Neutron Generation and Detection/ Neutron Optics and Instrumentation - Part 1

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CHESS Instrument Scientist

July 2022

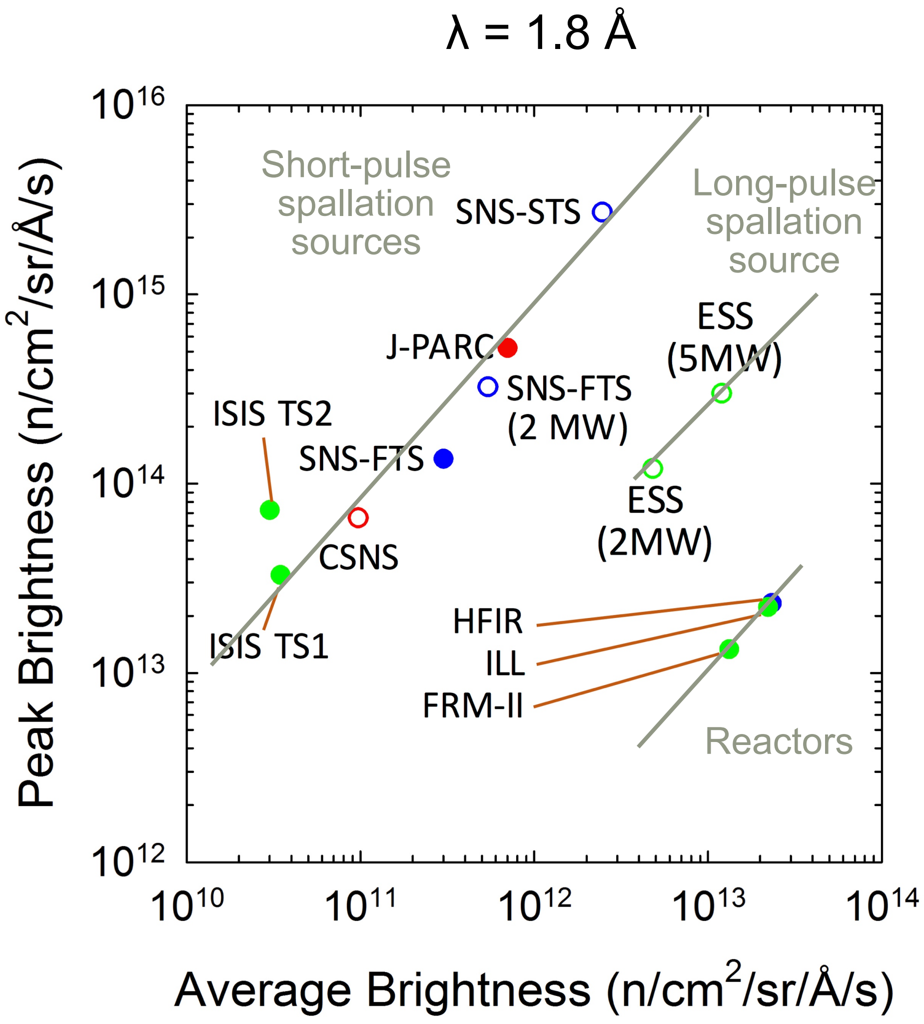
Neutron Generation and Detection/Neutron Optics and Instrumentation

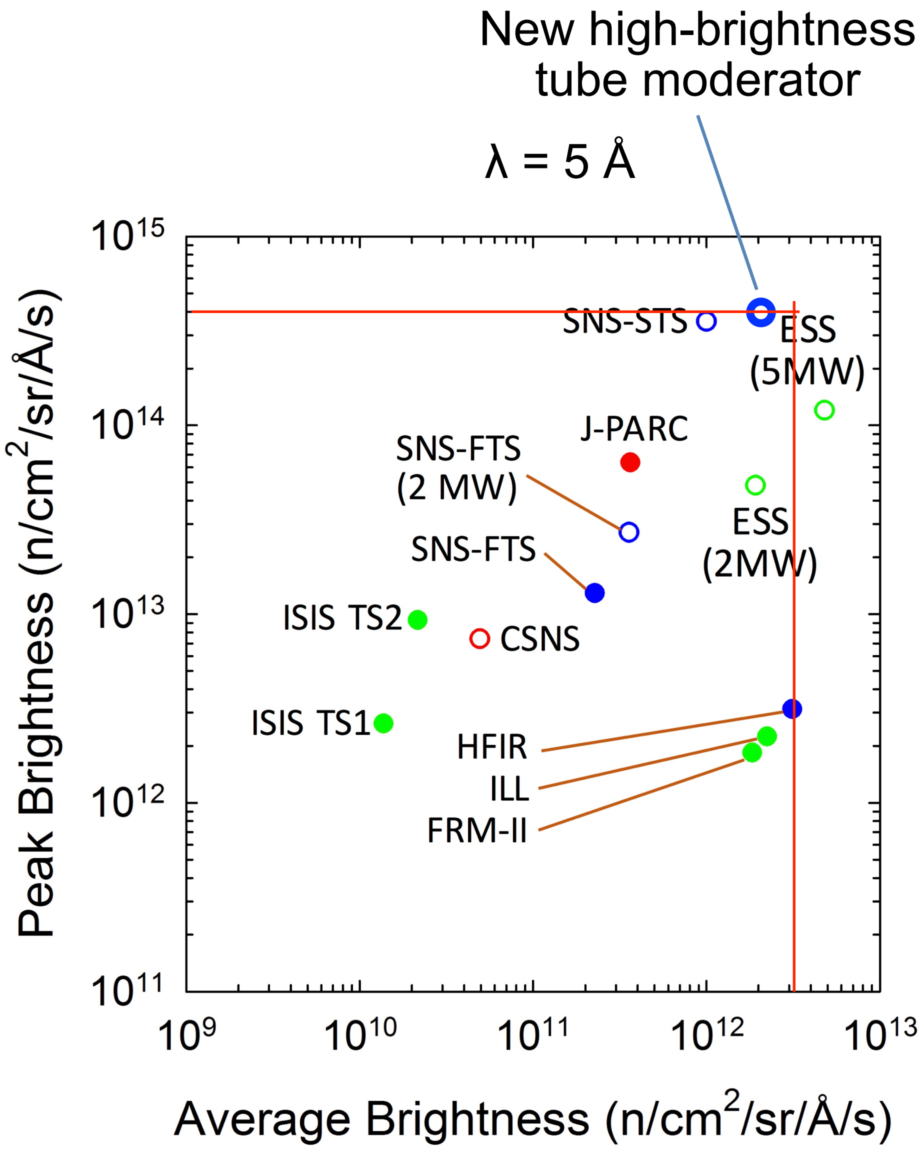
- How to build a neutron scattering instrument from scratch:
  - Make neutrons! **(Source)**
  - Transport neutrons! **(Guide + Optics)**
  - Scatter neutrons! (other people will tell you about this)
  - Detect neutrons! **(Detectors)**

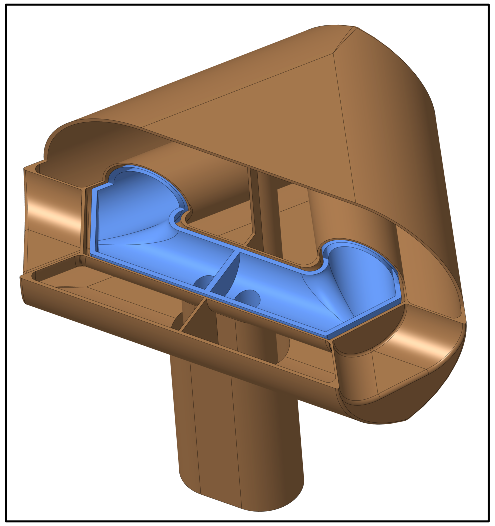
- Simulate Neutron Instruments

- Simulate X-rays Instruments

Neutron Sources in the world

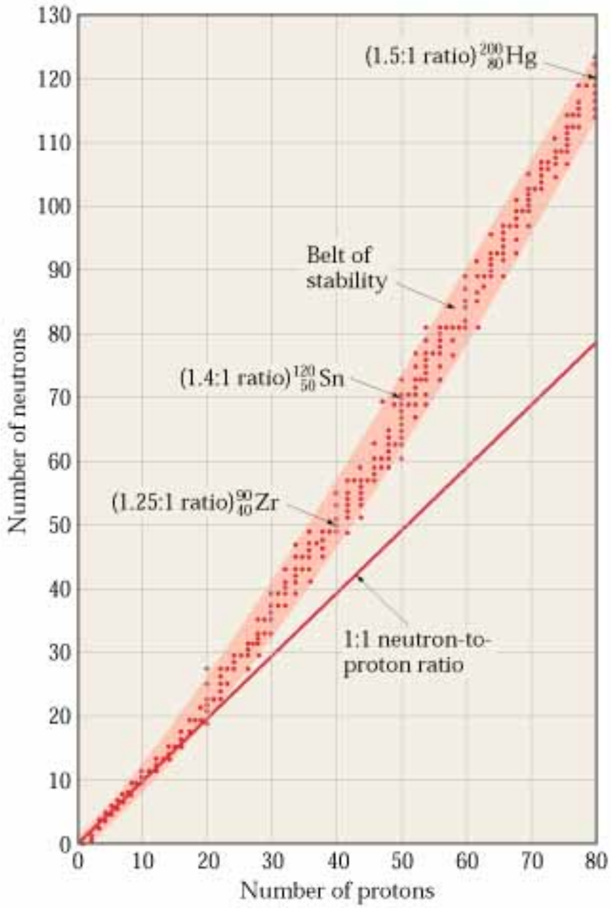


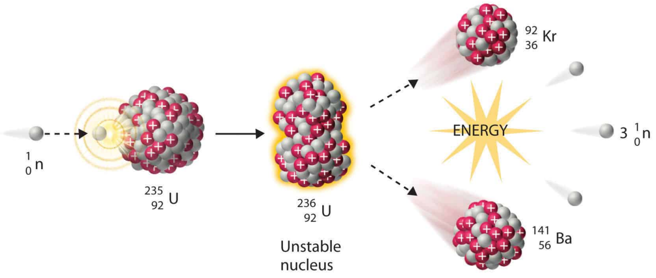


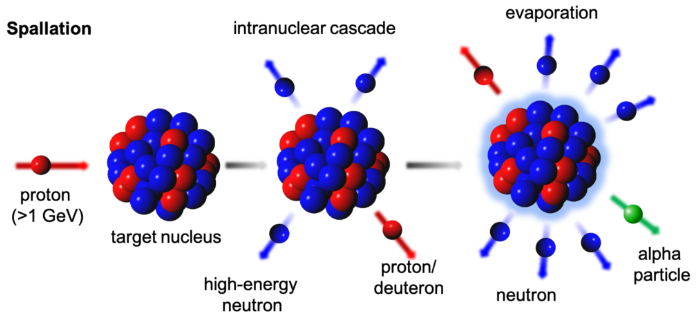


Make neutrons!

