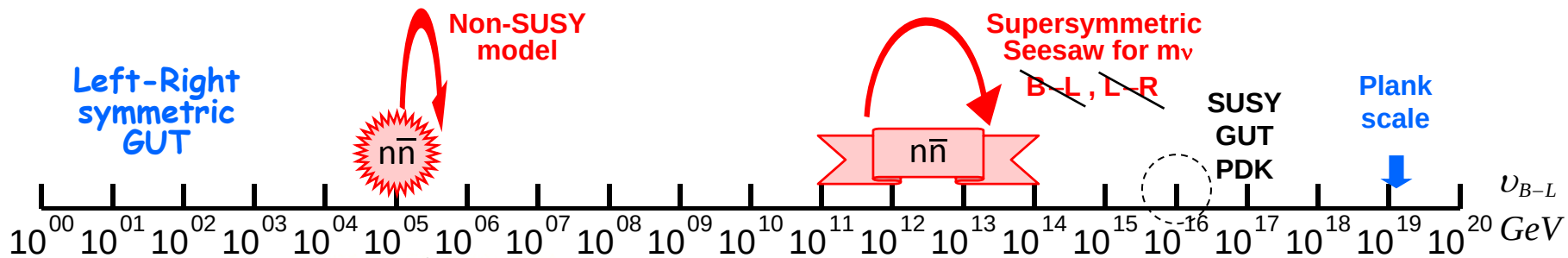
CSS 2013 / Snowmass on the Mississippi (Minnesota) • August 2, 2013

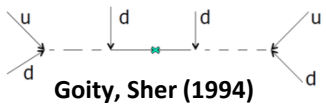
NNbarX
Baseline Configuration and Experimental Sensitivity

for NNbarX Collaboration

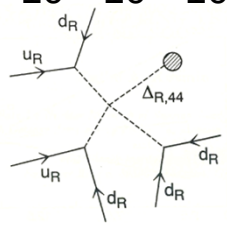
Yuri Kamyshkov/ University of Tennessee
email: kamyshkov@utk.edu

$Scales\ \ of\ \ n \to \bar{n}\ \ (B-L)V\ \ in\ \ theory$



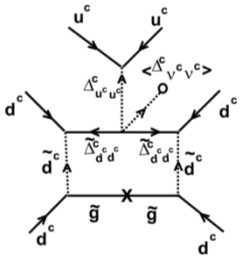


Goity, Sher (1994)



$\propto \upsilon_{B-L}^{-5}$

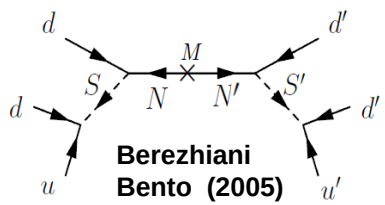
Mohapatra & Marshak (1980)



$\propto \upsilon_{B-L}^{-2} \cdot \upsilon_{WK}^{-3}$

Dutta-Mimura-Mohapatra (2005)

Observable effects at LHC
Berezhiani; Babu et al. (2013)

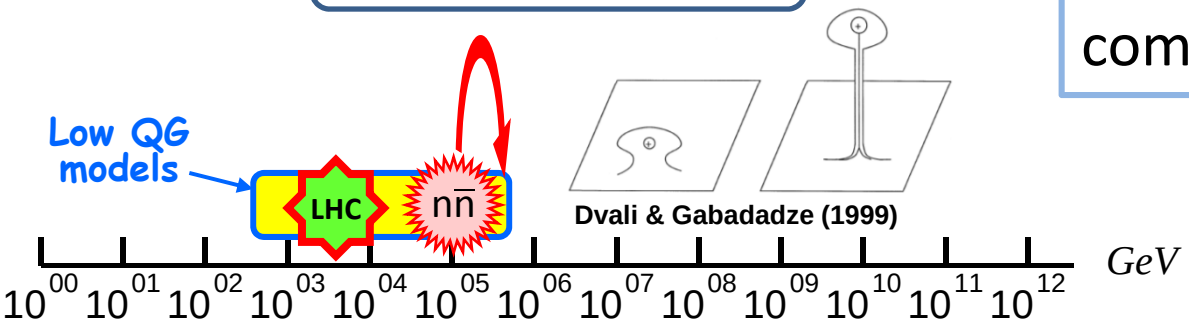


Berezhiani
Bento (2005)

Post-Sphaleron Baryogenesis
Babu, Mohapatra, et al.(2013)

Experimental motivation!

large increase of sensitivity:
factor of ×1,000 is possible
compared to existing limit



Dvali & Gabadadze (1999)

Shrock & Nussinov (2002)

Sensitivity or figure of merit

For experimental "quasifree conditions"
when external fields are approx. ~0
Practically n "observation" time
t ~ 0.1 s to 10 s

$$P_{n\to\bar{n}} = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

$$N \cdot \overline{t}^2 \doteq \text{sensitivity for free neutrons} \sim P$$

$$\tau_{n\bar{n}} = \tau_{free} \sim \sqrt{N \cdot \overline{t}^2}$$

$$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$

$\tau_{n\bar{n}} = \dfrac{\hbar}{\alpha}$ is characteristic "oscillation" time $[\alpha < 2 \cdot 10^{-24} eV$, as presently known]

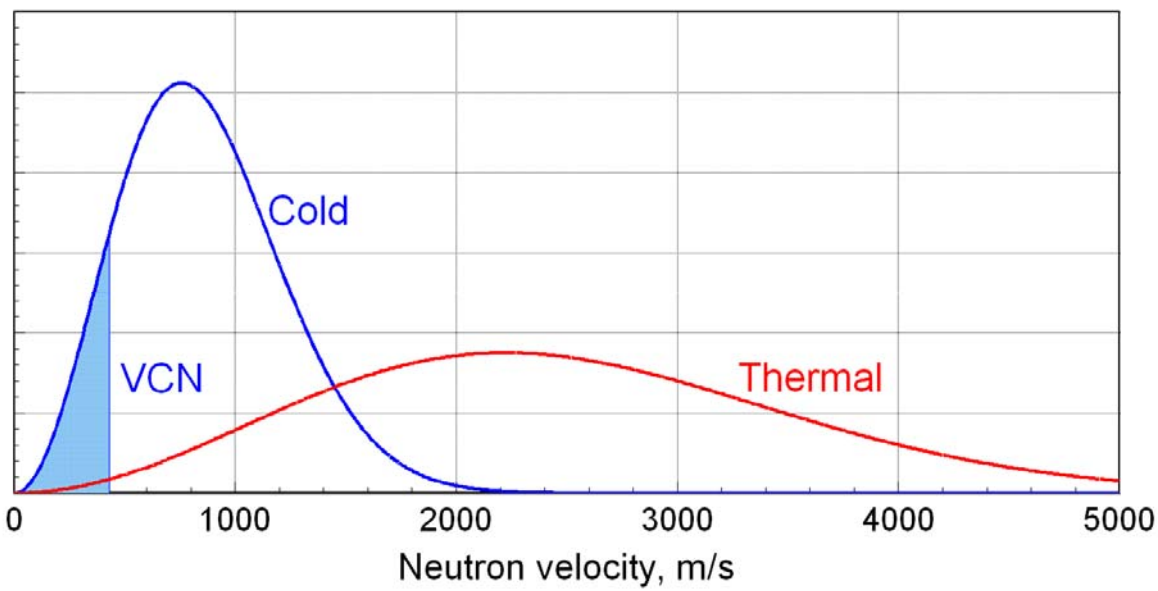
Existing exp. limits are set by at ILL (free n) and by Super-K (bound n)

Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

Sensitivity: $N \cdot \overline{t}^2$

$\Rightarrow$ many neutrons (large N) and very slow(large $\overline{t}$)

Neutrons	E kin	T,K	Velocity	Wavelength
Fast	~ 1 MeV	~ 10^{10}	~ 0.046 *c*	~ 0.0003 Å
Thermal	~ 25 meV	~ 300	~ 2.2 km/s	~ 1.8 Å
Cold	~ 3 meV	~ 35	~ 760 m/s	~ 5 Å
Very Cold (VCN)	$\lesssim$ 1 meV	~ 10	$\lesssim$ 430 m/s	$\gtrsim$ 9 Å
Ultra Cold (UCN)	~ 250 neV	~ 0.003	$\lesssim$ 8 m/s	$\gtrsim$ 600 Å

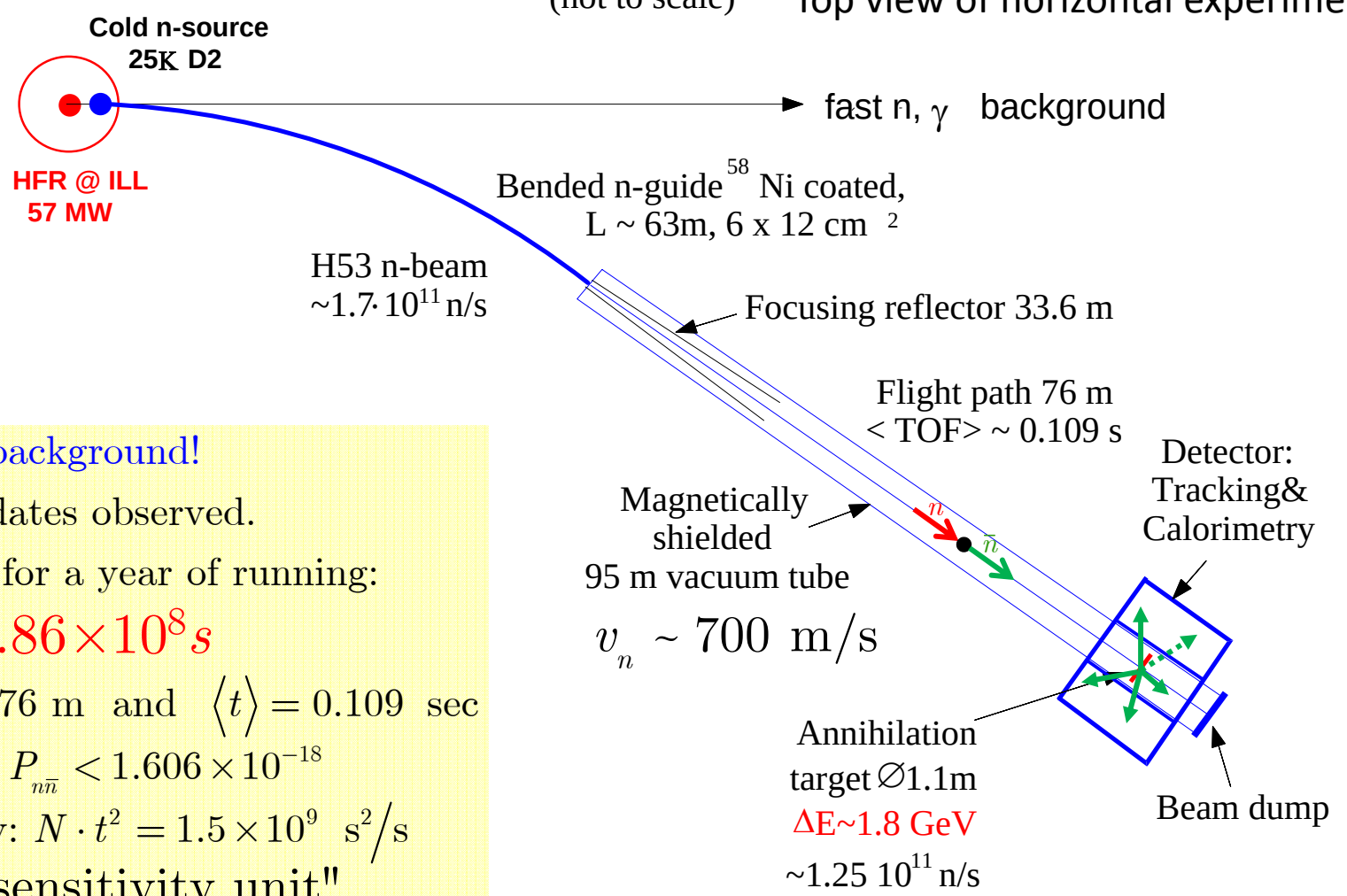


Previous state-of-the-art n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409

(not to scale) Top view of horizontal experiment



$v_n \sim 700 \text{ m/s}$

No GeV background!

