Cold & Ultra-cold Neutron Source Studies

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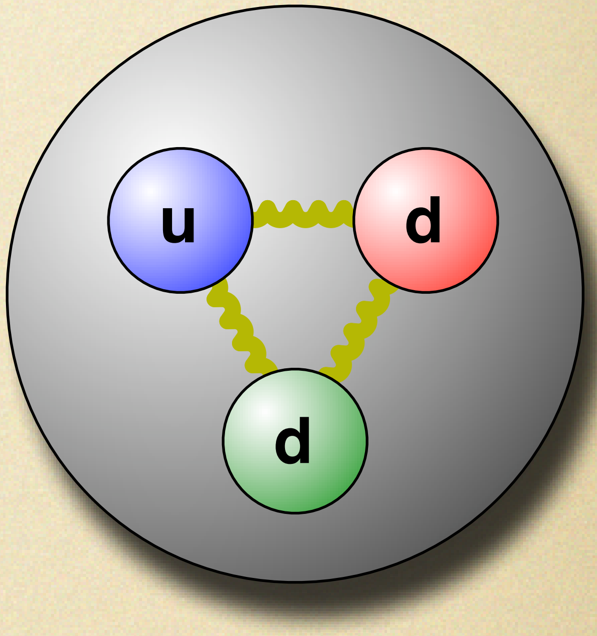
Outline

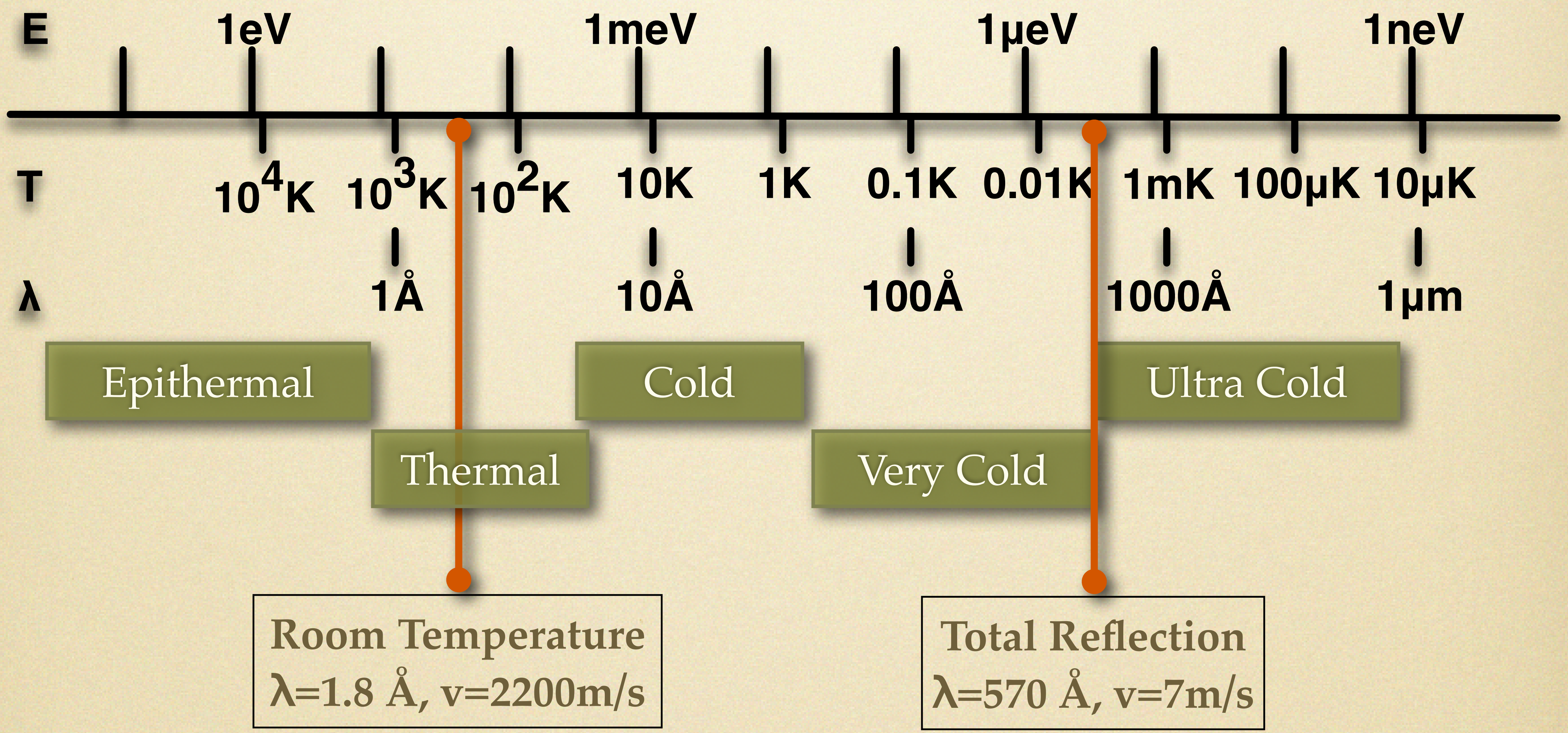
- Introduction
- Solid Methane $S(Q,\omega)$ Model development
- Cold neutron Flux Measurement from solid methane moderators
- Solid Oxygen - A new, more intense UCN Source?
- Solid Oxygen Experiments at LANSCE

Neutron

- Intrinsic Spin ***I* = 1/2**
- Mass $m_{\mathrm{n}} = 939.56563 \pm 0.00028$ MeV
- $\mu = -1.9130 \pm 0.0000005\ \mu_{\mathrm{n}}$
- Mean Life $\tau = 885.7 \pm 0.8$ s
- Electric Dipole Moment $d < 10 \times 10^{-26}$ e cm



Neutron Energy



Physics with Slow Neutrons

- **Fundamental Physics**

  a. Neutron β Decay Life time

  b. Electric Dipole Moment (nEDM)

  c. Neutron Nuclear Weak Interaction (nPDϒ)

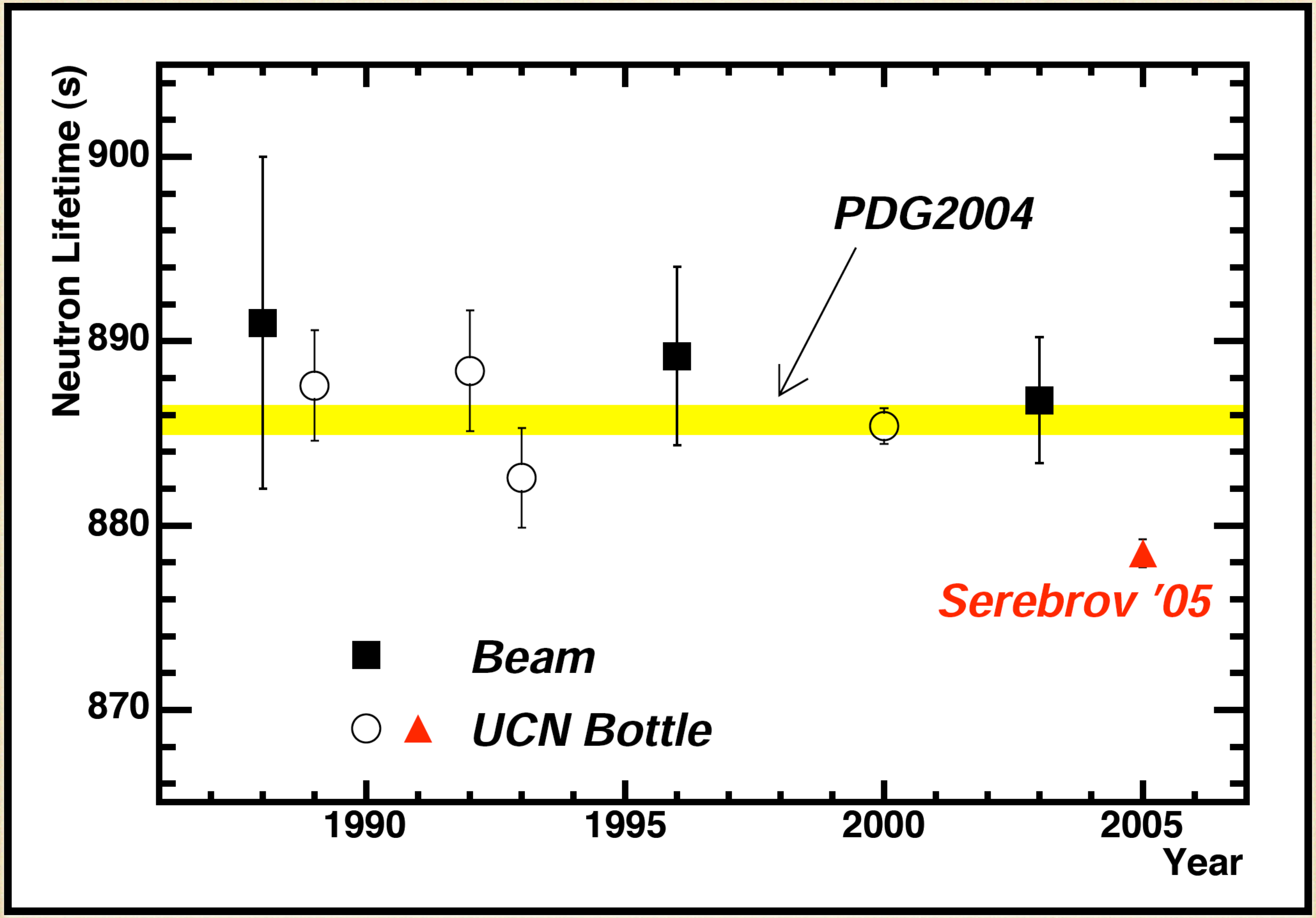
  d. Cosmology, Astrophysics, Neutrino Physics

- **Condensed Matter Physics**

  a. Small Angle Neutron Scattering

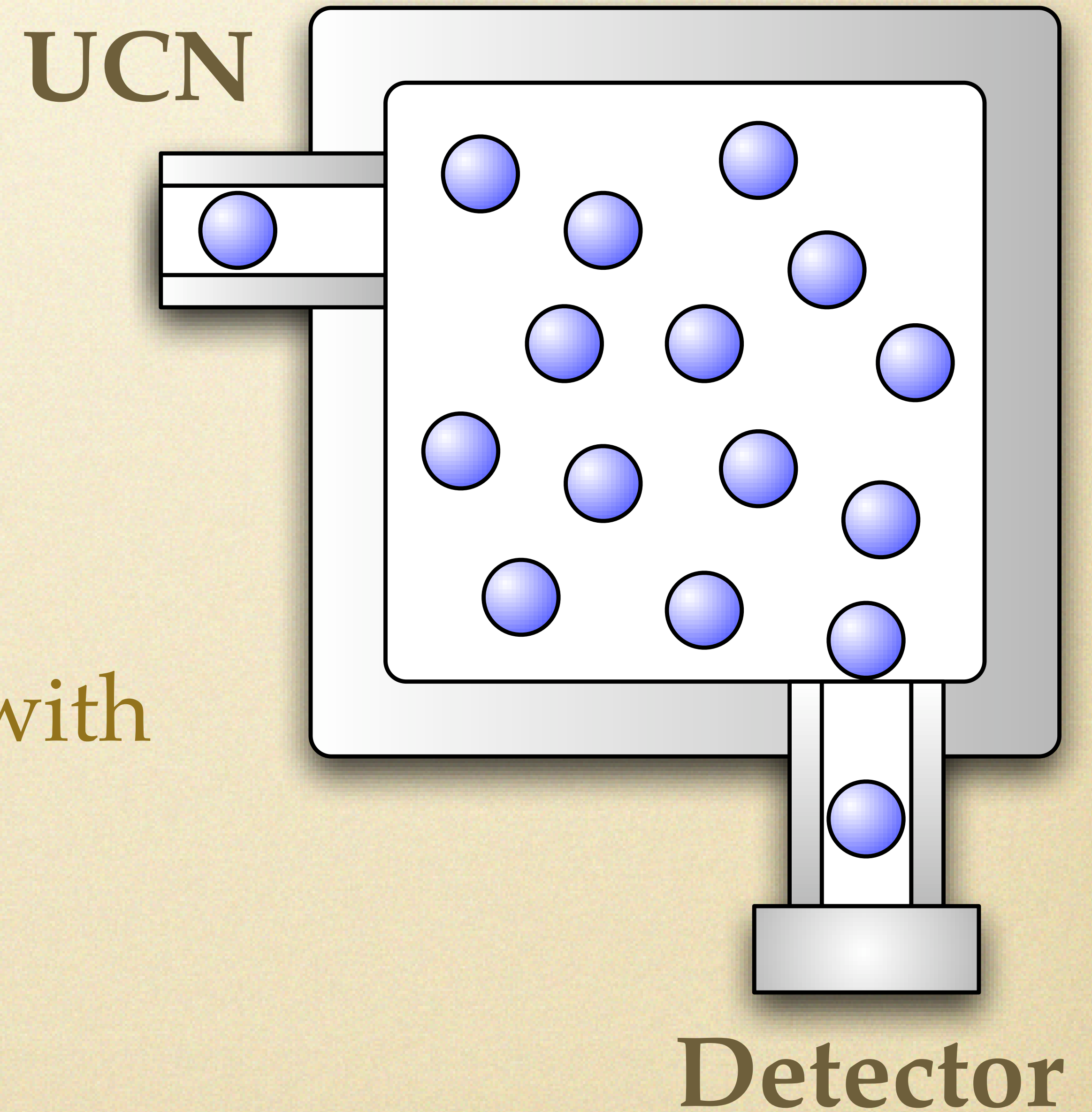
  b. Neutron Interferometry, Reflectometry

Neutron Life Time

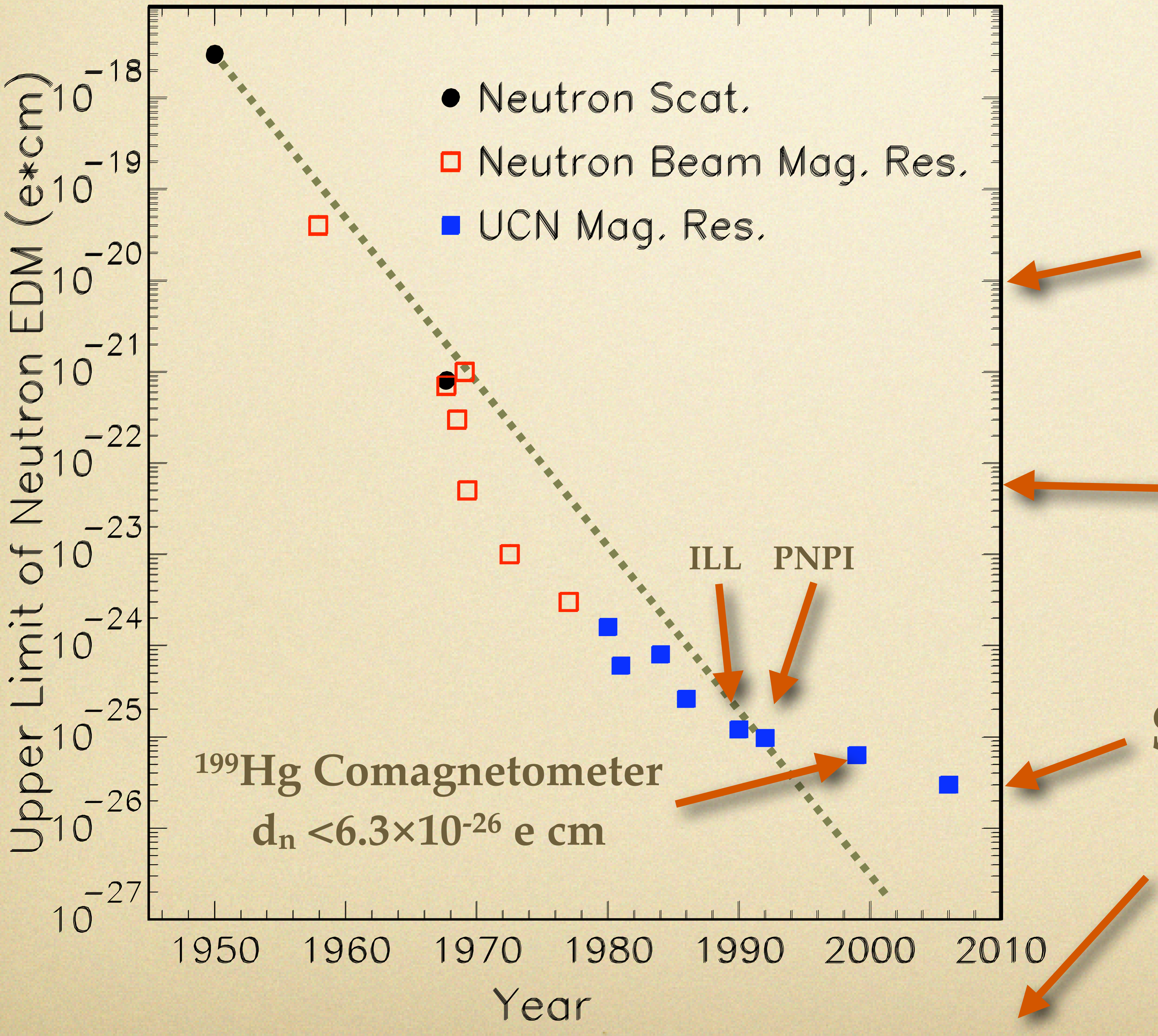


Neutron Life Time

- Bottled UCNs
- $N(t)=N(0)\exp(-t/\tau)$
- $\tau^{-1}=\tau^{-1}_{n}+\tau^{-1}_{loss}$
- Interaction of UCN with wall
- Magnetic Trapping



