Synchrotron Radiation

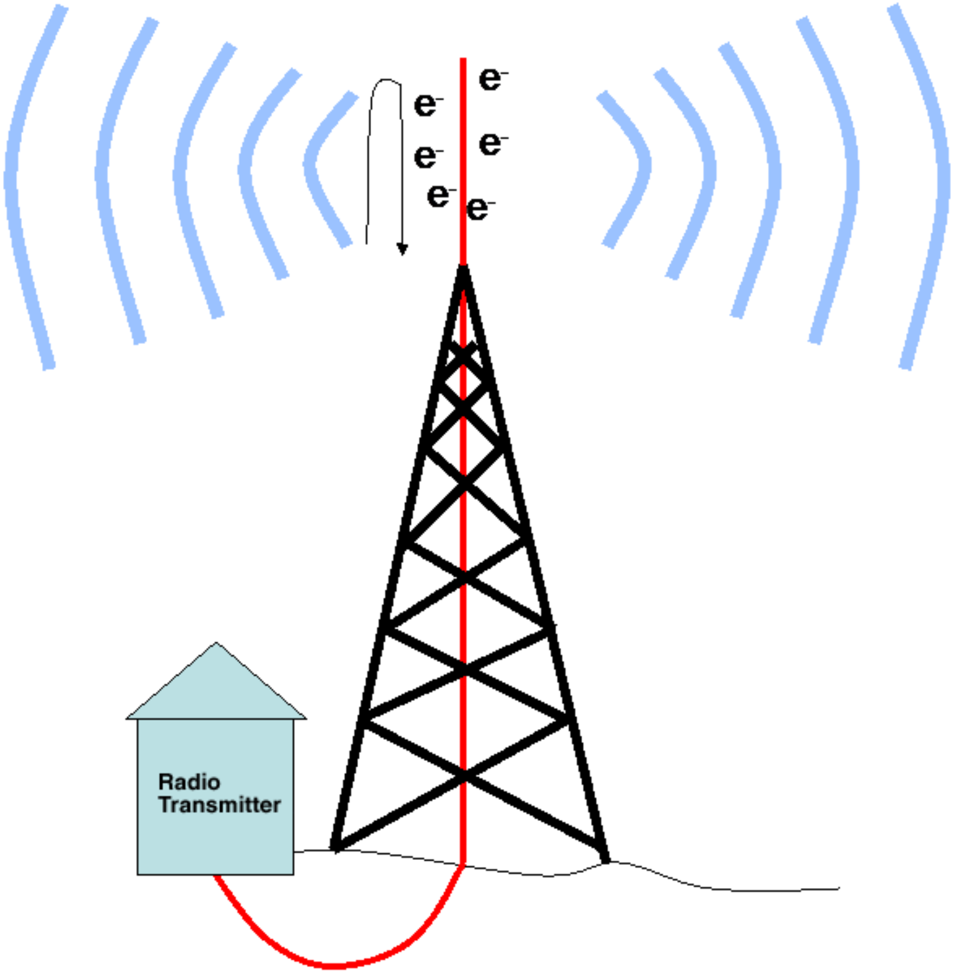
How is synchrotron light made?

by accelerating electrons

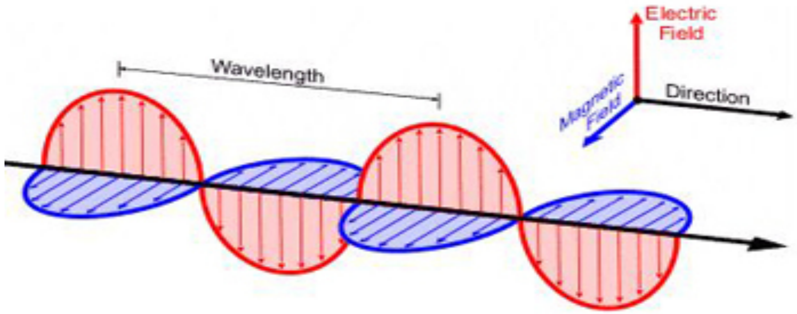
Electromagnetic Radiation

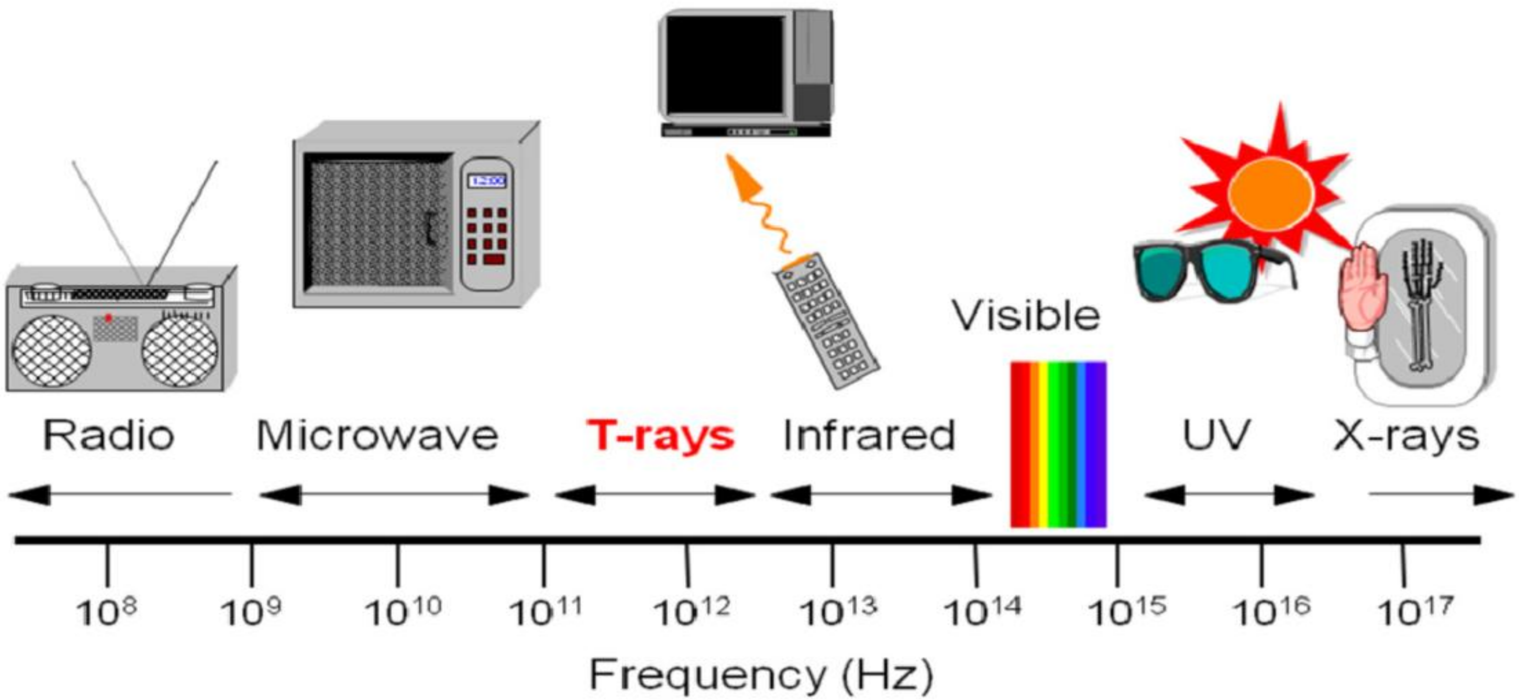
Electrons *accelerating* by running up and down in a radio antenna emit radio waves

Radio waves are nothing more than Long Wavelength Light



Electromagnetic Spectrum

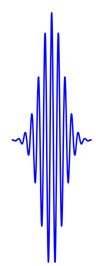




How far does light travel in 1 second? 1 femtosecond?

1 sec

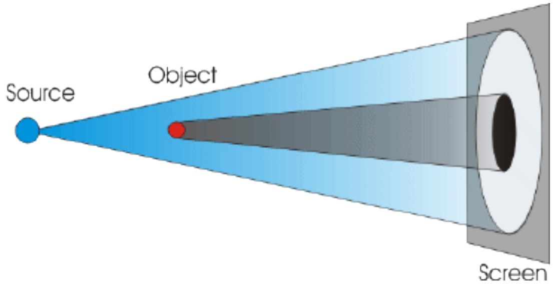
1 fs



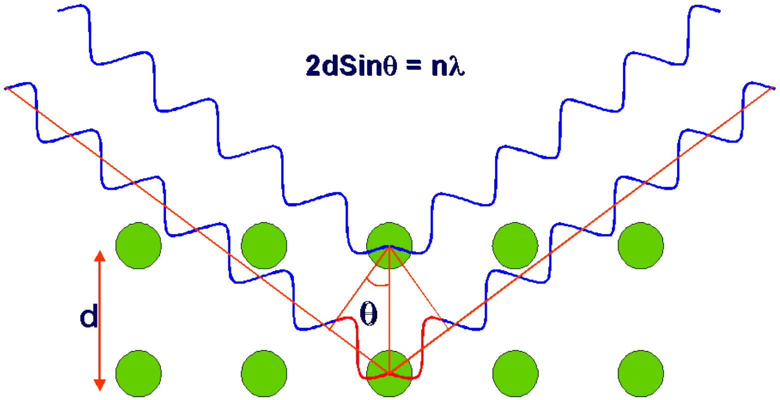
3,000 nm

(1/10 of a hair)

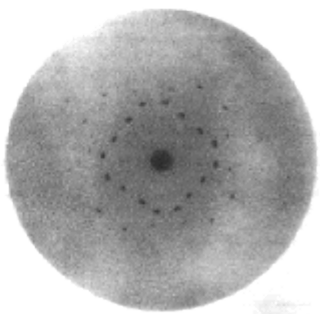
Interaction of photons with matter



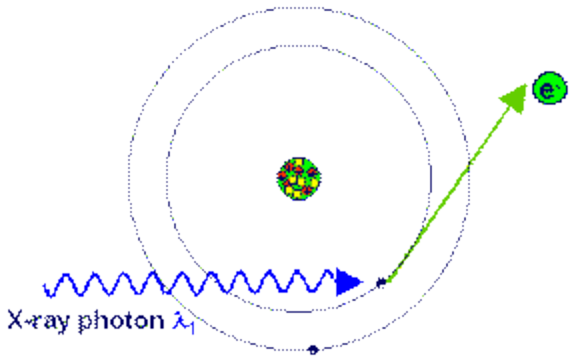
Radiagraphy



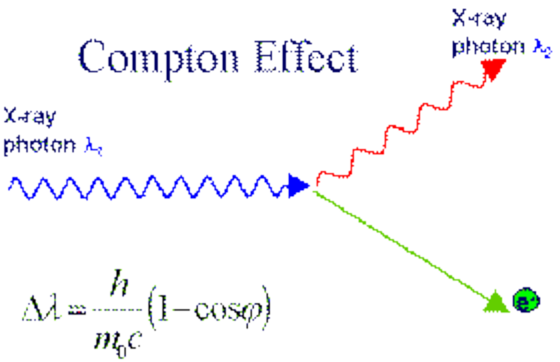
Bragg Diffraction



Laue Diffraction



Photoelectric Effect



Compton Scattering

Early History

1873 Maxwell' s Equations

- **Made evident that changing charge densities would result in electric fields that would radiate outward**

1887 Hertz demonstrated such waves

1895 Röntgen discovered X-Rays

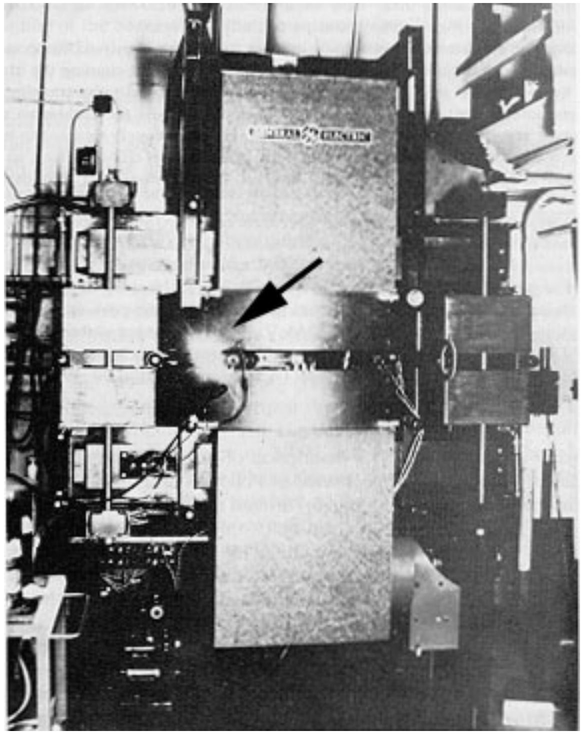
1897 Larmor derived an expression for the instantaneous total power radiated by an accelerated charged particle

1898 Lienard' s extended Larmor' s result to the case of a relativistic particle undergoing centripetal acceleration in a circular trajectory

1947 GE's 70-MeV synchrotron : First observation of Synchrotron Light in an accelerator

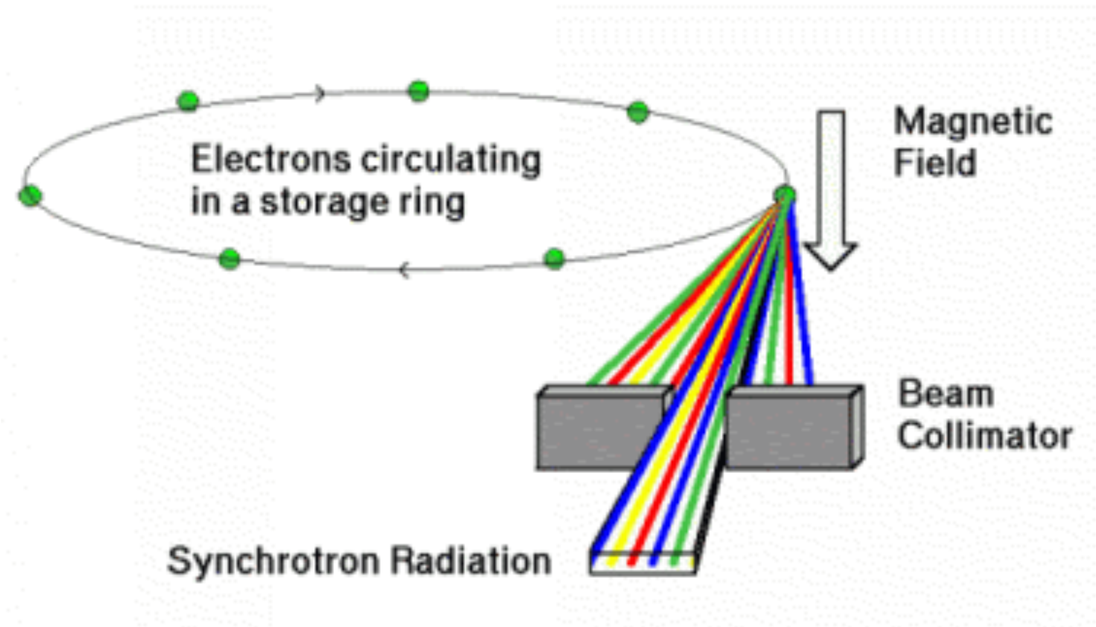
First observation of synchrotron radiation

GE Synchrotron
New York State



First light observed
1947

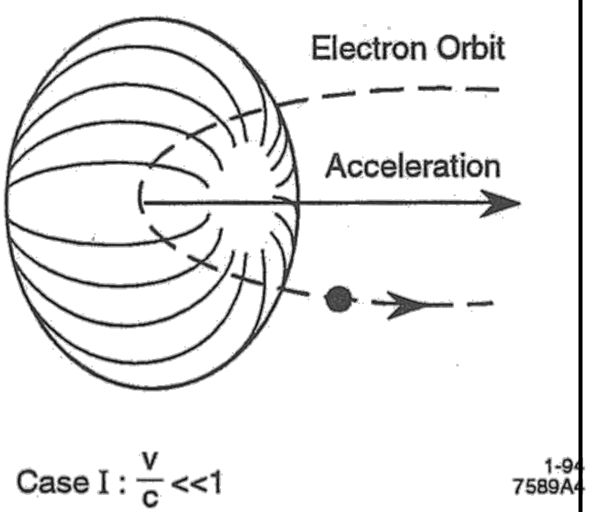
Why we need synchrotron radiation



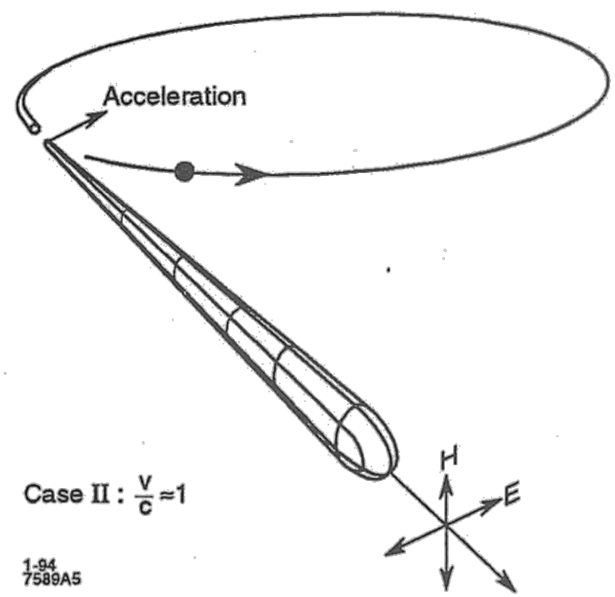
Synchrotron radiation is electromagnetic radiation emitted when charged particles are radially accelerated (move on a curved path).

