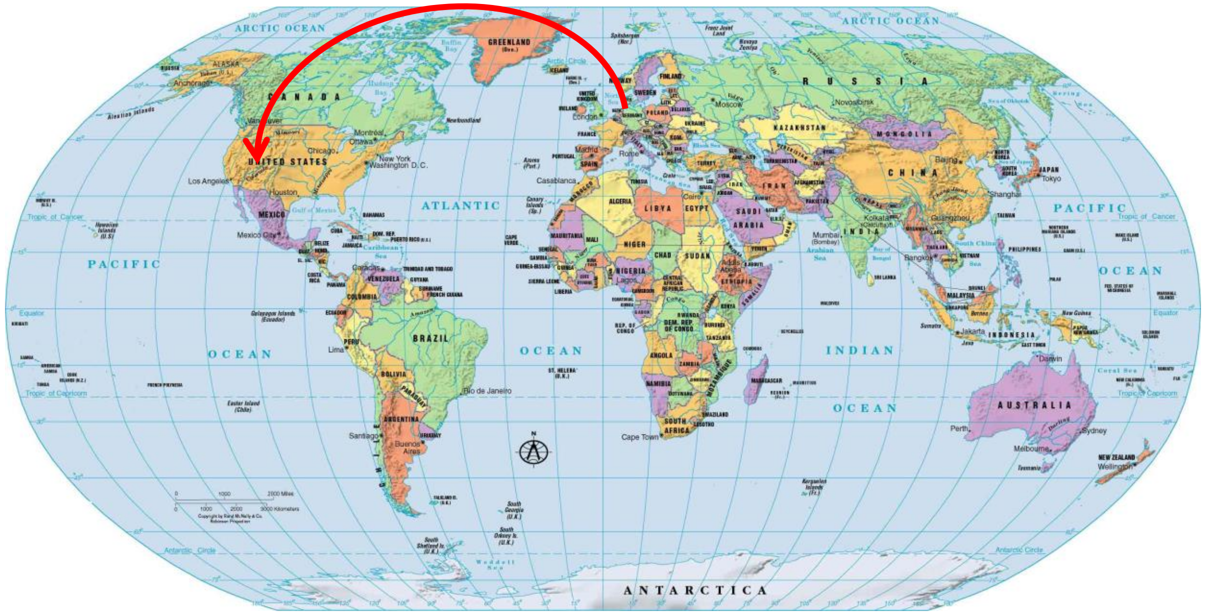
# Neutron Generation and Detection/Neutron Optics and Instrumentation

Thomas Huegle

Neutronics Scientist

August 2024

# Neutron school 2007 (Los Alamos)!

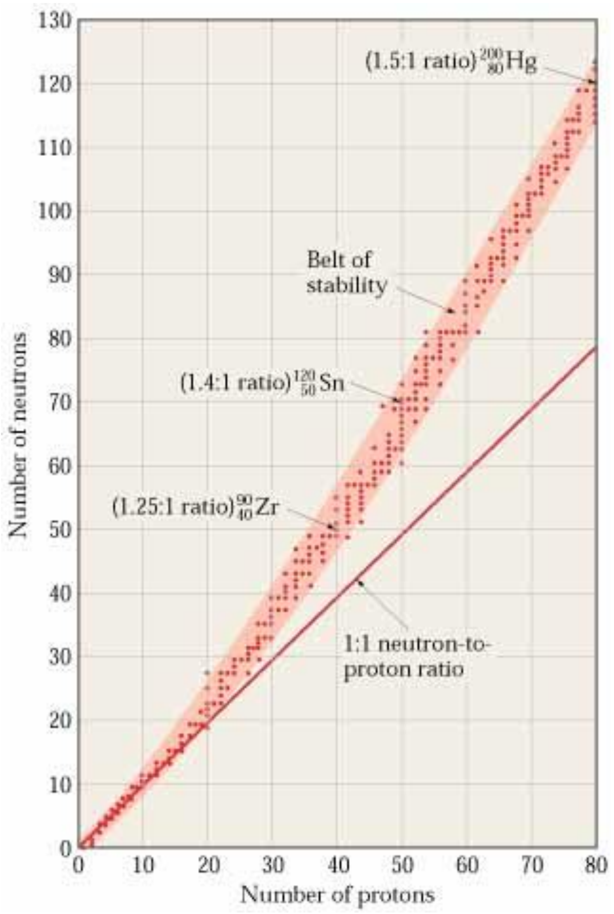


# Neutron Generation and Detection/Neutron Optics and Instrumentation

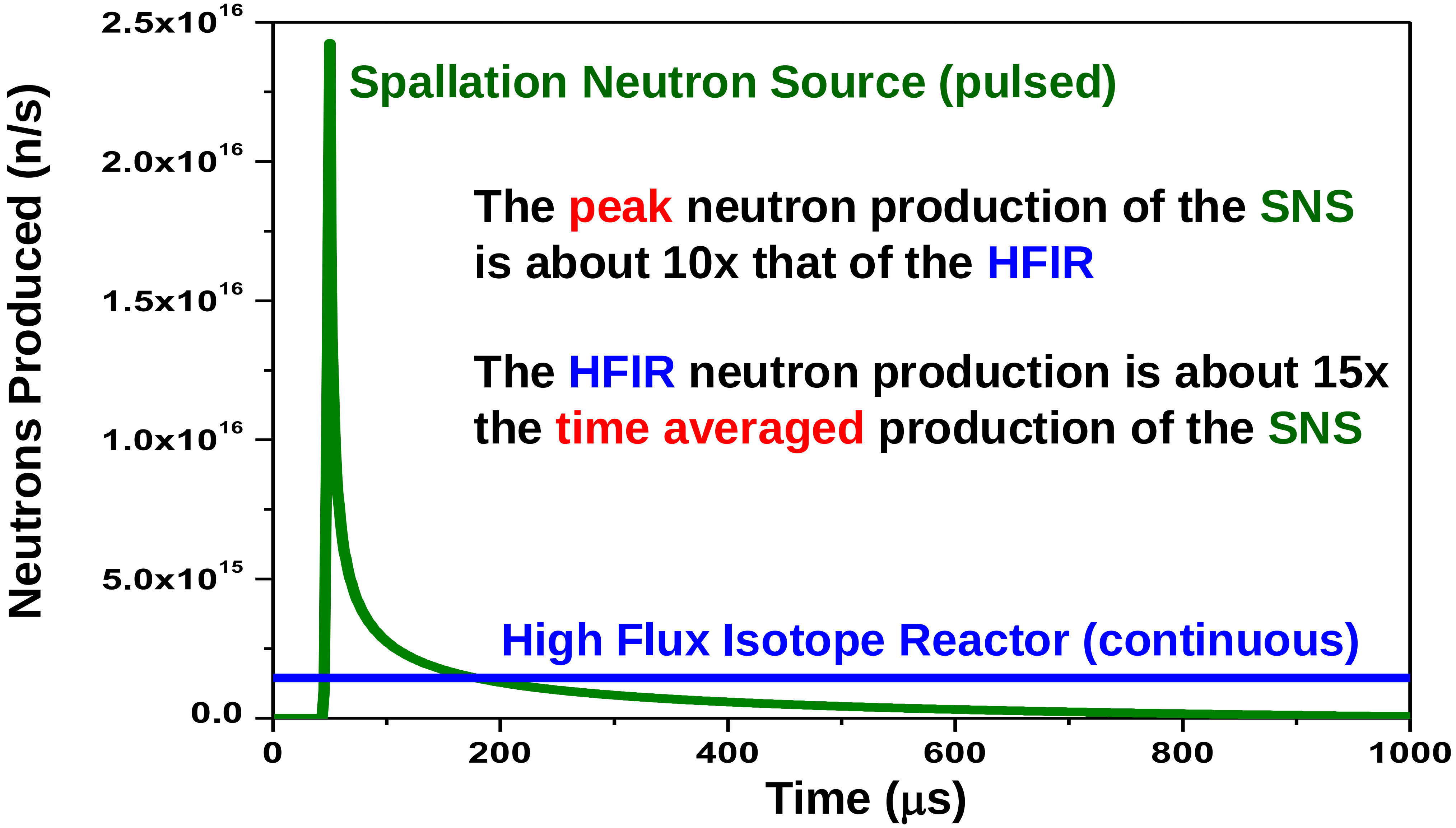
- How to build a neutron scattering instrument from scratch:
  – Make neutrons!
  – Transport neutrons!
  – Scatter neutrons! (other people will tell you about this)
  – Detect neutrons!

# Make neutrons!

- We don't make neutrons, we "liberate" them
- …by breaking atoms!
- Heavy atoms have disproportionally more neutrons
  - Split them into smaller atoms, and you have a surplus of neutrons!
- At HFIR: nuclear chain reaction (Uranium)
- At SNS: high power accelerator (Protons -> Mercury)



# Pulsed vs Continuous Neutron Sources








Slide courtesy of Lee Robertson

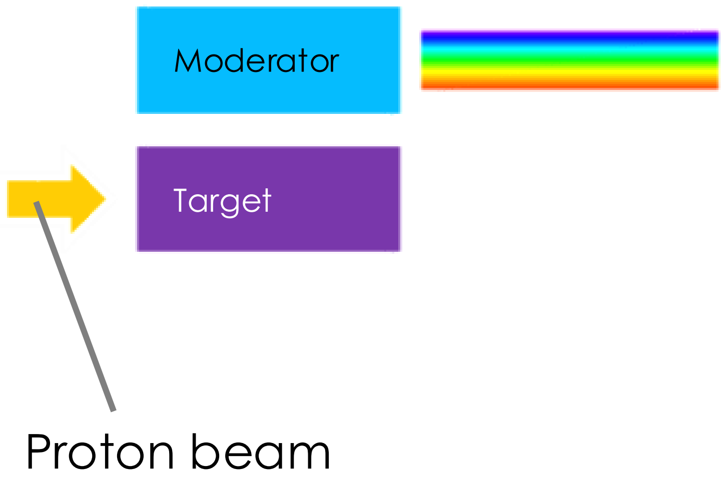
# Make <u>useful</u> neutrons!