No candidates observed.

Limit set for a year of running:

$\tau_{n\bar{n}} > 0.86 \times 10^8 s$

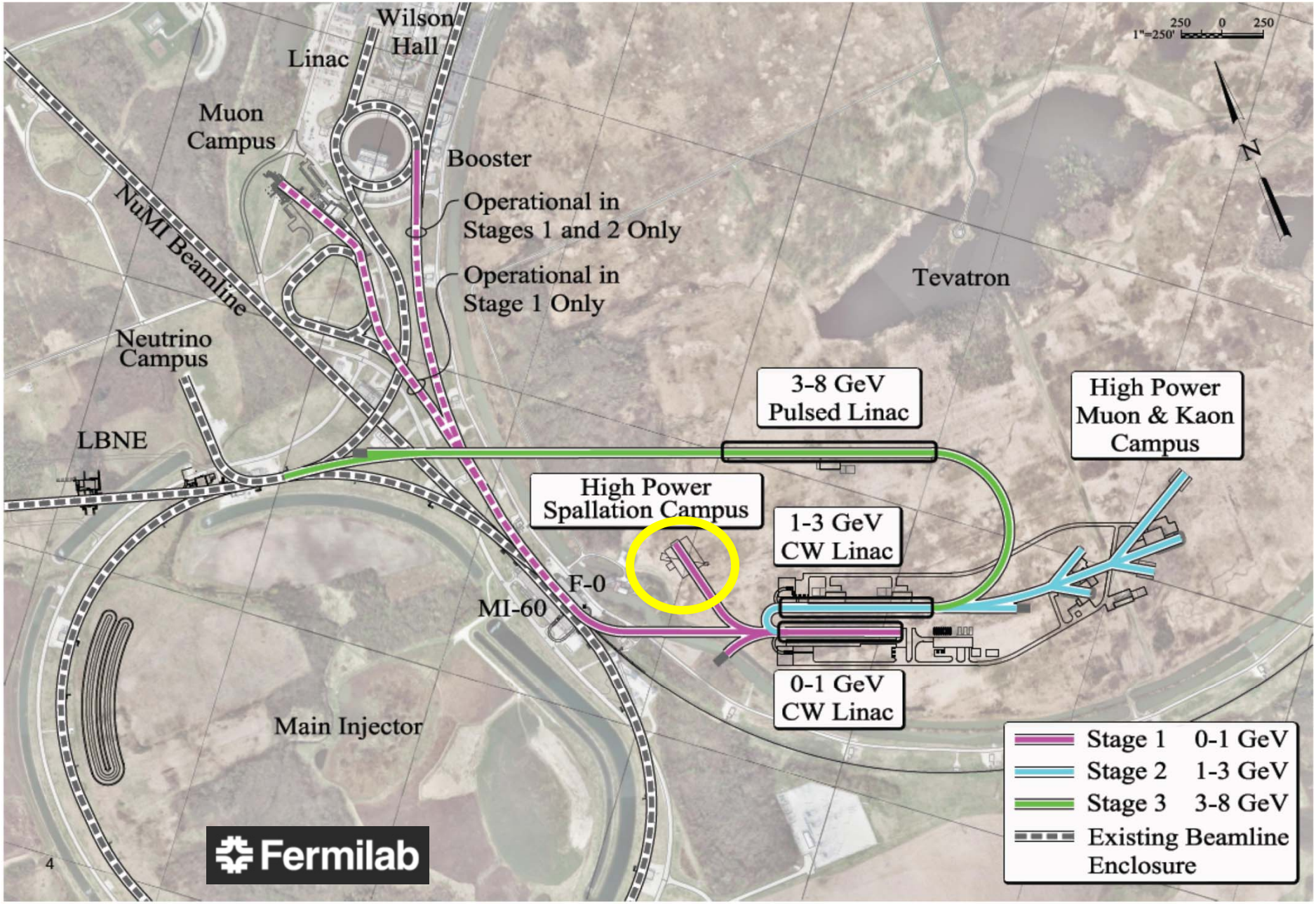
with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

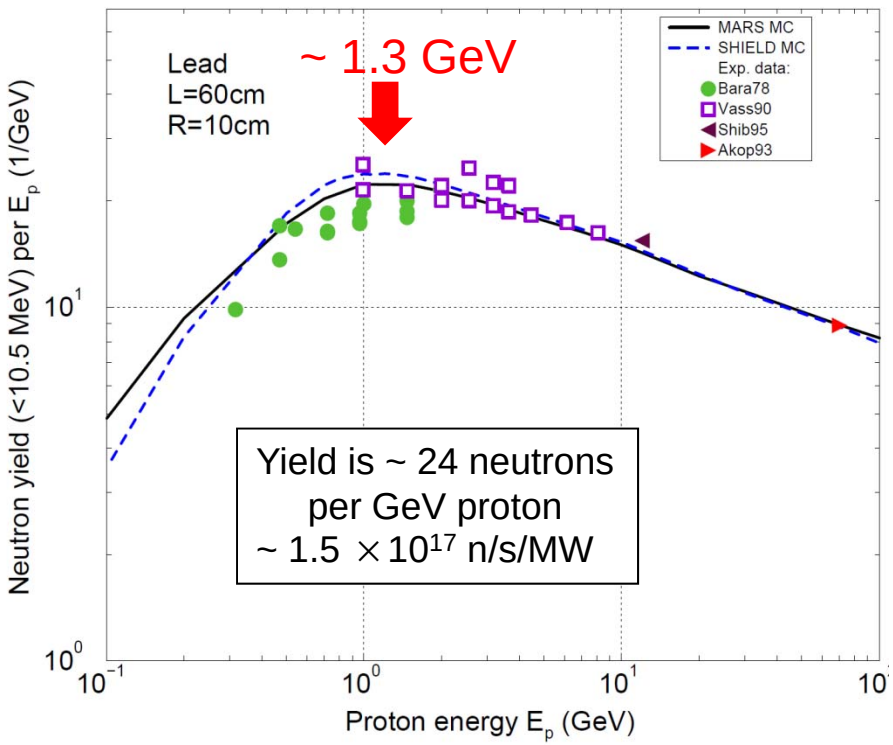
sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ \text{s}^2/\text{s}$

$\doteq$ "ILL sensitivity unit"

Spallation Target in Project X



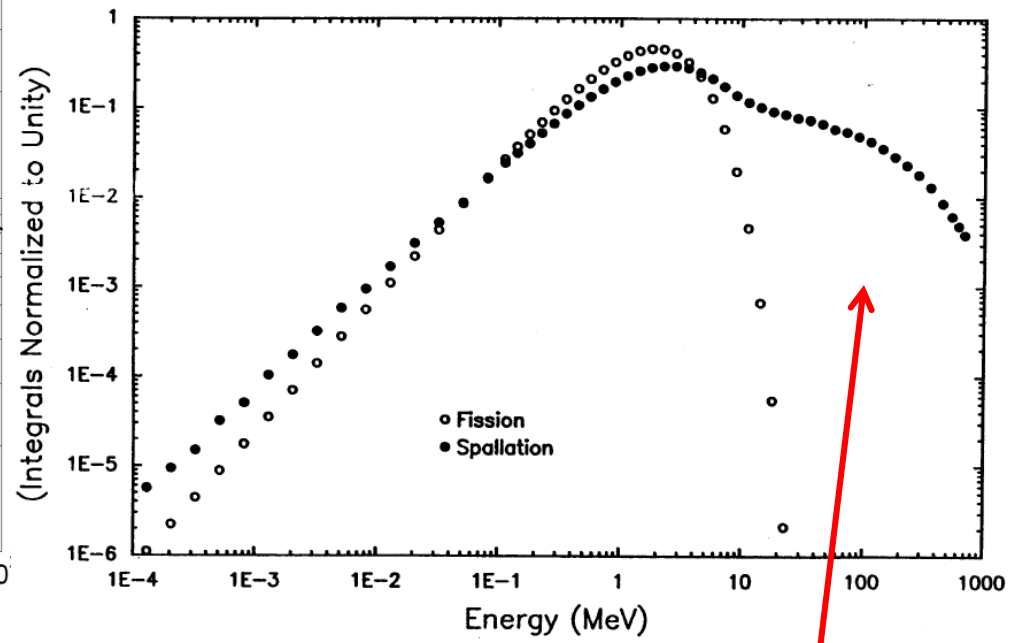
Optimal Neutron Production Energy



N. Mokhov, MARS simulations, FNAL, 2011

For target made of fissionable materials (e.g. Th, DU) neutron yield can be factor ~ 2 higher (geometry dependent)

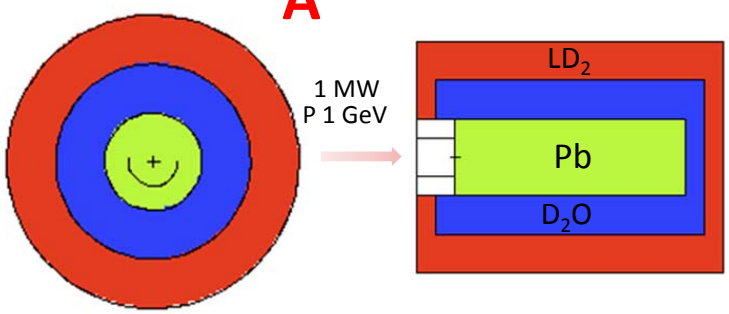
Spectrum of Primary Neutrons



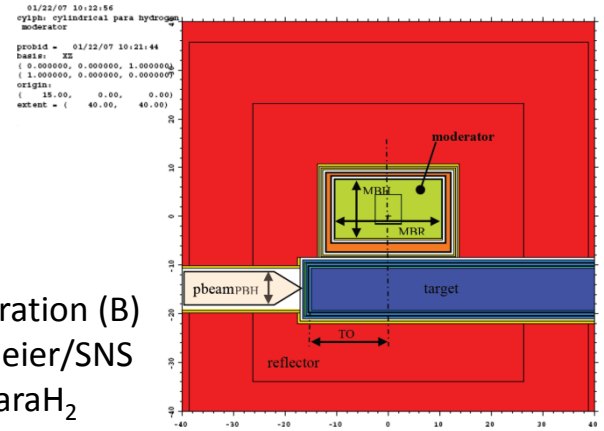
Spectrum of primary fast n from spallation target and from fission (Courtesy of Gary Russel).

