Summary of previous lecture

- We discussed α-decay theory, β-decay theory (Fermi-theory) and γ-ray theory

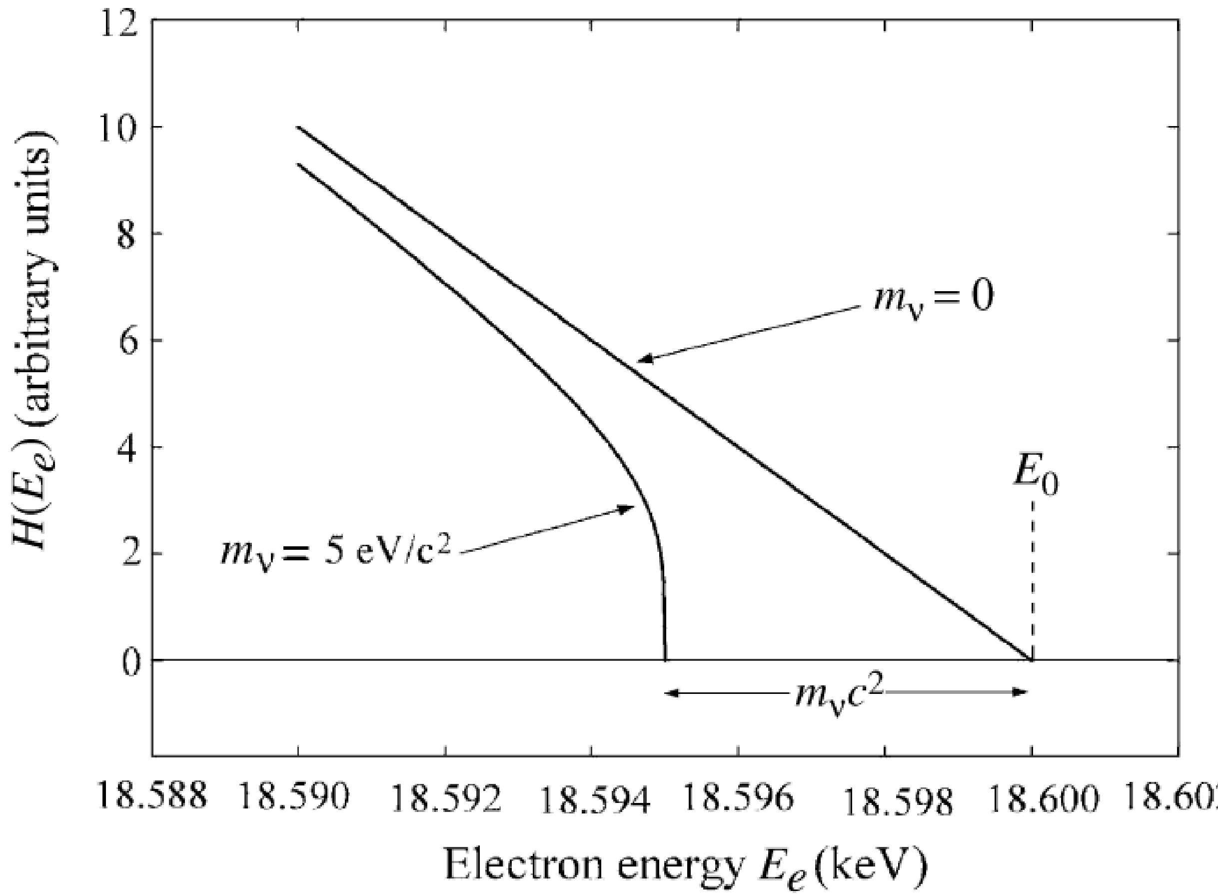
- We scetched the derivation of the electron spectrum for β-decay from Fermi-theory (main assumption: point-like interactions, short range Yukawa coupling, no Fermi screening), which is determined by the phase space factor.

Summary of previous lecture

- Geiger-Nutall relation for α-decay
  - relates half lives to Q-value
- Fermi-Kurie relation for β-decay
  - deviation can point to ”new” physics, e.g. neutrino mass
- Selection rules for γ decays
  - According to angular momentum and Parity conservation (n.b. internal conversion, internal pair production)

β decay and the neutrino: the Kurie plot

$$H(E_e) \equiv \left[\left(\frac{\mathrm{d}\omega}{\mathrm{d}p_e} \right) \frac{1}{p_e^2 K(Z, p_e)} \right]^{\frac{1}{2}} = E - E_e,$$