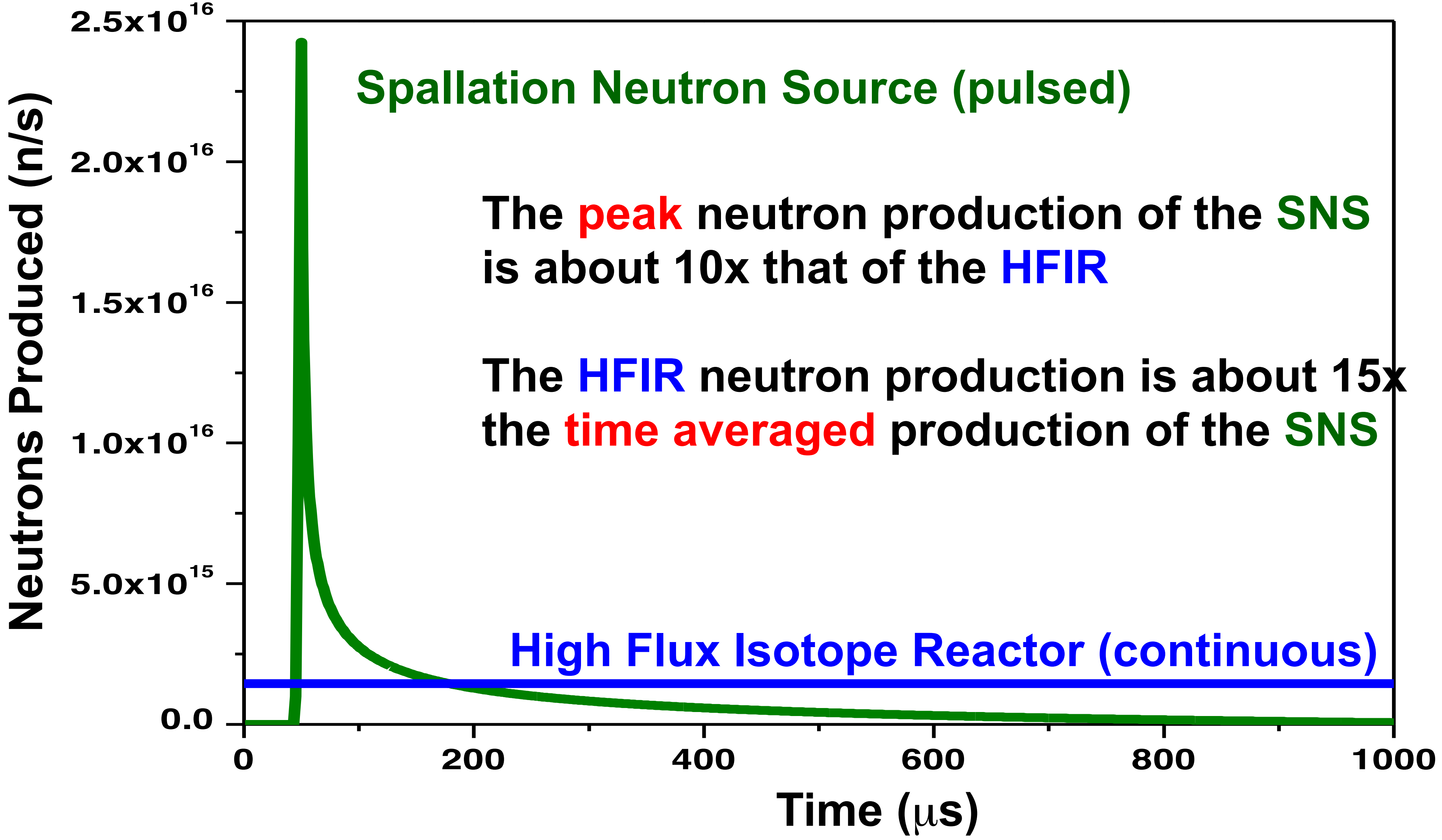
- We don't make neutrons, we "liberate" them
- …by breaking atoms!
- Heavy atoms have disproportionally more neutrons
  - Split them into smaller atoms, and you have a surplus of neutrons!
- At HFIR: FISSION Process
  nuclear chain reaction (Uranium)
- At SNS: SPALLATION Process
  high power accelerator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







Pulsed vs Continuous Neutron Sources



Make <u>useful</u> neutrons!

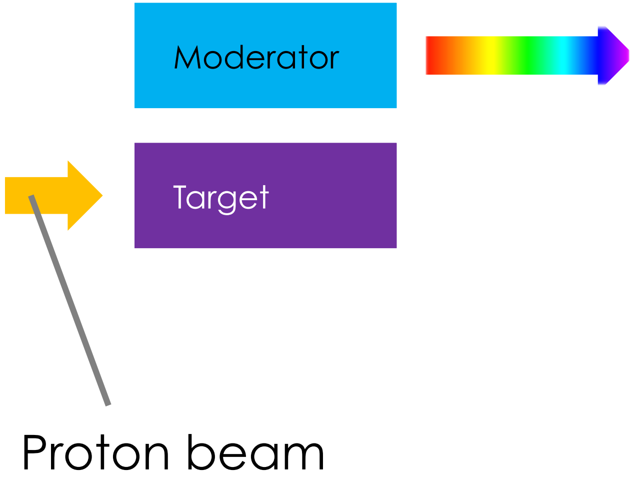
Energy (meV)	Velocity (m/s)	Temp (K)	Wavelength (Å)
0.1 – 5	100-1000	1 – 120 ("Cold")	4 – 30
5 – 100	1000-4000	120 – 1000 ("Thermal")	1 – 4
100 – 500	4000-40000	1000 – 6000 ("Hot")	0.4 –1
. . .			
> MeV	~1E7	1E9	< mÅ

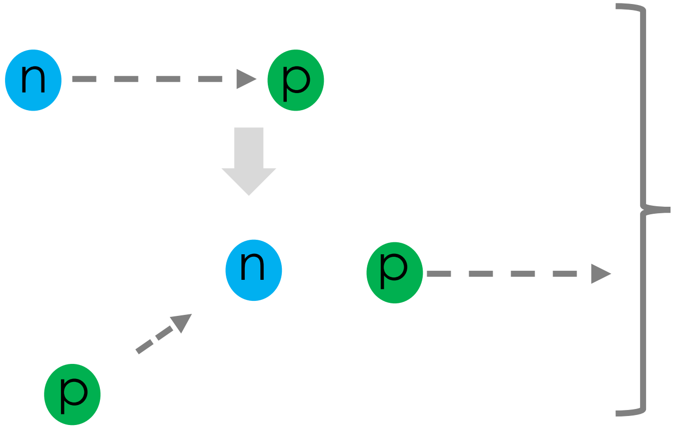
You are here!

We Need to Moderate Them

Moderators

usually: LH_2 or H_2O

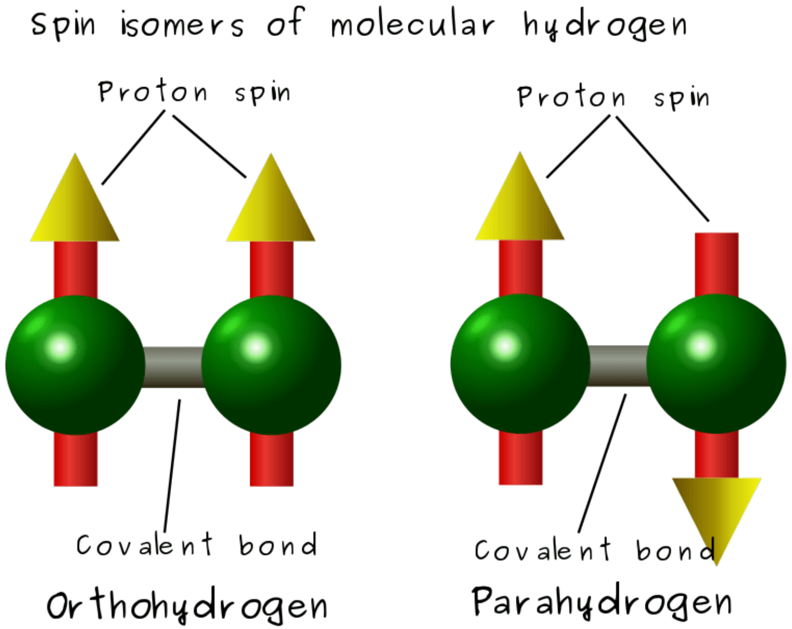


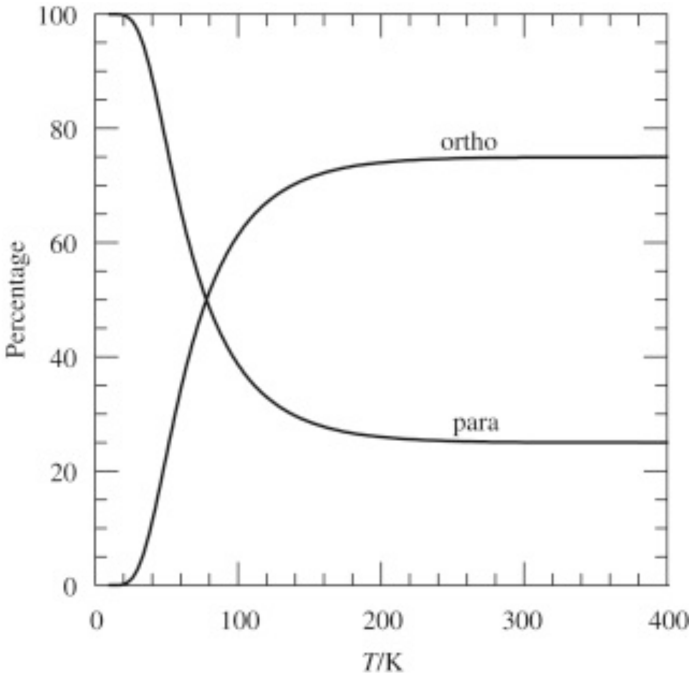


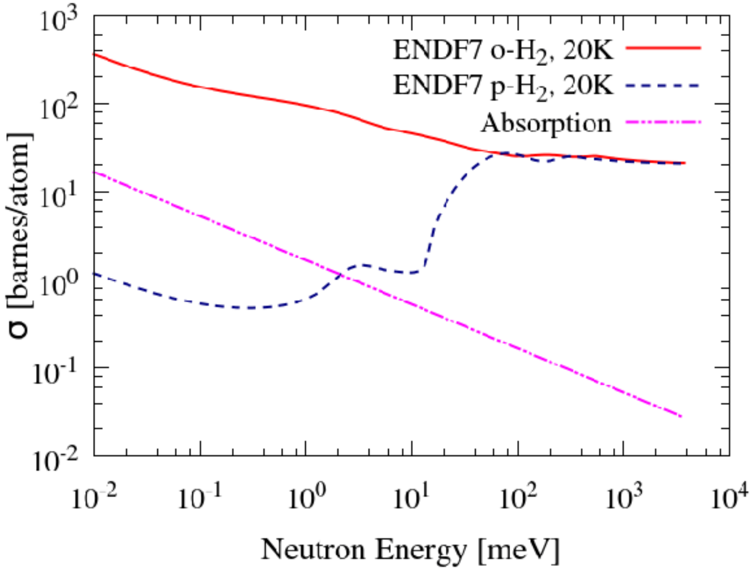
Within a few collisions, the energies will have equilibrated around the temperature of the moderator.