nEDM



Theoretical Prediction

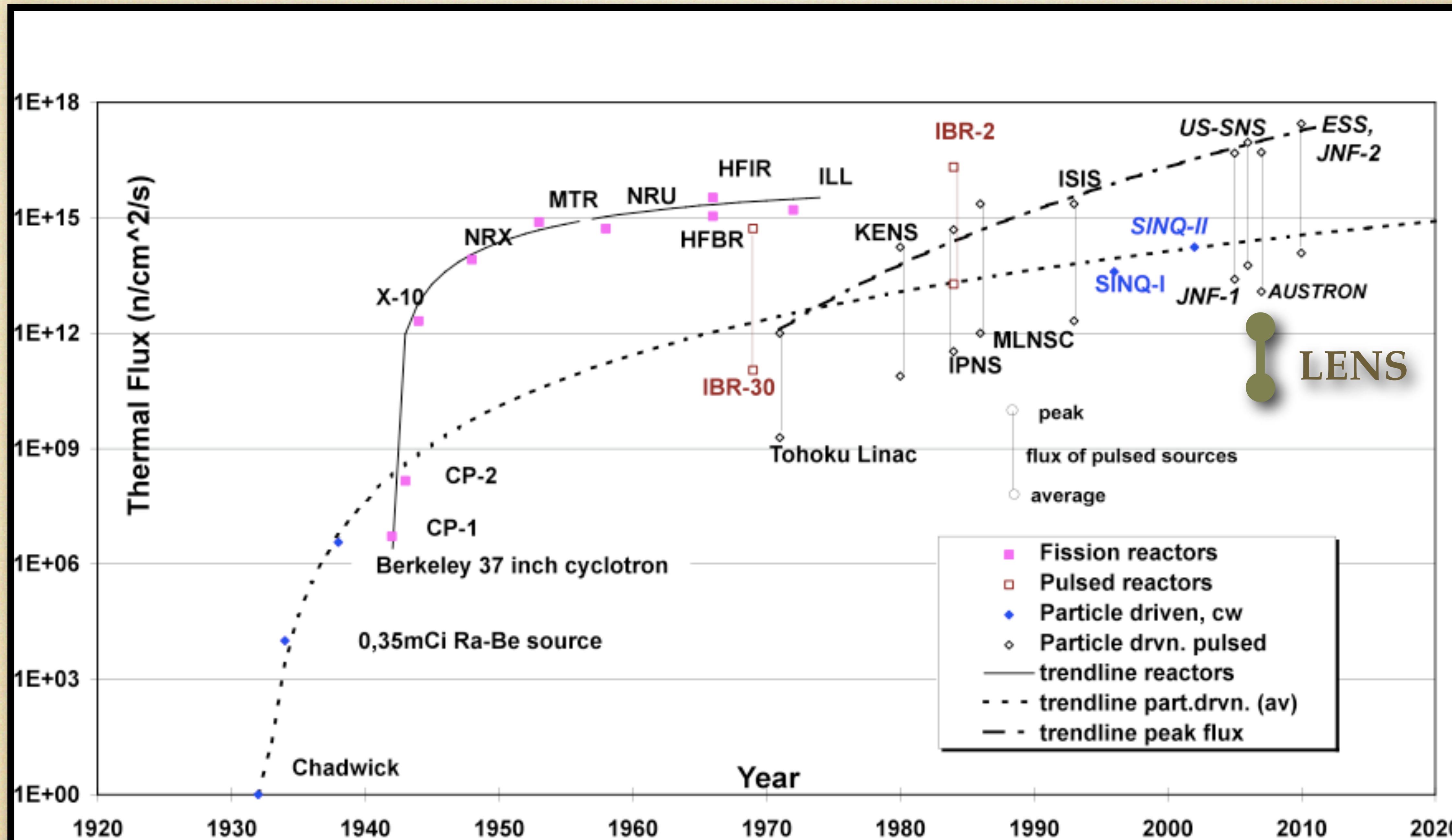
Electromagnetic

Milliweak

Super-symmetry

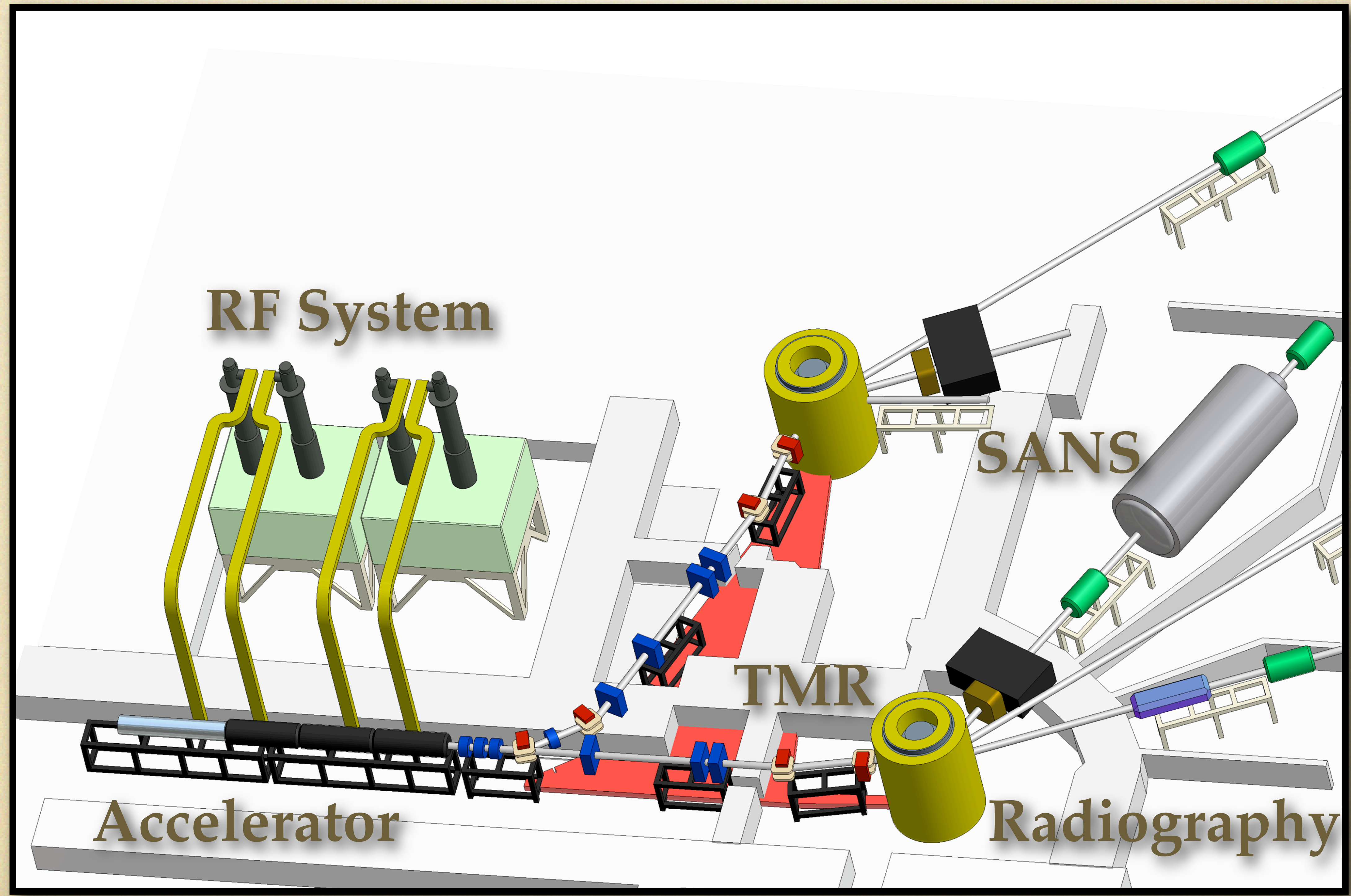
Standard Model
$\sim 10^{-30}$

Neutron Source

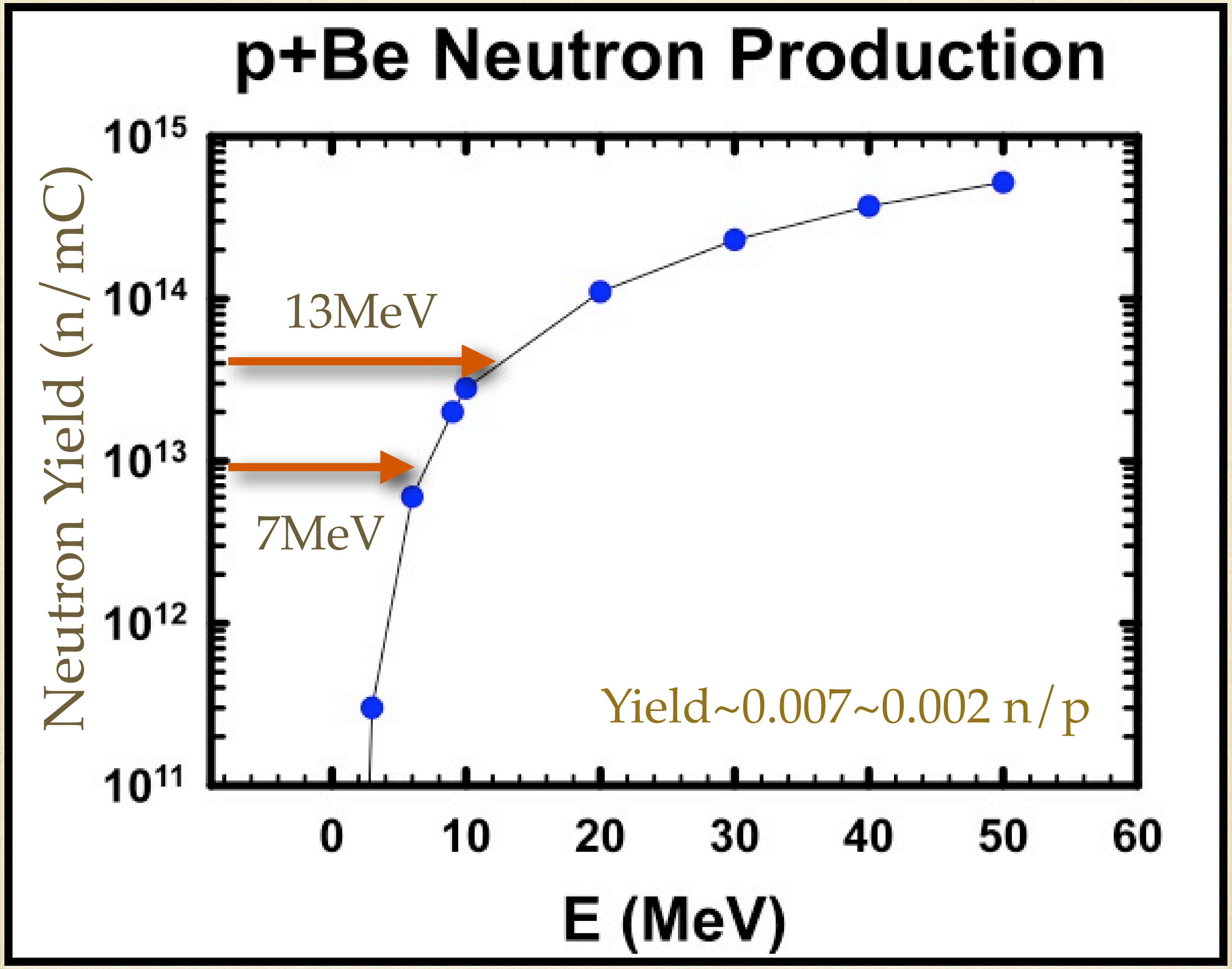


Ref. G. Bauer

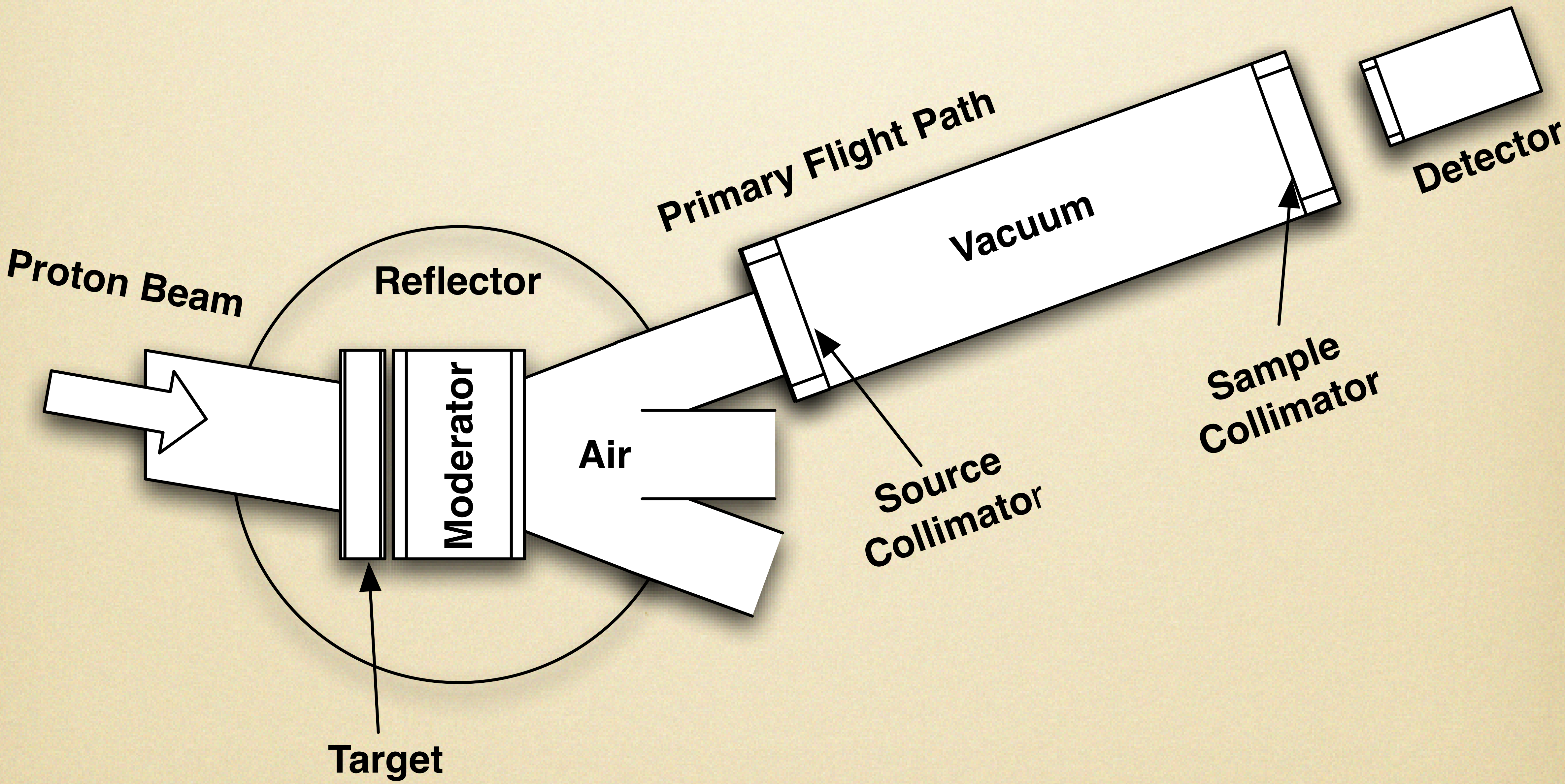
LENS at IUCF



p+Be Reaction



Target-Moderator-Reflector (TMR)



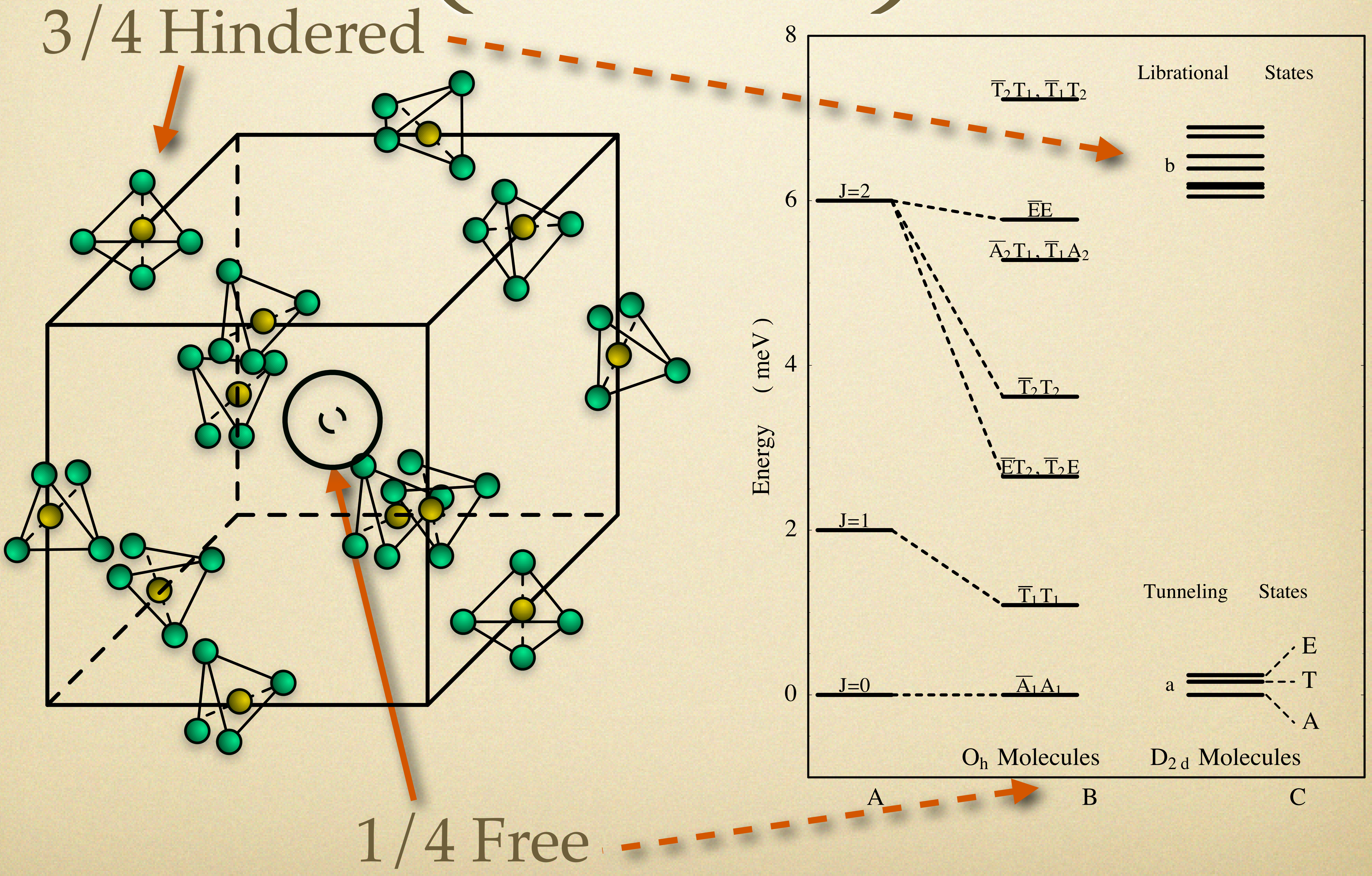
Solid CH_4 Moderator

- High proton density (~70% higher than liquid hydrogen at $T < 20K$)
- High Density of Rotational States in solid phases
- At LENS, $T < 20K$ Methane Operation - ***No MCNP kernels*** in this temperature regime!