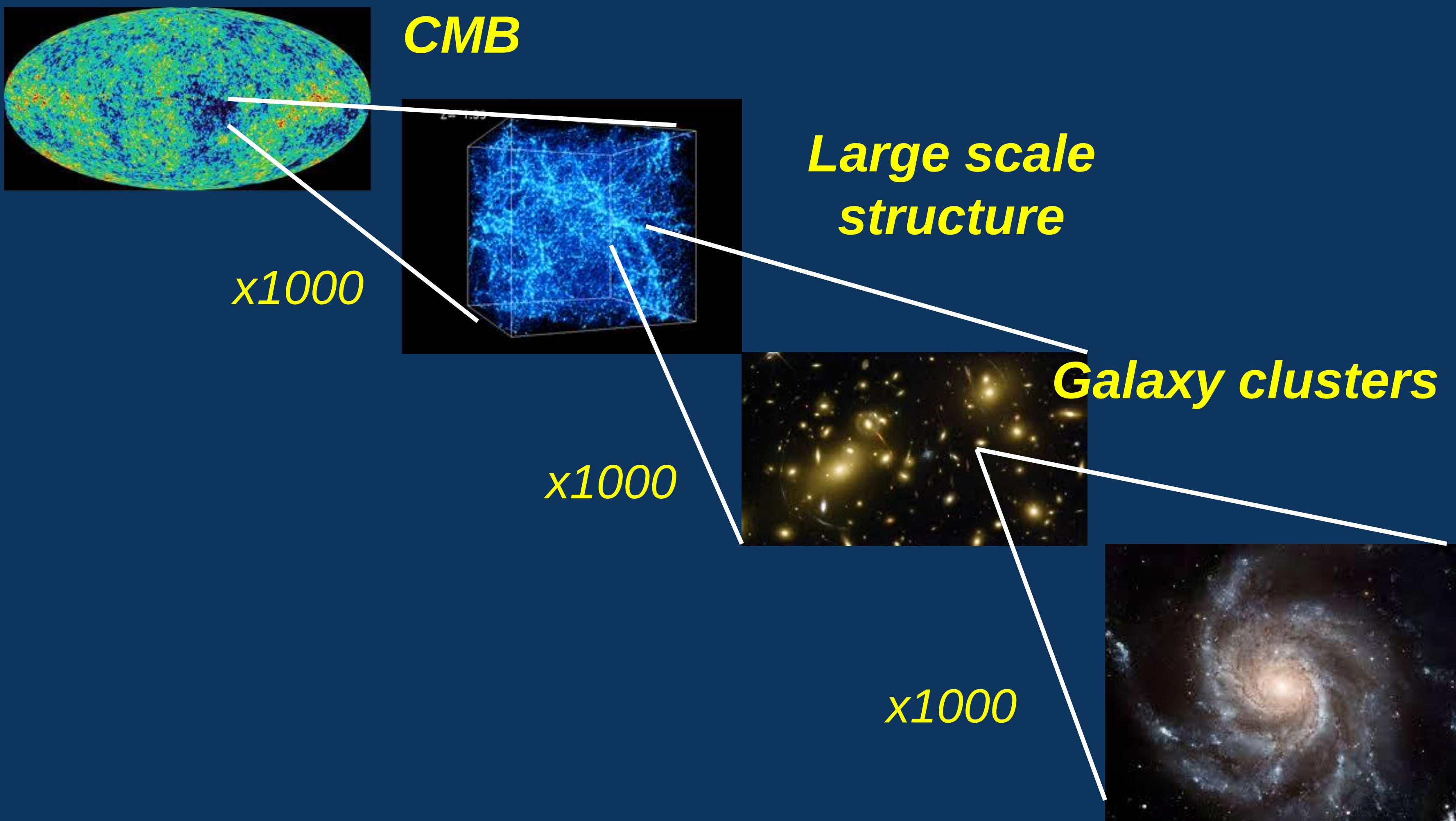
Lecture 5: Applications

Jan Conrad

Overview

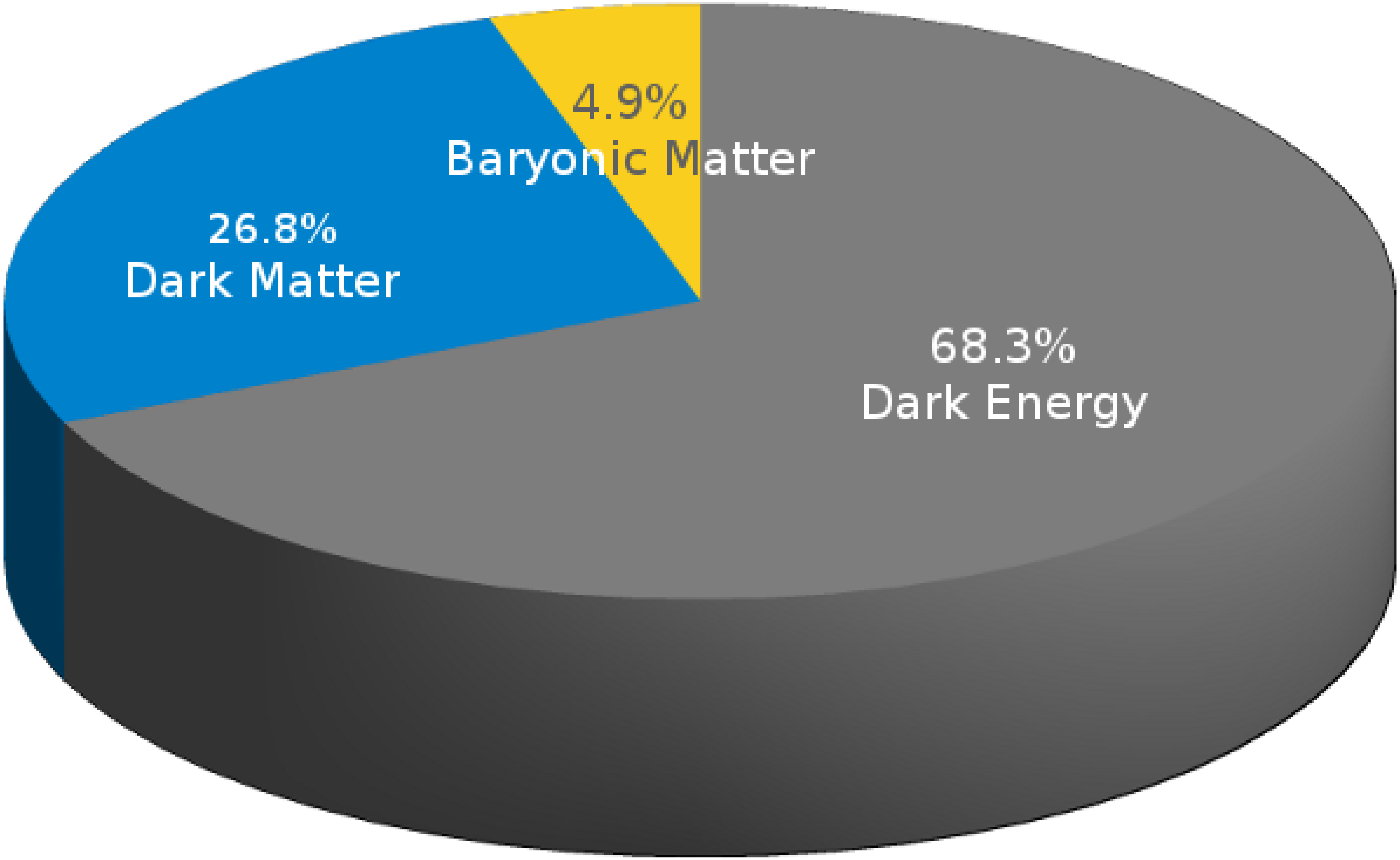
- Dark Matter Searches with rare event experiments ← impact of nuclear physics
- Atomic bombs and nuclear reactors

EFFECT PRESENT ON ALL SCALES



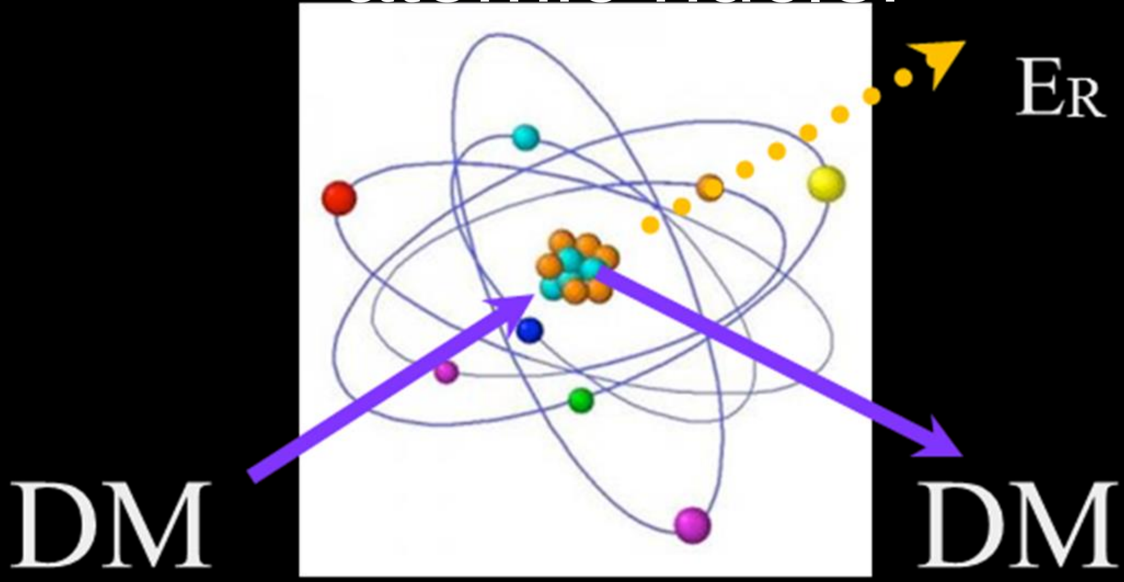
New Type(s) of Particle(s):
→ compelling, simple, (so far only) ***valid*** explanation.

The Universe as a pie chart

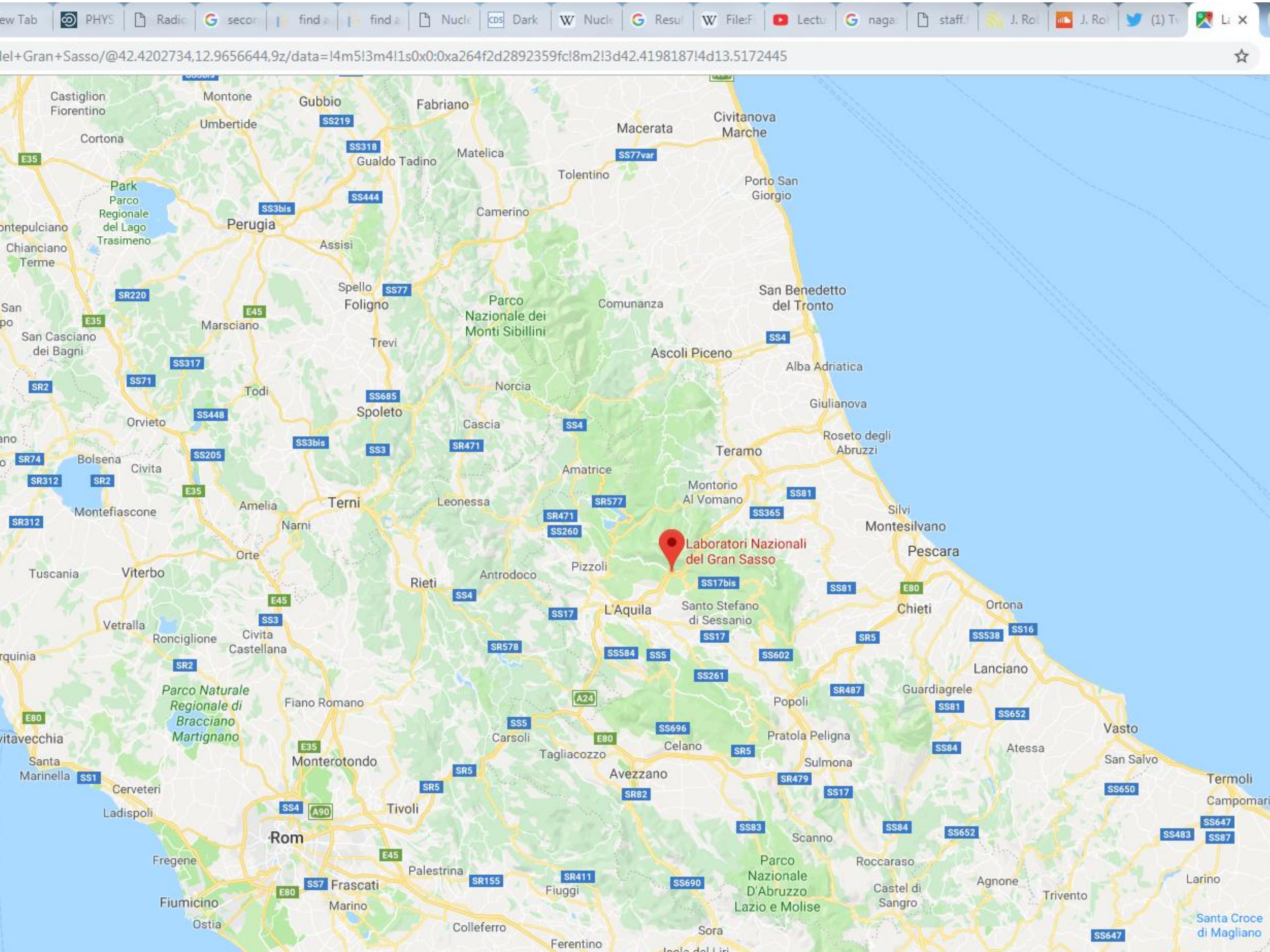


THE GENERAL IDEA

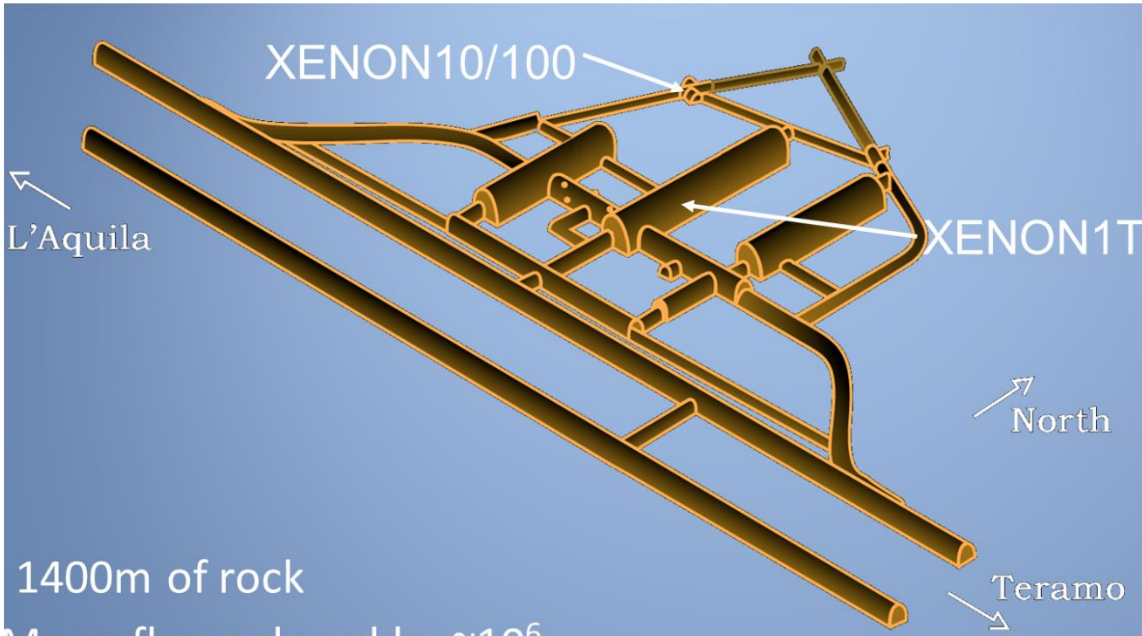
Elastic scattering of Dark matter on atomic nuclei