Synchrotron Radiation

- Radiated power increases at higher velocities
- Radiation becomes more focused at higher velocities

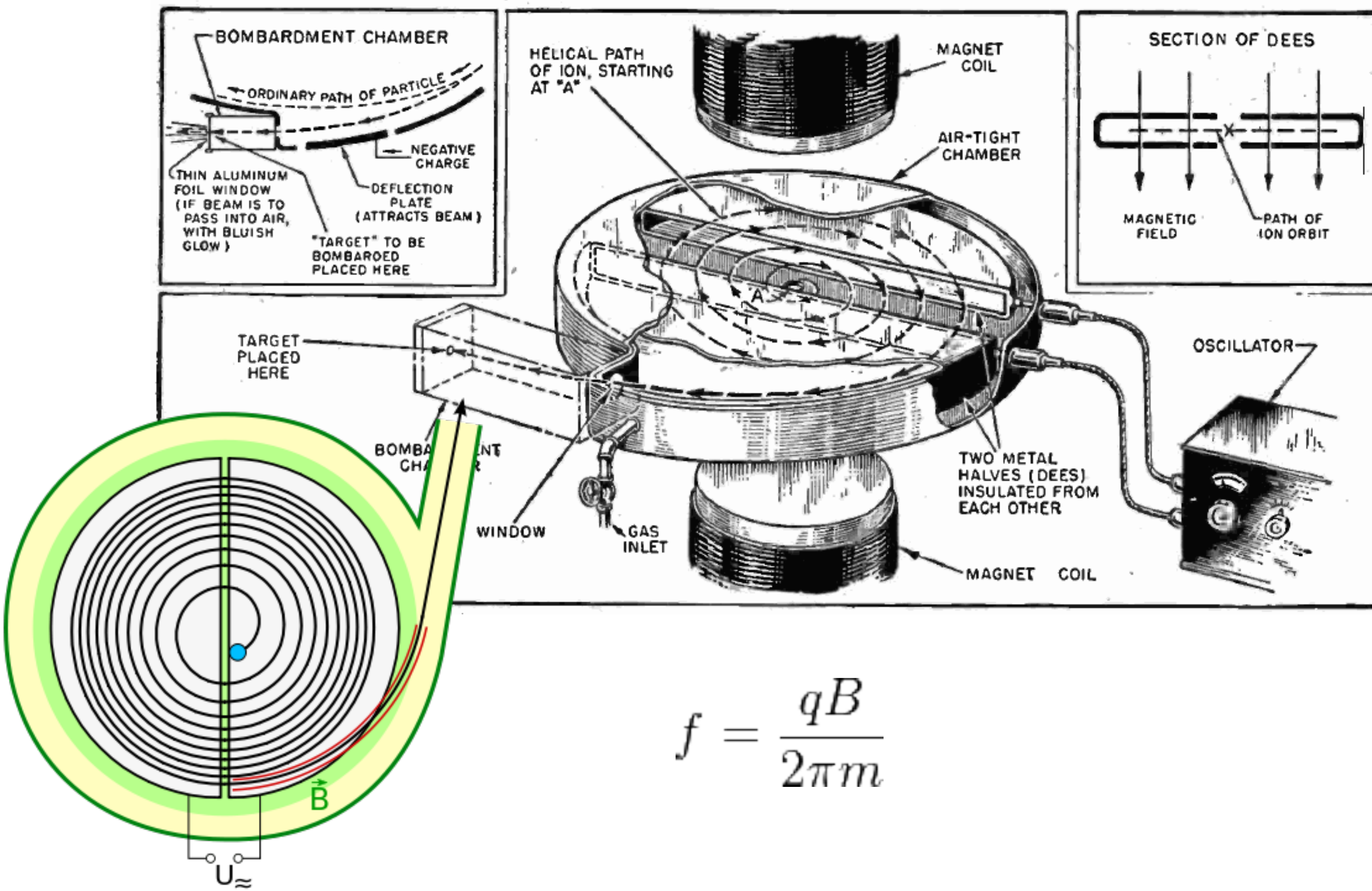


At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern



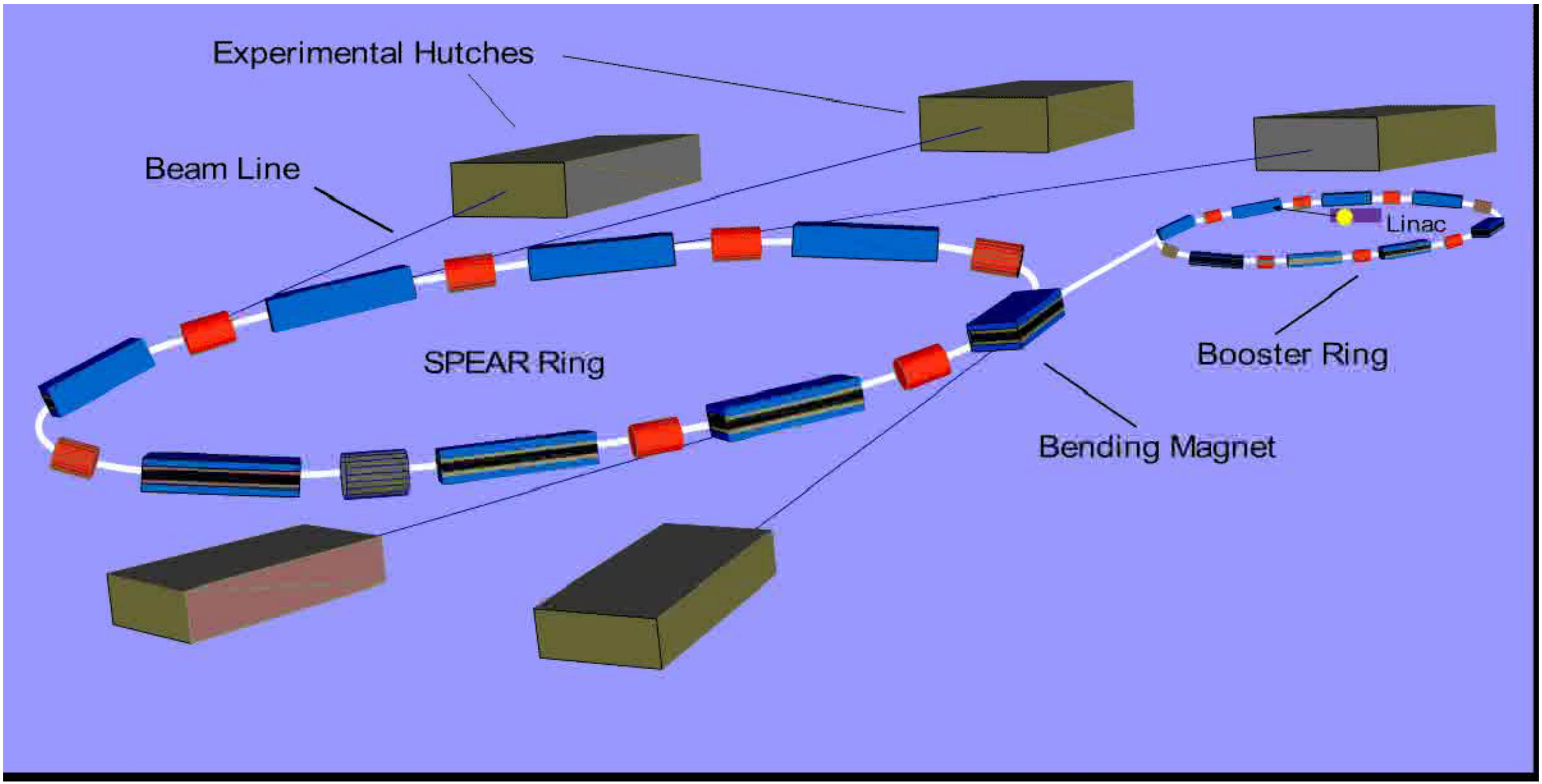
When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward. Also the radiated power goes up dramatically

Cyclotron



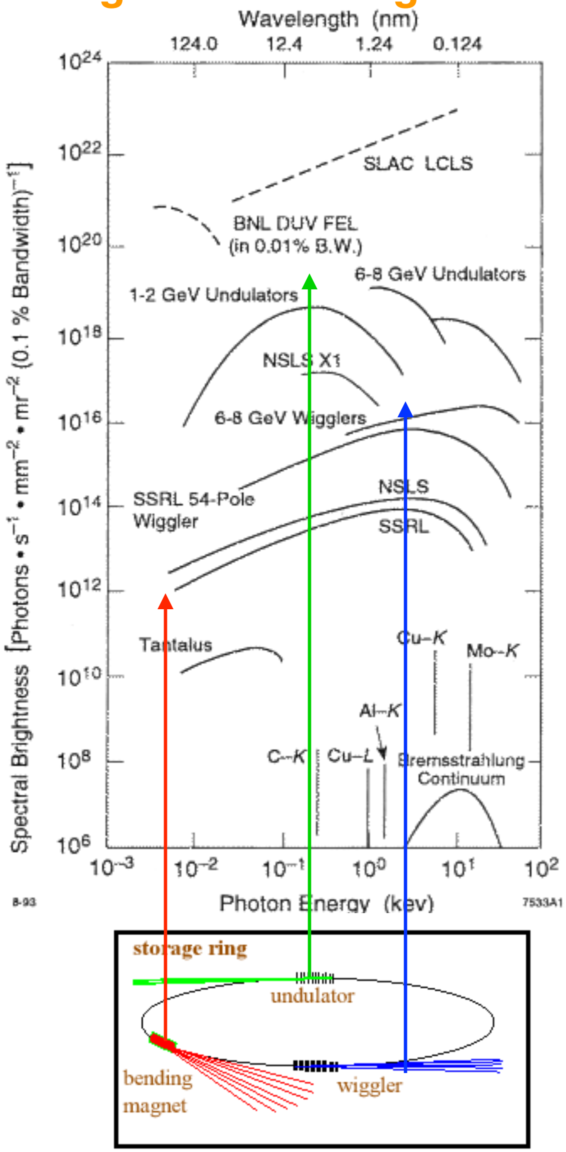
$$f = \frac{qB}{2\pi m}$$

How a storage ring light source works

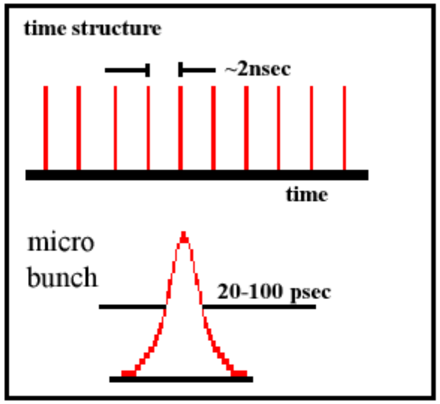


Synchrotron Radiation - Basic Properties

High flux and brightness



Pulsed time structure



Broad spectral range

Polarized (linear, elliptical, circular)

Small source size

Partial coherence

High stability

Flux = # of photons in given $\Delta\lambda/\lambda$ / sec

Brightness = # of photons in given $\Delta\lambda/\lambda$ / sec, mrad θ, mrad φ, mm^2

(a measure of concentration of the radiation)

Basic Properties of Synchrotron Radiation

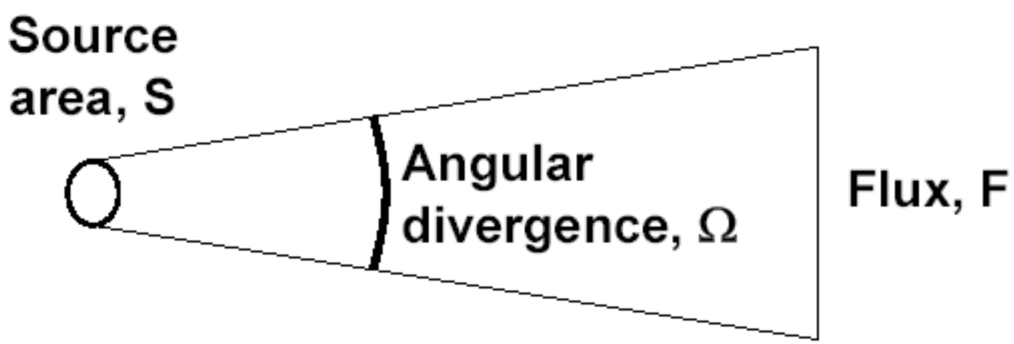
1. **HIGH FLUX, BRIGHTNESS, STABILITY**
2. **BROAD SPECTRAL RANGE - Tunability**
3. **POLARIZATION (linear, elliptical, circular)**
4. **PULSED TIME STRUCTURE (0.01 - 1 nsec)**
5. **SMALL SOURCE SIZE ($\leq$ mm)**
6. **PARTIAL COHERENCE**

The brightness of a light source

Flux = $\frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec}}$

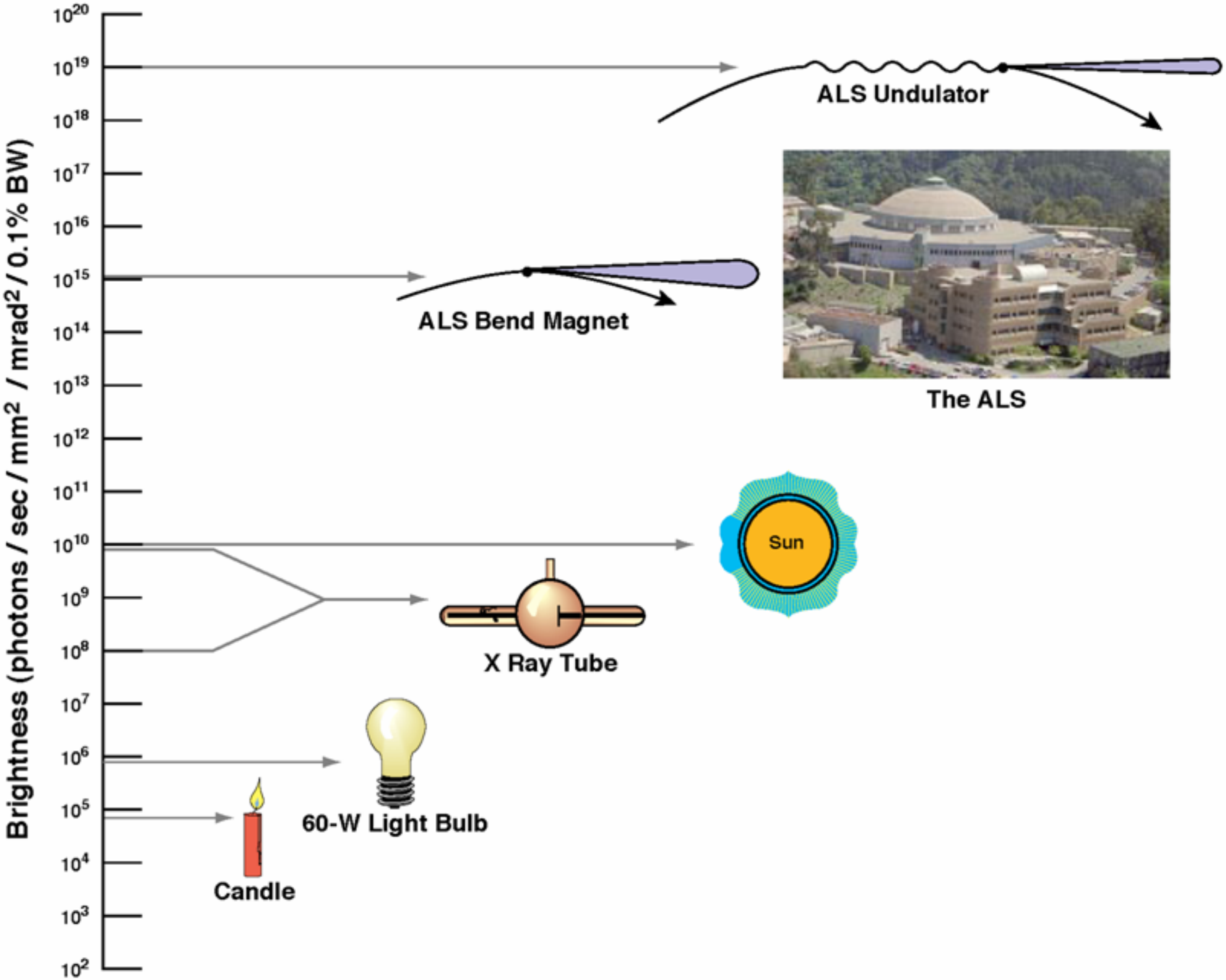
Brightness = $\frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$

(a measure of concentration of the radiation)



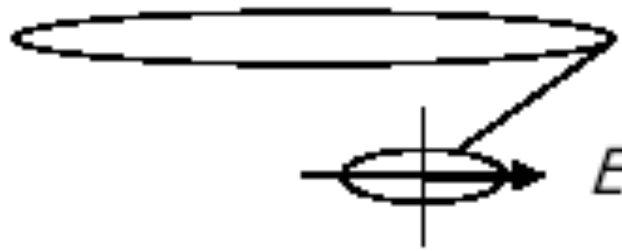
Brightness = constant x $\frac{F}{S \times \Omega}$

How Bright Is the Advanced Light Source?

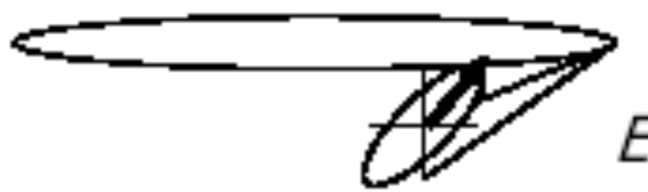


Polarisation

Synchrotron radiation observed in the plane of the particle orbit is horizontally polarized, i.e. the electric field vector is horizontal



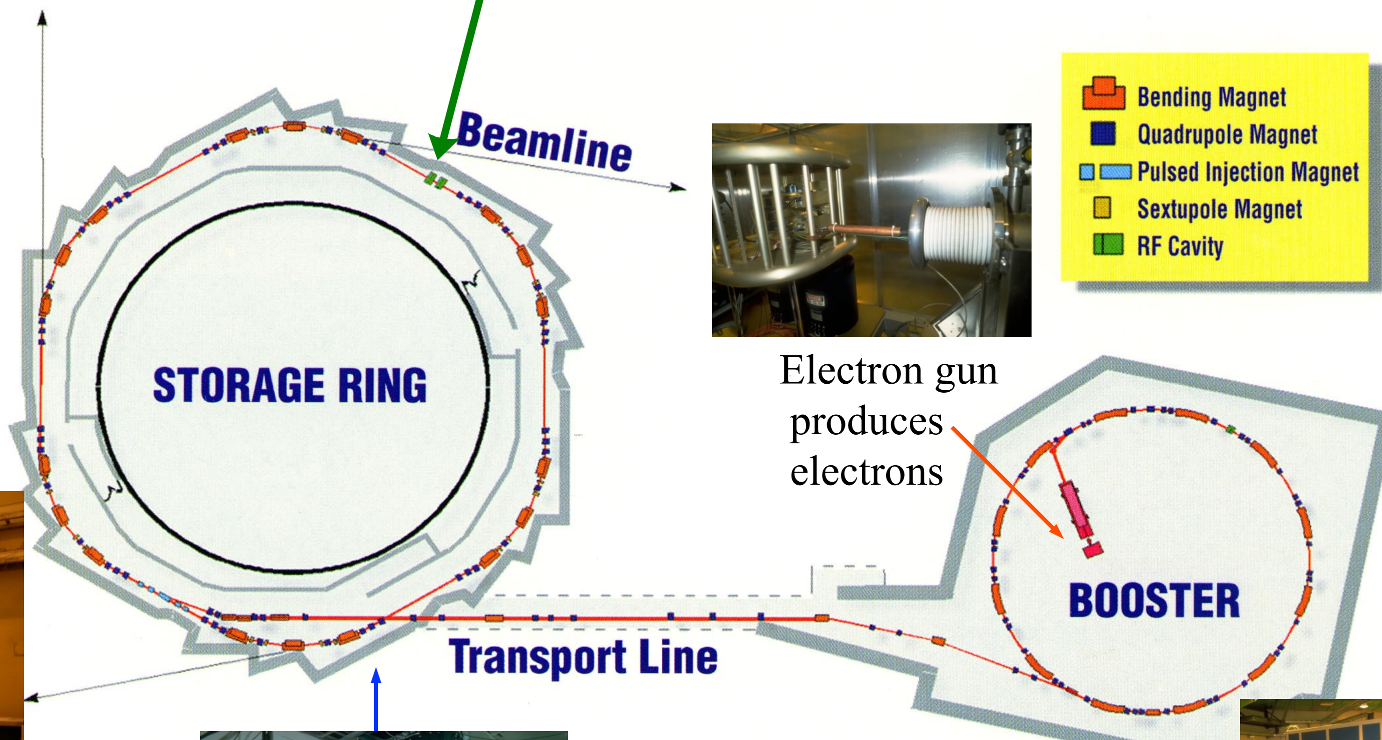
Observed out of the horizontal plane, the radiation is elliptically polarized



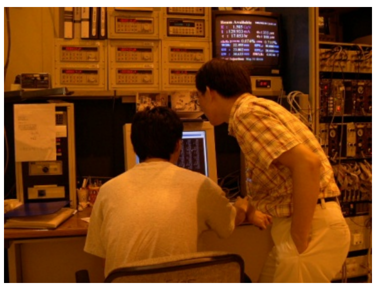
How is it Practically Produced and Used for Research?