Developing a Kernel

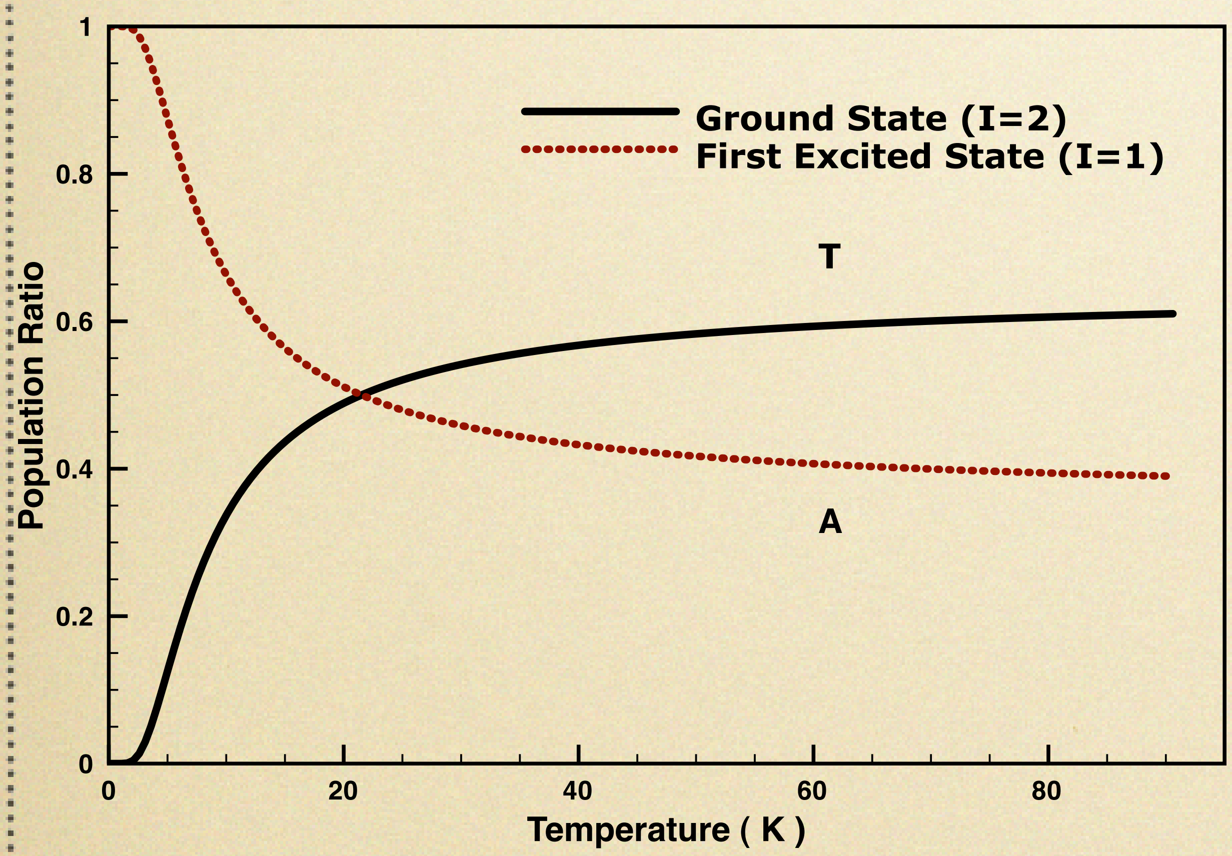
- Construct a microscopic model for neutron dynamic structure factor of solid methane
- Total Scattering Cross Section Model ➔ $S(Q, \omega)$ ➔ $\rho(\omega)$
- LEAPR module of NJOY needs a frequency spectrum $\rho(\omega)$

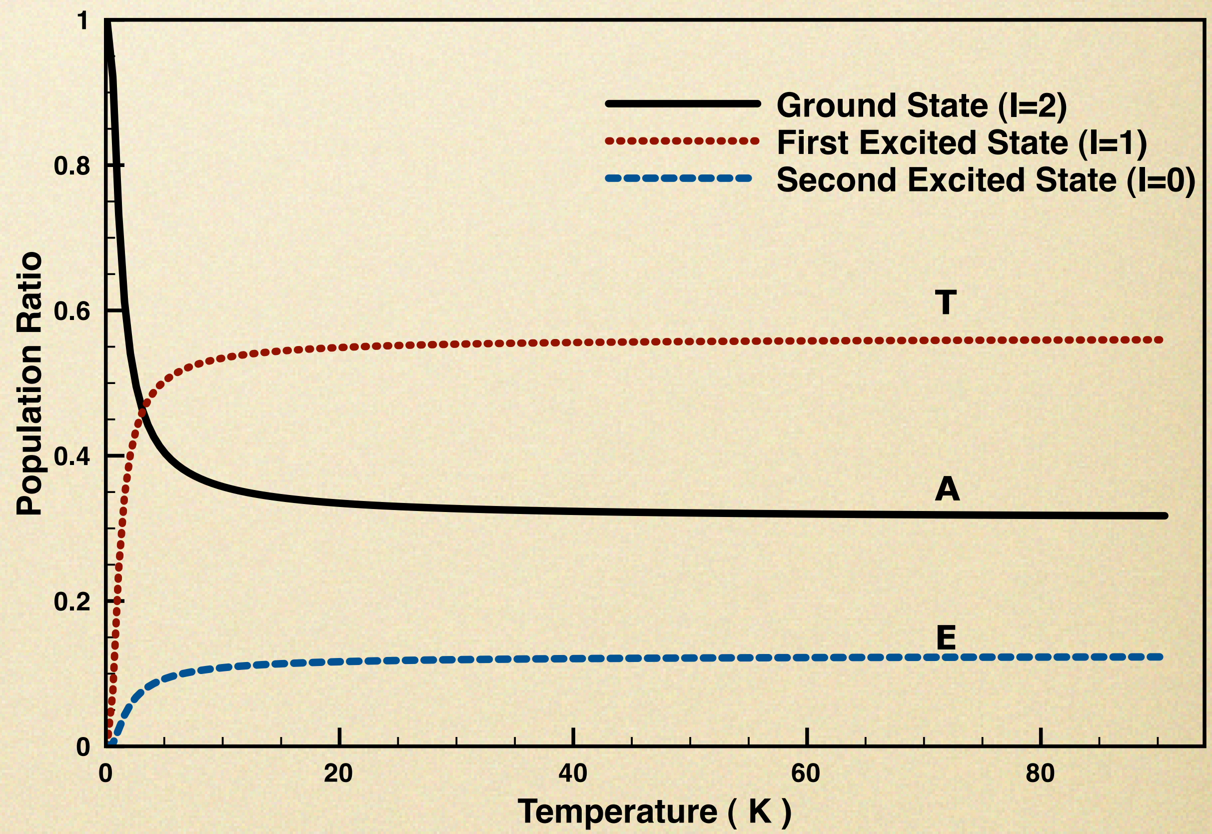
CH_4 at Phase II (T<20K)



Nuclear Spin

Spin Distribution $$P_i = g_i \frac{\exp(-E_i/k_BT)}{\sum_i \exp(-E_i/k_BT)}$$





Free Rotation

Hindered Rotation

Neutron Scattering in Solid CH_4

- The Rotation of Tetrahedral Hydrogens ($E_n \leq 10$ meV)
- Inter-molecular Vibration ➔ Multi-Phone Excitation ($10 \leq E_n \leq 100$ meV)
- Intra-molecular Vibration ➔ Harmonic Vibration ($100 \leq E_n \leq 1000$ meV)

Approximations

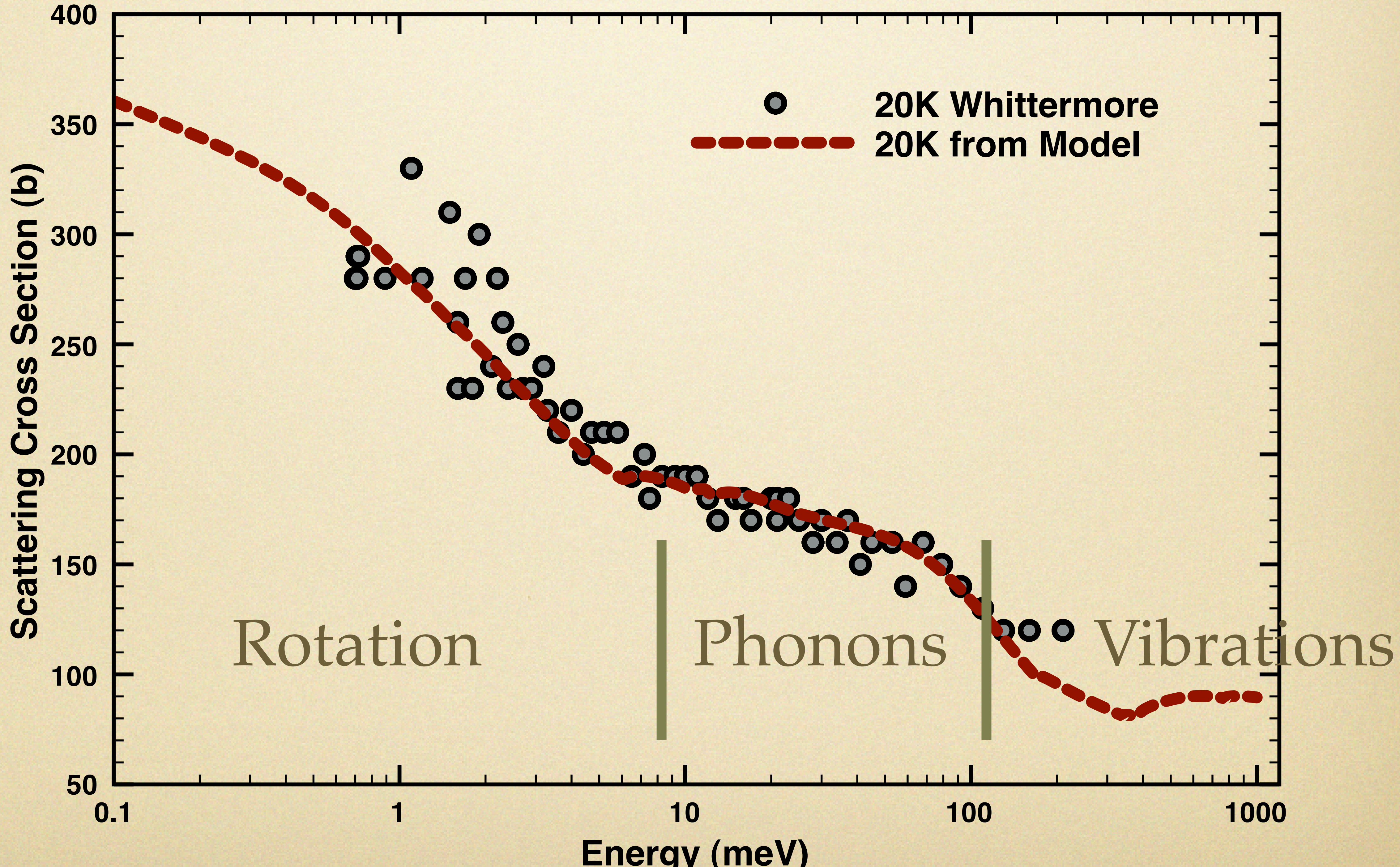
$$S(Q,\omega) = S_{rot}(Q,\omega) \otimes S_{trans}(Q,\omega) \otimes S_{vib}(Q,\omega)$$

- Convolution of degrees of freedom of motion

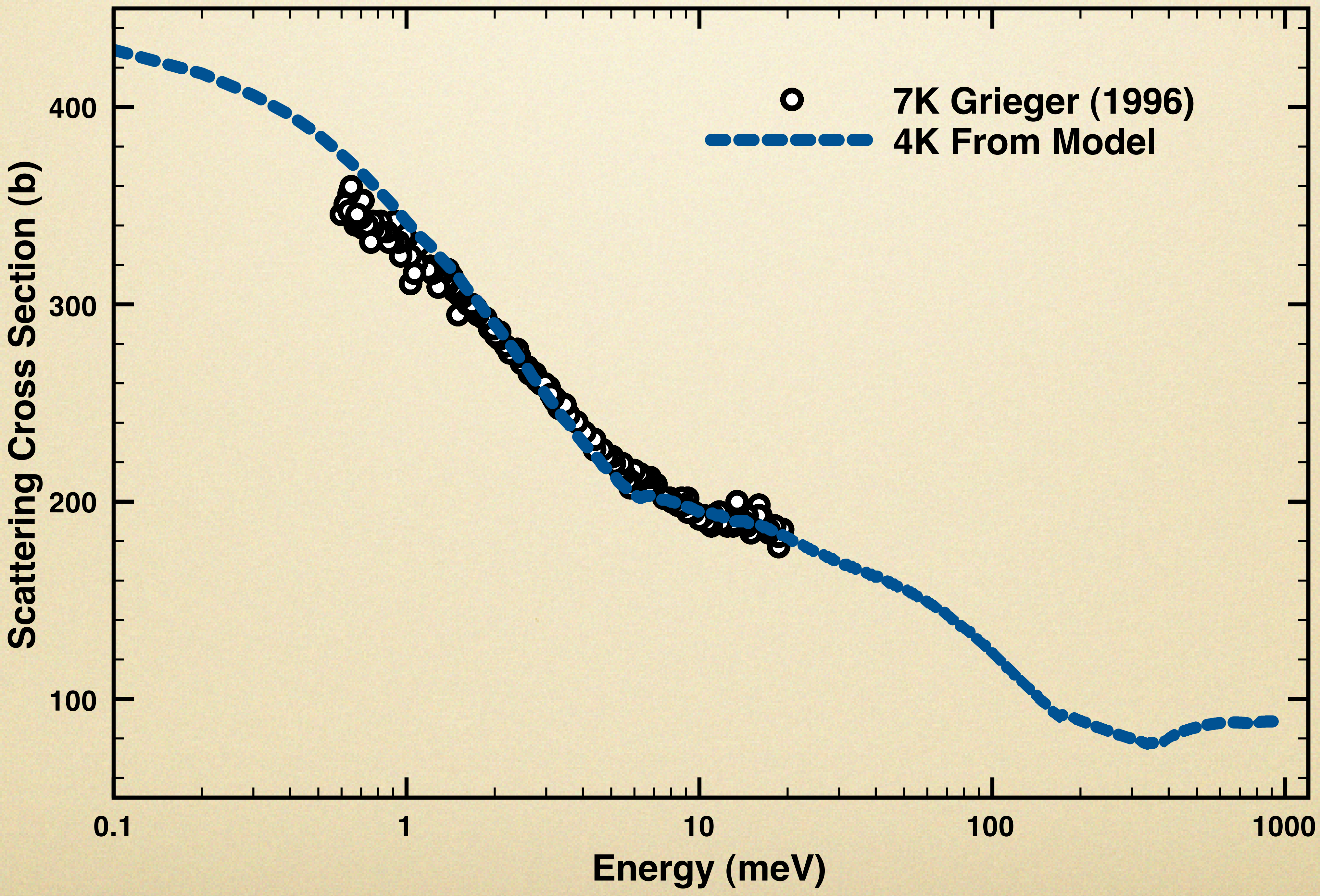
$$\begin{aligned} \simeq \quad & S_{rot}(Q,\omega)\exp(-\gamma Q^2) \\ & +S_{trans}(Q,\omega)\exp(-\gamma Q^2) \\ & +S_{vib}(Q,\omega)\exp(-\gamma Q^2) \end{aligned}$$

- Treat them as uncoupled one depending on E_n

σ_{tot} (20K)