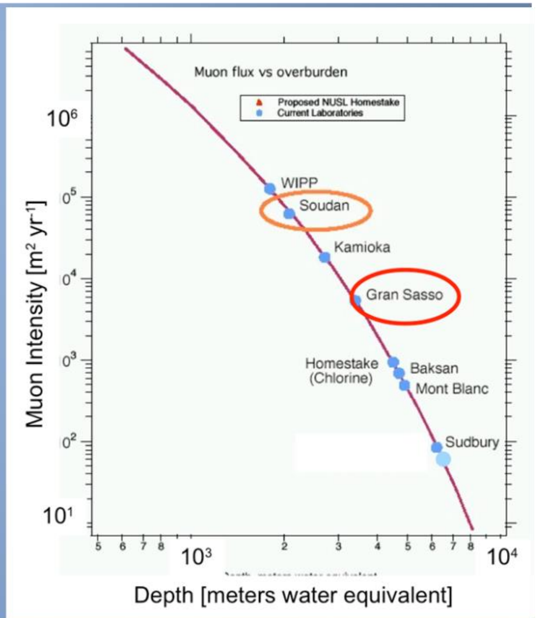


$$E_R = \frac{q^2}{m_n} < 100 \text{ keV}$$



lel+Gran+Sasso/@42.4202734,12.9656644,9z/data=!4m5!3m4!1s0x0:0xa264f2d2892359fc!8m2!3d42.4198187!4d13.5172445
Laboratori Nazionali del Gran Sasso
Castiglion Fiorentino
Montone
Gubbio
Fabriano
Macerata
Civitanova Marche
Umbertide
Cortona
Gualdo Tadino
Matelica
Tolentino
Porto San Giorgio
Park Parco Regionale del Lago Trasimeno
Perugia
Camerino
Chianciano Terme
Assisi
Spello
Foligno
Parco Nazionale dei Monti Sibillini
Comunanza
San Benedetto del Tronto
Marsciano
San Casciano dei Bagni
Trevi
Ascoli Piceno
Alba Adriatica
Todi
Norcia
Giulianova
Orvieto
Spoleto
Cascia
Roseto degli Abruzzi
Bolsena
Civita
Amatrice
Teramo
Montorio Al Vomano
Terni
Leonessa
Amelia
Montefiascone
Narni
Silvi
Montesilvano
Pescara
Orte
Tuscania
Viterbo
Rieti
Antrodoco
Pizzoli
L'Aquila
Santo Stefano di Sessanio
Chieti
Ortona
Vetralla
Ronciglione
Civita Castellana
Lanciano
Guardiagrele
Parco Naturale Regionale di Bracciano Martignano
Fiano Romano
Popoli
Vasto
Carsoli
Tagliacozzo
Celano
Pratola Peligna
Atessa
Santa Marinella
Monterotondo
Sulmona
San Salvo
Termoli
Cerveteri
Avezzano
Ladispoli
Tivoli
Rom
Scanno
Fregene
Palestrina
Parco Nazionale D'Abruzzo Lazio e Molise
Roccaraso
Frascati
Fiuggi
Castel di Sangro
Agnone
Trivento
Larino
Fiumicino
Marino
Ostia
Colleferro
Sora
Ferentino
Santa Croce di Magliano

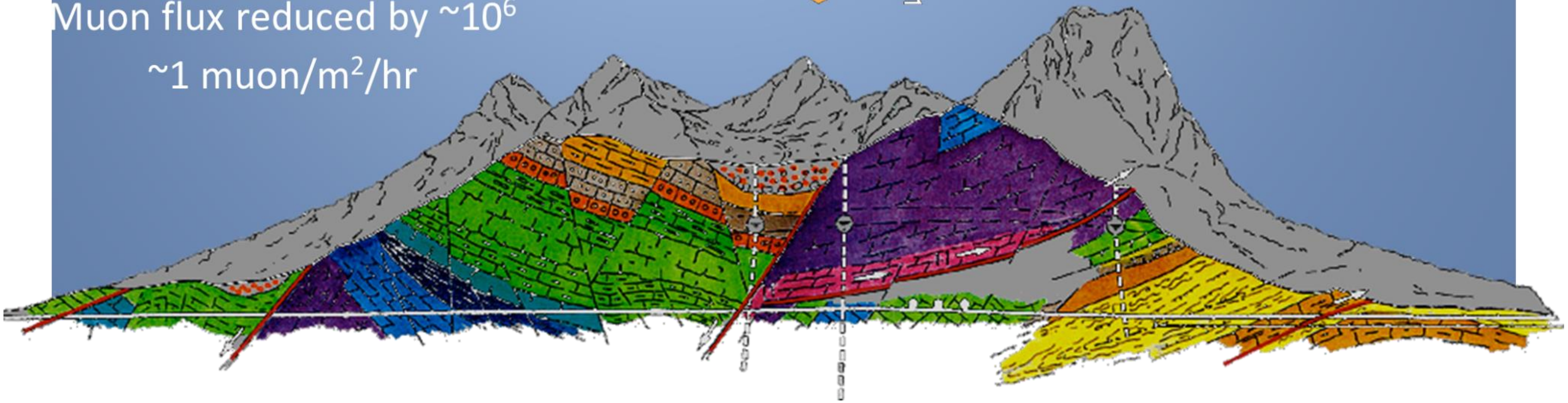




1400m of rock

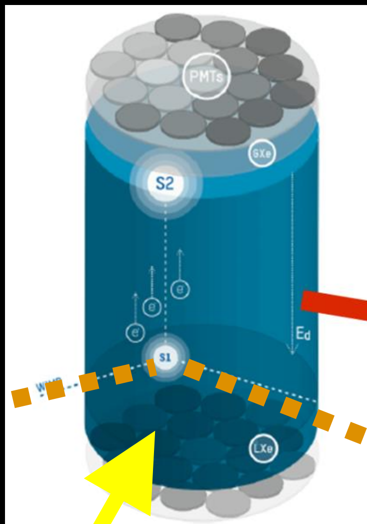
Muon flux reduced by ~10^6

~1 muon/m^2/hr

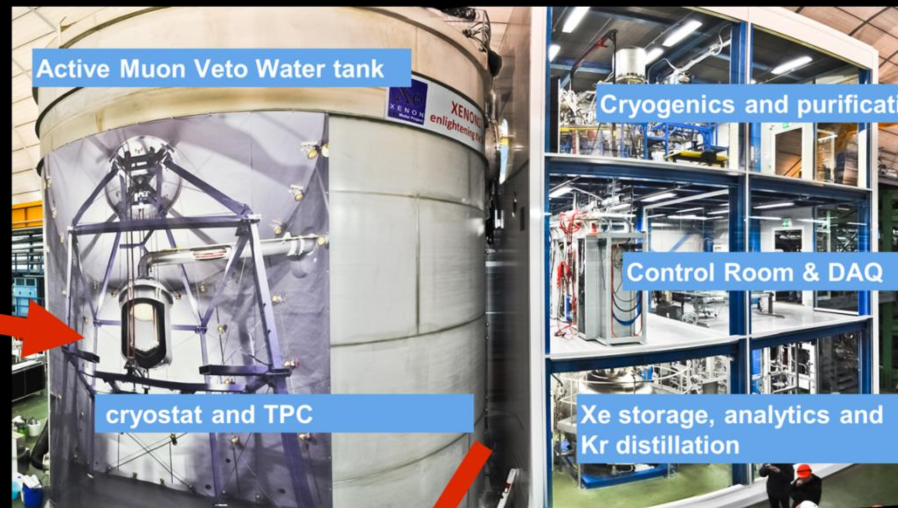


DIRECT DETECTION: XENON1T@LNGS

WIMP



liquid xenon
(~few tonnes)



Knut och Alice Wallenbergs Stiftelse

Need to identify one interaction in 10 trillion!

The world's most sensitive dark matter detector

Natural radioactivity

- Radioactive substances in all materials and in the environment

- Natural radioactivity is on the order of 10^{-3} Bq m^3 of air → 30000 decays/yr/m^3

- We expect about 1/yr/m^3 from dark matter detection.

What to do?

→we'll attempt to use only the cleanest materials (i.e. we'll have to measure the nuclear decays happening in the materials before we use them)

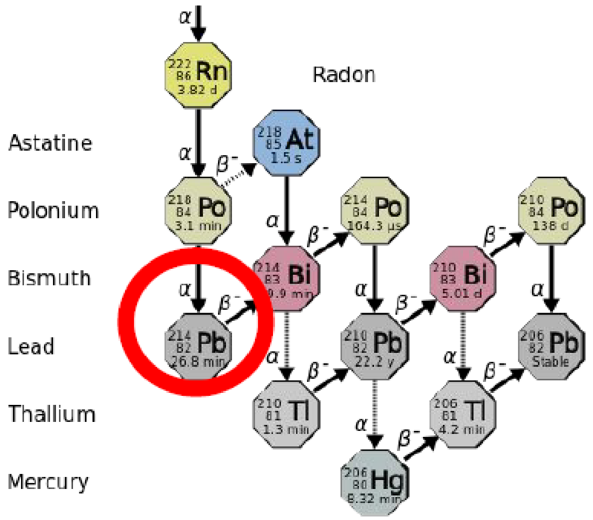
→we'll try to get rid of the remaining nuclear decays by understanding how they look in the detector.