Potential source of the "fast" background for n-nbar that was non-existent in the previous ILL experiment

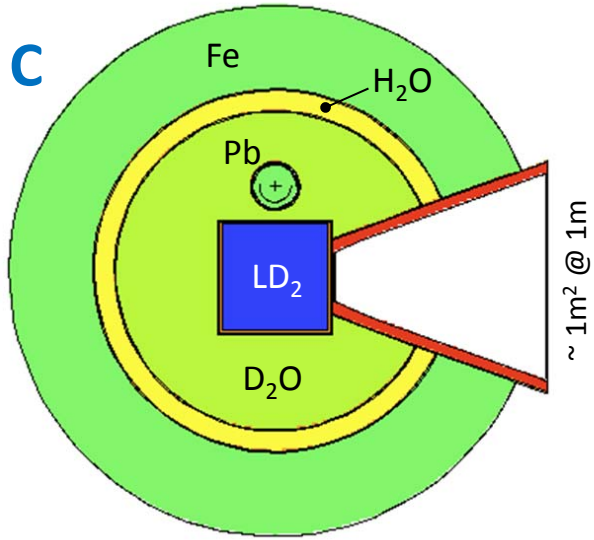
Target Models in MCNPX (NNbarX studies for Project X)



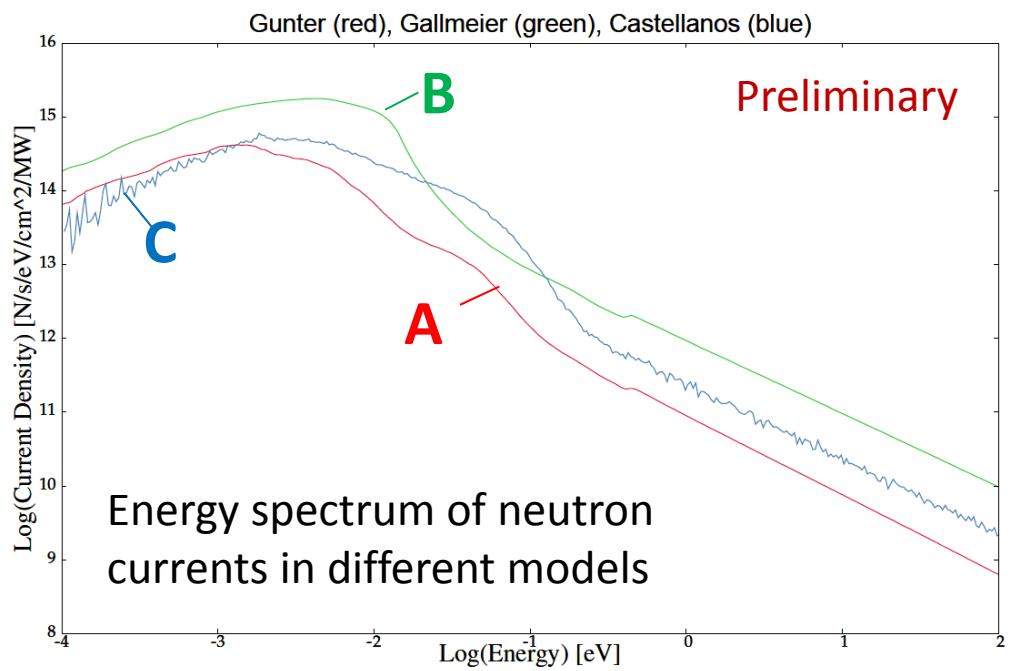
Configuration (A) G. Muhrer/LANL



Configuration (B)
F. Gallmeier/SNS
with $LparaH_2$



Initial UT model (C) L. Castellanos/UT



Energy spectrum of neutron currents in different models

Goal is high source brightness with possibly large source area

Key concepts for improvement of Sensitivity factor $N \cdot t^2$

(1) Use of elliptical focusing neutron super-mirror reflector.

Implement well-known and commercially available technologies.
Horizontal baseline configuration with conservative design.
Improvement mostly due to increase of N.
Sensitivity increase > 100 "ILL units" $\times$ number of years.

(2) Enhanced production of and use of VCN and UCN.

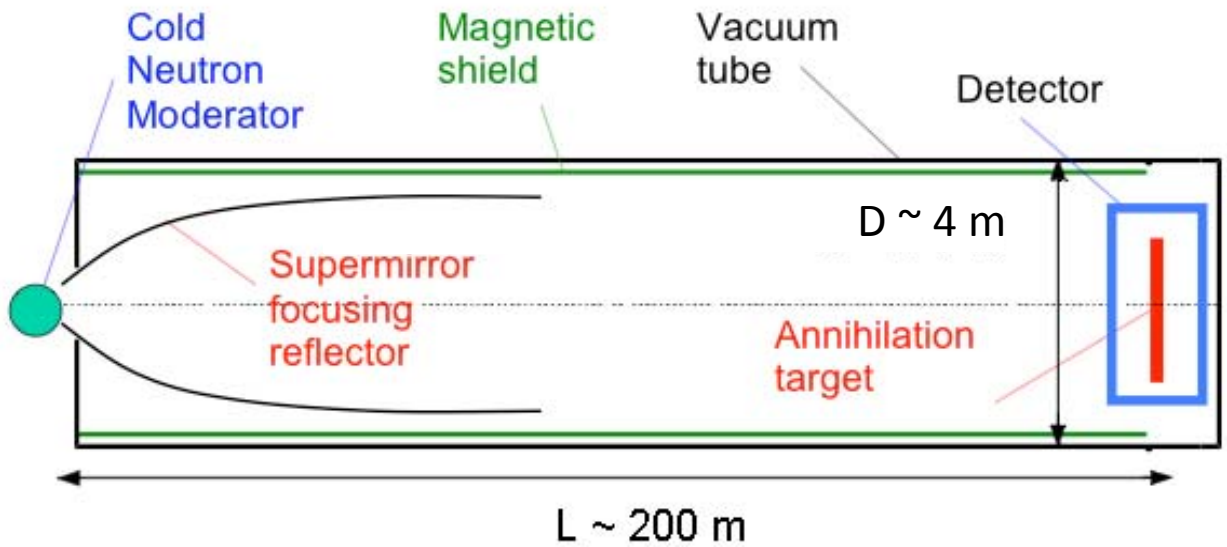
Will require vertical configuration of experiment.
VCN and UCN enhanced production and manipulation require R&D work.
More improvements due to increase $t^{2.}$
Additional factor of 50-100 in sensitivity.

R&D ideas being explored:

- Colder neutron moderators, UCN converters
- Neutron optics, mirrors, reflectors, filters
- Technologies withstanding radiation damage
- Cost-effective technologies

Conceptual Horizontal Baseline Configuration

with elliptical focusing reflector (method proposed by us in 1995)



Typical initial baseline parameters:

Cold source configuration	C type
Luminous source area, dia	30 cm
Annihilation target, dia	200 cm
Reflector starts at	1.5 m
Reflector ends at	40 m
Reflector semi-minor axis	2.0 m
Distance to target	200 m
Super-mirror	m=6
Vacuum	$< 10^{-5}$ Pa
Residual magnetic field	< 1 nT

MC Simulated sensitivity Nt^2:

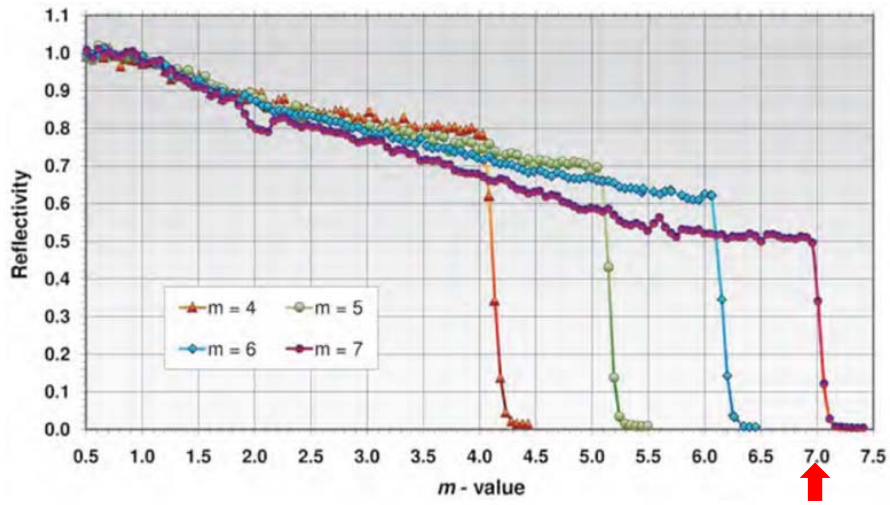
110 "ILL units" x years

Sensitivity and parameters are subject of optimization by Monte-Carlo including overall cost

N-nbar effect can be suppressed by weak magnetic field.

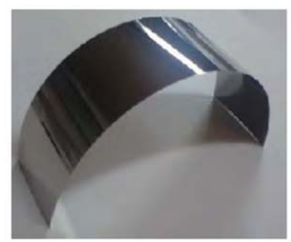
Super-mirrors material for large elliptical focusing reflector

