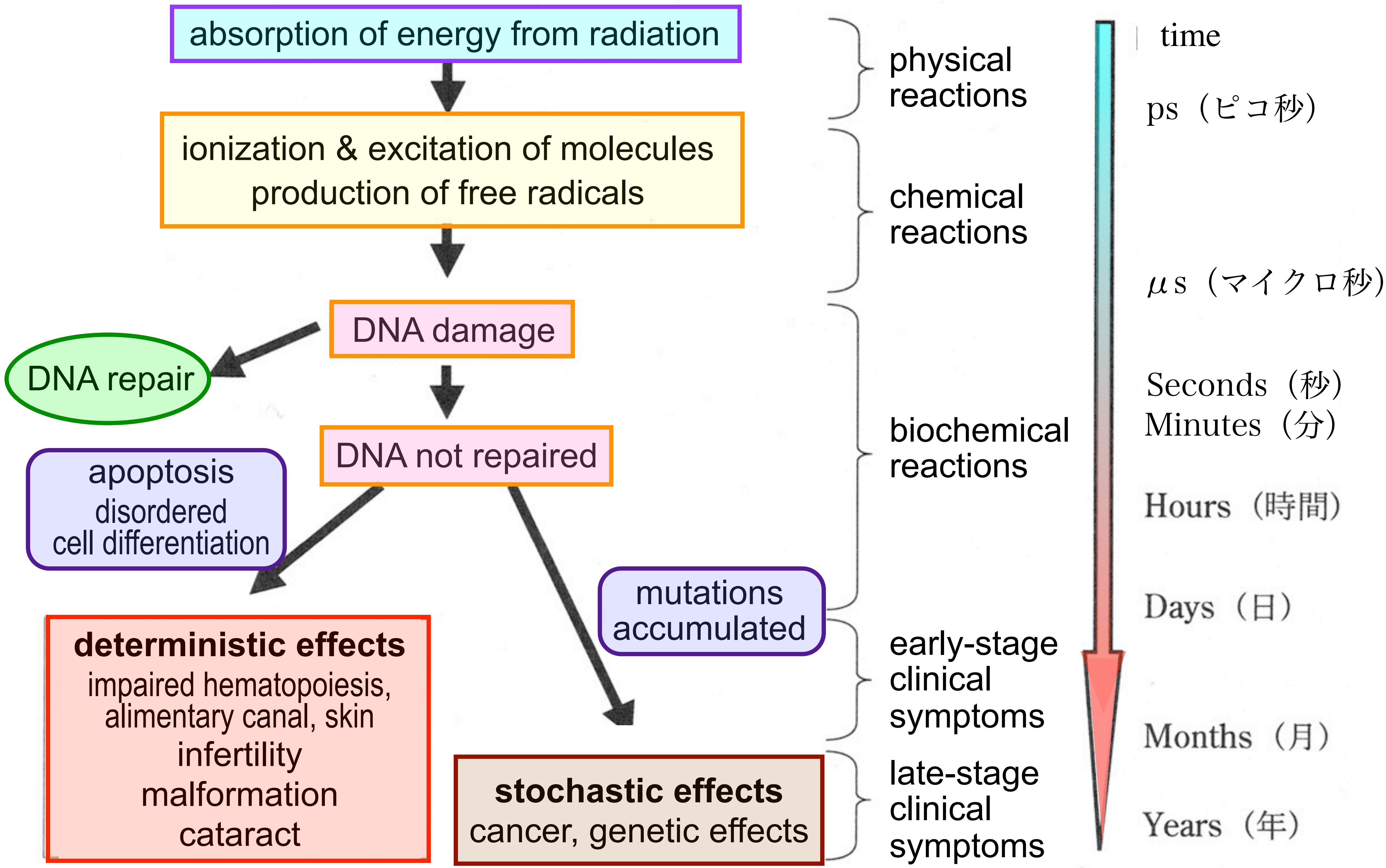
damage also by UV light

図２　放射線照射を受けた細胞から抽出された ＤＮＡに見られる種々の損傷

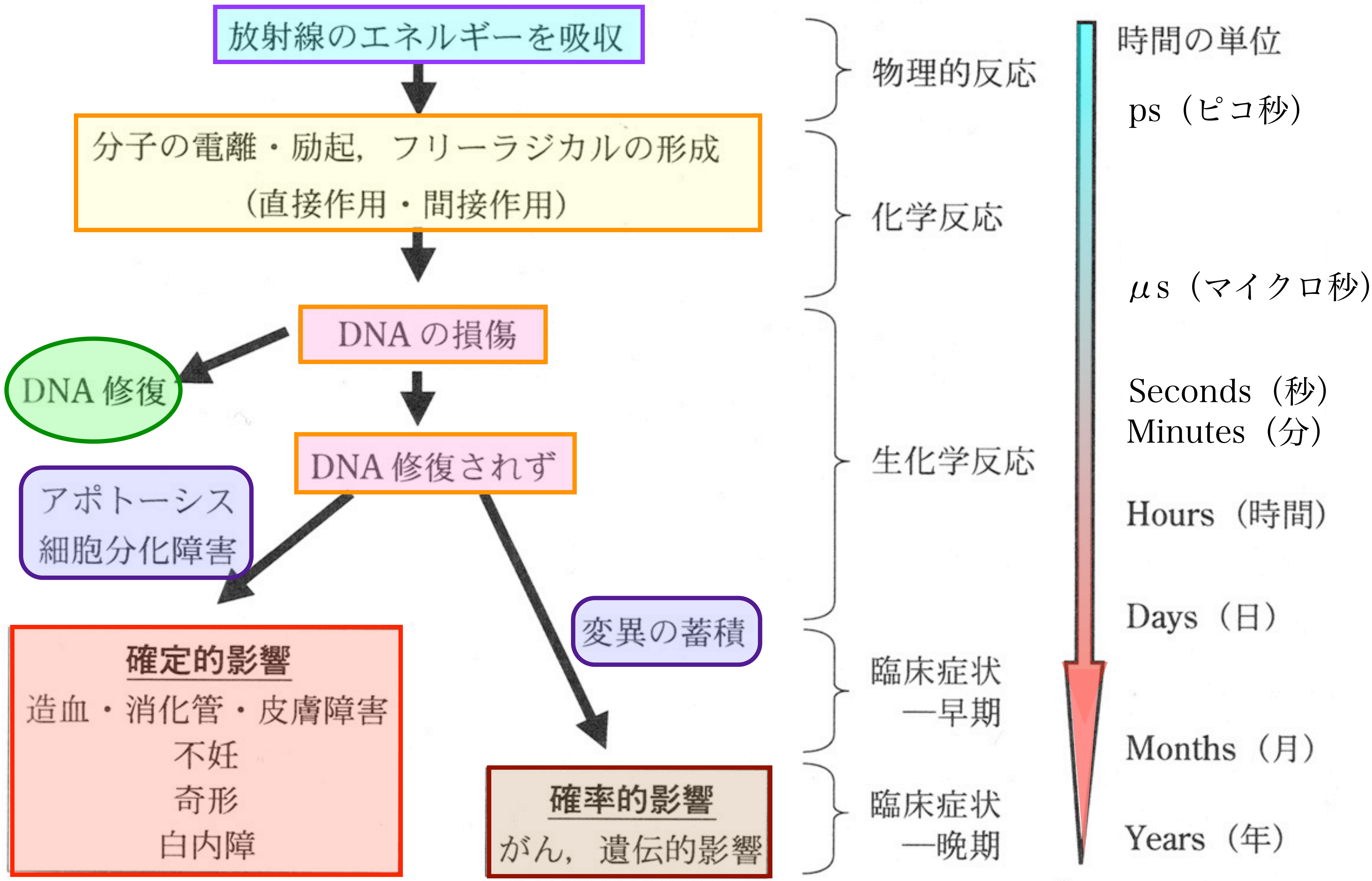
various kinds of DNA damages by radiation

［出典］江上信雄：生き物と放射線、東京大学出版会、 1975

図は一部内容を改変。



Chronological changes of vital reactions after exposure to radiation.



