Our Field of Research: Atomic Physics

Atomic Physics with Heavy Ions

SPECTROSCOPY
QED, many body effects

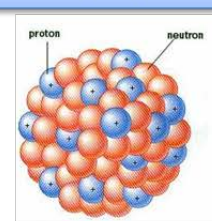
Collisions
strong perturbations,
photon matter interaction

Borderline to Nuclear Physics
two body decay etc.

Hot plasma physics

Astrophysics

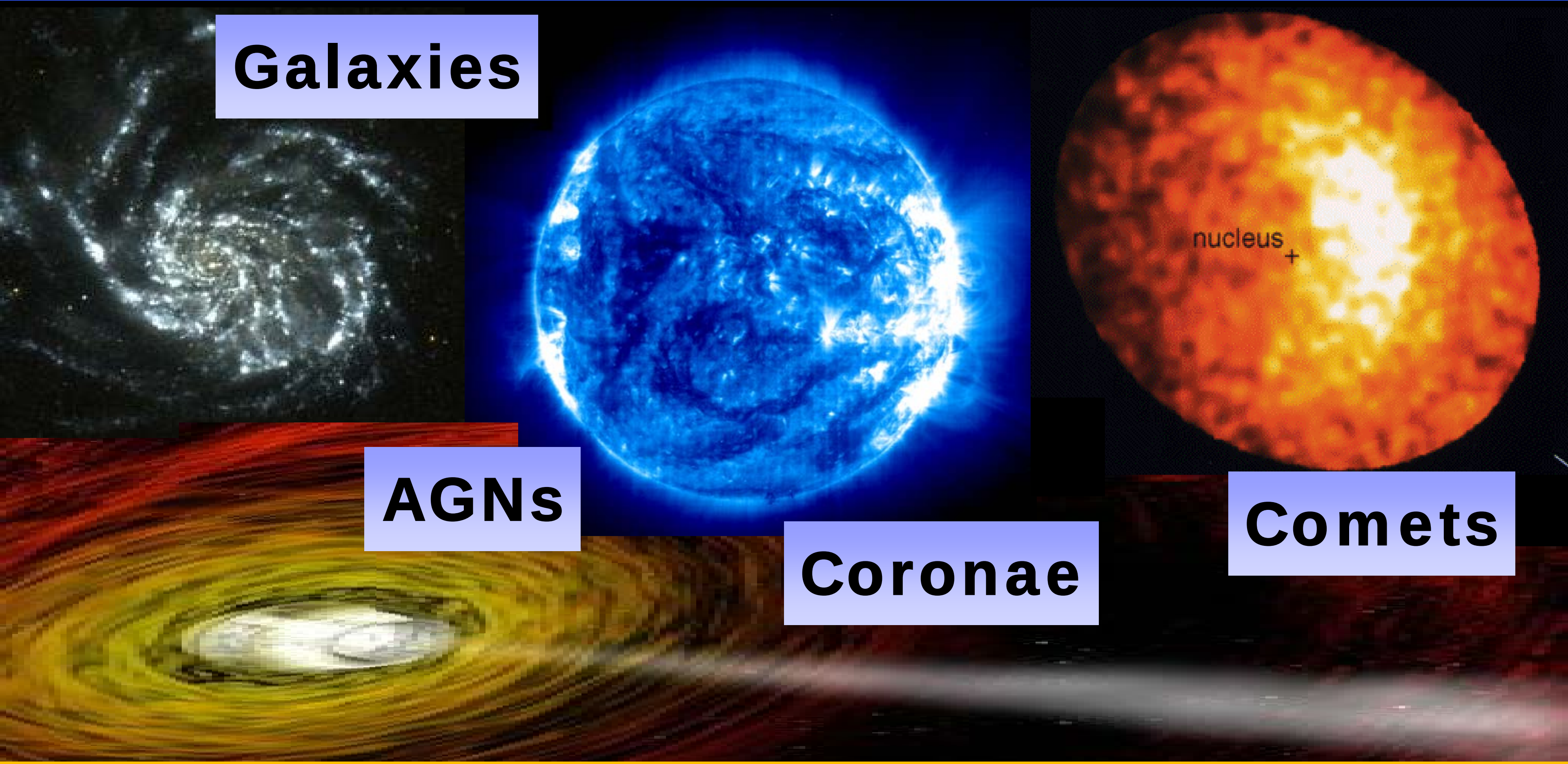
Nuclear physics



Accelerator physics

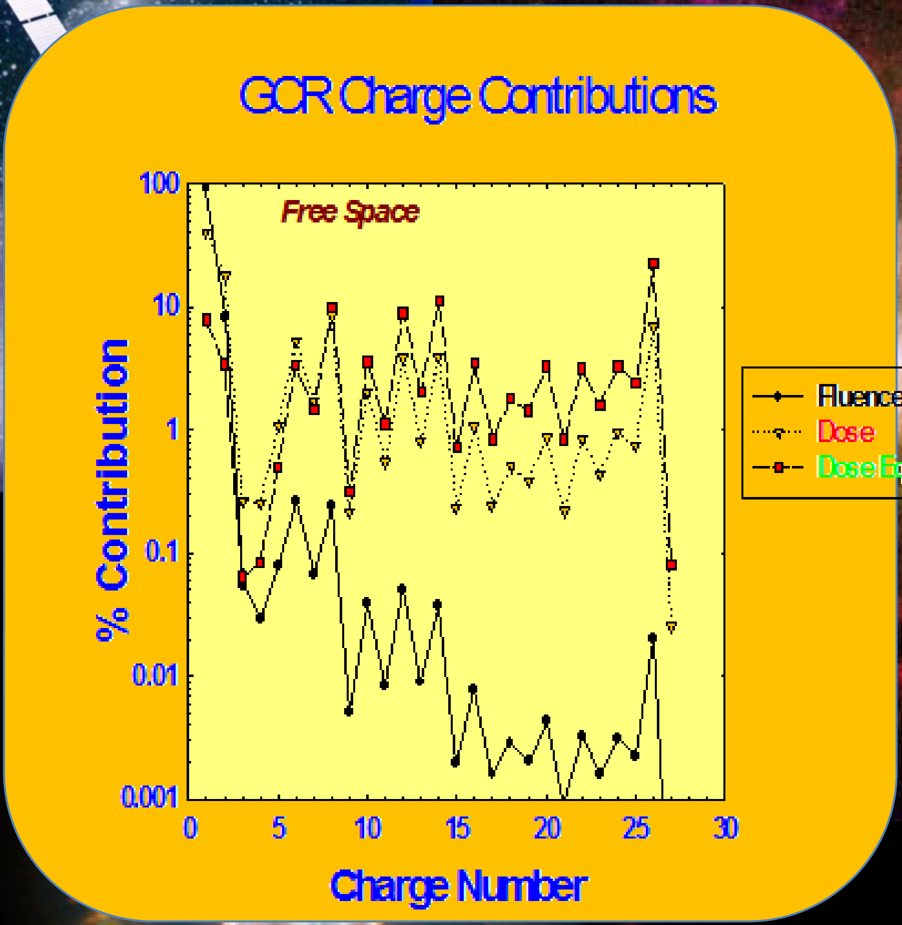
Physics beyond the standard model

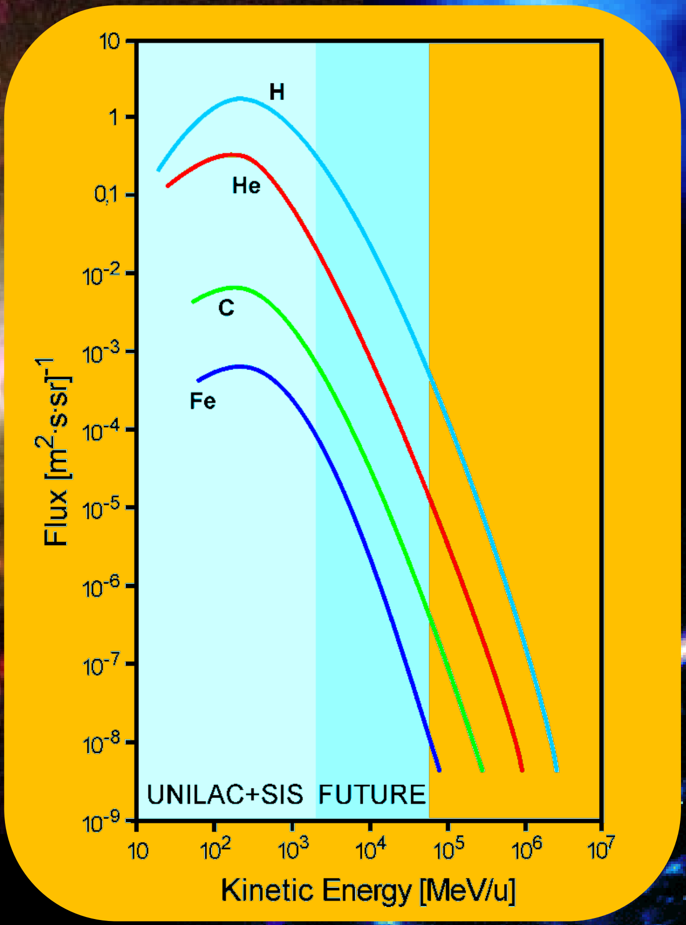
Highly Charged Ions / Strong EM Fields



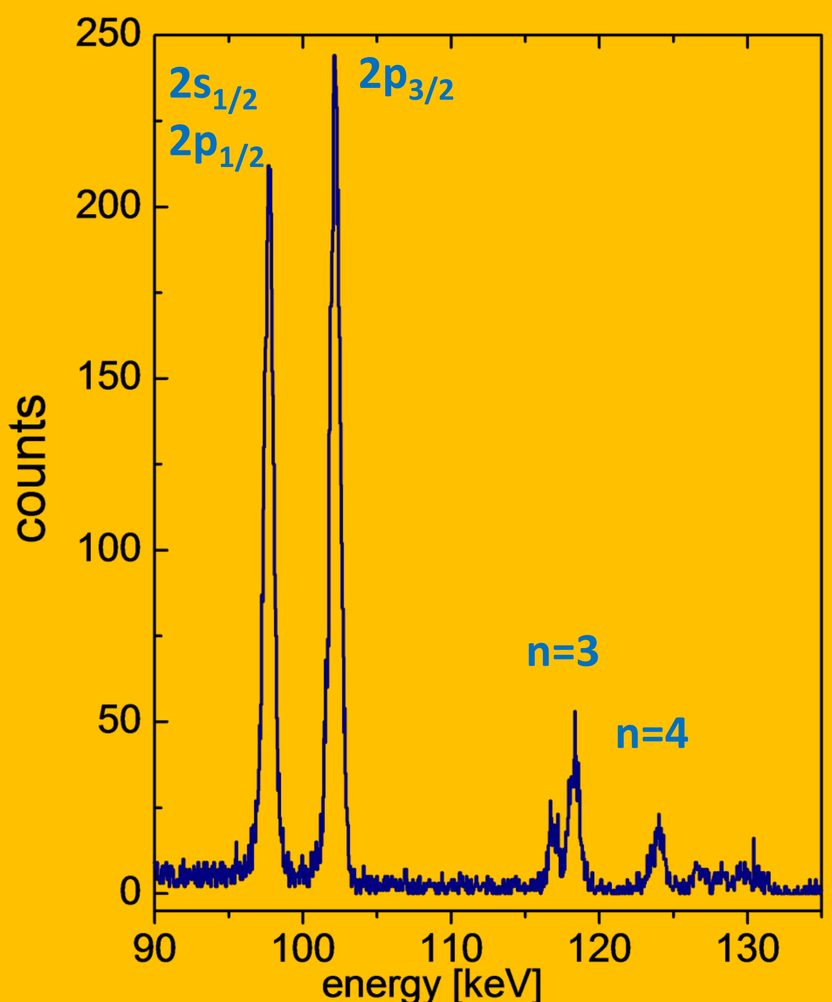
- Ionization and Particle Production Phenomena
- Radiative Processes

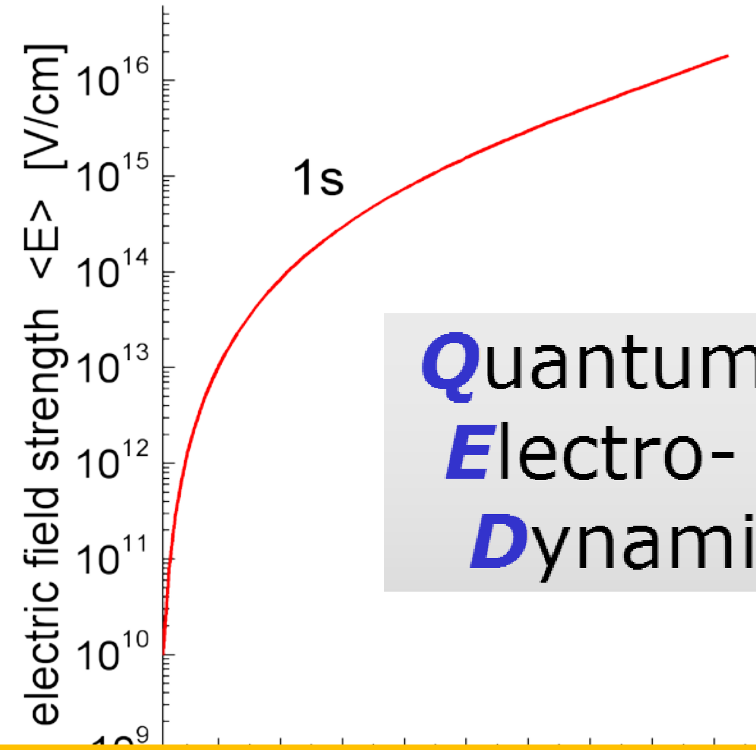
Relativistic Energies: Galactic Cosmic Radiation (GCR)





Structural properties of heavy ions





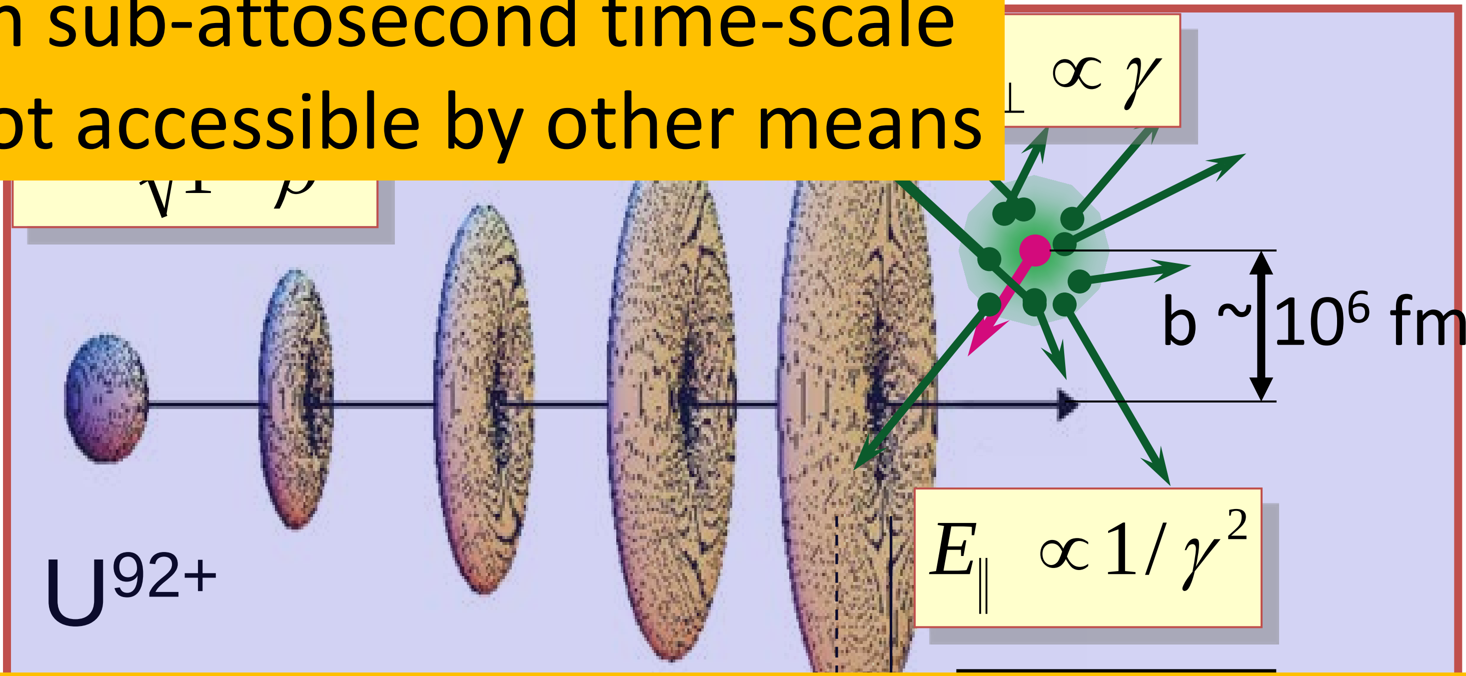
QED, the most precise theory

the non-perturbative regime

- not well-known up to now!