Backgrounds: nuclear physics

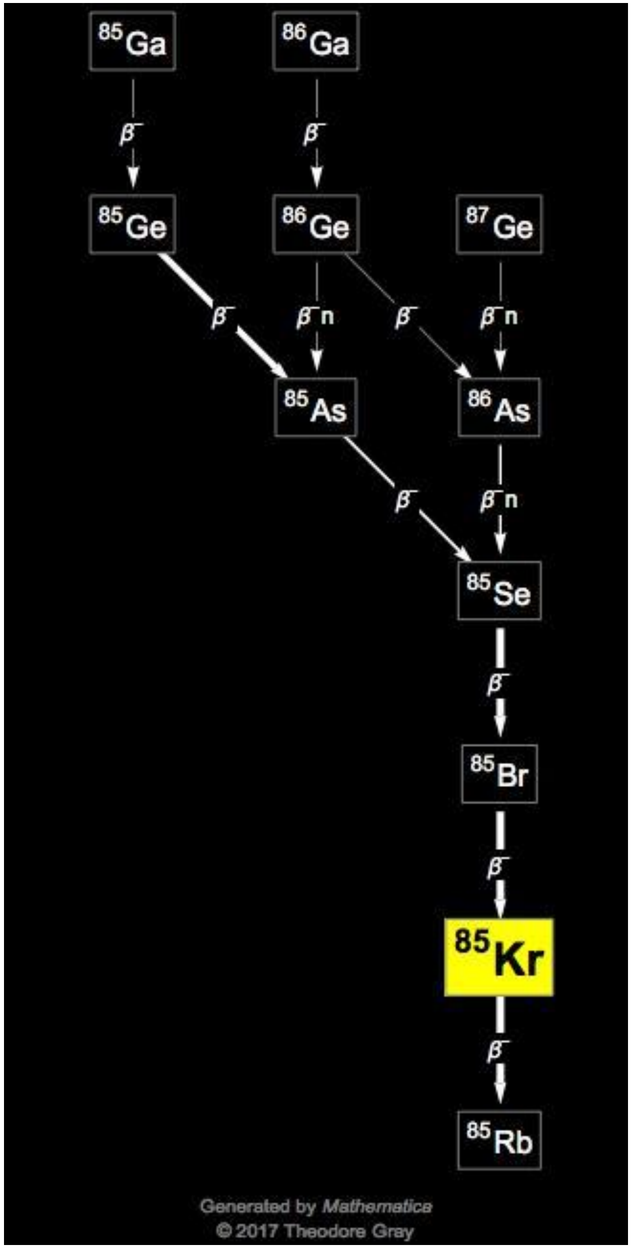
- Radon sticks on surfaces and emanates into the detector material.

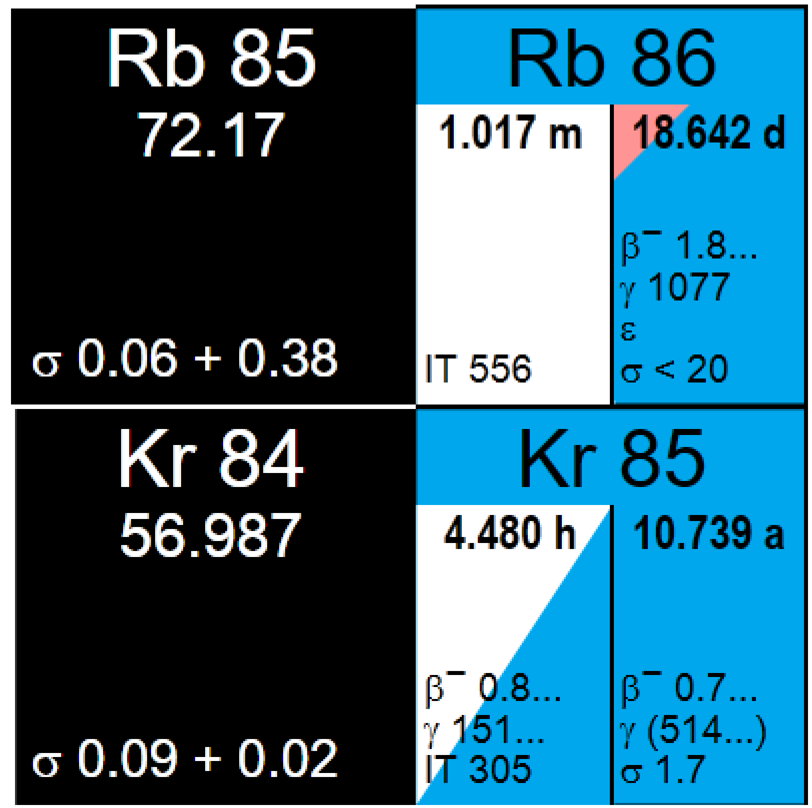
- Rn-222: 10 µBq/kg, → 1 decay /28 hours
- Kr-85: sub-ppt Kr/Xe,
- Materials background: selected using HPGe gamma screening

Radon and Krypton reduced using online cryogenic distillation.