放射線被ばく後に起こる生体反応の経時的変化

Radiation effects to human body

deterministic effects 確定的影響

JCO accident in Tokai village (1999)
Firemen at Chernobyl NPP accident (1986)

Radiation causes impediment or disorder of cells and tissues.

Only at high dose (with **threshold**). **no effect below 150 mSv**

Criticality of the disease depend on the dose.

Accute effect : impaired hematopoiesis, alimentary canal, infertility etc. (generative cell) **150 – 6000 mSv**

late effect : cataract. **500 – 5000 mSv**

急性影響：造血障害、消化管障害、不妊（生殖細胞）など
晩発性影響：白内障

Death : half population killed at **4 Gy**, all killed at 7 Gy (acute exposure).
急性被曝

stochastic effects 確率的影響

Caused by DNA damage of cells due to raditaion.

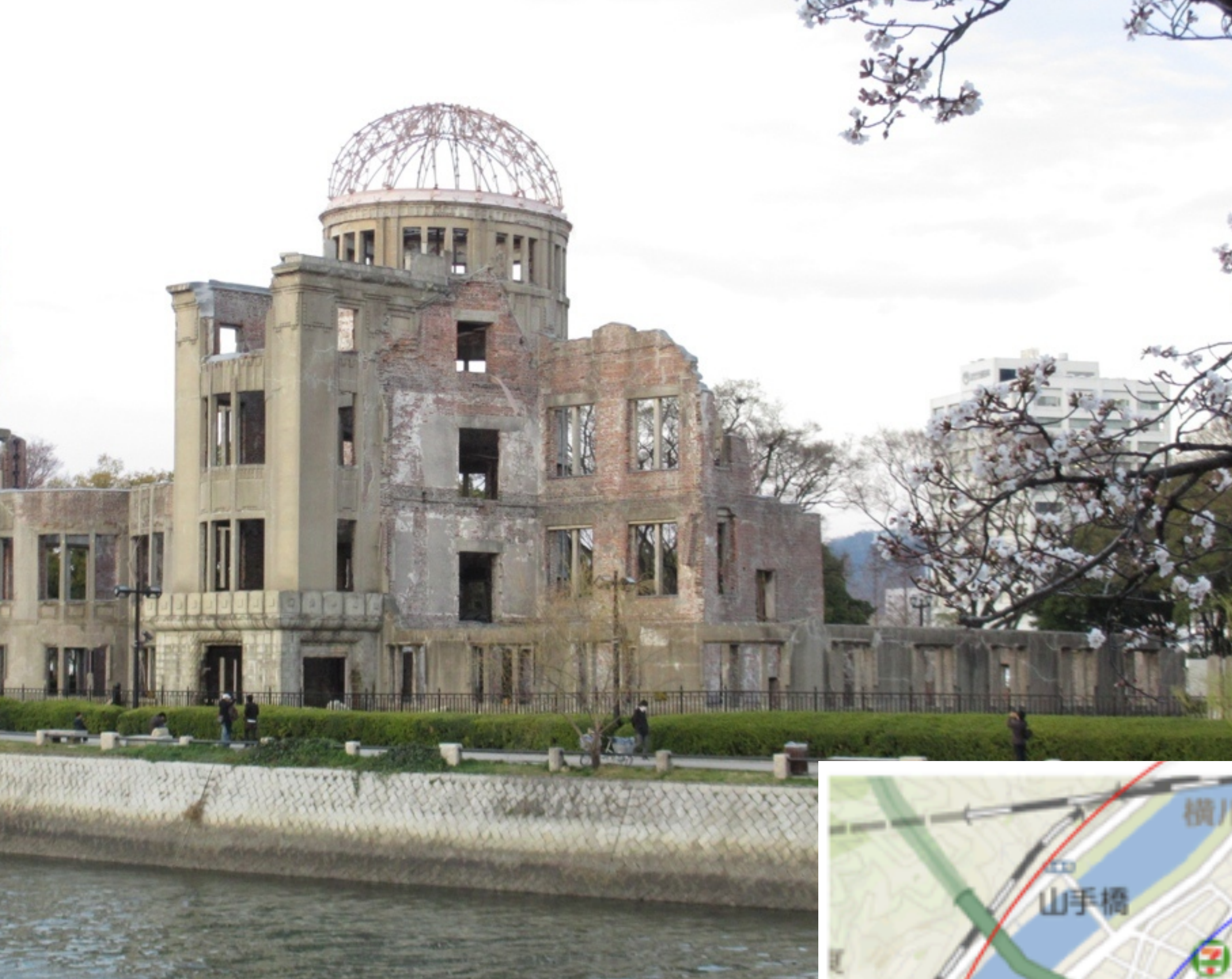
Most of the damages are repaired, but failure of repair can result in cancer after a long period of time.

The **probability** increases with dose. (**No threshold** is assumed.)

Criticality of the disease **is not related** with the **dose**.

late effect : **cancer** and hereditary effects for germ cells.

(not observed for human) 遺伝的影響はヒトでは観察されていない。



Atomic Bomb Dome in Hiroshima

Estimated dose (mGy)