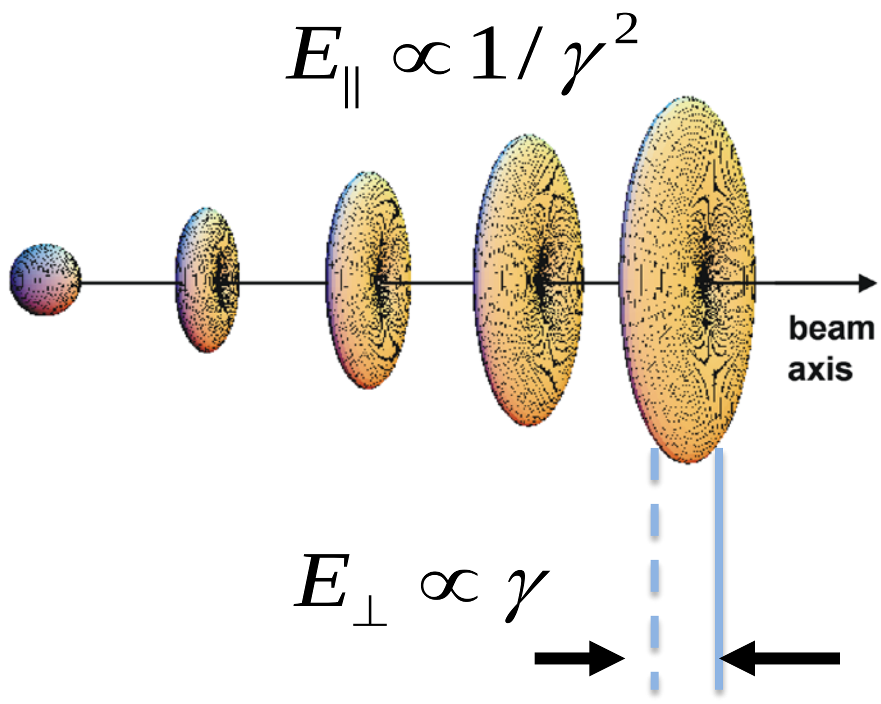
Extreme Dynamic Fields

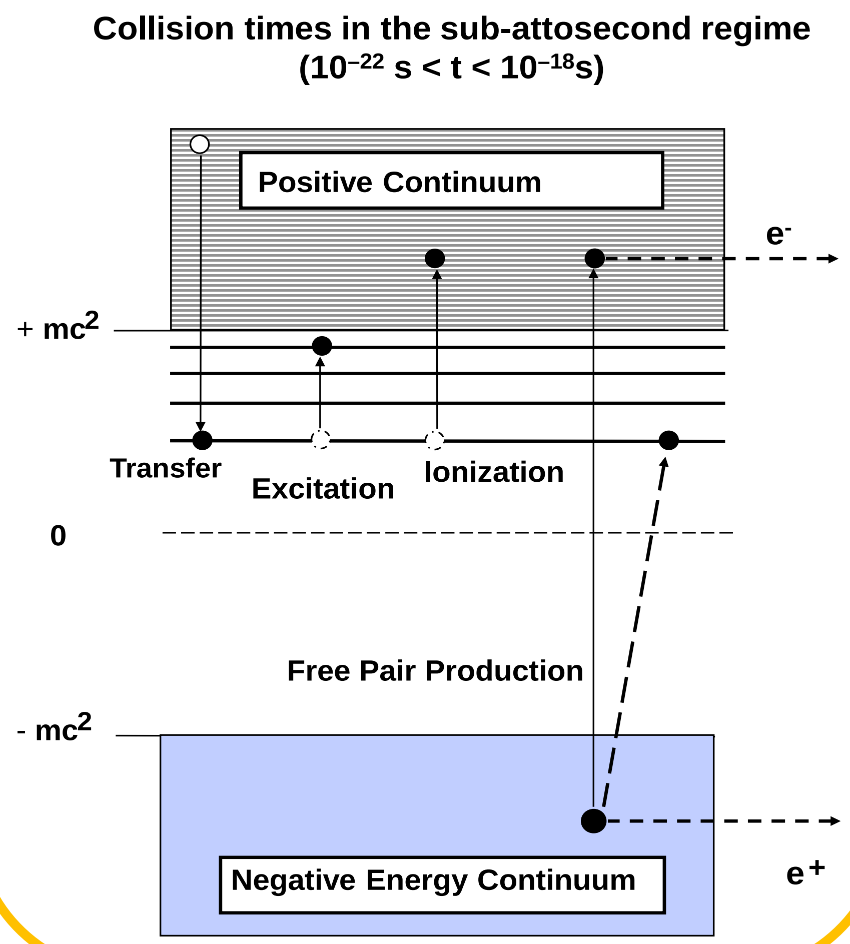
Explore correlated electron dynamics
- on sub-attosecond time-scale
- not accessible by other means



Explore relativistic quantum dynamics
- particle production
- non-perturbative regime
- coupling to the radiation field

Electromagnetic Phenomena under Extreme & Unusual Conditions

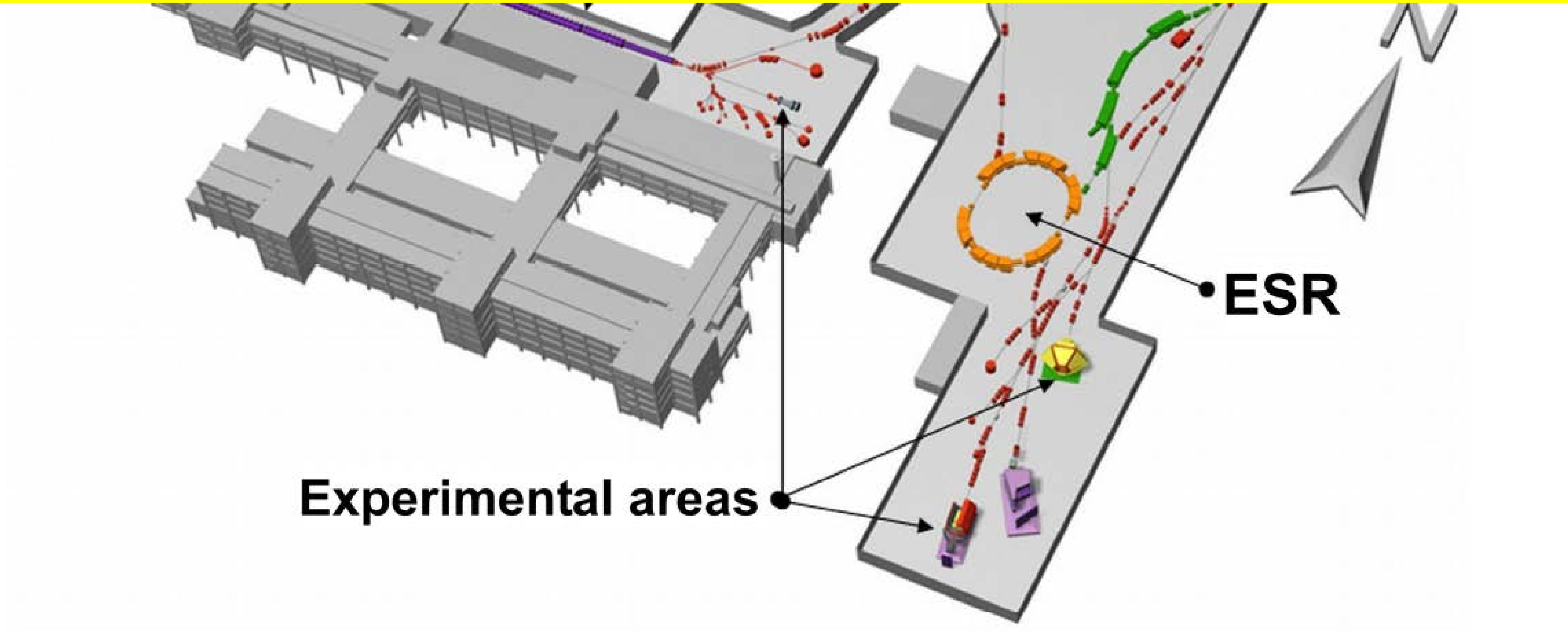




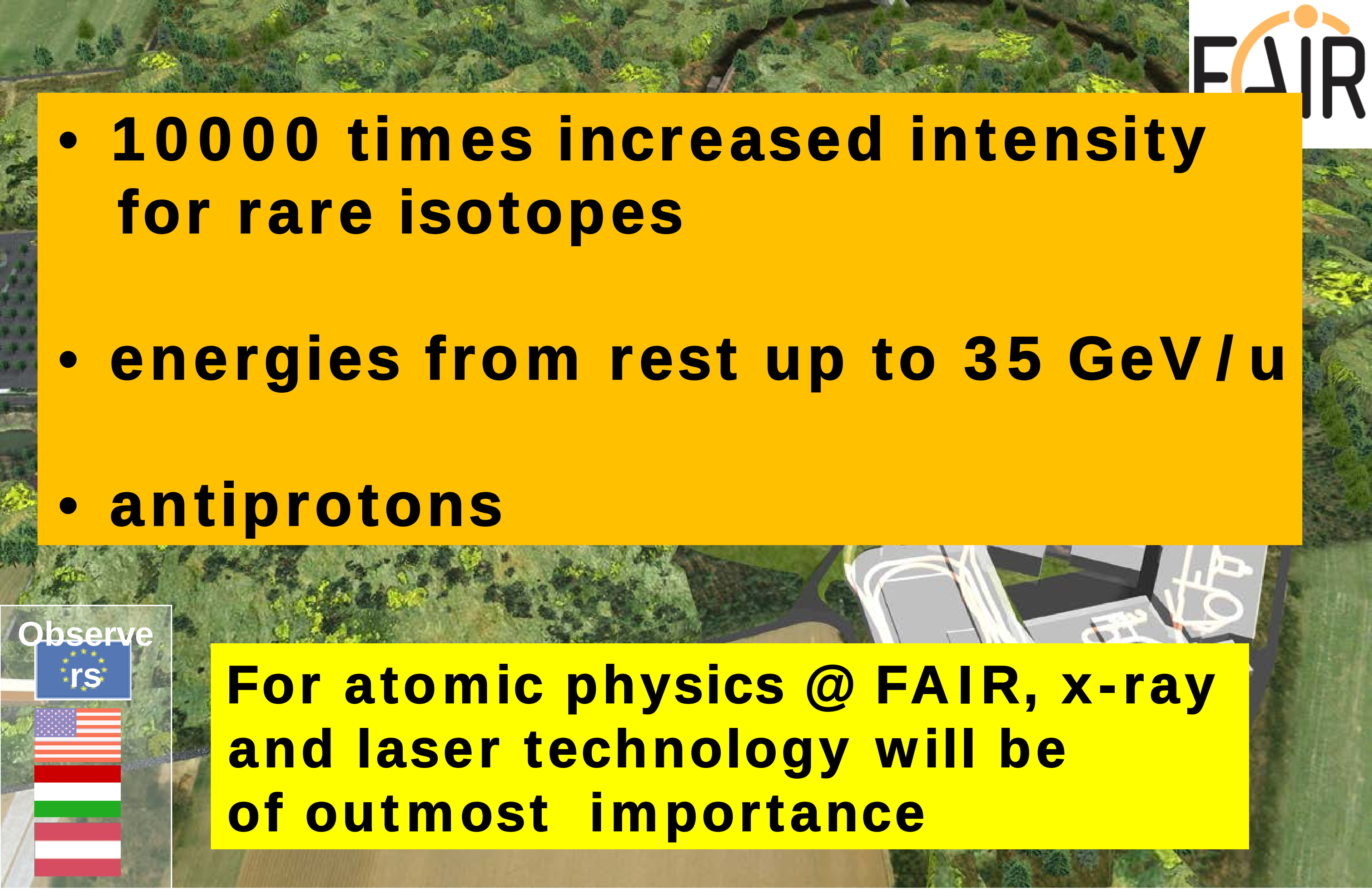
Heavy Ion Accelerator System

- **Every element in arbitrary charge state up to bare uranium are available for experiments**

- **Energies: from rest up to 1 GeV/u**



- **10000 times increased intensity for rare isotopes**
- **energies from rest up to 35 GeV/u**
- **antiprotons**



For atomic physics @ FAIR, x-ray and laser technology will be of outmost importance

September 2013

I. Extreme Dynamic Fields

II. Extreme Static Fields

III. Fundamental Physics

Our Tools

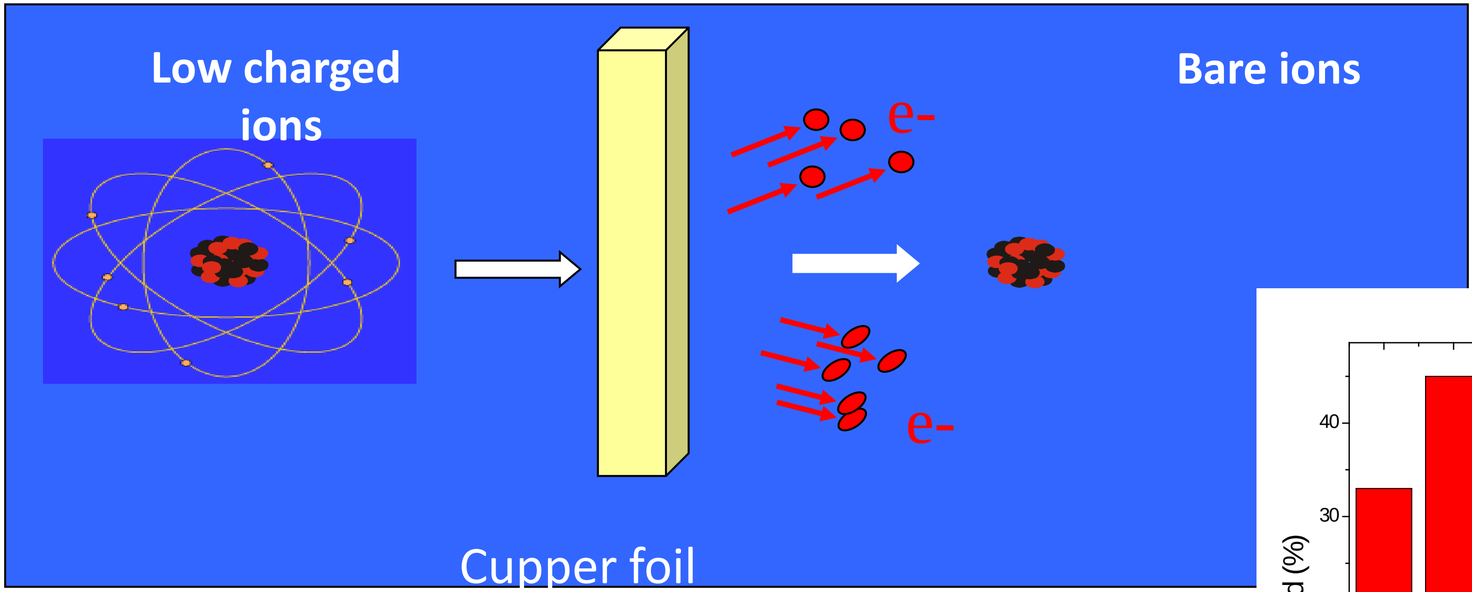
Why relativistic velocities?

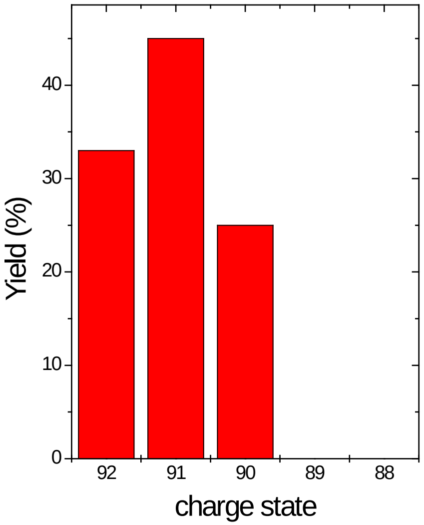
Bohr criteria: *Largest ionization cross section at* $v \approx v_K$

Uranium

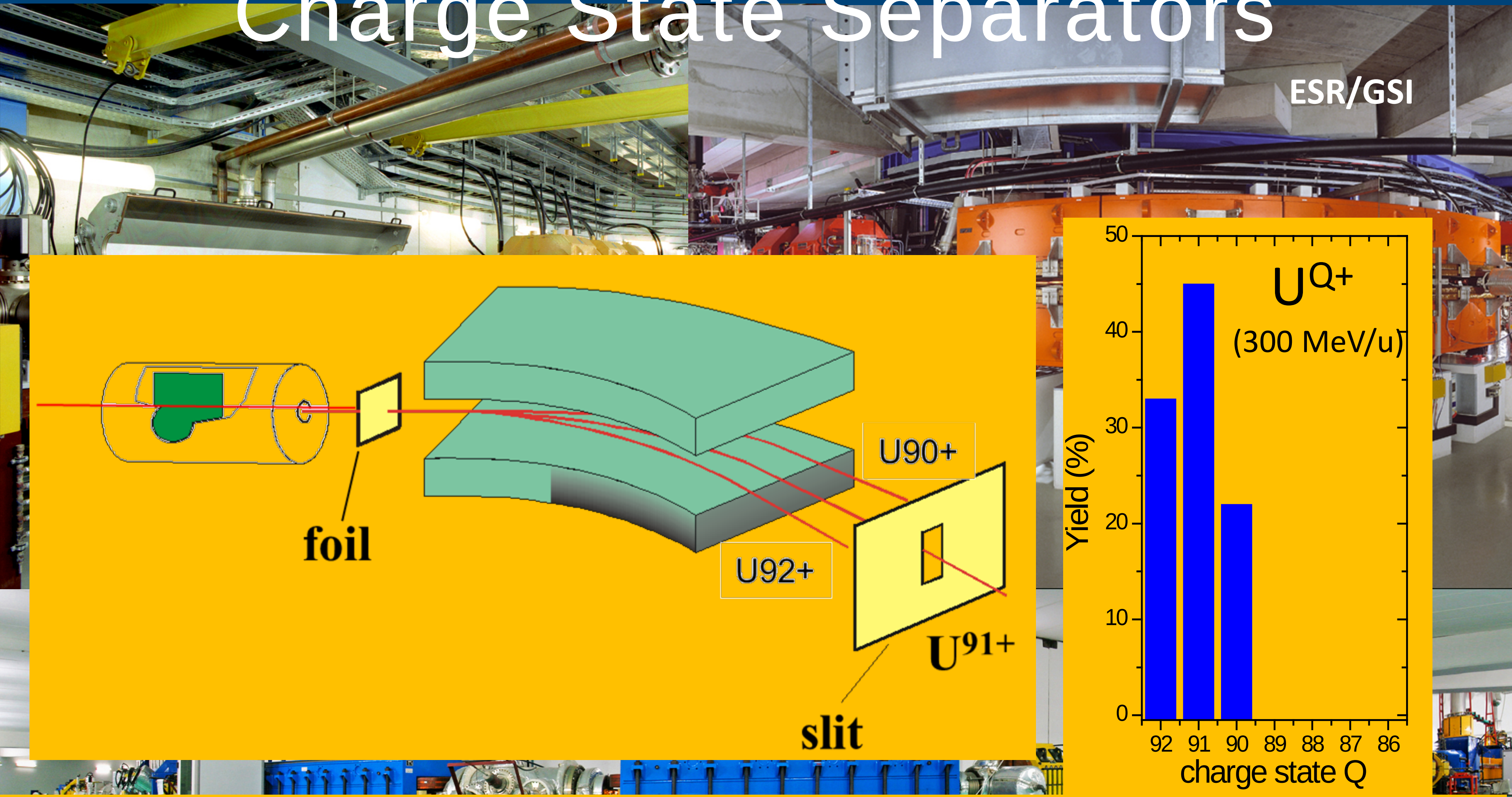
$v_K / c \approx 0.67$

Beam energy ???