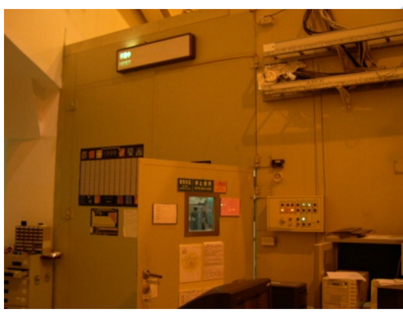
The storage ring circulates electrons, where they are bent, synchrotron radiation is produced

Klystrons generate high power radio wave to sustain electron acceleration, replenishing energy lost to synchrotron radiation

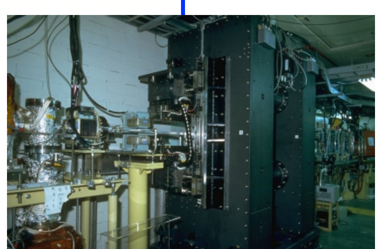


Electron gun produces electrons

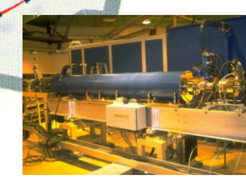




Beam lines transport radiation into “hutches”, where instrumentation is available for experiments



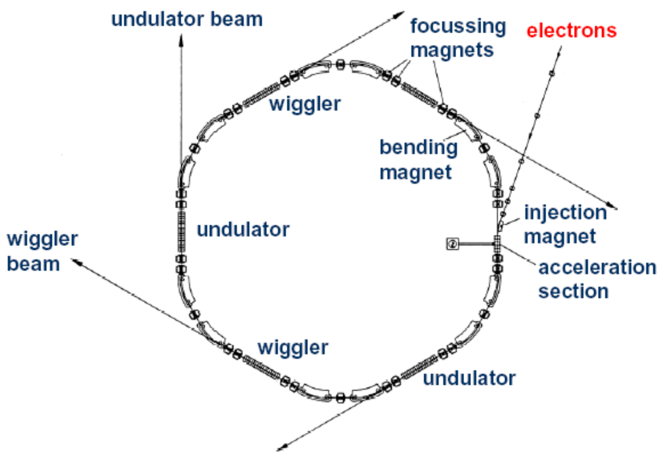
Wiggler / Undulator insertion devices generate strong x-ray beams



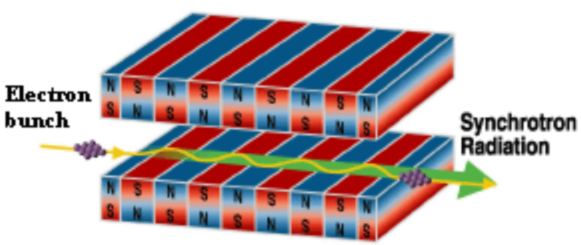
Linear accelerator/ booster accelerate e^- which are transported to storage ring

Bending magnet & insertion device

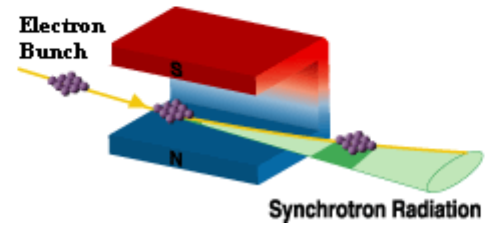
Storing Ring



Undulator / Wiggler

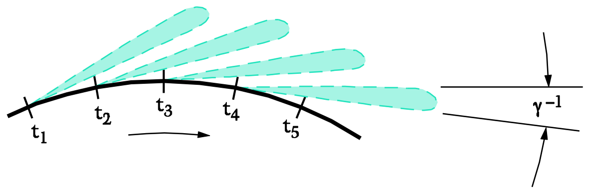


- **Bending Magnet**
  - White X-rays
  - Wide horizontal divergence
  - $1/\gamma$ limited vertical divergence
  - Moderate power
  - Moderate power density

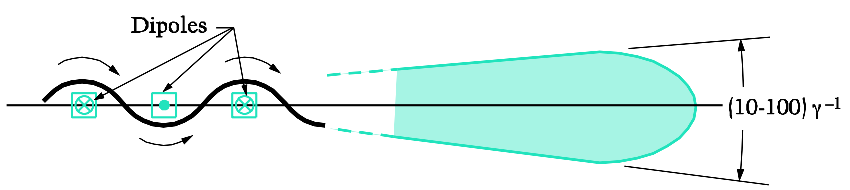


- **Wiggler**
  - White X-rays
  - Moderate horizontal divergence
  - $1/\gamma$ Limited vertical divergence
  - High power
  - High power density
  - Elliptically polarized/linearly polarized
- **Undulator**
  - Quasi-monochromatic X-rays
  - Small vertical and horizontal divergence (Central Cone)
  - High power
  - Extremely high power density
  - Circularly polarized/ linearly polarized

Bending Magnets and Insertion Devices on Storage Rings



bending magnet - a "sweeping searchlight"

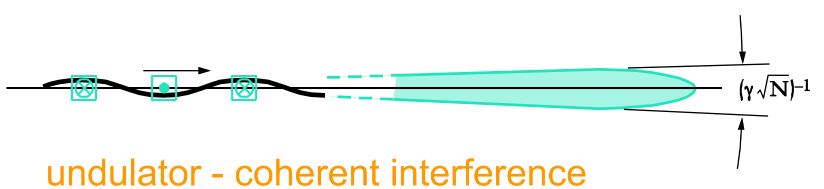


wiggler - incoherent superposition

Continuous spectrum characterized by ε_c = critical energy

ε_c(keV) = 0.665 B(T)E^2(GeV)

eg: for B = 1.35T E = 2GeV
ε_c = 3.6keV



undulator - coherent interference

Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_U}{\gamma_2} \text{ (fundamental)}$$

+ harmonics at higher energy

$$\varepsilon_1 \text{ (keV)} = \frac{0.95\, E^2 \text{ (GeV)}}{\lambda_u^{(cm)} \left(1 + \frac{K^2}{2}\right)}$$

K = $\gamma\theta$ where θ is the angle in each pole

Synchrotron Radiation Facilities Around the World

- **54 in operation in 19 countries used by more than 20,000 scientists**

  (Brazil, China, India, Korea, Taiwan, Thailand)

- **8 in construction**

  Armenia, Australia, China, France, Jordan, Russia, Spain, UK

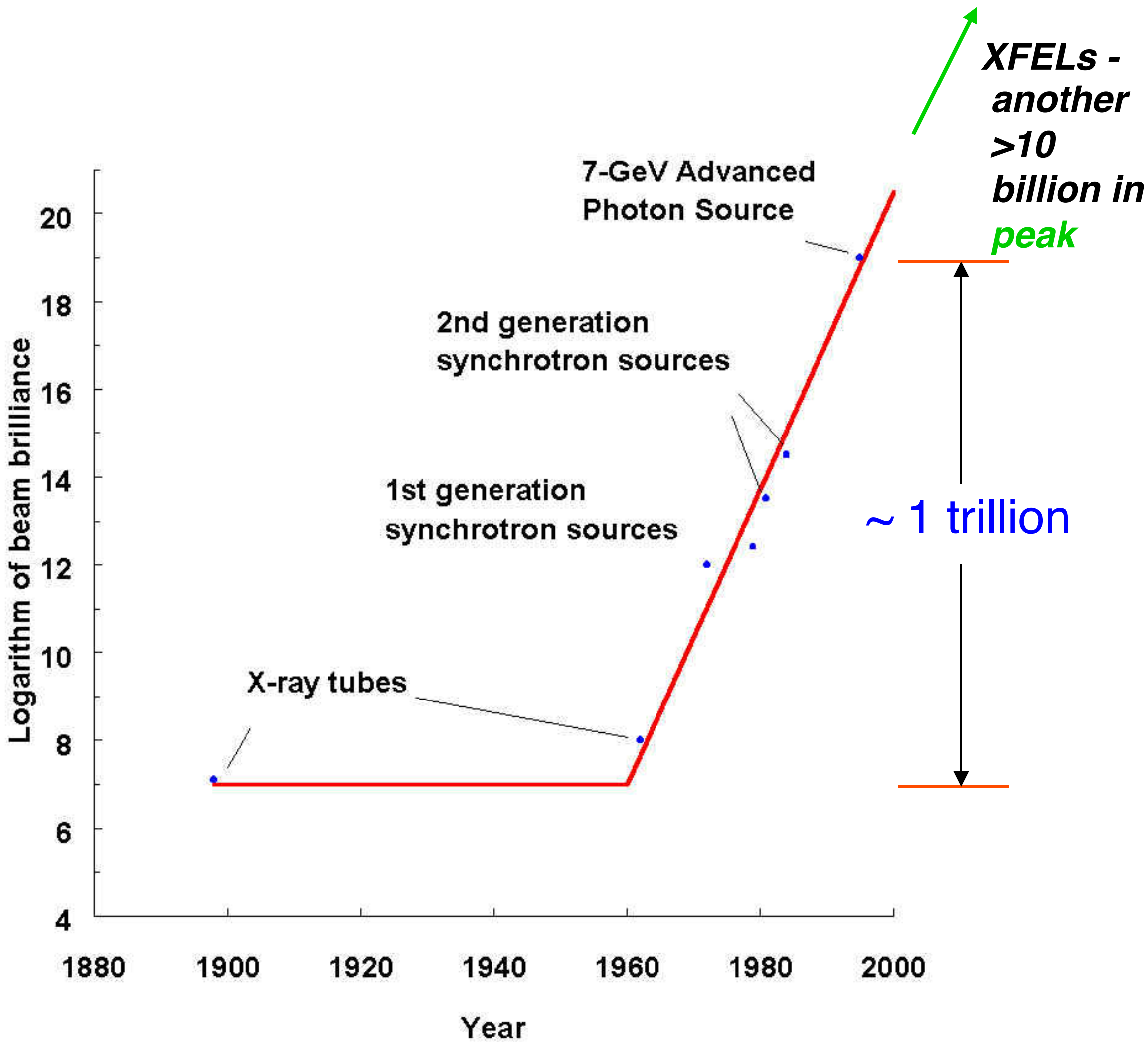
- **11 in design/planning**

For a list of SR facilities around the world see

http://ssrl.slac.stanford.edu/SR_SOURCES.HTML

www.sesame.org.jo

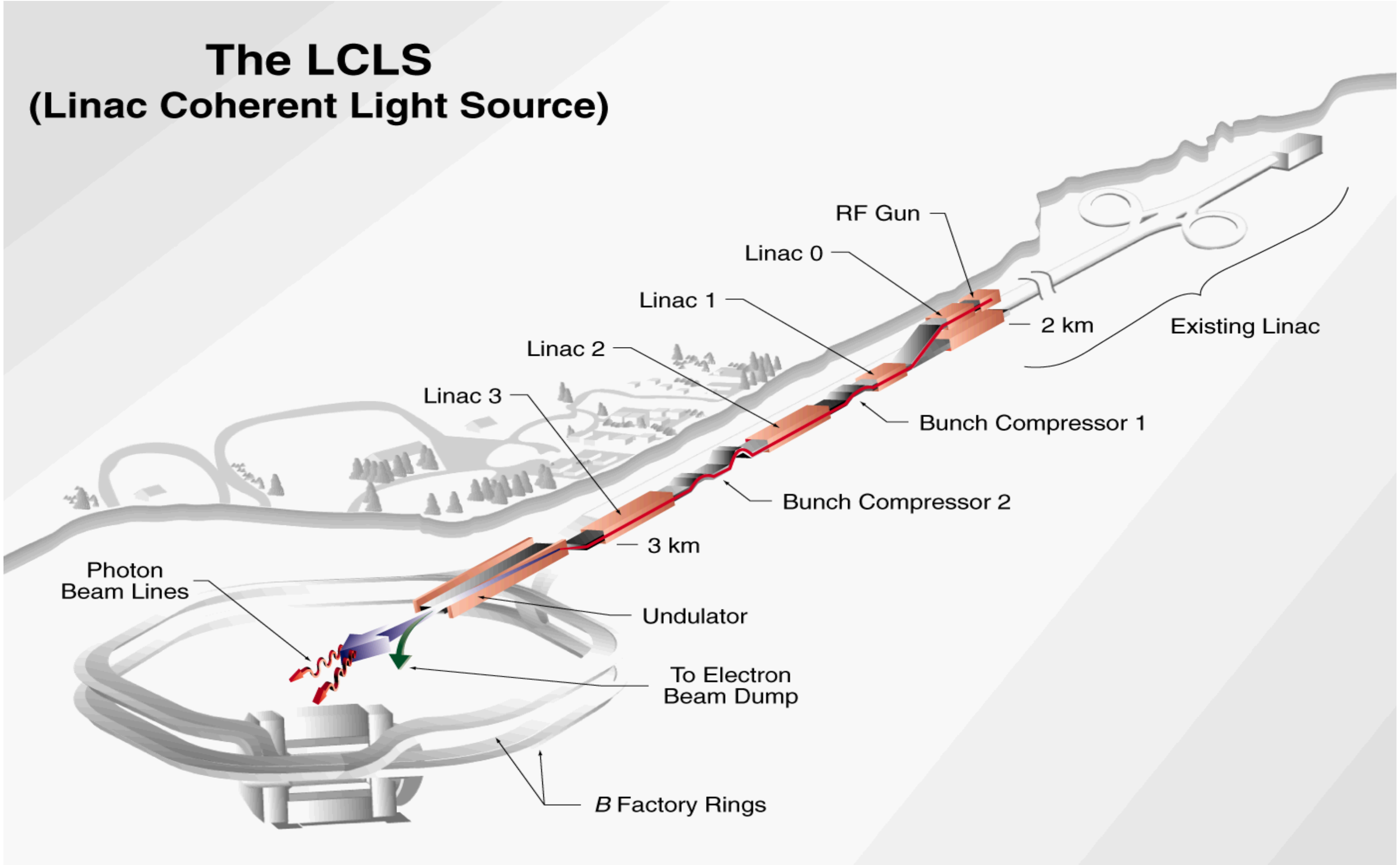
Steep growth in brightness



Future of Synchrotron Radiation

- Higher Brightness
  - Free Electron Lasers
- Shorter Pulse Lengths
  - Femto (10^{-12}) and Attosecond (10^{-15})
- Terahertz (T-rays)
  - Coherent Synchrotron Radiation

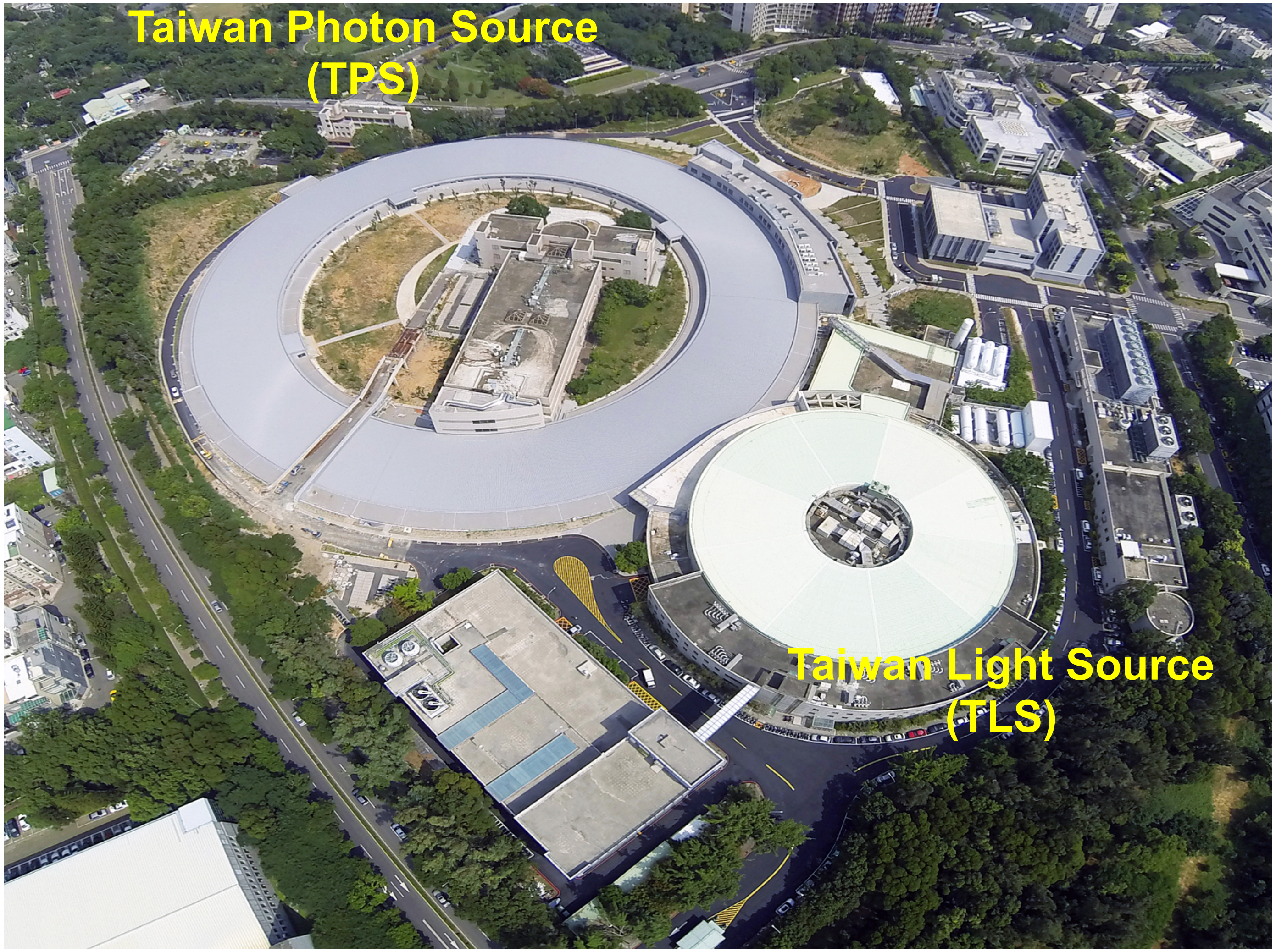
Linac-driven Light Sources - Toward the 4th Generation (operation in 2008)



ADVANCED PHOTON SOURCE · Stanford Linear Accelerator Center · SSRL · LLNL · UCLA · nsls · Los Alamos science serving society

