Ultrafast Dynamics and Phase Changes in Highly Excited Semiconductors

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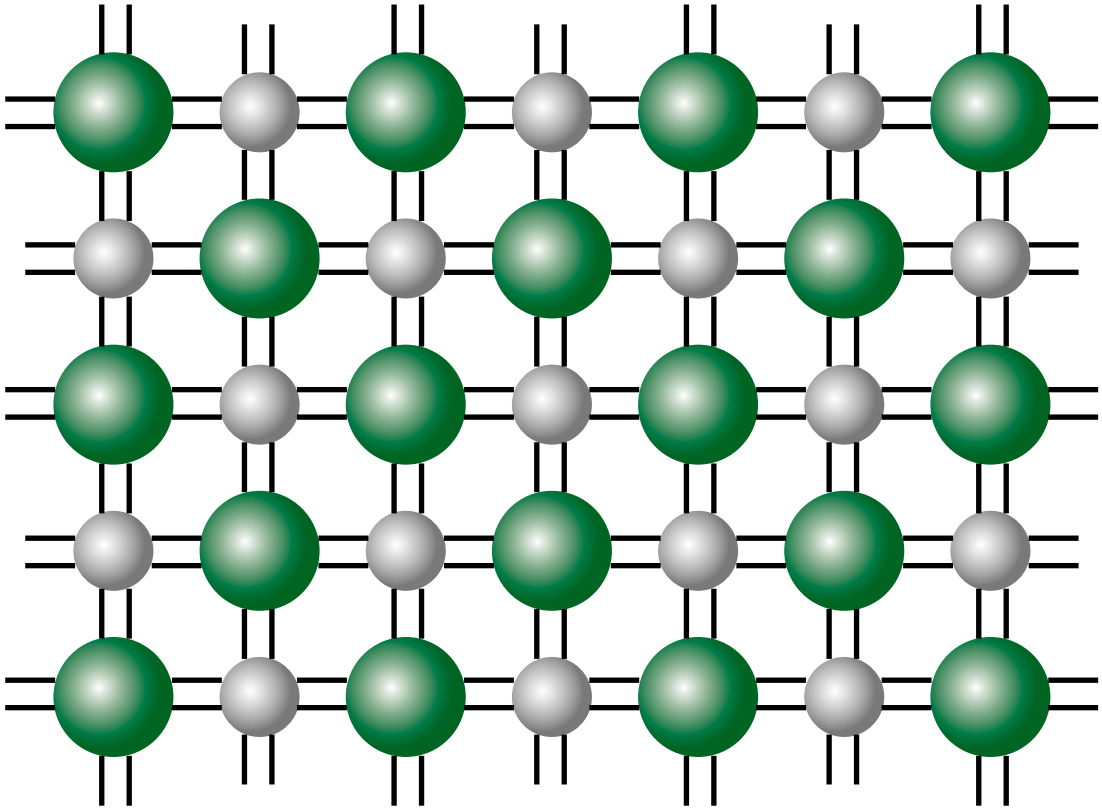
Albert Kim
Chris Roeser
Paul Callan