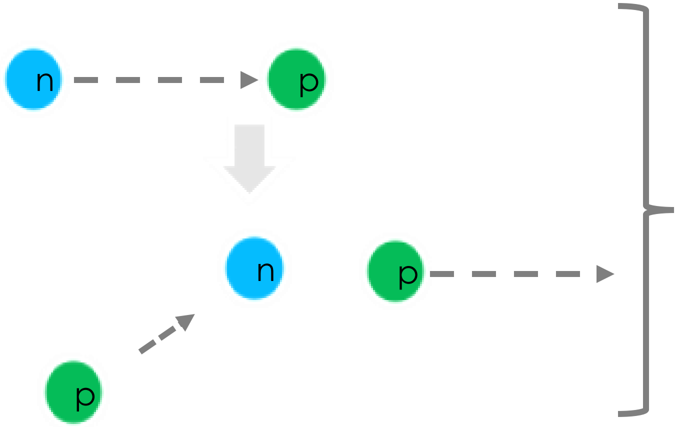
| Energy (meV) | Velocity (m/s) | Temp (K) | Wavelength (Å) |
|---|---|---|---|
| 0.1 – 5 | 100-1000 | 1 – 120 (“Cold”) | 4 – 30 |
| 5 – 100 | 1000-4000 | 120 – 1000 (“Thermal”) | 1 – 4 |
| 100 – 500 | 4000-40000 | 1000 – 6000 (“Hot”) | 0.4 –1 |
| . . . | | | |
| > MeV | ~1E7 | 1E9 | < mÅ |

*You are here!*

# Moderators

usually: $LH_2$ or $H_2O$

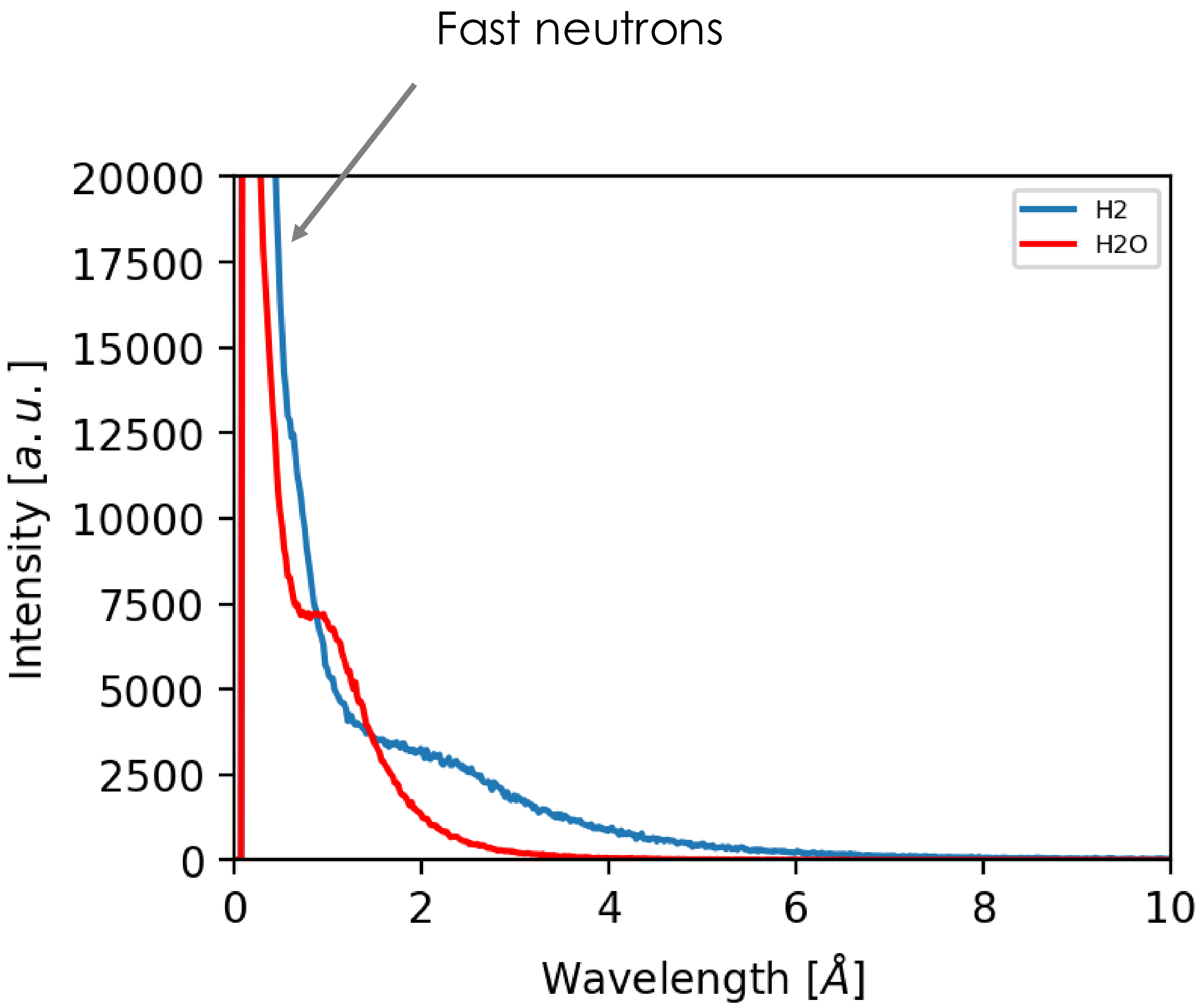



Within a few collisions, the energies will have equilibrated around the temperature of the moderator.

| Energy (meV) | Velocity (m/s) | Temp (K) | Wavelength (Å) |
|---|---|---|---|
| 0.1 – 5 | 100-1000 | 1 – 120 ("Cold") | 4 – 30 |
| 5 – 100 | 1000-4000 | 120 – 1000 ("Thermal") | 1 – 4 |
| 100 – 500 | 4000-40000 | 1000 – 6000 ("Hot") | 0.4 –1 |

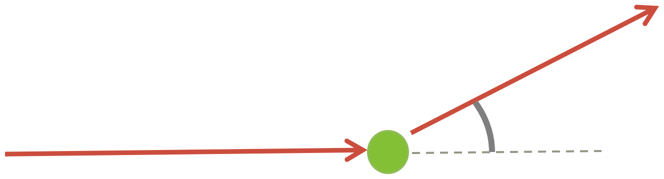
# Spectra H2 vs H2O @ SNS



# Two instrument concepts

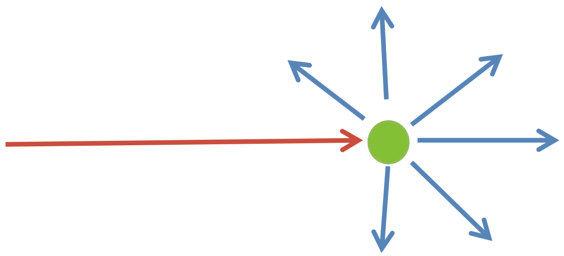
## Diffractometer (elastic scattering)