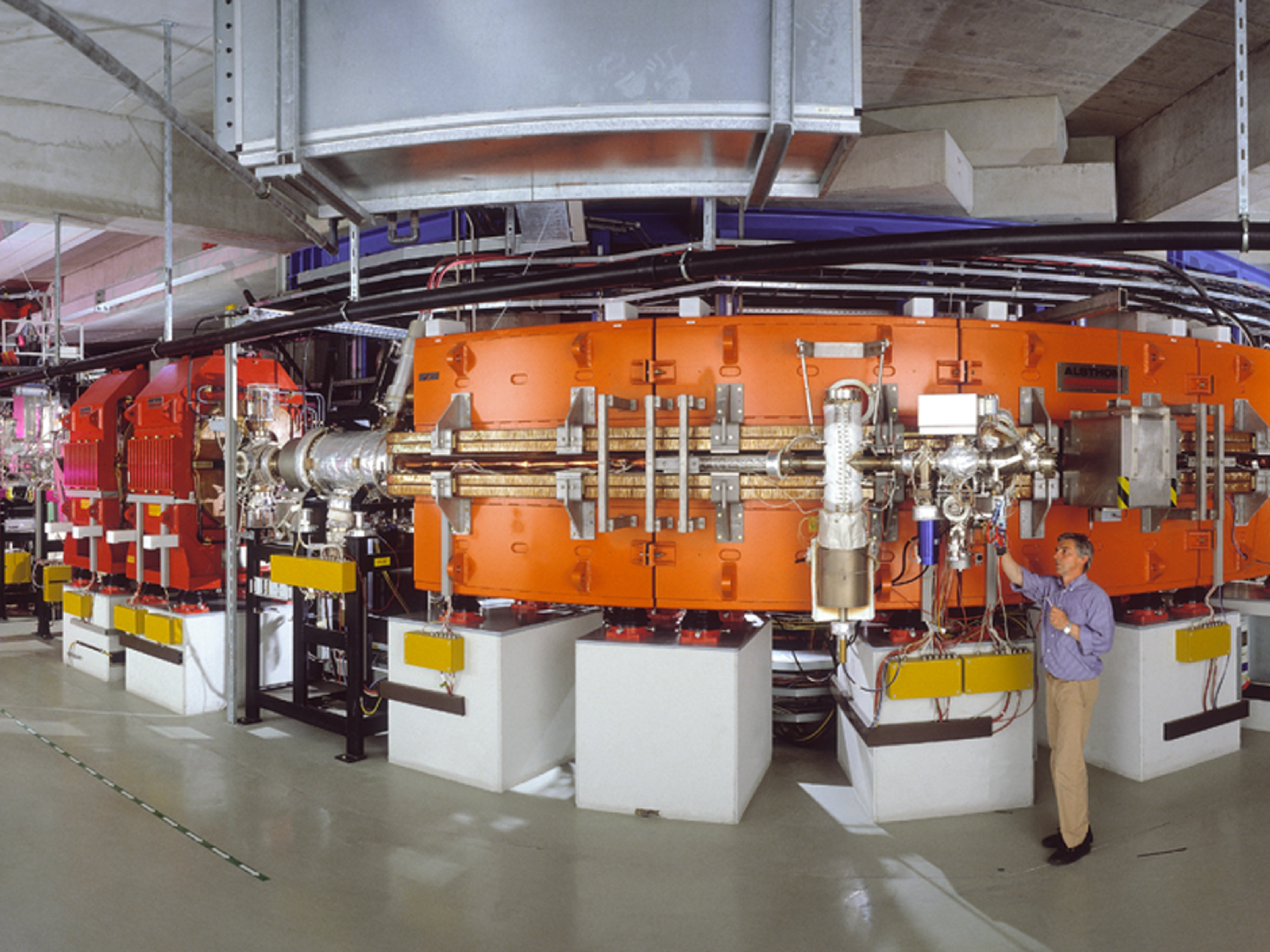




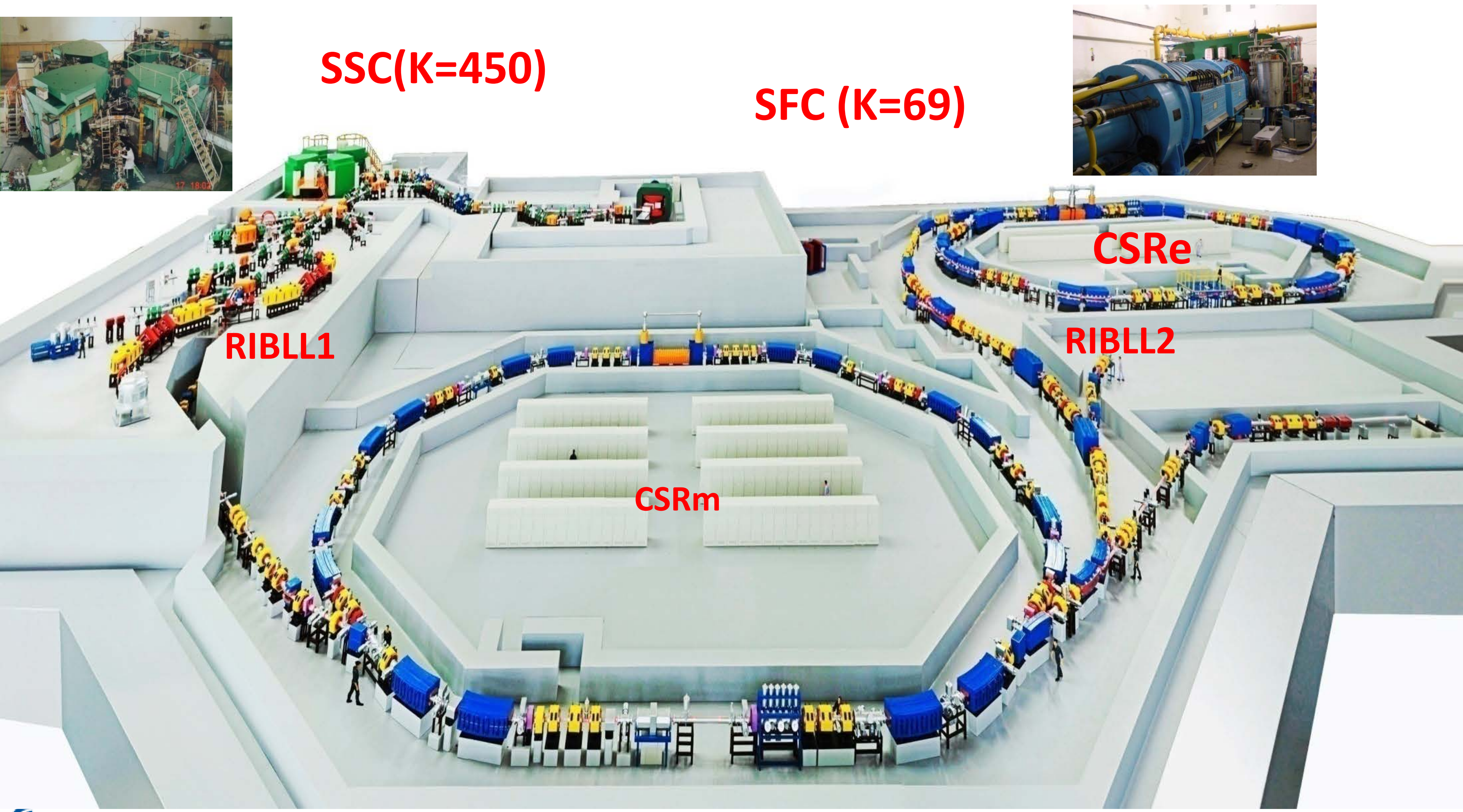
Storage Rings /Synchrotrons/ Charge State Separators



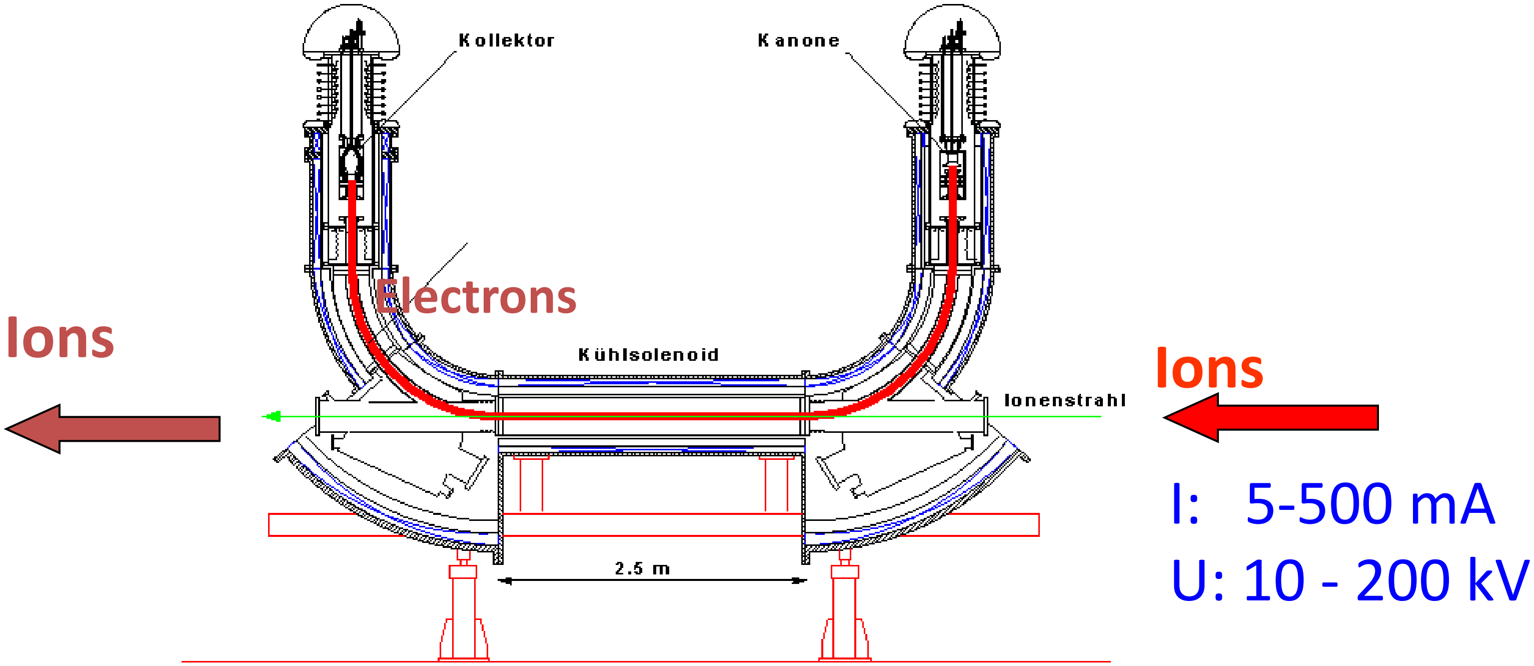
Every element in arbitrary charge state up to the heaviest bare elements are available for experiments


ALSTHOM

Heavy Ion Research Facility in Lanzhou (HIRFL)



Electron Cooling



Ions interact 10^6 1/s with a collinear beam of cold electrons

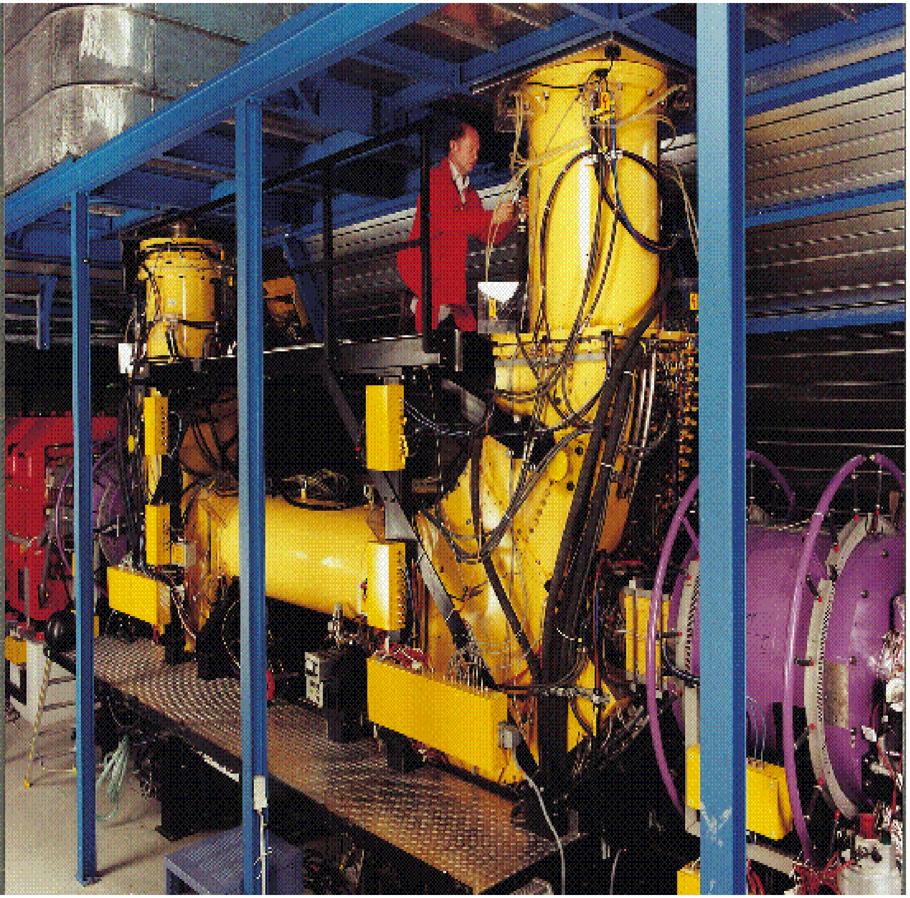
Properties of the cold ions

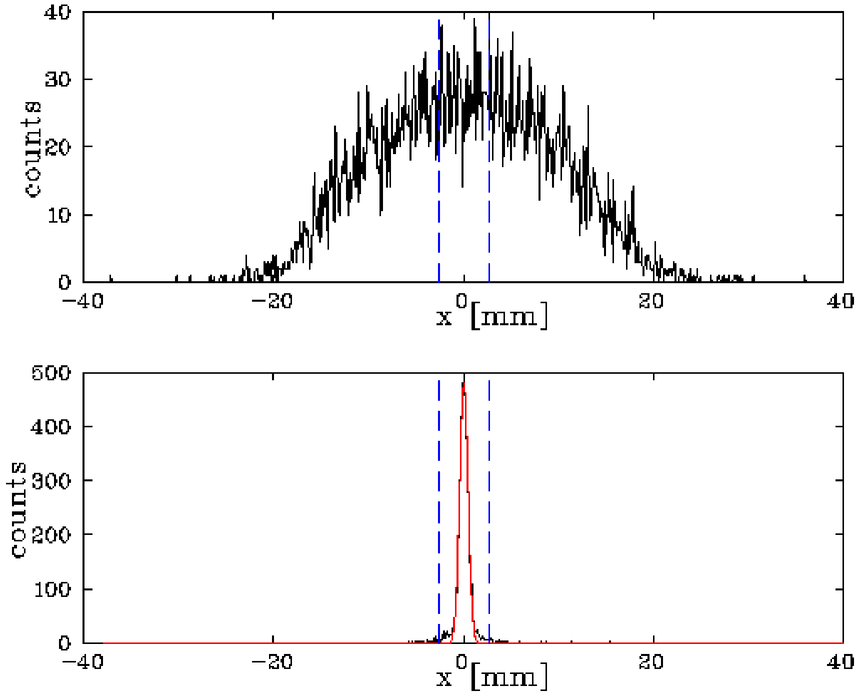
Momentum spread $\Delta p/p$: $10^{-4} - 10^{-5}$

Diameter 2 mm

'Cooling': narrowing velocity, size and divergence of the stored ions

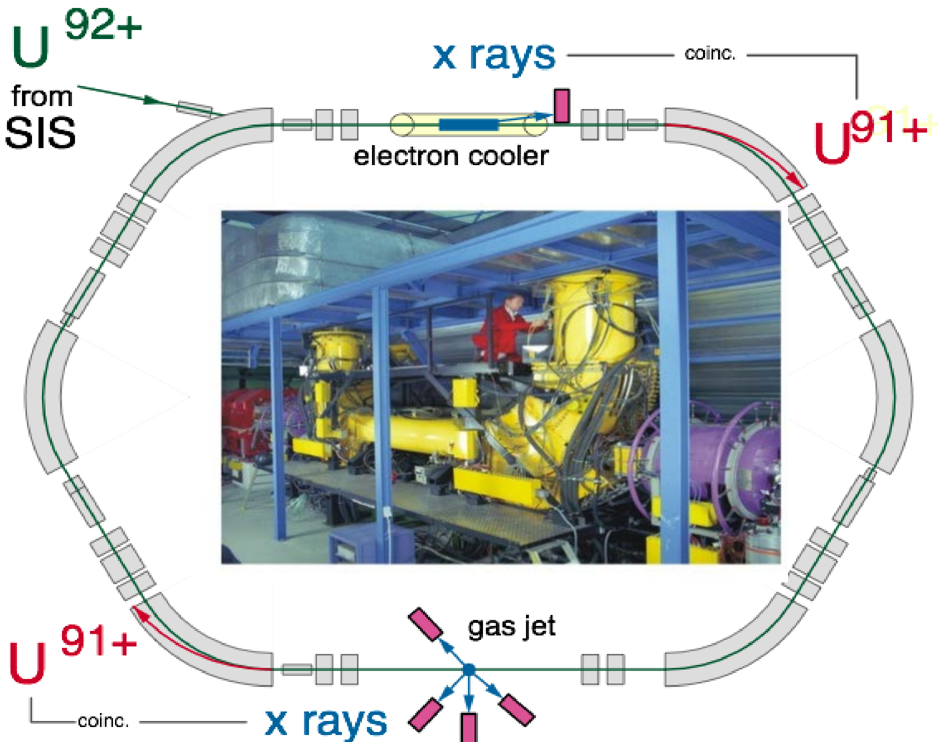
Electron cooling: Budker, 1967 Novosibirsk