Photonics West 2001
25 January 2001

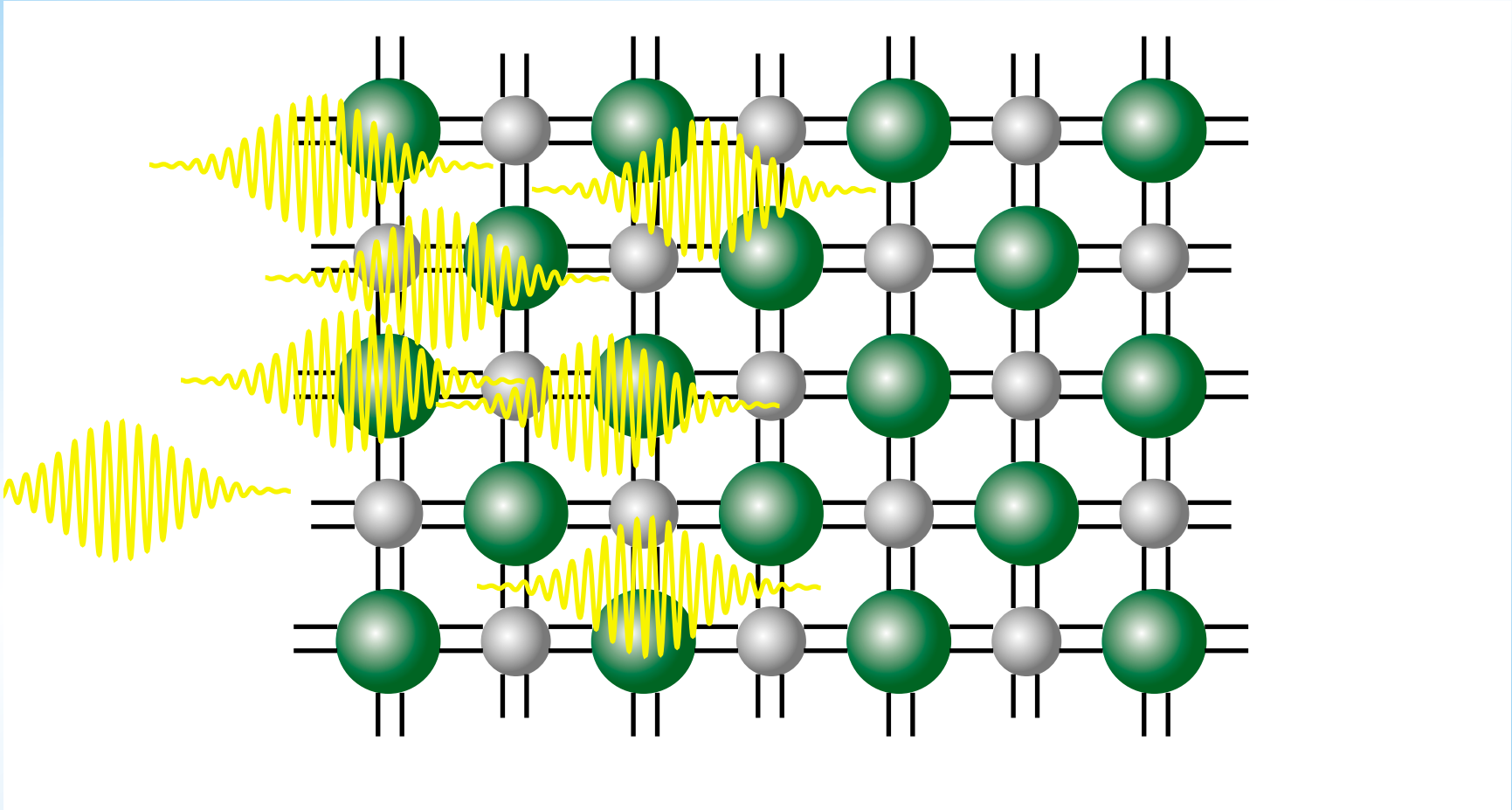
Introduction

how do femtosecond laser pulses alter a solid?