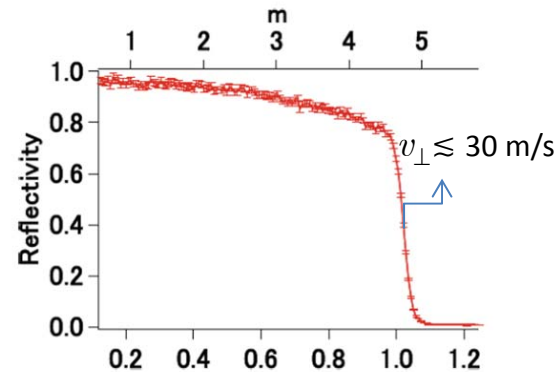
Commercial products of Swiss Neutronics



$v_\perp \lesssim 50$ m/s

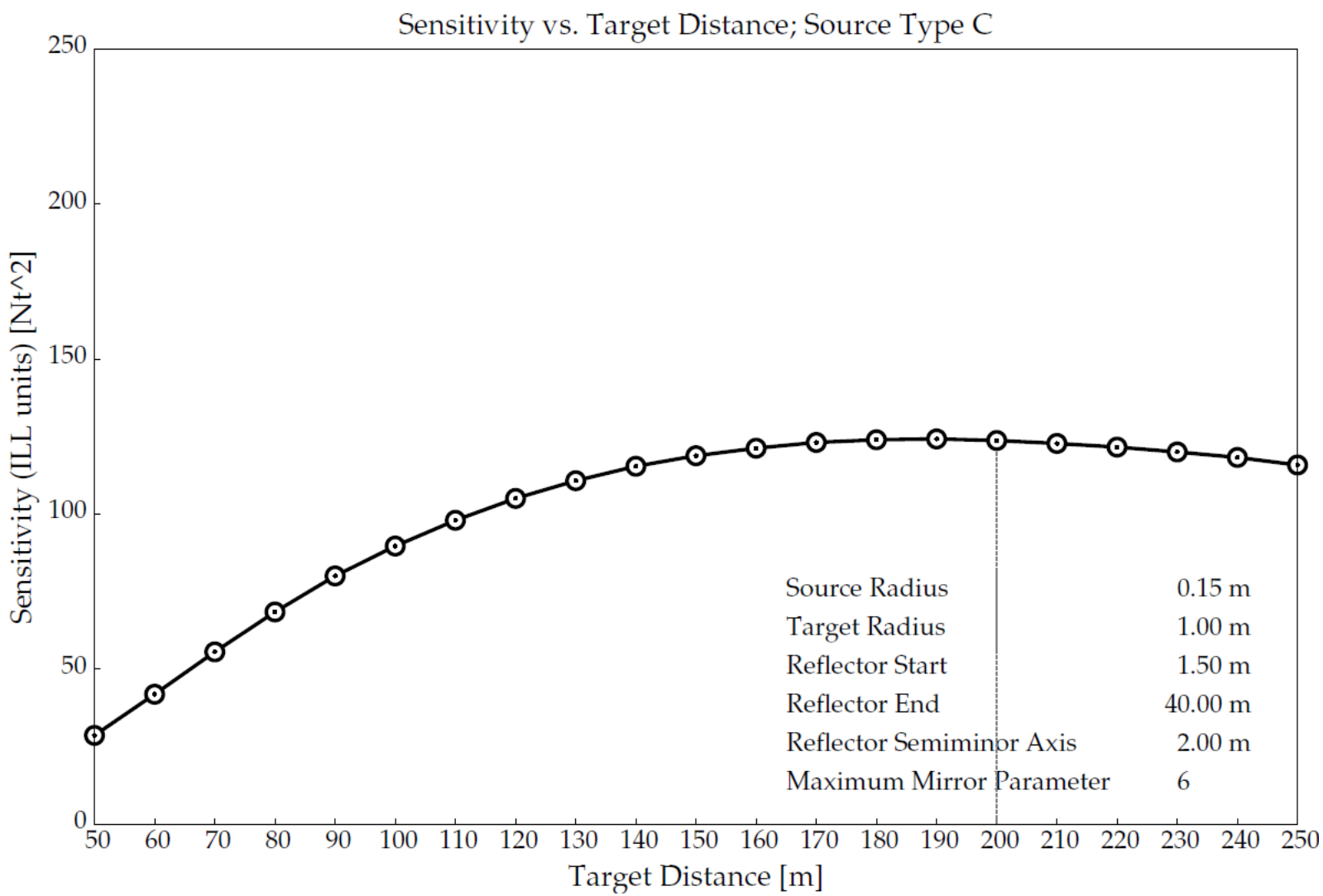
Progress in neutron super-mirrors



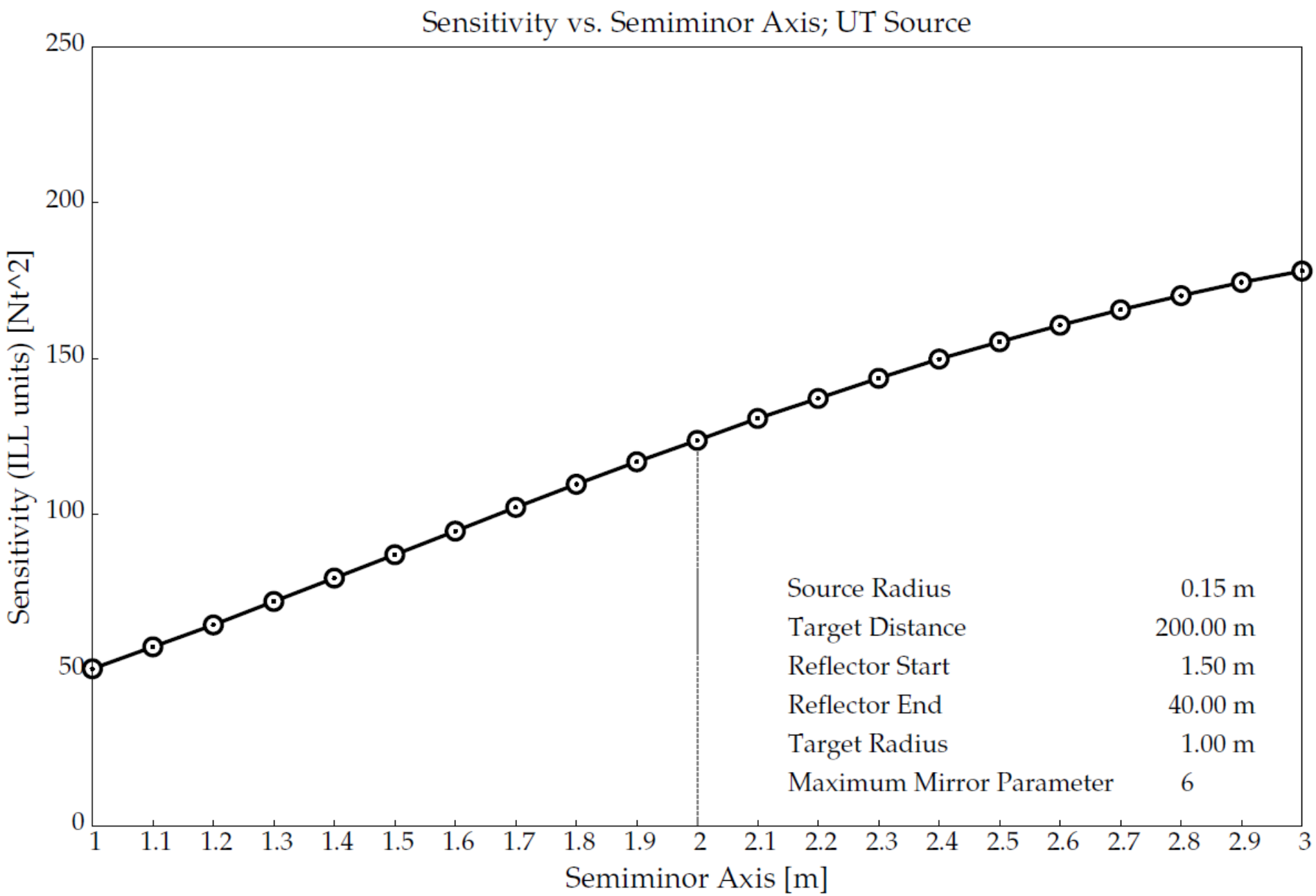


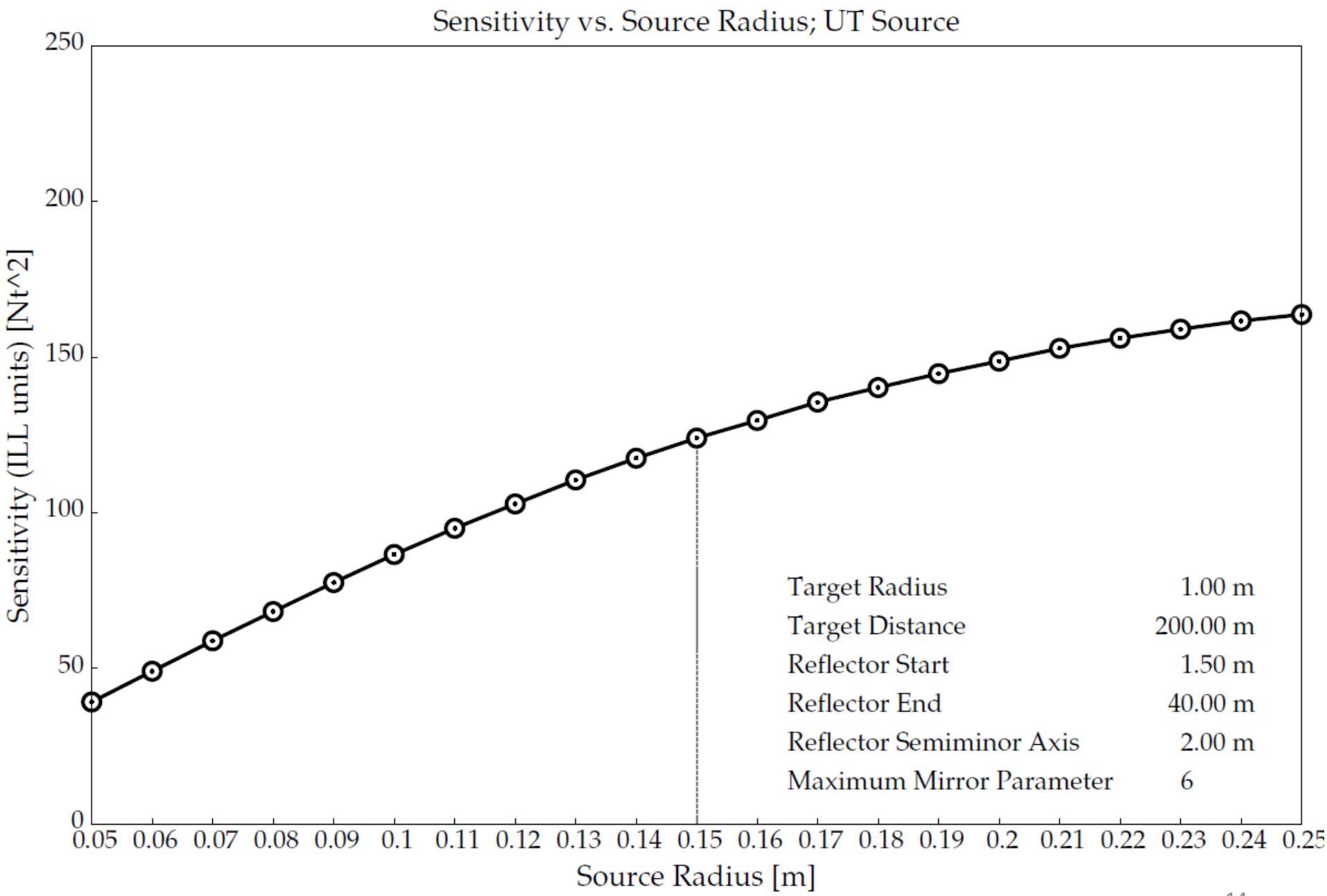
no substrate (radiation hardness expected)