- Characteristic changes in angle
- No change in wavelength

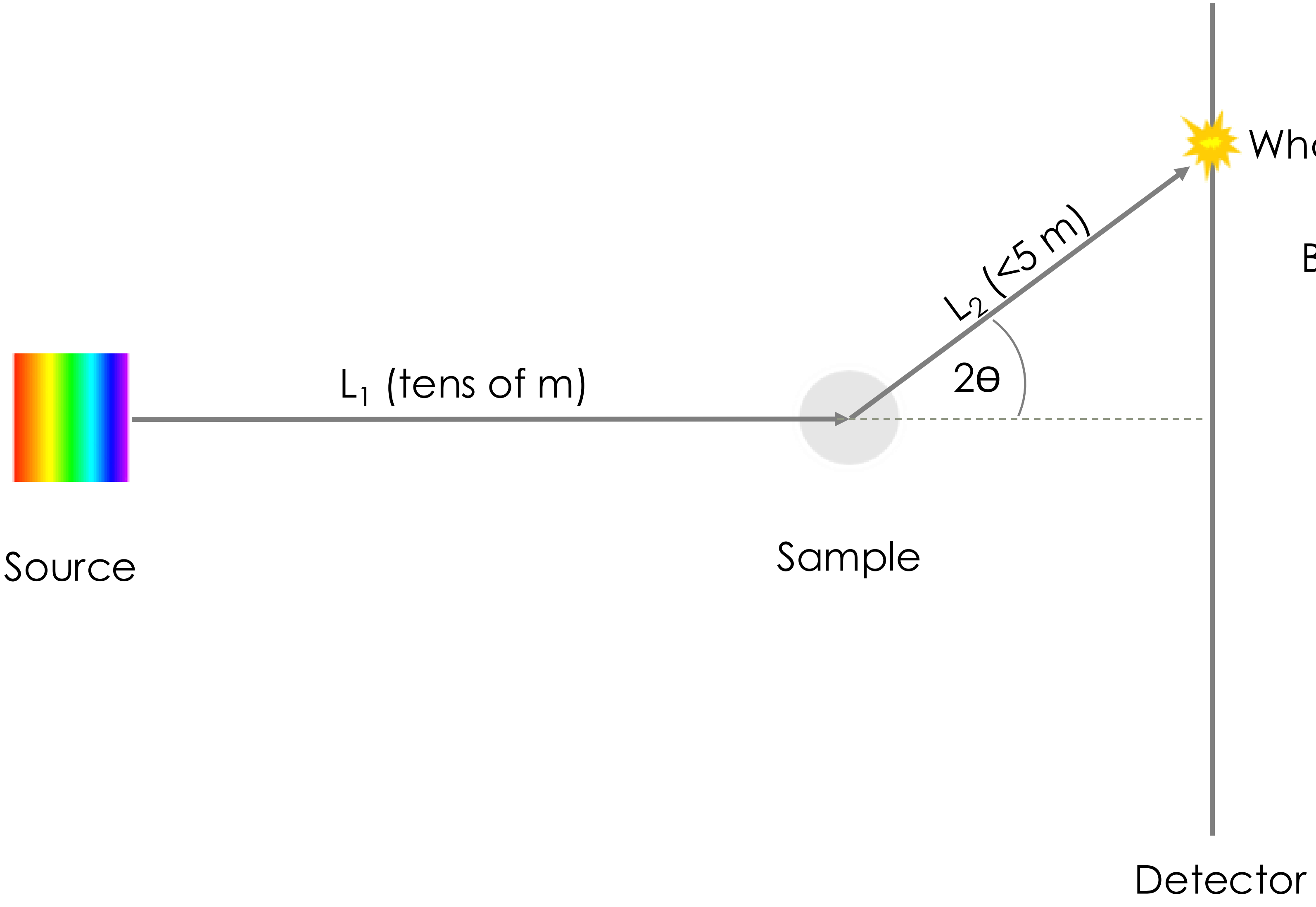


## Spectrometer (inelastic scattering)

- Isotropic change in angle
- Characteristic change in wavelength



# Let's build an instrument already!




Bragg's law: $n\lambda = 2d \sin\theta$

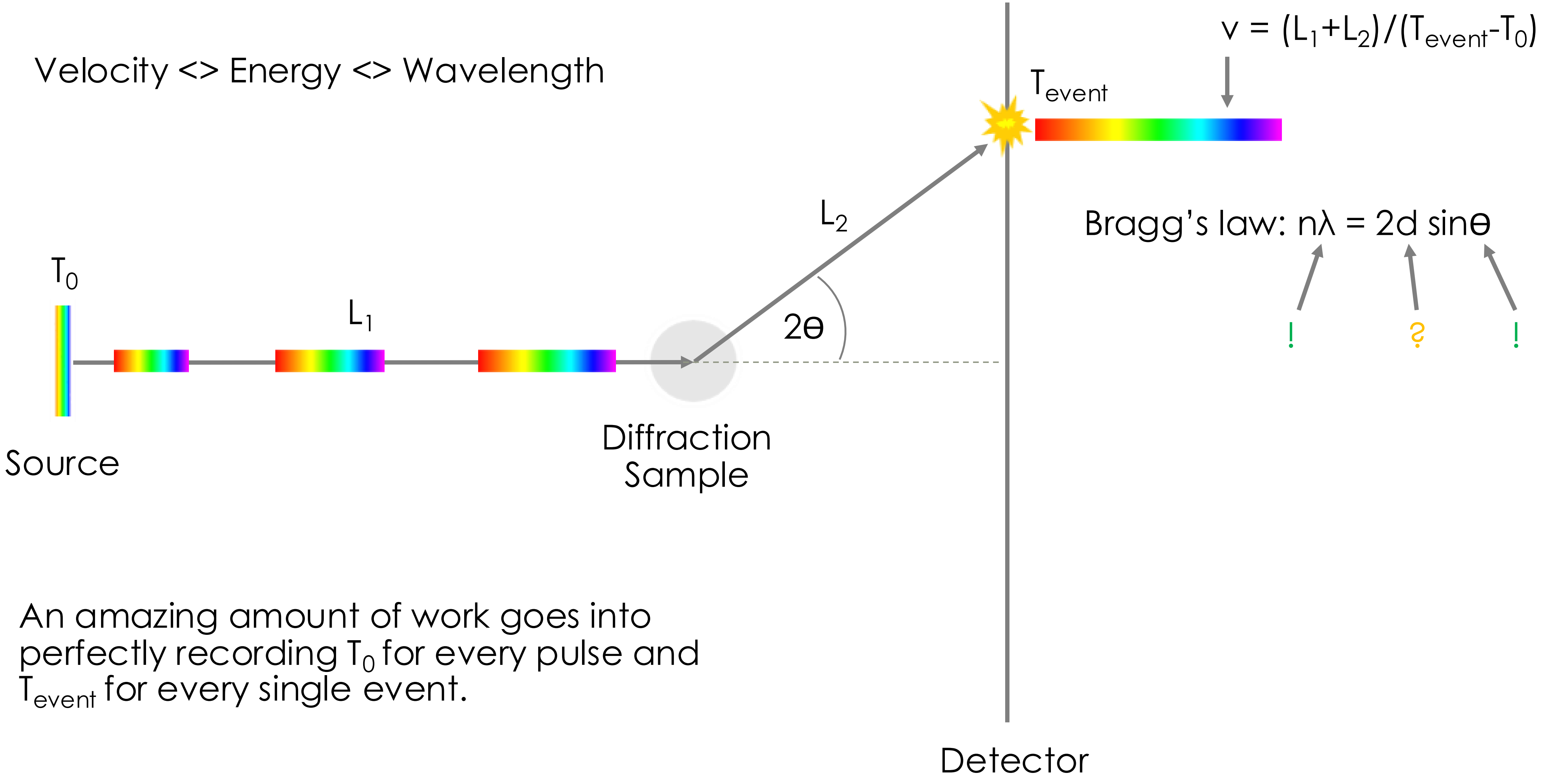
?? ? !



OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

# At a pulsed source: Time Of Flight (TOF) - elastic

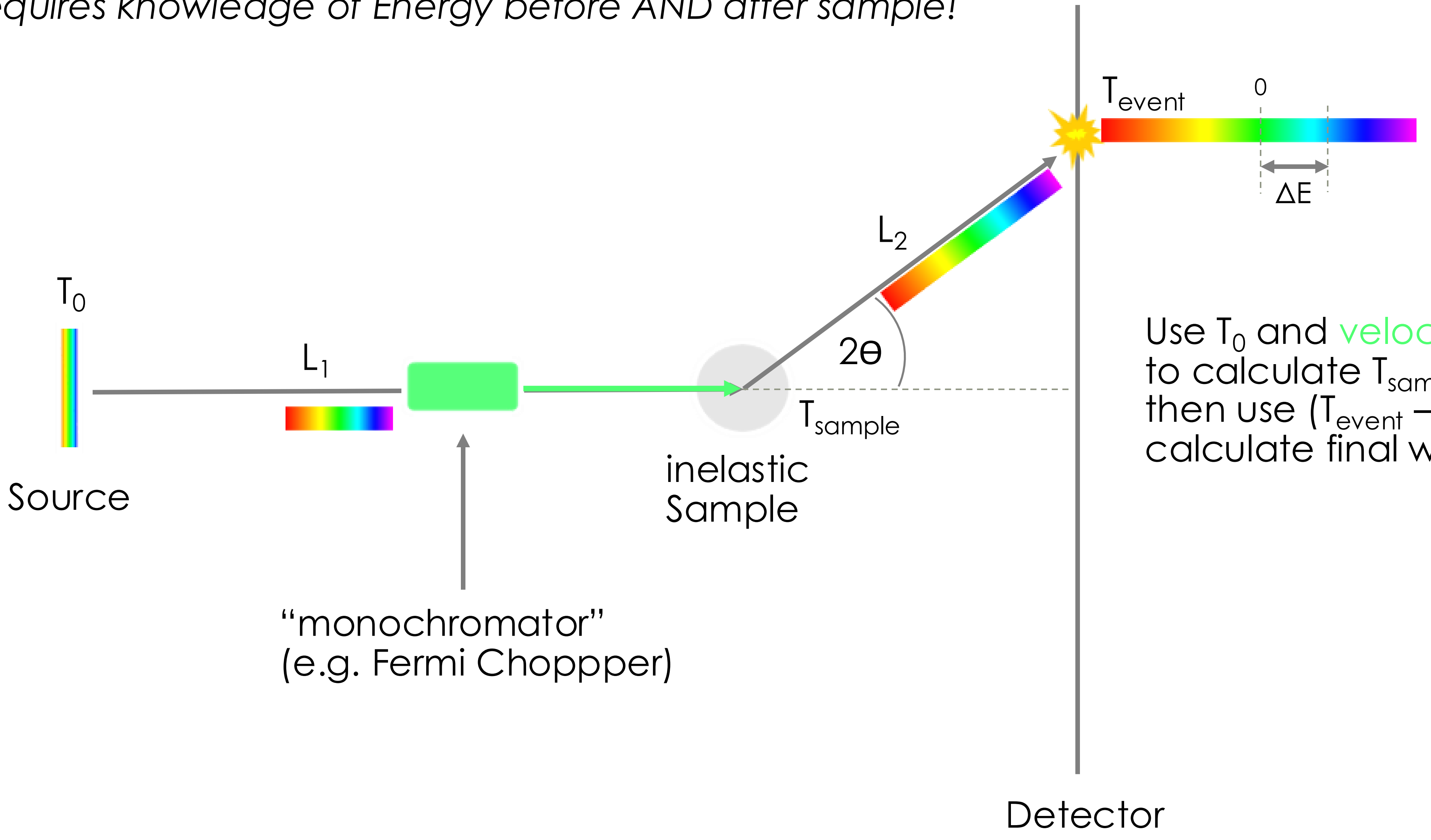
Velocity <> Energy <> Wavelength




An amazing amount of work goes into perfectly recording $T_0$ for every pulse and $T_{event}$ for every single event.

# At a pulsed source: Time Of Flight (TOF) - inelastic

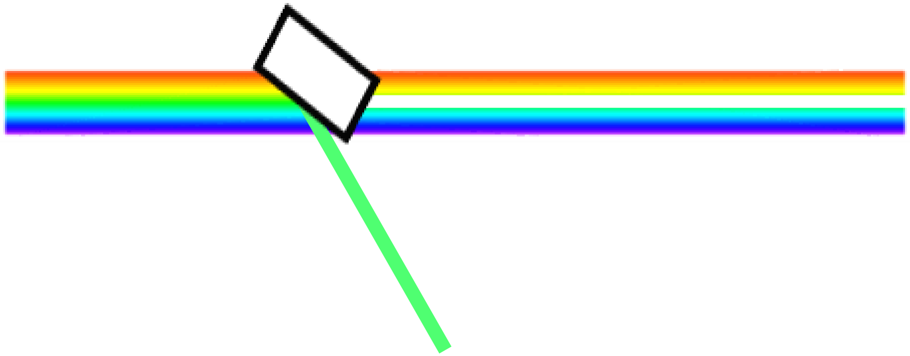
*Requires knowledge of Energy before AND after sample!*



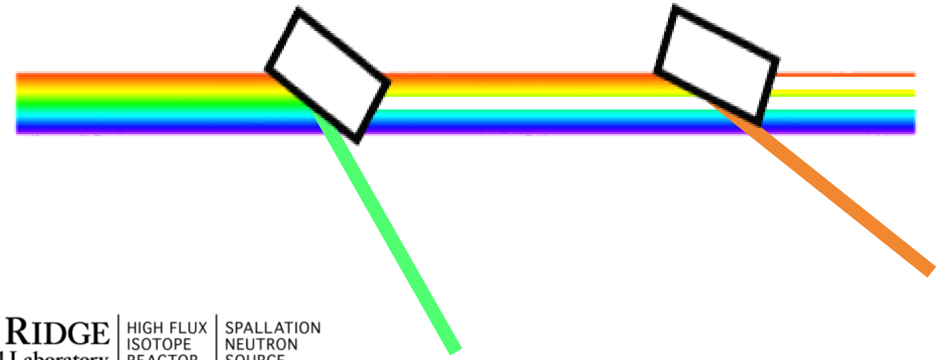

Use $T_0$ and velocity to calculate $T_{sample}$, then use $(T_{event} - T_{sample})/L_2$ to calculate final wavelength.

# Detour: Crystal monochromators

- Bragg's law: $n\lambda = 2d \sin\theta$
    - Known d-spacing, can select $\lambda$ by choosing $\theta$

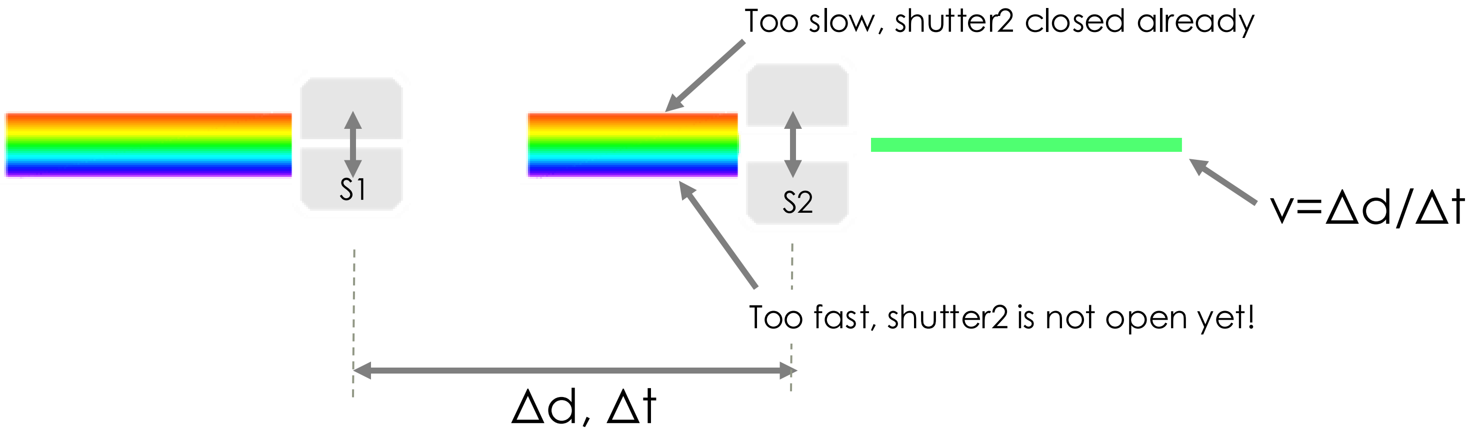


- Can re-use the transmitted beam for other wavelengths!