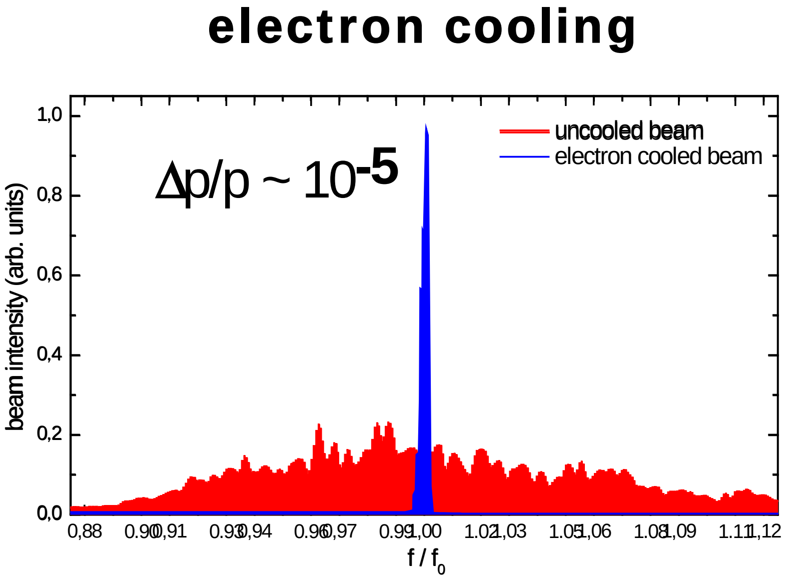


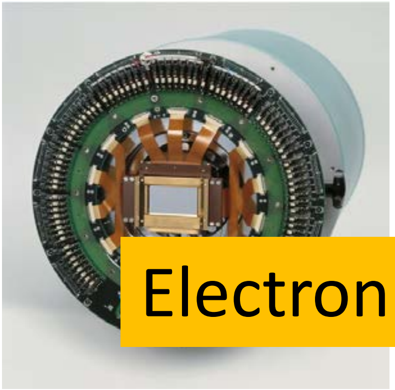


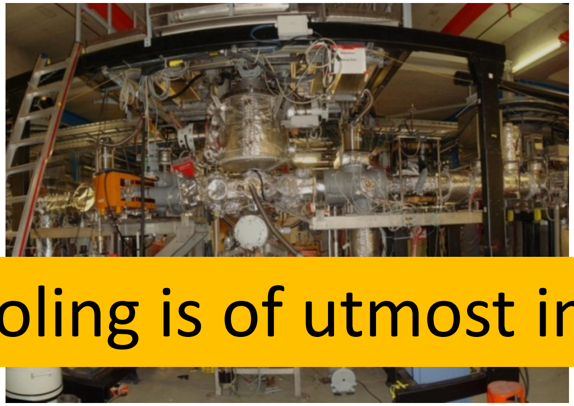
momentum exchange
with 'cold', collinear e- beam. The ions get the **sharp velocity** of the electrons, small size and divergence

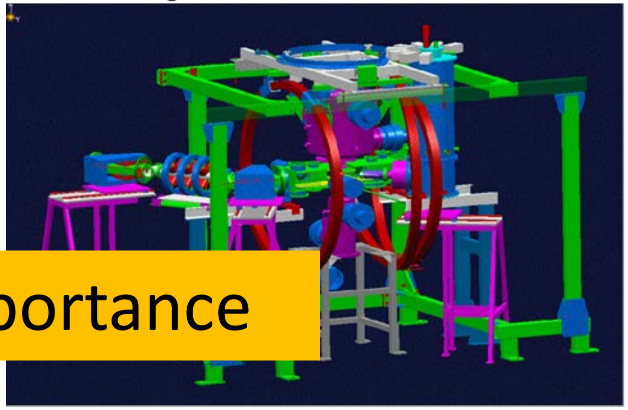
Storage Rings







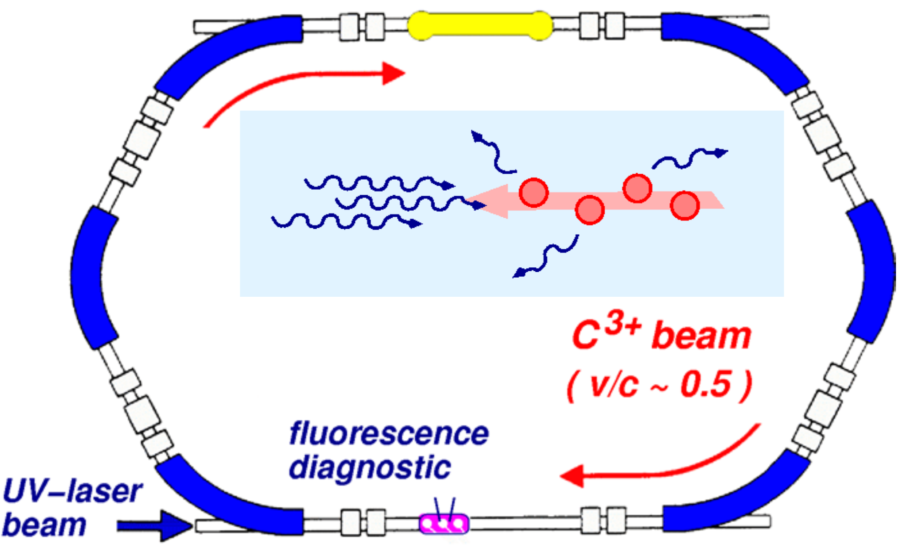


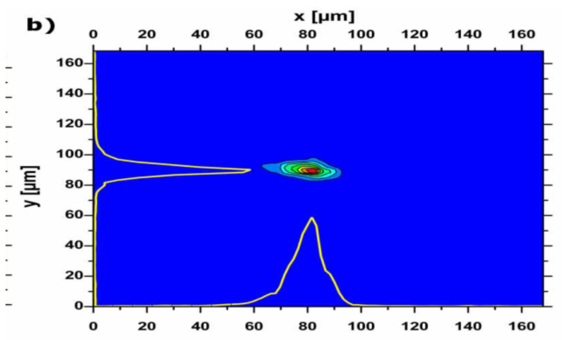


Electron Cooling is of utmost importance

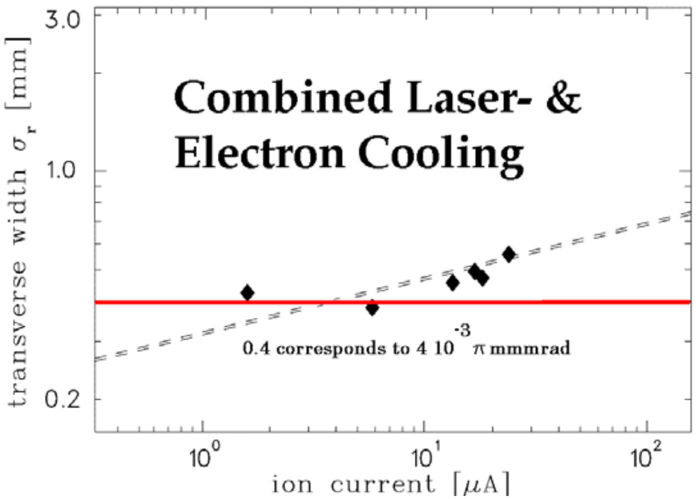
Laser cooling of C^{3+} beams

momentum dependent (Doppler tuned) laser deceleration + bunching (restoring force) => cooling





Demonstration of laser cooling of C^{3+} Ions at 122 MeV/u in the ESR for application at SIS 100/300

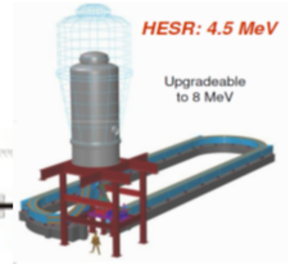


bunch length reduced by a factor 2
beam diameter reduced by a factor 4
momentum spread reduced by a factor 10

U. Schramm et al.,

Experimental Conditions at the HESR

location of target stations



Worldwide premiere:
Precision experiments using cooled relativistic ion beams

- species: p, pbar, HCI, RIB
- circumference 574 m
- injection energy 740 MeV
- Bρ = 50 Tm
- for U^{92+}: 4.937 GeV/u
- γ_{MAX}=6.30; β_{MAX}=0.987
- momentum (energy) rang
(0.8-14.
ng / e-coo

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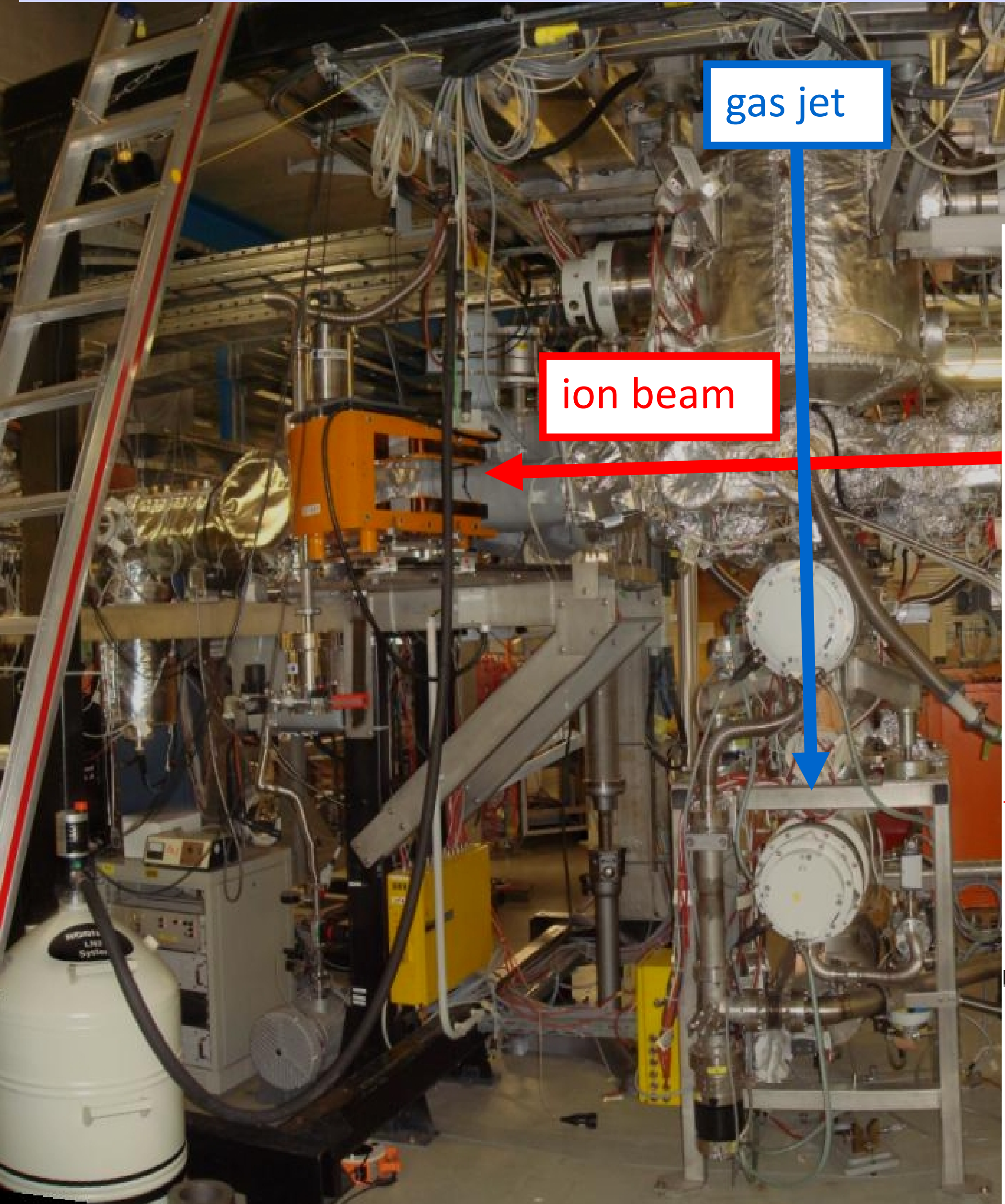
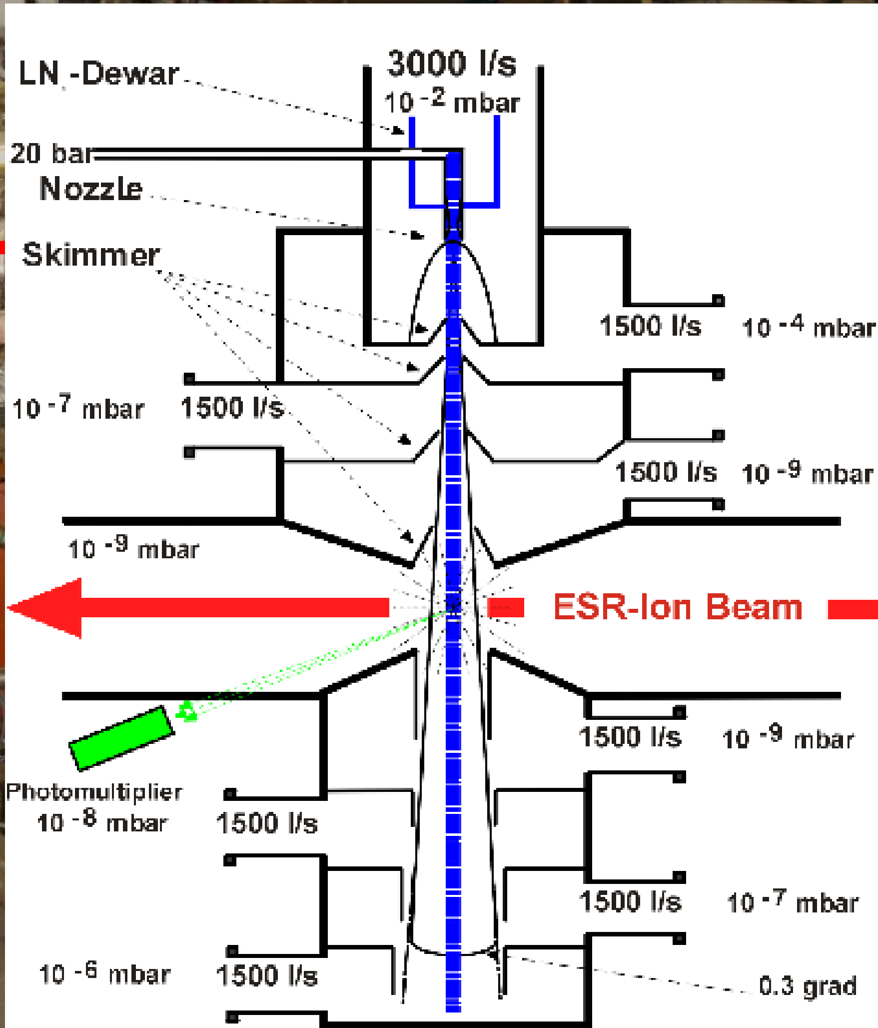
SR

P

- **Stochastic cooling & electron cooling**
- **electron-, gasjet-, fiber-targets (!)**
- **Particle detectors**
- **Ion stacking**
- **Luminosity (number of stored ions)**
- **Beam diameter/charge separation**
- **Acceleration and deceleration**
- **Coupling of laser to the ion beam line**
- **Building / Space for setups**

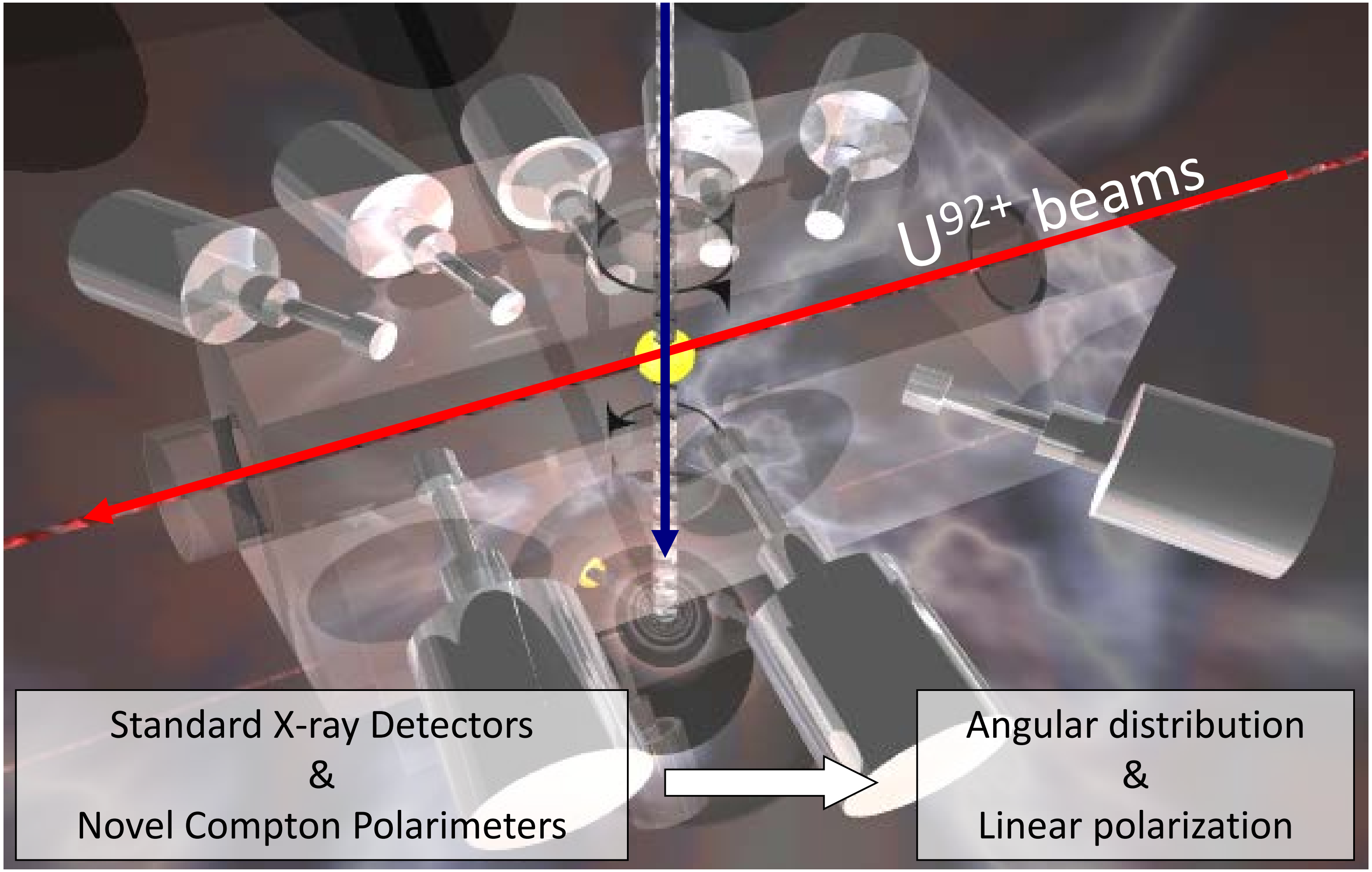
Targets and spectrometer …





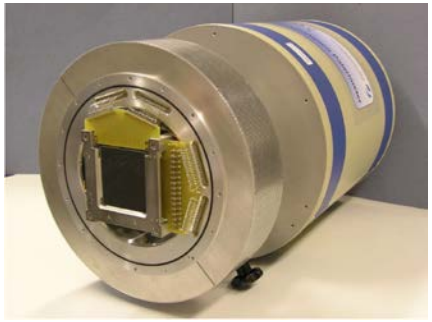
Setup at an gas target for x-ray detection (spectroscopy, angular distributions, polarimetry)