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

Moderators: Ortho vs Para-Hydrogen

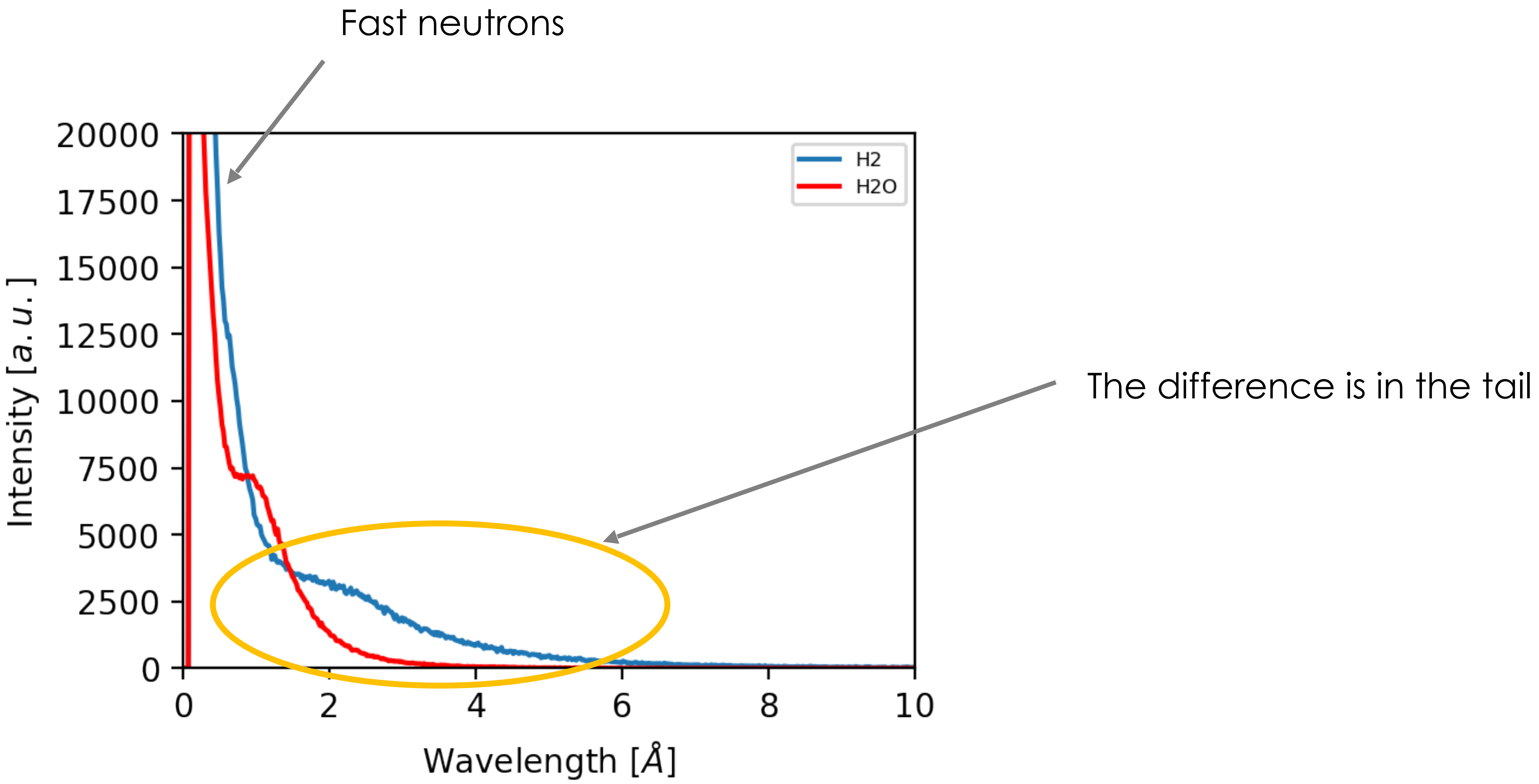






Ideally, we want **100%**
Para-Hydrogen in our moderators

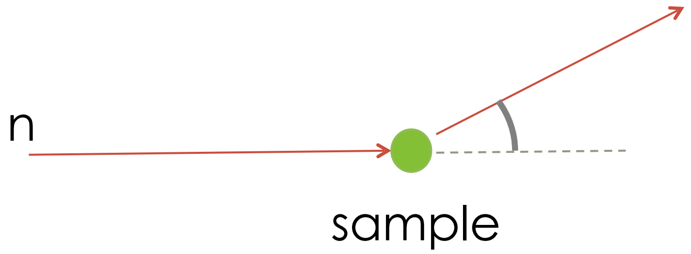
Spectra H2 vs H2O @ SNS



Two instrument concepts

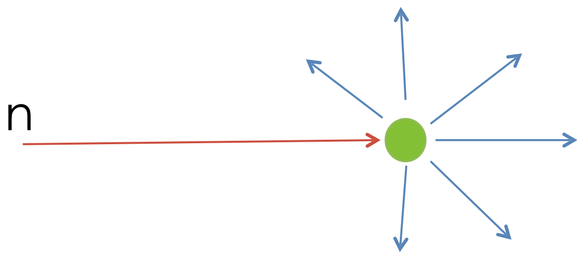
Diffractometer (elastic scattering)

- Characteristic changes in angle
- No change in wavelength

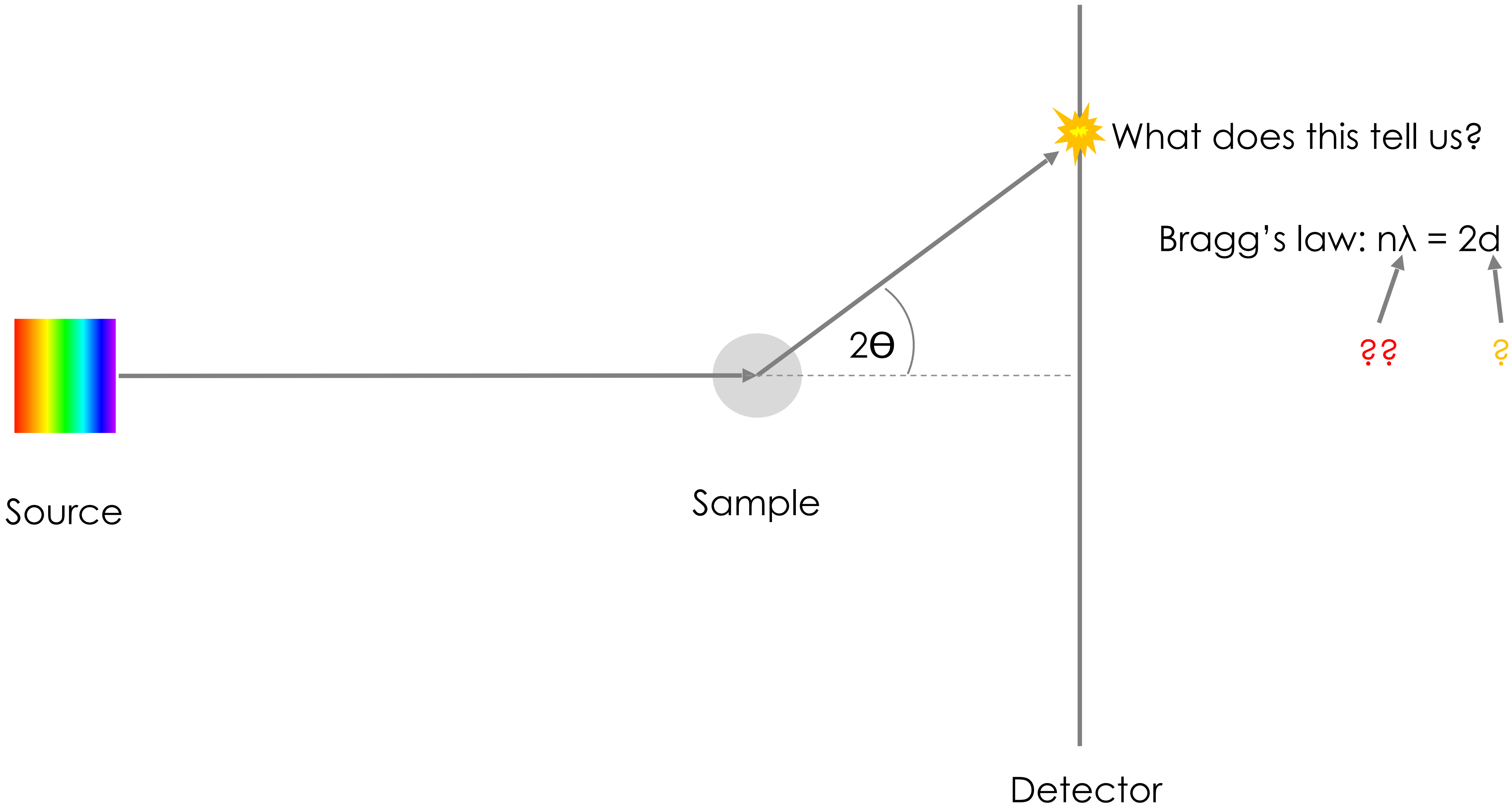


Spectrometer (inelastic scattering)

- Isotropic change in angle
- Characteristic change in wavelength



Let's build an instrument already!

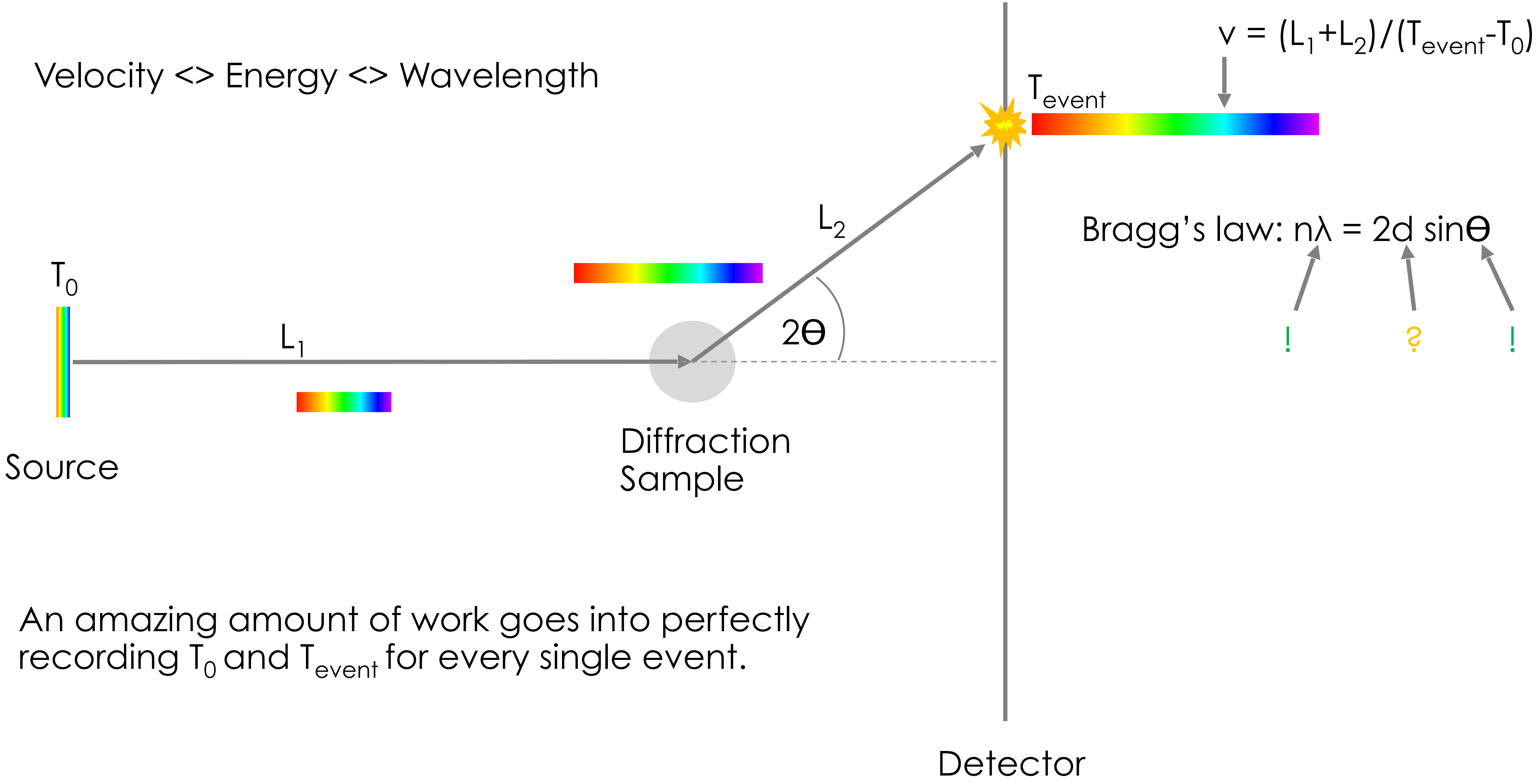


Bragg's law: $n\lambda = 2d \sin\theta$

??   ?   !