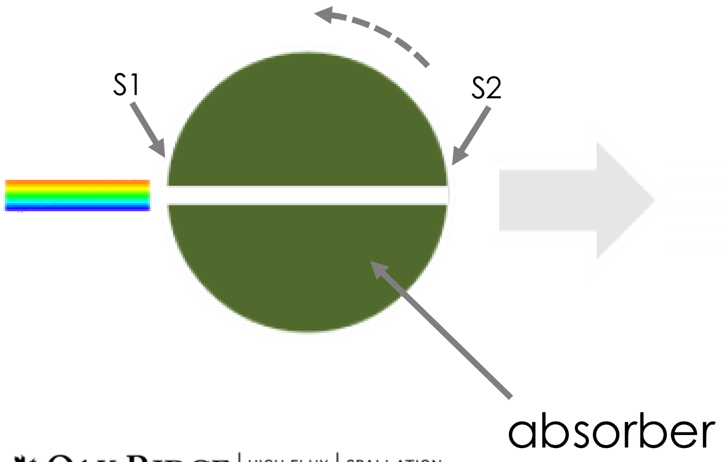


USANS @ SNS

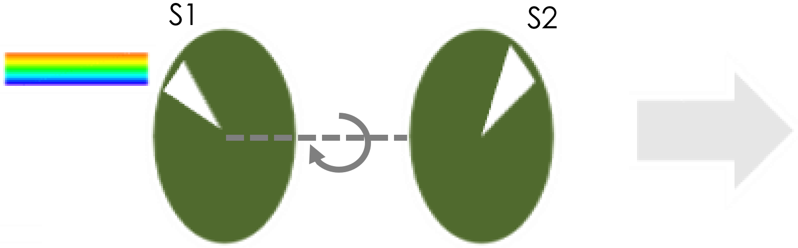
# Detour: Fermi Choppers, velocity selectors