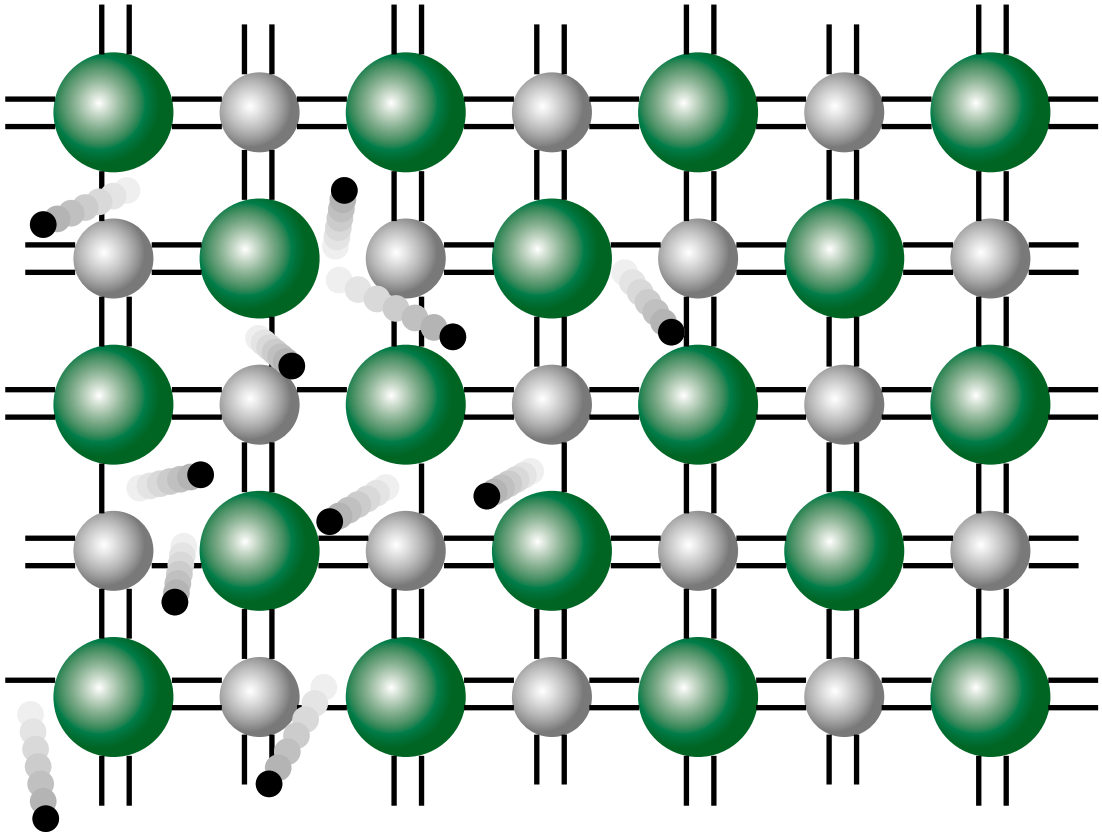
Introduction

photons excite valence electrons…



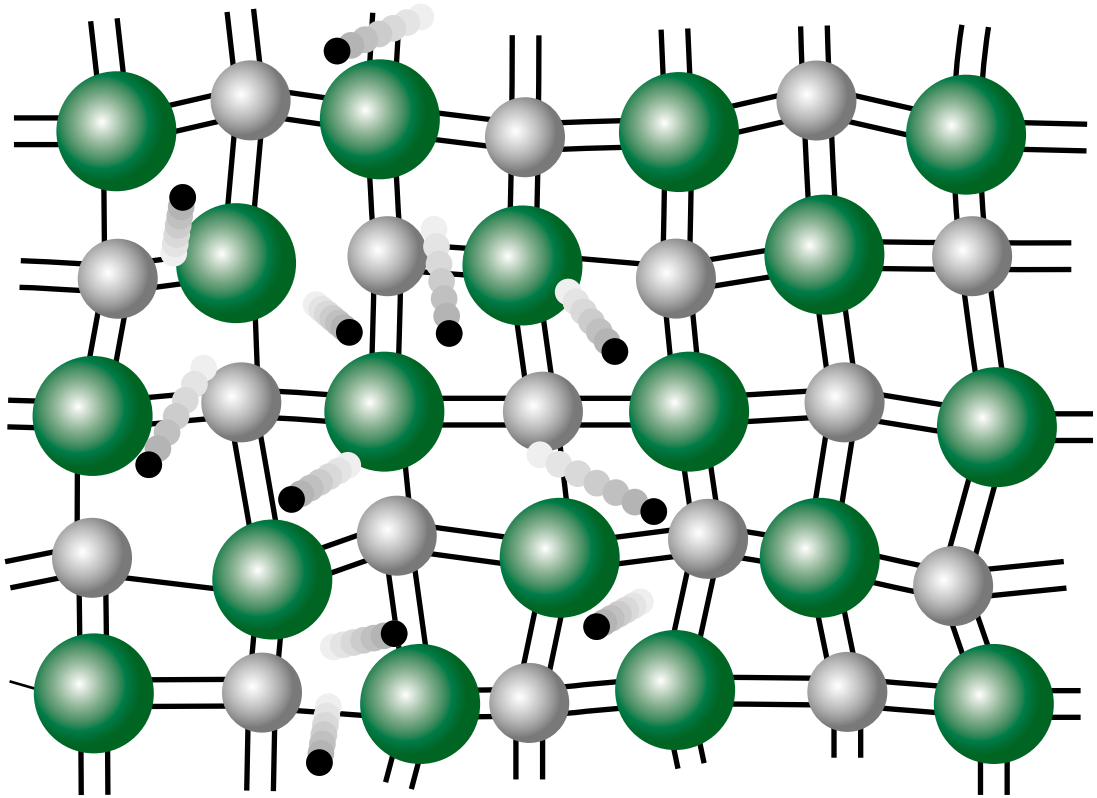
Introduction

...and create free electrons...