Taken from a presentation of Bart Pelssers



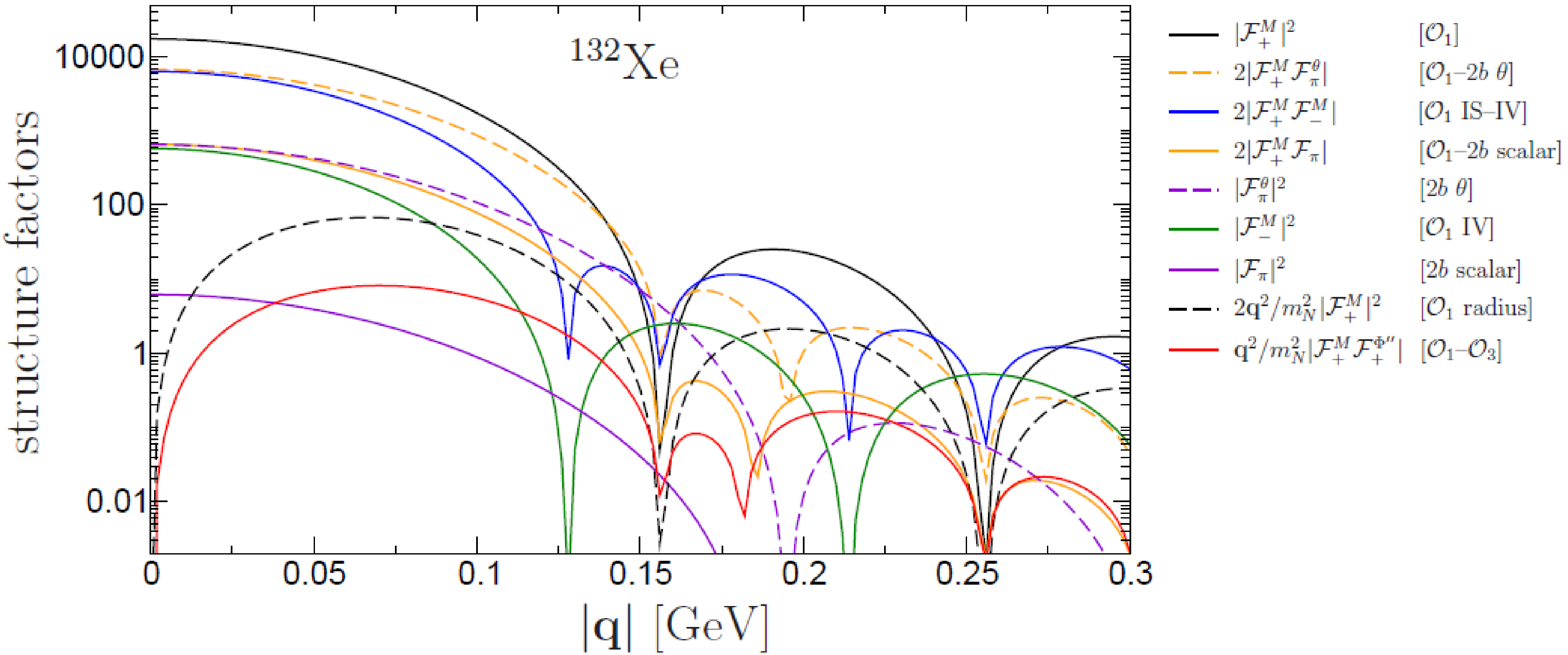


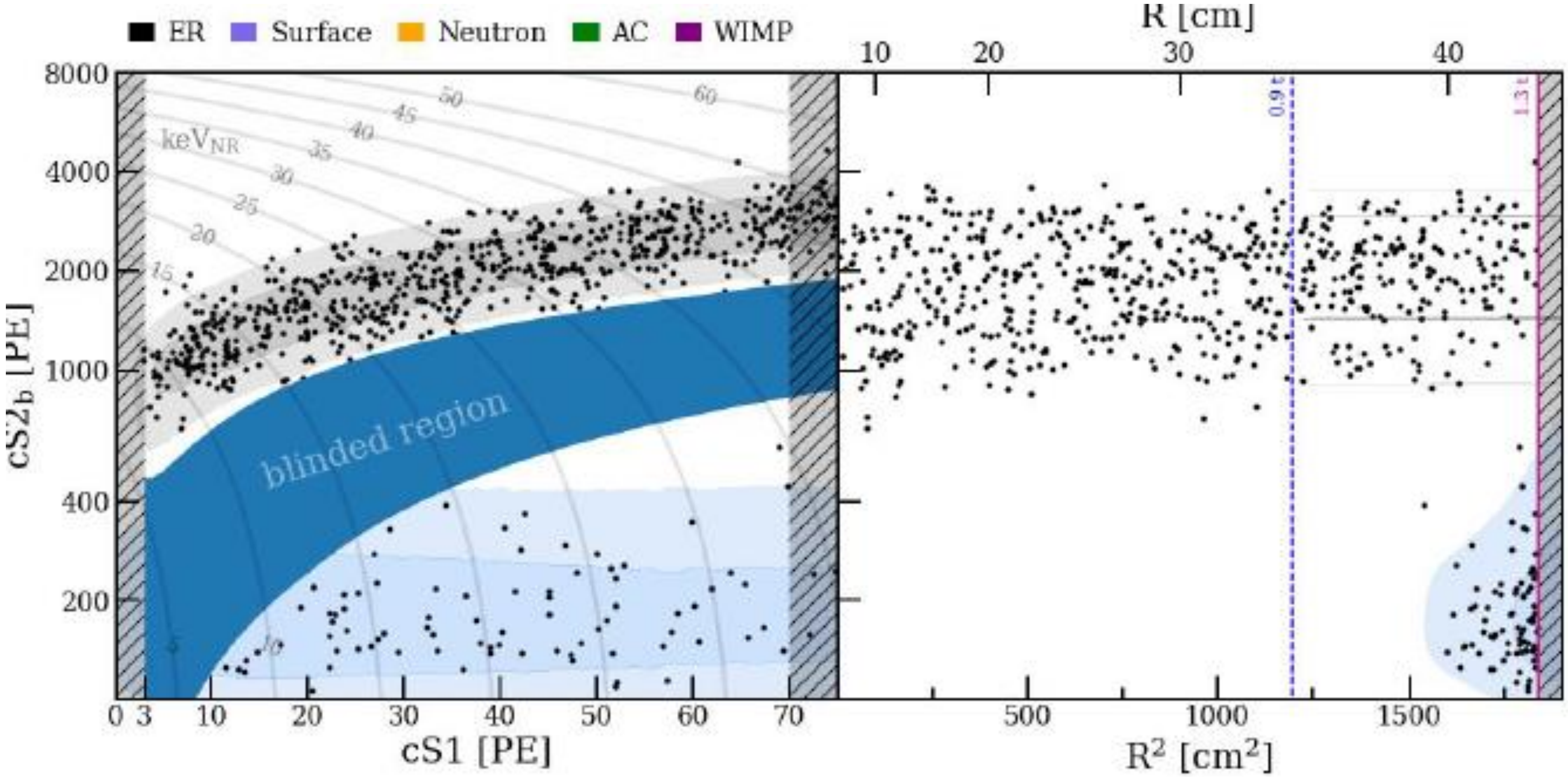
Nuclear isomer, IT Isomeric transition

More nuclear physics?

- To learn about their properties of the dark matter particles, we'll have to understand how they would interact with the nucleus.

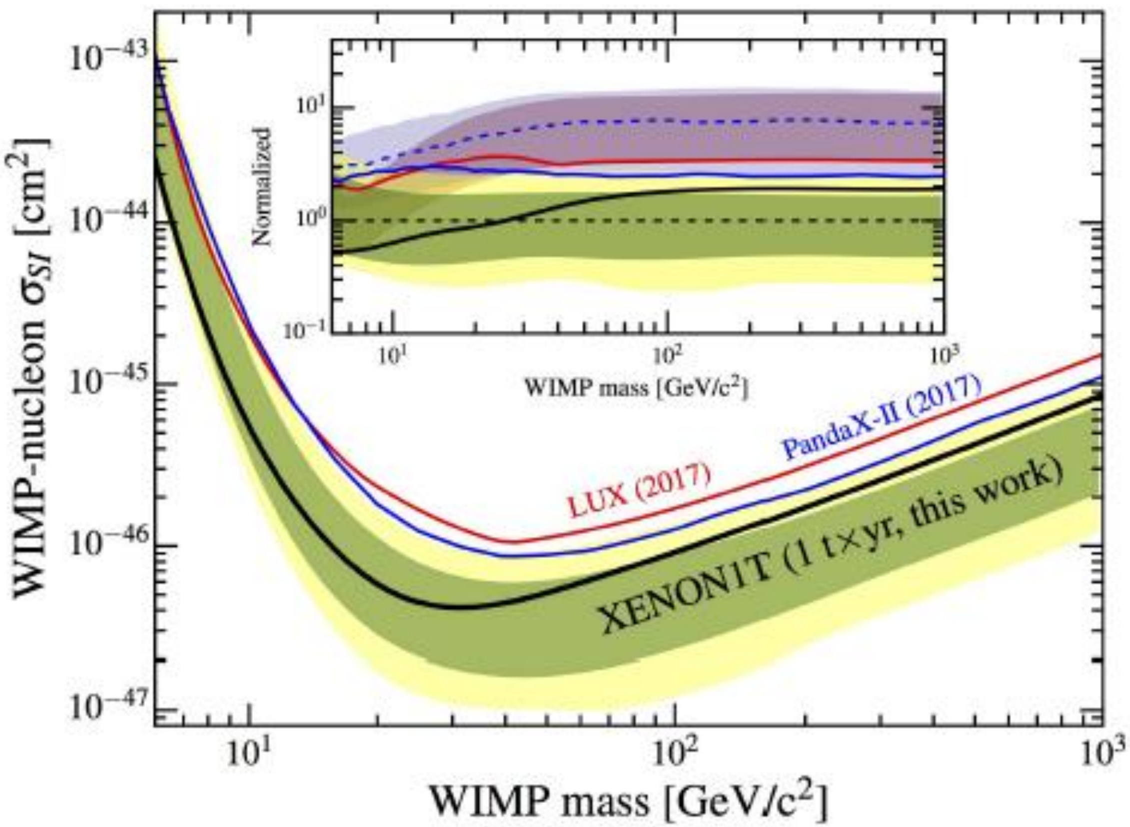
WIMP-nucleus interactions





ER
Surface
Neutron
AC
WIMP
R [cm]
cS2b [PE]
cS1 [PE]
R² [cm²]
blinded region
keV_NR
0.9t
1.3t

...



WIMP-nucleon σ_{SI} [cm^2]
WIMP mass [GeV/c^2]
Normalized
WIMP mass [GeV/c^2]
LUX (2017)
PandaX-II (2017)
XENON1T (1 t×yr, this work)

Neutron induced fission

- Spontanous fission is inhibited by Coulumb barrier and does become the dominant decay mode only for very heavy nuclei (A>250)

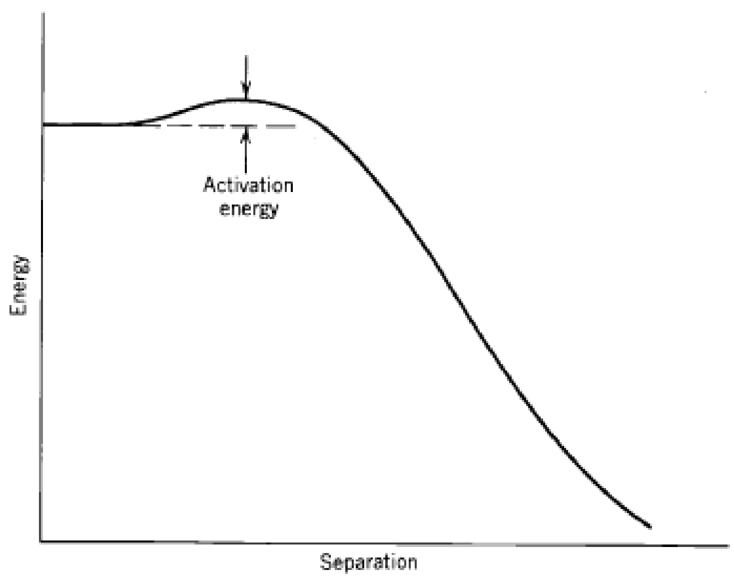


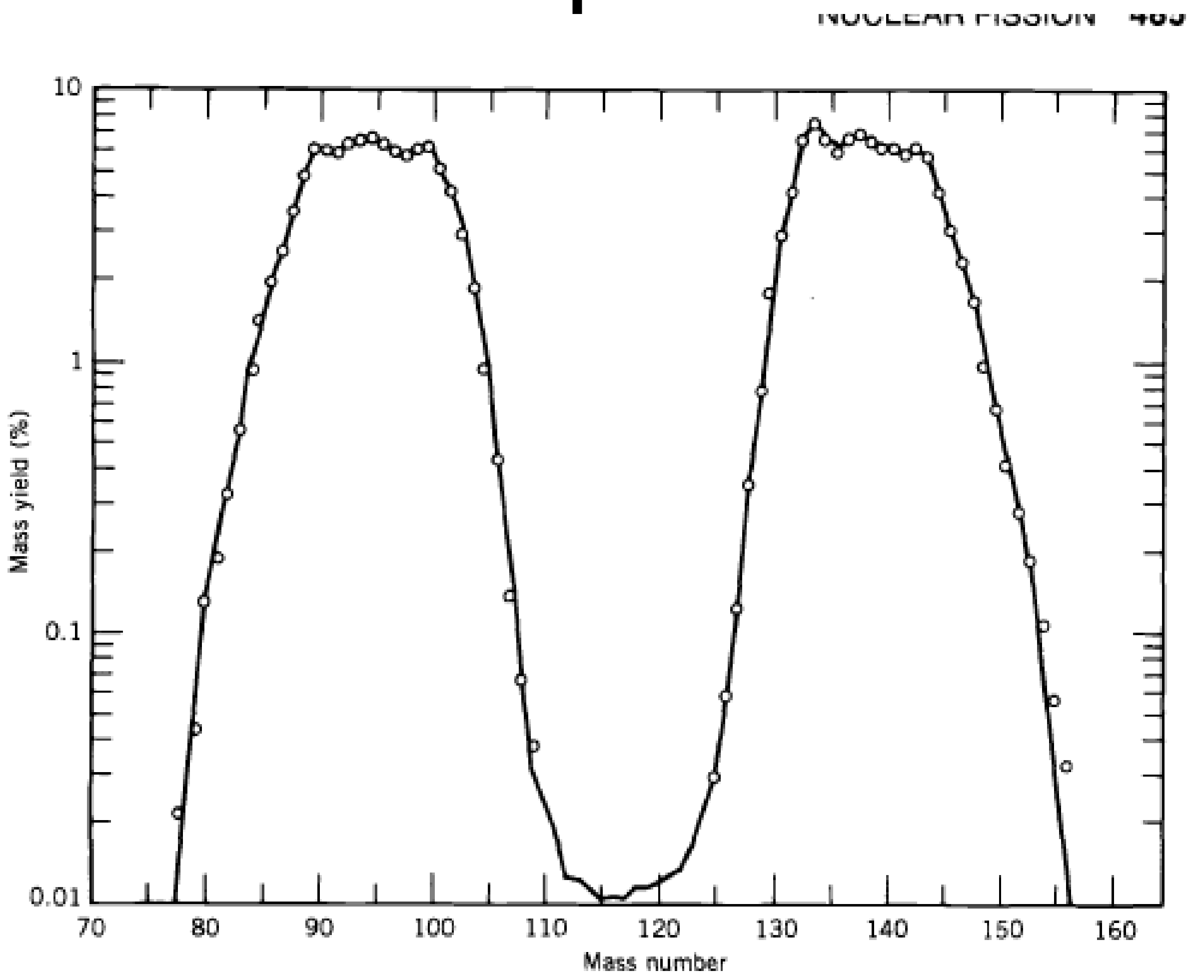
Figure 13.2 A smooth potential barrier opposing the spontaneous fission of ^{238}U. To surmount the fission barrier, we must supply an amount of energy equal to the activation energy.