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

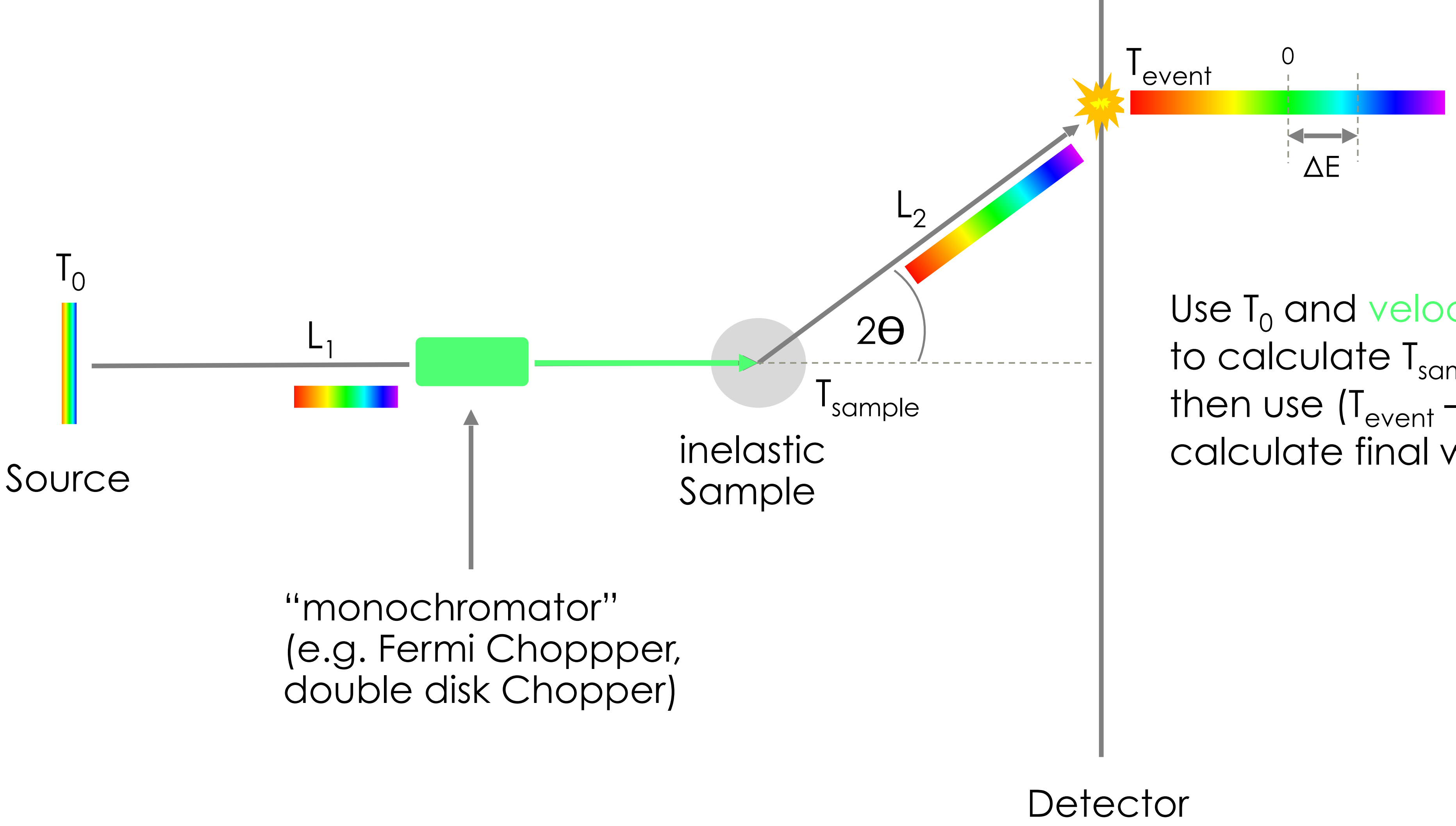
Velocity <> Energy <> Wavelength



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

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

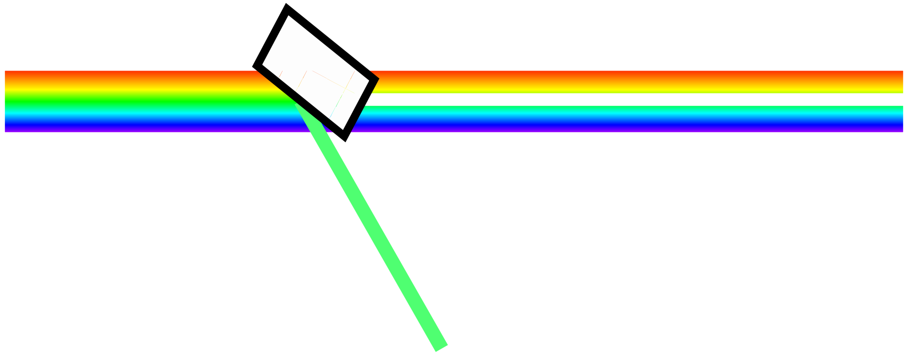
Requires knowledge of Energy before AND after sample!



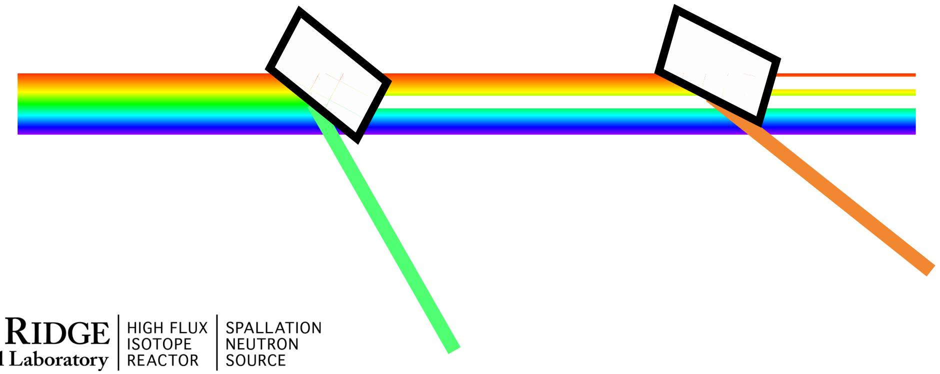
Use T_0 and velocity to calculate T_{sample}, then use $(T_{event} - T_{sample})/L_2$ to calculate final wavelength.

Detour: Crystal monochromators

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

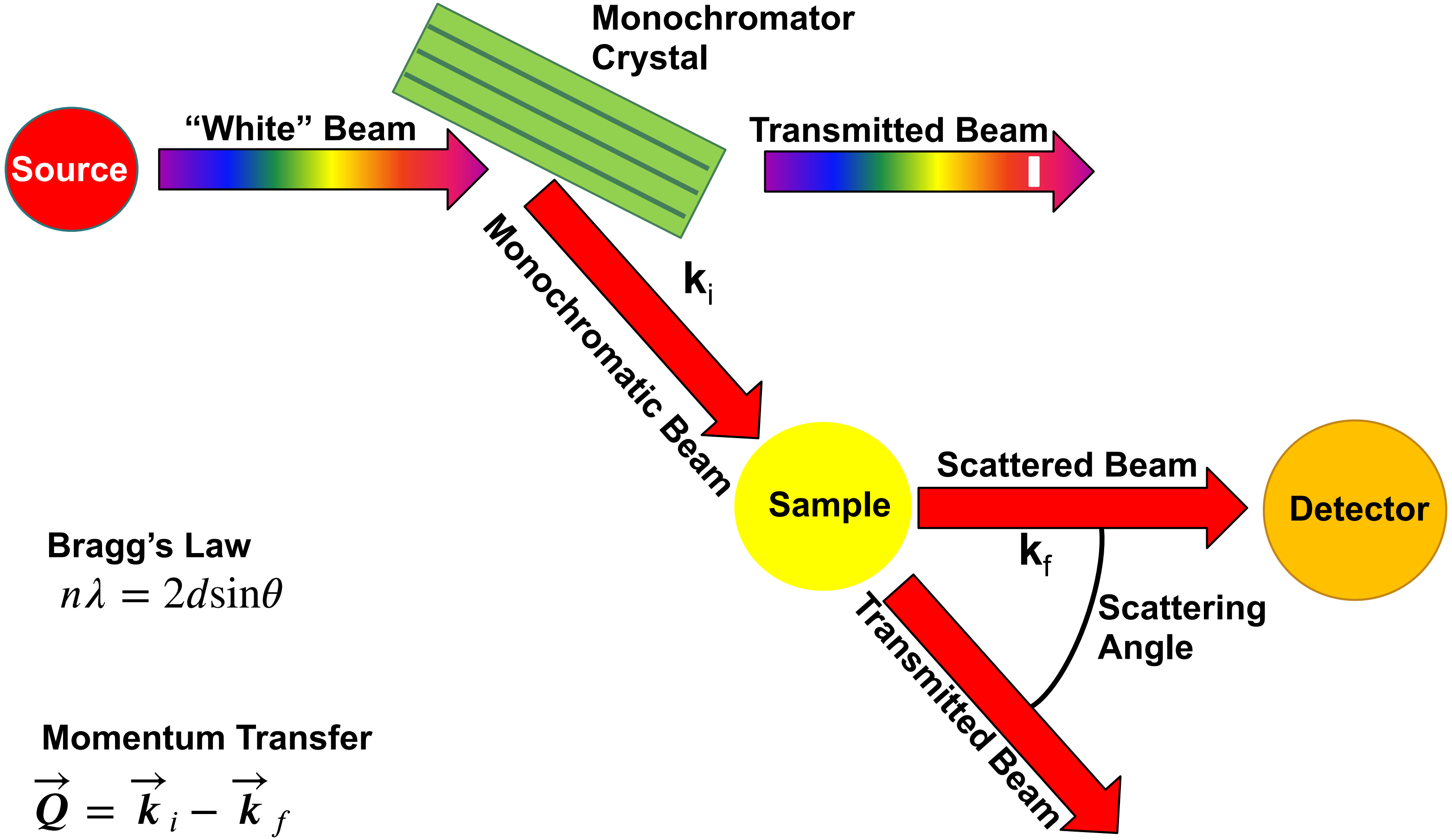


- Can re-use the transmitted beam for other wavelengths!