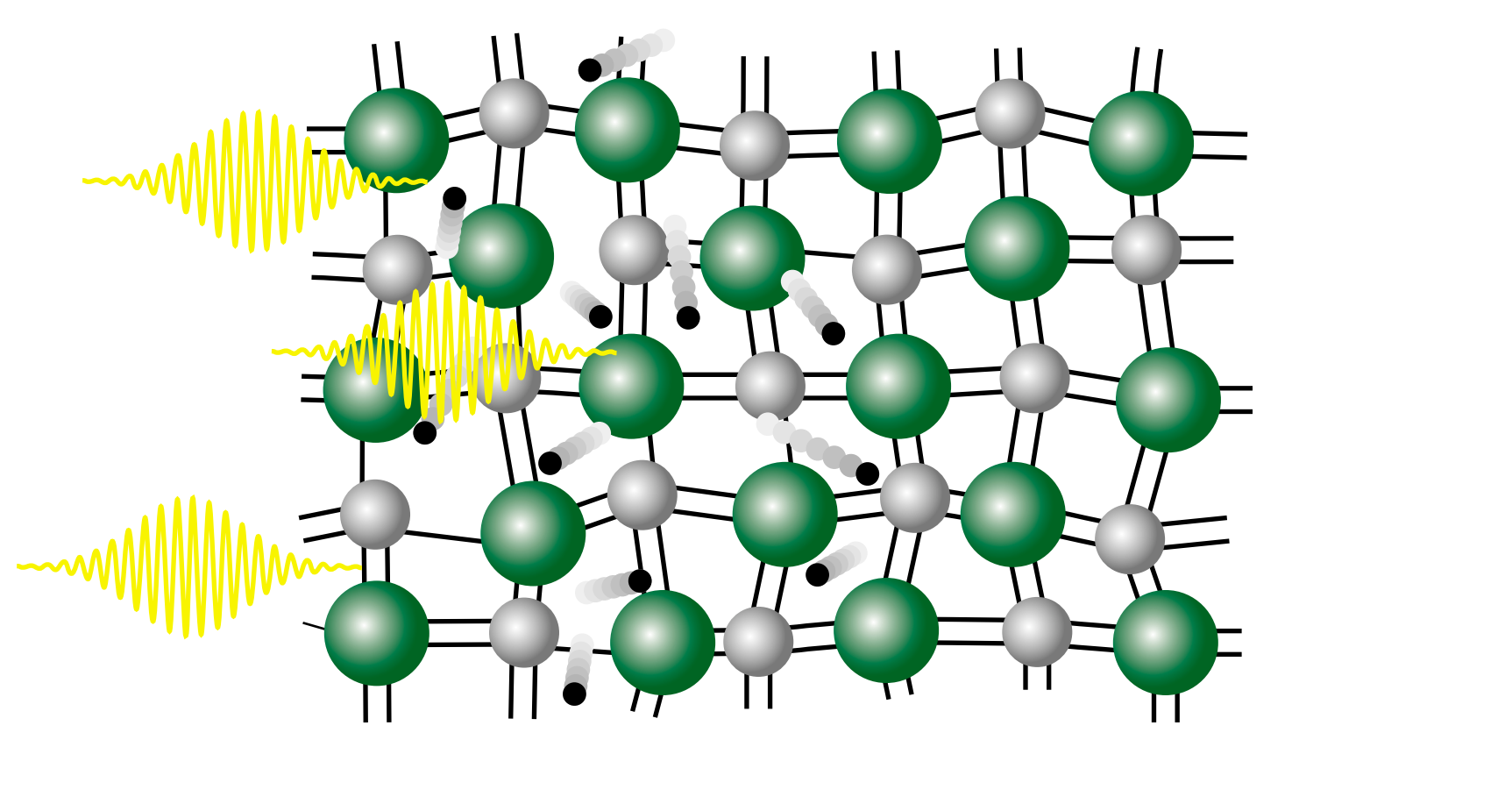
Introduction

…causing electronic and structural changes…



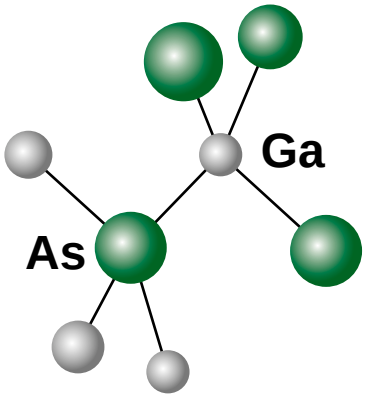
Introduction

…which we measure with another pulse



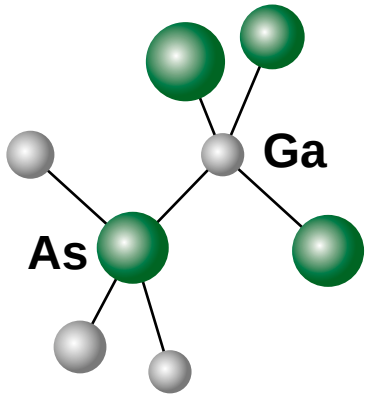
Introduction

structure

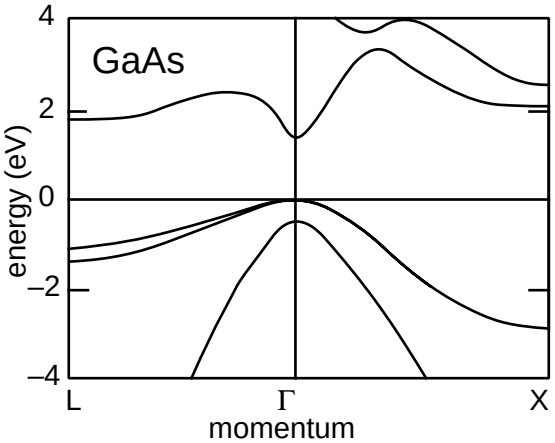