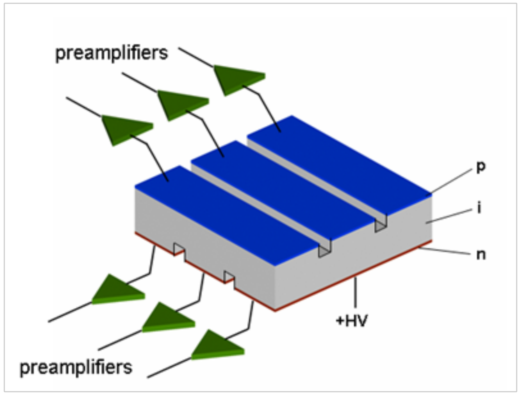
H2, He, N2, Ne, ... Xe gas target



Novel detectors

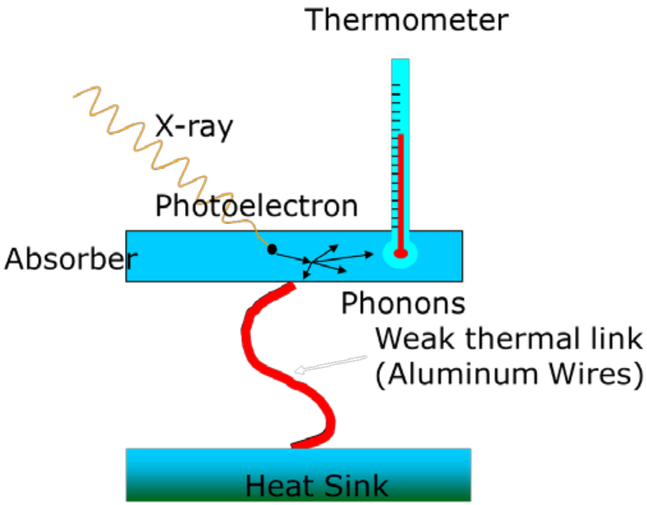
Micro-strip semiconductor detectors



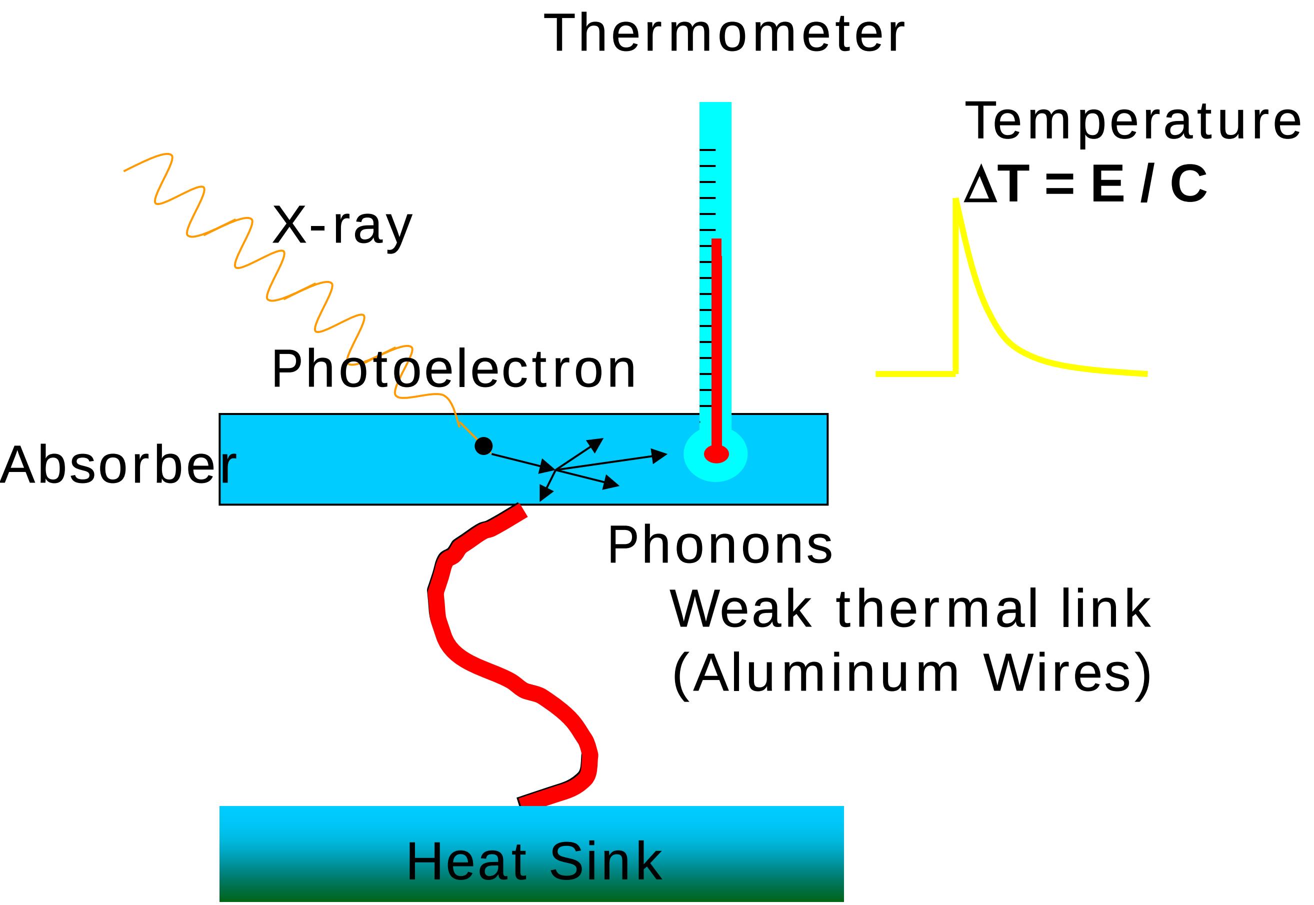


- ☑ Si(Li) or Ge(i)
- ☑ energy resolution
- ☑ timing
- ☑ 2D (3D) position sensitivity
- ☑ multi-hit capability

Micro-Calorimeter



Micro-Calorimeter



Heat capacity: $C = c \cdot m$

$C \sim T^3$

Spezific heat capacity : c

Detector mass: m

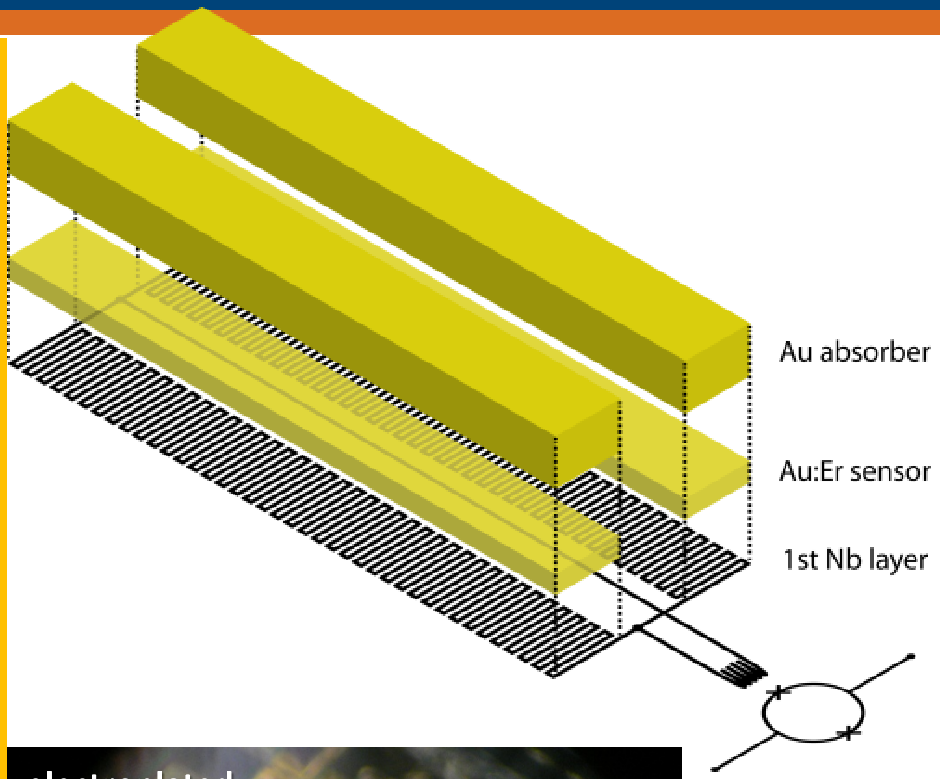
Detector operates at about 50 mK

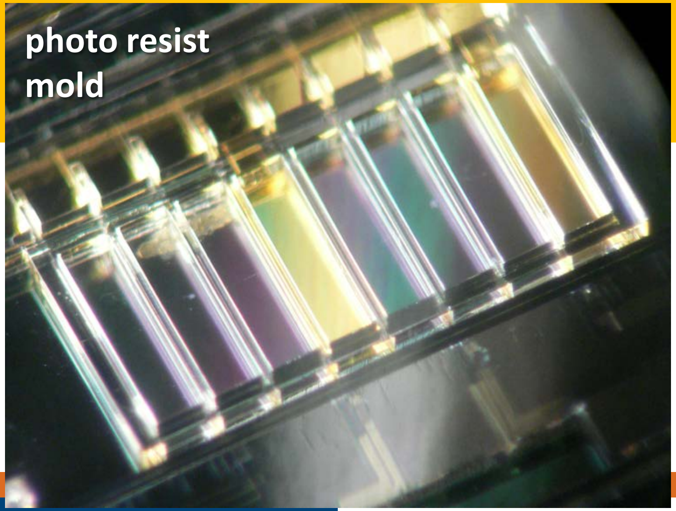
Micro-calorimeter detector: large wavelength acceptance, large quantum efficiency, and excellent energy resolution (4 keV@5eV => 35 keV@30 eV).

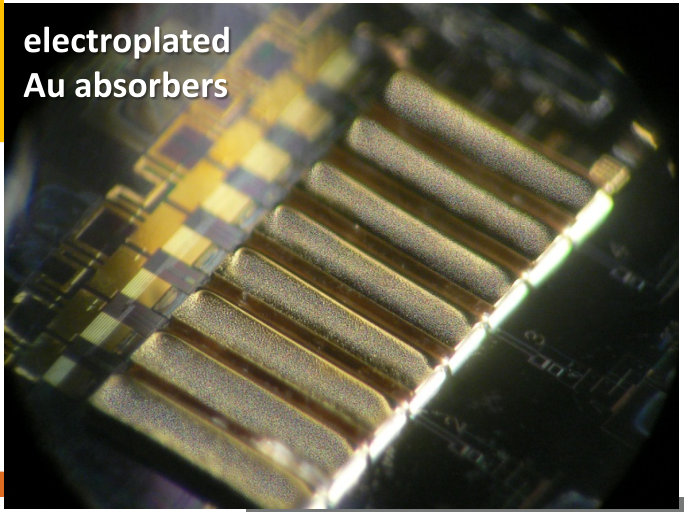
maXs-200: detector arrays for hard x-rays

First array prototype

- **1x8 x-ray absorbers**
  - **2 mm x 0.5 mm**
  - 200 µm thick electroplated Au
  - **80% QE at 100 keV**
- **ΔE_{FWHM} < 50 eV**
- **4 electronic channels**
- **modular extension to longer arrays**

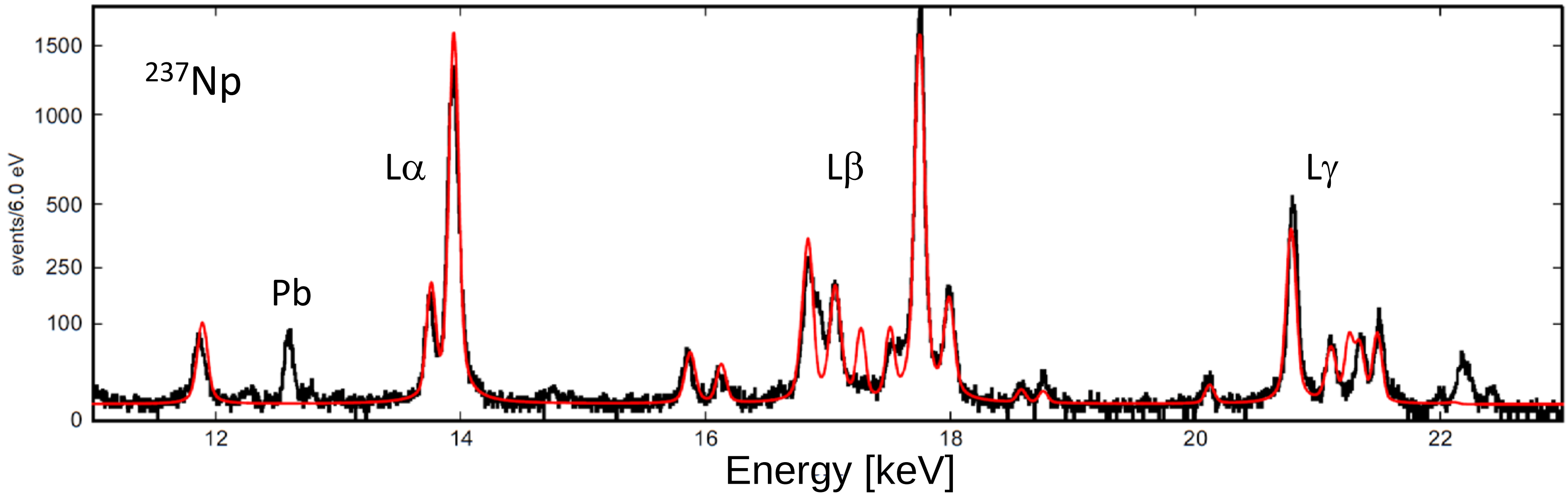






maXs-200: detector arrays for hard x-rays

<u>First</u> characterization with an ^{241}Am-source



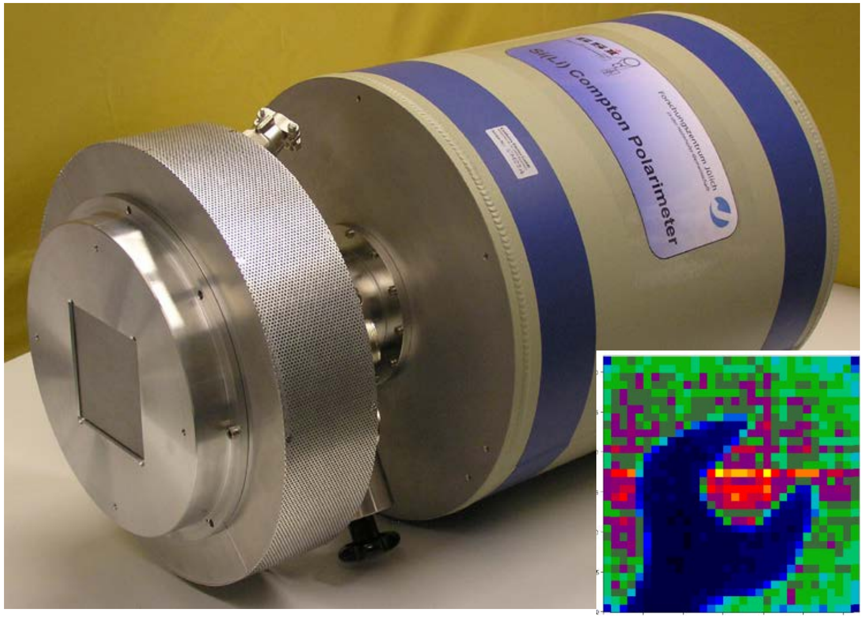
ΔE_{FWHM} = 40 eV @ 0-10 keV

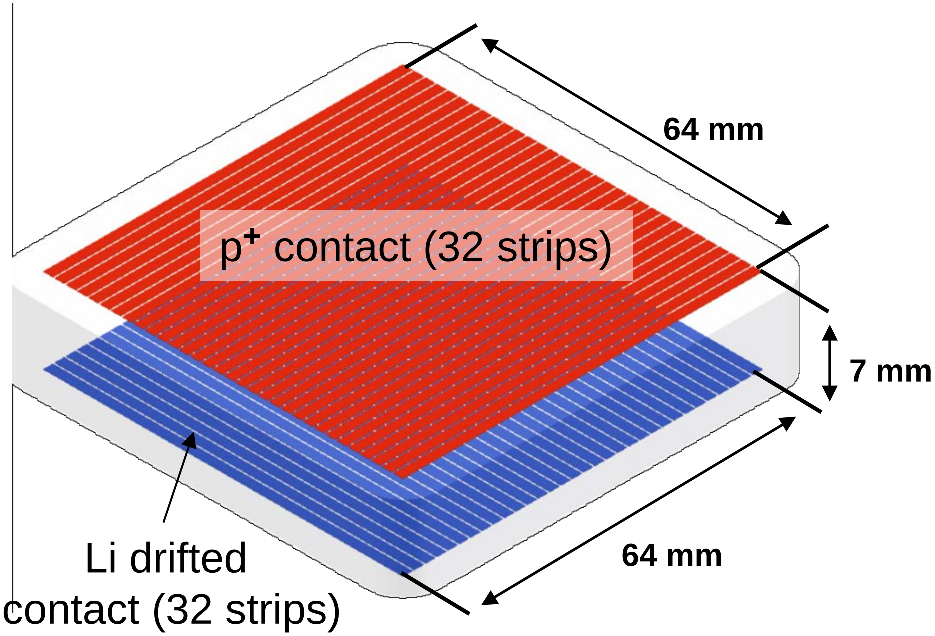
ΔE_{FWHM} = 60 eV @ 60 keV

Slight degradation towards higher energies due to

- **Poor temperature stability** in this first experiment
- **Possible marginal position dependence**,
  to be fixed by stems between absorber and sensor