USANS @ SNS

Reactor instruments - elastic



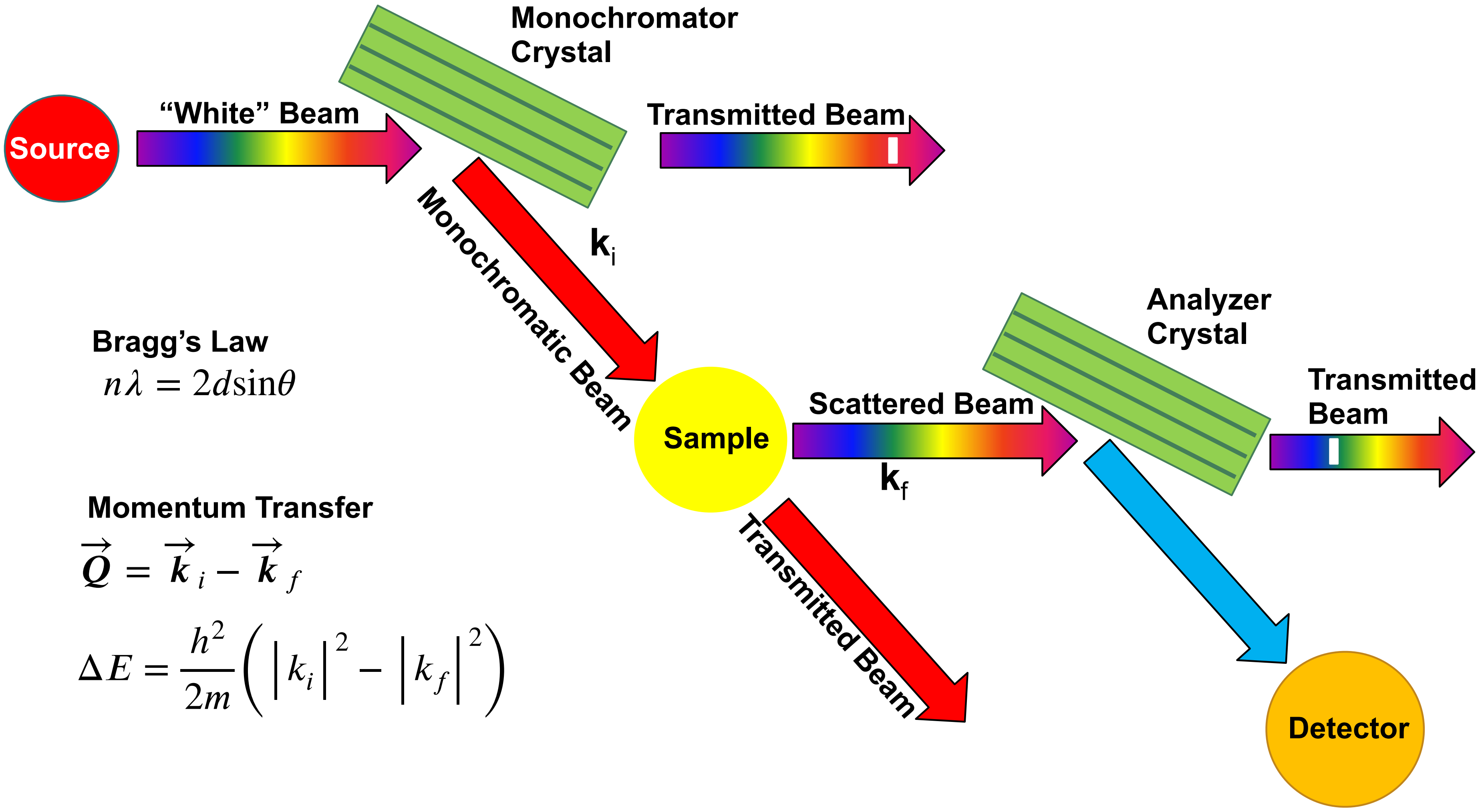
Bragg's Law

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

Momentum Transfer

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

Reactor instruments - inelastic



Bragg's Law

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

Momentum Transfer

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

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

Questions / Break

Lecture (11:00 – 12:00)

Neutron Generation and Detection/Neutron Optics and Instrumentation - Gabriele Sala

https://forms.office.com/g/p5TXaaa542

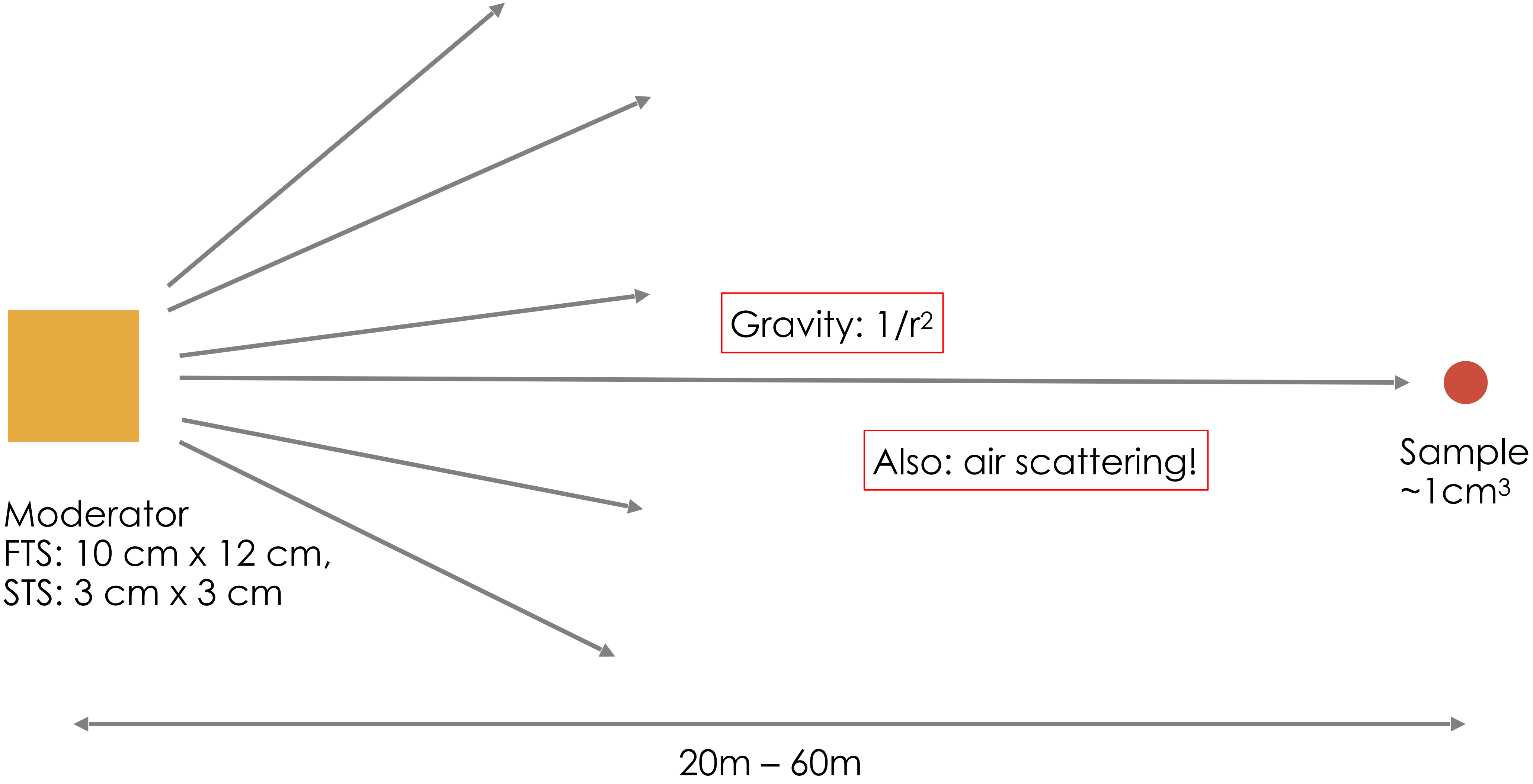
Neutron Generation and Detection/ Neutron Optics and Instrumentation - Part 2

Gabriele Sala

CHESS Instrument Scientist

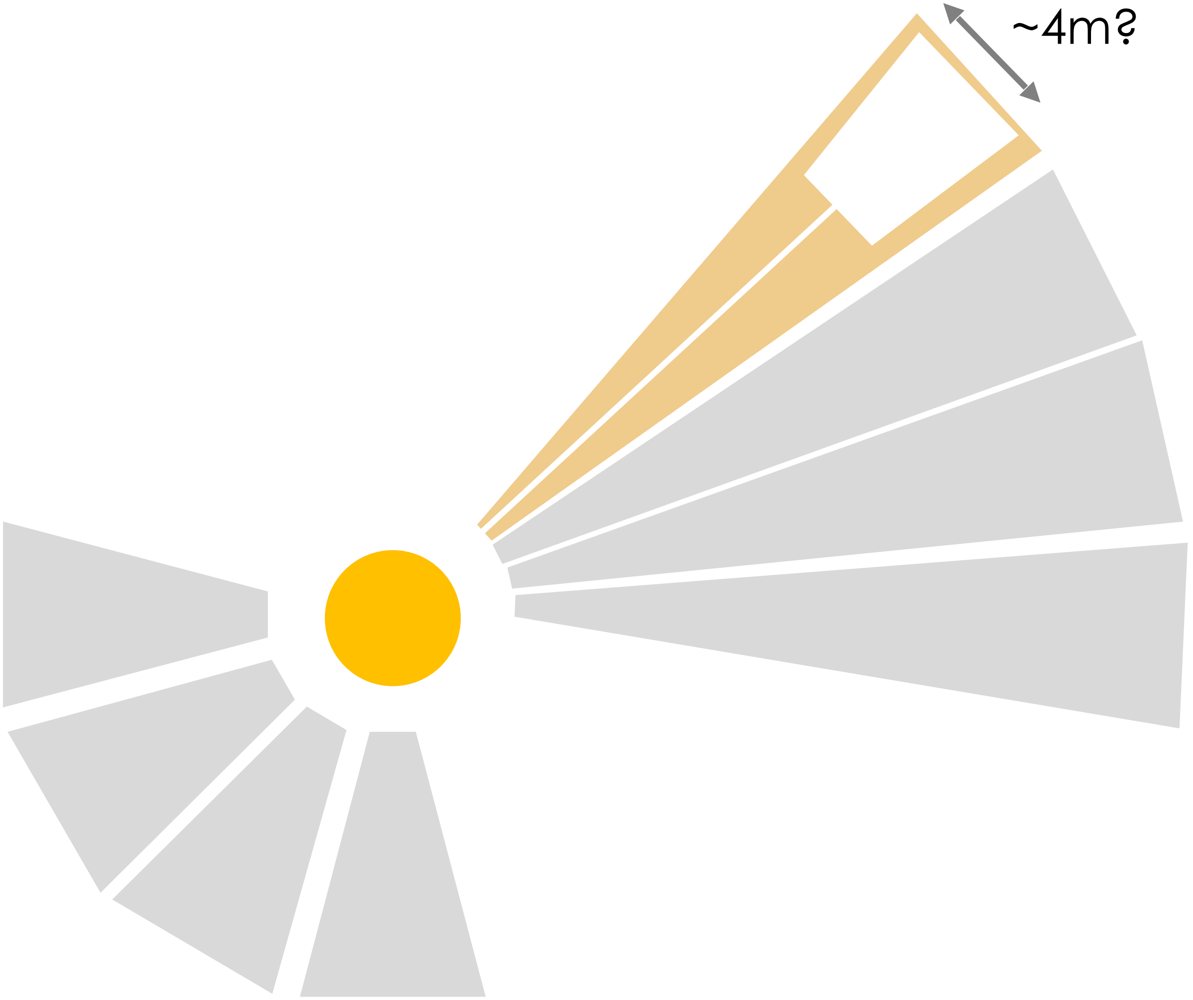
July 2022

Transport neutrons!



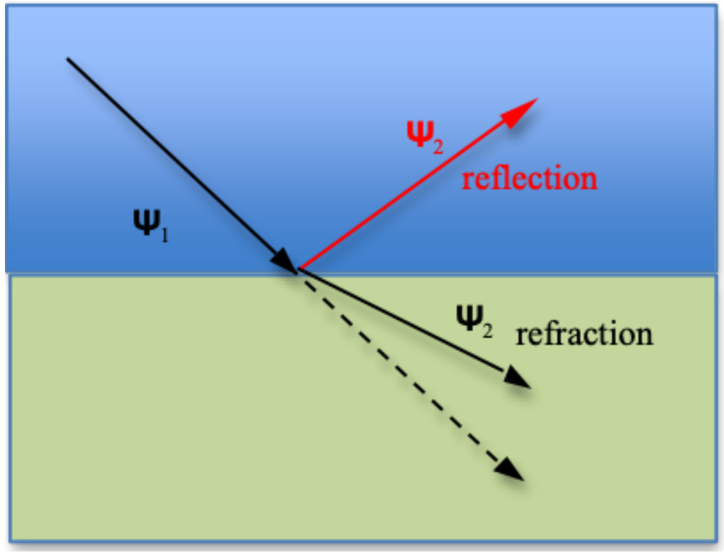
Why not build closer to the source?