Taiwan Photon Source (TPS) – Hsinchu, Taiwan

http://www.nsrrc.org.tw



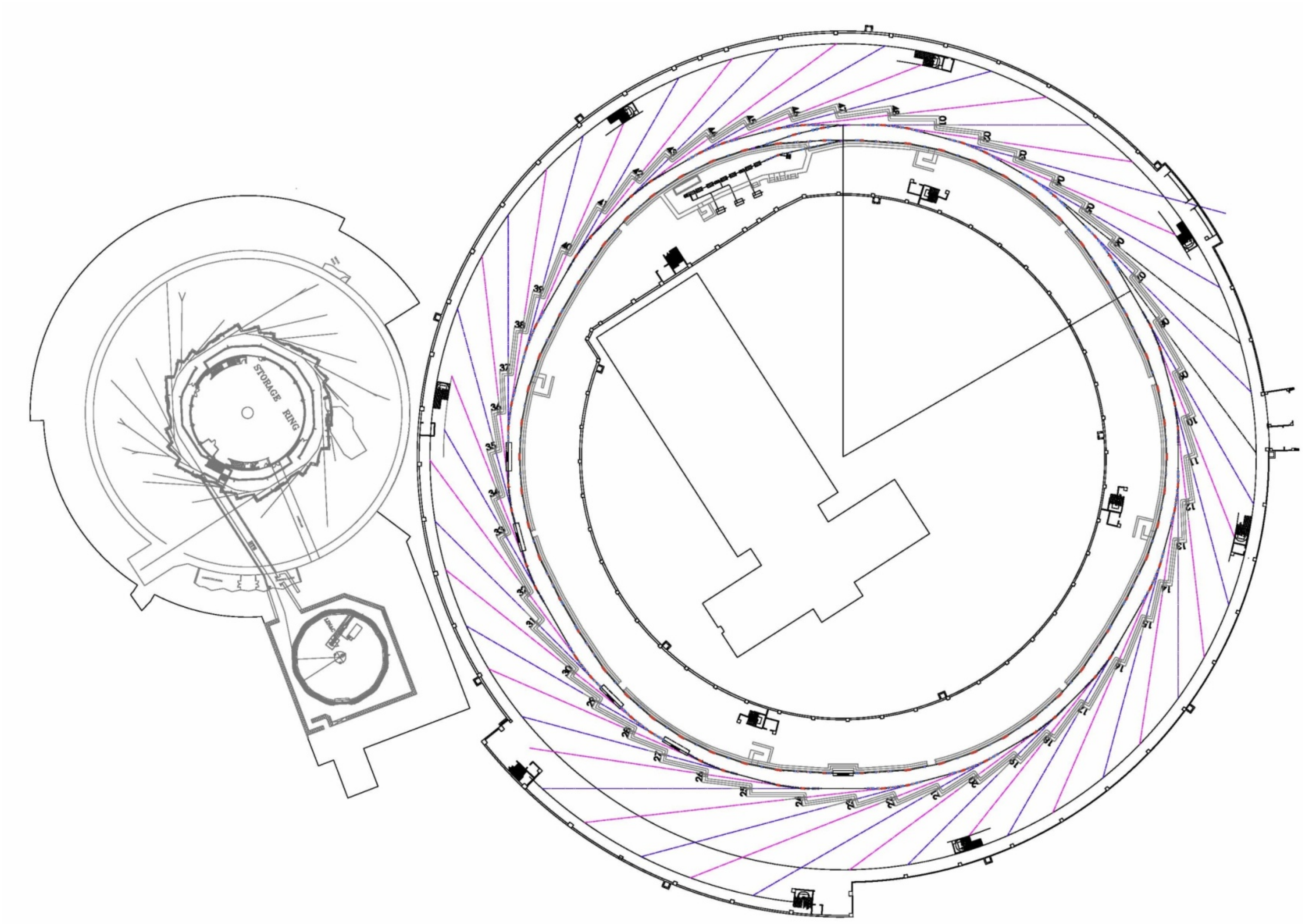
Taiwan Photon Source (TPS) – Hsinchu, Taiwan (continued)

Major Parameters of Taiwan Photon Source

Energy	3 GeV (maximum 3.3 GeV)
Current	500 mA at 3 GeV (Top-up injection)
SR circumference	518.4 m (h = 864 = $2^5 \cdot 3^3$, dia.= 165.0 m)
BR circumference	496.8 m (h = 828 = $2^2 \cdot 3^2 \cdot 23$, dia.= 158.1 m)
Lattice	24-cell DBA
Straight sections	12 m x 6 (σ_v = 12 μm, σ_h = 160 μm) 7 m x 18 (σ_v = 5 μm, σ_h = 120 μm)
Bending magnets	48
Emittance	1.6 nm·rad at 3 GeV (Distributed dispersion)
Coupling	1 %
RF frequency	500 MHz
RF gap voltage	2.8~3.5 MV (3 SRF cavities)
RF power	750 kW (3 SRF cavities)
Location	No. 101, Hsin-Ann Road, Hsinchu, Taiwan
Building	Outer diameter 210 m ; Inner diameter 129 m

Taiwan Photon Source (TPS) – Hsinchu, Taiwan (continued)

TPS & TLS Lattice Diagram



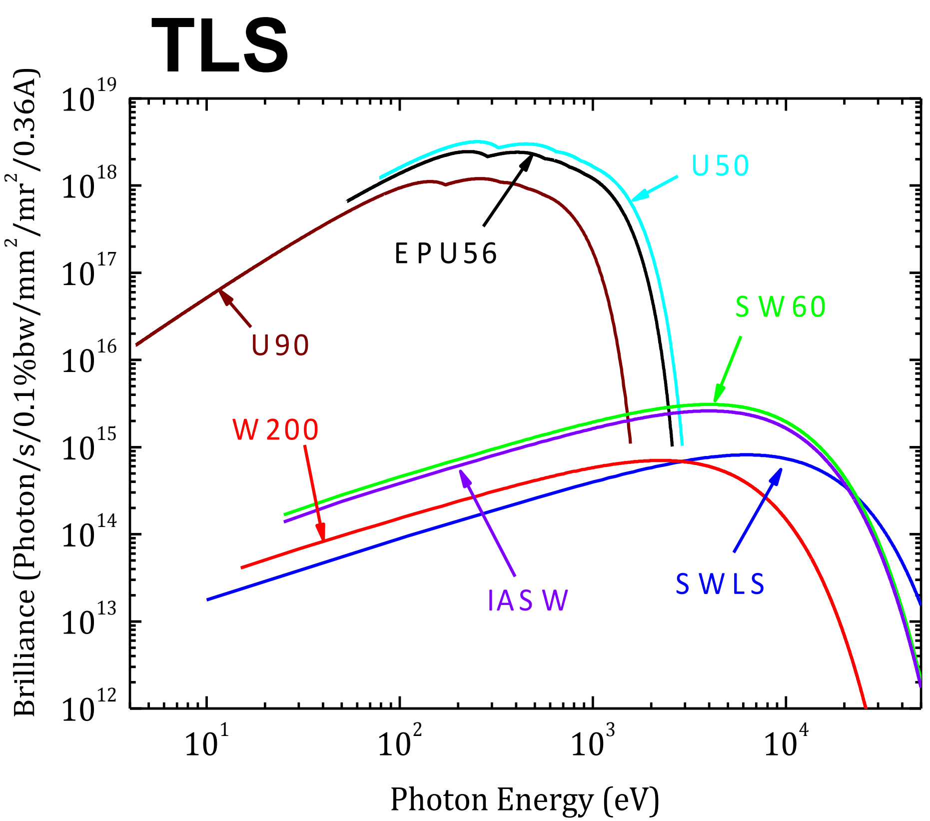
Taiwan Photon Source (TPS) – Hsinchu, Taiwan (continued)

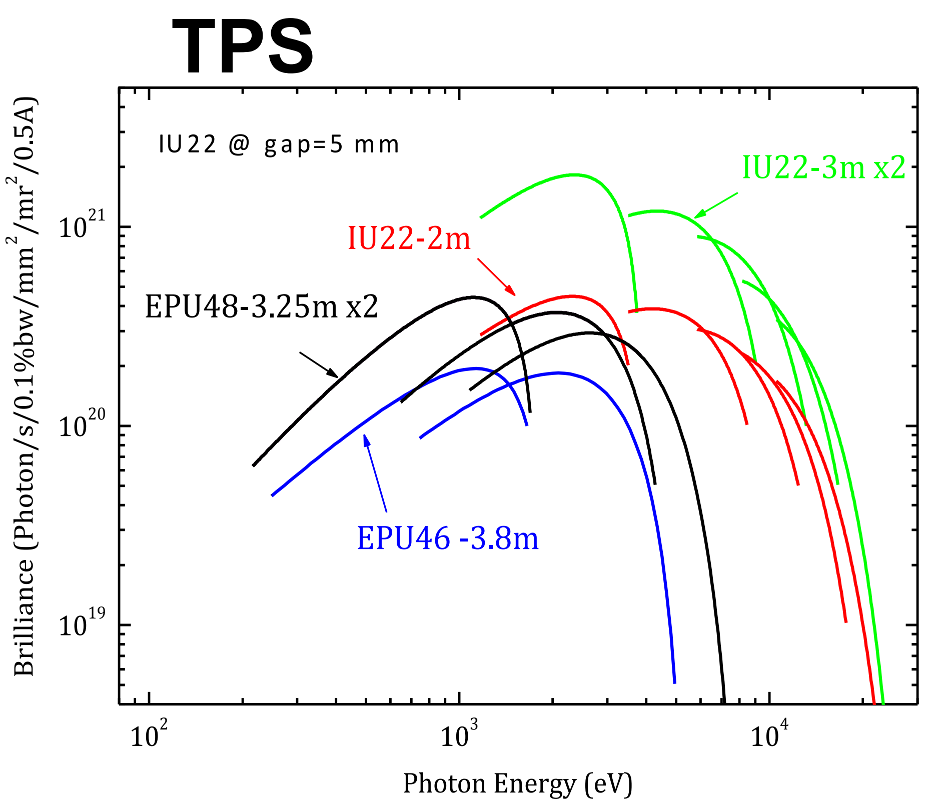
Brightness Comparison of TLS and TPS

The X-ray spectrum (photon energy 8 keV~70 keV)：

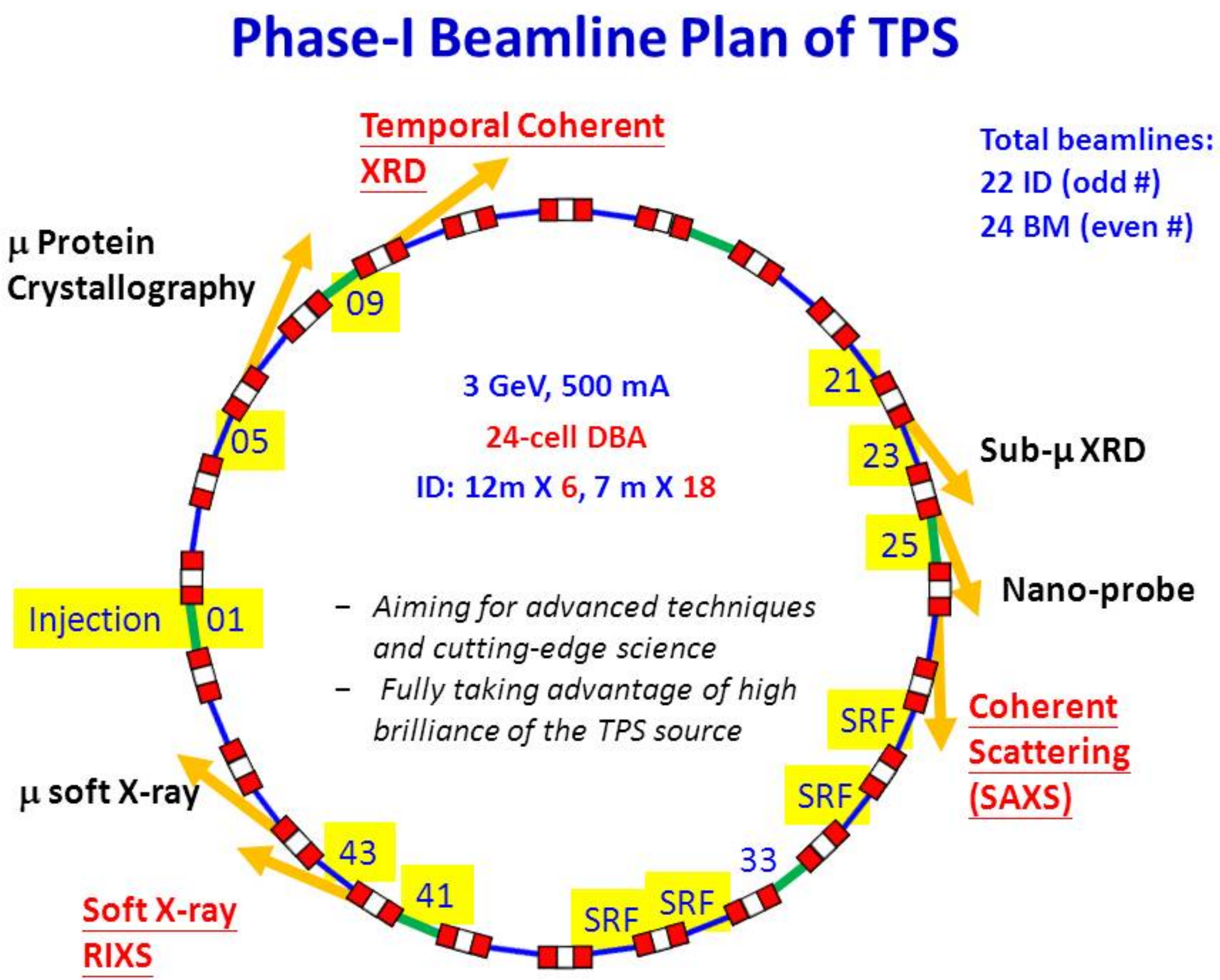
the brilliance of bending magnet increases by $>10^2$.

the brilliance of bending IDs increases by 4~6 orders of mag.





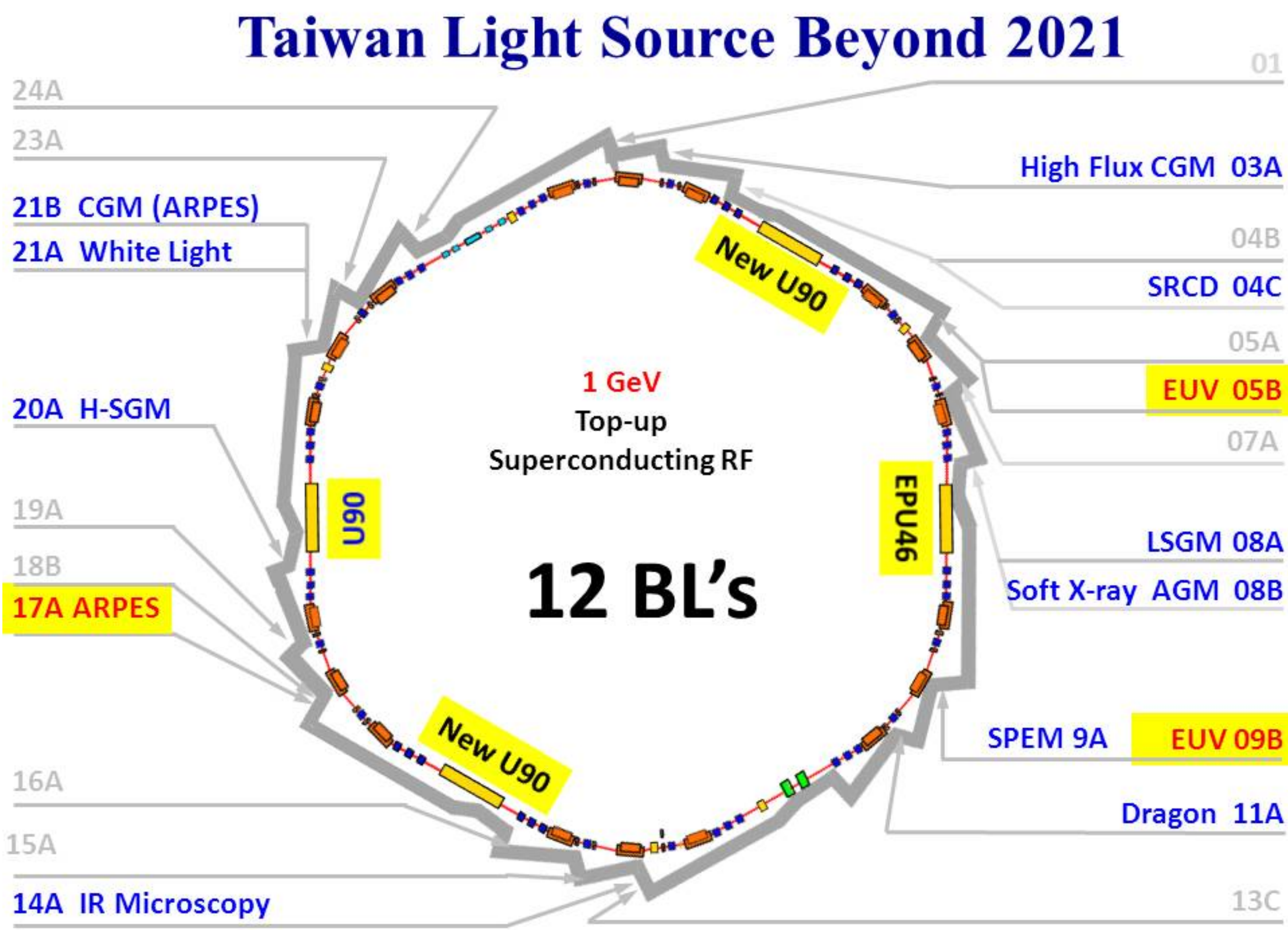
Taiwan Photon Source (TPS) – Hsinchu, Taiwan (continued)



TPS Phase I Beamlines

- *μ-focus macromolecular crystallography* (2013)
  *(*微聚焦巨分子結晶學光束線*)*
- *High resolution inelastic soft-x-ray scattering* (2013)
  *(*高解析非彈性軟X光散射學光束線*)*
- *Sub-μ soft x-ray photoelectron & fluorescence emission* (2013)
  (次微米軟X光能譜學光束線)
- *Coherent x-ray scattering (SAXS/XPCS)* (2014)
  *(*軟物質小角度散射學光束線*)*
- *Sub-μ x-ray diffraction* (2014)
  *(*次微米繞射光束線光束線*)*
- *Nano-probe* (2014)
  *(*奈米探針光束線*)*
- *Temporal coherent x-ray scattering* (2014)
  *(*時間同調性散射光束線*)*

Taiwan Photon Source (TPS) – Hsinchu, Taiwan (continued)

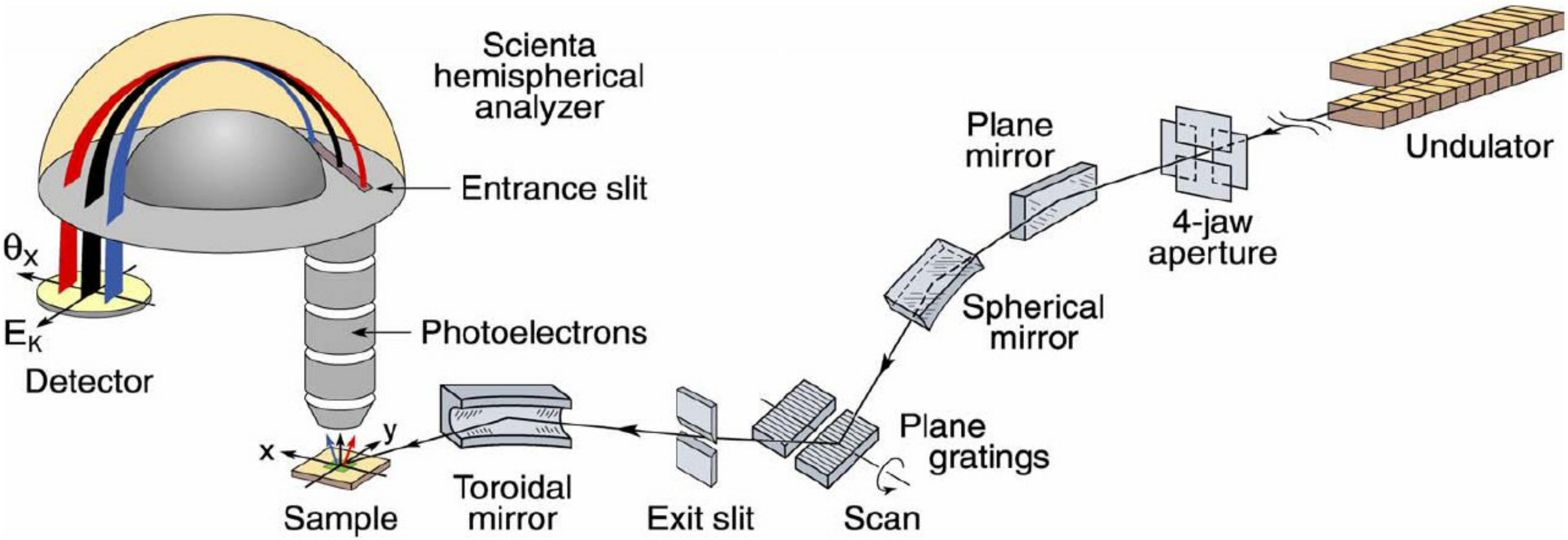


Angle-Resolved Photo-Emission Spectroscopy (ARPES)

Working of ARPES

- An atomically flat sample is illuminated by a beam of monochromatic light.
- Due to the photoelectric effect, the sample emits electrons.
- The kinetic energy and direction of these electrons are measured by the rotatable spectrometer.
- The obtained data are used to map out the Fermi surface of the sample material.