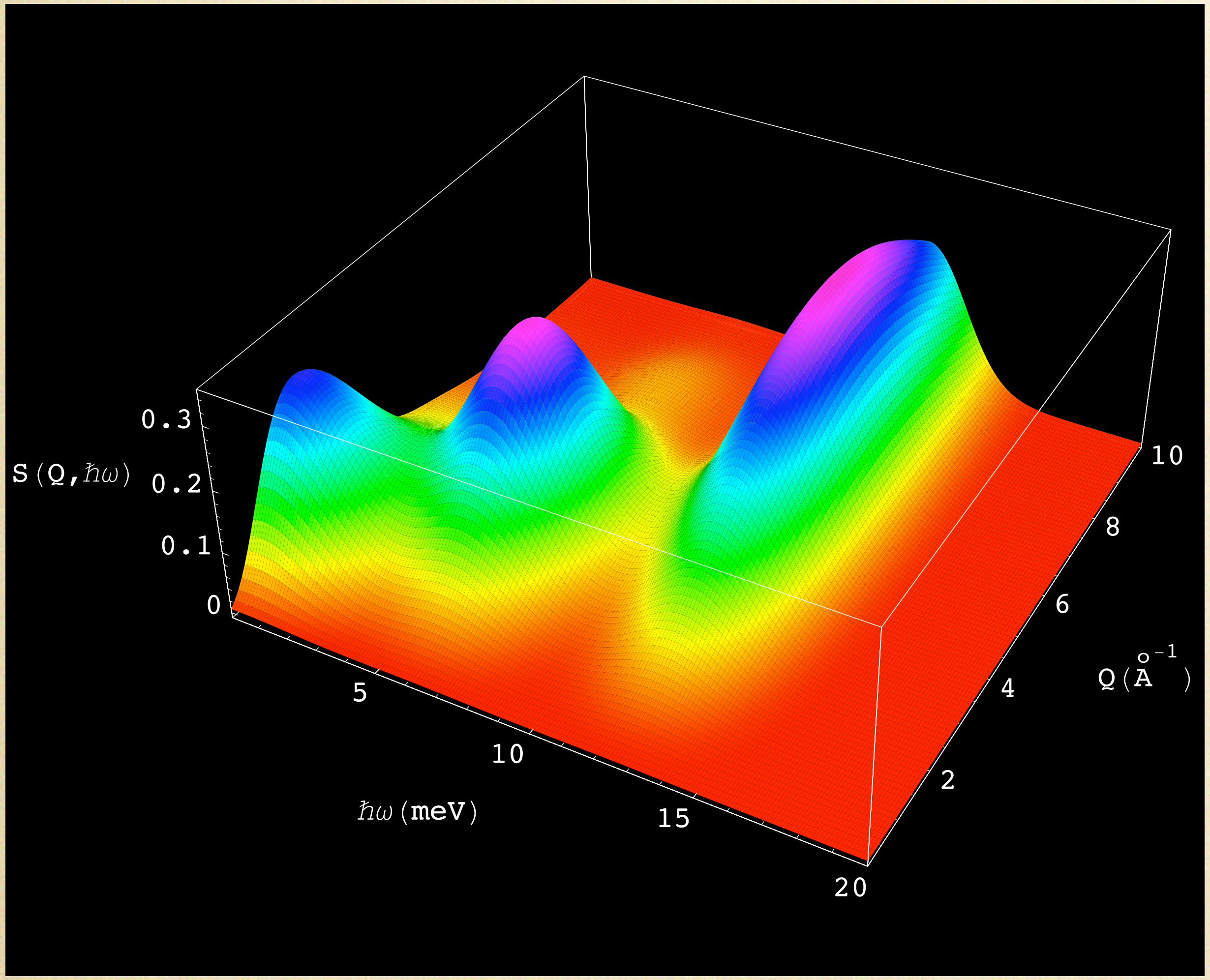


σ_{tot} (4K)

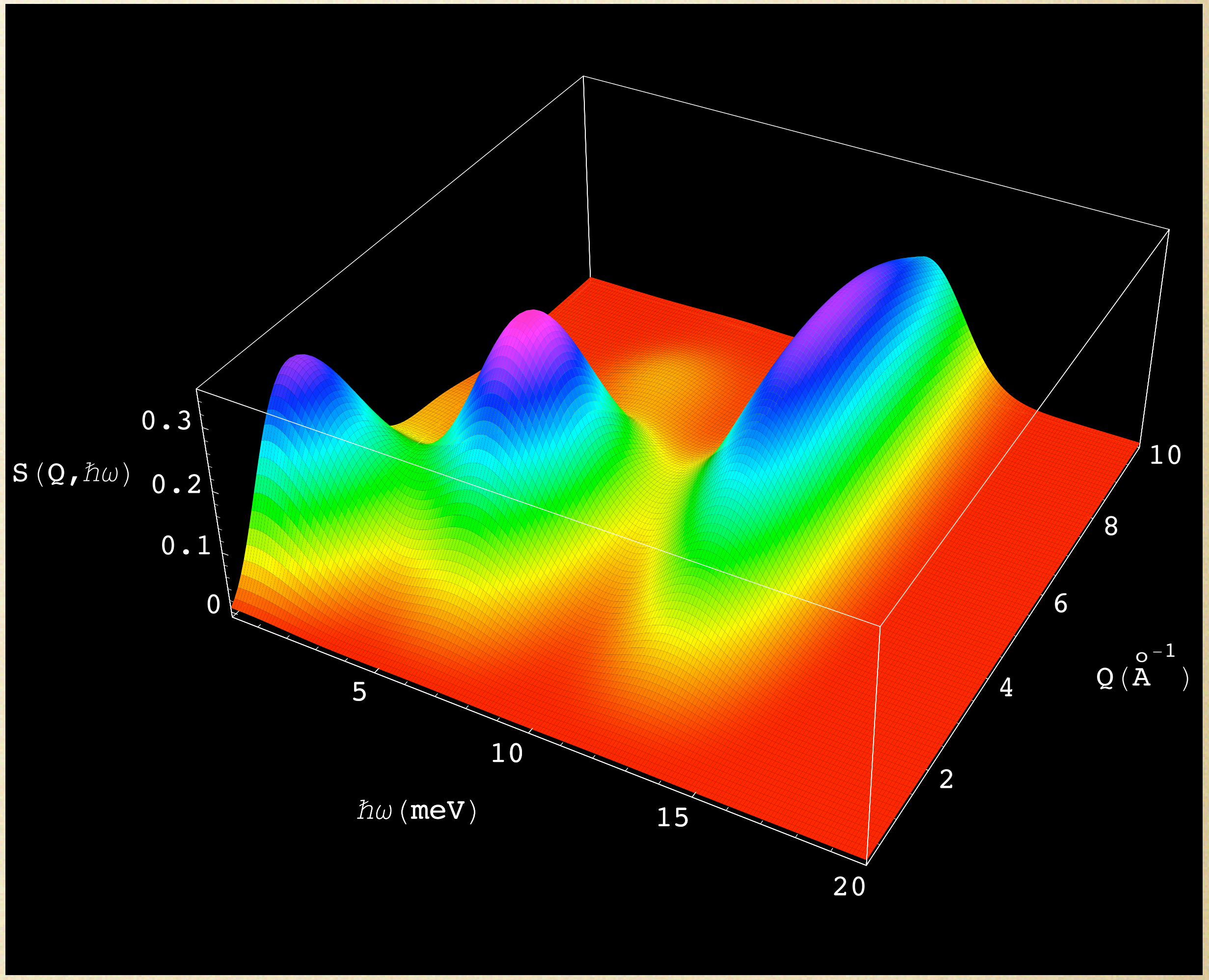


7K Grieger (1996)
4K From Model
Scattering Cross Section (b)
400
300
200
100
0.1
1
10
100
1000
Energy (meV)

Scattering Function



20K



4K

- $\hbar\omega$=(0~20 meV), Q=(0~10 $Å^{-1}$)

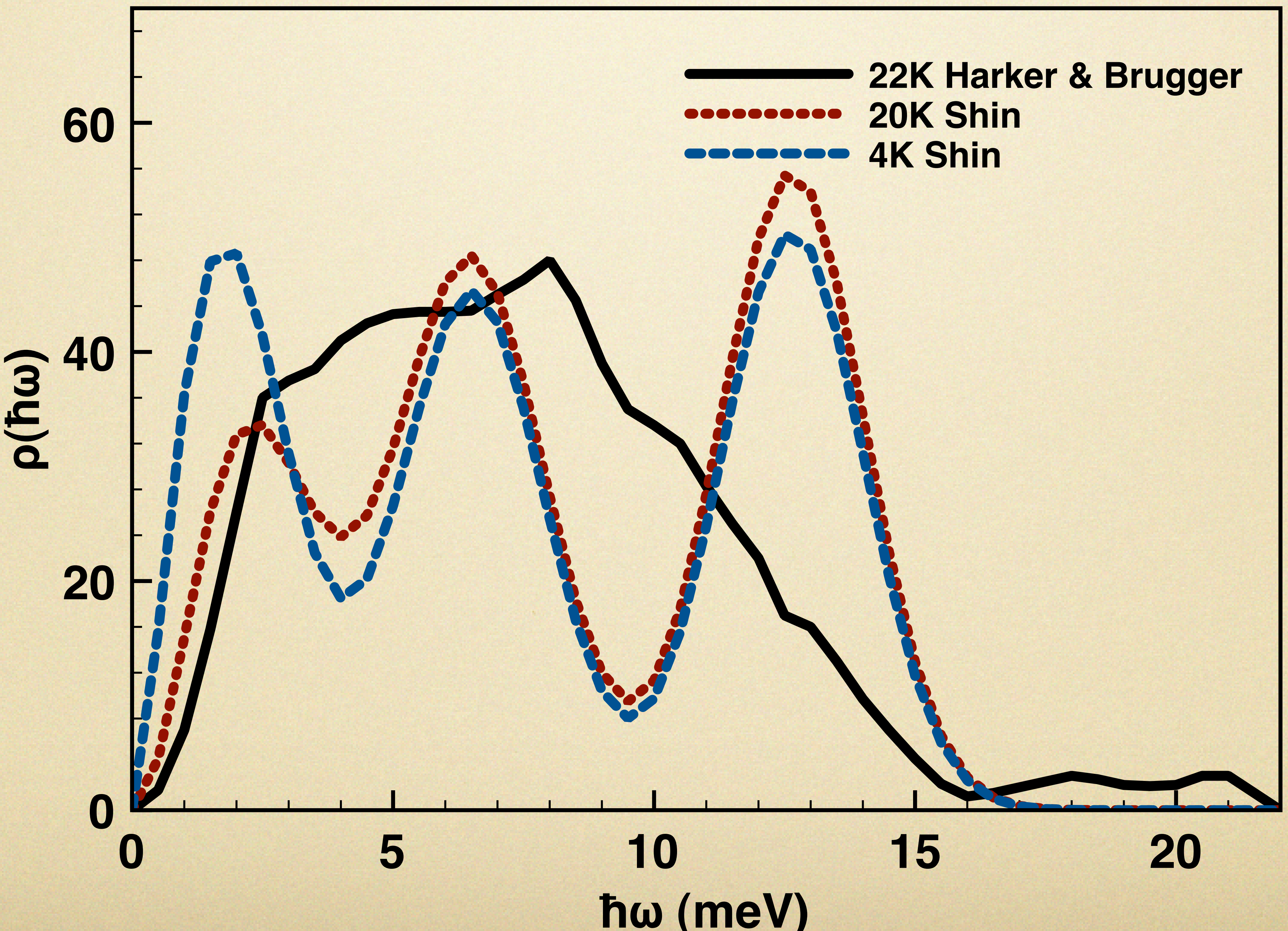
Frequency Spectrum

$$\left[\frac{\omega^2 e^{-\frac{\hbar\omega}{2k_BT}} S(Q,\omega)}{Q^2}\right]_{Q\to 0} = \frac{e^{-\frac{\hbar\omega}{2k_BT}}}{2\pi}\int_{-\infty}^{+\infty} \langle v_Q(0) v_Q(\tau)\rangle \, e^{-i\omega\tau} d\tau = \frac{k_BT}{2M} p(\omega)$$

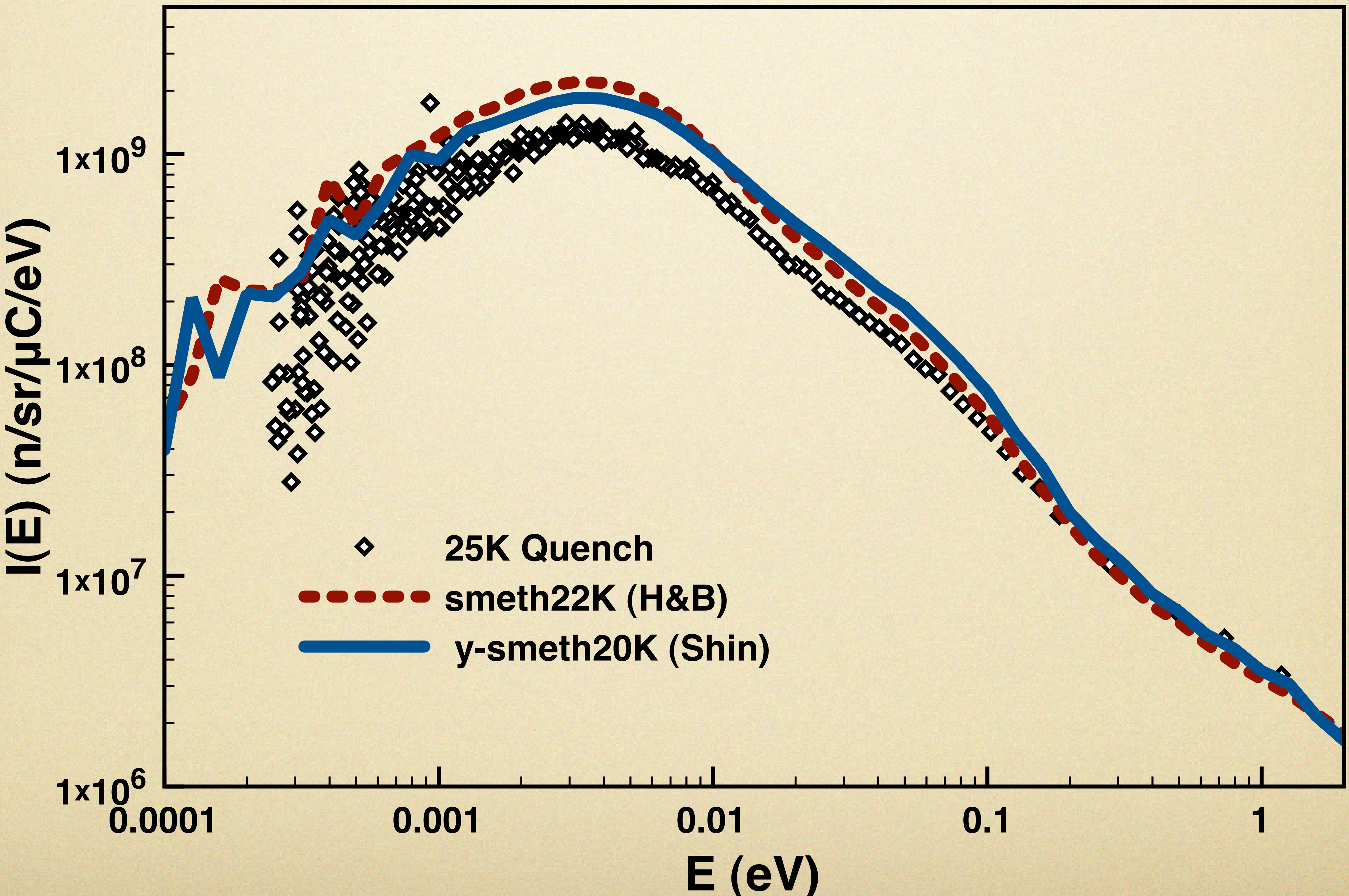
$$z(\omega) = \frac{2k_BT}{\hbar\omega}\sinh\left(\frac{\hbar\omega}{2k_BT}\right) p(\omega)$$

- $z(\omega)$ is equal to " Generalized Frequency Spectrum" $\rho(\omega)$
- Incoherent approximation ➜ lose coherent information

Frequency Spectrum



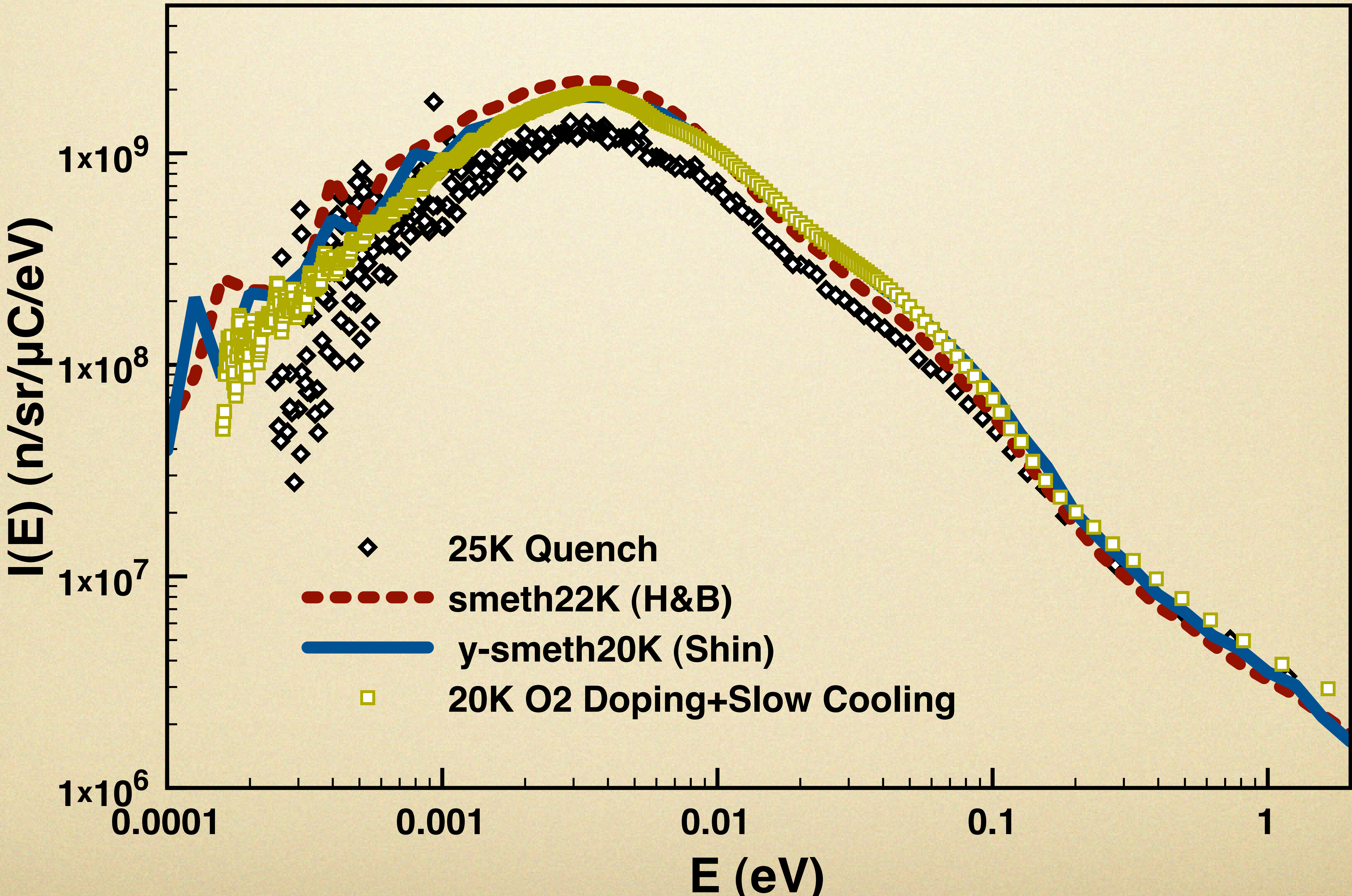
MCNP & Measurements (25K)