Induced fission

- A zero-energy neutron can form a compound nucleus with excitation energy above the Coulumb barrier → fission possible

$$^{235}U+n \rightarrow {}^{236}U \rightarrow {}^{141}Ba+{}^{92}Kr+3n$$

Fission products



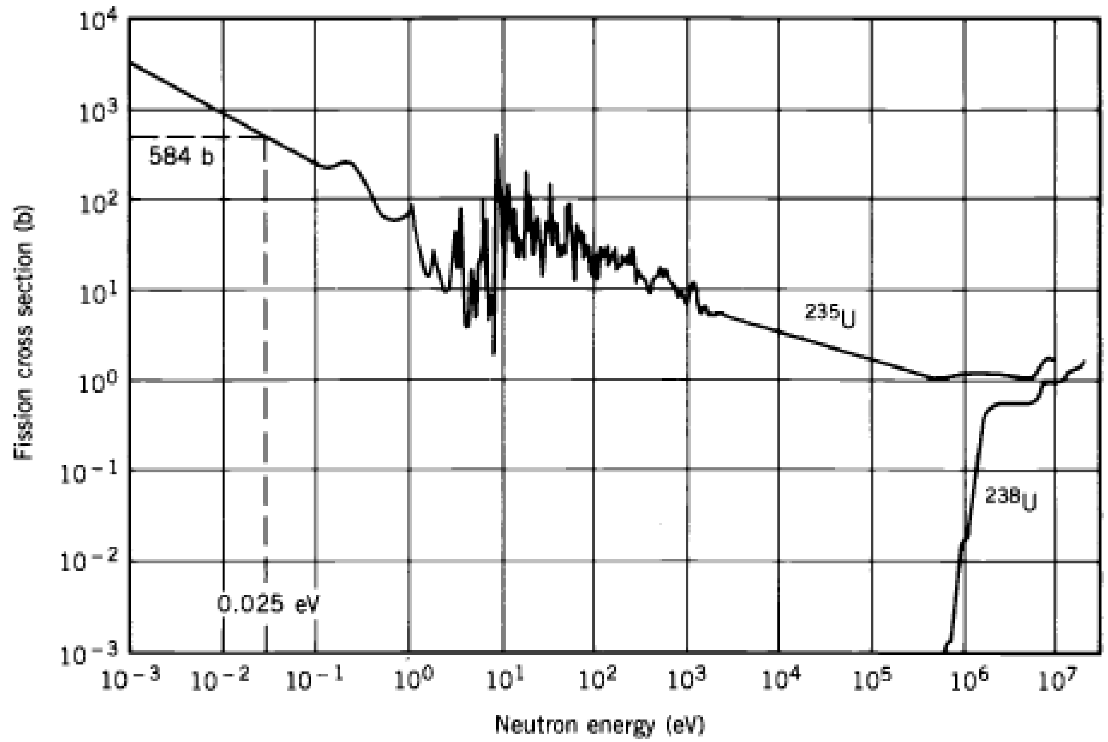
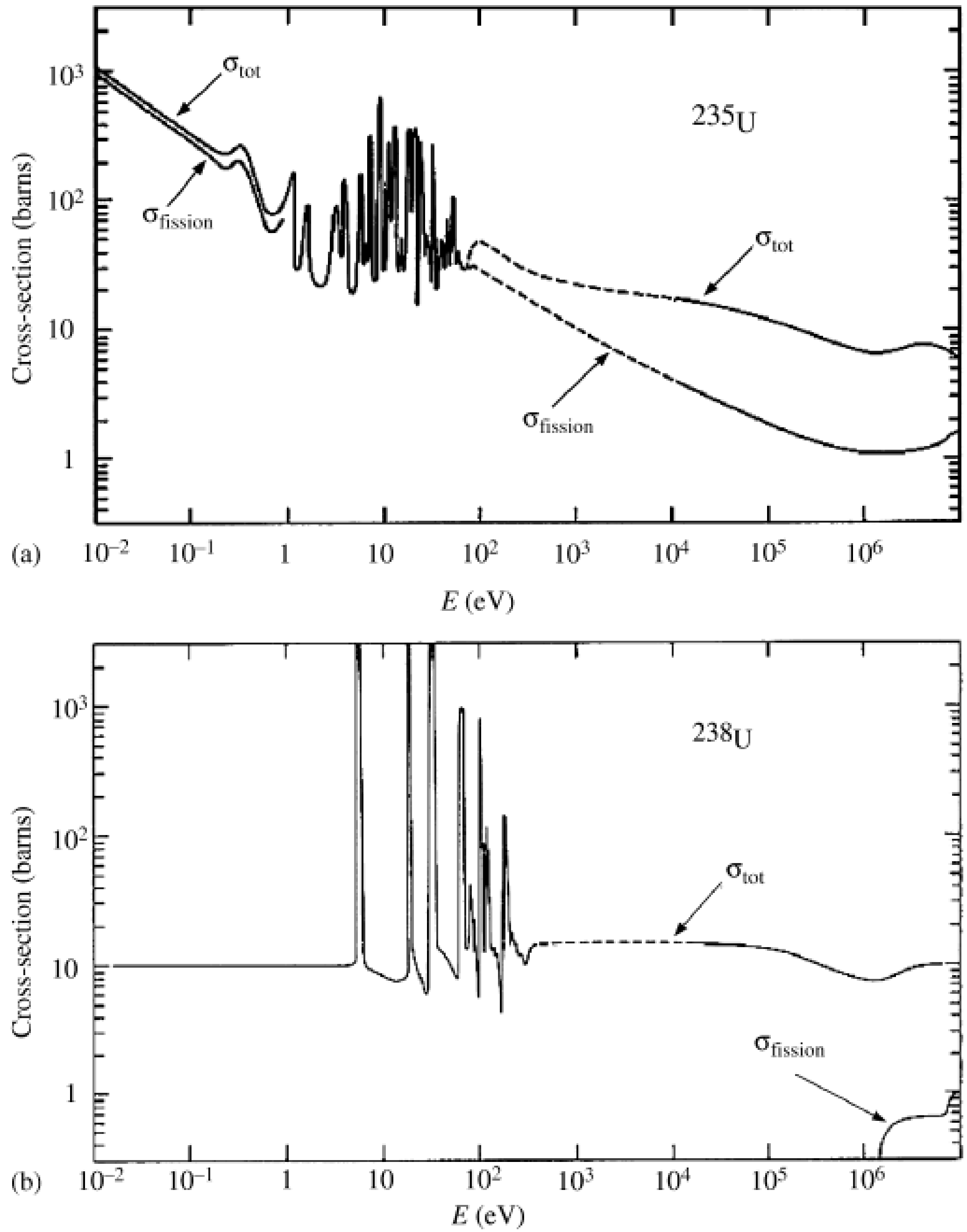
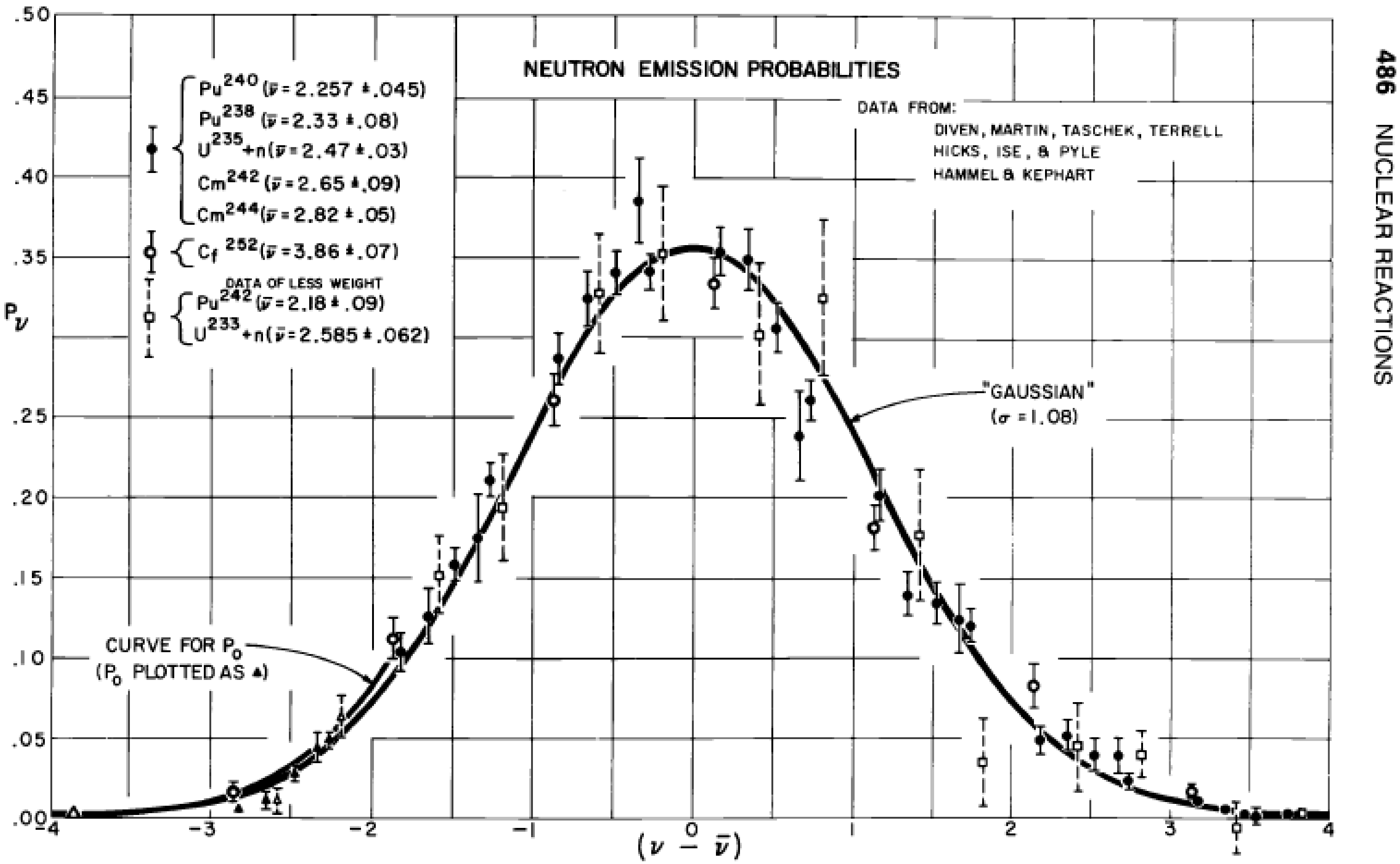