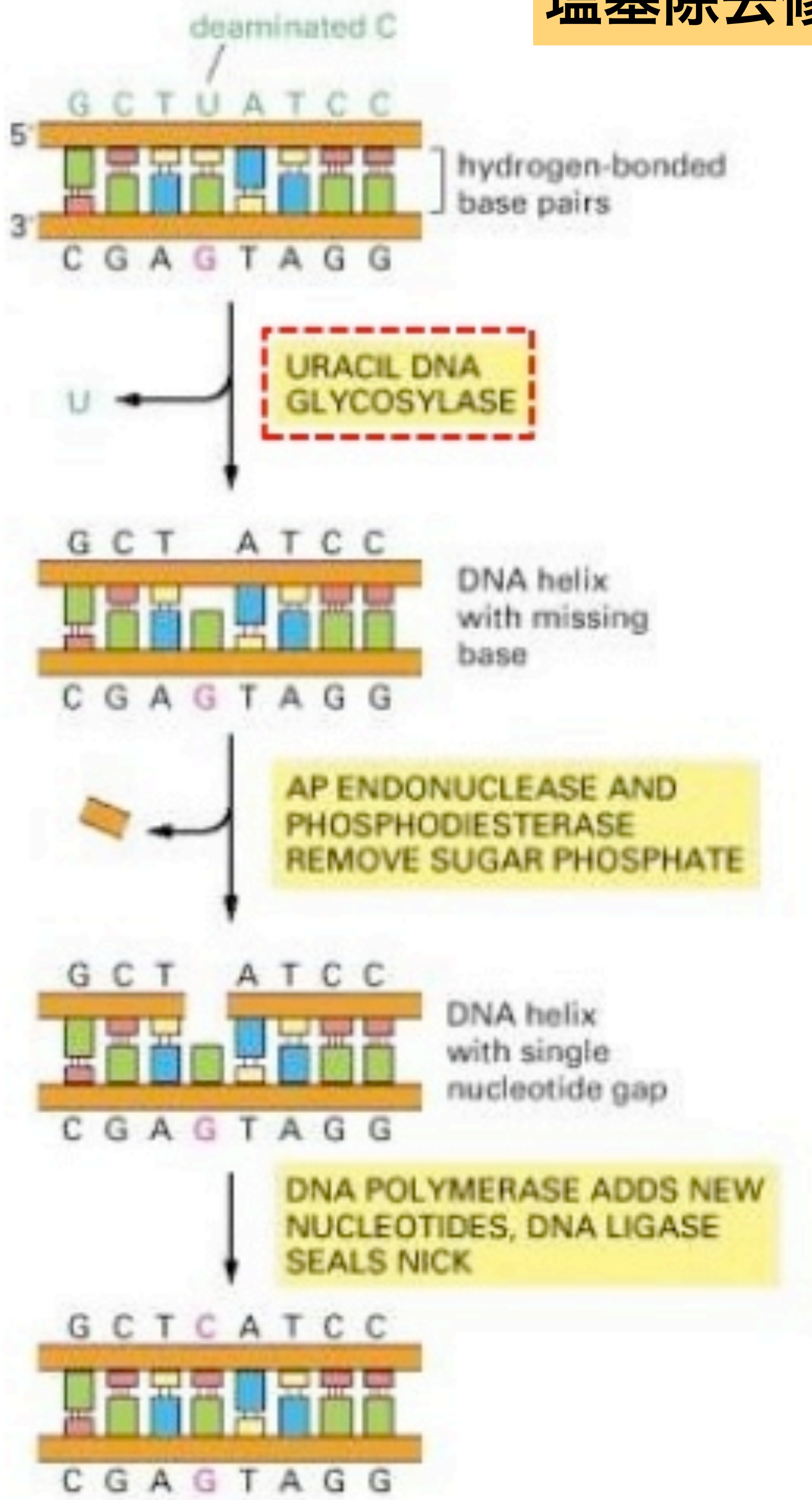
by gamma-rays

by neutrons

DNA repair

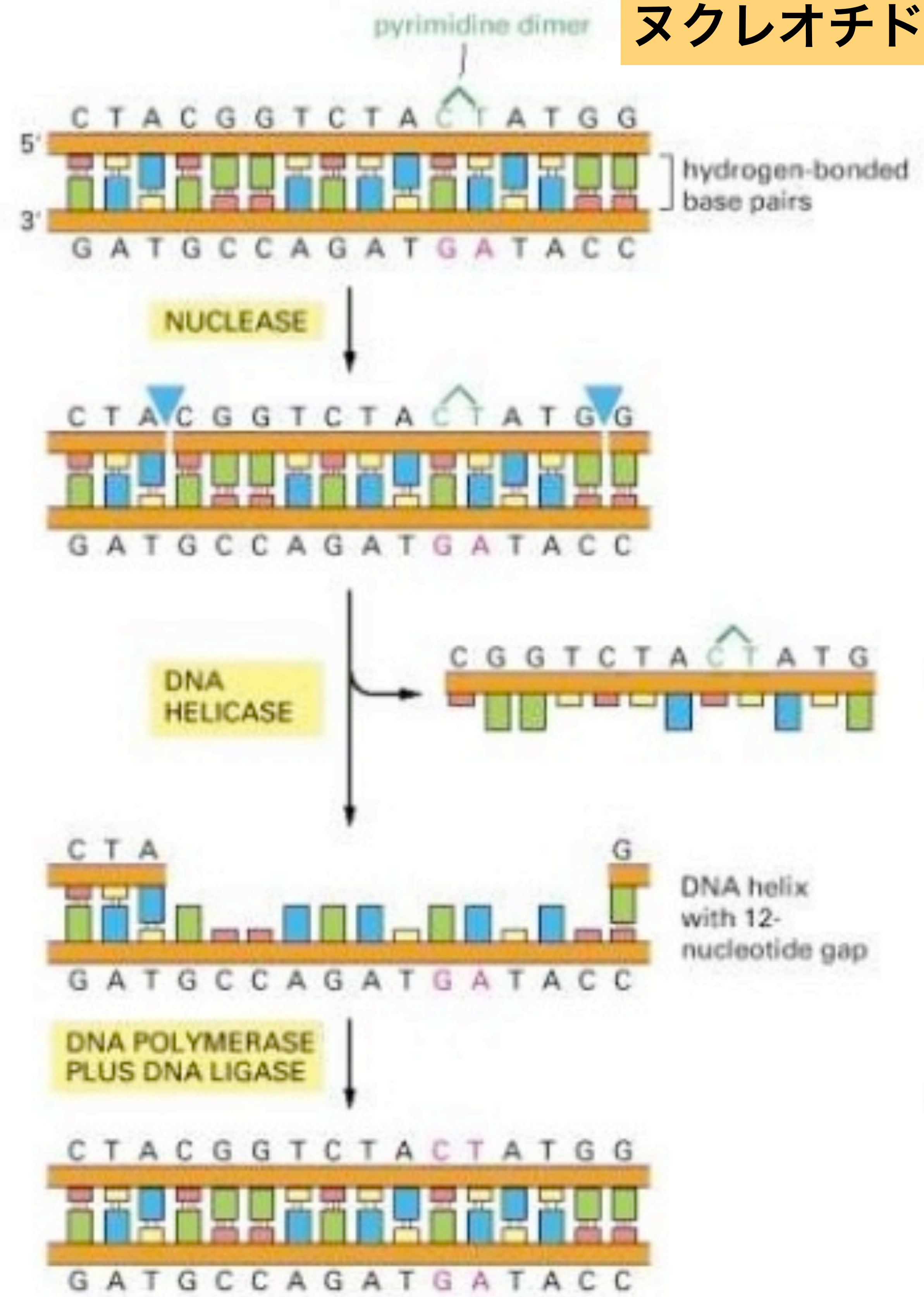
Base excision repair

塩基除去修復



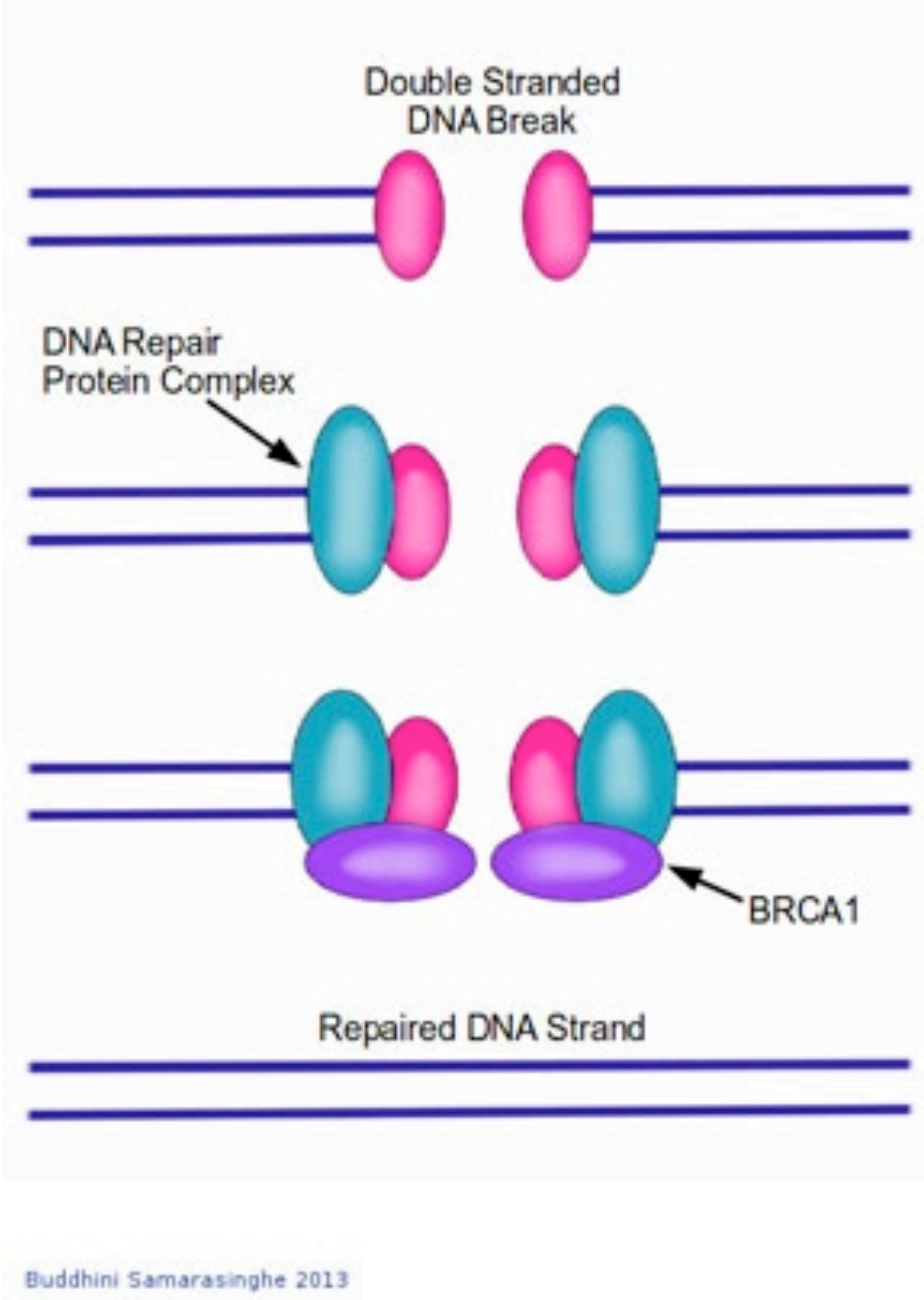
Nucleotide excision repair

ヌクレオチド除去修復

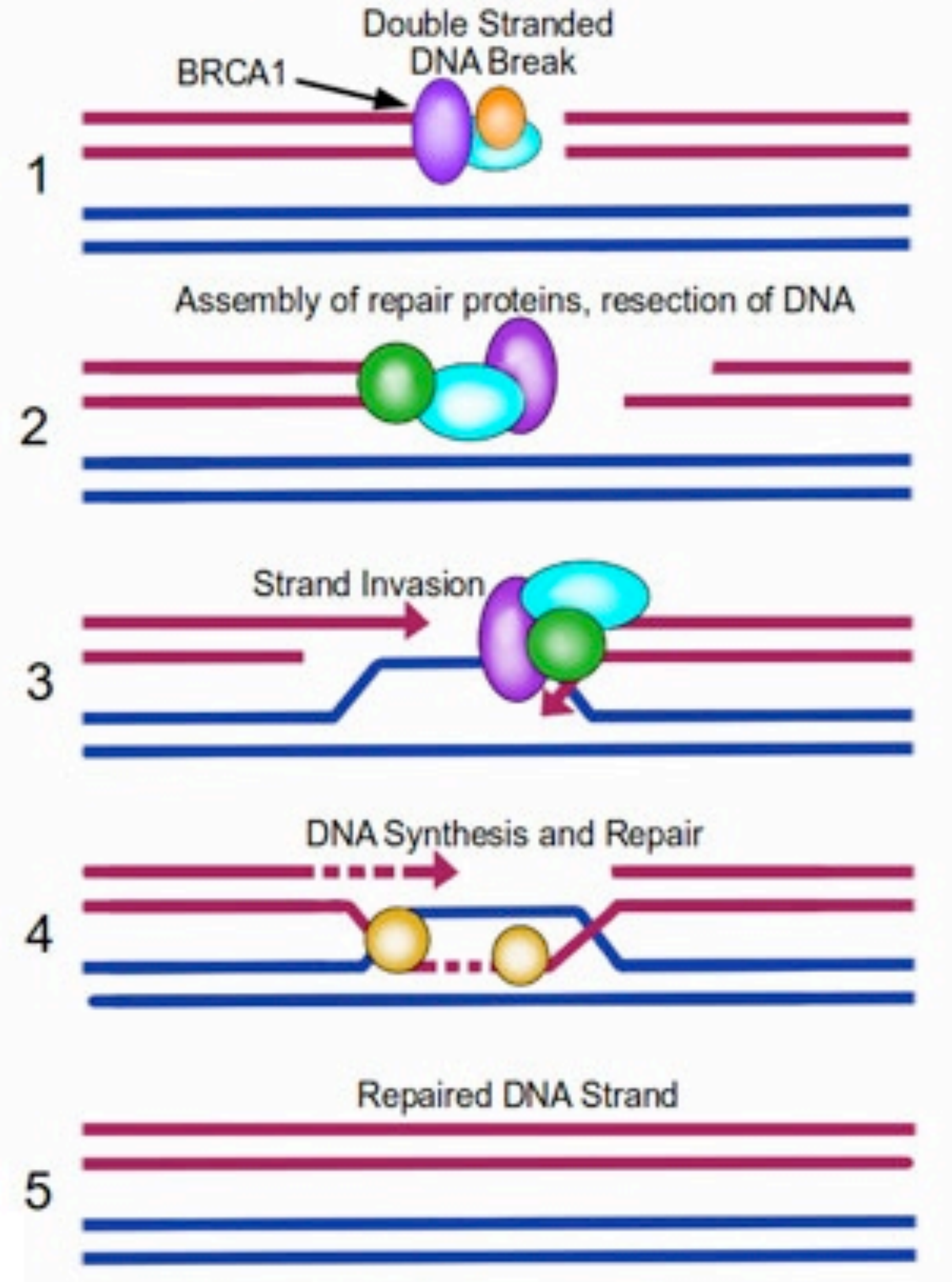


DNA repair for double-strand breaking

Non-homologous End Joining 非相同末端結合修復



Homologous Recombination DNA Repair 相同組み換え修復