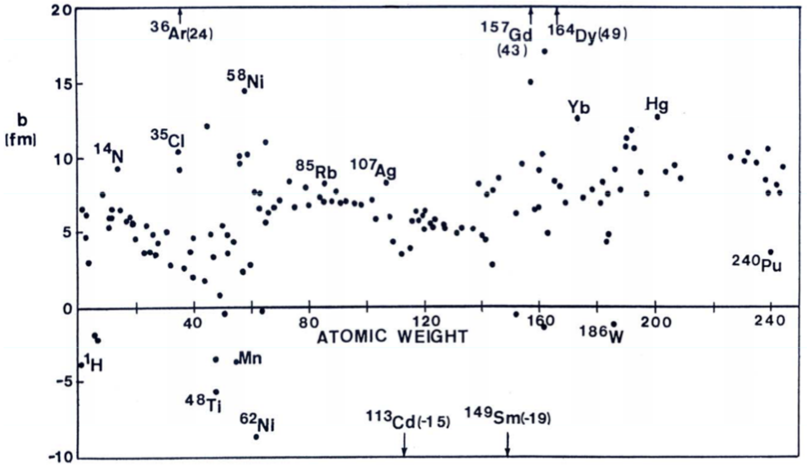
- Real estate
- Background
- TOF Resolution:



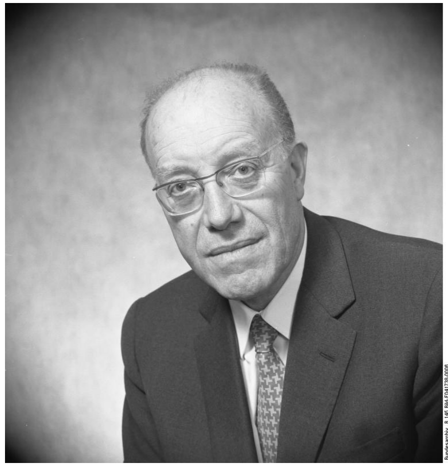
Neutron guides

- 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



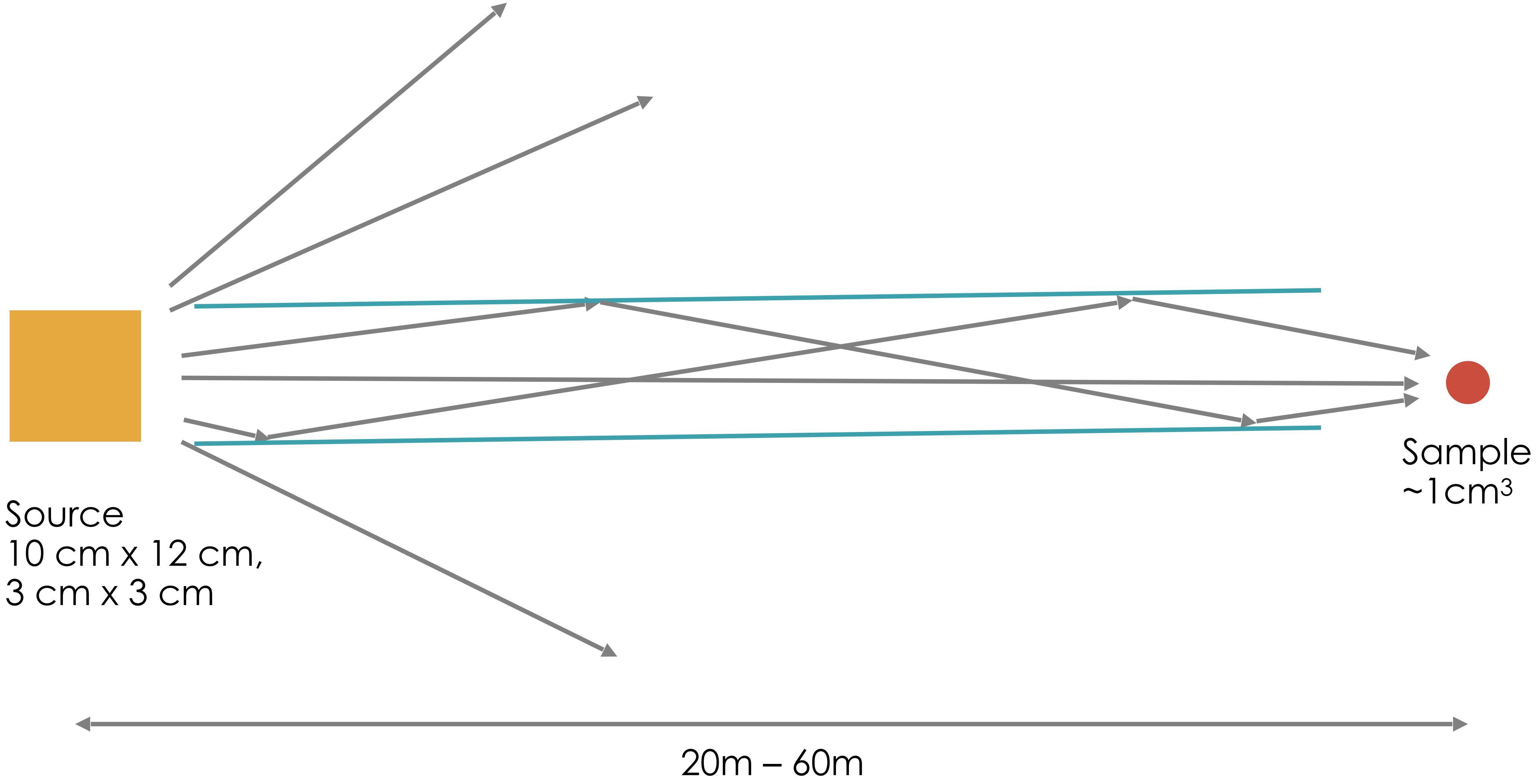


Bound coherent scattering length

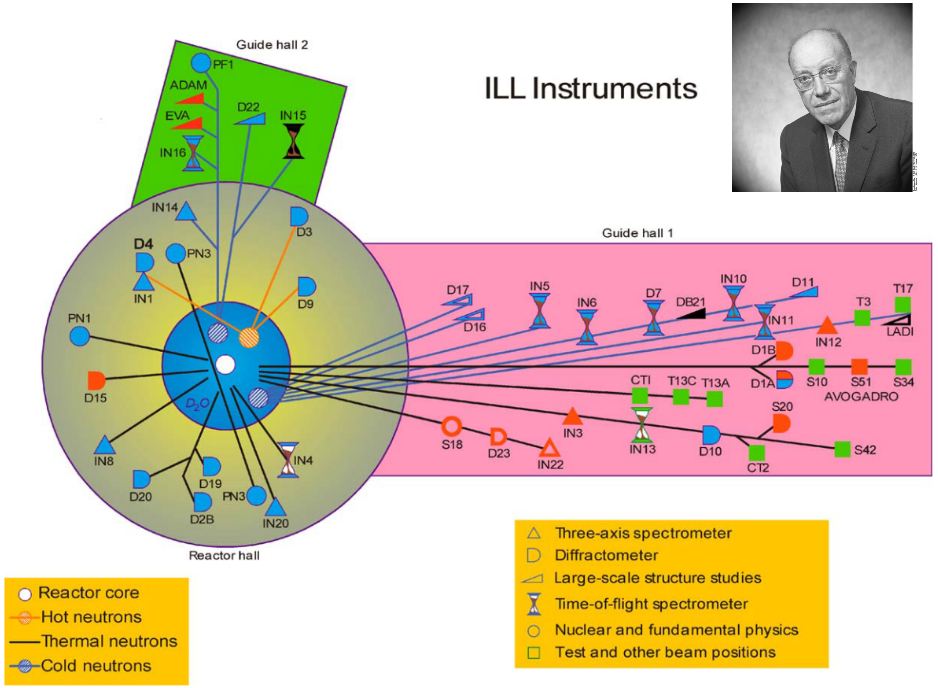


H. Maier-Leibnitz and T. Springer, React. Sci. Technol. 17, 217 (1963)

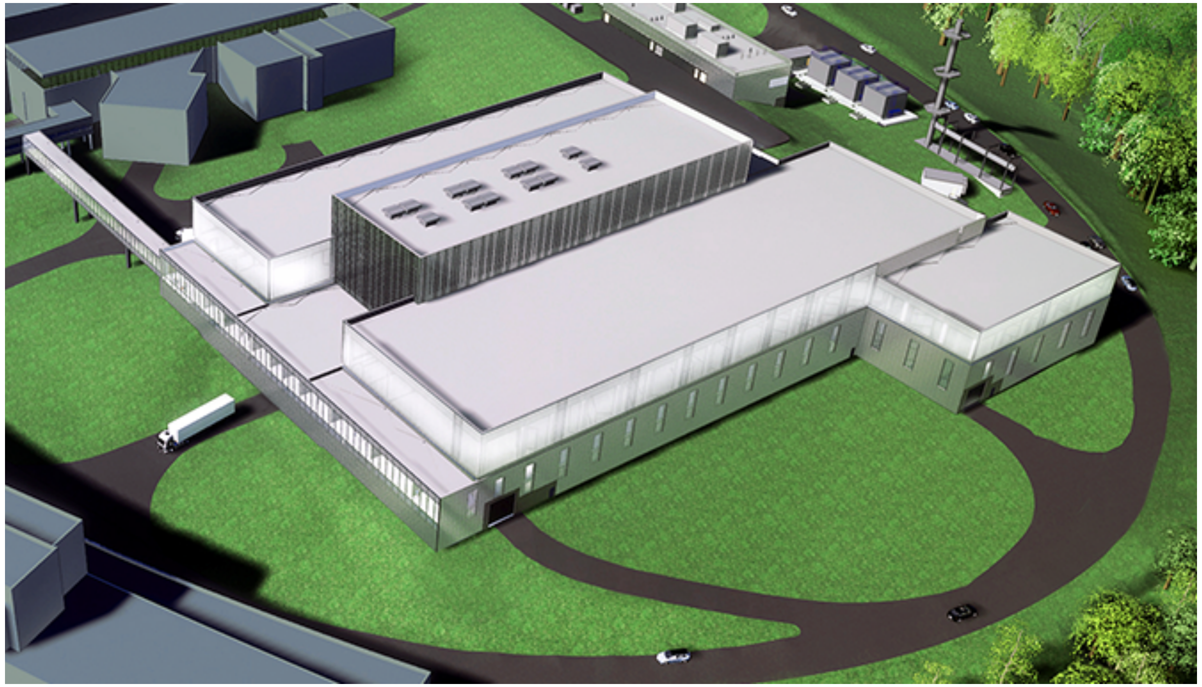
Transport neutrons – with guides!



Neutron Guides allow unparalleled Utilization of Neutron Beams



https://www.ill.eu/

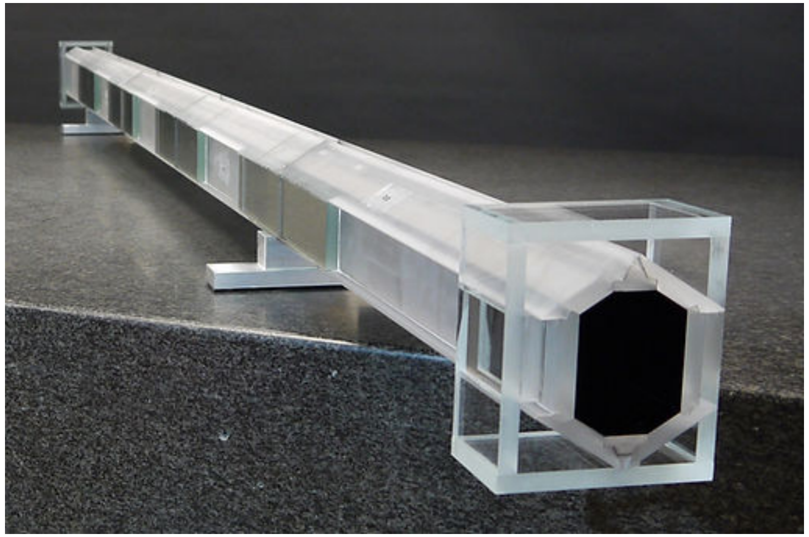


ORNL STS conceptual design

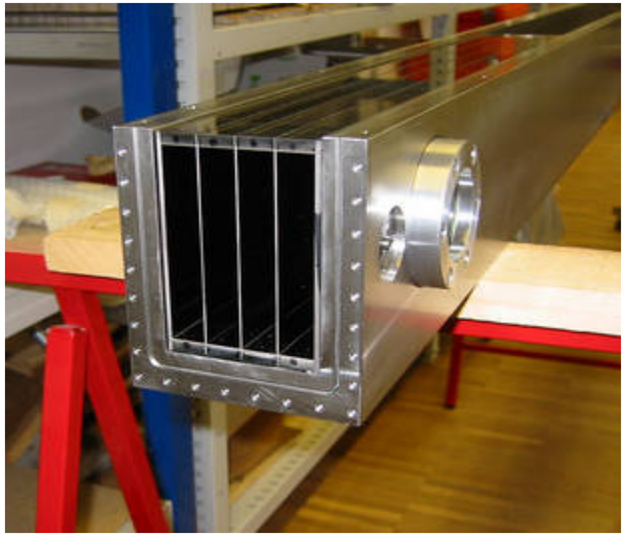
https://neutrons.ornl.gov/sts

Typical Guides currently available!