2D Si(Li) X-ray Detector as a Compton Polarimeter





32 x 32 strips → 1024 pixels

64 x 64 mm → 4096 mm² active area

readout rate: a few kHz

Energy (1.5 keV FWHM) **+ Timing** (100 ns) **+ 2D Position** (2 mm) **+ Multihit Capability**

Dedicated to efficient and precise polarization studies from 70 keV to a few 100 keV

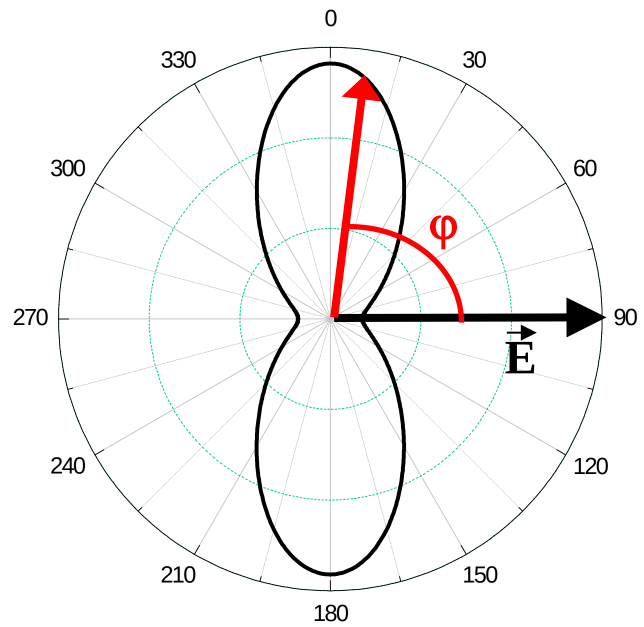
How to Measure Polarization for Hard X-Rays

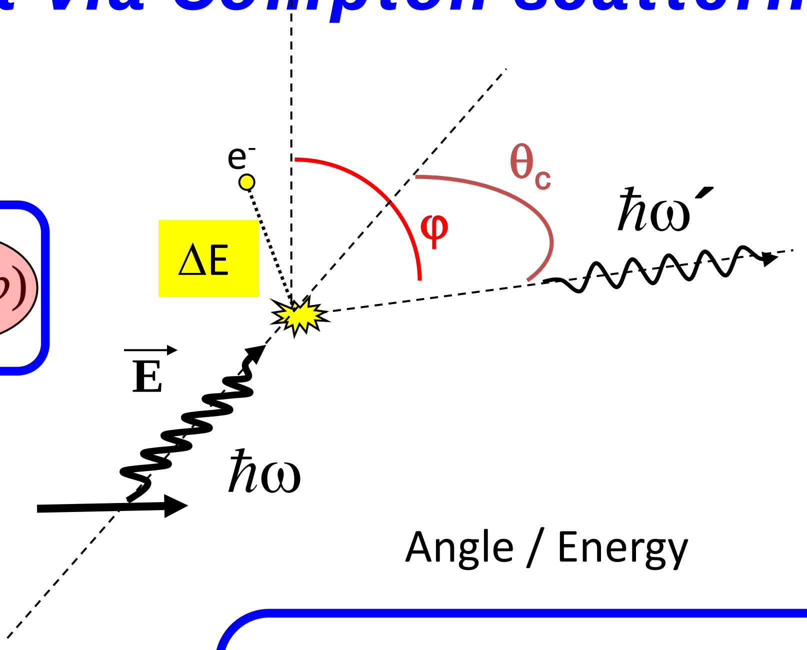
Polarization Measurement via Compton scattering

Linearly polarized radiation

Klein-Nishina equation

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta_c \cos^2\varphi\right)$$





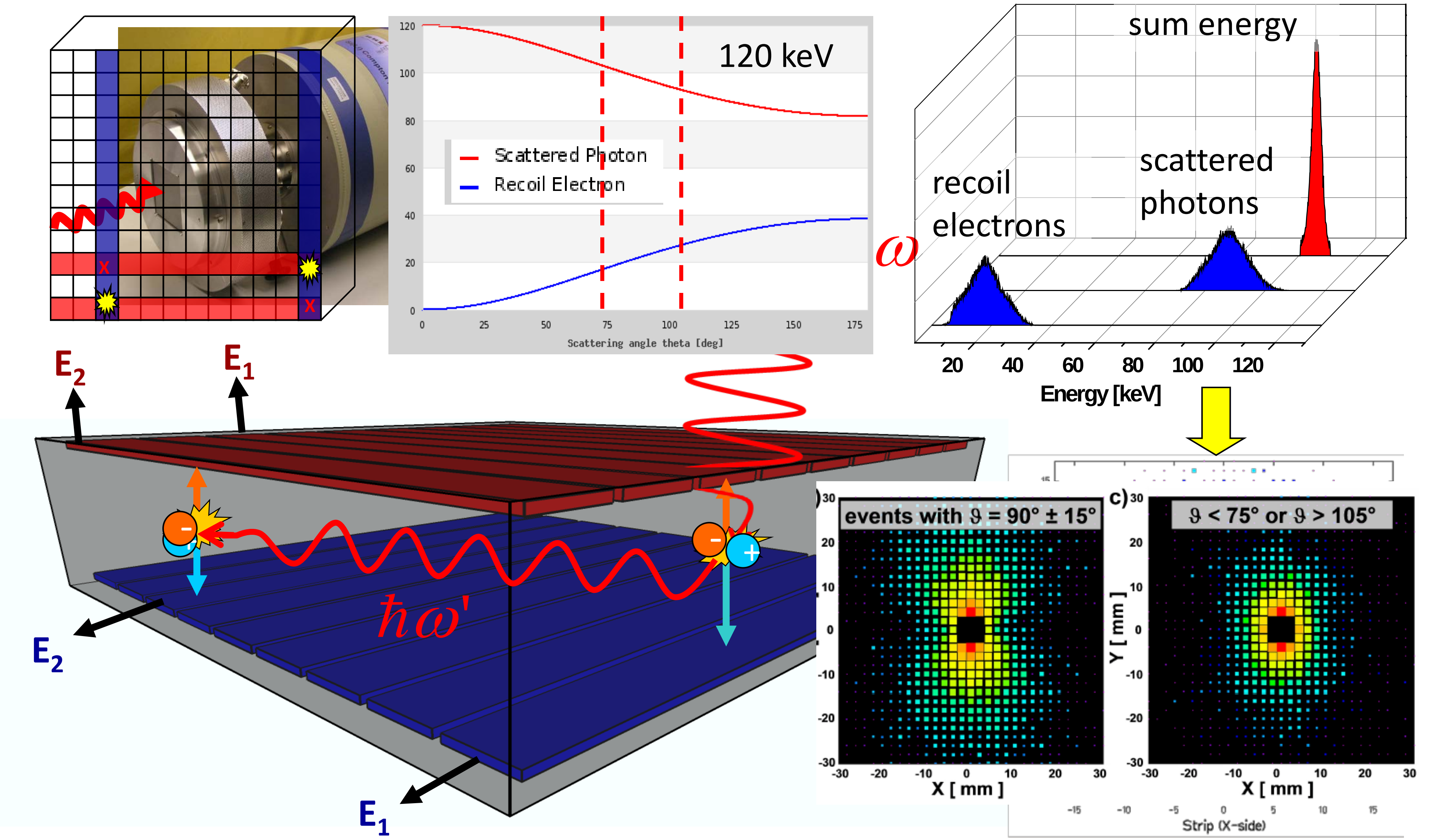
Angle / Energy

$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_e c^2}(1 - \cos\theta_c)}$$

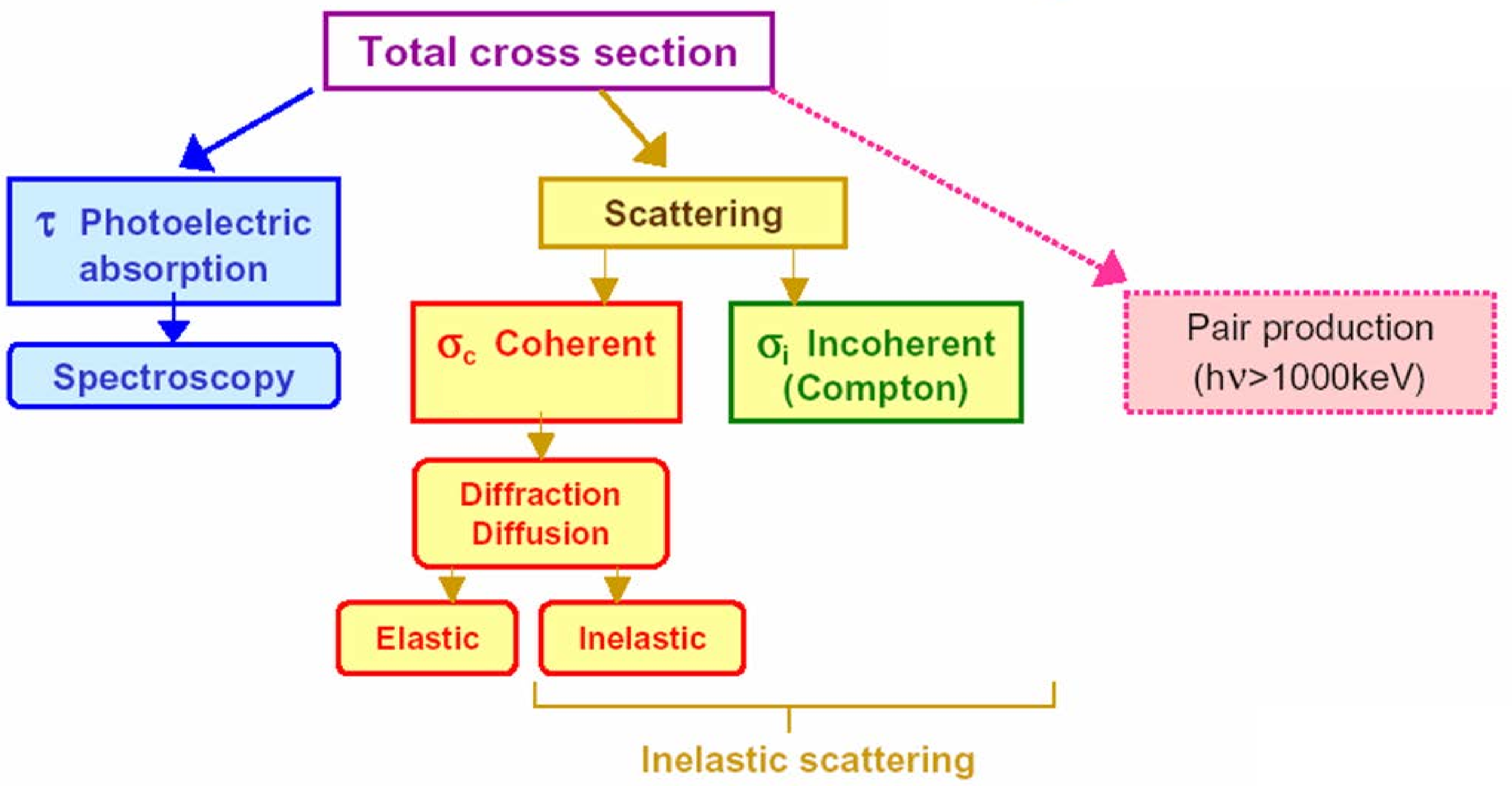
$$\hbar\omega = \hbar\omega' + \Delta E$$

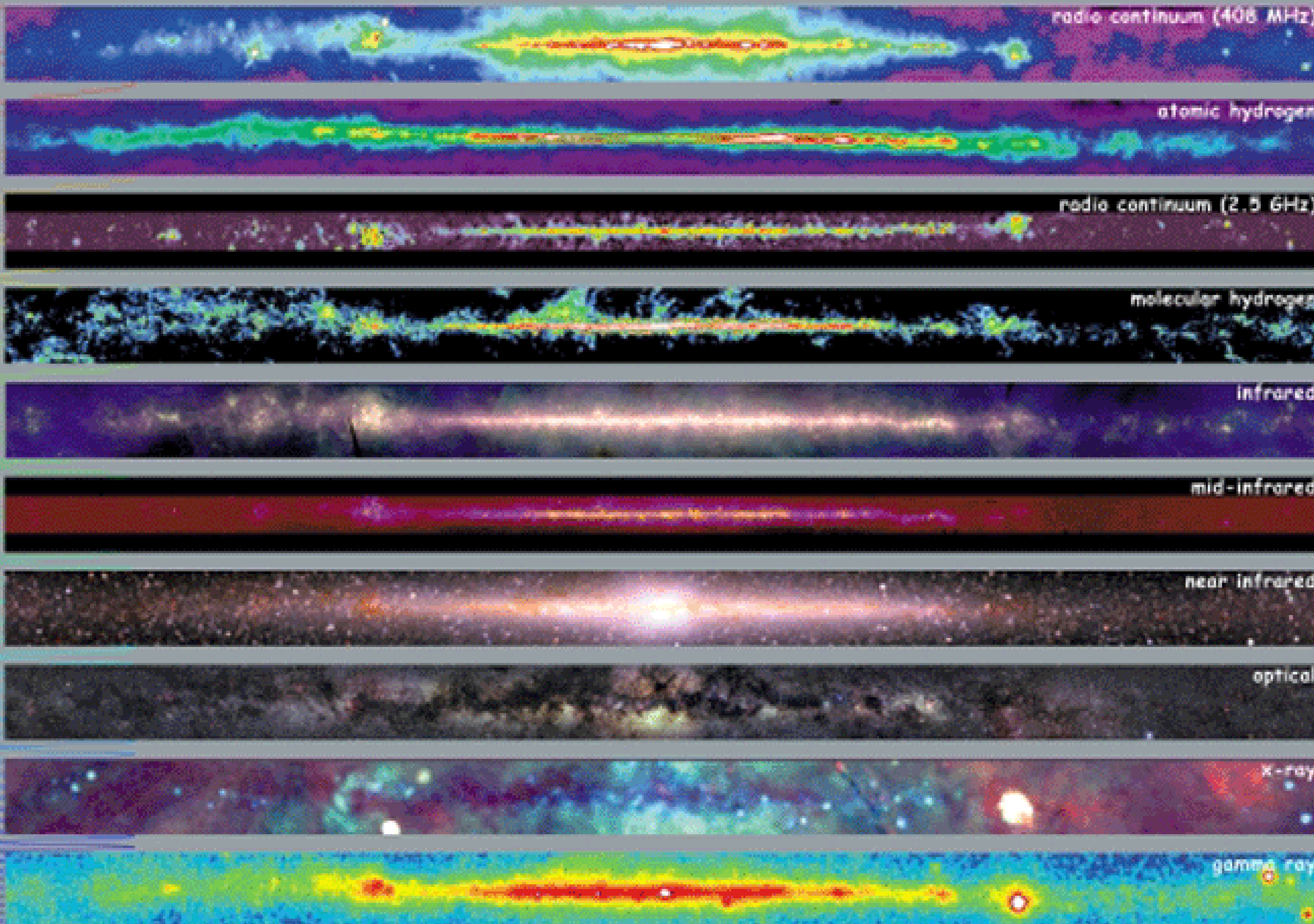
ΔE : electron recoil energy

Reconstruction of the Compton events



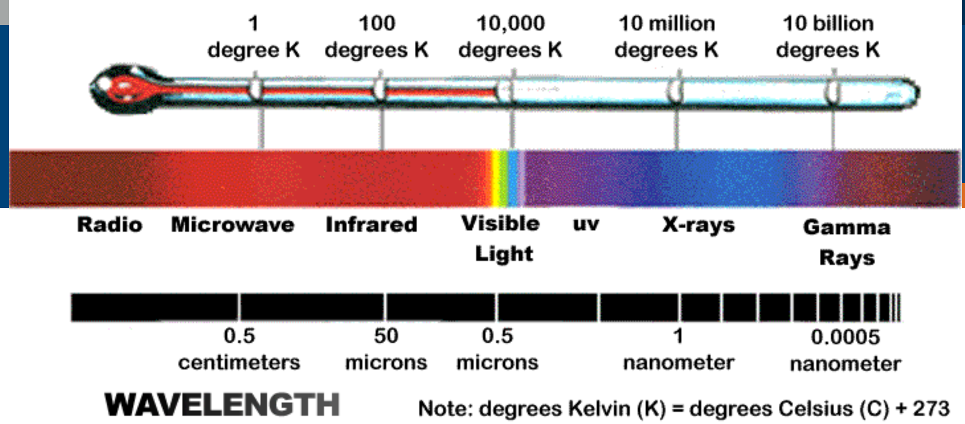
Interaction of radiation and matter



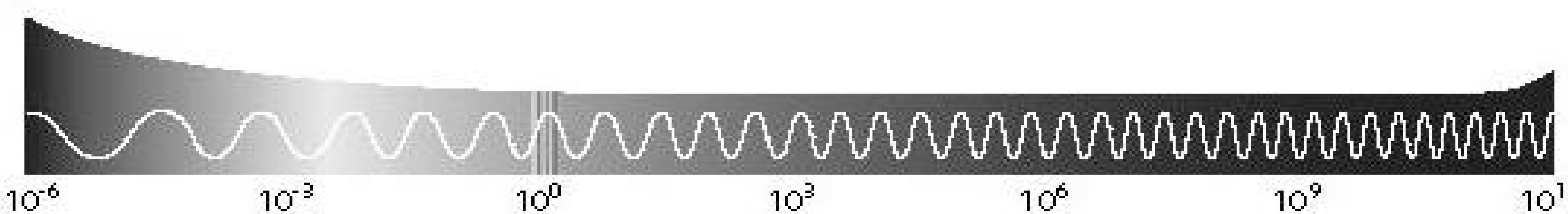


http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way



Radio Infrared Visible UV X-Ray Gamma ray



E (eV)