The Nobel Prize in Chemistry 2015

Photo: Cancer Research UK

Tomas Lindahl

Prize share: 1/3

Photo: K. Wolf/AP Images for HHMI

Paul Modrich

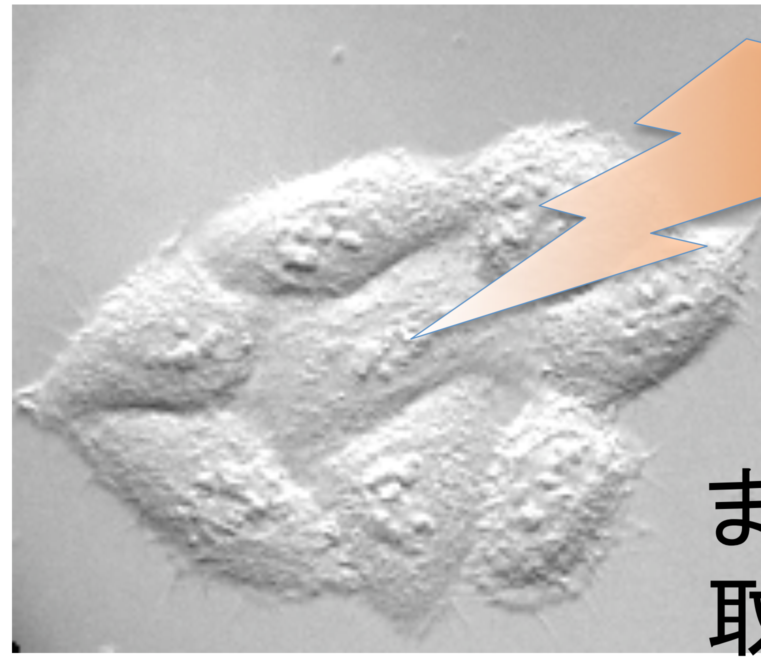
Prize share: 1/3

Photo: M. Englund, UNC-School of Medicine

Aziz Sancar

Prize share: 1/3

The Nobel Prize in Chemistry 2015 was awarded jointly to Tomas Lindahl, Paul Modrich and Aziz Sancar *"for mechanistic studies of DNA repair"*.