Figure 13.9 Cross sections for neutron-induced fission of ^{235}U and ^{238}U.


σtot
σfission
235U
Cross-section (barns)
E (eV)
(a)
238U
(b)

Neutron emission probabilities



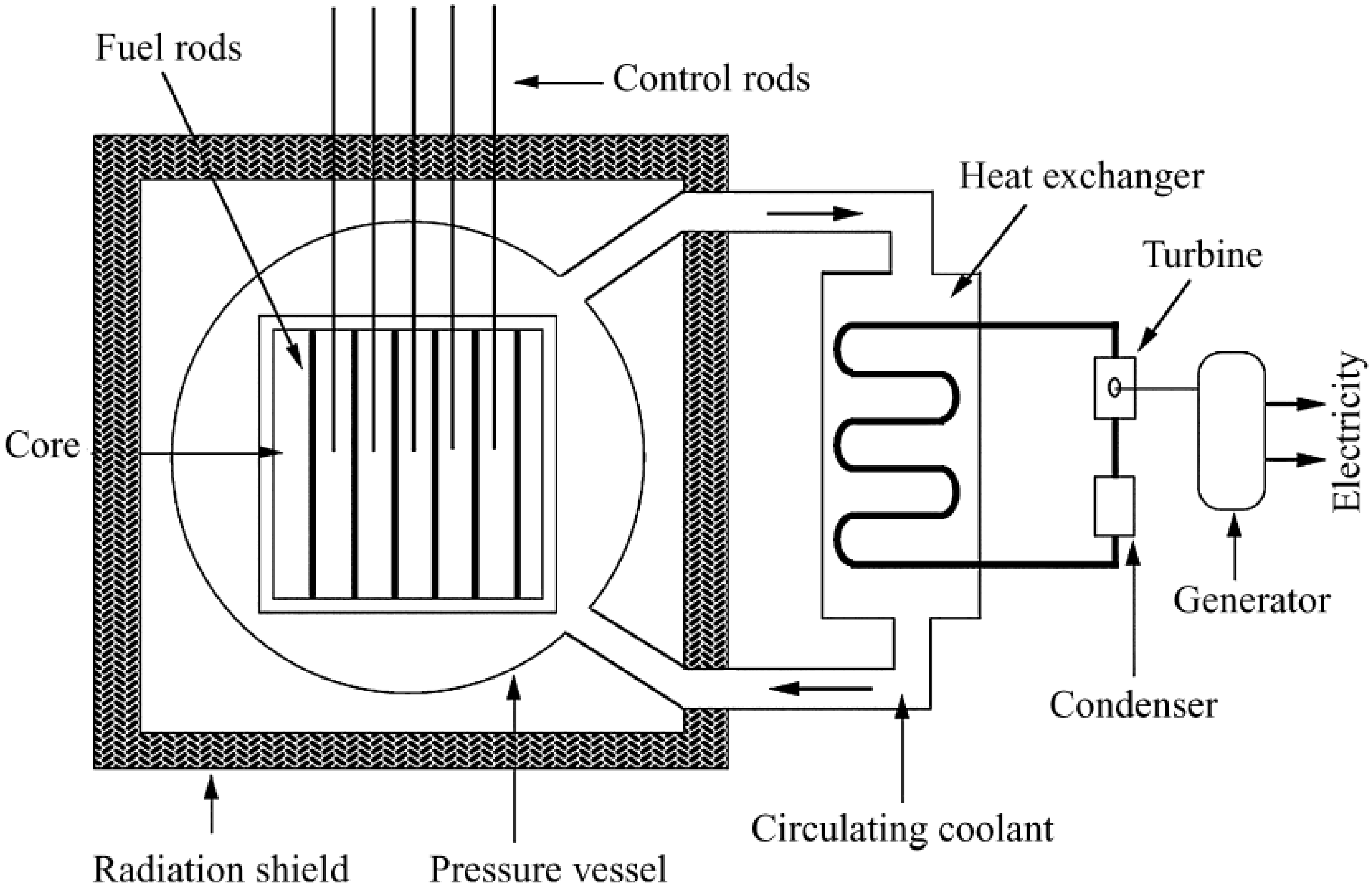
Fission chains

- We saw the distribution of produced neutrons. It makes sense to define the neutron reproduction factor:

$$k \equiv \frac{\text{number of neutrons produced in the } (n+1) \text{ th stage of fission}}{\text{number of neutrons produced in the } n\text{th stage of fission}},$$

- $k>1$: supercritical, $k=1$ critical, $k<1$ sub-critical
- In natural Uranium, on average 2.5 neutrons are produced in each fission but most of them are fast → moderation

Nuclear reactor



Atomic bombs

- Atomic bombs are supercritical assemblies of fissile material.

- Trigger: sponteanous fission: e.g. U-235 will have about 15 spontaneous fission decays/second in its critical mass (see below).

Rough estimate of critical mass
of pure ^{235}U

Neutron needs to induce fission.

b) What is the mean free path of ~ 2 MeV
neutron?

$\sigma_A \sim 2$ barns $(2 \cdot 10^{-24} cm^2)$

$$l = \frac{1}{n\sigma}$$

$$n = \frac{\rho_u}{A_u} \cdot N_A = \frac{16\,g/cm^3}{235\,g/mol} \cdot 6 \cdot 10^{23}$$

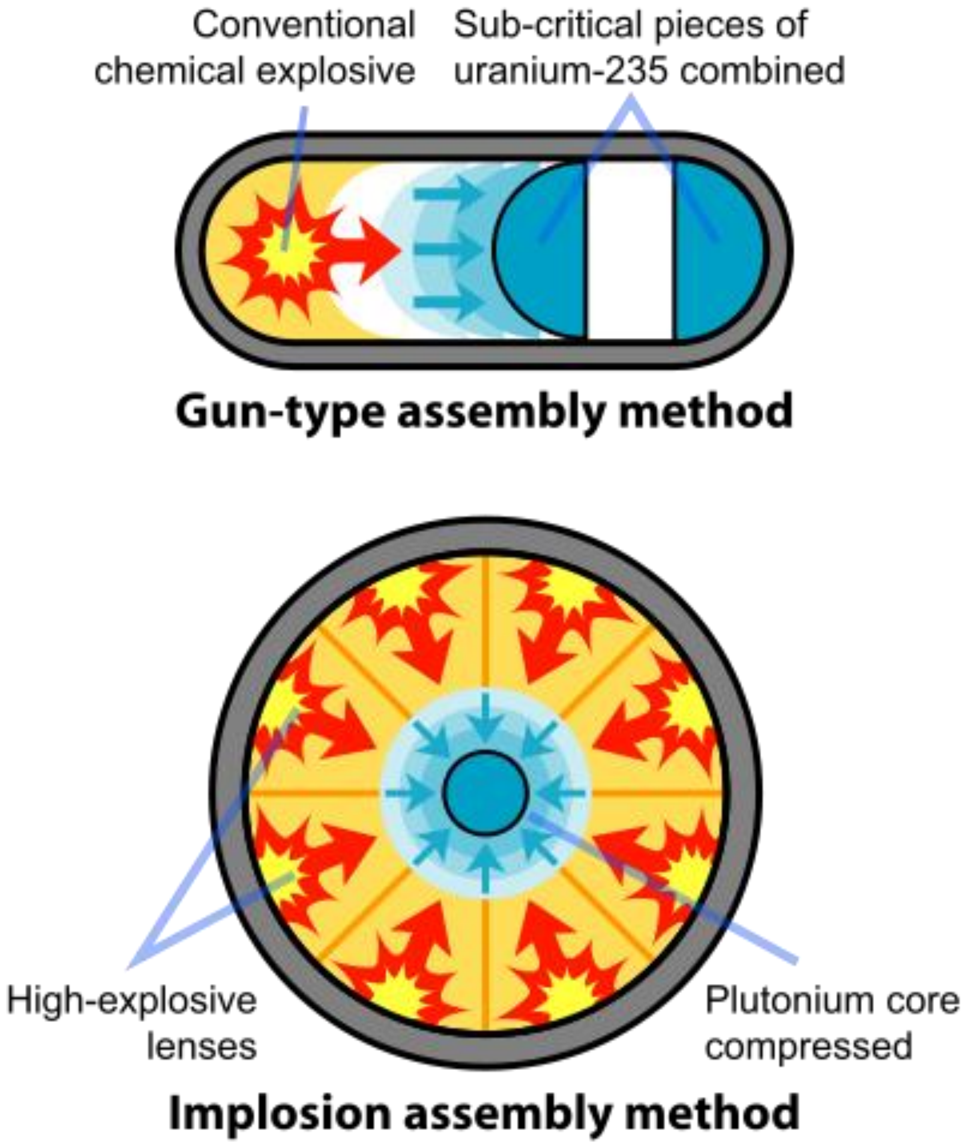
$$\approx 5 \cdot 10^{22} /cm^3$$

$$\Rightarrow \quad l = \frac{1}{(2 \cdot 10^{-24} cm^2)(5 \times 10^{22} cm^{-3})} \sim 10\ cm$$