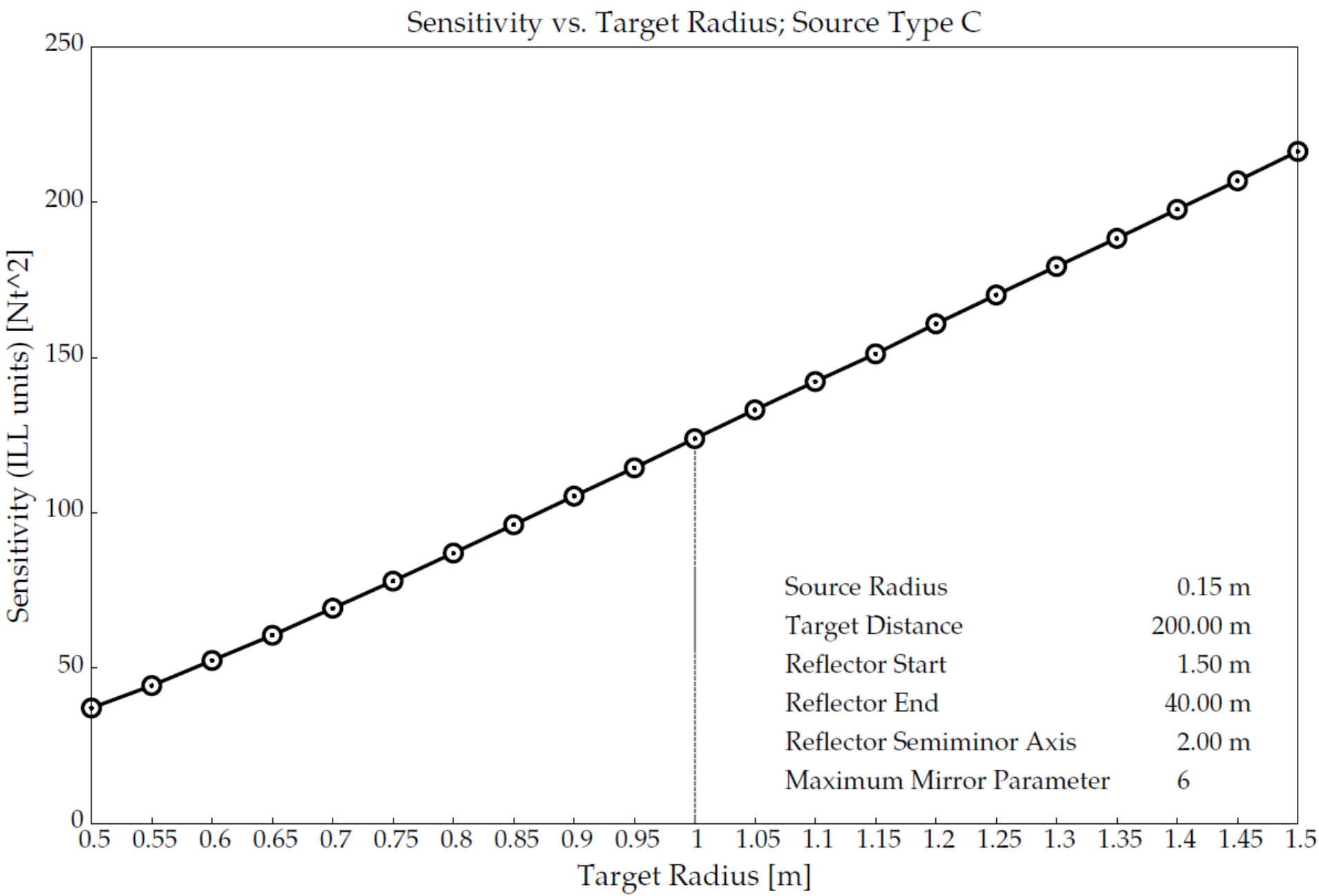
(H. Shimizu, 2012)