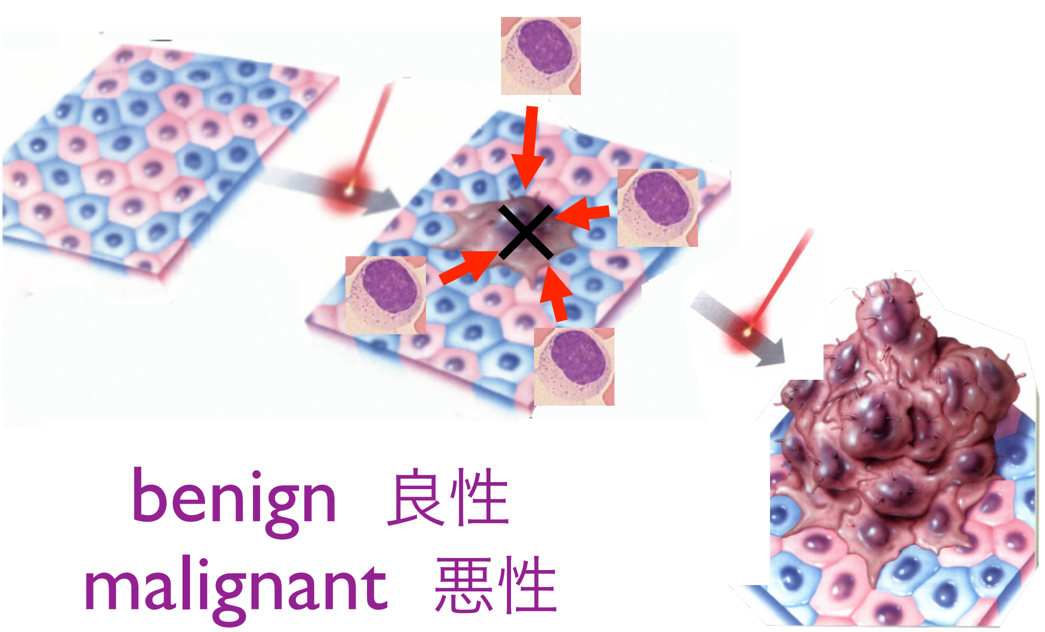
Very rarely removal of
damages in the DNA fails
and the damages can remain.

まれにDNA分子の傷が
取り除けずに残ってしまう

(failure to repair DNA)
修復の失敗

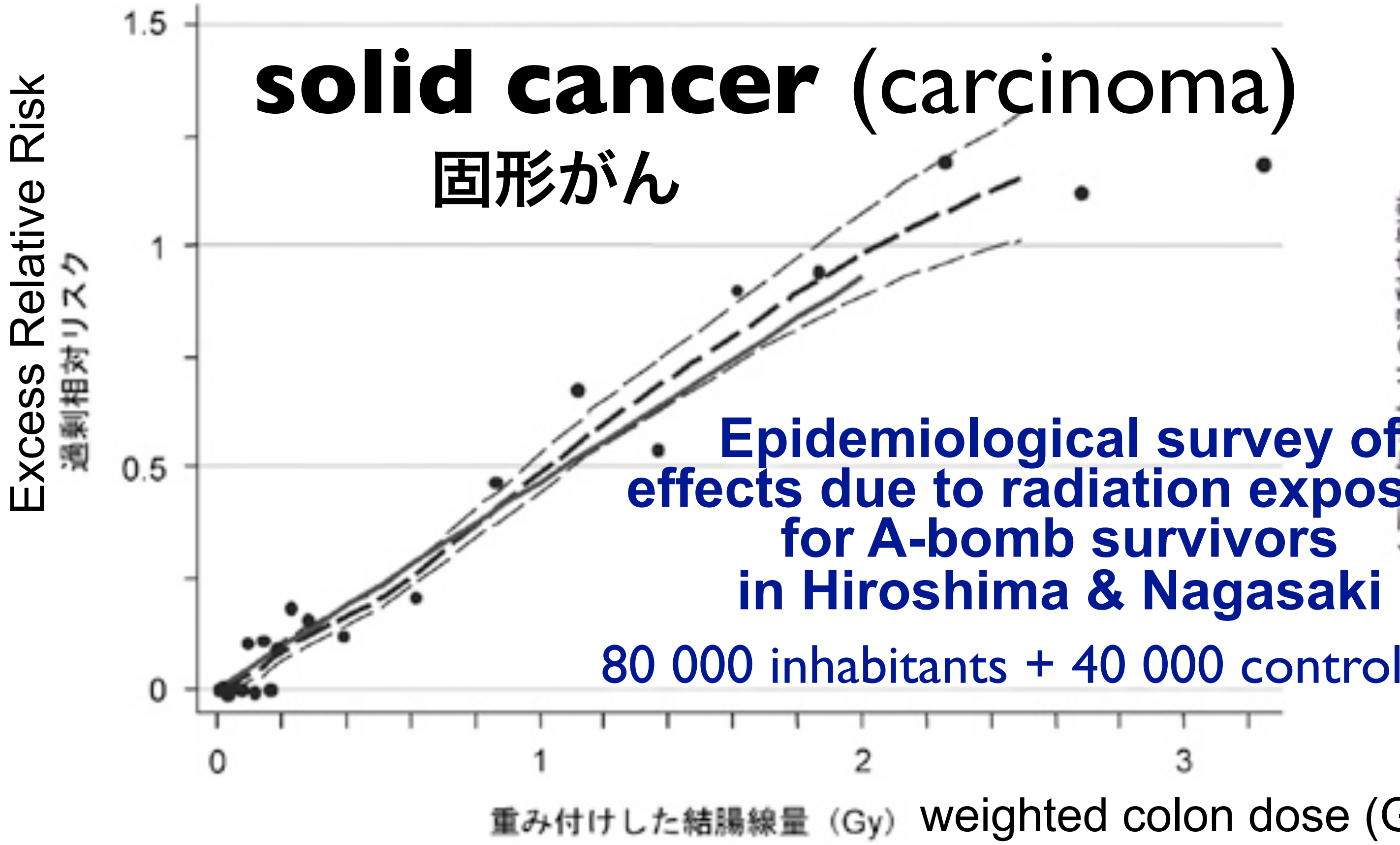
p53 gene
Apoptosis (programmed cell death)
細胞死も起こらない fails to work.

Natural Killer cell fails to capture
NK細胞も取り逃がした those
abnormal cells.
（自然免疫系）
(natural immune system)



benign 良性
malignant 悪性
infiltrative 浸潤性

がん細胞が残ってしまう
One or some cancer cell(s) remain(s) by chance.