## Fermi Chopper

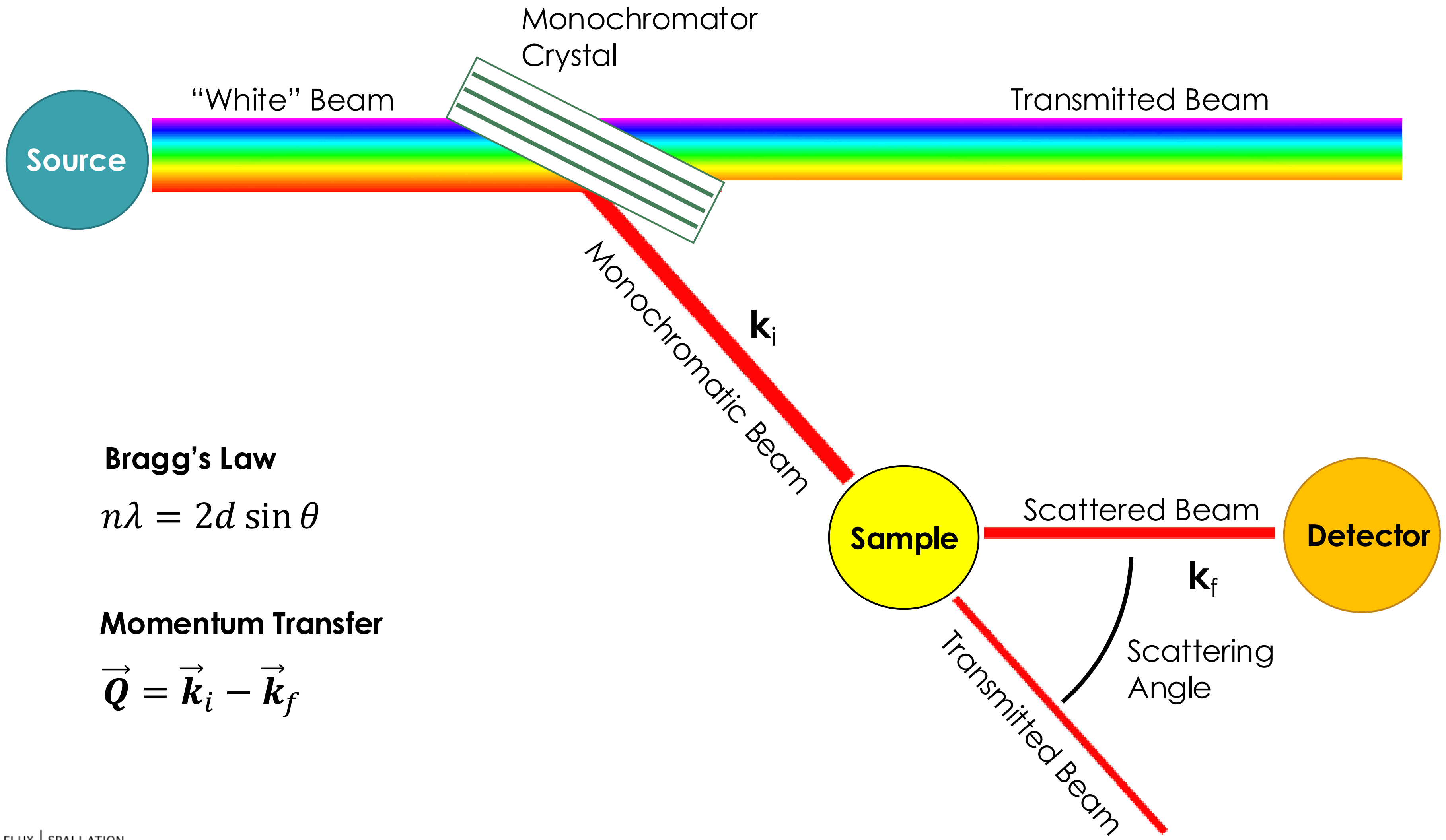



## Velocity selector




Astrium
Formerly: Dornier

# Reactor instruments - elastic



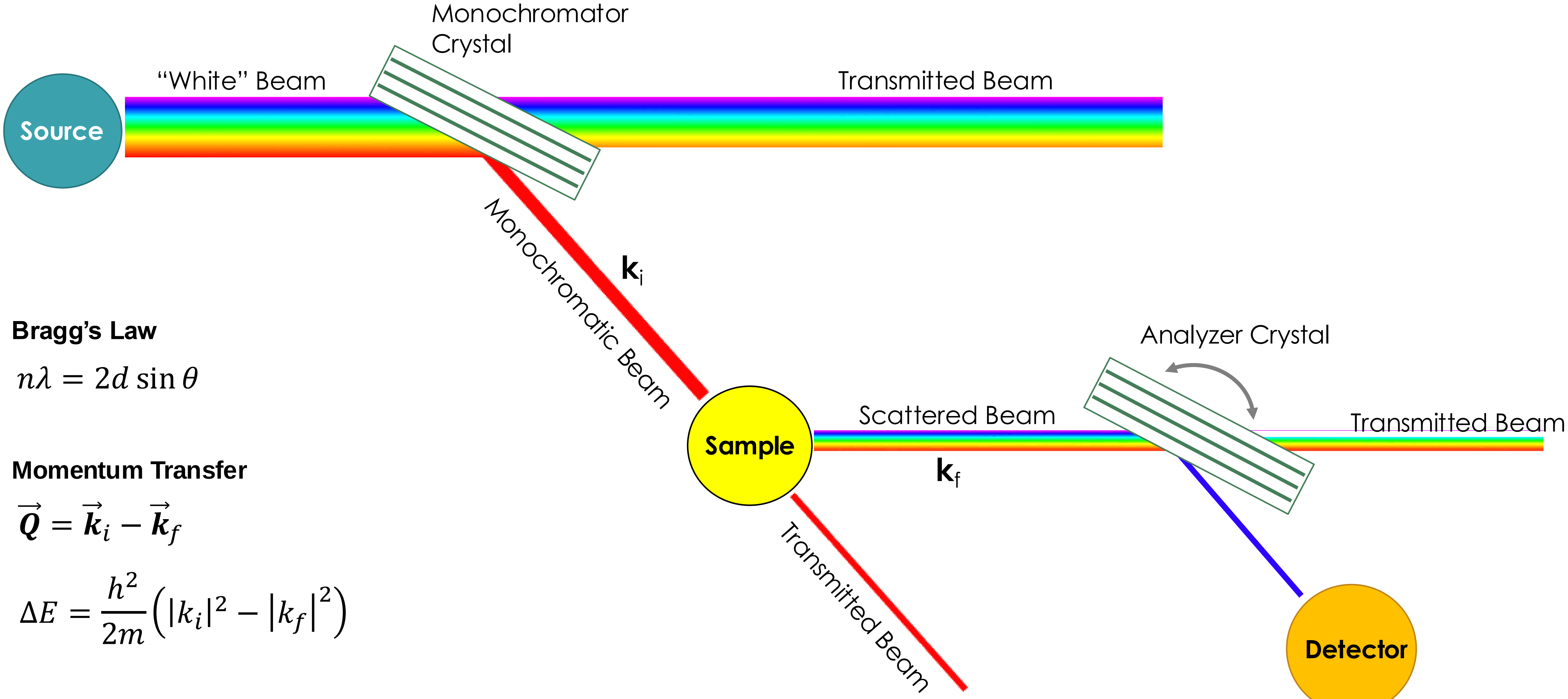

**Bragg's Law**

$$n\lambda = 2d\sin\theta$$

**Momentum Transfer**

$$\vec{\boldsymbol{Q}} = \vec{\boldsymbol{k}}_i - \vec{\boldsymbol{k}}_f$$

# Reactor instruments - inelastic




**Bragg's Law**

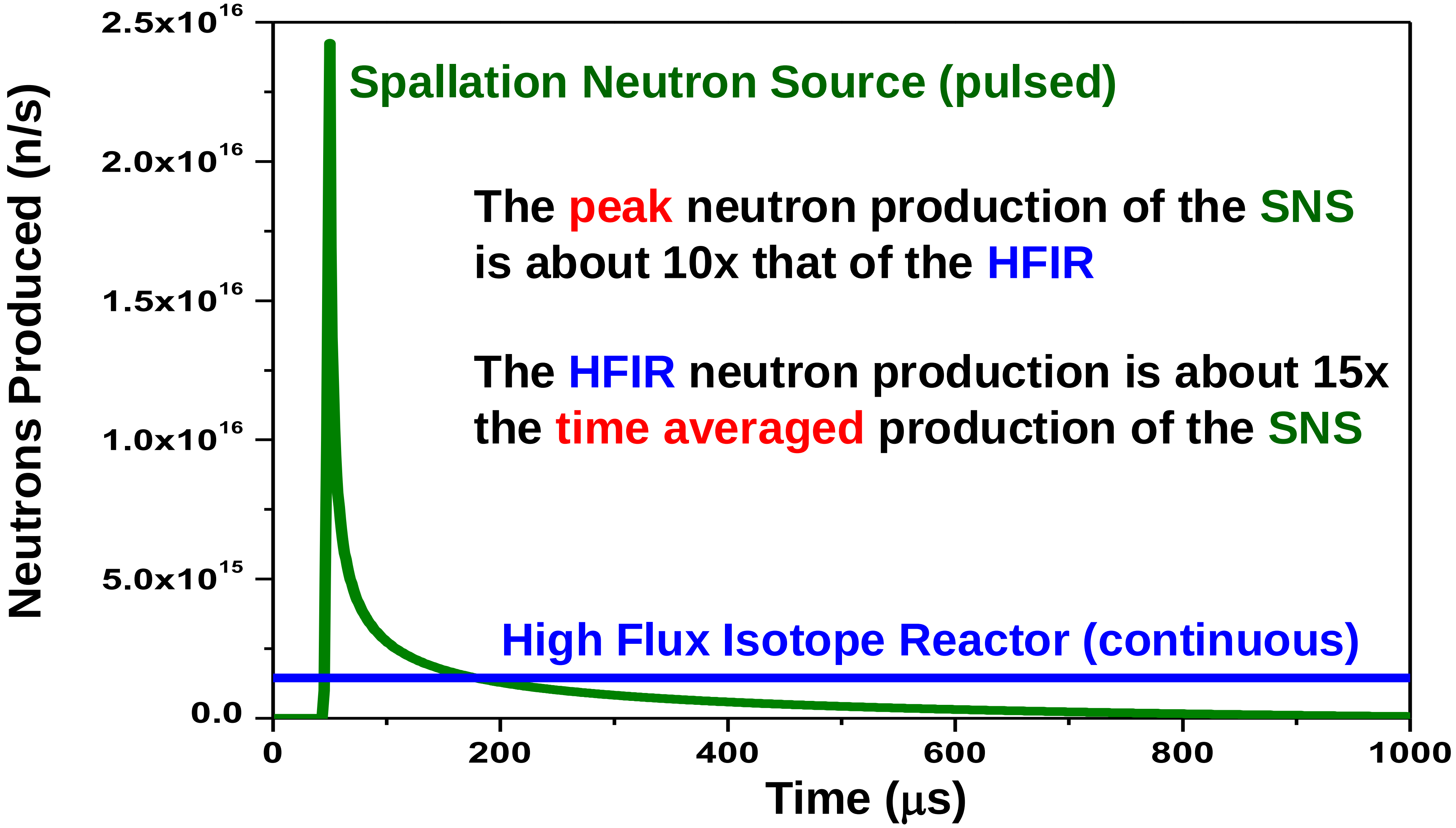
$$n\lambda = 2d \sin\theta$$

**Momentum Transfer**

$$\vec{\boldsymbol{Q}} = \vec{\boldsymbol{k}}_i - \vec{\boldsymbol{k}}_f$$

$$\Delta E = \frac{h^2}{2m}\left(|k_i|^2 - |k_f|^2\right)$$

# Pulsed vs Continuous Neutron Sources

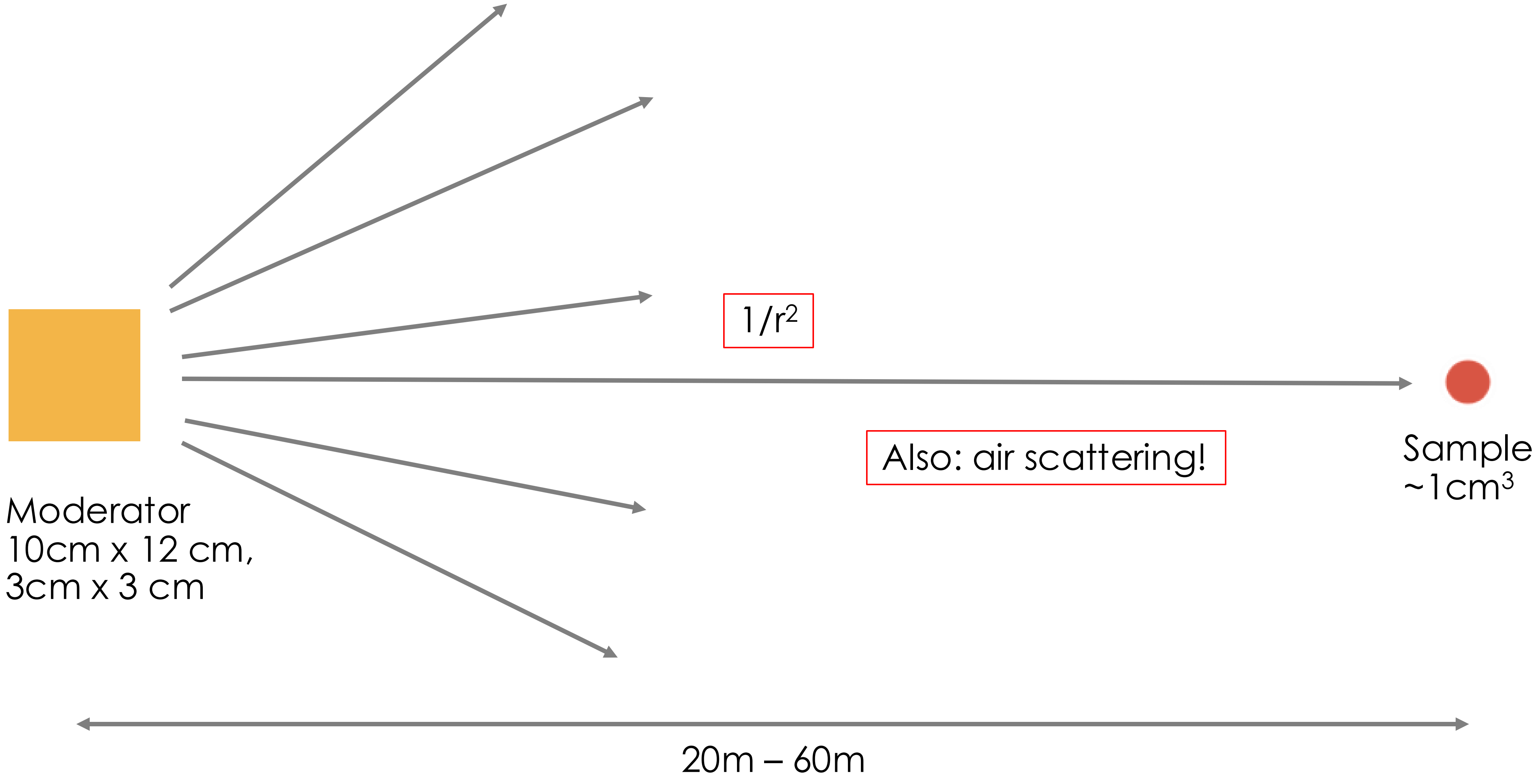





OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

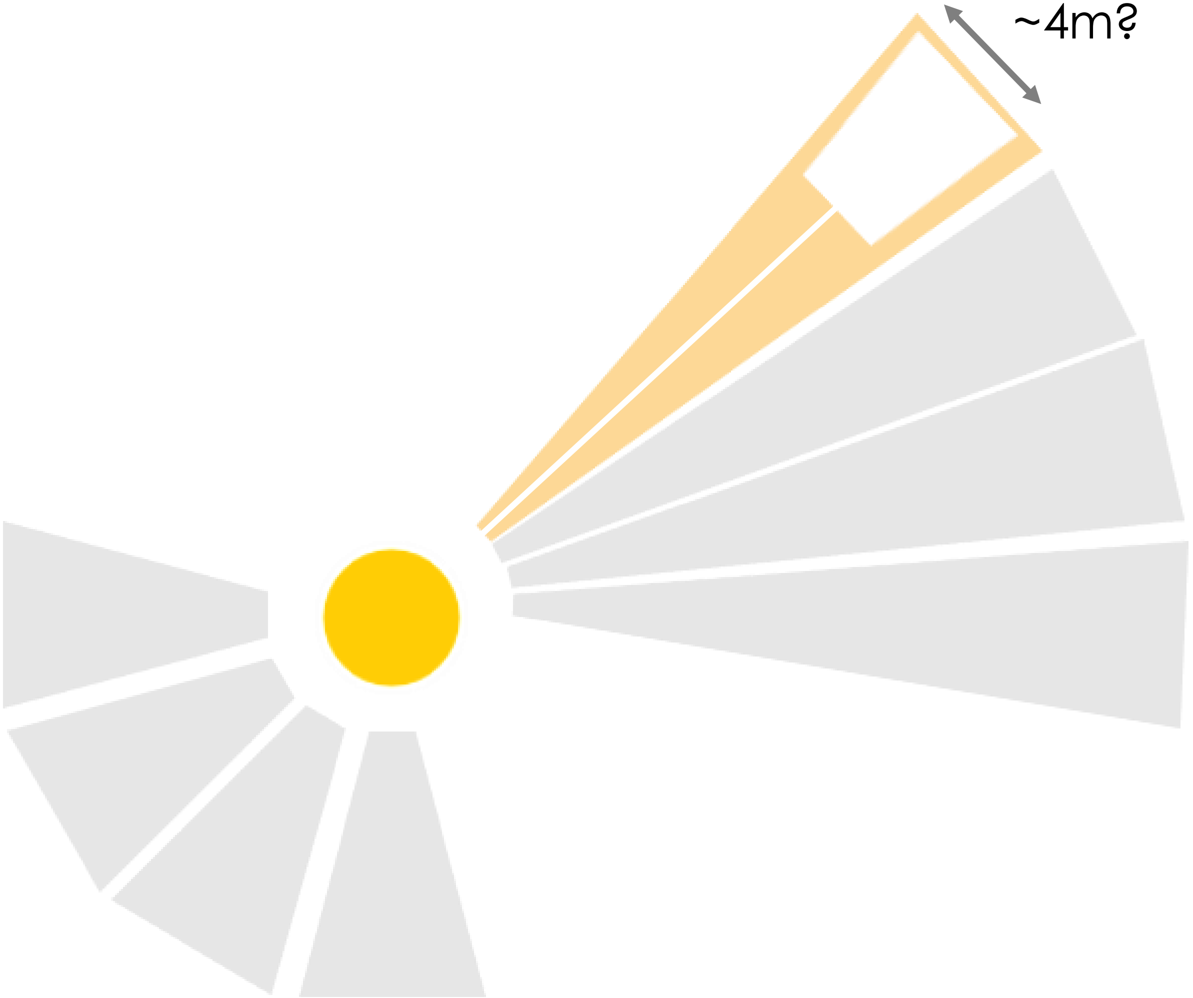
Slide courtesy of Lee Robertson

# Transport neutrons!



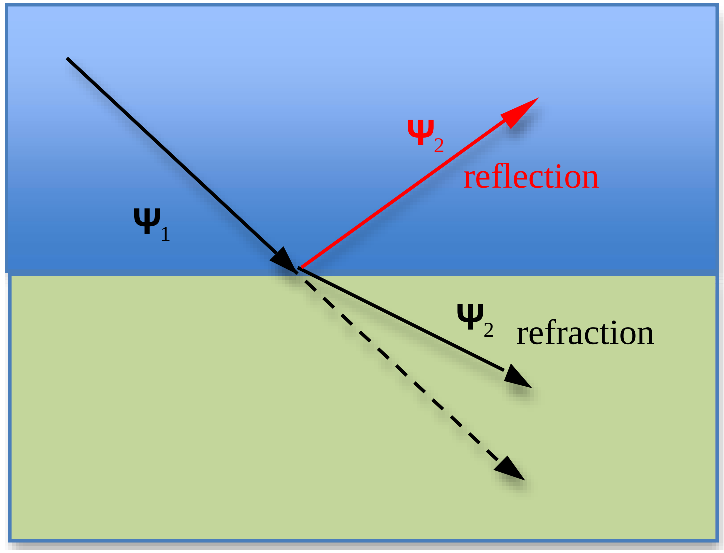
# Why not build closer to the source?