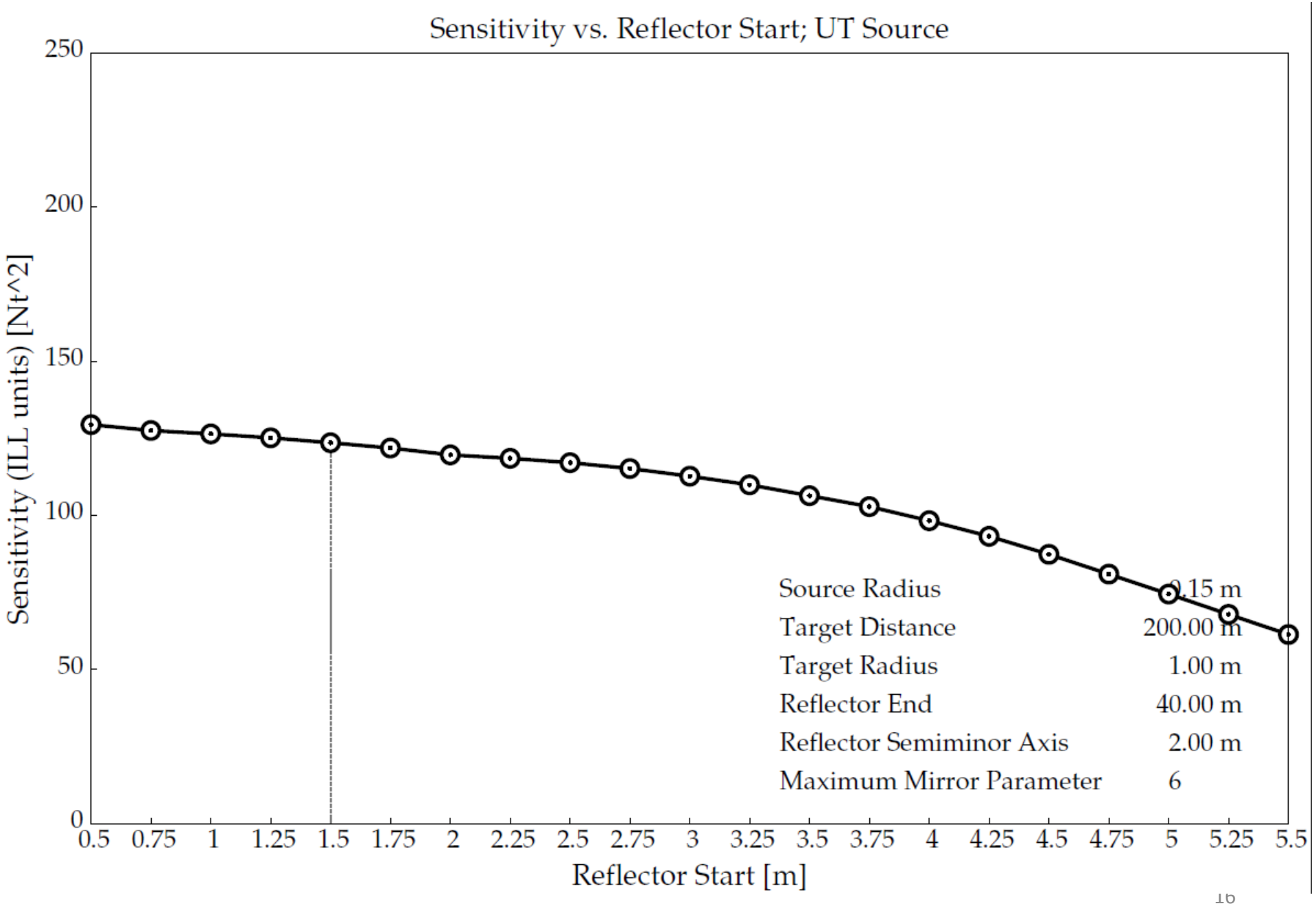


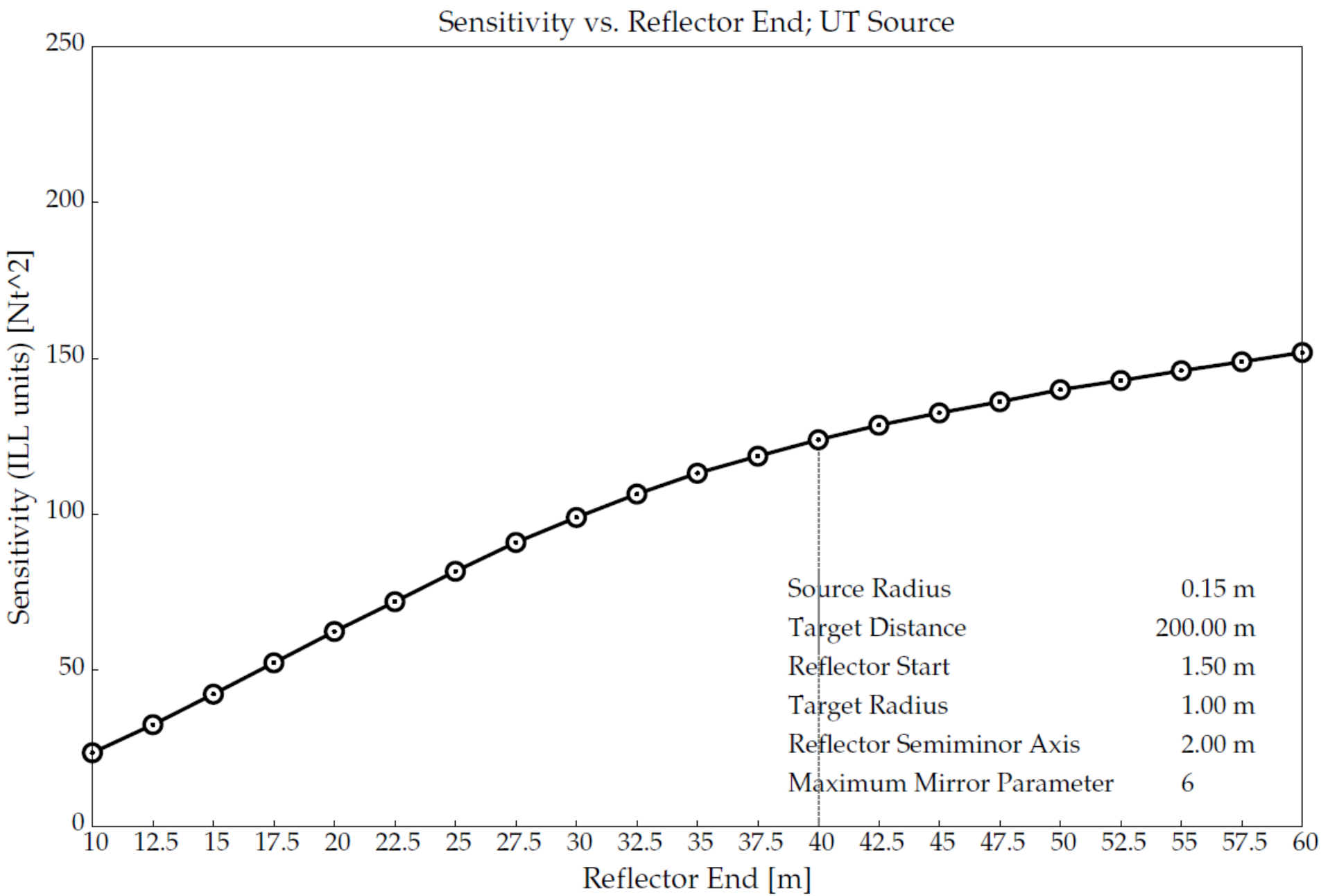
Chris Coppola

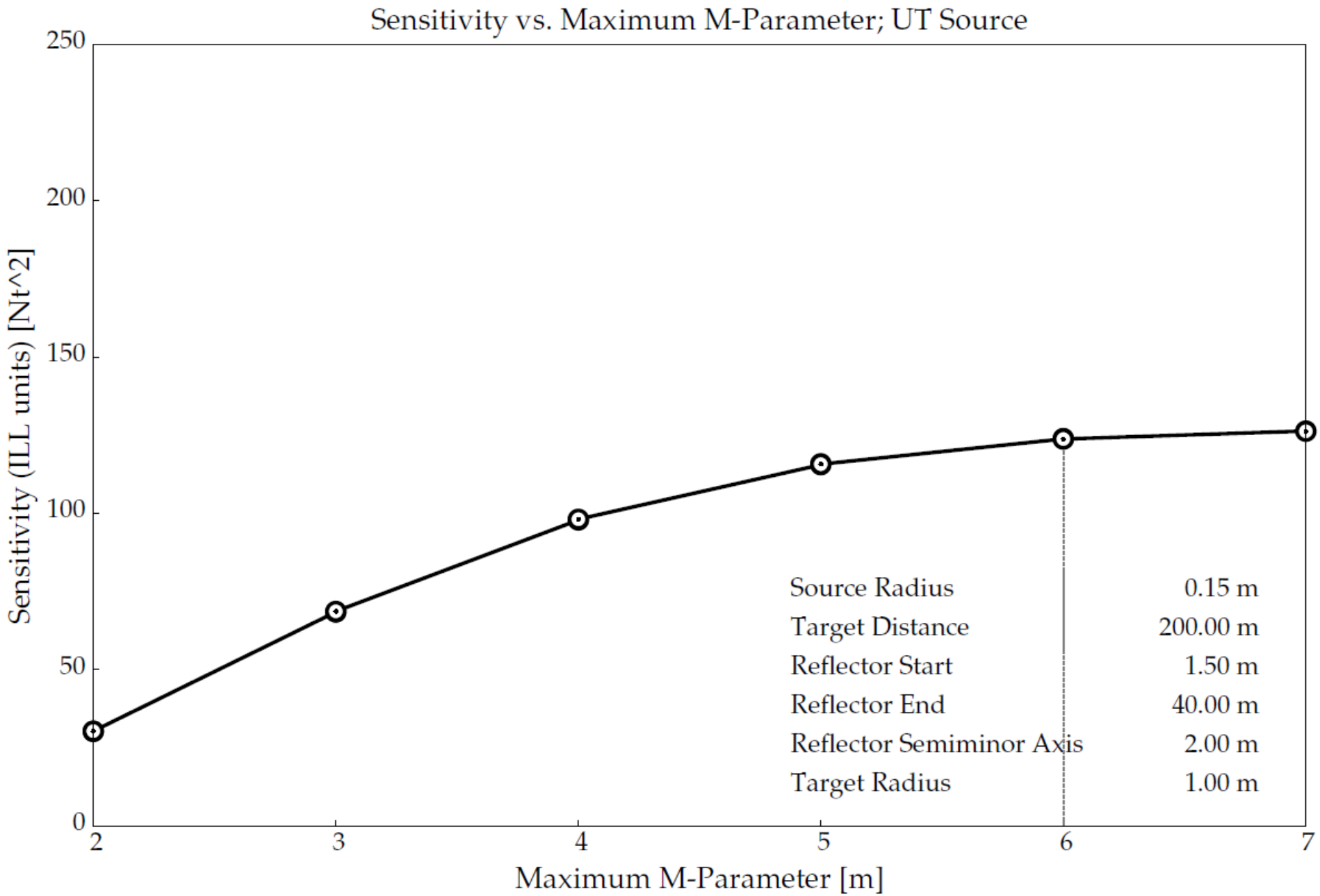

Sensitivity vs. Semiminor Axis; UT Source
Sensitivity (ILL units) [Nt^2]
Semiminor Axis [m]
0
50
100
150
200
250
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3
Source Radius 0.15 m
Target Distance 200.00 m
Reflector Start 1.50 m
Reflector End 40.00 m
Target Radius 1.00 m
Maximum Mirror Parameter 6

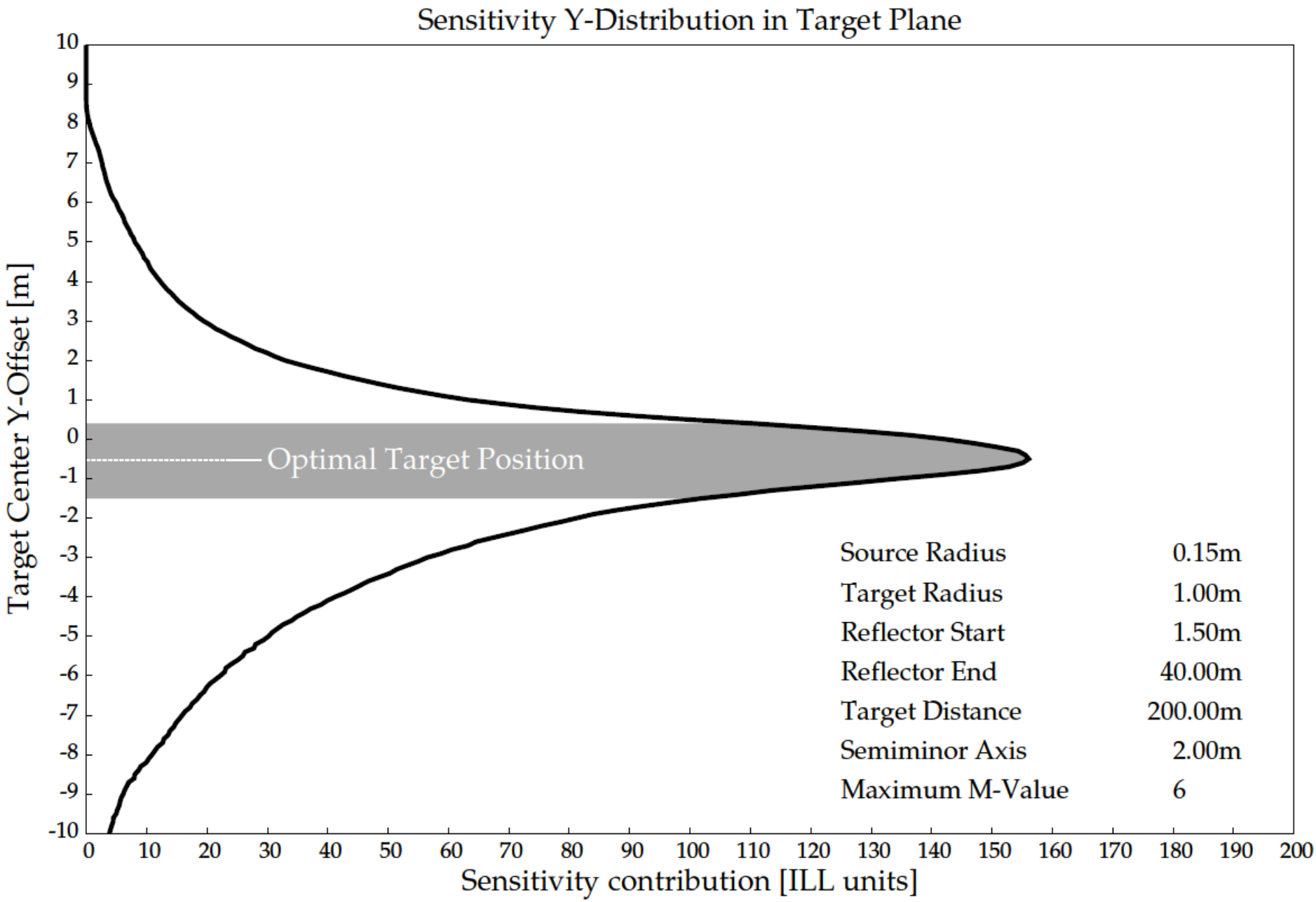

Sensitivity vs. Source Radius; UT Source
Sensitivity (ILL units) [Nt^2]
Source Radius [m]
0
50
100
150
200
250
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0.21
0.22
0.23
0.24
0.25
Target Radius 1.00 m
Target Distance 200.00 m
Reflector Start 1.50 m
Reflector End 40.00 m
Reflector Semiminor Axis 2.00 m
Maximum Mirror Parameter 6

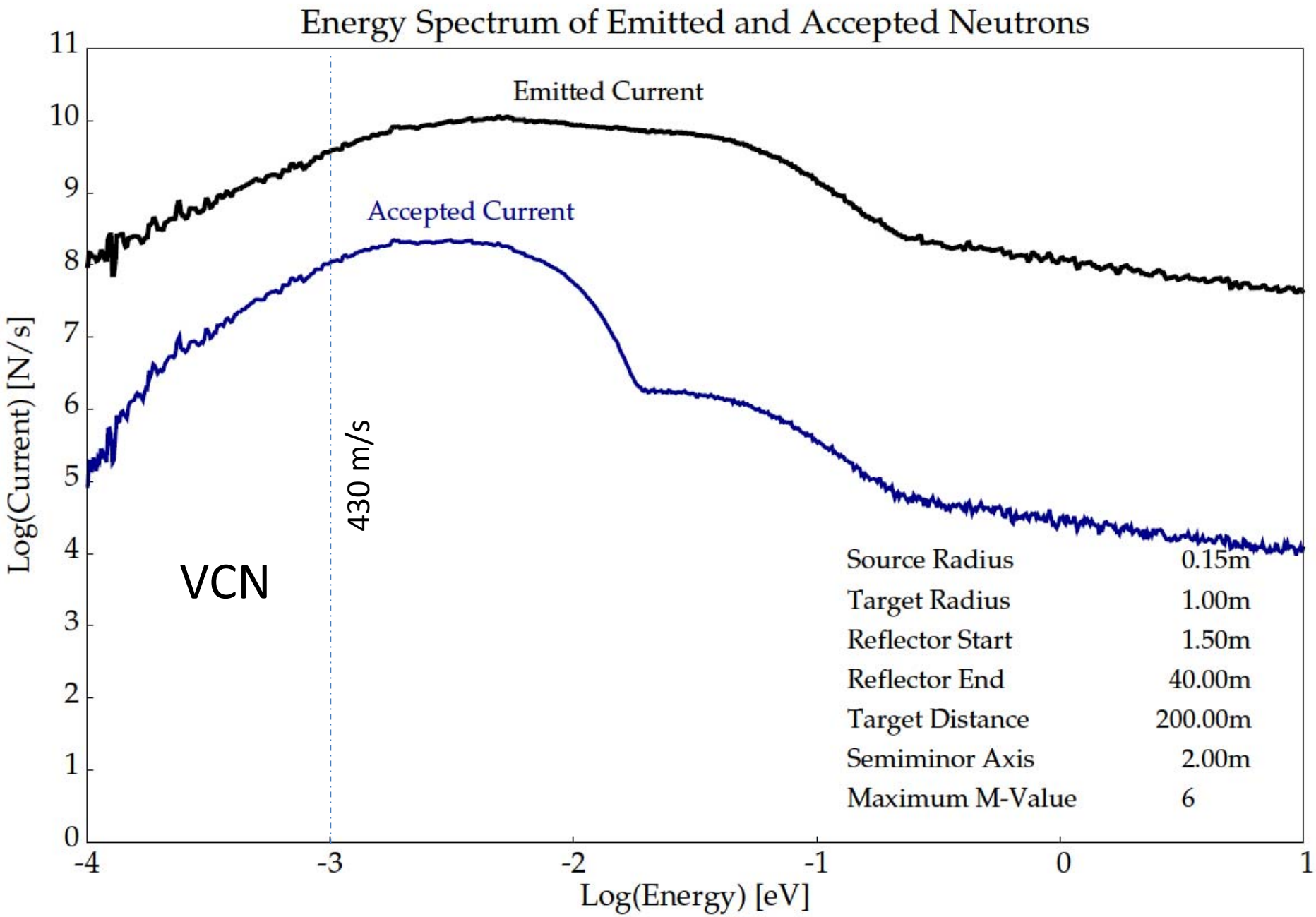

Sensitivity vs. Target Radius; Source Type C
Sensitivity (ILL units) [Nt^2]
Target Radius [m]
0
50
100
150
200
250
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5
Source Radius 0.15 m
Target Distance 200.00 m
Reflector Start 1.50 m
Reflector End 40.00 m
Reflector Semiminor Axis 2.00 m
Maximum Mirror Parameter 6