Epidemiological survey of effects due to radiation exposure for A-bomb survivors in Hiroshima & Nagasaki

80 000 inhabitants + 40 000 control

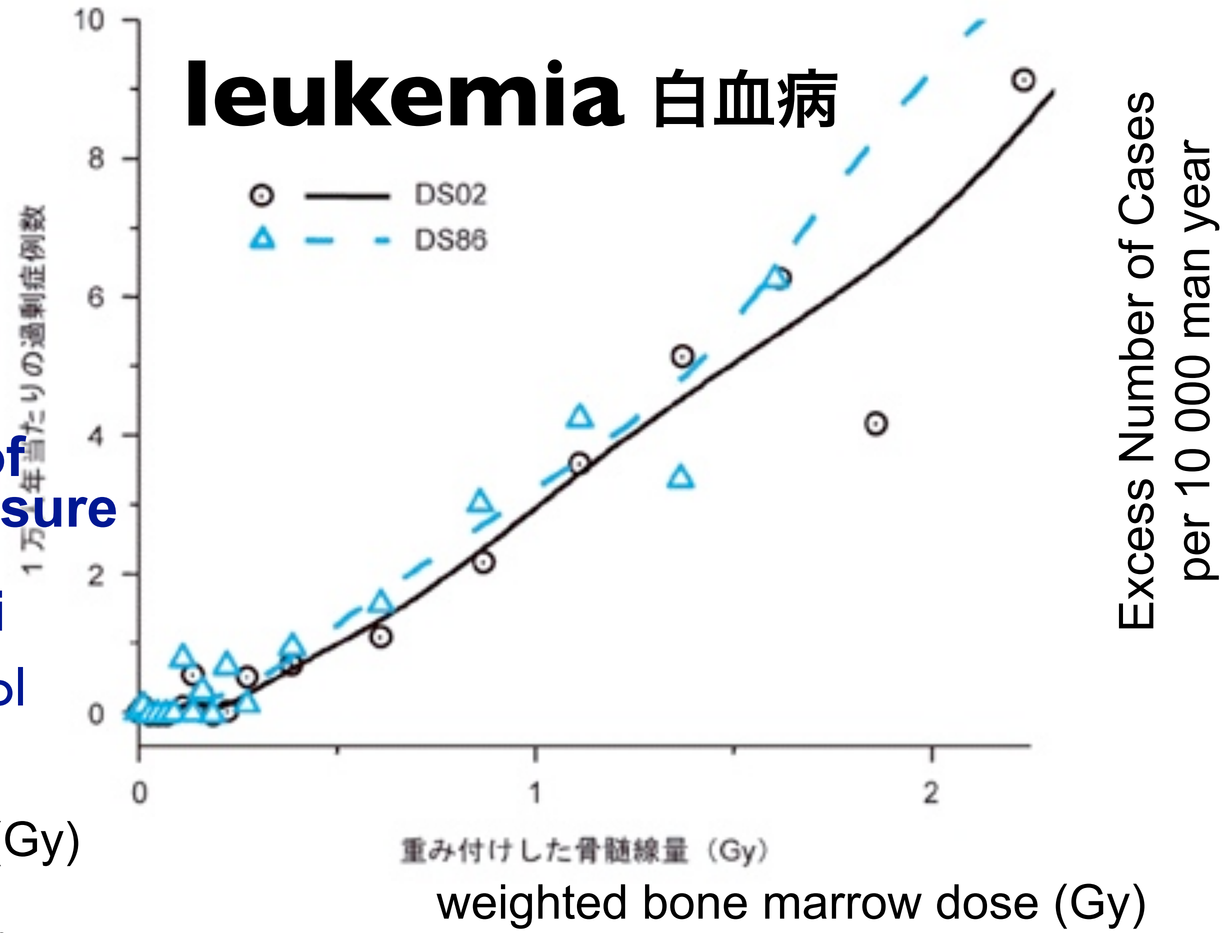


図　LSS (寿命調査) 集団における固形がん発生の過剰相対リスク（線量別）1958－1998年。太い実線は、被爆時年齢30歳の人が70歳に達した場合に当てはめた、男女平均過剰相対リスク（ERR）の線形線量反応を示す。太い破線は、線量区分別リスクを平滑化したノンパラメトリックな推定値であり、細い破線はこの平滑化推定値の上下1標準誤差を示す。

図. DS02とDS86による白血病のノンパラメトリックな線量反応、1950－2000年。被爆時年齢20－39歳の人の1970年における男女平均リスク。

表. LSS集団における固形がん発生のリスク（線量別）、1958－1998年

重み付けした結腸線量（Gy）	対象者数	がん		寄与率
		観察数	推定過剰数	
0.005 - 0.1	27,789	4,406	81	1.8%
0.1 - 0.2	5,527	946	75	7.6%
0.2 - 0.5	5,935	1,144	179	15.7%
0.5 - 1.0	3,173	688	206	29.5%
1.0 - 2.0	1,647	460	196	44.2%
>2.0	564	185	111	61.0%
合　計	44,635	7,851	848	10.7%

（財）放射線影響研究所 データ

表. LSS集団における白血病による死亡の観察数と推定過剰数、1950－2000年

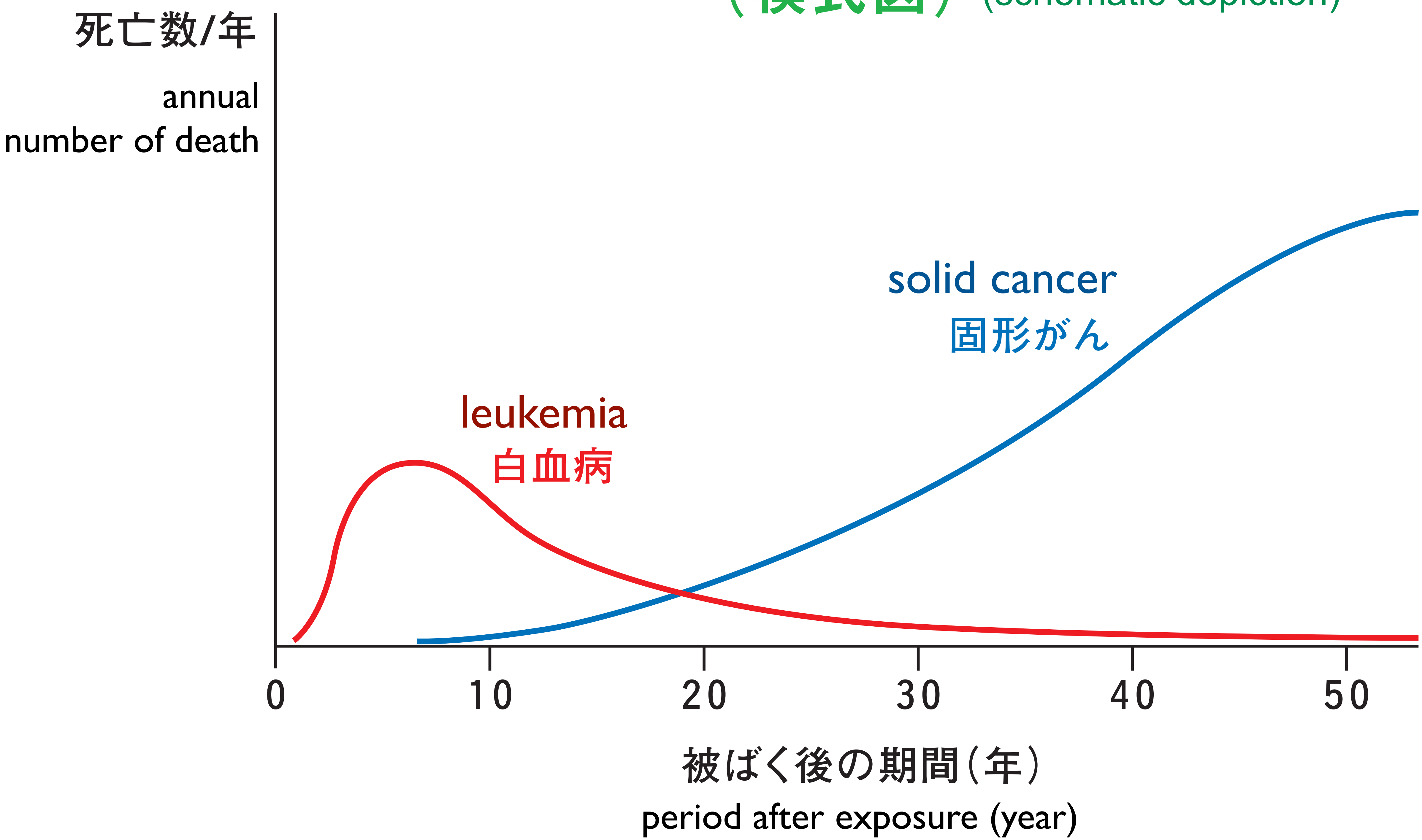
重み付けした骨髄線量（Gy）	対象者数	死亡		寄与率
		観察数	推定過剰数	
0.005 - 0.1	30,387	69	4	6%
0.1 - 0.2	5,841	14	5	36%
0.2 - 0.5	6,304	27	10	37%
0.5 - 1.0	3,963	30	19	63%
1.0 - 2.0	1,972	39	28	72%
>2.0	737	25	28	100%
合　計	49,204	204	94	46%

It is very difficult to deduce decisive conclusions about the effects of **low-dose exposure** from the result of the **epidemiological survey**, due to **statistical** uncertainties.