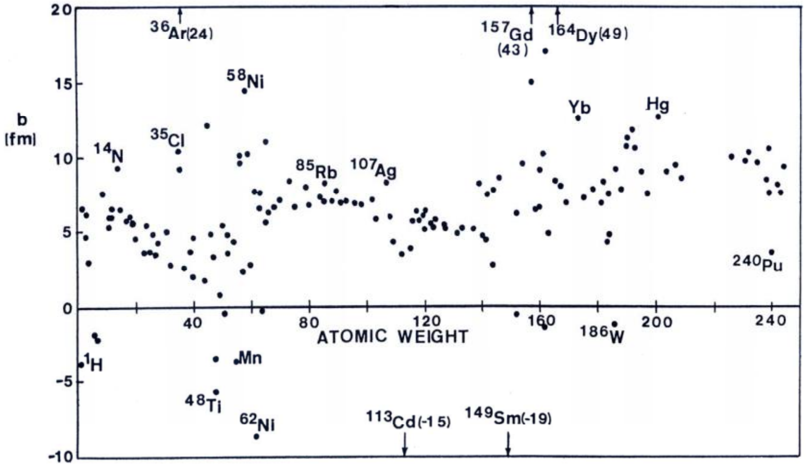
- Real estate
- Background
- TOF Resolution:



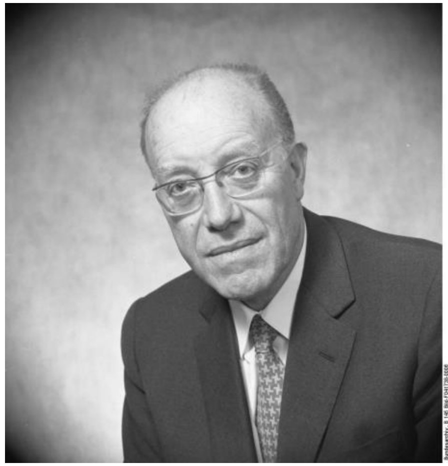
# Neutron guides

- Like any wave, neutrons can reflect off a surface under certain conditions (see reflectometry lecture!)
  - Low angles, long wavelengths
  - Ni-58 layers deposited on glass
- Invented by Heinz Maier-Leibnitz at FRM reactor



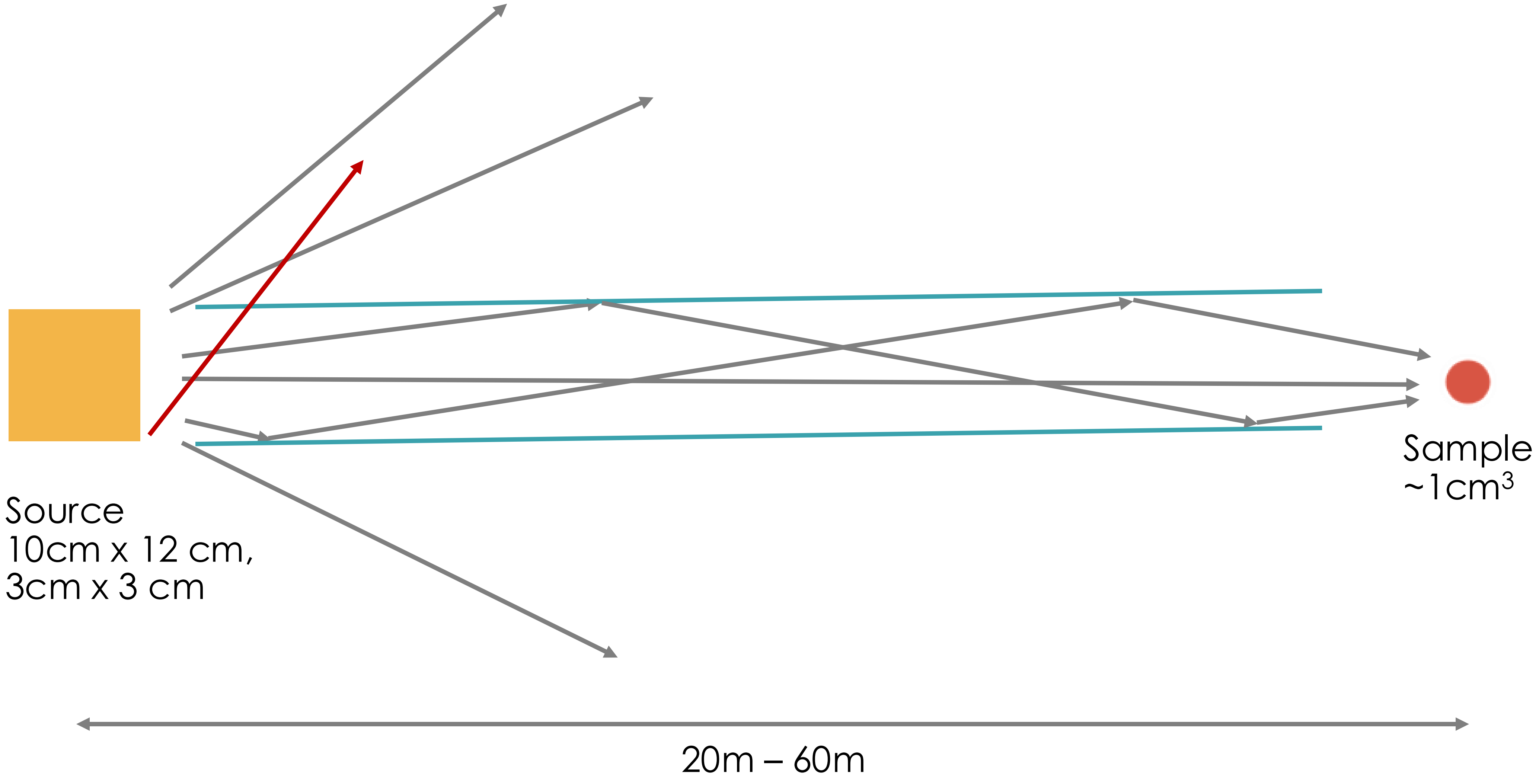




Bound coherent scattering length

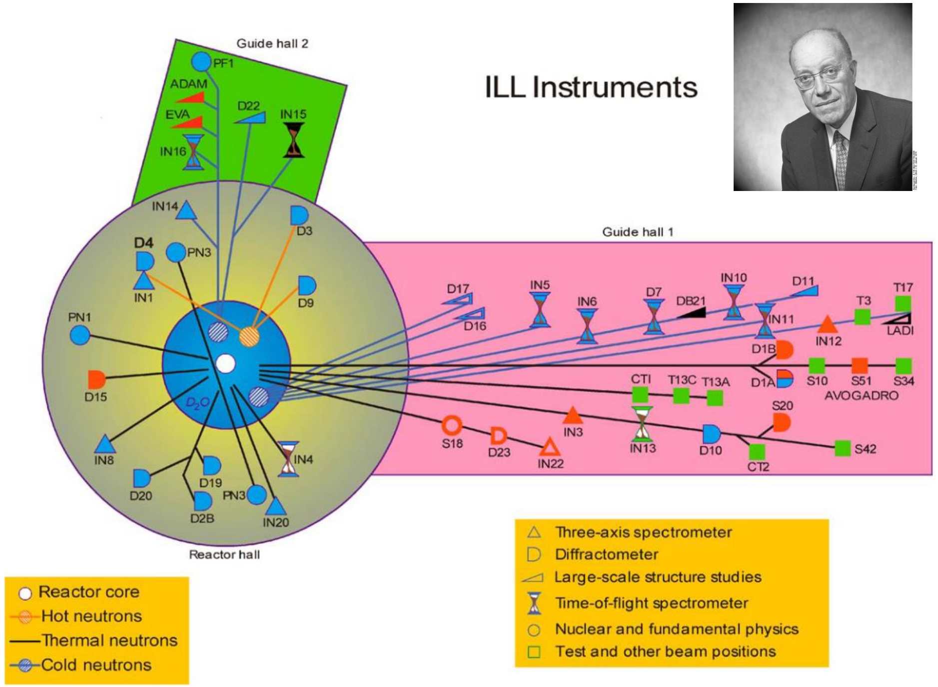


H. Maier-Leibnitz and T. Springer, React. Sci. Technol. 17, 217 (1963)

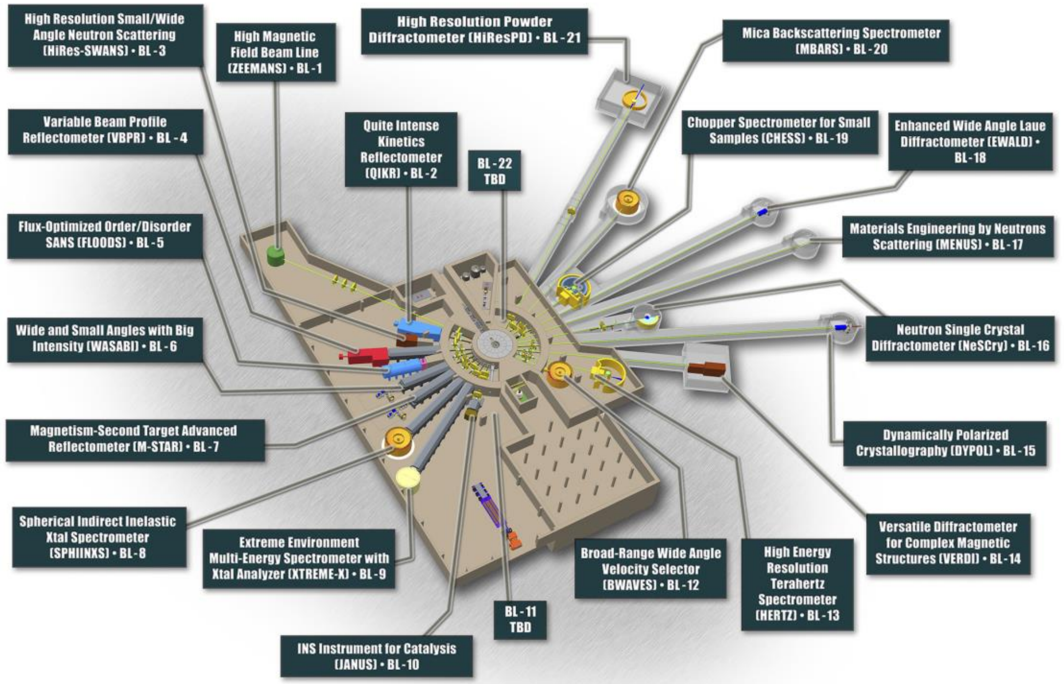
# Transport neutrons – with guides!