1	1×10^{-3}	1×10^{-6}	1×10^{-9}	1×10^{-12}	1×10^{-15}	1×10^{-18}	λ (m)
2×10^{8}	2×10^{11}	2×10^{14}	2×10^{17}	2×10^{20}	2×10^{23}	2×10^{26}	ν (Hz)

$E: h c / \lambda$

$\lambda: c / \nu$

$\nu: c / \lambda$

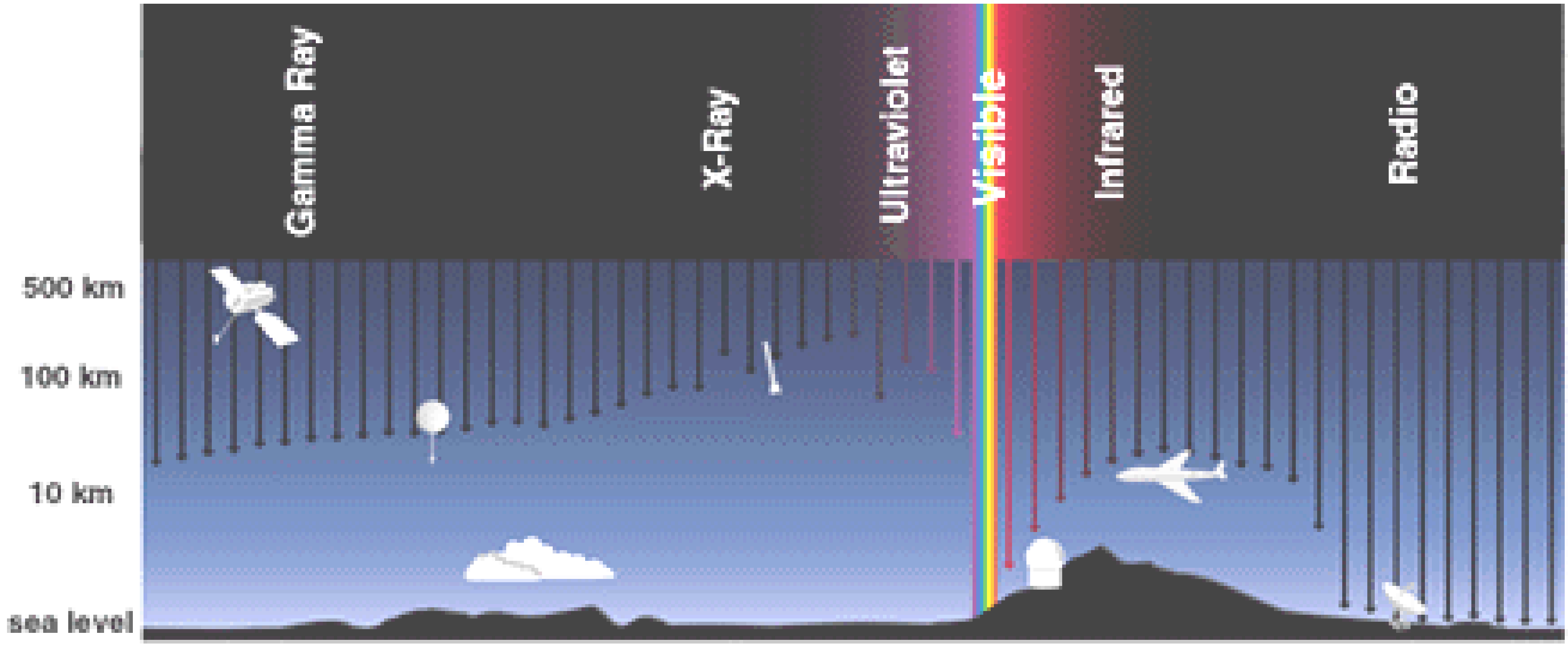
E: Energy

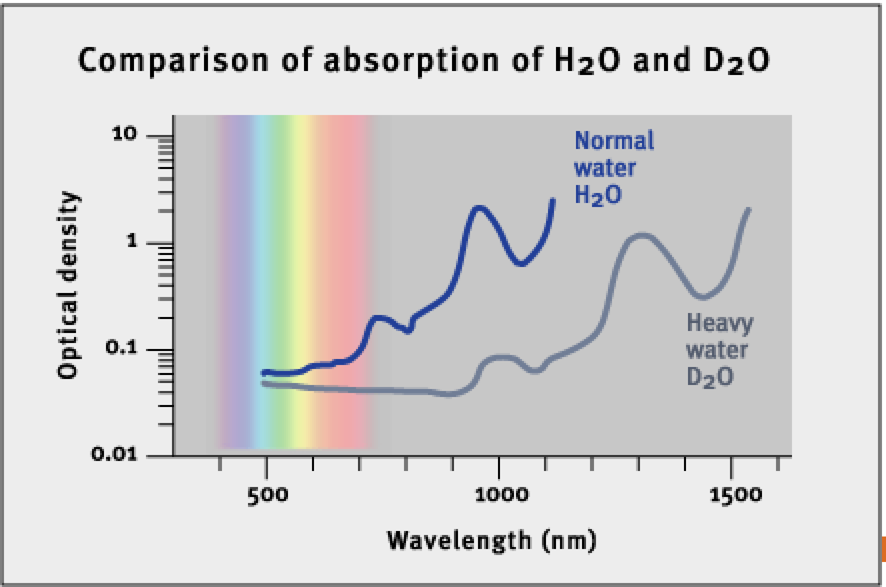
λ: Wavelength

ν: Frequency

h: Planck constant $= 4 \times 10^{-15}$ eV s

c: speed of light $= 3 \times 10^{8}$ m/s





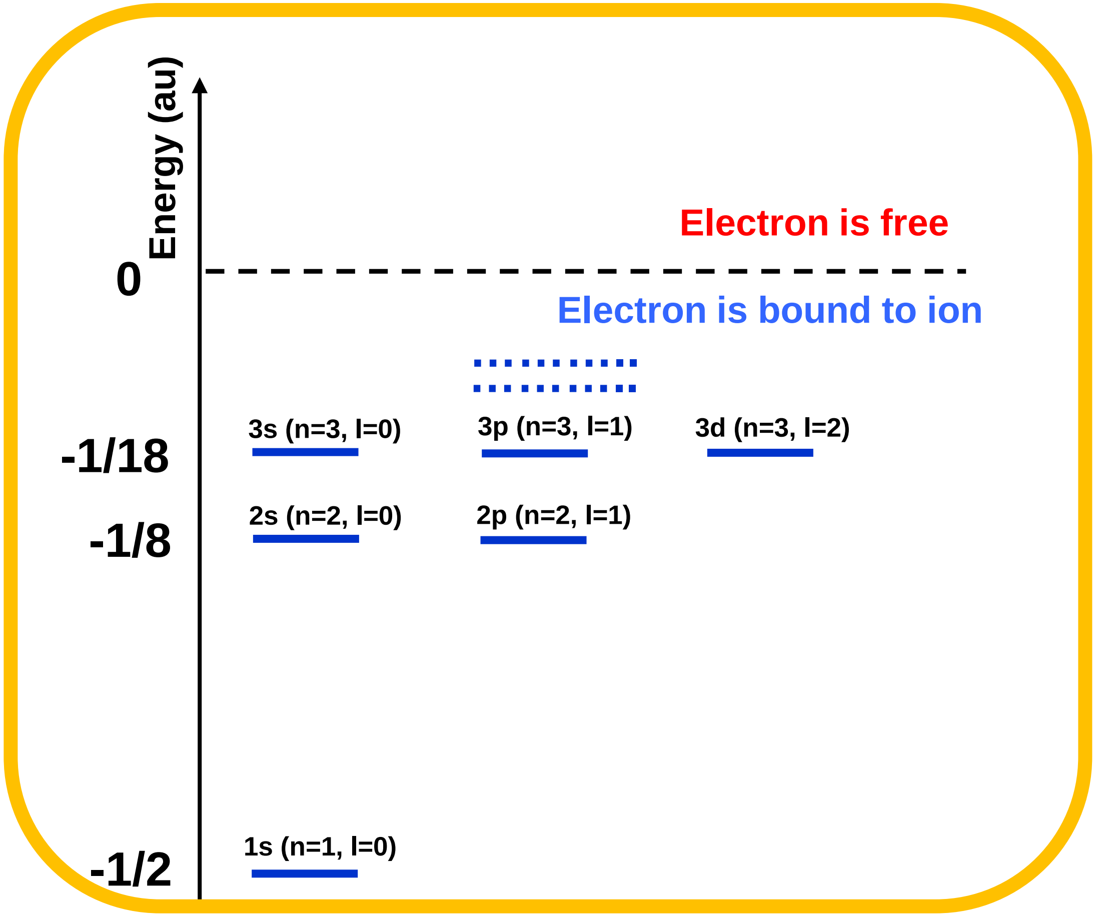
http://imagers.gsfc.nasa.gov/ems/atmosphere.gif

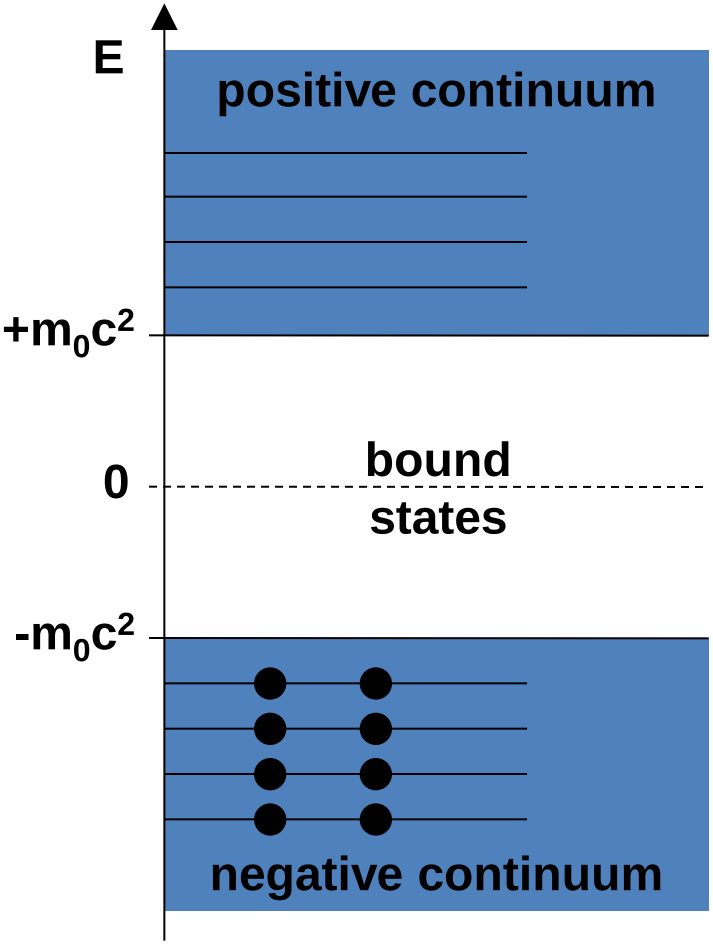
atmospheric interactions

reflection
refraction
scattering
absorption

Lecture 1
Dirac Theory

The Theorie of Matter and Anti-Matter

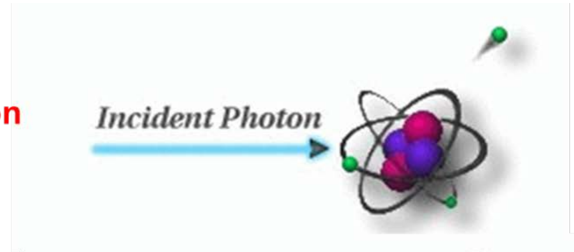




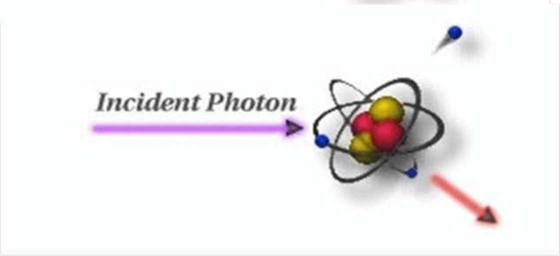
Interaction of photons and matter
x-ray and gamma-regime

$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{mc^2}(1 - \cos\theta)}$$

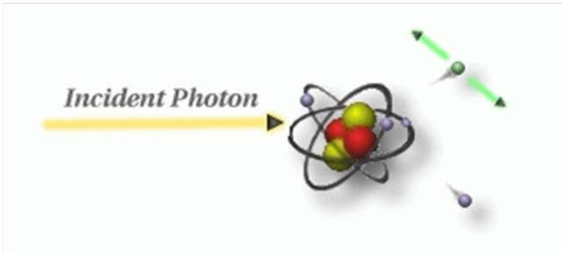
photo-effect / photo-absorption



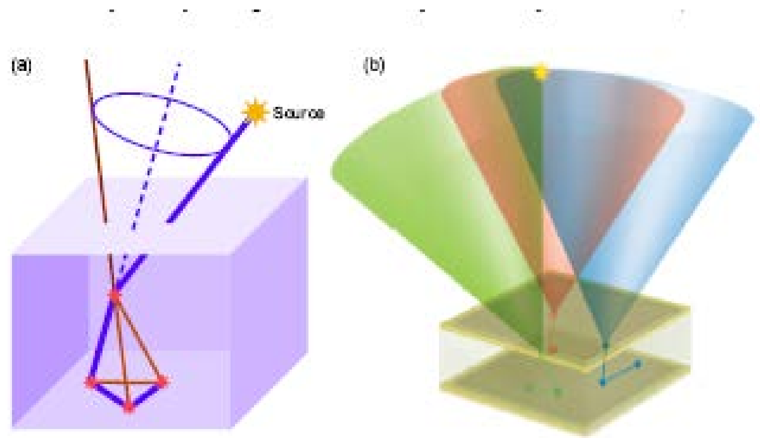
Compton-scattering

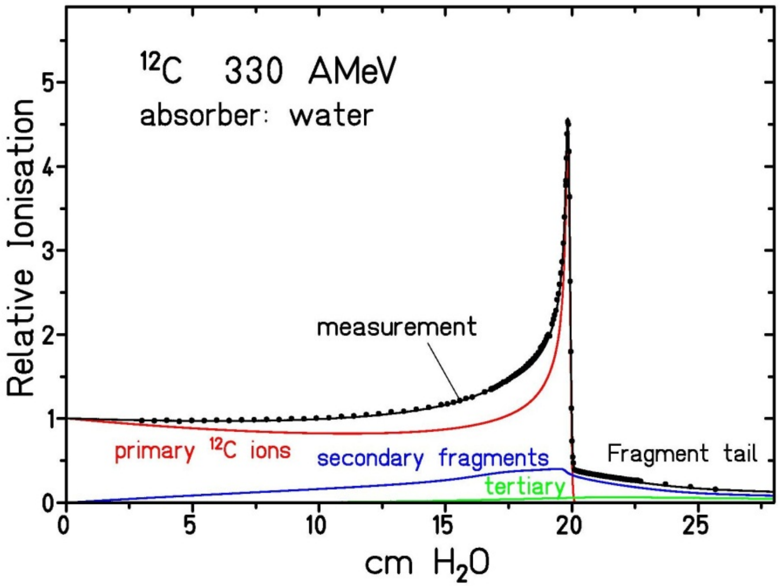


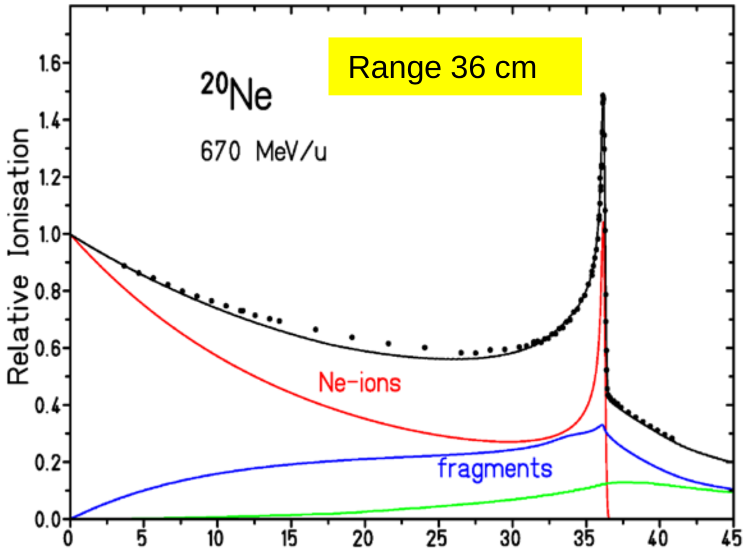
Pair production



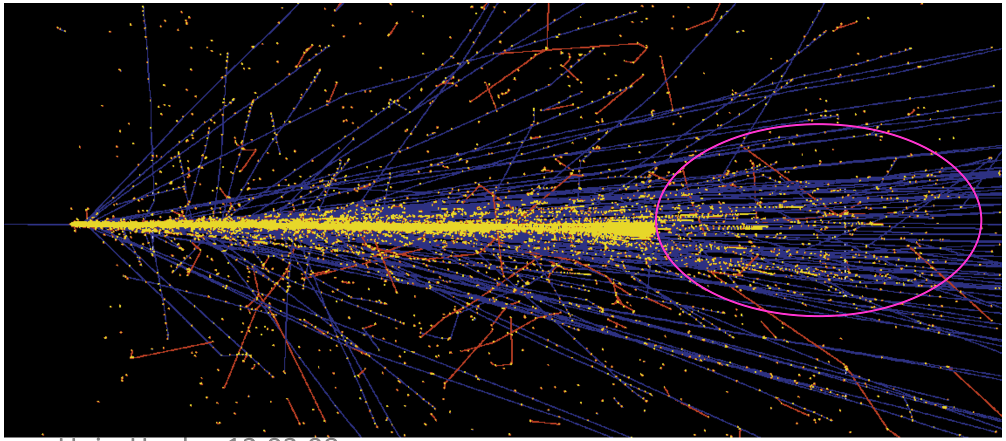
Compton Camera

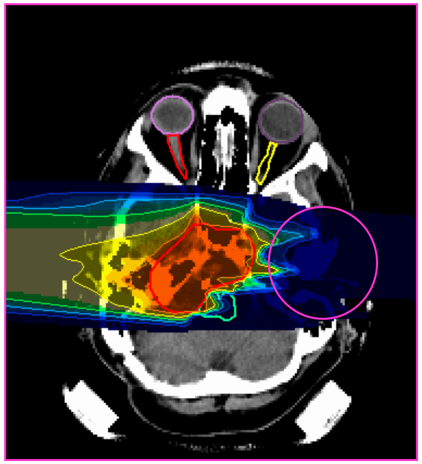




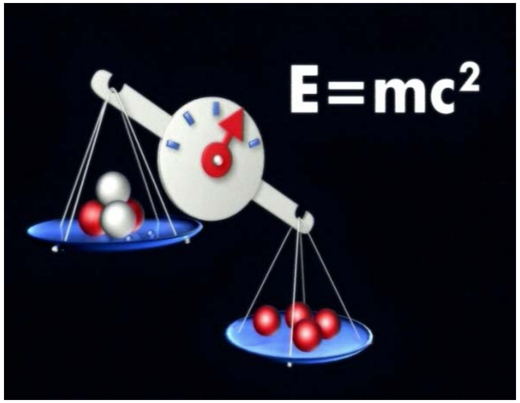


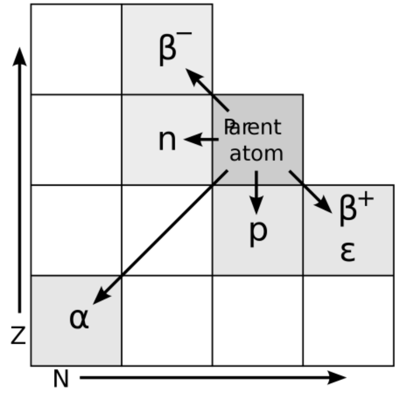
High-energy carbon beam stopping in water