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

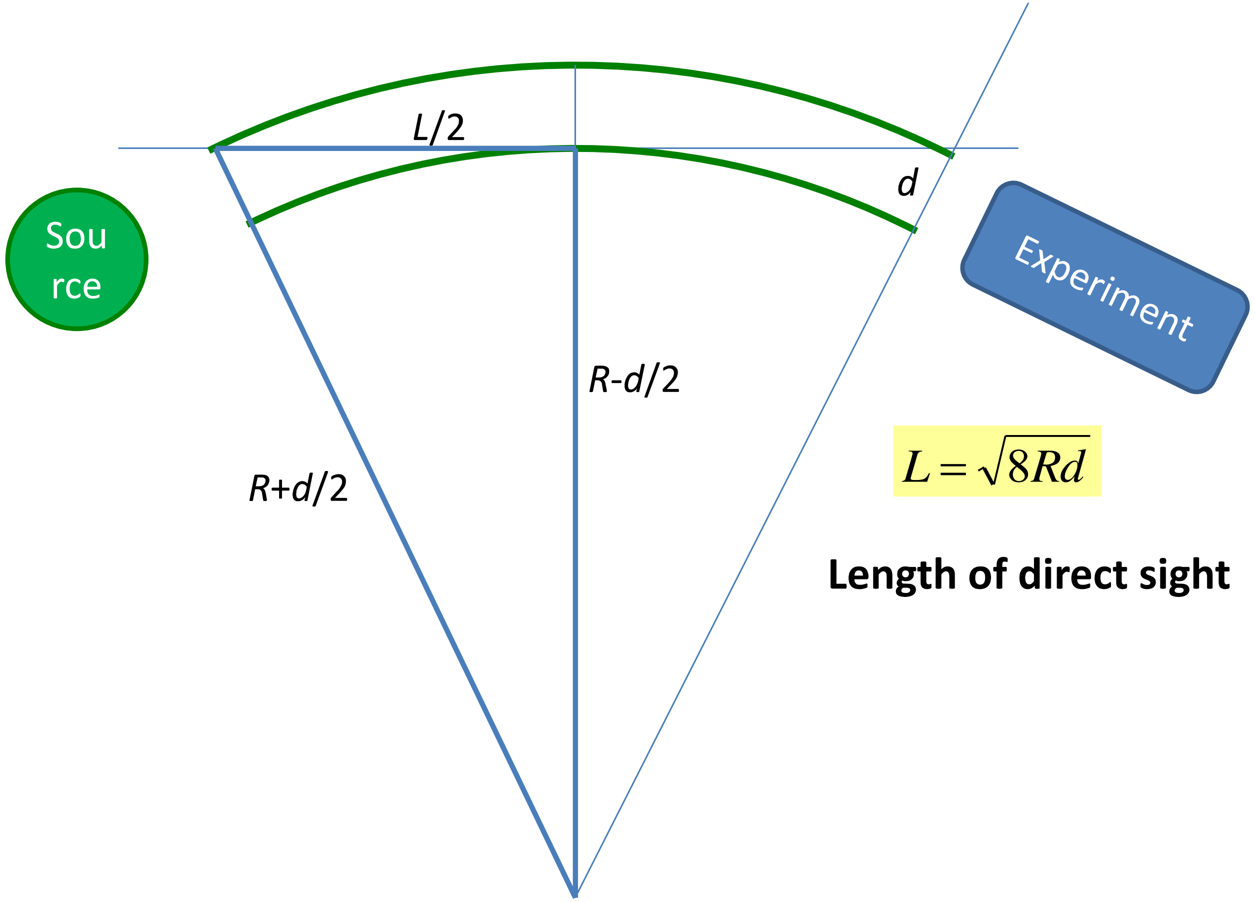


30m Guide for CHESS at STS
Fabricated by Swiss Neutronics



Multichannel Curved Guide
Fabricated by Swiss Neutronics

Not just straight!



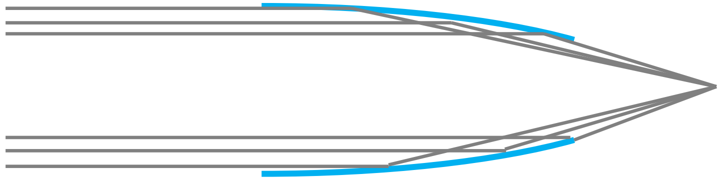
$$L = \sqrt{8Rd}$$

Length of direct sight

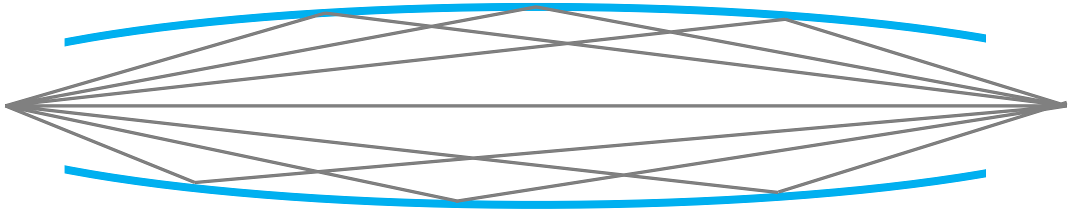
Getting out of direct line of sight reduces background from source

Advanced neutron optics

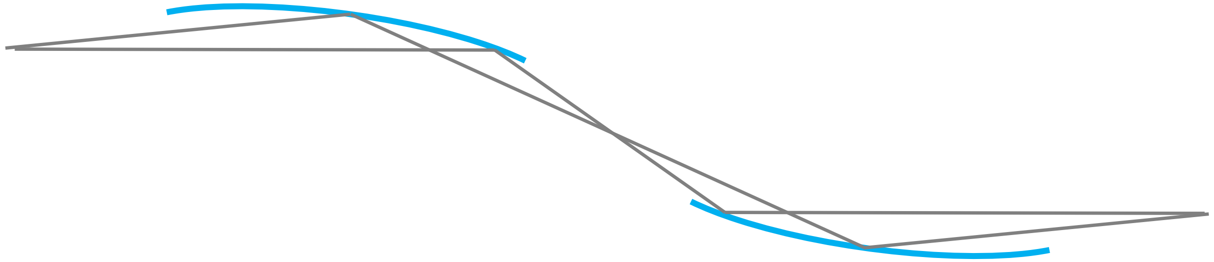
- Parabola: focusing



- Elliptic: focusing and avoid optical aberrations



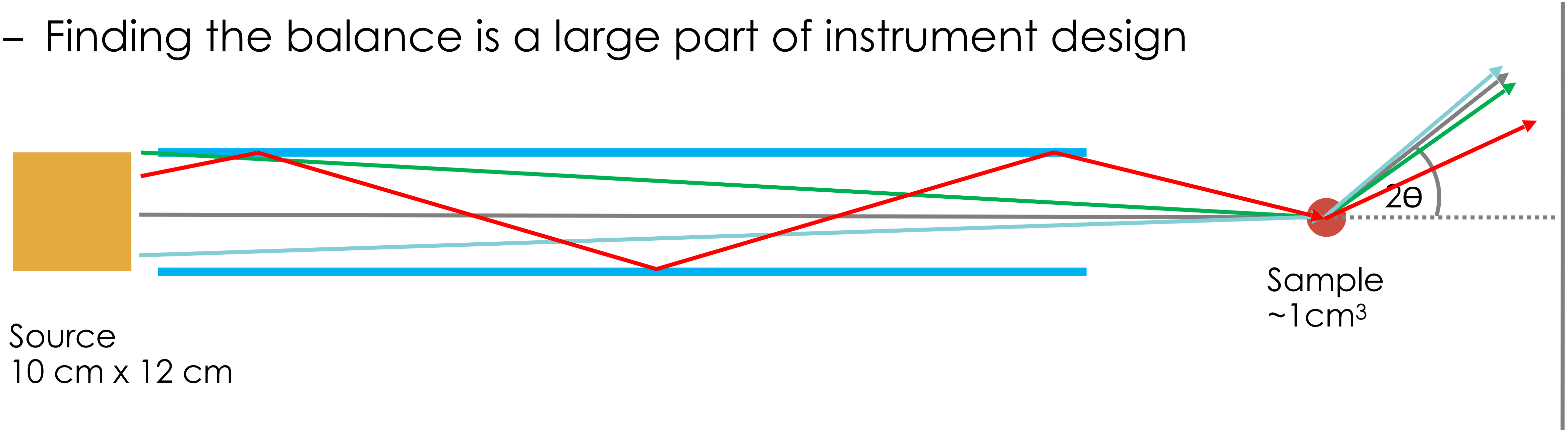
- Zig-Zag (half ellipses):
  - Imaging + line of sight



BUT!

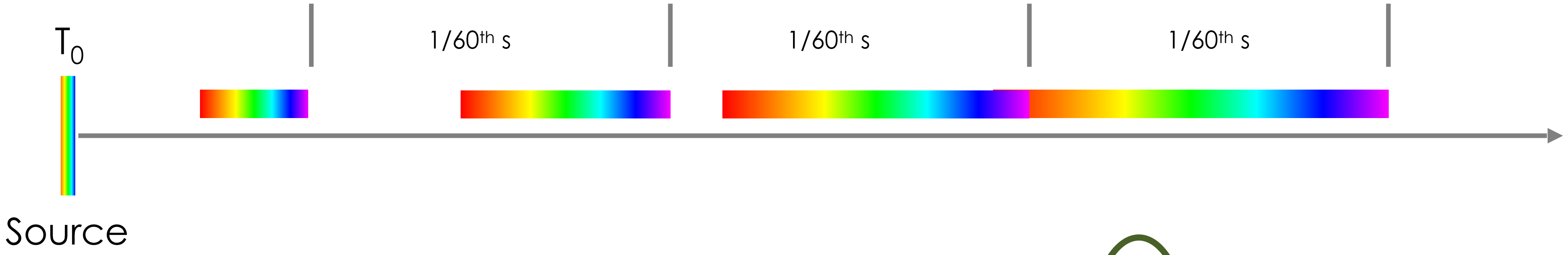
- Angle/wavelength limited
- Liouville is watching you!
  - No free lunches.
  - Increase in neutron flux comes with decreased resolution
  - Finding the balance is a large part of instrument design