ARPES setup



Parallel multi-angle recording

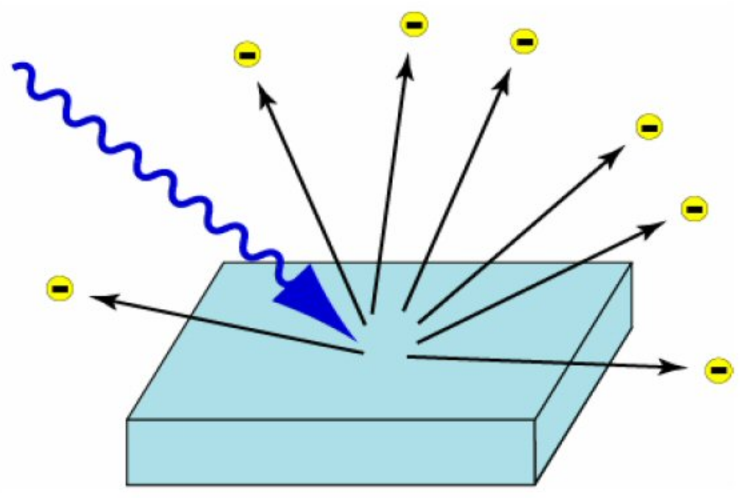
- Improved **energy resolution**
- Improved **momentum resolution**
- Improved **data-acquisition efficiency**

	ΔE *(meV)*	$\Delta\theta$
past	*20-40*	*2°*
now	*2-10*	*0.2°*

Photoelectric Effect

- Explained by Einstein (1905):

$$E_{k_{\max}} = hf - \phi$$



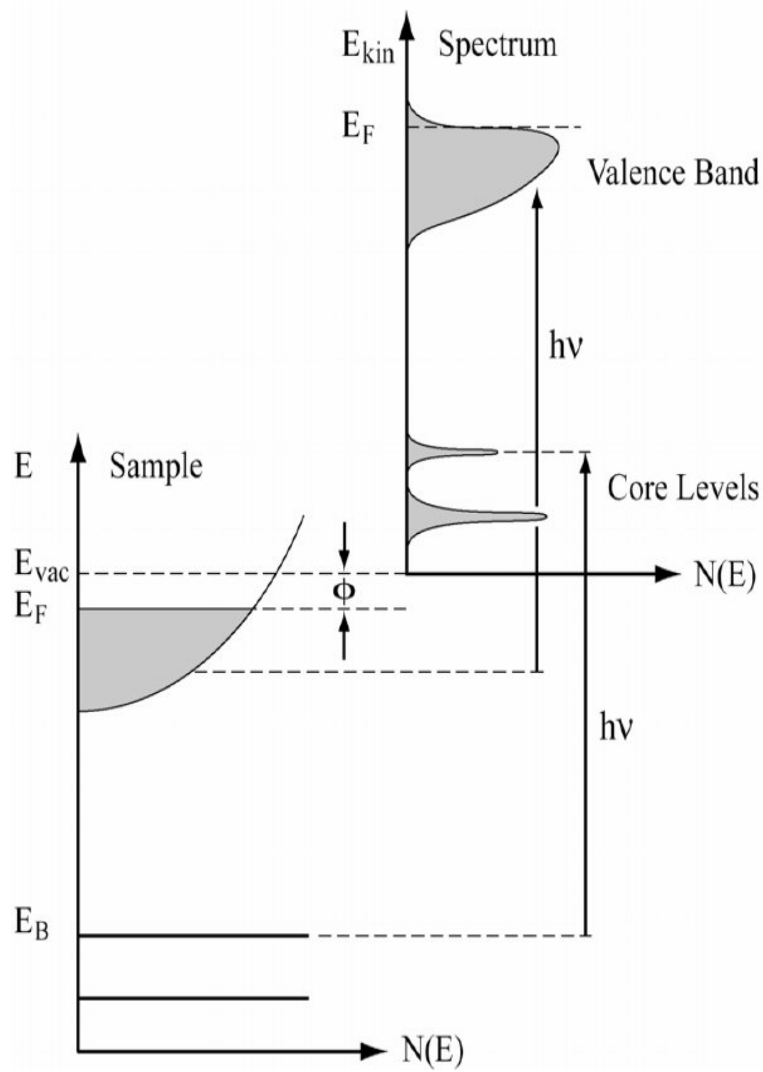
- More generally,

$$E_k = hf - \phi - |E_B|$$

where E_B is the binding energy of the electron.

Photoemission Spectra

- The work function is known/ measurable.
- The photon energy is known.
- We can calculate the energy of the electron in the solid!

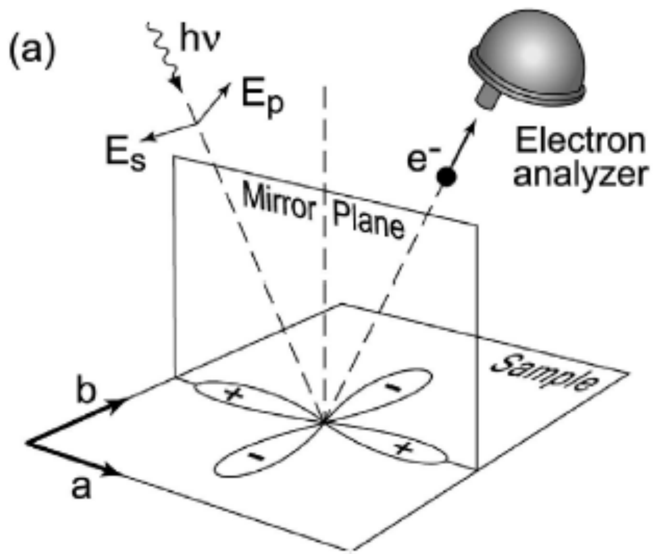


Basis of ARPES

ARPES is directly measuring the components of electron momentum that are parallel to the surface

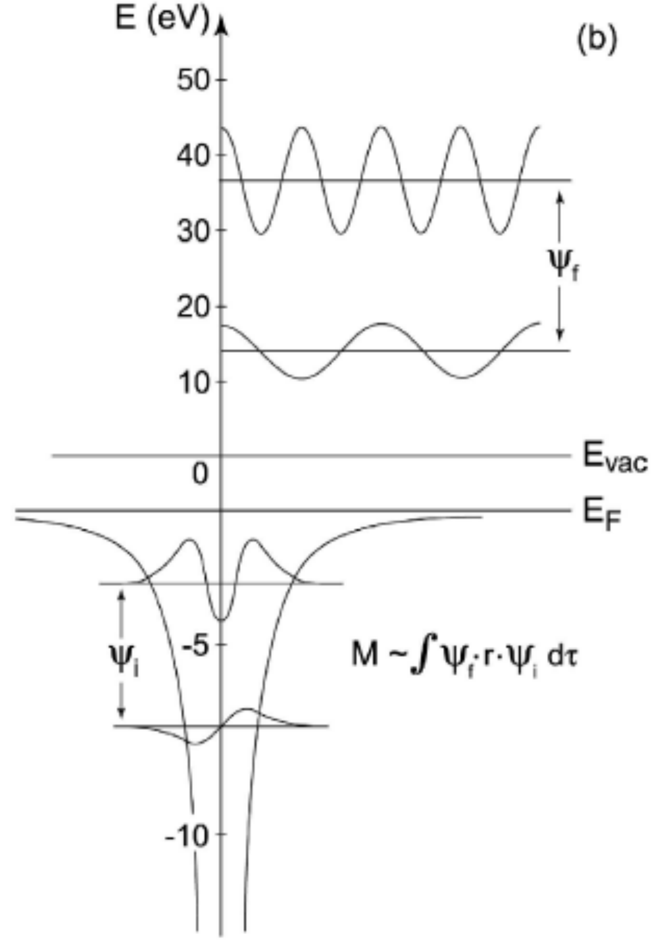
- The flat surface of the sample has translational symmetry. Therefore, as electrons escape from the solid, linear momentum is conserved parallel to the surface.

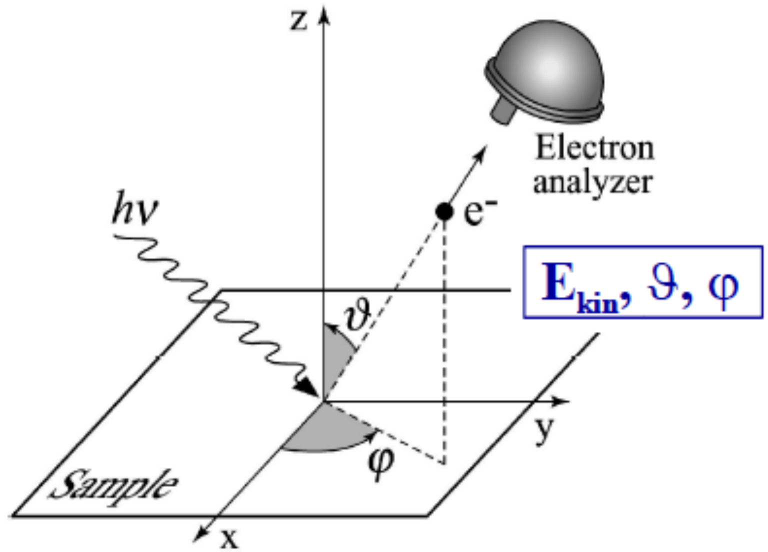
- The photon momentum is small and can be neglected.



$$w_{fi}=\frac{2\pi}{\hbar}\left|\langle\Psi_f^N|H_{int}|\Psi_i^N\rangle\right|^2\delta(E_f^N-E_i^N-h\nu)$$

$$H_{int}=-\frac{e}{2mc}(\mathbf{A}\cdot\mathbf{p}+\mathbf{p}\cdot\mathbf{A})=-\frac{e}{mc}\mathbf{A}\cdot\mathbf{p}$$



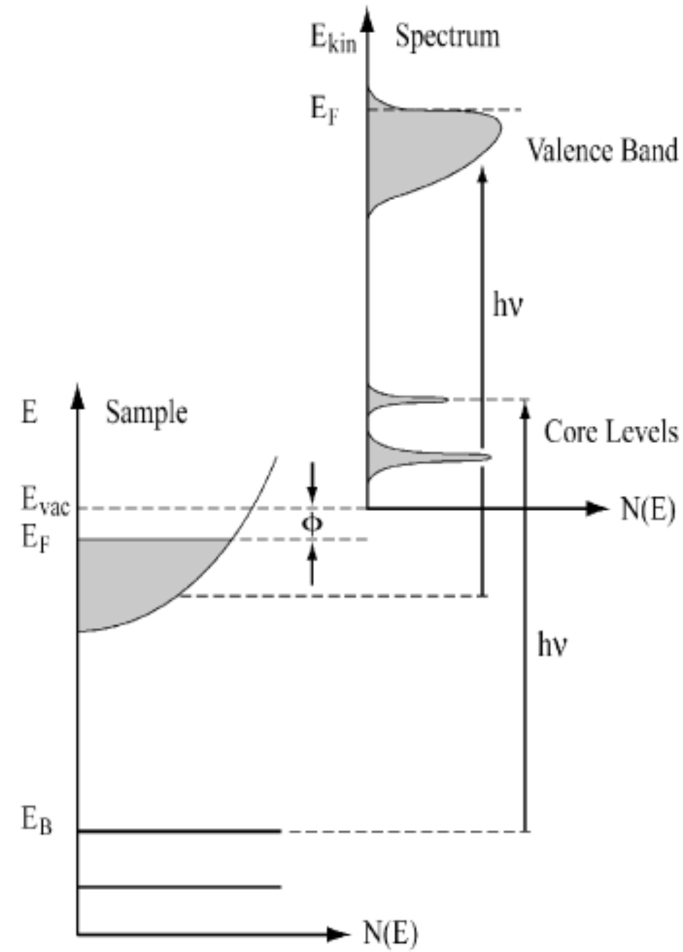


Energy Conservation

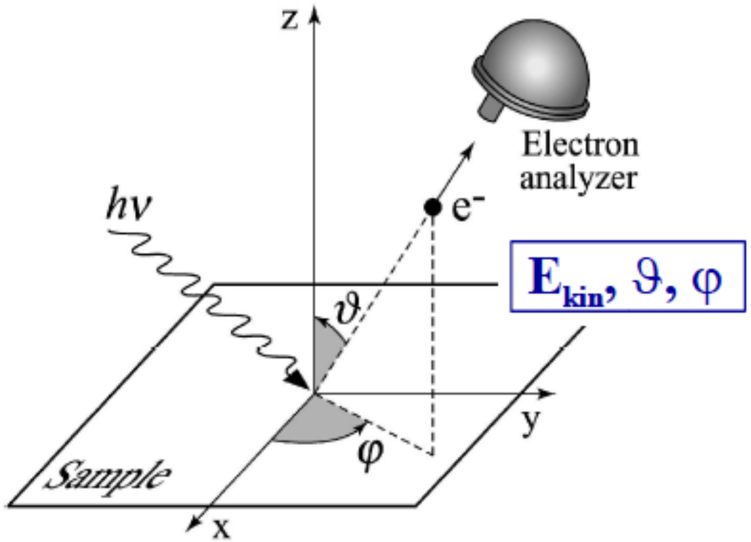
$$E_{kin} = h\nu - \phi - |E_B|$$

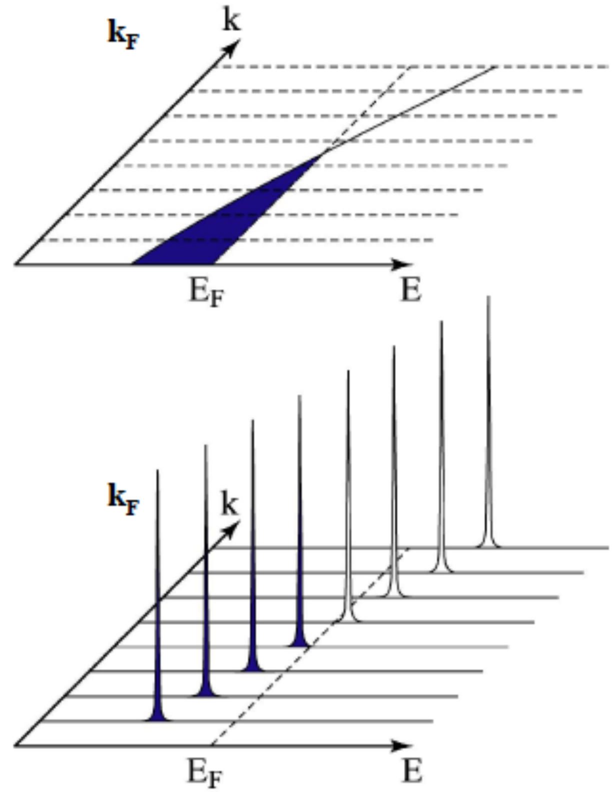
Momentum Conservation

$$p_{\parallel} = \hbar k_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$



Electrons in Reciprocal Space



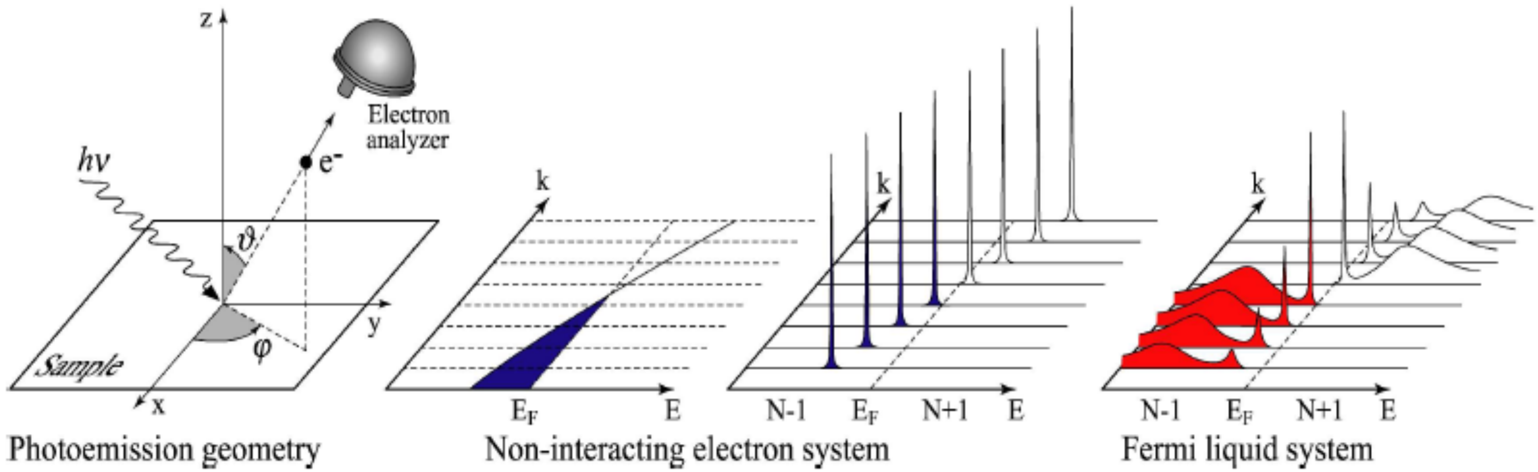


Energy Conservation

$$E_{kin} = h\nu - \phi - |E_B|$$

Momentum Conservation

$$\mathbf{p}_{\parallel} = \hbar \mathbf{k}_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$



Photoemission intensity: $I(k,\omega)=I_0\,|M(k,\omega)|^2 f(\omega)\, A(k,\omega)$

Single-particle spectral function

$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega-\epsilon_{\mathbf{k}}-\Sigma'(\mathbf{k},\omega)]^2+[\Sigma''(\mathbf{k},\omega)]^2}$$

$\Sigma(\mathbf{k},\omega)$ **: the "self-energy" - captures the effects of interactions**

What is ARPES used for?

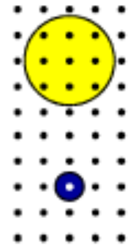
- ARPES is an almost ideal tool for imaging the Fermi surface of 1-D and 2-D solids.

- Since many of the high temperature superconductors are essentially 2-D materials, much of the work in this field is done using ARPES.