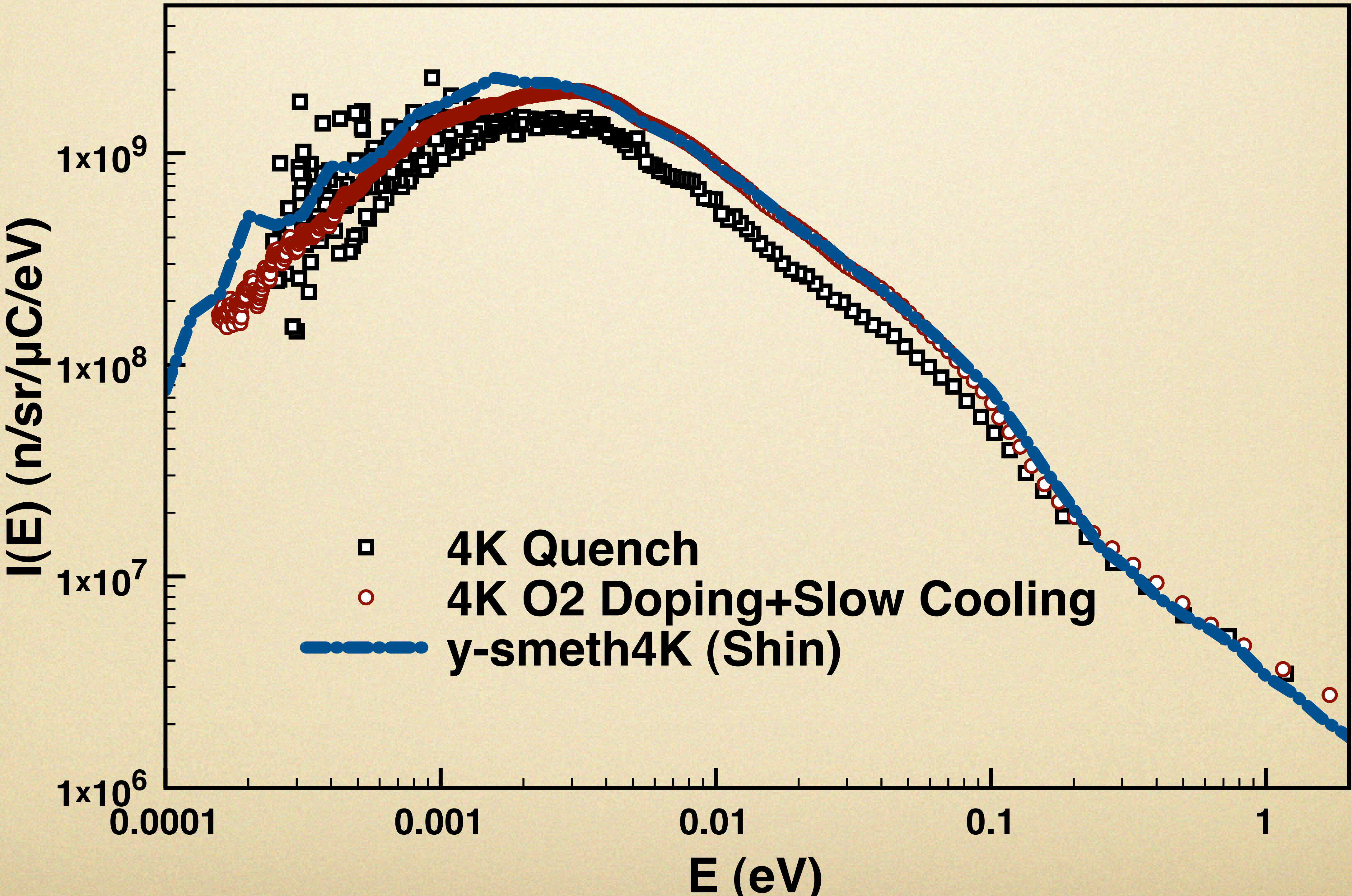
Moderator Operation

- O_2 doping (~1%) ➜ Boost Spin Relaxation of Rotational modes
- Slow Cooling (~20h) ➜ Reduce developing ``cracks" and ``holes" inside of moderator media
- Fully utilize the ``Neutron Scattering Cross Section" (equilibrium spin distribution is better than quenched spin distribution)

MCNP & Measurements (20K)



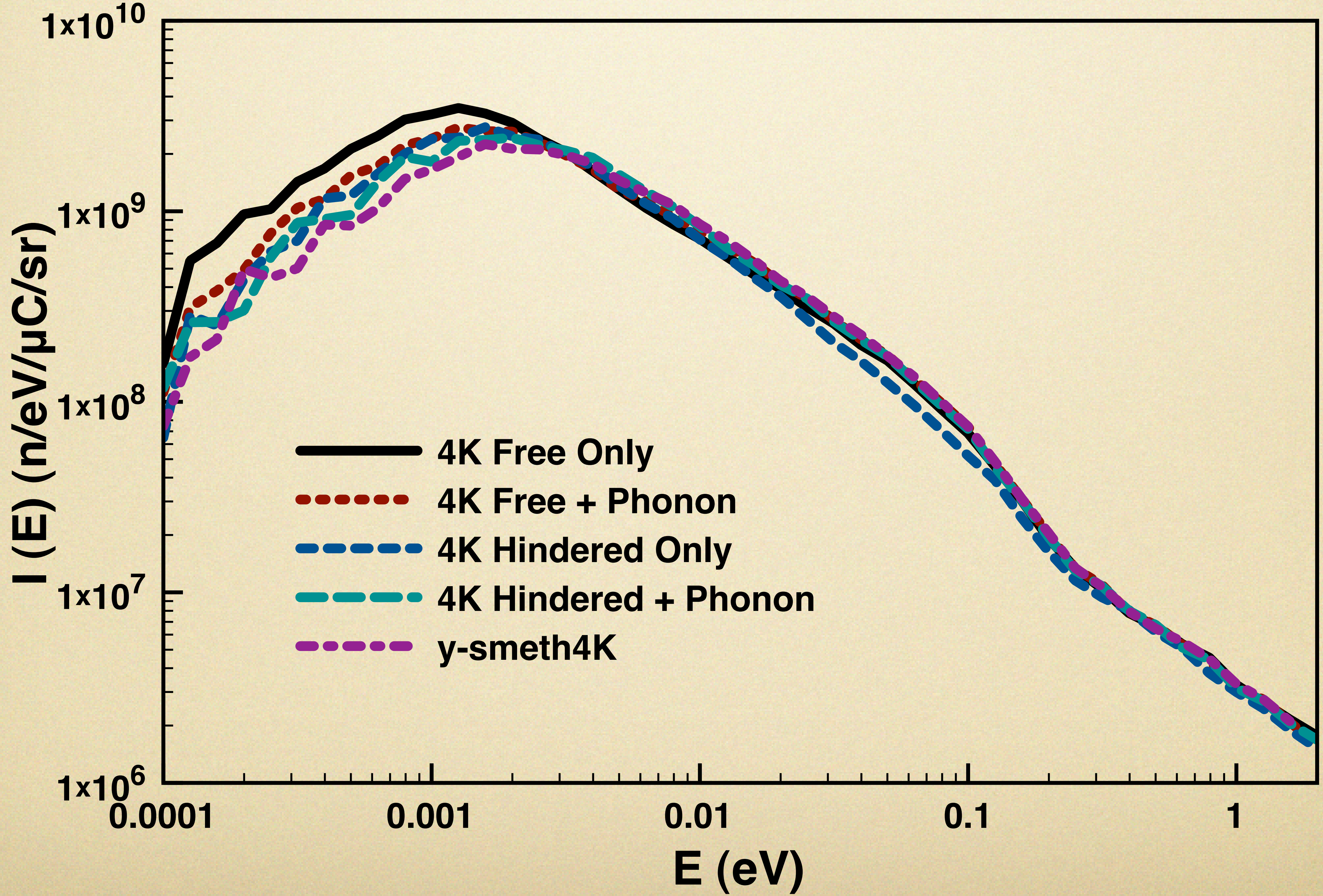
MCNP & Measurements (4K)



New Model can do..

- Model generates Scattering Kernel for Monte-Carlo Modeling between 4K < T < 20K
- Model can check non-spin equilibrium conditions
- Decompose contribution from the rotational, phonon degree of freedoms on the moderated neutron flux→``Free" vs ``Hindered" rotations

Decomposition of modes in 4K



Summary

- Construct New Scattering Kernel based on theory and
- Check its validity in MCNP modeling and measurements of Neutron Flux at LENS
- Optimize LENS with accurate new model
- Application to Very-Cold Neutron Sources

Solid Oxygen as Ultra-cold Neutron Source

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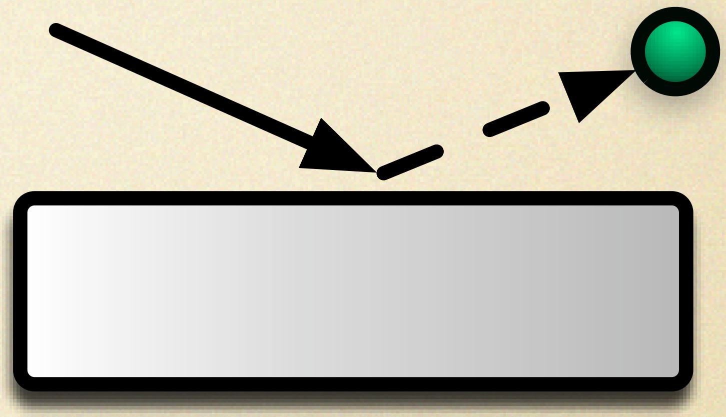
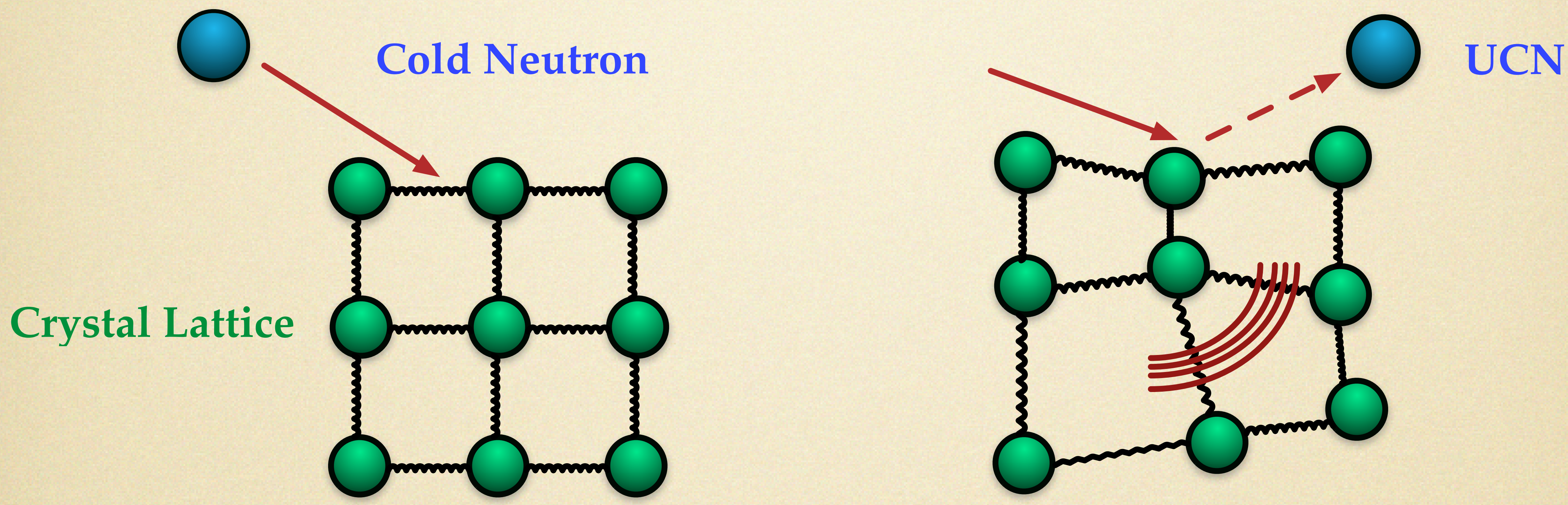
What is UCN ?



- E < 335 neV
- λ > 500 Å
- Three order of magnitude lower than cold neutron
- Total Reflection in material surface and large magnetic field gradient.
- Fundamental Physics with UCNs.

Super-thermal UCN Production

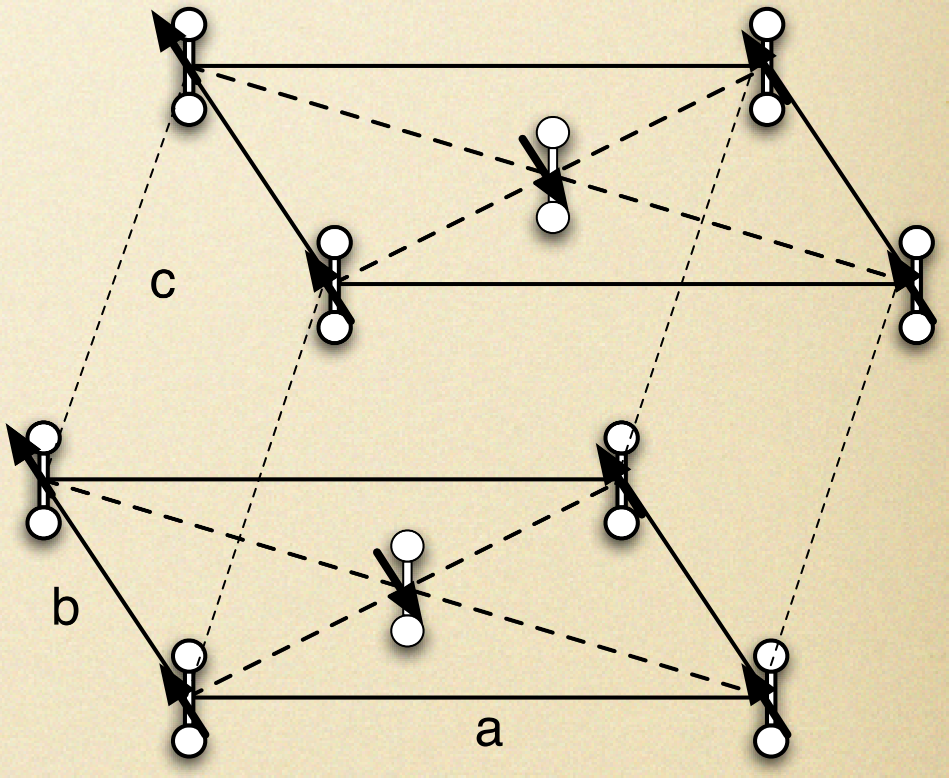


- Cold neutron loses energy in the matter by exciting collective mode and down-scattered to UCN
    - R. Golub and J.M. Pendlebury, Phys.Lett, 53A.133 (1975)

Solid Oxygen

- The oxygen's small nuclear absorption cross section.

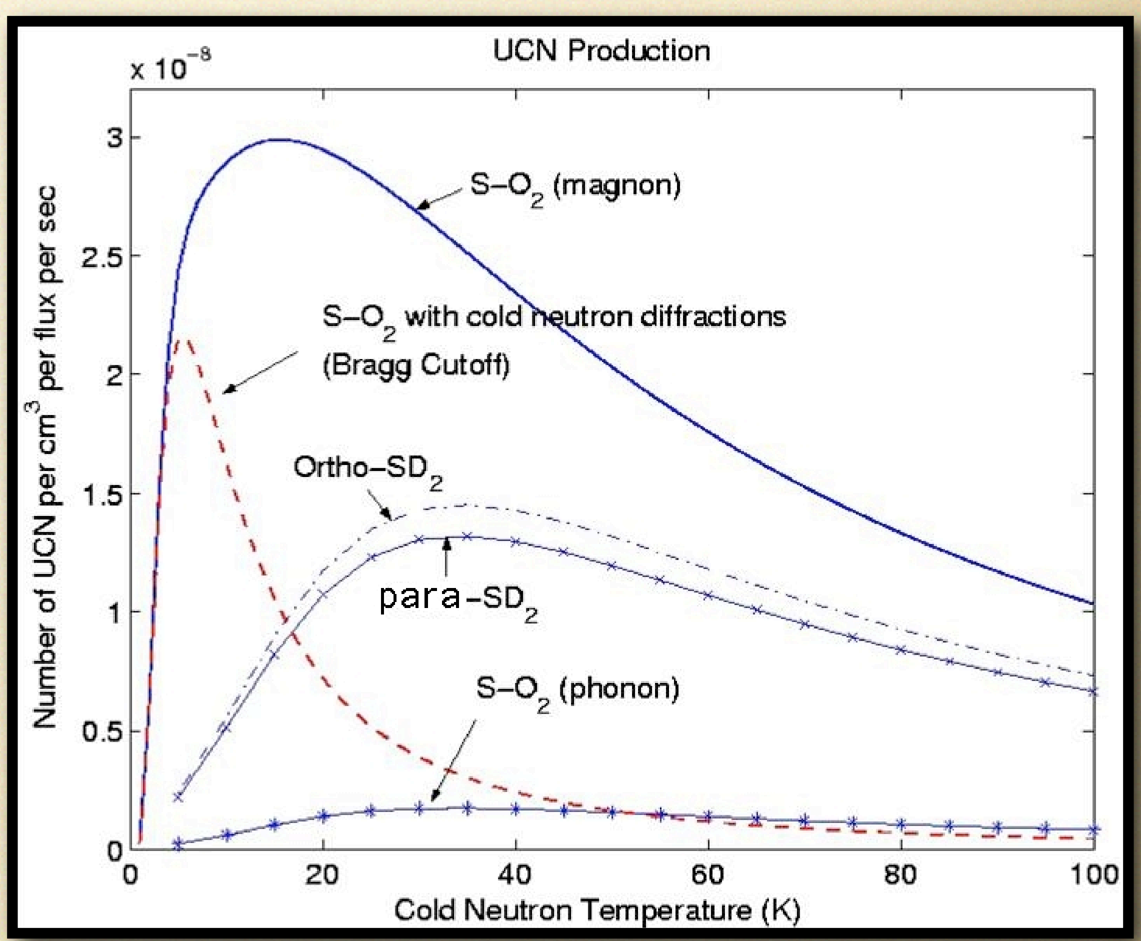
Isotope	σ_{coh}	σ_{inc}	σ_{abs}
^2D	5.59	2.04	$5.2E^{-4}$
^{16}O	4.23	0	$1.0E^{-4}$