# Neutron Guides allow unparalleled Utilization of Neutron Beams




https://www.ill.eu/

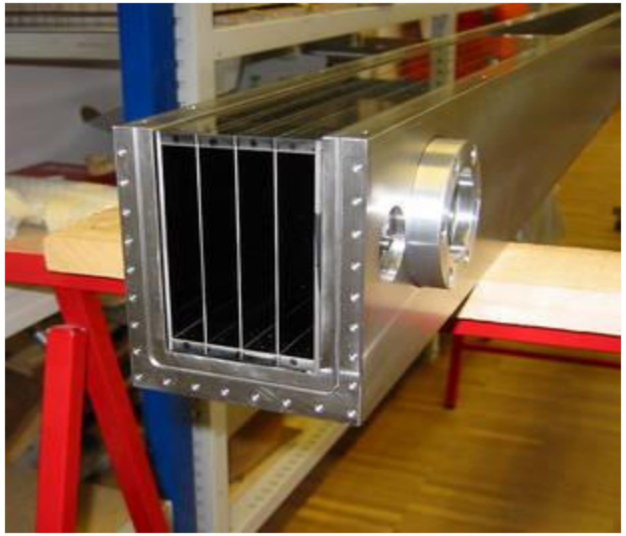



16-G00038/gim

ORNL STS conceptual design

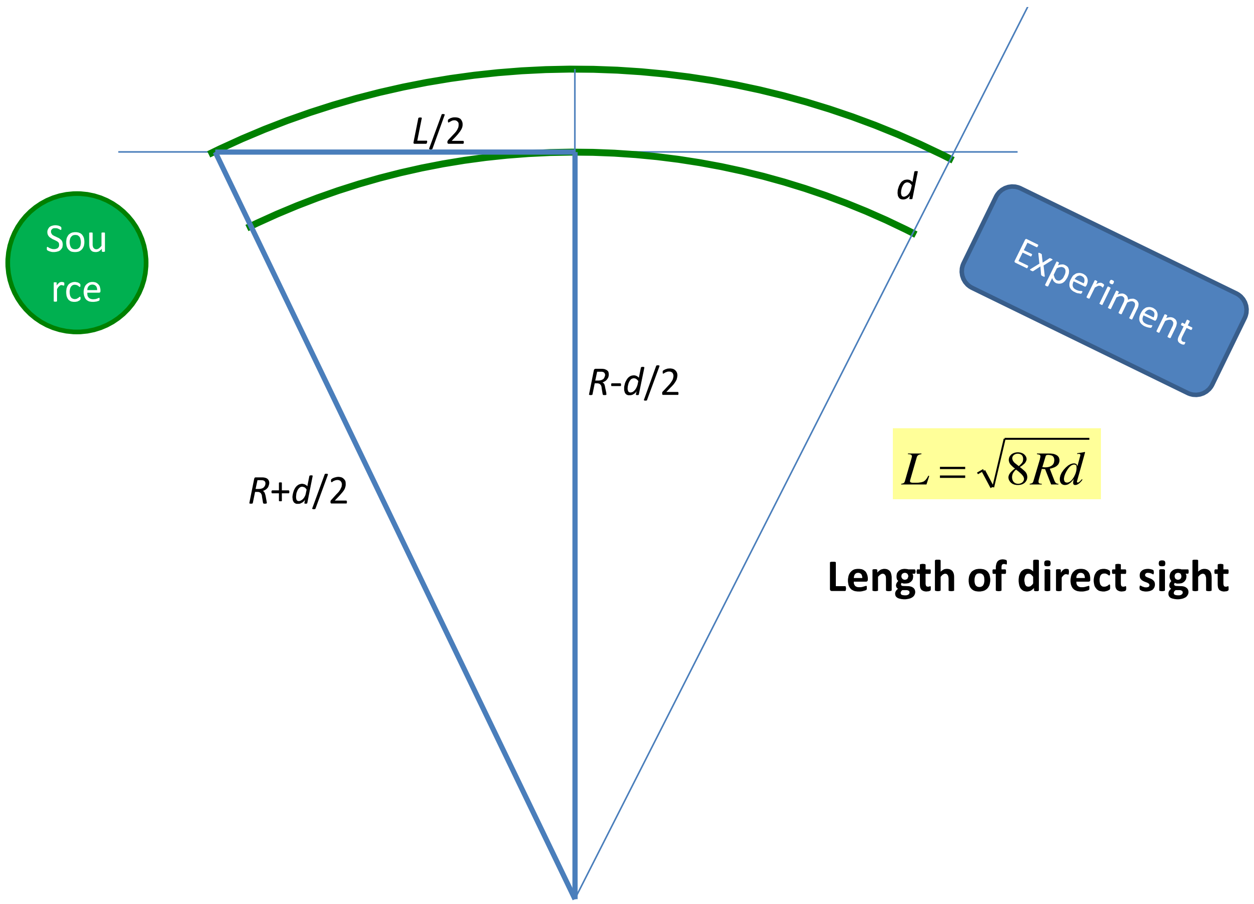
# Pictures!

80m Guide for HRPD at J-PARC
*Fabricated by Swiss Neutronics*



Multichannel Curved Guide
*Fabricated by Swiss Neutronics*

# Not just straight!



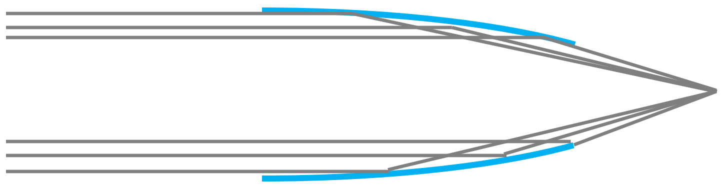

$$L = \sqrt{8Rd}$$

**Length of direct sight**

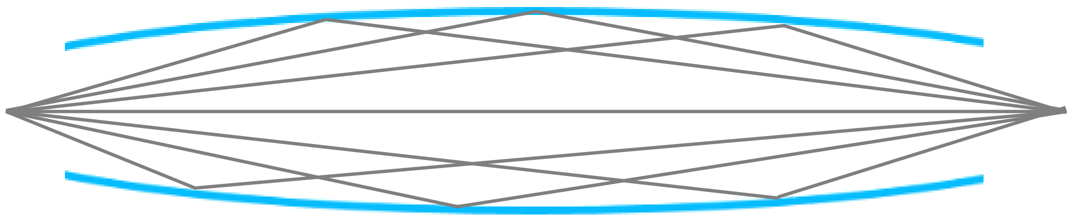
Getting out of direct line of sight reduces background from source

# Advanced neutron optics

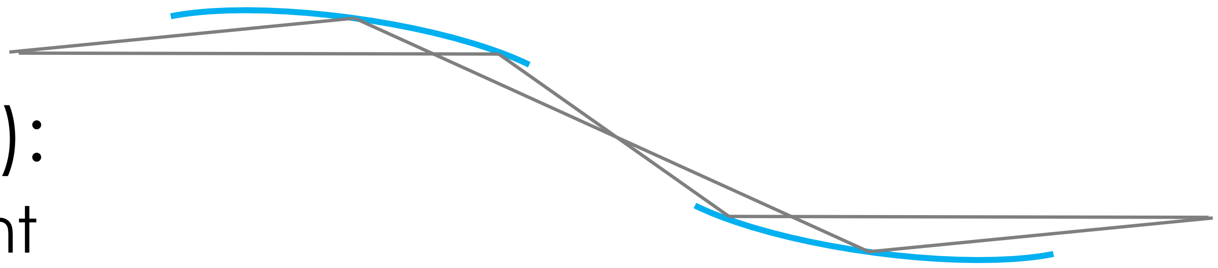
- Parabola: focusing



- Elliptic: imaging



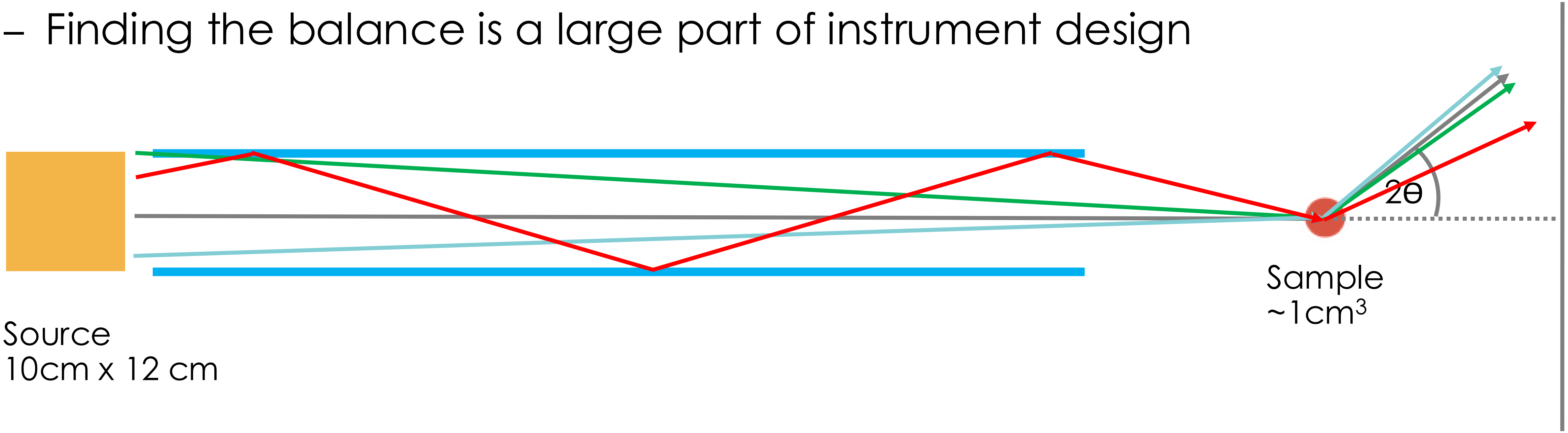
- Zig-Zag (half ellipses):
  - Imaging + line of sight



# BUT!

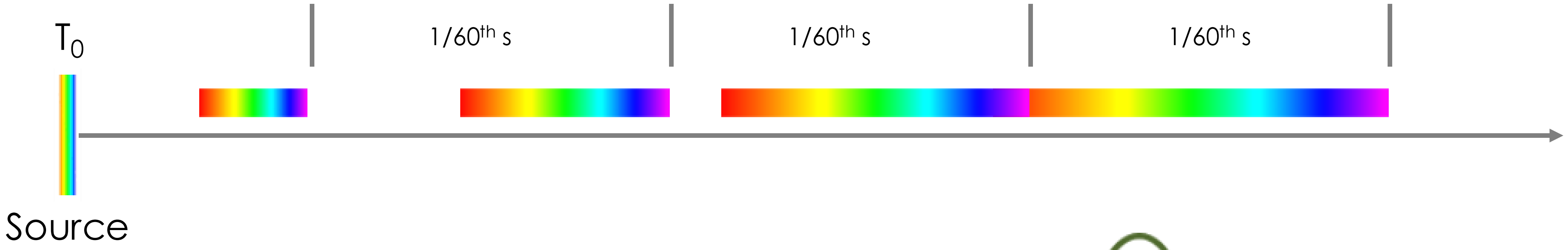
- Angle/wavelength limited
- Liouville is watching you!
  - No free lunches.
  - Increase in neutron flux comes with decreased resolution
  - Finding the balance is a large part of instrument design