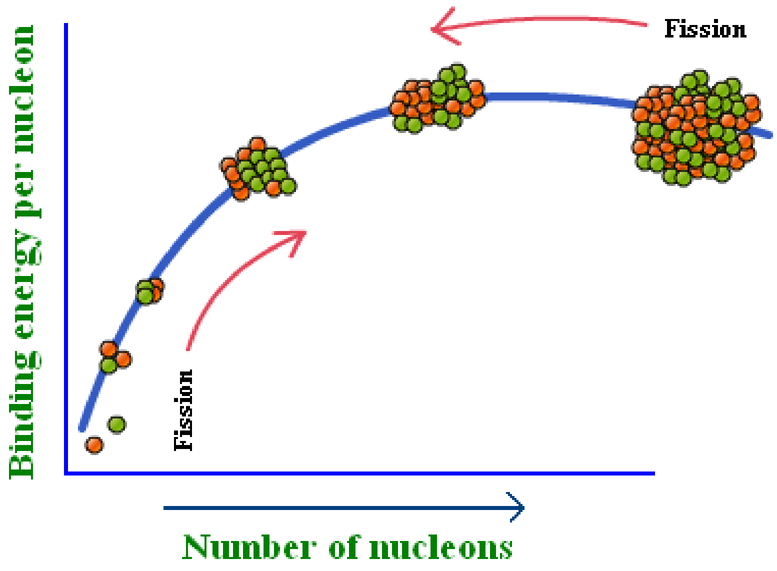


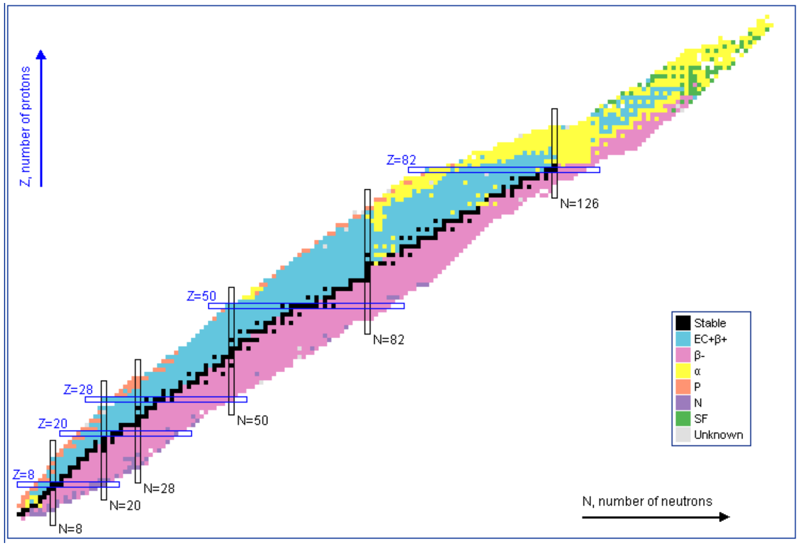


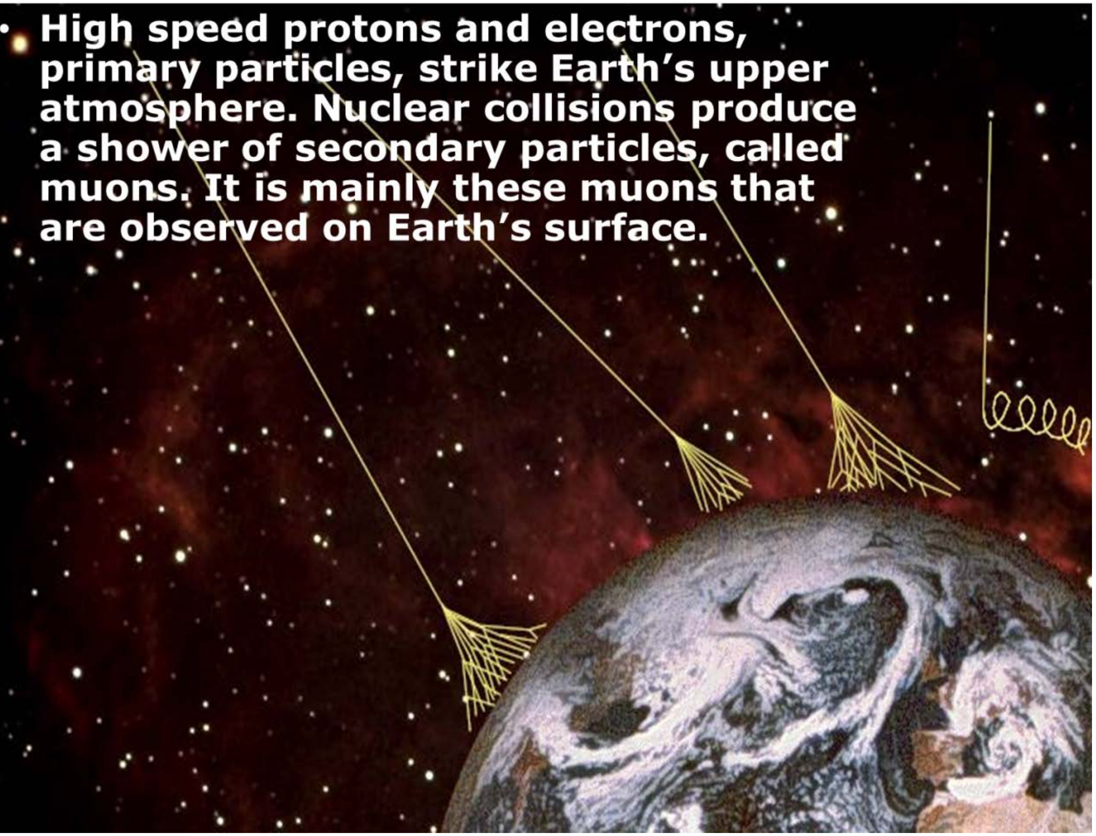
Lecture 7 Nuclei and Their Decay Modes



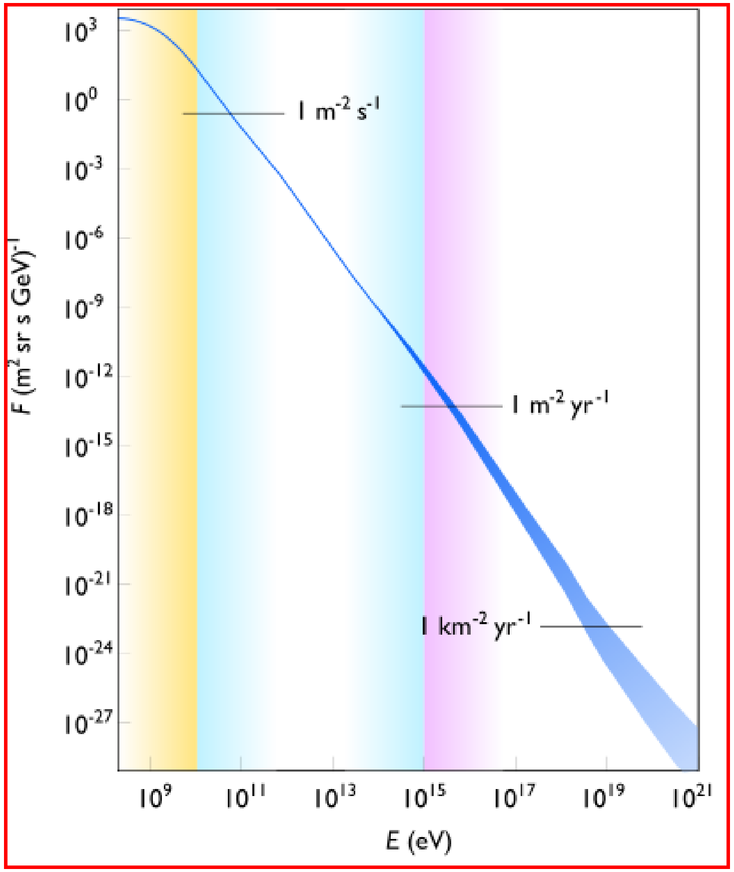






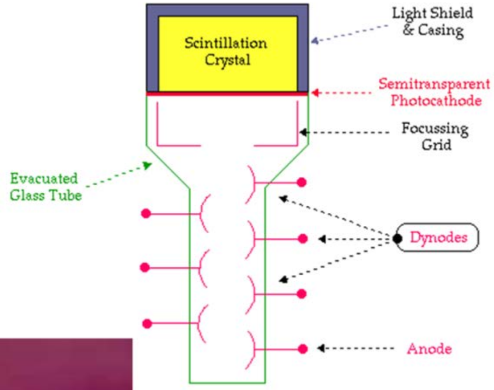


Flux: number of particles per unit area per second.

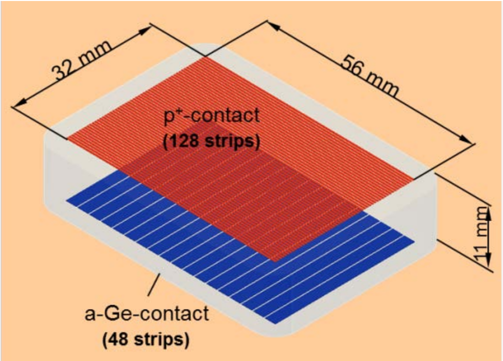


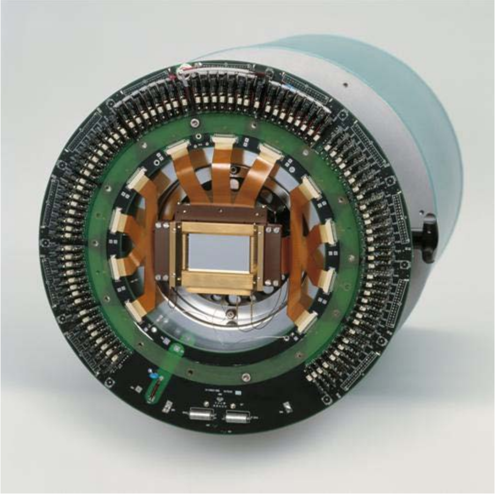
Lecture 9 Photon-, x-ray-, gamma-detectors

Inorganic Scintillators

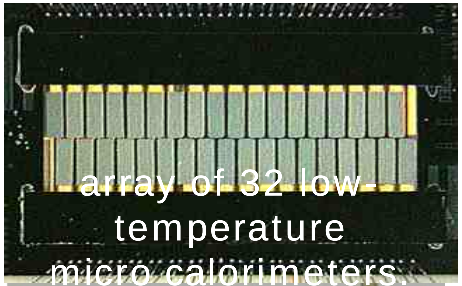


Semi-conductors





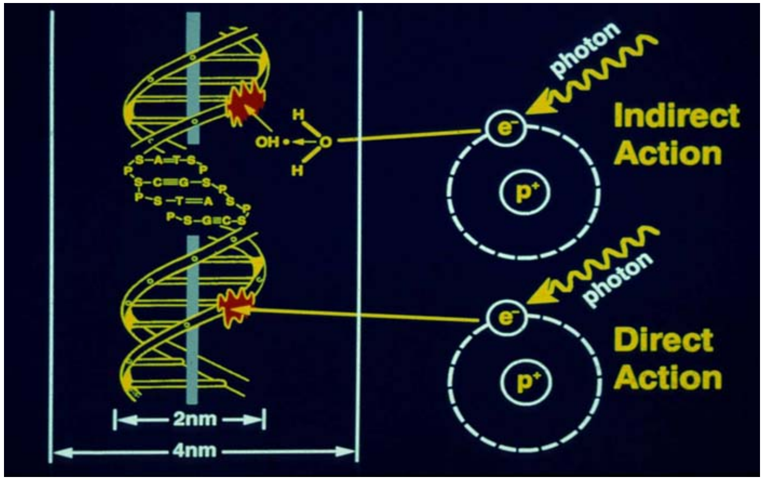
micro-calorimeters



array of 32 low-temperature micro calorimeters.

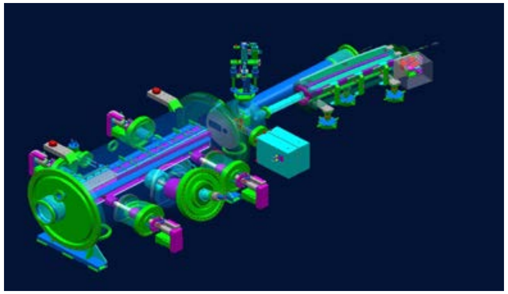
Lecture 11 Radiation and their Biological Effectiveness

- Radiobiology
  - Acute (deterministic) effects
  - Late (stochastic) effects
- Heavy ions
  - Space radiation
- Radiotherapy
  - Conventional X-ray therapy
  - Particle therapy

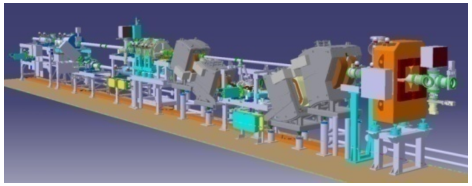


Ion/electron sources, linacs, synchrotrons

$$\vec{F}_L = q\left(\vec{v} \times \vec{B}\right)$$

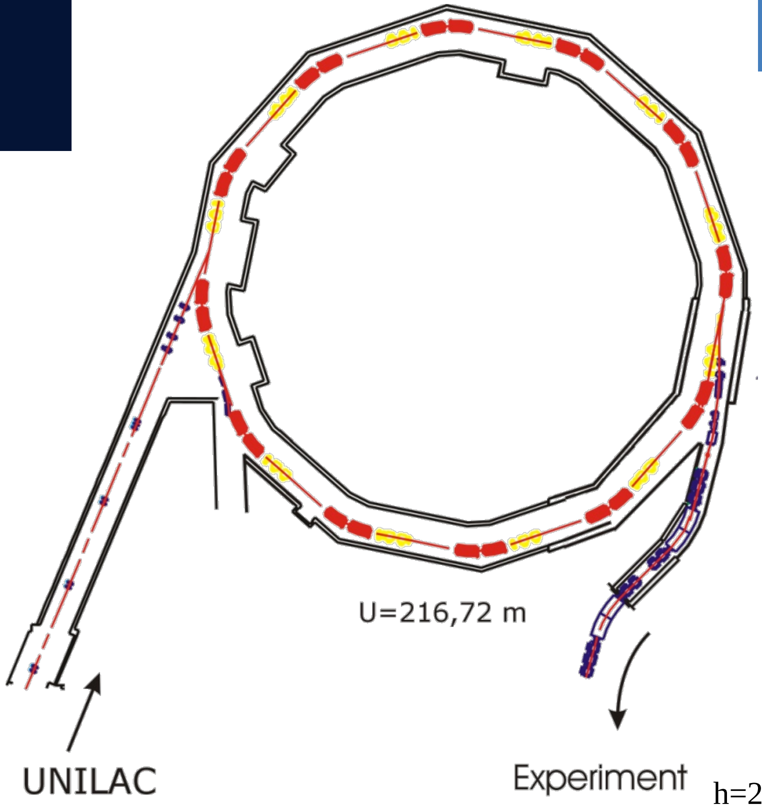


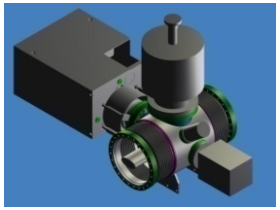
Injection system for low charged state heavy ions



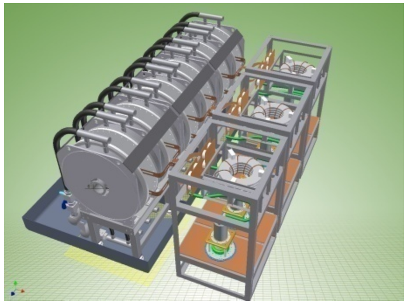
Charge separator for higher intensity and high quality beams

Power grid connection





Scrapers and NEG coating for pressure stabilization



h=2 acceleration cavity for faster ramping