- α phase (T<23.0K) oxygen has long range anti-ferromagnetic ordering
- It sustains spin wave excitation ➔ Magnon
- Interaction with magnon provides down-scattering

Solid O_2 and D_2

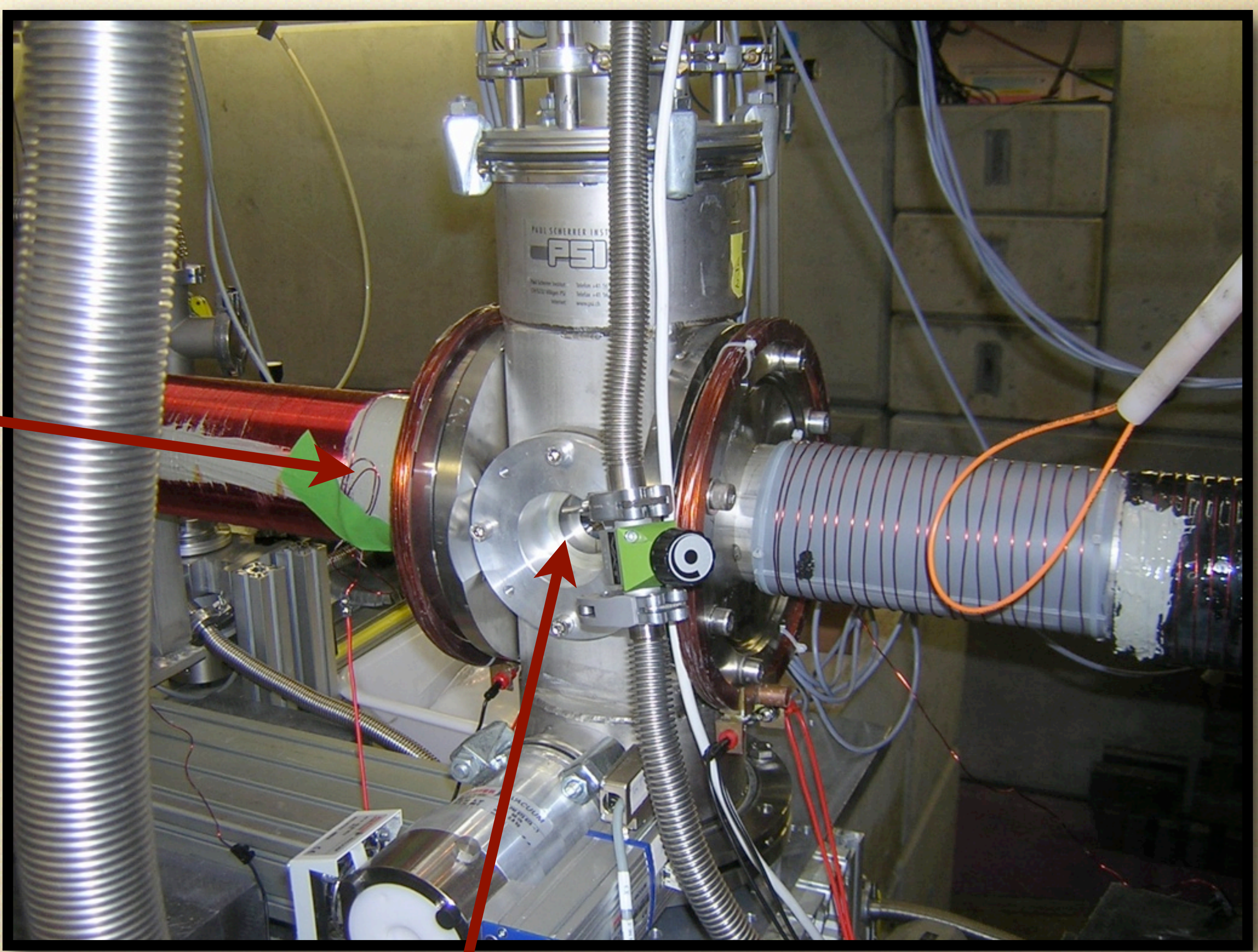
- UCN Production rate (~2)
  - $3.0 \times 10^{-8}\ \Phi_0$ (12K CN in SO_2)
  - $1.5 \times 10^{-8}\ \Phi_0$ (30K CN in Ortho-SD_2)
- $\rho_{ucn} = P_{ucn} \times \tau$
- Lifetime (~10)
  - 375 ms in SO_2
  - 40 ms in SD_2 due to bigger absorption
- Flux gain with source volume (~50)
  - 8 cm in SD_2 (incoherent scattering length)
  - 380 cm in SO_2 (absorption length)



UCN in Solid O_2

in PSI, Switzerland

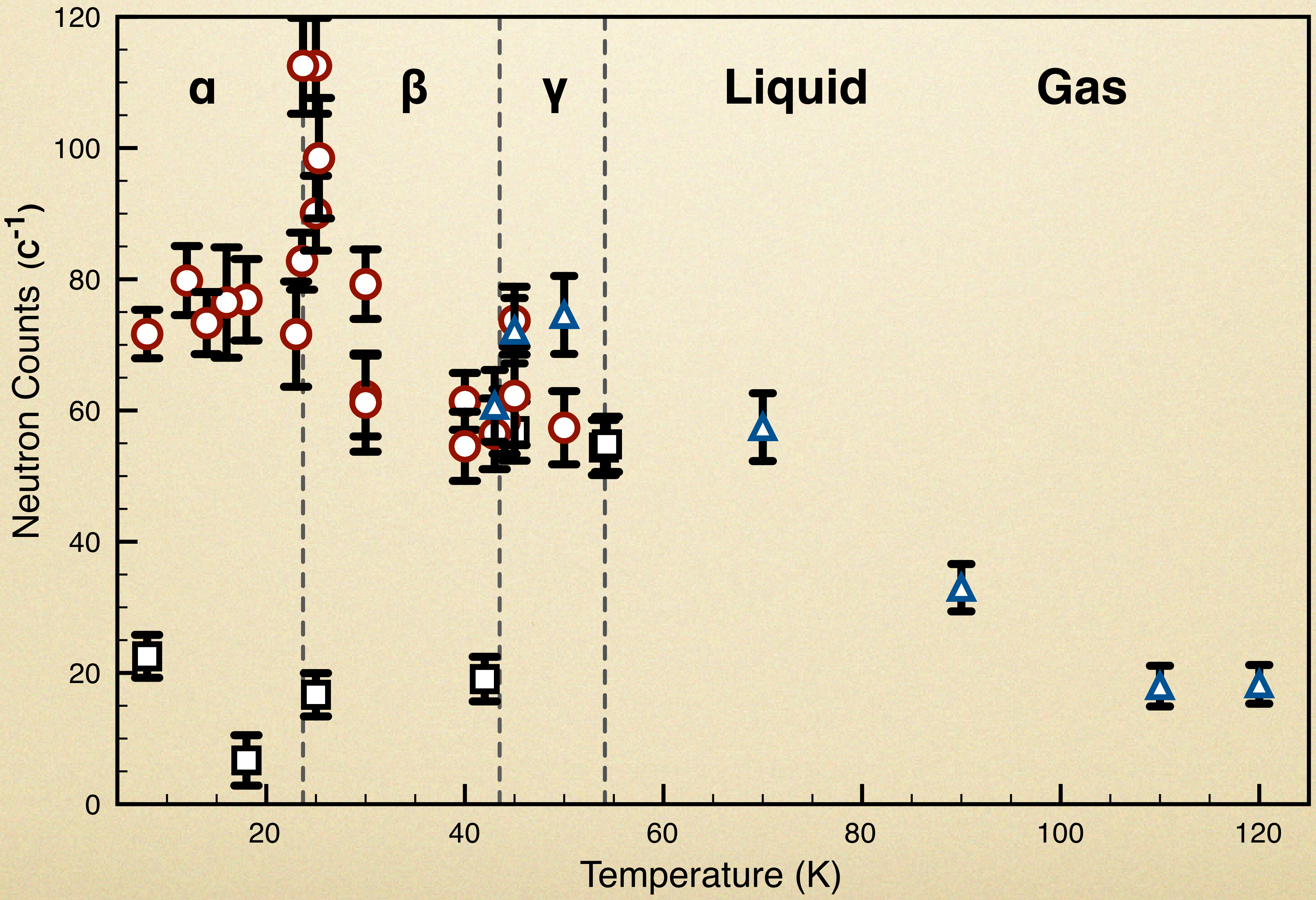
- FunSpin beamline in SINQ
- $\phi_{CN}=(4.5\pm1.0)\times10^7$ (cm^2-s-mA) with 1.2 mA proton on SINQ target
- PSI UCN group used this setup to study UCN production with Solid D_2