Mass of ^{235}U sphere with $r = 10\ cm$:

$$\frac{4}{3}\pi (10\ cm)^3 \left(\frac{16 g}{cm^3}\right) \approx 60\ kg. \quad \square$$

Assembly

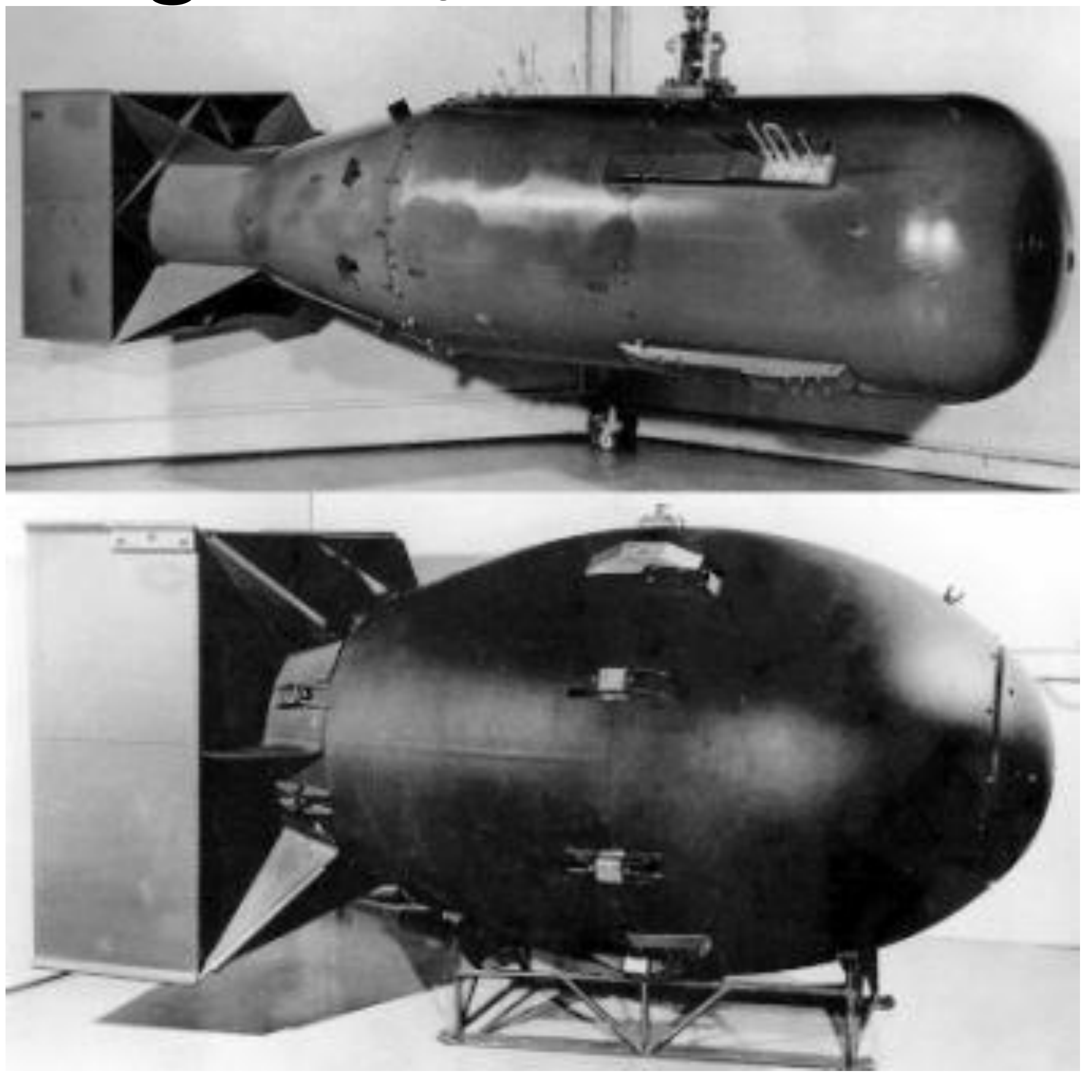


Conventional chemical explosive
Sub-critical pieces of uranium-235 combined
Gun-type assembly method
High-explosive lenses
Plutonium core compressed
Implosion assembly method

https://soundcloud.com/atomicheritage/j-robert-oppenheimer

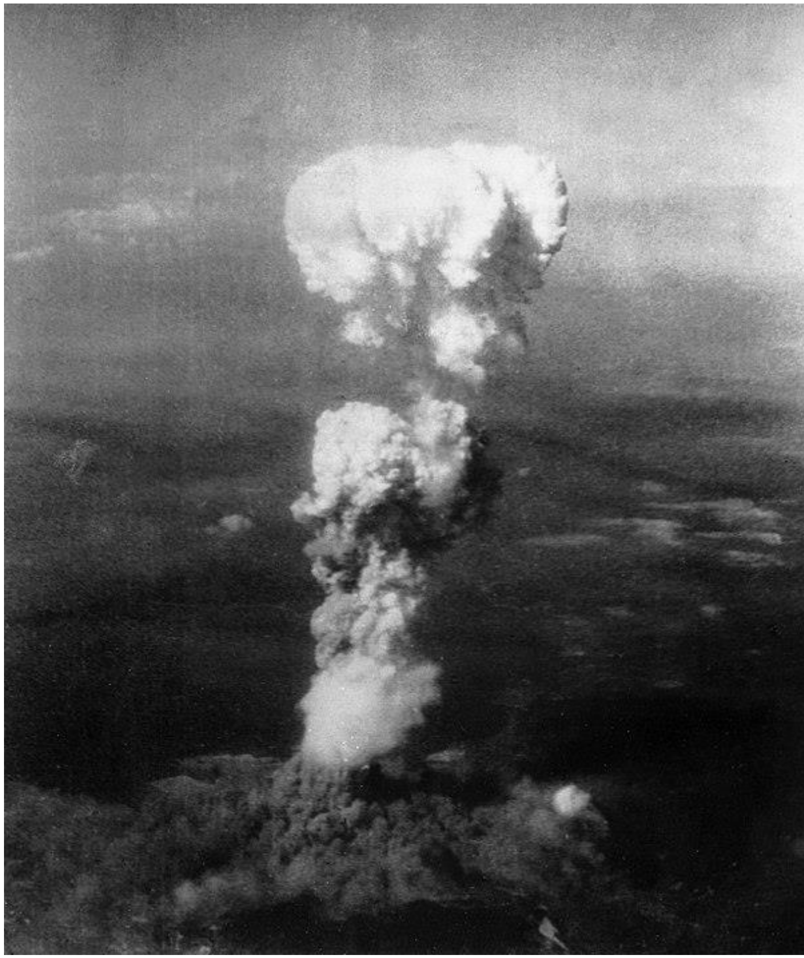
https://www.manhattanprojectvoices.org/

Nagasaki/Hiroshima

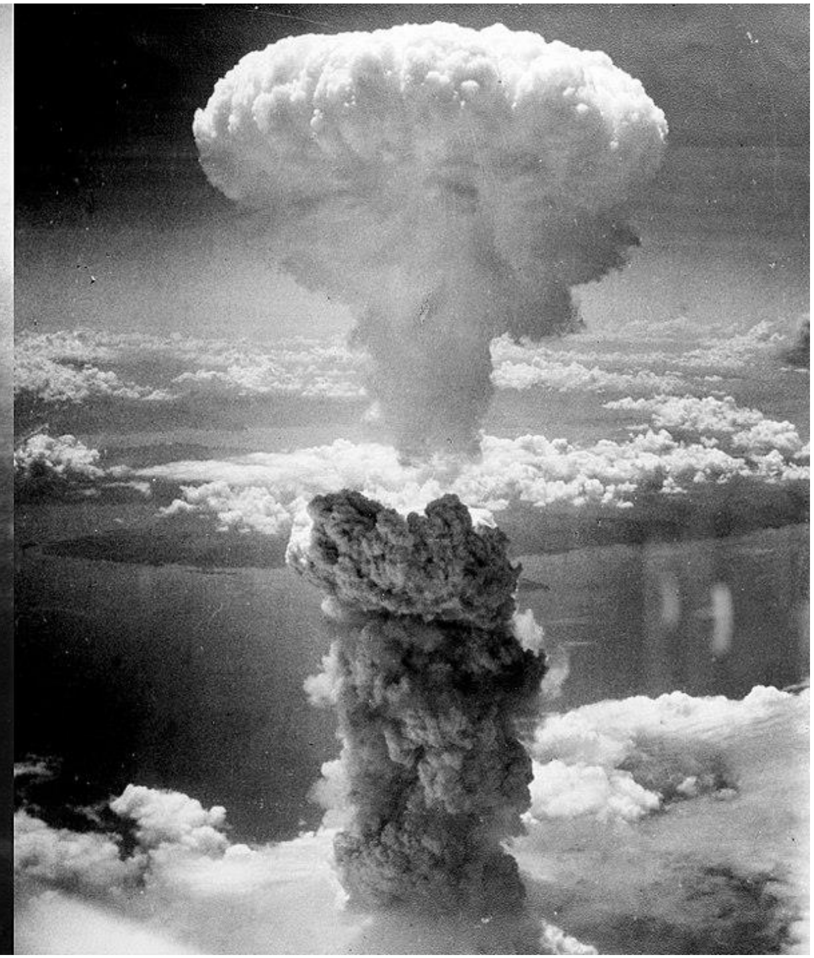


Little Boy and Fat Man

Nagasaki/Hiroshima



Hiroshima: gun-type, U235 bomb (16 kt TNT)



Nagasaki: implosion type, plutonium bomb (21-25 kt TNT)

Summary of today's lecture

- We discussed two applications of nuclear physics.