Joseph Liouville

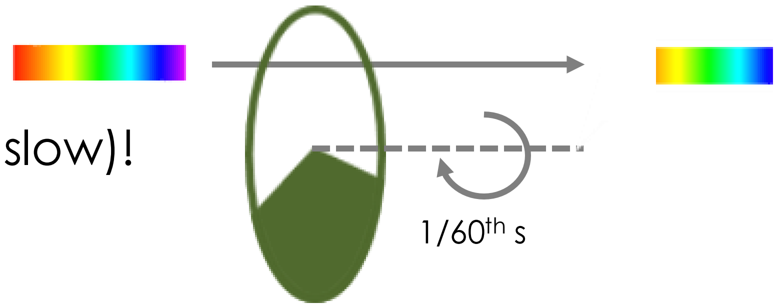


# Other problems: Frame overlap

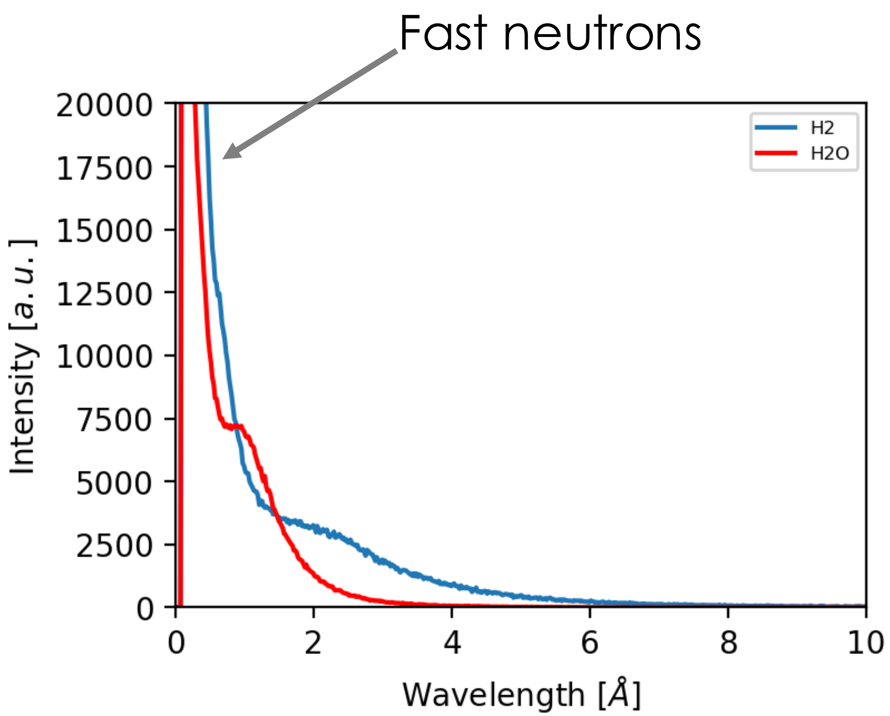
- There is usually more than one pulse in a beam line
- It is important (and difficult) to keep track of which pulse started when for TOF analysis
- Fast neutrons from one pulse can overtake the slow ones from the previous pulse “Frame overlap”
- TOF analysis becomes impossible
- The longer the beam line and the higher pulse frequency the worse

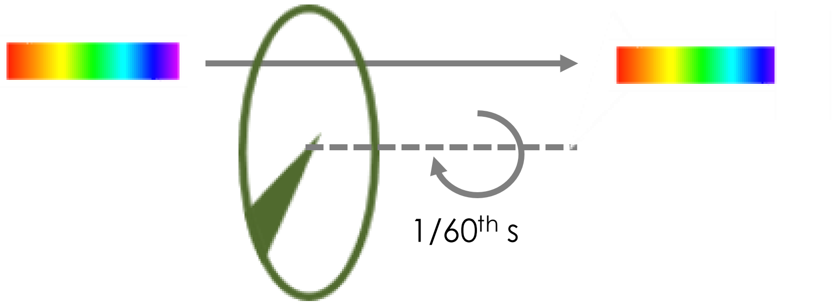



- Solution: Get rid of those neutrons (fast/slow/fast+slow)!
- Use a chopper in phase with the pulsed source
- Select time offset to chose spectrum
- Might need to measure twice for full spectrum

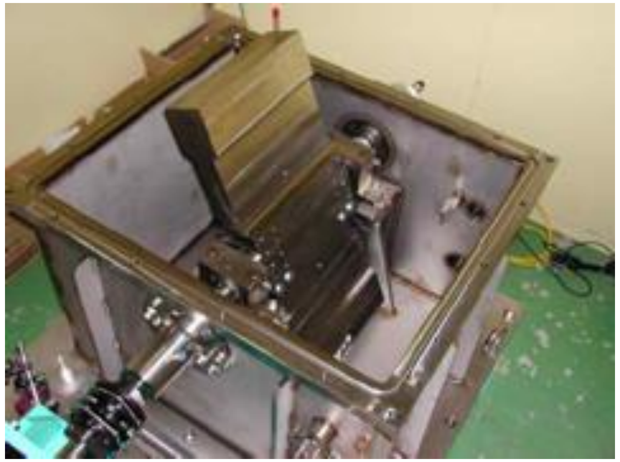


# T0 choppers




- Fast neutrons and gammas arrive first after proton pulse delivery
- 20-50 cm thick steel blade attenuates these
- Requires well-balanced flywheel for good lifetime and prevention of vibrations



Unit running at JPARC

# Detectors…

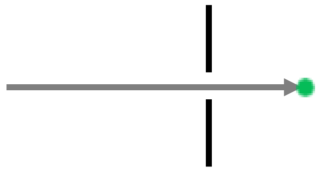
- Several types of detectors
- Idea: trigger a nuclear reaction that releases an energetic charged particle that can then be detected (e.g. through an ionization event)
- Requirements:
  - Position resolution
  - Timing resolution
  - Not sensitive to background
  - Cheap

# … and where to put them

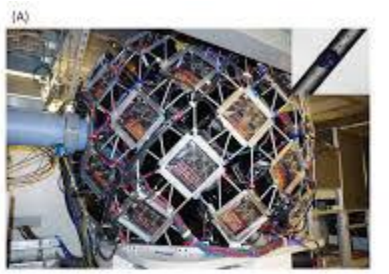
SANS:


Wide Q range:

High resolution powder diffraction:

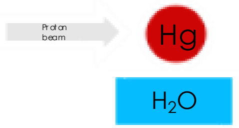


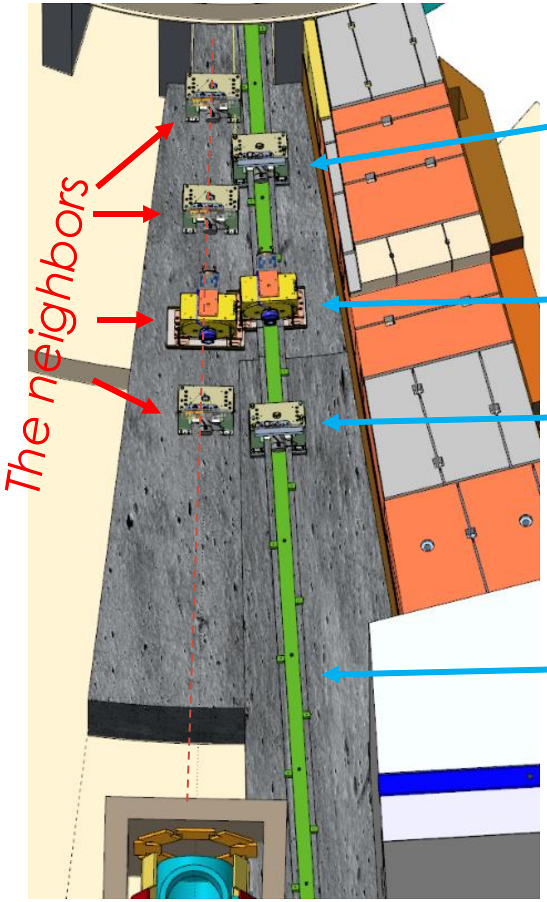
Single Crystal Diffractometer:




TOPAZ @ SNS

# DISCOVER (planned @ SNS)



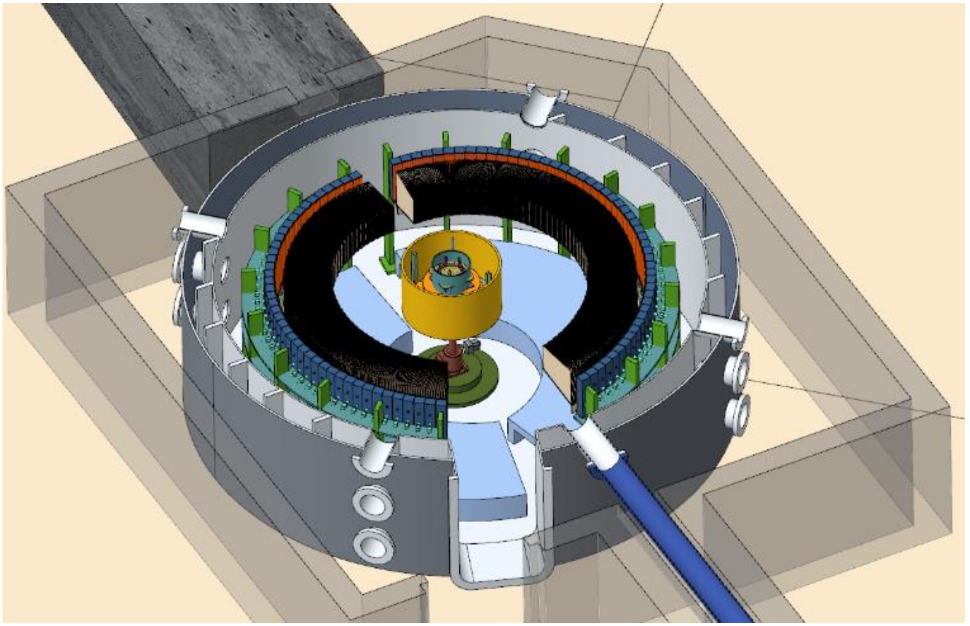
The neighbors

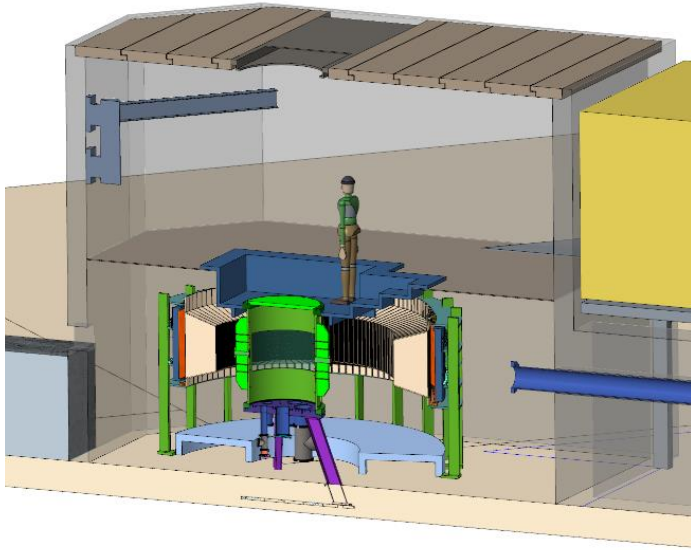
Frame overlap chopper 1

T0 chopper

Frame overlap chopper 2

Guide





# Second Target Station