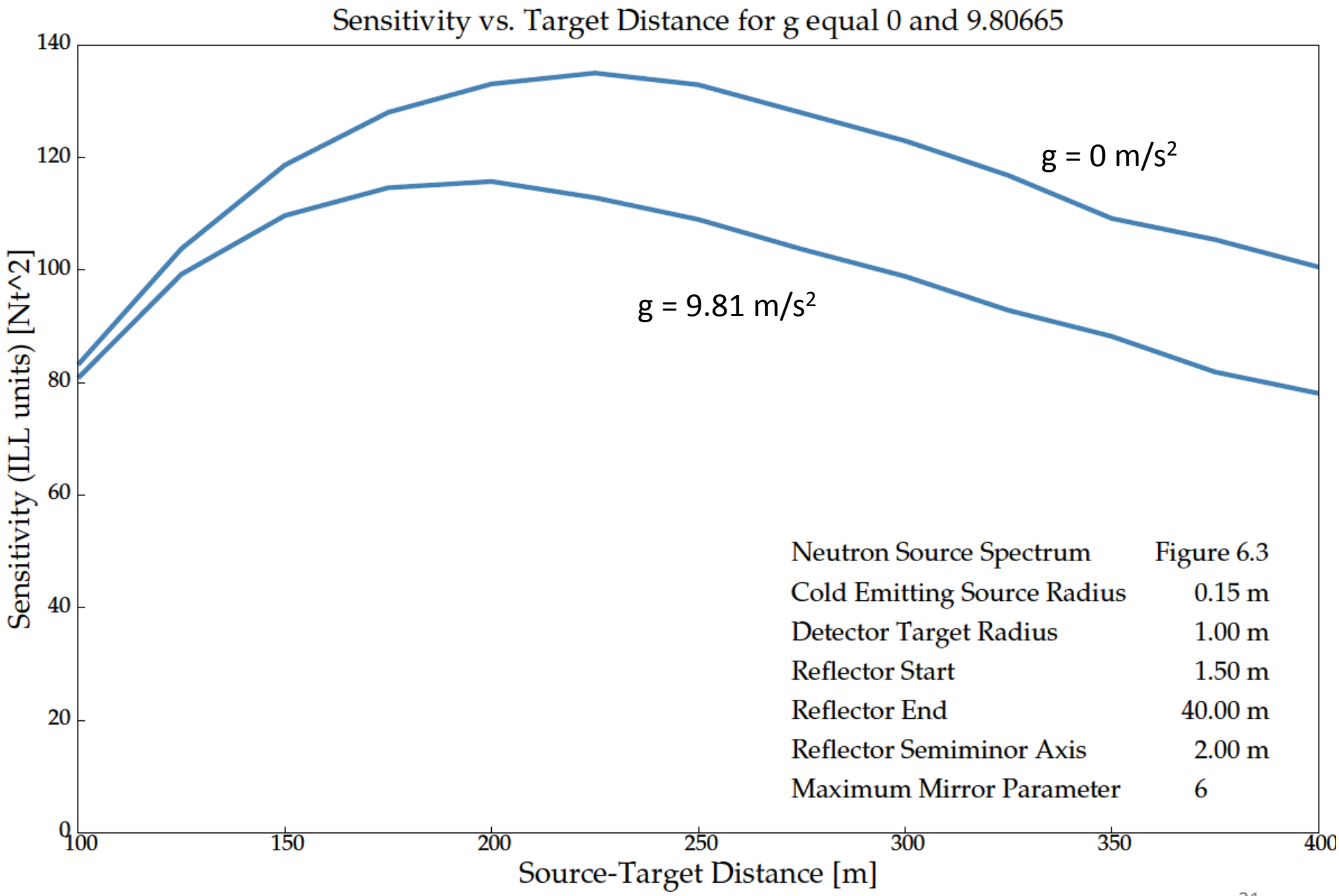

Sensitivity vs. Reflector Start; UT Source
Sensitivity (ILL units) [Nt^2]
250
200
150
100
50
0
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
3.5
3.75
4
4.25
4.5
4.75
5
5.25
5.5
Reflector Start [m]
Source Radius 0.15 m
Target Distance 200.00 m
Target Radius 1.00 m
Reflector End 40.00 m
Reflector Semiminor Axis 2.00 m
Maximum Mirror Parameter 6


Sensitivity vs. Reflector End; UT Source
Sensitivity (ILL units) [Nt^2]
Reflector End [m]
0
50
100
150
200
250
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
37.5
40
42.5
45
47.5
50
52.5
55
57.5
60
Source Radius 0.15 m
Target Distance 200.00 m
Reflector Start 1.50 m
Target Radius 1.00 m
Reflector Semiminor Axis 2.00 m
Maximum Mirror Parameter 6


Sensitivity vs. Maximum M-Parameter; UT Source
Sensitivity (ILL units) [Nt^2]
Maximum M-Parameter [m]
0
50
100
150
200
250
2
3
4
5
6
7
Source Radius 0.15 m
Target Distance 200.00 m
Reflector Start 1.50 m
Reflector End 40.00 m
Reflector Semiminor Axis 2.00 m
Target Radius 1.00 m


Sensitivity Y-Distribution in Target Plane
Target Center Y-Offset [m]
Sensitivity contribution [ILL units]
Optimal Target Position
Source Radius 0.15m
Target Radius 1.00m
Reflector Start 1.50m
Reflector End 40.00m
Target Distance 200.00m
Semiminor Axis 2.00m
Maximum M-Value 6

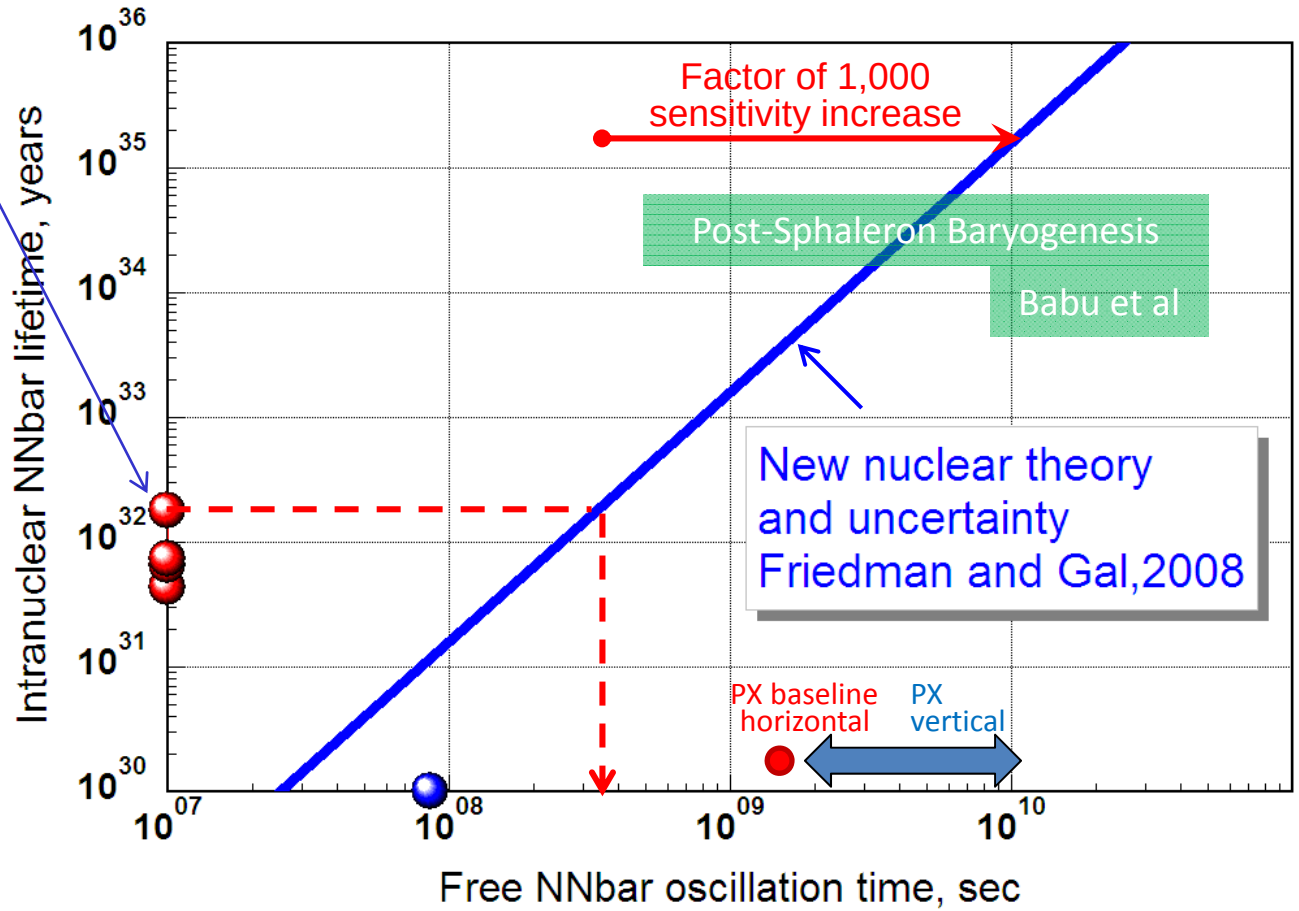

Energy Spectrum of Emitted and Accepted Neutrons
Emitted Current
Accepted Current
430 m/s
VCN
Source Radius 0.15m
Target Radius 1.00m
Reflector Start 1.50m
Reflector End 40.00m
Target Distance 200.00m
Semiminor Axis 2.00m
Maximum M-Value 6
Log(Current) [N/s]
Log(Energy) [eV]
11
10
9
8
7
6
5
4
3
2
1
0
-4
-3
-2
-1
0
1


Sensitivity vs. Target Distance for g equal 0 and 9.80665
Sensitivity (ILL units) [Nt^2]
Source-Target Distance [m]
0
20
40
60
80
100
120
140
100
150
200
250
300
350
400
g = 0 m/s²
g = 9.81 m/s²
Neutron Source Spectrum Figure 6.3
Cold Emitting Source Radius 0.15 m
Detector Target Radius 1.00 m
Reflector Start 1.50 m
Reflector End 40.00 m
Reflector Semiminor Axis 2.00 m
Maximum Mirror Parameter 6

Free Neutron and Bound Neutrons NNbar Search Limits Comparison

Large improvement with free-neutron experiments is possible

Recent S-K (2011) limit based on 24 candidates and 24.1 bkgr.