UCN Source

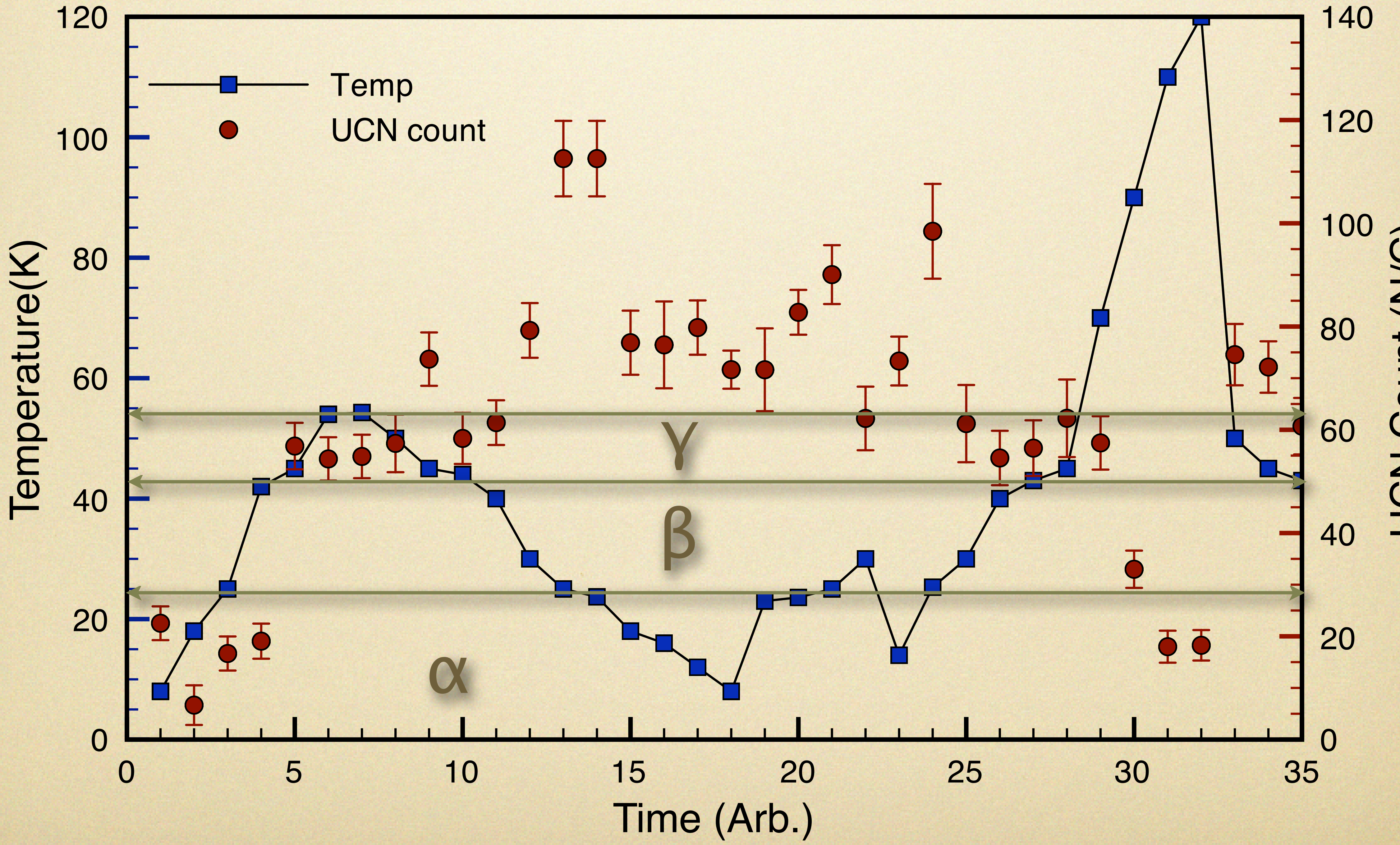
UCN in Solid O_2

FunSpin beam line in SINQ at PSI, Switzerland



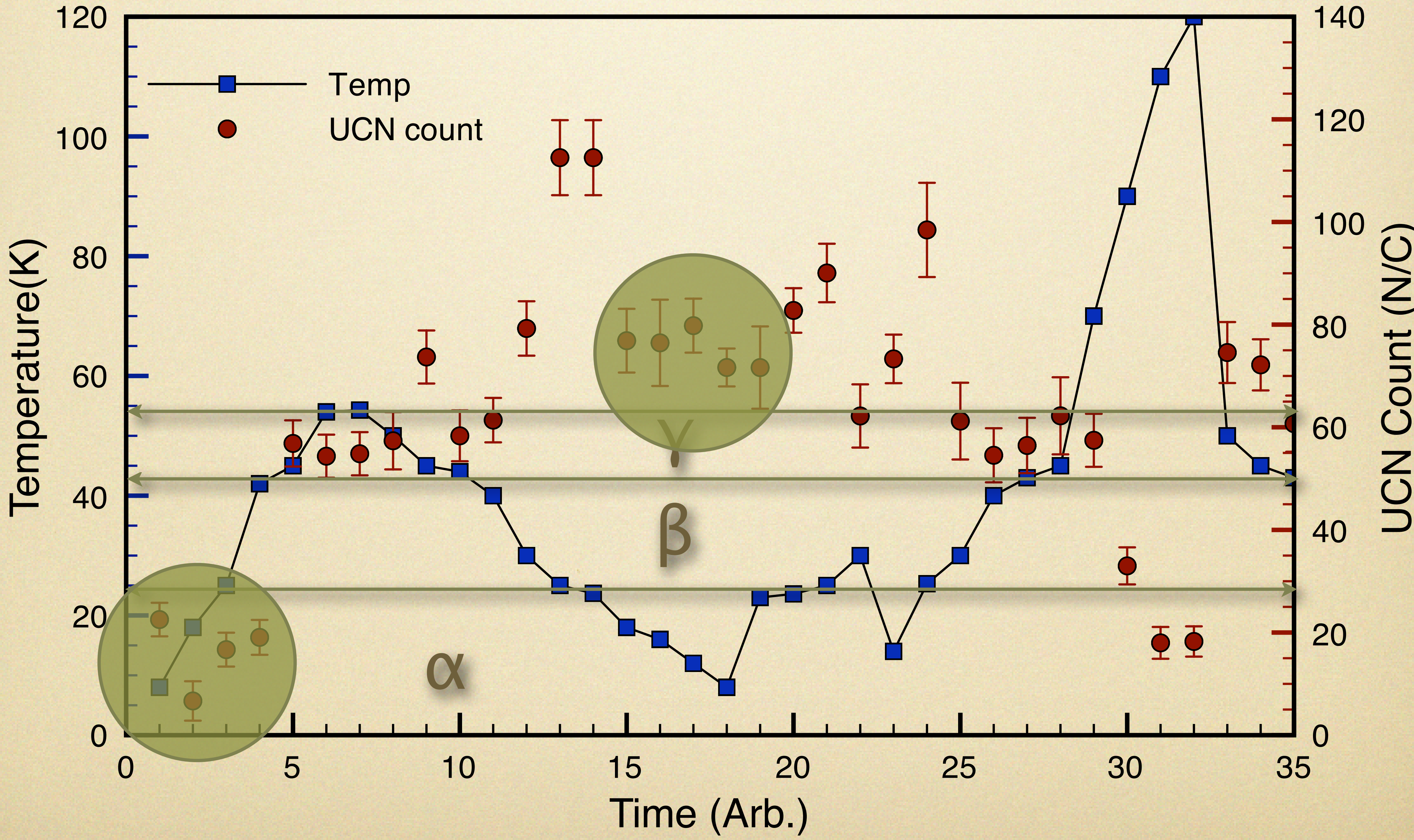
UCN in Solid O_2

FunSpin beam line in SINQ at PSI, Switzerland



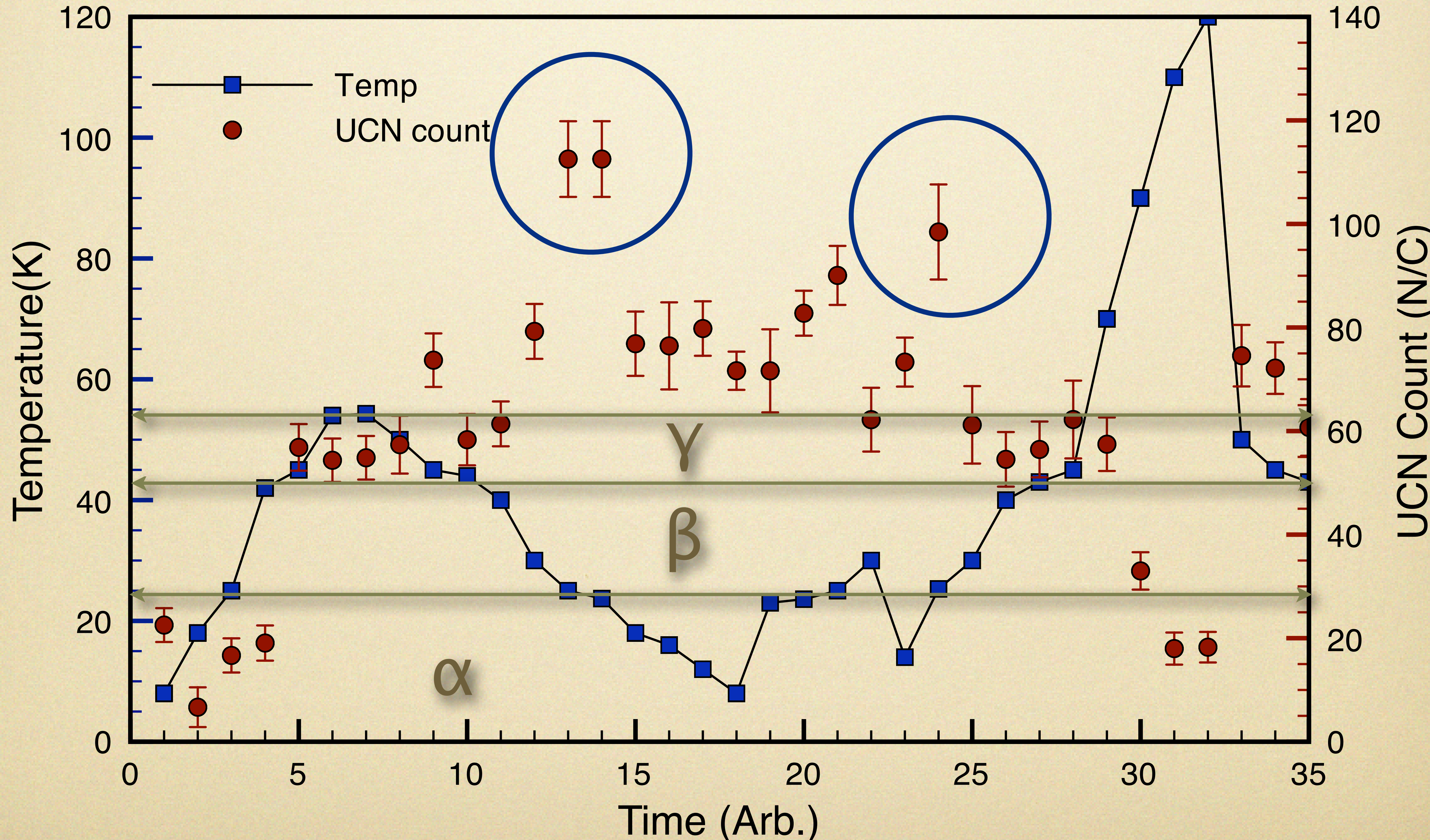
UCN in Solid O_2

FunSpin beam line in SINQ at PSI, Switzerland



UCN in Solid O_2

FunSpin beam line in SINQ at PSI, Switzerland

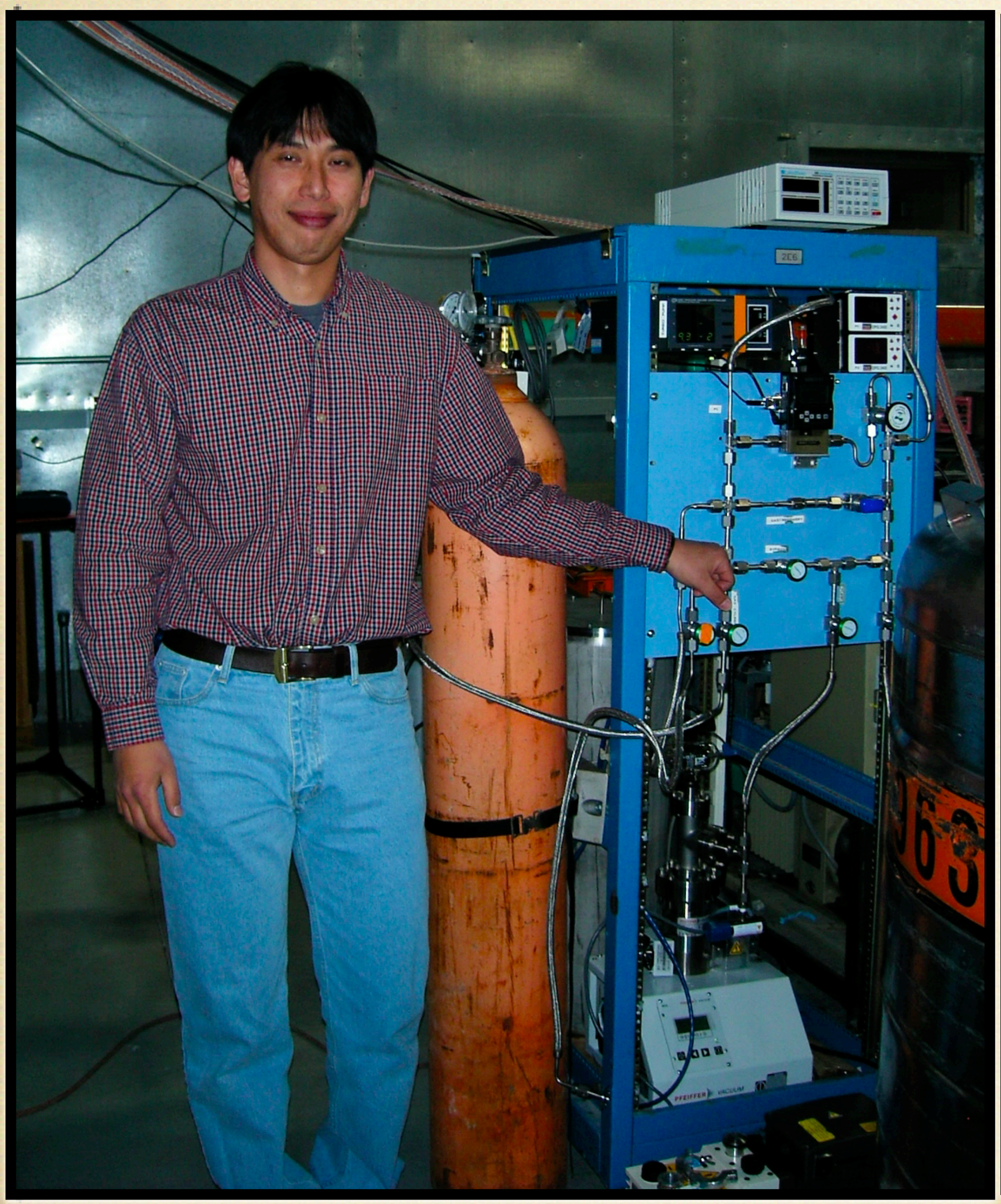


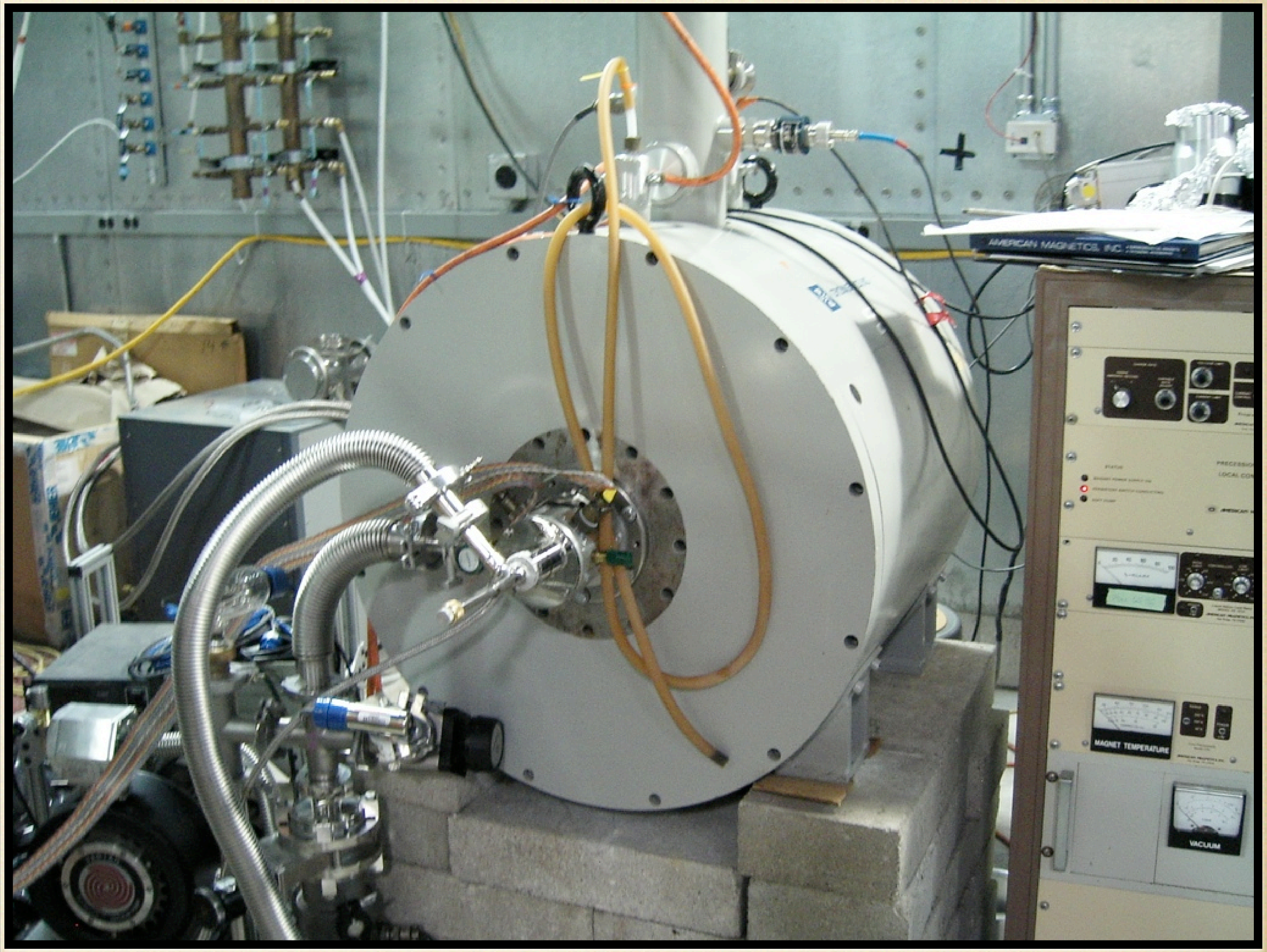
UCN in Solid O_2

in PSI, Switzerland

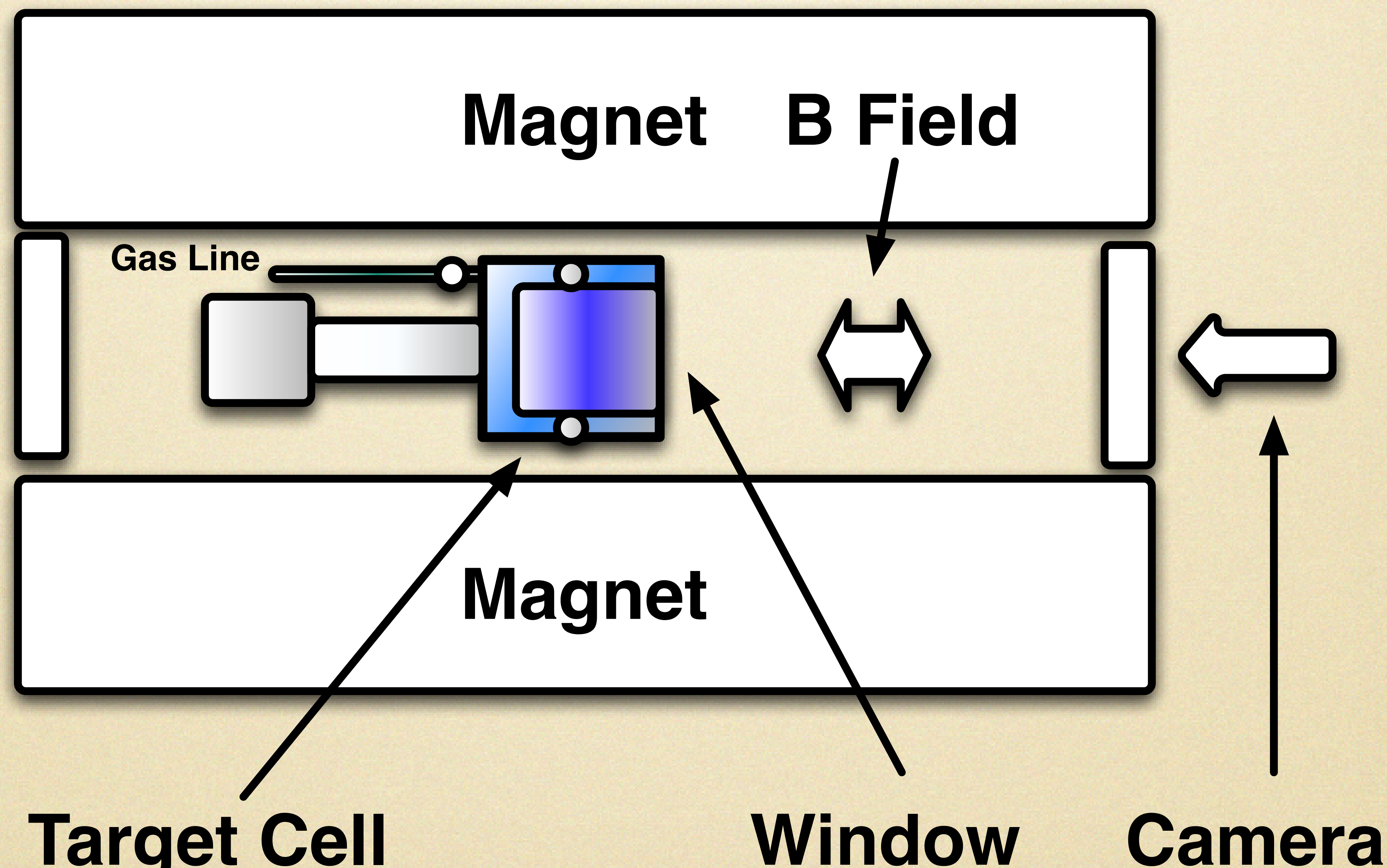
- The yield of UCN is about 3 times less than in S-D_2.
- UCN yields is correlated with quality of crystal
- How does cool down affect UCN yield?
- How does state of magnetic excitations affect UCN yield?

Solid O_2 at IUCF





Solid O_2 at IUCF



Conditions

- Search for First Solid Phase Transition T

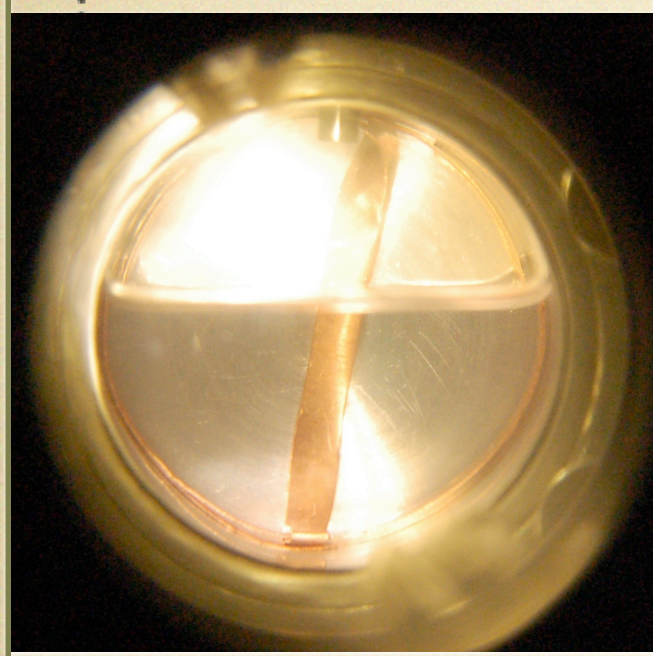
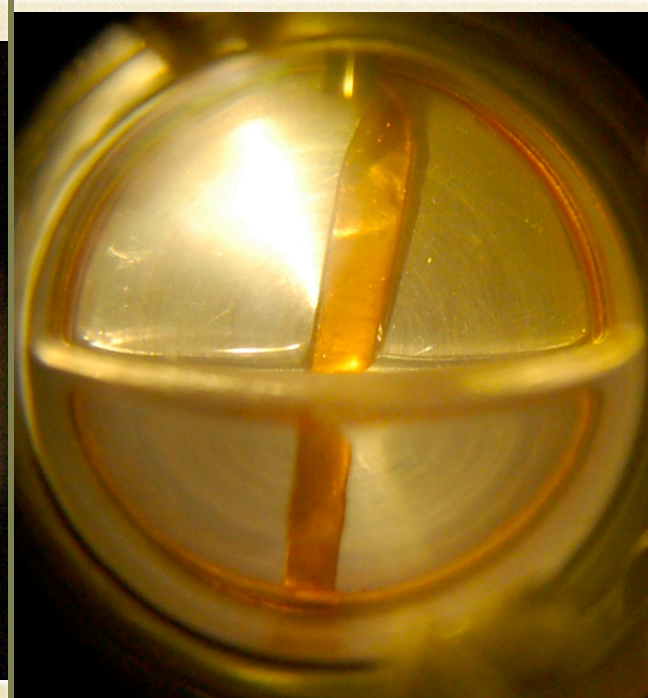
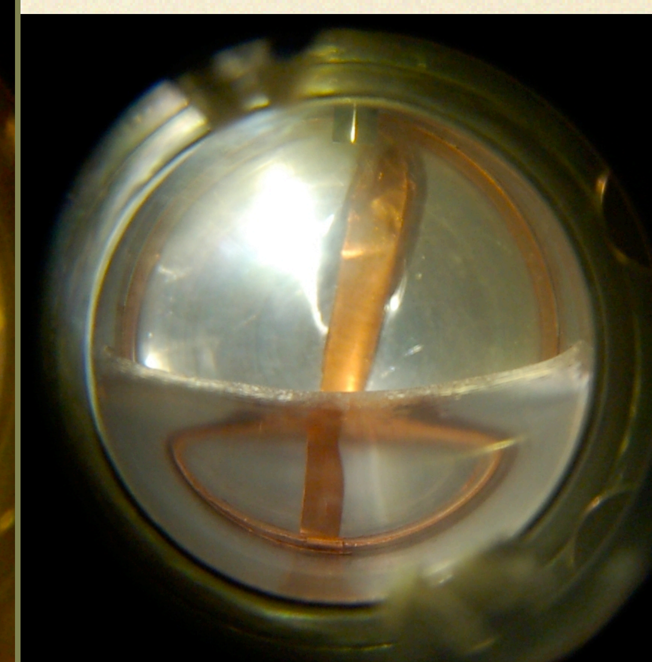
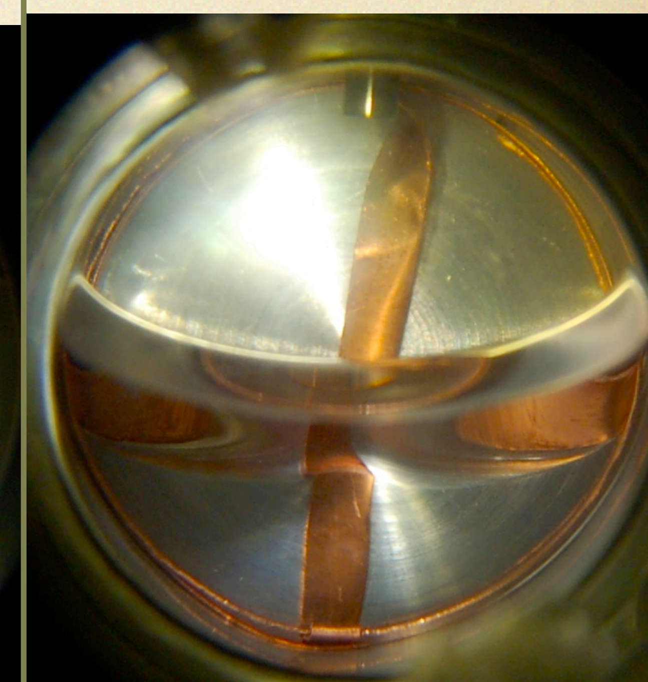
  a. 43.6~43.8K in literature