Strongly correlated systems

d - f

open shells materials

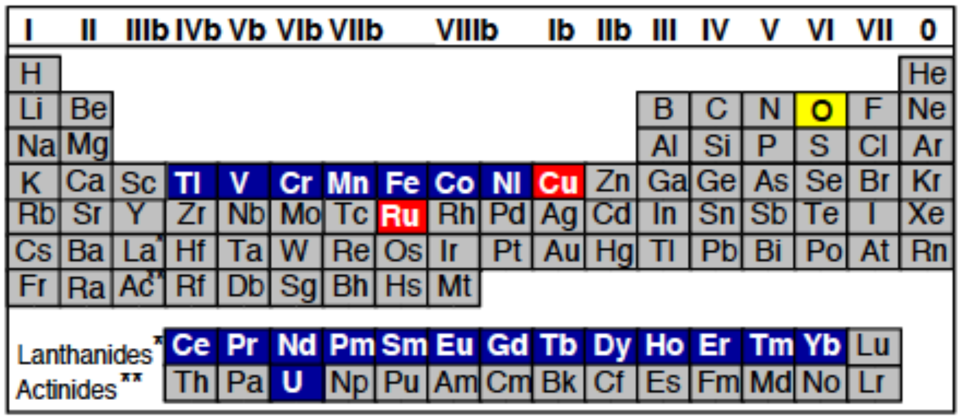


U<<W
Charge fluctuations

U>>W
Spin fluctuations

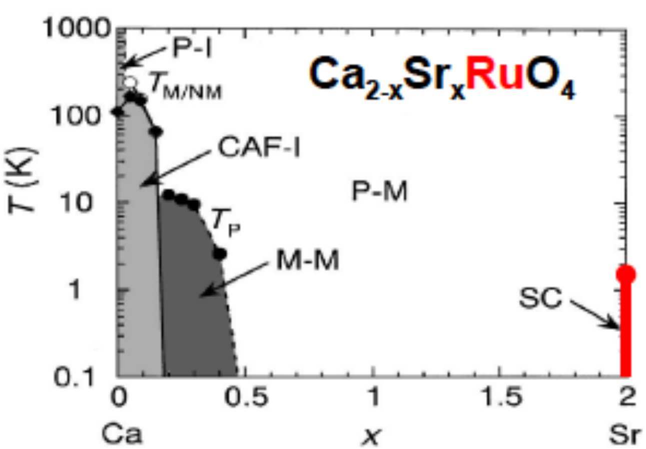
Control parameters

Bandwidth (U/W)
Band filling
Dimensionality

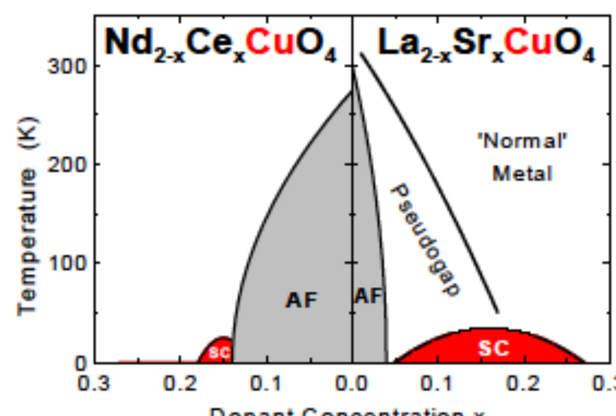


Degrees of freedom

Charge / Spin
Orbital
Lattice



- Kondo
- Mott-Hubbard
- Heavy Fermions
- Unconventional SC
- Spin-charge order
- Colossal MR



Understand the
macroscopic electronic properties
and the role of
competing degrees of freedom

↓

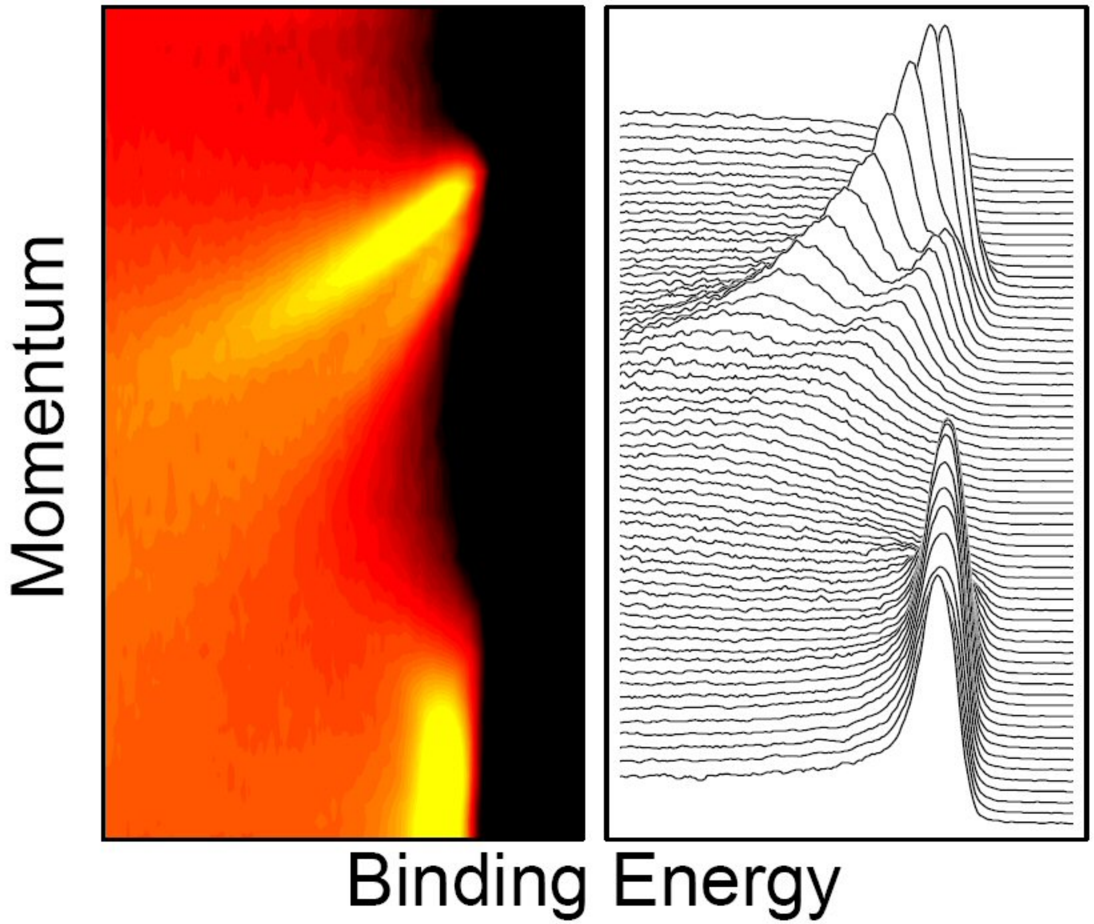
Study the low-energy electronic excitations

↓

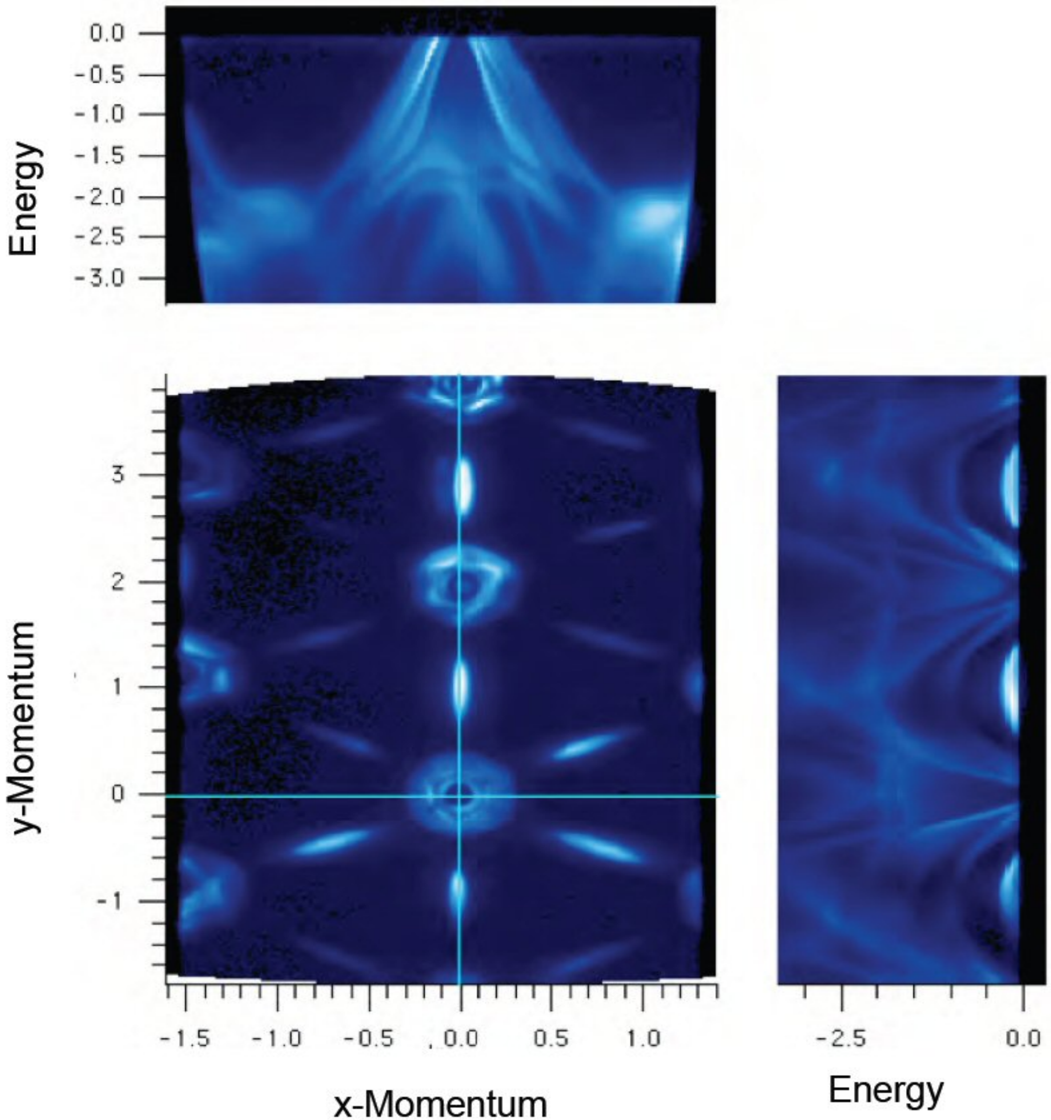
ARPES

Velocity and direction of
the electrons in the solid

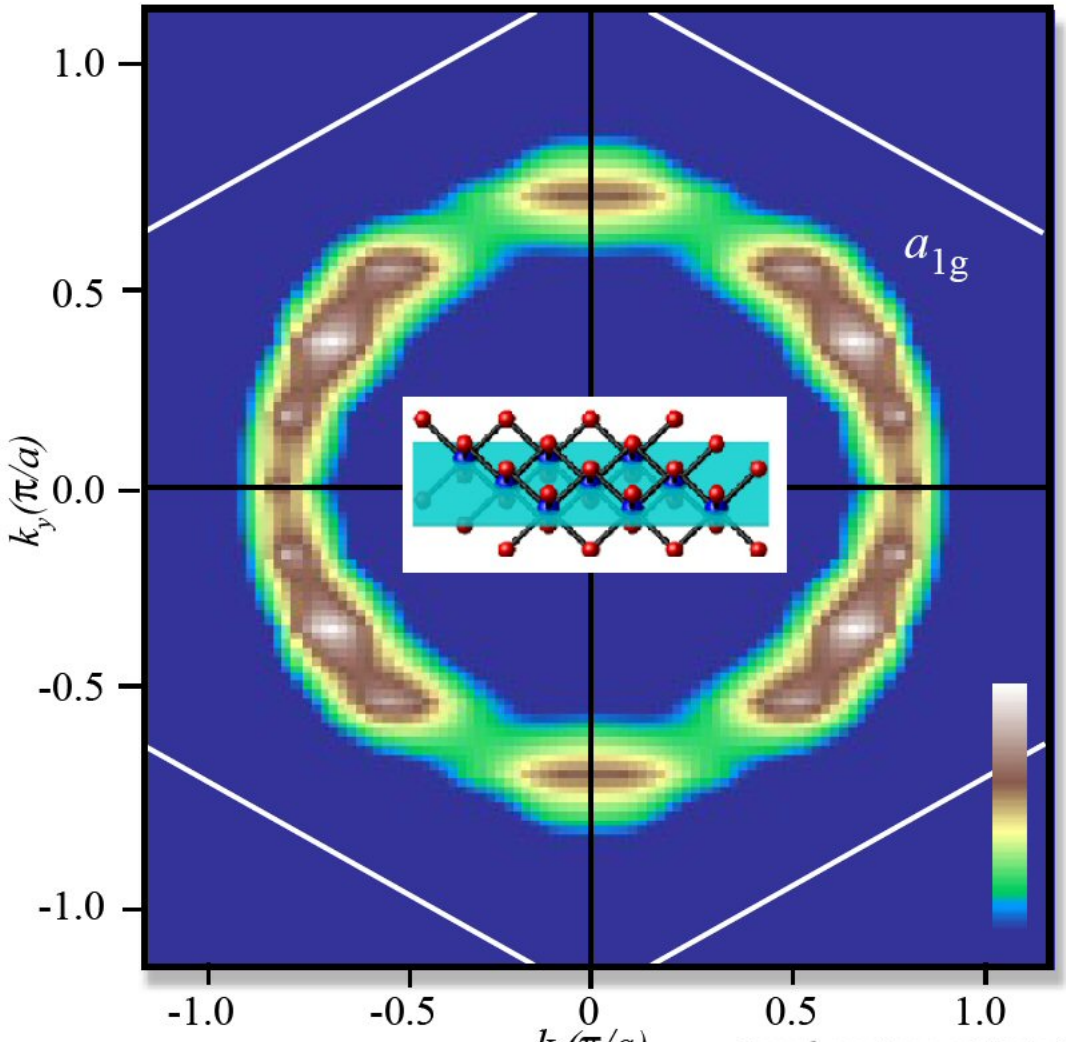
Momentum and Binding Energy



Direct *k* Space Imaging

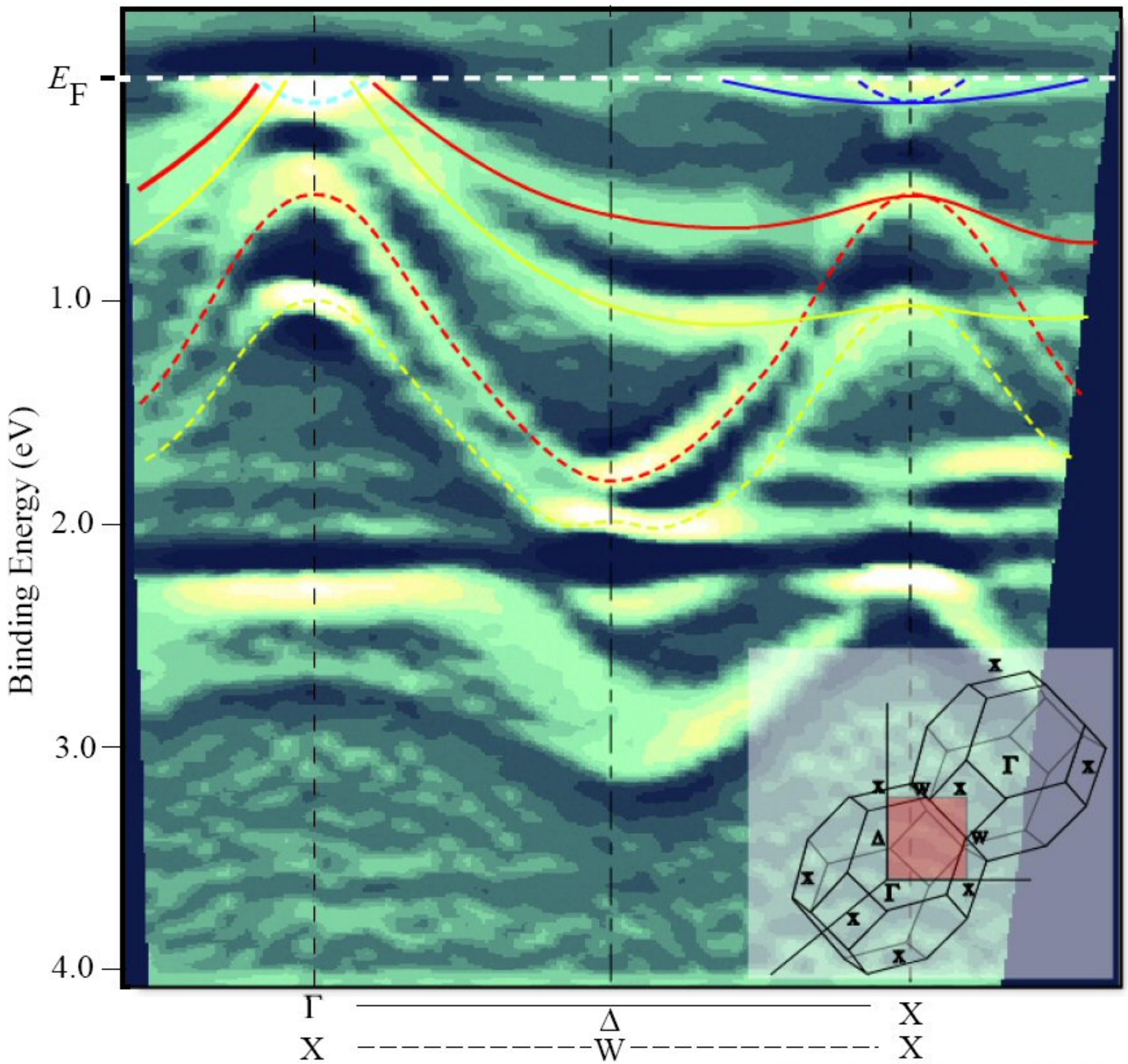


Fermi Surface Images



Fermi surface of K_xCoO_2

Band Structure Images

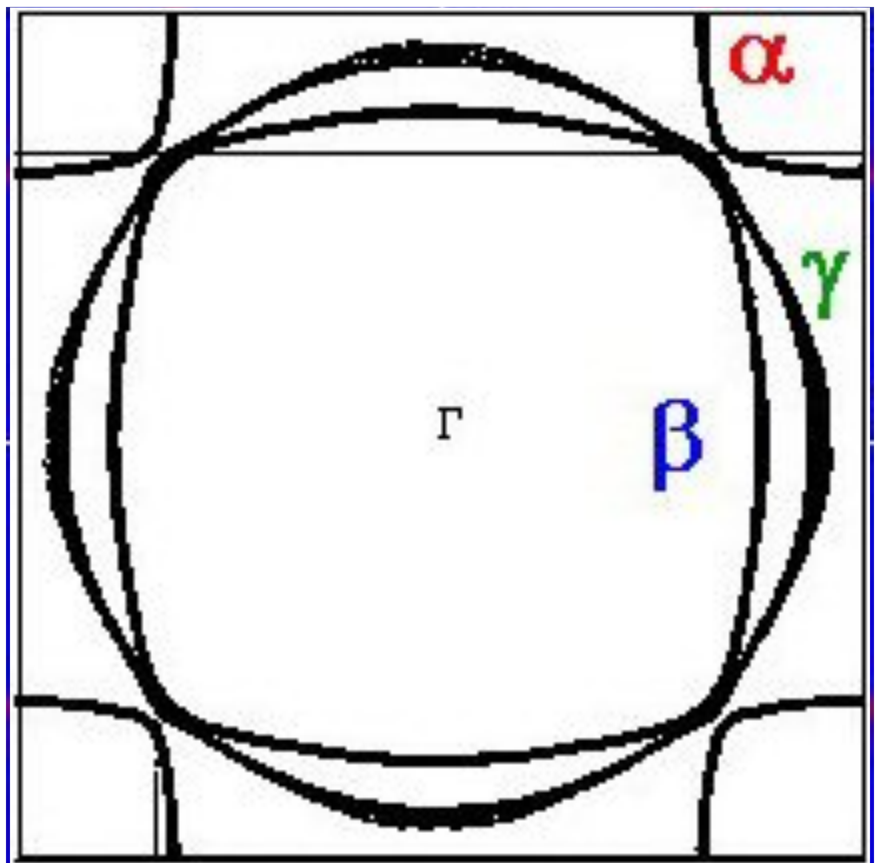


Band structure of CeSb

Validation of Predictions

Sr_2RuO_4 : Theoretical Calculation

Sr_2RuO_4 : ARPES Measurement



Advantages

• **Direct information about electronic states!**

• Straightforward comparison with theory - little or no modelling.