Nuclear Instruments and Methods in Physics Research A 595 (2008) 631–636

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The reflection of very cold neutrons from diamond powder nanoparticles

V.V. Nesvizhevsky [a,*], E.V. Lychagin [b], A.Yu. Muzychka [b], A.V. Strelkov [b], G. Pignol [c], K.V. Protasov [c]

[a] Institute Laue-Langevin, 6 rue Jules Horowitz, F-38042 Grenoble, France
[b] Joint Institute for Nuclear Research, 141980 Dubna, Russia
[c] LPSC, UJF-CNRS/IN2P3-INPG, 53 rue des Martyrs, F-38026 Grenoble, France

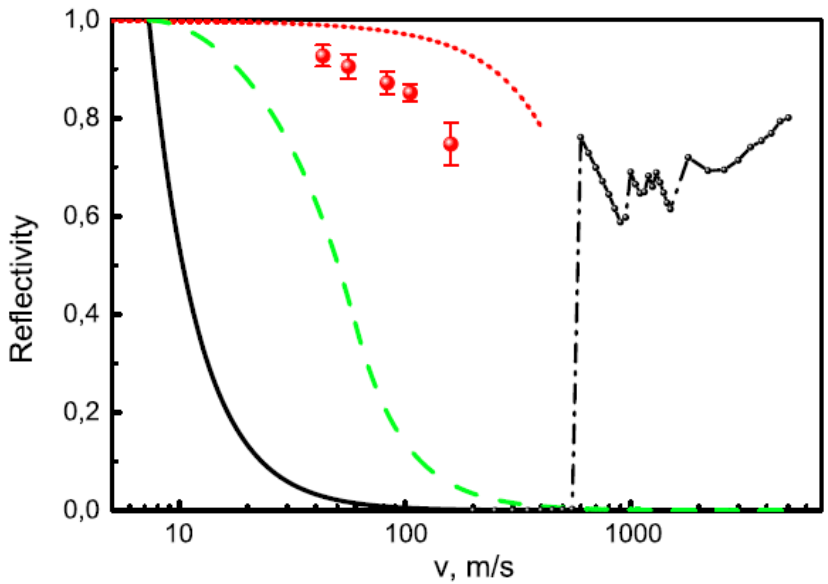
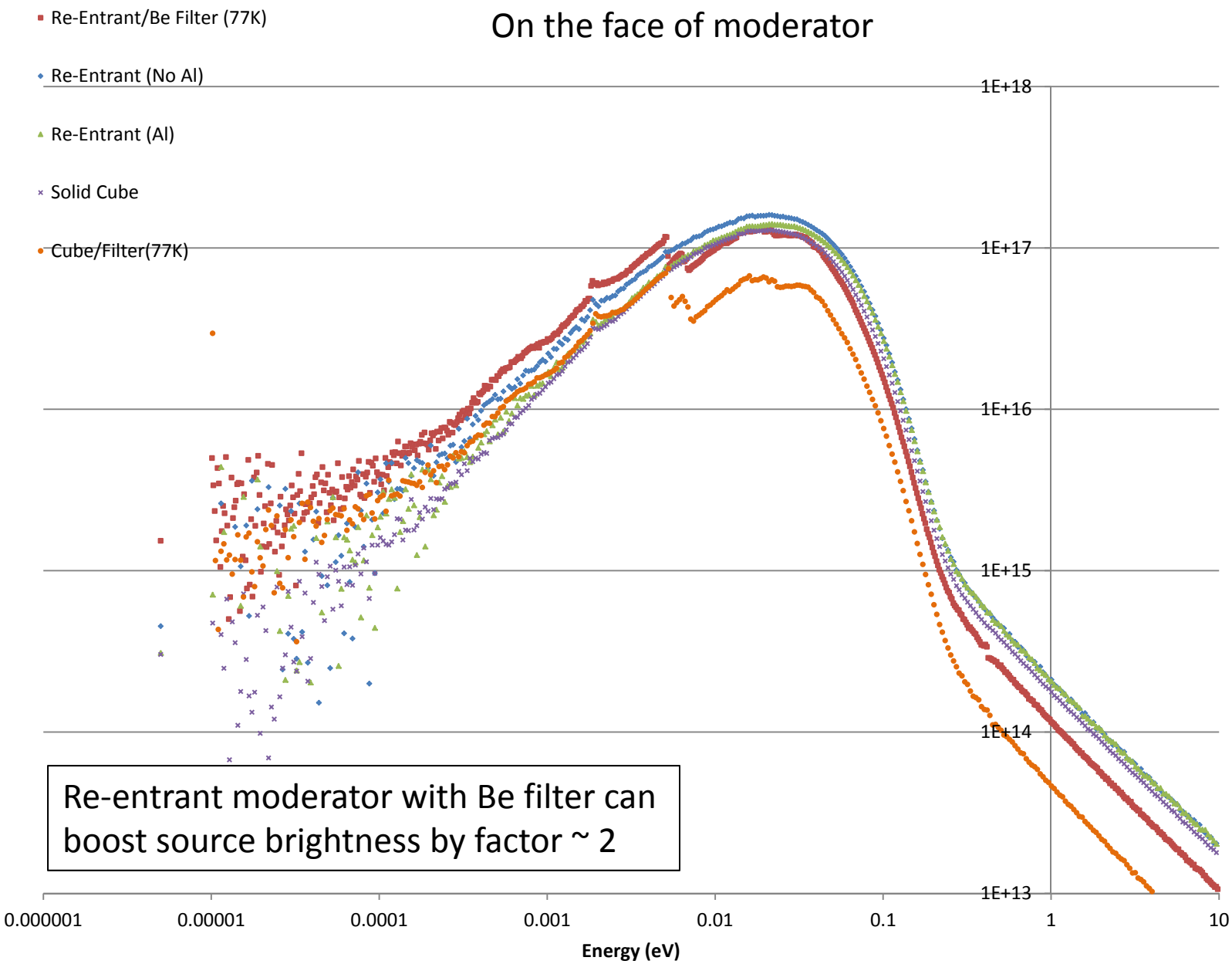


Fig. 9. The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror [16] (dashed line), (3) Hydrogen-free ultradiamond [15] powder with the infinite thickness (dotted line). Calculation. (4) VCN reflection from 3 cm thick diamond nanopowder at ambient temperature (points), with significant hydrogen contamination [this Letter]. Experiment. (5) MCNP calculation for reactor graphite reflector [2] with the infinite thickness at ambient temperature.

On the face of moderator



Re-entrant moderator with Be filter can boost source brightness by factor ~ 2

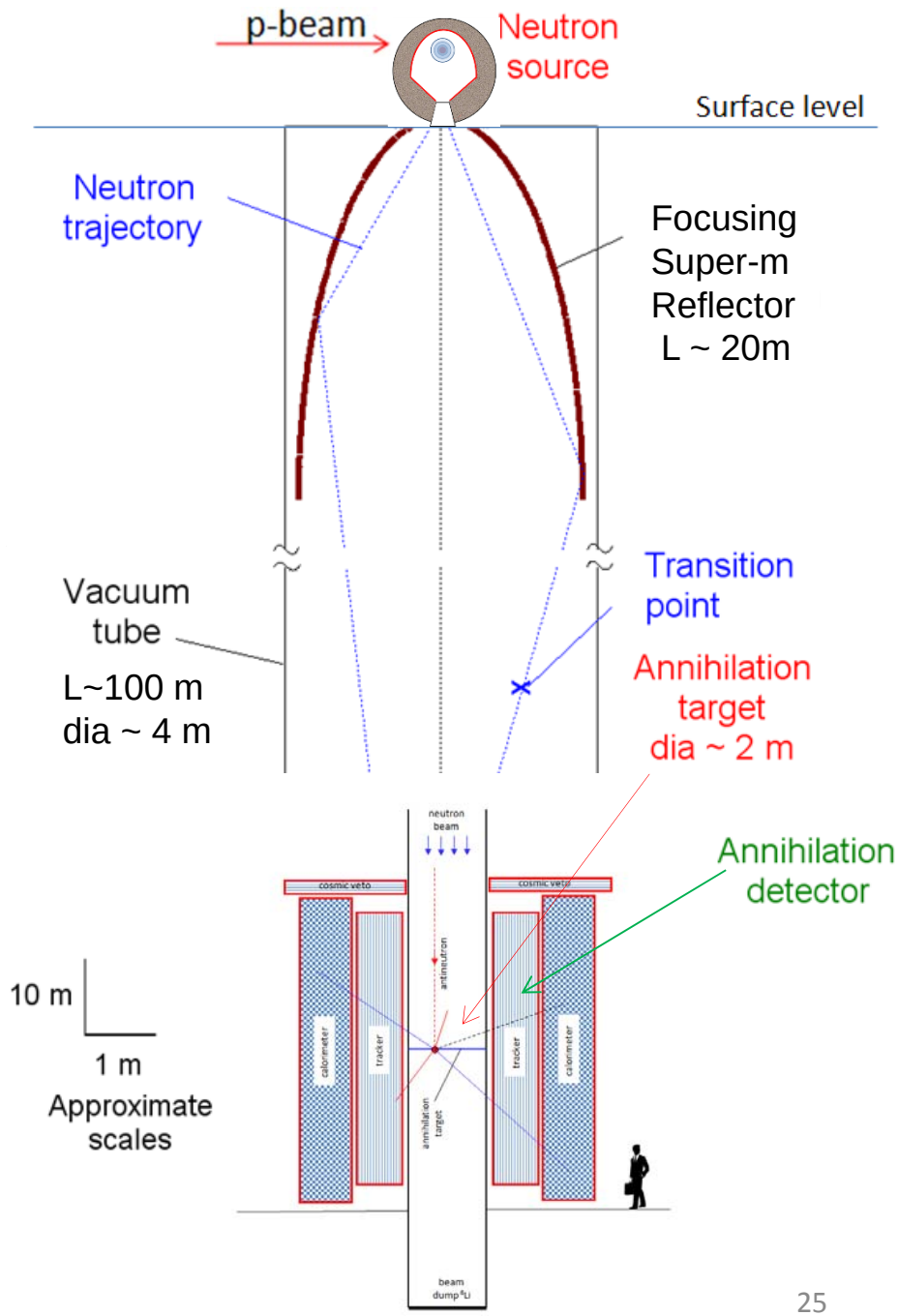
Example of Vertical layout

Vertical layout enables use of the whole cold spectrum incl.UCN

$$h = v_0 t + \frac{1}{2} g t^2$$

$$105\ \mathrm{m} = 100\ \mathrm{m/s} \cdot 1\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 1^2 \mathrm{s}^2$$

$$105\ \mathrm{m} = 10\ \mathrm{m/s} \cdot 3.7\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 3.7^2 \mathrm{s}^2$$



Fermilab Physics Advisory Committee Meeting
2012 October 15-17

Comments and Recommendations

The previous state-of-the-art experiment (at ILL, Grenoble) provided the current lower limit on the n-$\bar{n}$ oscillation time of about 10^8 s. An interesting increase of sensitivity is projected for NNbarX, by a factor of 20–30 for a first proposed phase with a horizontal detector layout. A second stage with a vertical layout could give a further factor of 100, corresponding to probing the oscillation time up to 10^{10} s. The vertical layout would be more challenging to construct, but would allow the use of very slow neutrons (which would suffer excessive gravitational deflection in a horizontal layout). The main improvements in sensitivity reportedly come from increase of the neutron flux delivered to the annihilation target, optimized with super-mirrors or diamond nanoparticle reflectors, and from extending the observation time through increased length of the vacuum vessel or the use of slower neutrons. A dedicated spallation source would be required at Project X, a challenging design with cryogenic moderator surrounding the solid metal target.

Sensitivity improvement development

- Fermilab PAC recommendation sets for horizontal option a "minimal sensitivity goal" of ~ 30 ILL units or $\tau_{free} \cong 5 \times 10^8$ s

- Our present baseline configuration should allow improvement by factor of ~ 350 ILL for 3 years of running or $\tau_{free} = 1.6 \times 10^9$ s

- With more R&D work and feasibility studies we will improve the sensitivity in our baseline (in either horizontal or vertical configuration)

End