Chronological course of the number of death related to A-bomb radiation

原爆放射線に関連する死亡数の時間的経過

（模式図） (schematic depiction)



公益財団法人　放射線影響研究所
（放影研 RERF）

Radiation Effects Research Foundation

predecessor : Atomic Bomb Casualty Commission (ABCC)
前身は原爆傷害調査委員会

@広島市南区　比治山公園

Hiroshima

@長崎市螢茶屋

Nagasaki

low-dose and low-dose-rate exposure and cancer death

旧ソ連

ロシア語　現地 ウクライナ語

Чернобыль / Чорнобиль

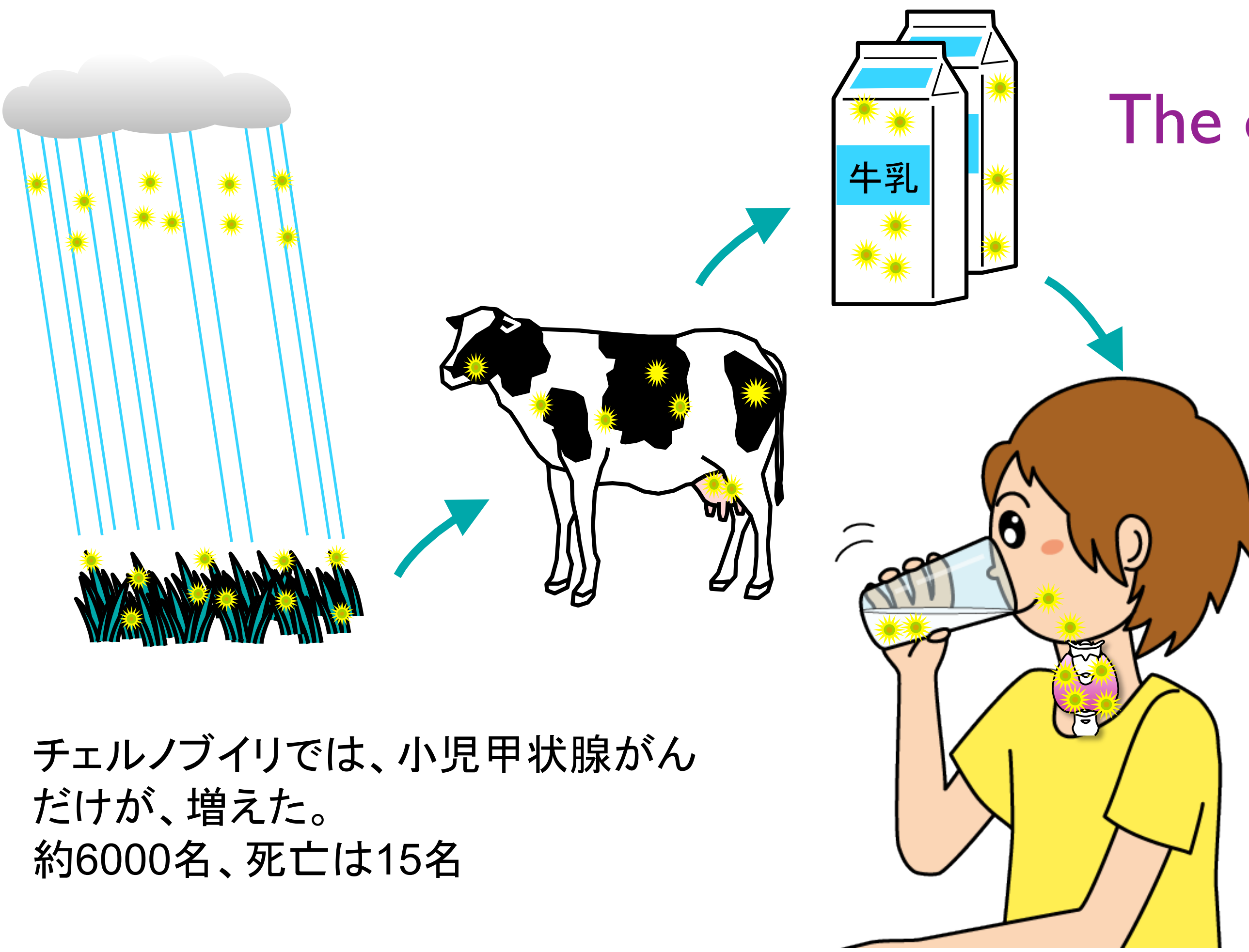
Chenobyl NPP accident

^{131}I (iodine-131) total **2 EBq** !!

The only health effect observed for general public was increase of infant thyroid cancer only.
(due to ingestion of local cotaminated milk)
1 patient / 300,000 per year → 1 p. /10,000
(total 5000–6000 patients, 15 dead)

average dose to thyroid
2 Gy = 2000 mSv !!