  b. 44. 779~44.569K in T_{Cell}

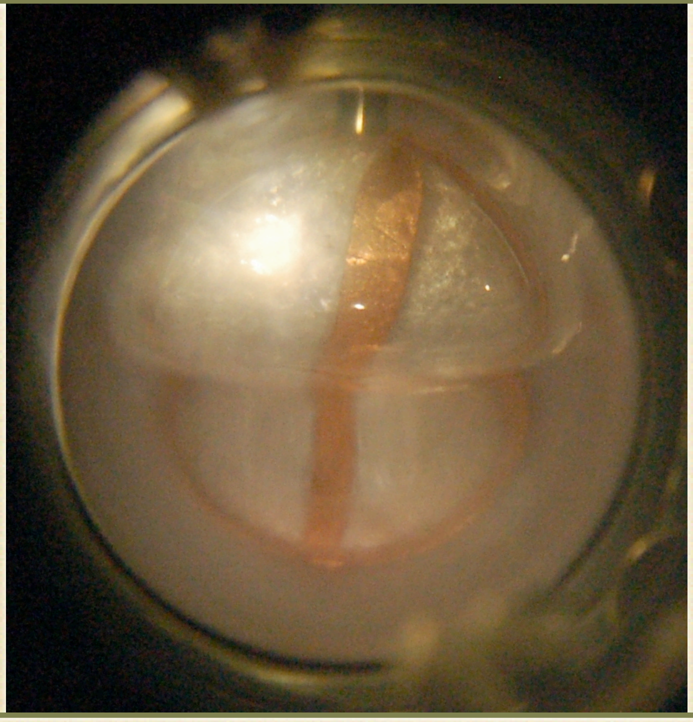
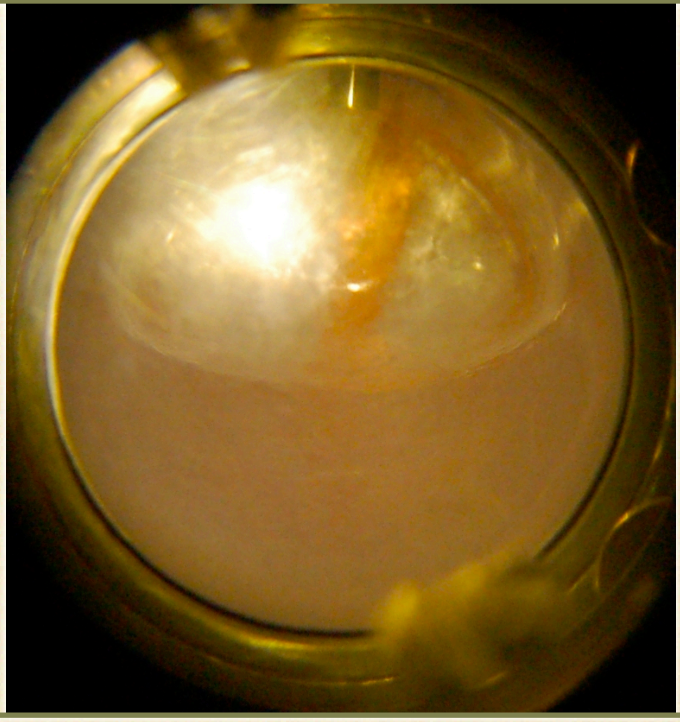
- Magnetic Field effect (1~2.5 Tesla)

- Cooling Rate (1~0.1mK/hr)

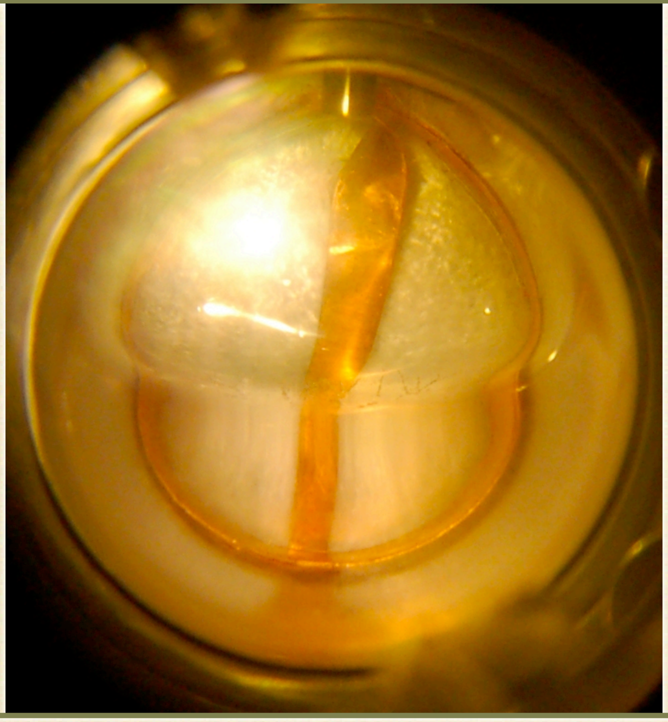
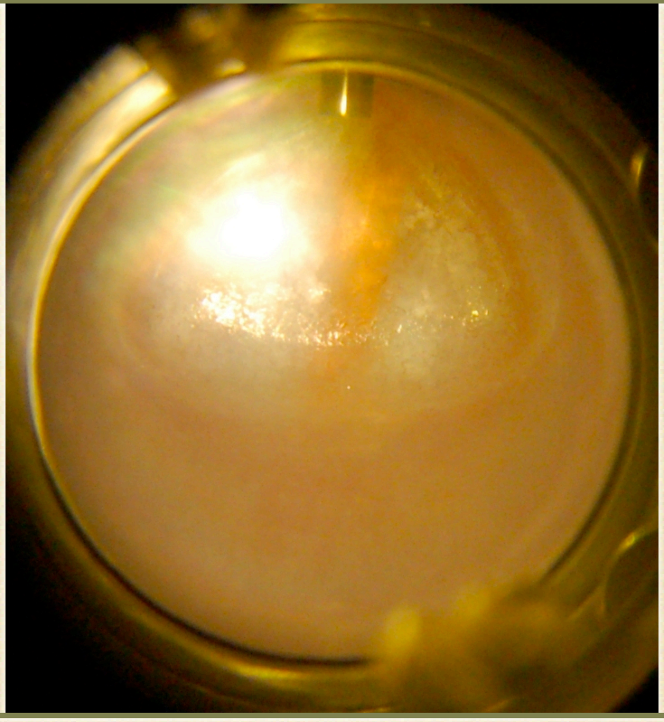
$T_{\text{Liquid-}\gamma}$ (54.6K)

Mar 07	Mar 31	Mar 16	Mar 29
			
B=0T	1T	1.5 T	2.5T

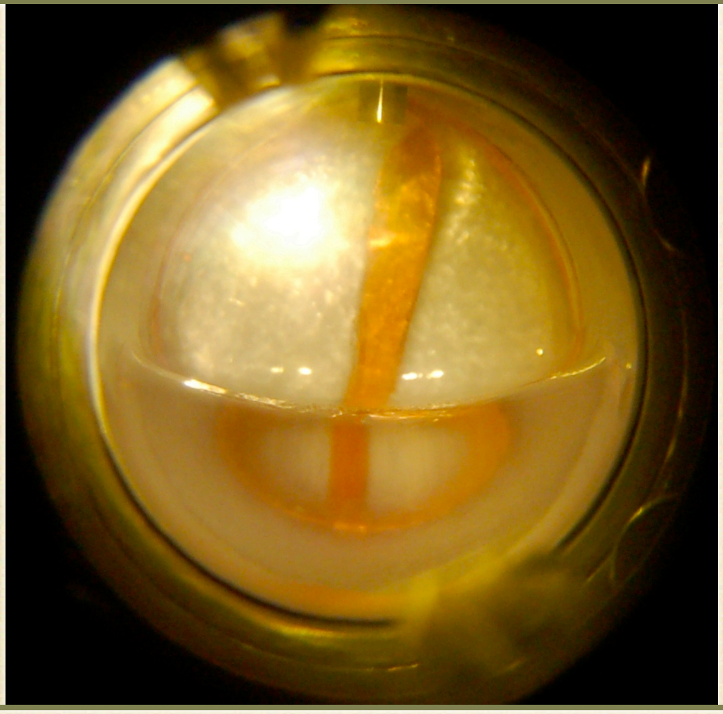
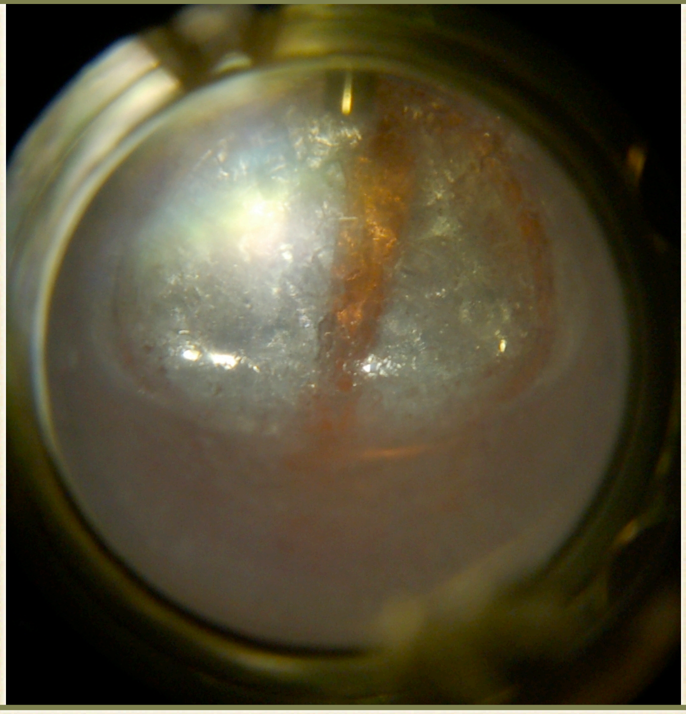
March 07, B=0T

Initial $T_{\gamma-\beta}$	Final $T_{\gamma-\beta}$ (~2h)
	
T_C=44.467 K	44.213 K

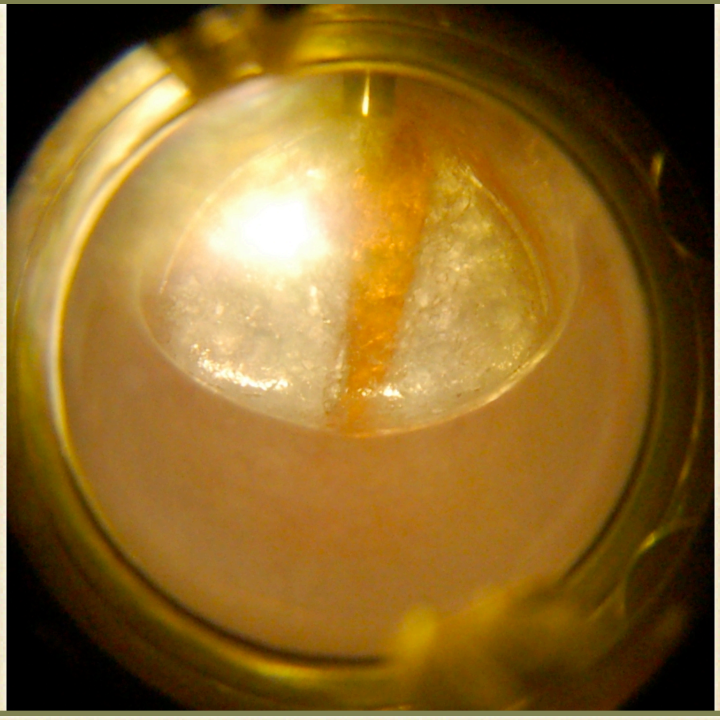
March 31, B=1T

Initial $T_{\gamma\text{-}\beta}$	Final $T_{\gamma\text{-}\beta}$ (~3h)
	
44.578 K	44.487 K

March 16, B=1.5T

Initial $T_{\gamma\text{-}\beta}$	Final $T_{\gamma\text{-}\beta}$ (~6h)
	
44.566 K	44.233 K

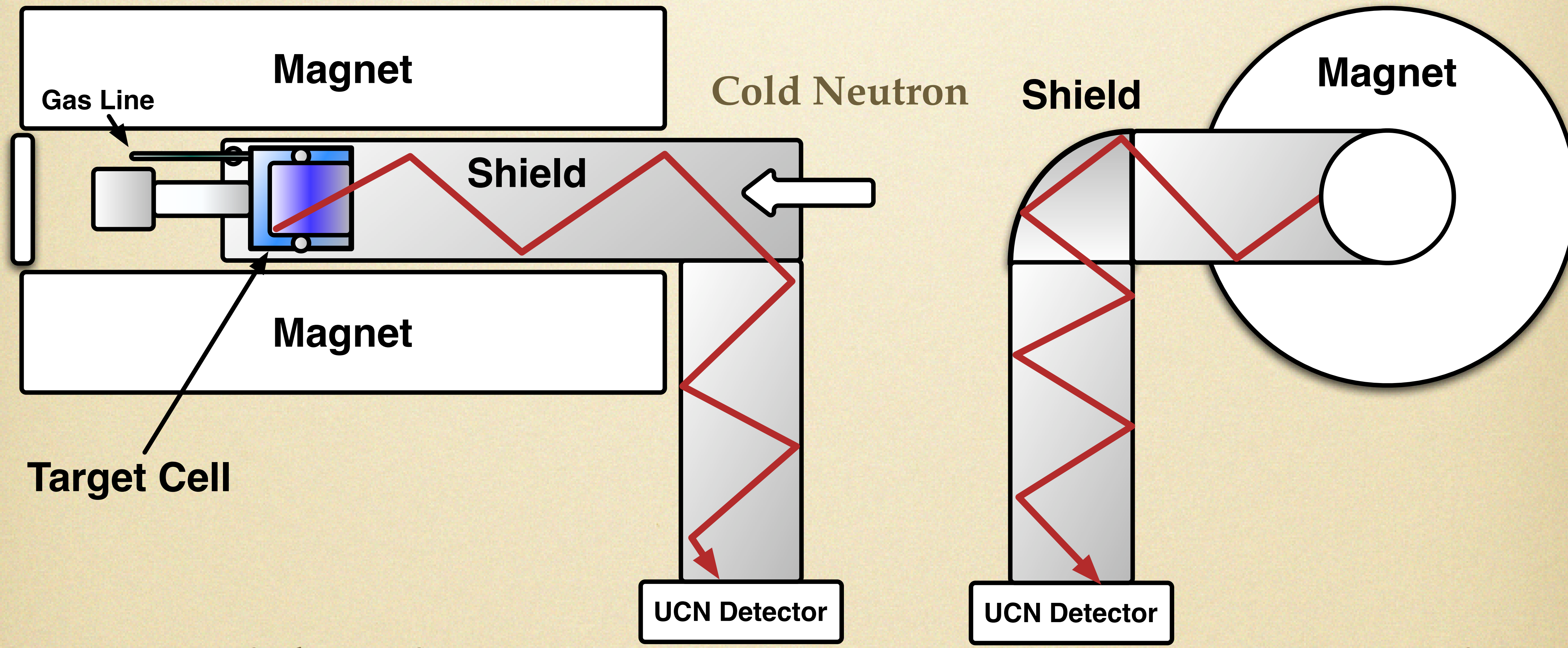
March 29, B=2.5T

Initial $T_{\gamma\text{-}\beta}$	Final $T_{\gamma\text{-}\beta}$ (~4h)
	
44.591 K	44.553 K

Running Summary

	Mar 07	Mar 31	Mar 16	Mar 29
O_2 Purity (%)	99.99	99.999	99.999	99.999
B Field(T)	0	1	1.5	2.5
Ramp(K/h)	0.16	0.001	0.001	0.002
$T_{L-\gamma}$ (K)	55.6	55.6	55.6	55.6
$T_{\gamma-\beta}$ (K)	44.467	44.578	44.566	44.591

UCN production at LANSCE



Side View

Front View

Summary

- Magnons in Solid O_2 offer additional scattering for UCN production.
- Study the crystal growing of Solid Oxygen.
- Study the magnetic field influence on UCN production in FP-12 at LANSCE

nEDM

$$h\nu = -2(\mu_n \cdot B \pm d_n \cdot E) \longrightarrow d_n = h\Delta\nu/4E$$