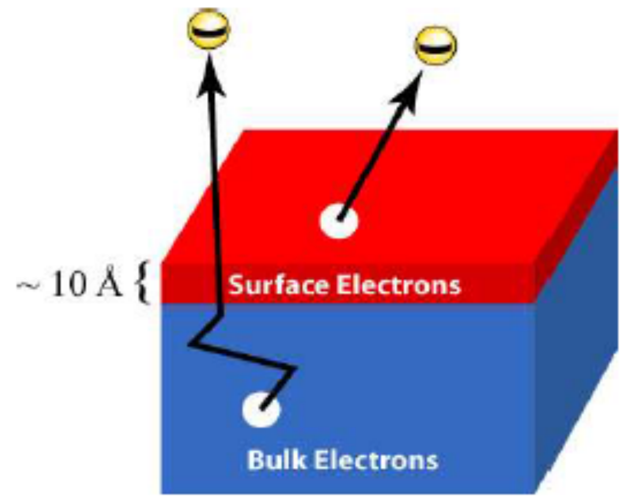
• High-resolution information about **BOTH energy** and **momentum**

• **Surface-sensitive probe**

• Sensitive to “many-body” effects

• Can be applied to small samples (100 μm x 100 μm x 10 nm)

Limitations



• **Not bulk sensitive**

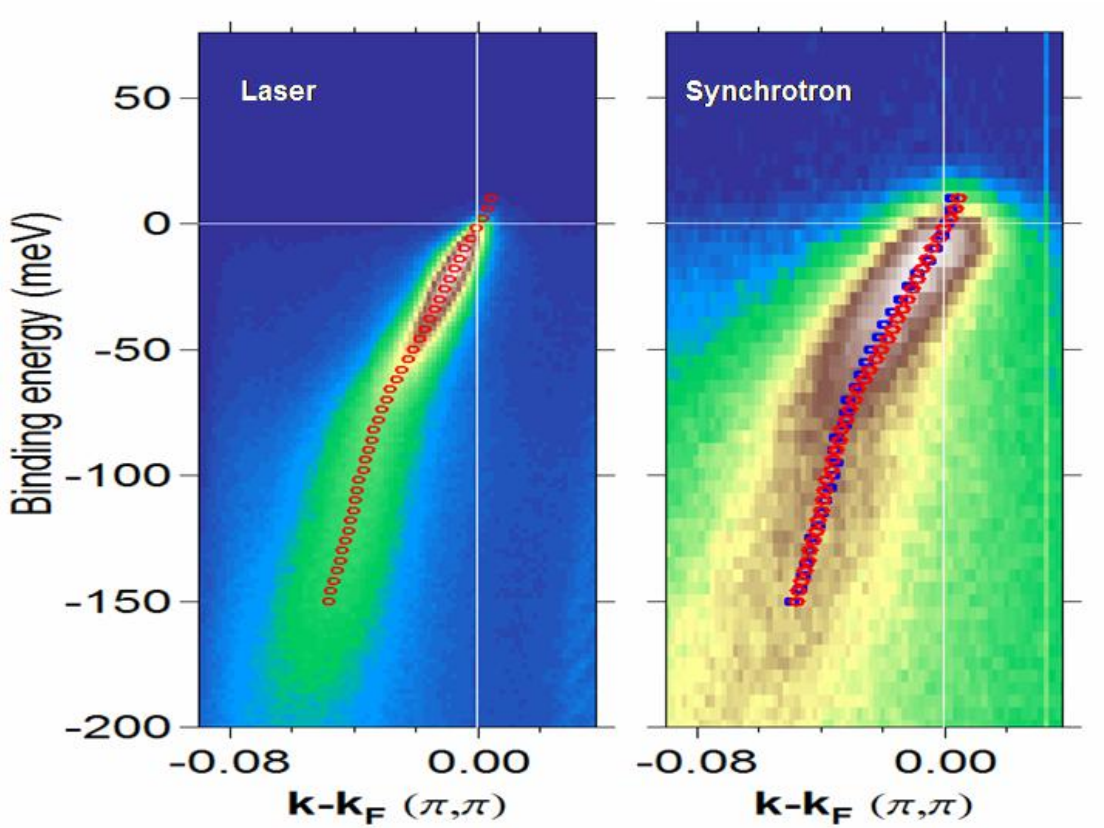
• Requires clean, atomically flat surfaces in **ultra-high vacuum**

• Cannot be studied as a function of pressure or magnetic field

Further Advances

- Laser ARPES: lower energy means sharper pictures

(image of $Bi_2Sr_2CaCu_2O_8$ in "nodal" direction)



Neutron Scattering

Neutrons have No Charge!

- Highly penetrating
- Nondestructive
- Can be used in extremes

Neutrons have a Magnetic Moment!

- Magnetic structure
- Fluctuations
- Magnetic materials

Neutrons have Spin!

- Polarized beams
- Atomic orientation
- Coherent and incoherent scattering

The Energies of neutrons are similar to the energies of elementary excitations!

- Molecular Vibrations and Lattice modes
- Magnetic excitations

The Wavelengths of neutrons are similar to atomic spacing!

- Sensitive to structure
- Gathers information from 10^{-10} to 10^{-7} m
- Crystal structures and atomic spacings

Neutrons probe Nuclei!

- Light atom sensitive
- Sensitive to isotopic substitution

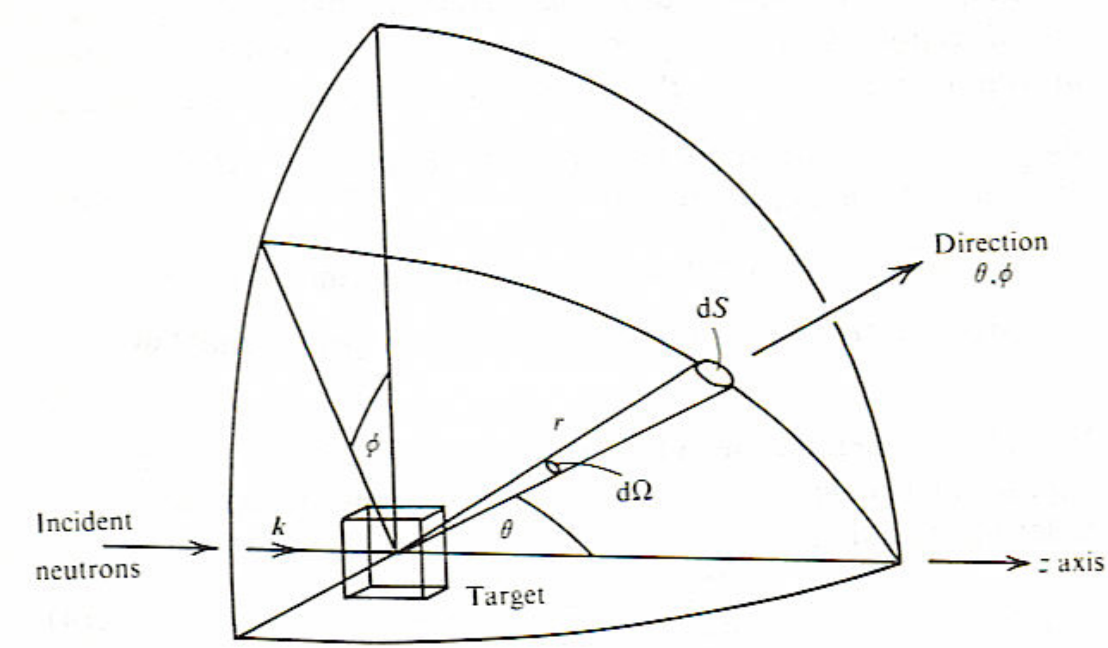
de Broglie Wavelength

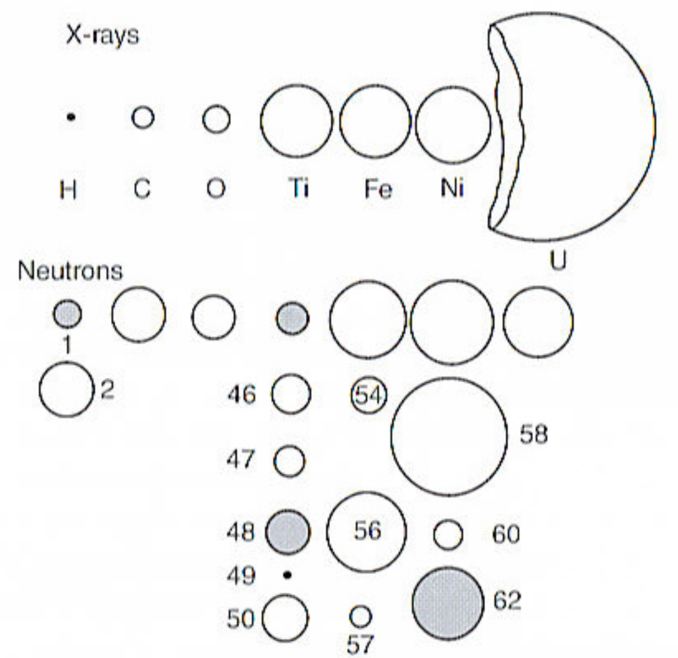
$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}$$

$$E = 81.6\ meV$$
$$v = 3950\ m/s$$
$$\lambda = 1\times10^{-10}\ m$$

$$E = 1\ meV$$
$$v = 437\ m/s$$
$$\lambda = 9\times10^{-10}\ m$$

Neutrons vs. X-rays

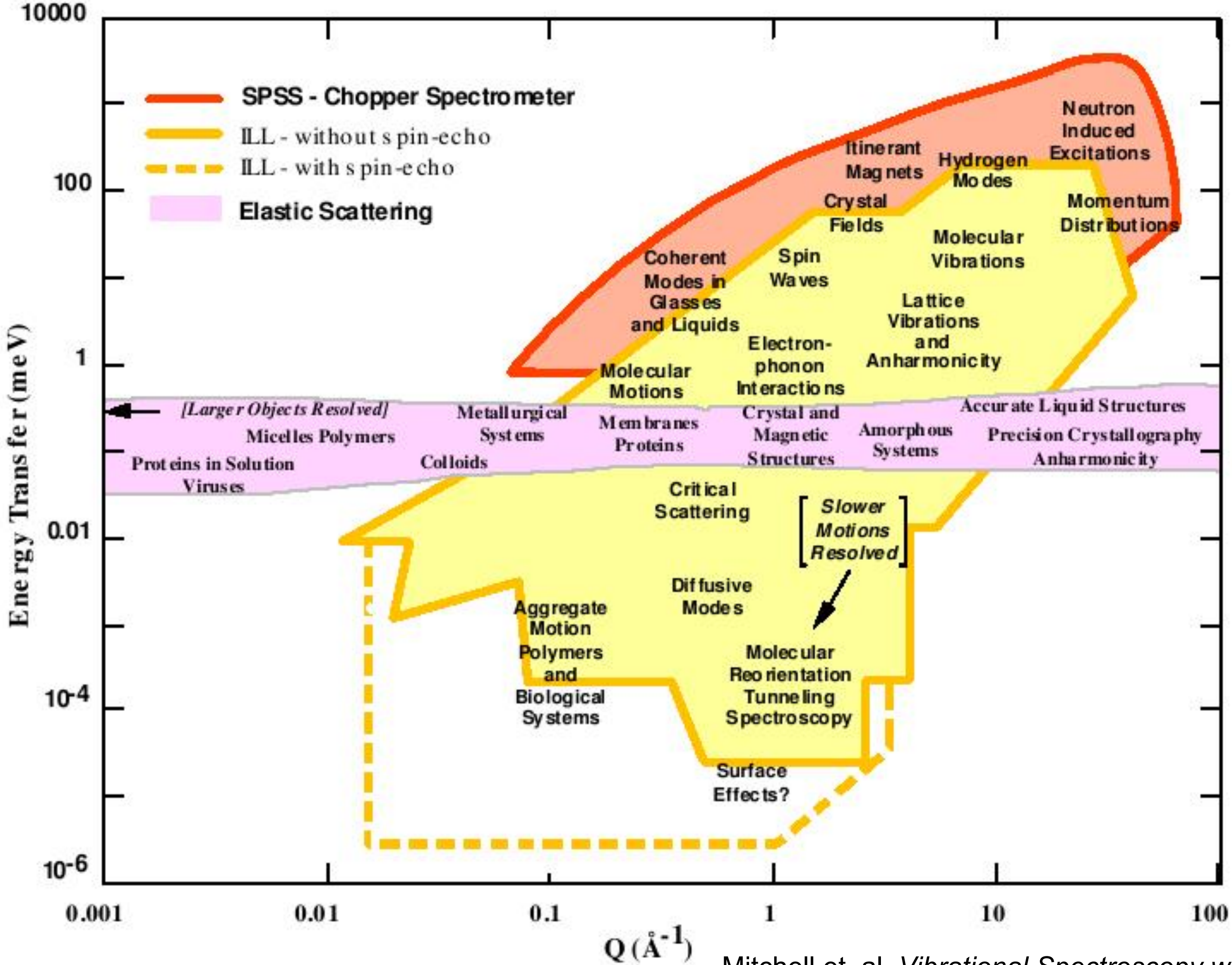




Chatterji, *Neutron Scattering from Magnetic Materials* (2006)

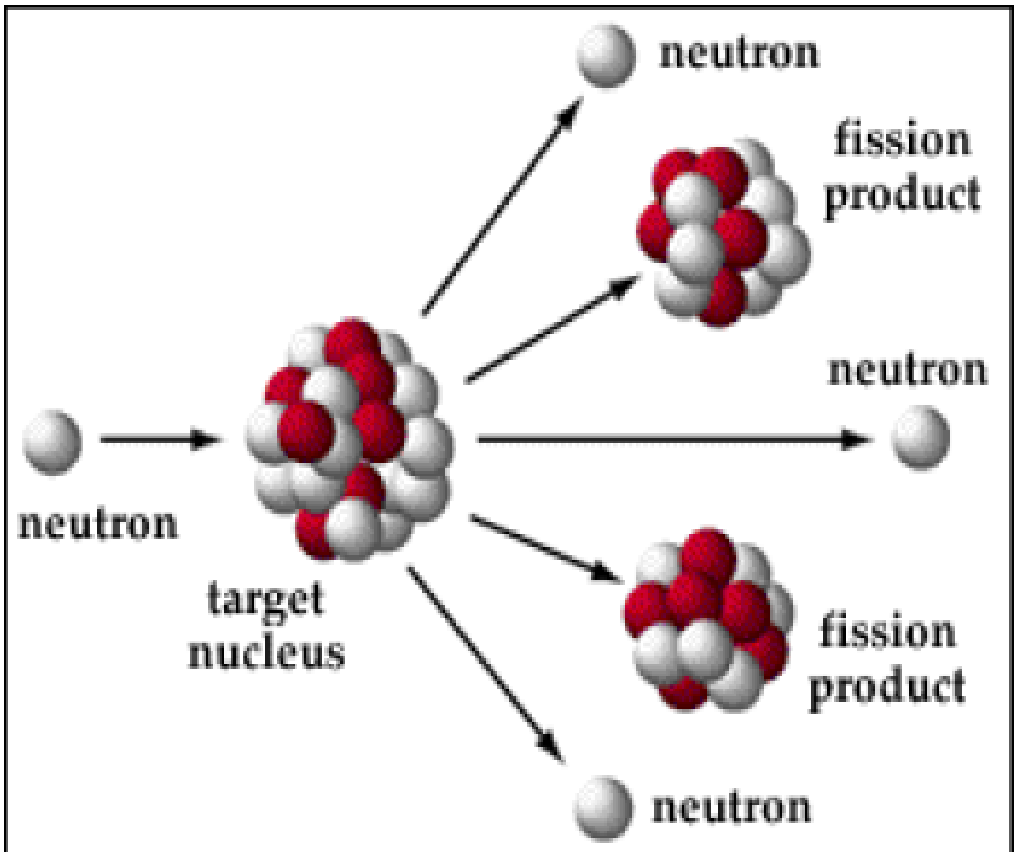
Neutrons allow easy access to atoms that are usually unseen in X-ray Scattering

How are neutrons useful?



Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

Neutrons from Reactor Sources

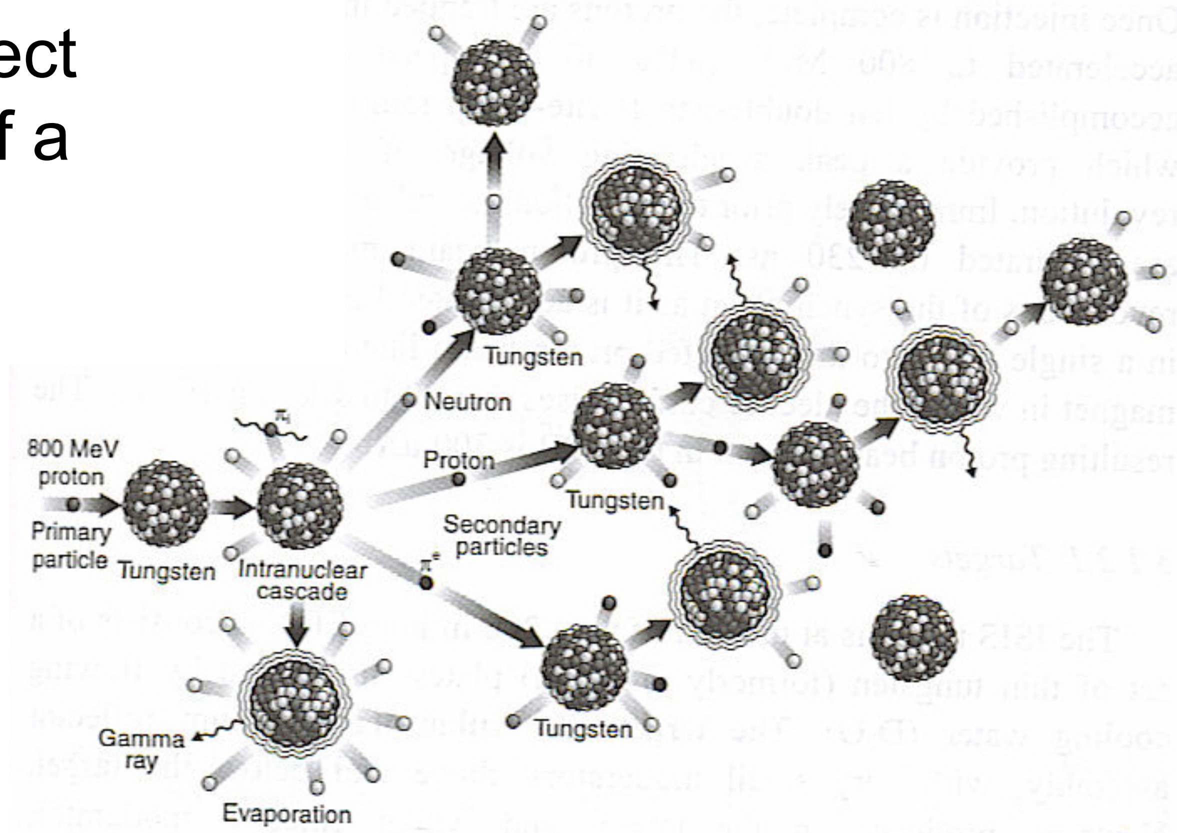


- Uses nuclear fission to create neutrons
- Continuous neutron flux
- Flux is dependent on fission rate
- Limited by heat flow in from the reaction
- Creates radioactive nuclear waste

Pynn, *Neutron Scattering: A Primer* (1989)

Neutrons from Spallation Sources

- Uses a cascade effect from the collision of a proton on a heavy metal.
- Pulsed Source
- High Intensity
- Heat production is relatively low



Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

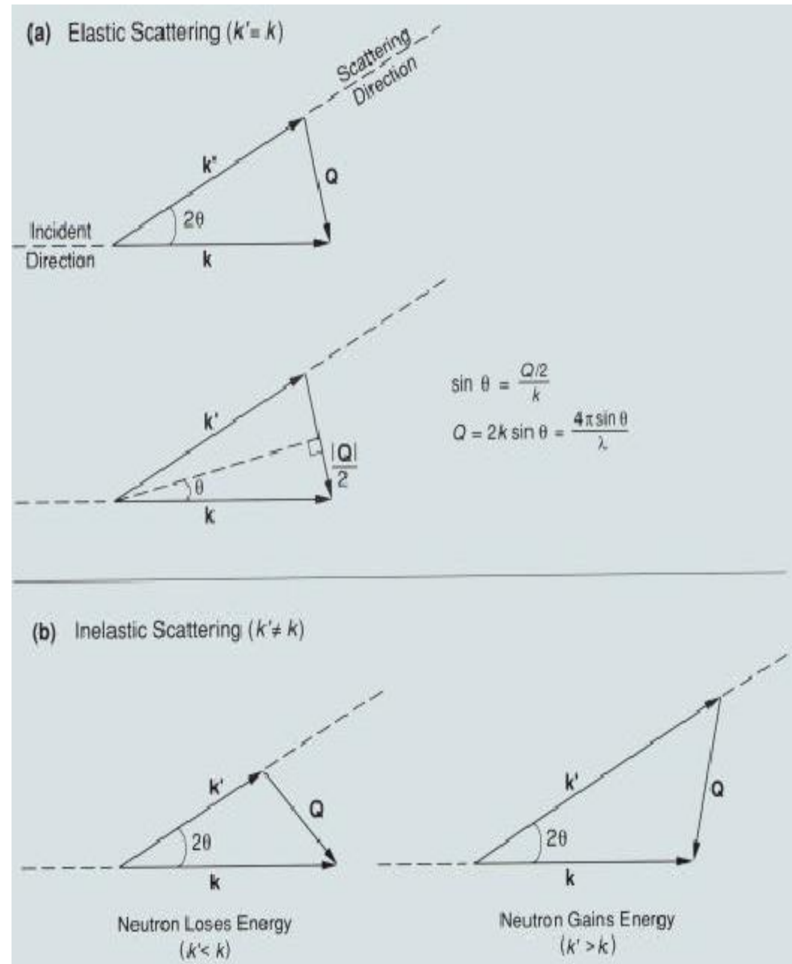
Neutron scattering

Elastic Neutron Scattering

- No loss of energy
- Examines the change in momentum or angle of the neutrons.