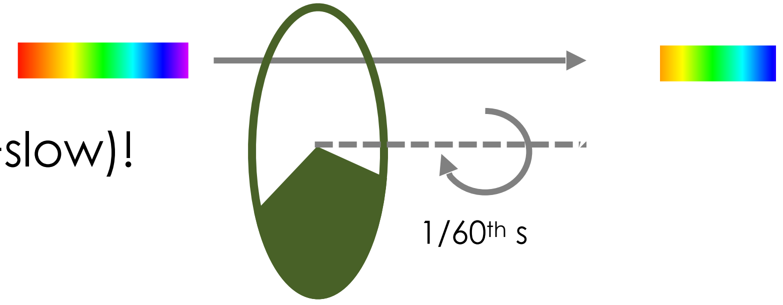

Joseph Liouville



Other problems: Frame overlap

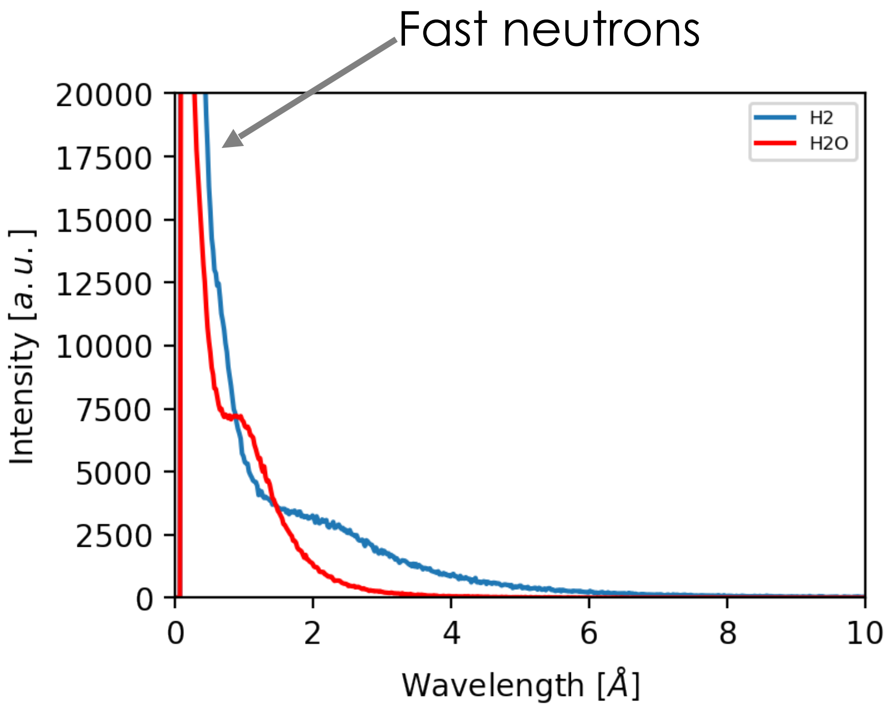
- There is usually more than one pulse in a beam line
- It is important (and difficult) to keep track of which pulse started when for TOF analysis
- Fast neutrons from one pulse can overtake the slow ones from the previous pulse “Frame overlap”
- TOF analysis becomes impossible
- The longer the beam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

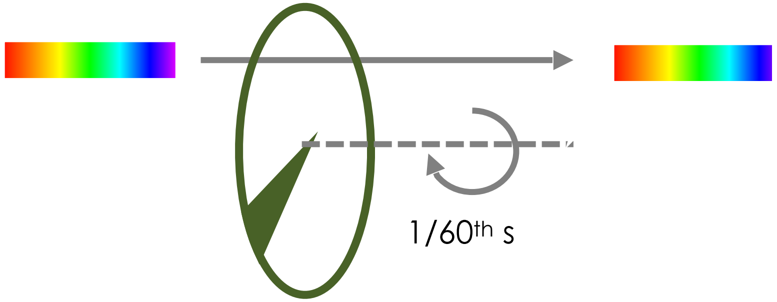




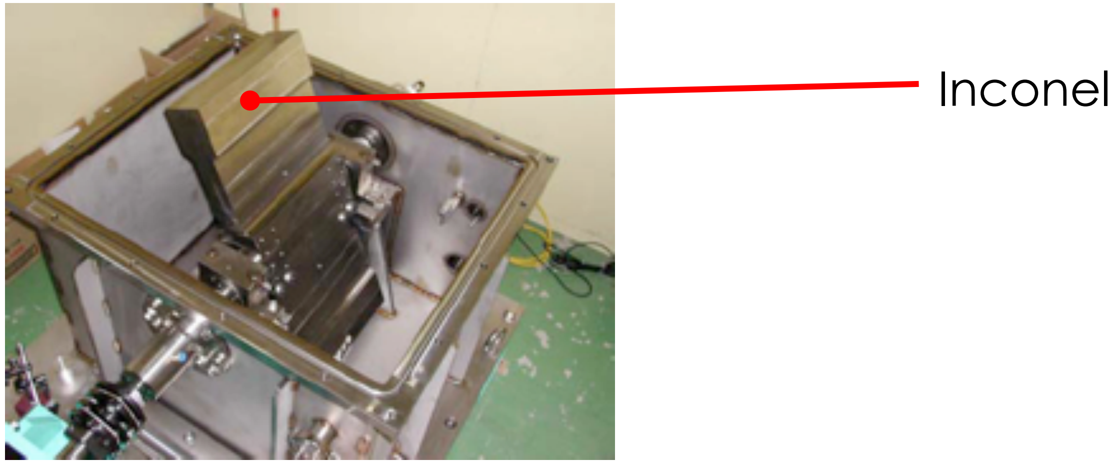
- Solution: Get rid of those neutrons (fast/slow/fast+slow)!
- Use a chopper in phase with the pulsed source
- Select time offset to chose spectrum
- Might need to measure twice for full spectrum

T0 choppers





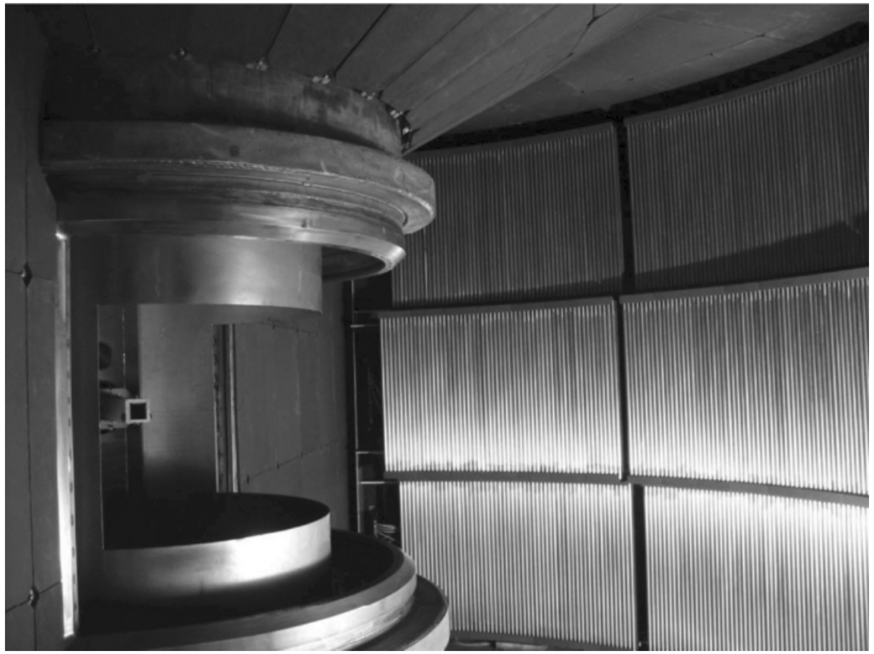
- Fast neutrons and gammas arrive first after proton pulse delivery
- 20-50 cm thick steel blade attenuates these
- Requires well-balanced flywheel for good lifetime and prevention of vibrations



Unit running at JPARC

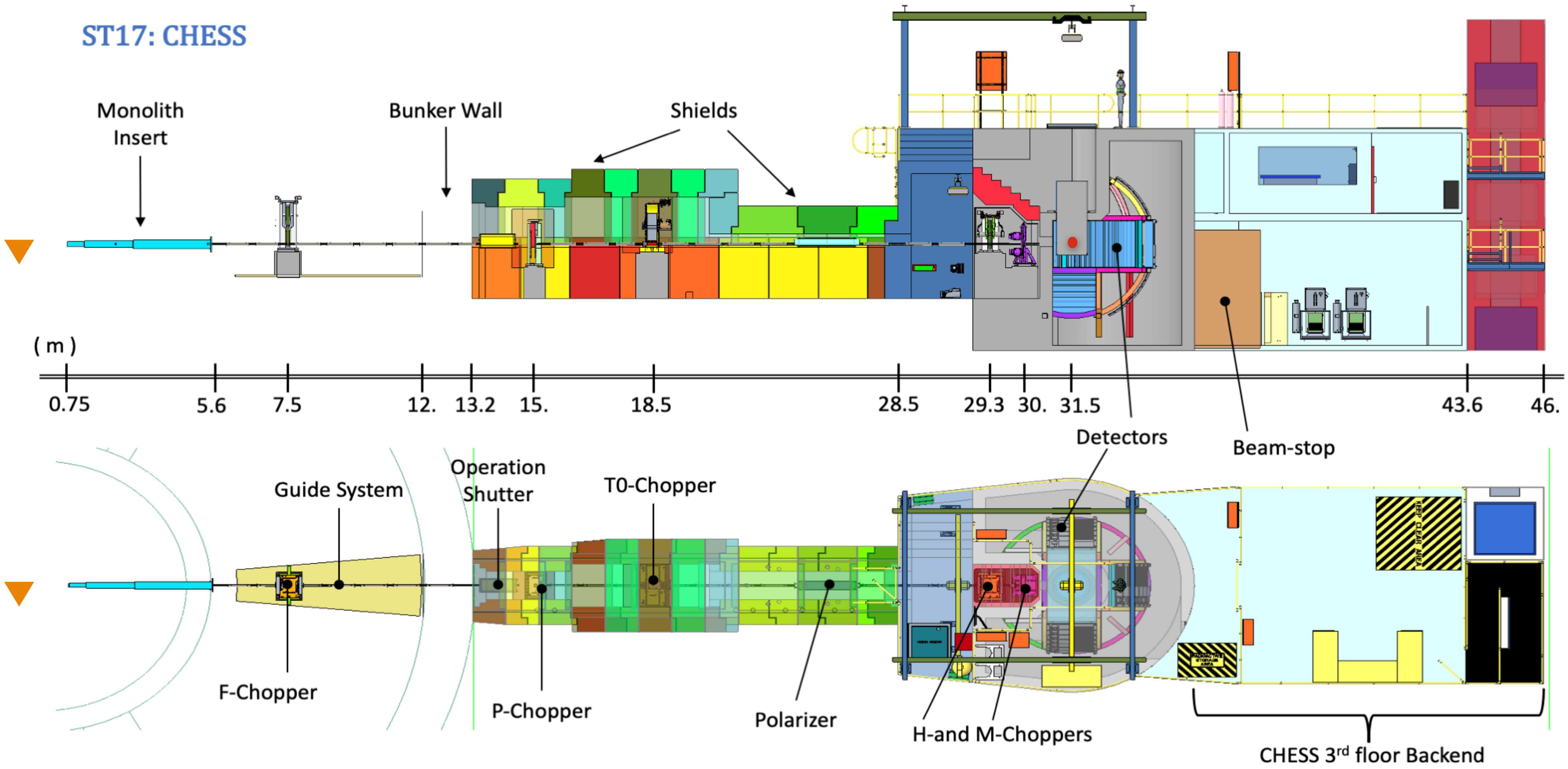
Detectors

- 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
  - They are NOT Cheap



ARCS Detectors @ SNS

Overview of the CHESS instrument



More Questions

Slack Channel:
nxs2022-gabrielesala

Lecture (11:00 – 12:00)

Neutron Generation and Detection/Neutron Optics and Instrumentation - Gabriele Sala

https://forms.office.com/g/p5TXaaa542

Thank you for your kind attention,
Enjoy the rest of the School