More important was disorder due to stress.
（ストレスによる失調がずっと重大）



チェルノブイリでは、小児甲状腺がんだけが、増えた。
約6000名、死亡は15名

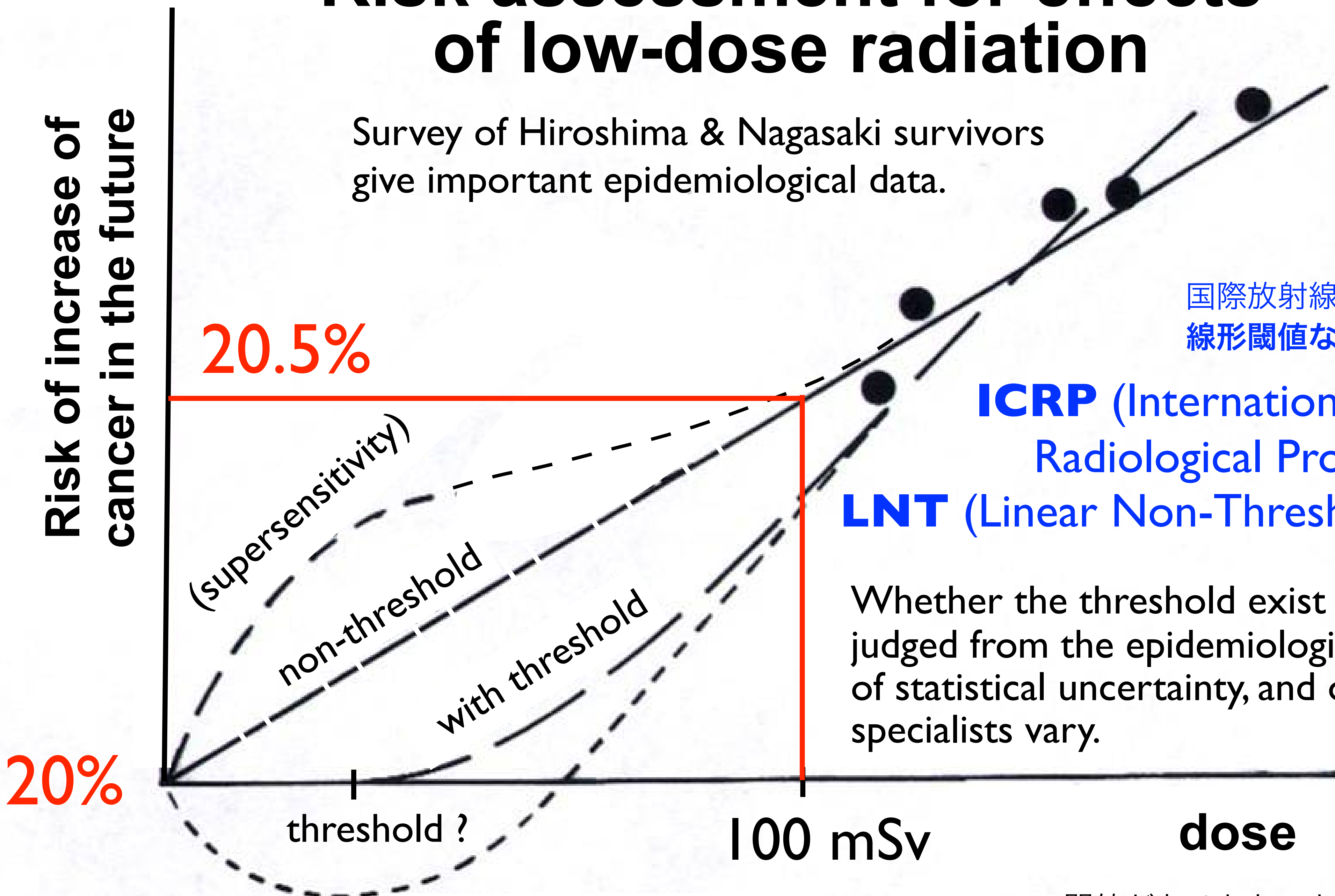
いわき市、飯舘村の**こどもの甲状腺被曝**調査

Survey of infant thyroid exposure in Fukushima showed that maximum equivalent dose to the thyroid was **35 mSv**.

Sense of loss due to the disaster and the accident is common to Chernobyl.

Risk assessment and protection against radiation

Risk assessment for effects of low-dose radiation



Survey of Hiroshima & Nagasaki survivors give important epidemiological data.

国際放射線防護委員会 (**ICRP**) は
線形閾値なし (LNT) 仮説を採用。

ICRP (International Comission on Radiological Protection) accepts **LNT** (Linear Non-Threshold) hypothesis.

Whether the threshold exist or not cannot be judged from the epidemiological survey because of statistical uncertainty, and opinions of the specialists vary.

閾値があるかないかは、疫学調査から
統計学的に判断がつかず、意見が分かれる。

Risk of future cancer death for Japanese people:
26% for male, 16% for female.

Radiation protection

- distance
- time
- shielding

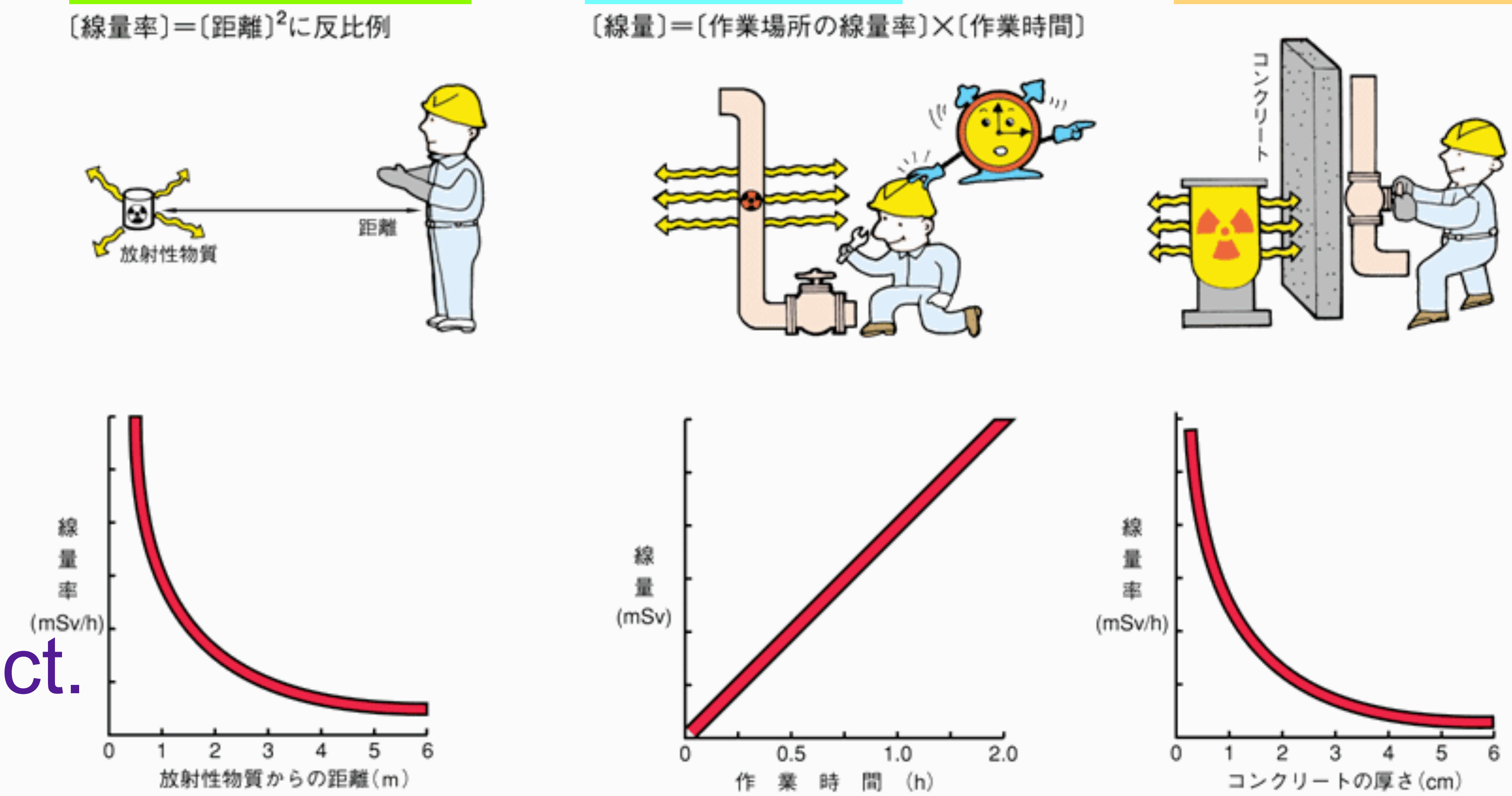


図1 遮へい3原則の図

[出典] 電気事業連合会:「原子力・エネルギー」図面集2003-2004、p.130

Prevent deterministic effect.

Reduce stochastic effect.

Optimization : all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.

(**ALARA** principle = As Low As *Reasonably Achievable*)

Dose limit : **1 mSv/yr** for general public (in addition to natural BG).

100 mSv/ 5 yrs and 50 mSv/yr max. for male radiation workers.

Fine. Per oggi è tutto.

Fini pour aujourd'hui

That’s all for today.

Всё за сегодня.

오늘은 이만 마치겠습니다.

今天就学到这儿了。

Ci vediamo la prossima settimana.

On se voit la semaine prochaine.

See you next week.

Увидимся на следующей неделе.

다음 주에 또 만납시다.

下周见。