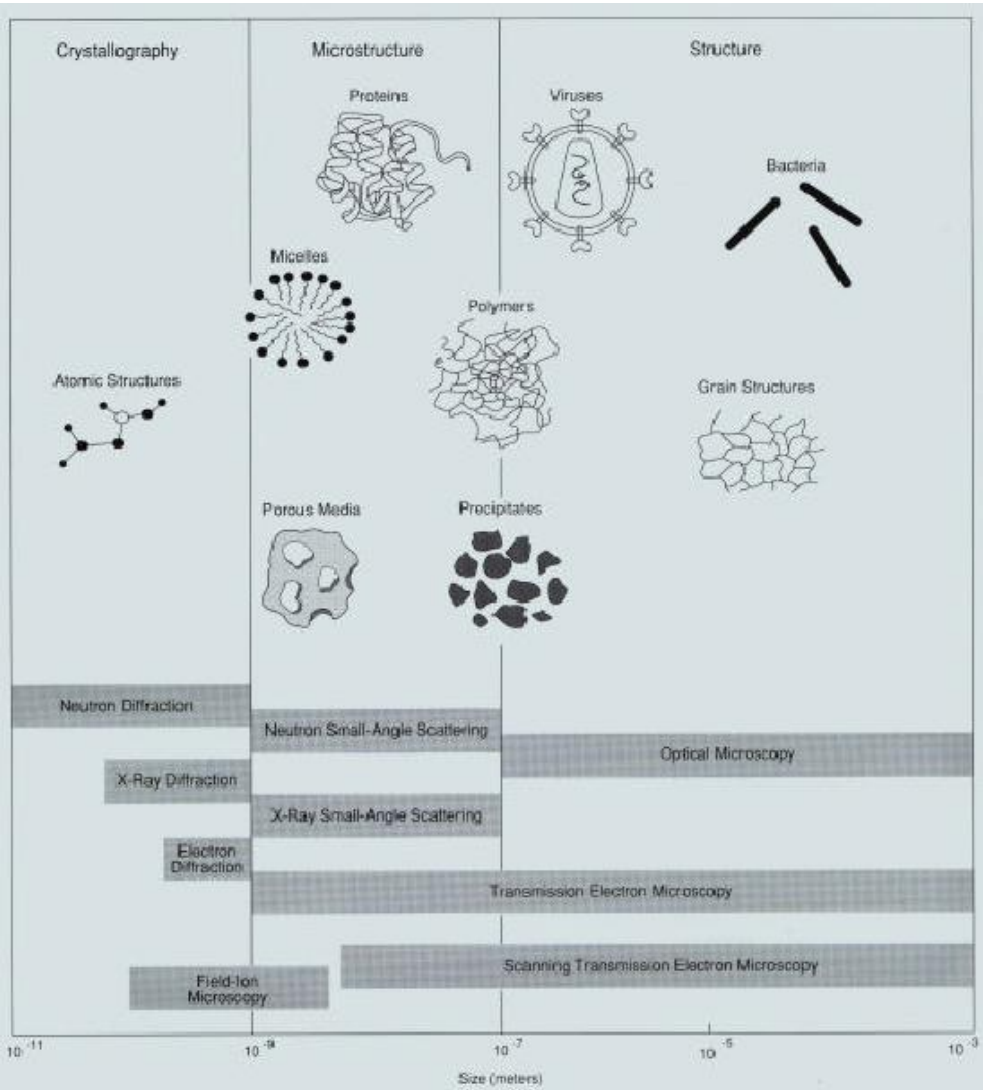
Inelastic Neutron Scattering

- Examines both momentum and energy dependencies.

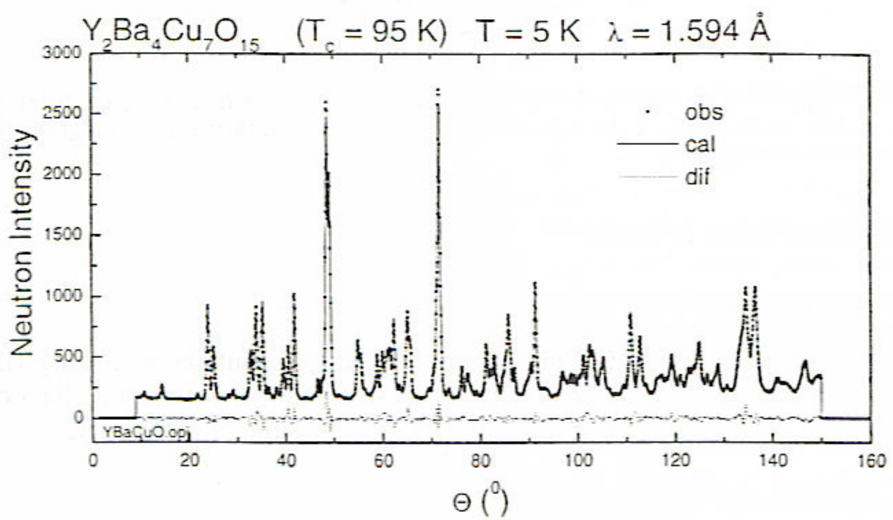


Pynn, *Neutron Scattering: A Primer* (1989)

Elastic Neutron Scattering



Pynn, *Neutron Scattering: A Primer* (1989)

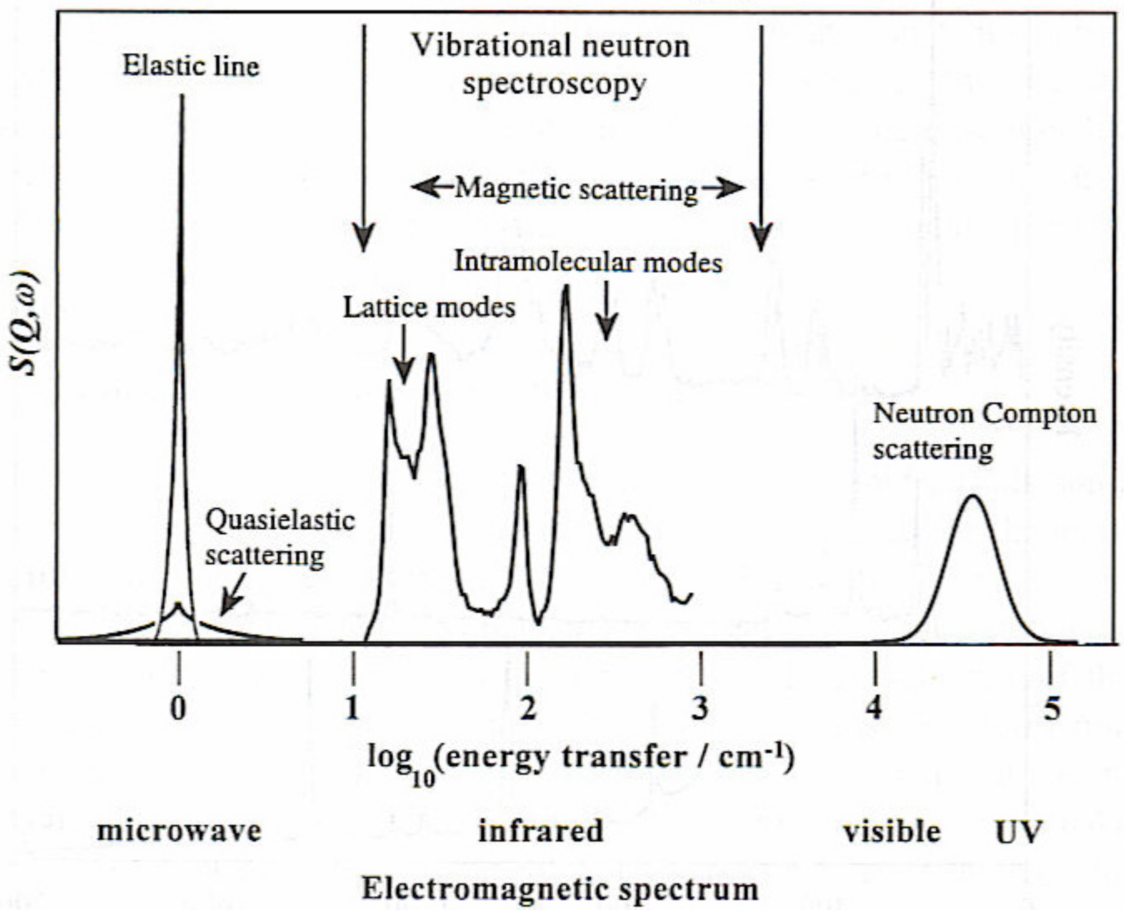


Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

- Determine length scales and differentiate between nano-, micro-, and macro-systems.
- Utilizes position and momentum correlation.

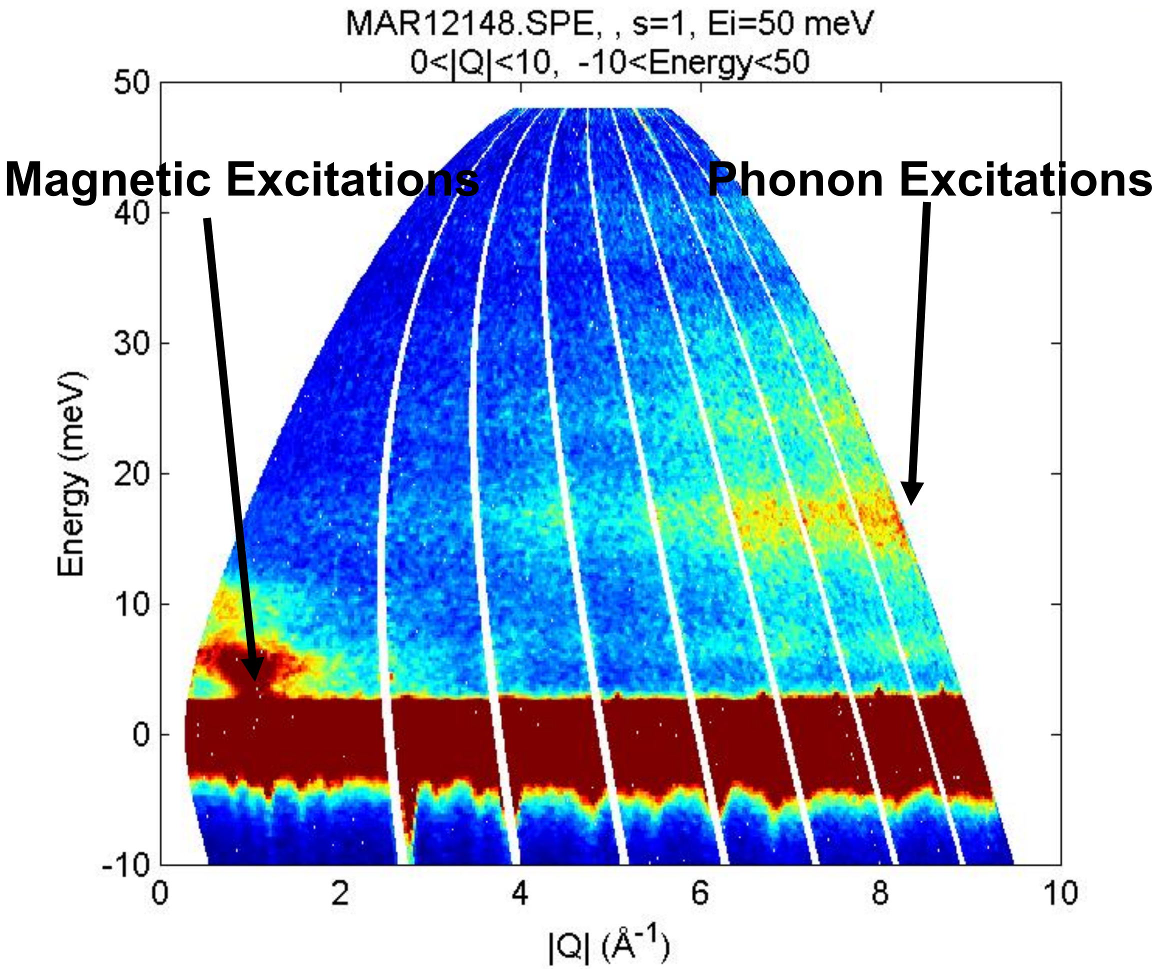
Inelastic Neutron Scattering

Uses both change in momentum and energy to characterize a systems vibrational, magnetic, and lattice excitations.



Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

Vibrational and Magnetic Excitations



M. B. Stone et al. Unpublished (2007)

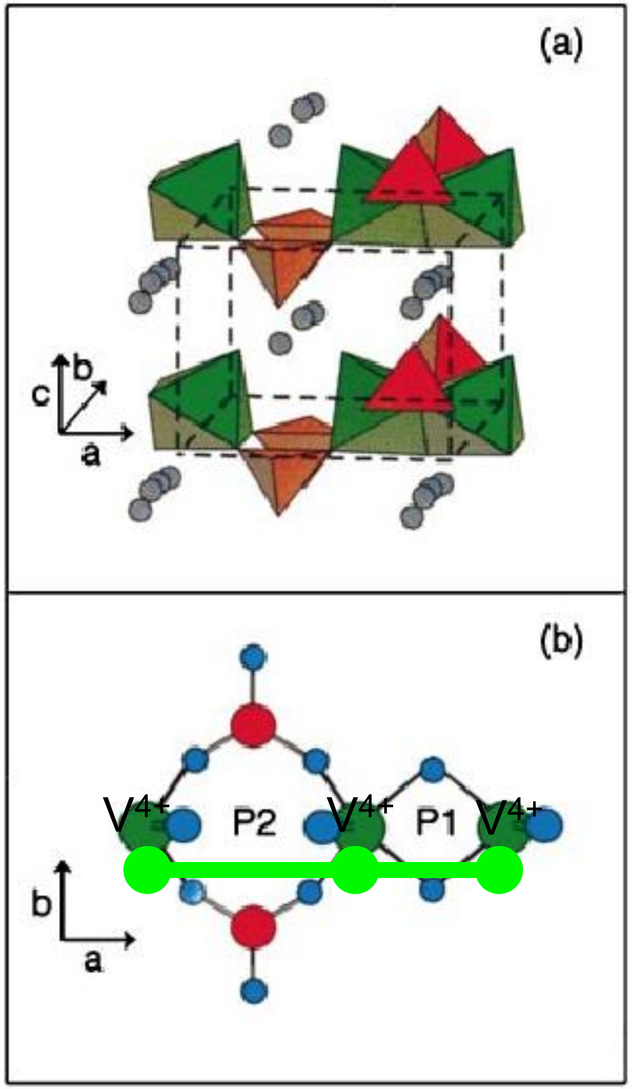
- Vibrational excitations are broad, large excitations.

Neutrons observe all phonon and vibrational excitations. The intensity is determined by the phonons polarization vectors.

- Magnetic excitations are detailed by spin transitions of ΔS = 0 and ± 1.

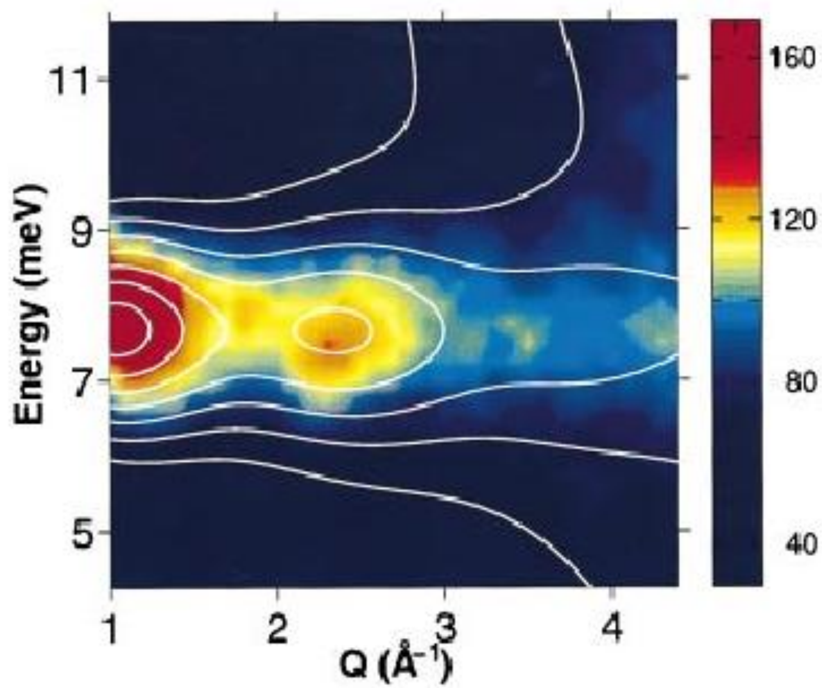
Q-dependence of magnetic excitations help determine the magnetic structure within the material.

Inelastic Neutron Scattering from magnetic sample



Tennant et. al, PRL (1997)

The use of neutron scattering on the material of $VODPO_4 \bullet \frac{1}{2} D_2O$ clarified the magnetic structure of the material.



Summary

- Neutrons are produced in two main ways
  - Research Reactors
  - Spallation Sources
- Utilizes the properties of the neutron.
- Neutrons are useful in determining not only structural properties of a material, but also the vibrational, magnetic, and lattice excitations.