Introduction

structure

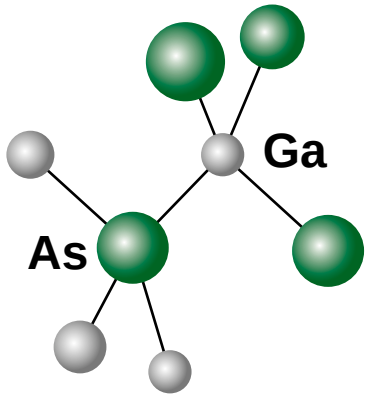


bandstructure

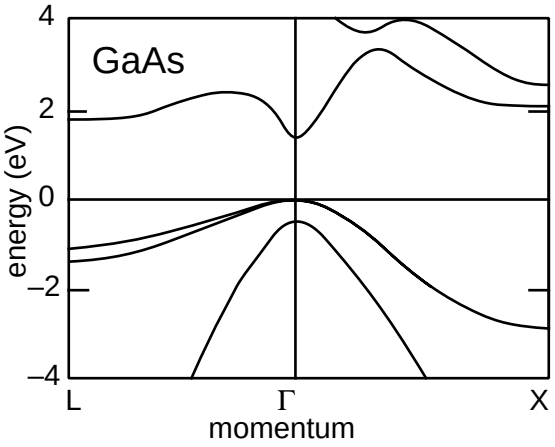


Introduction

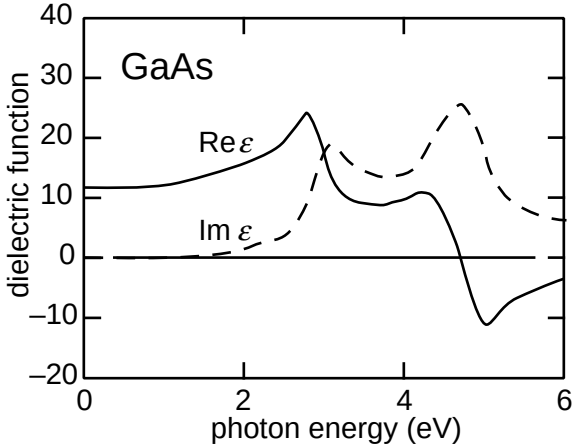
structure



bandstructure



dielectric function



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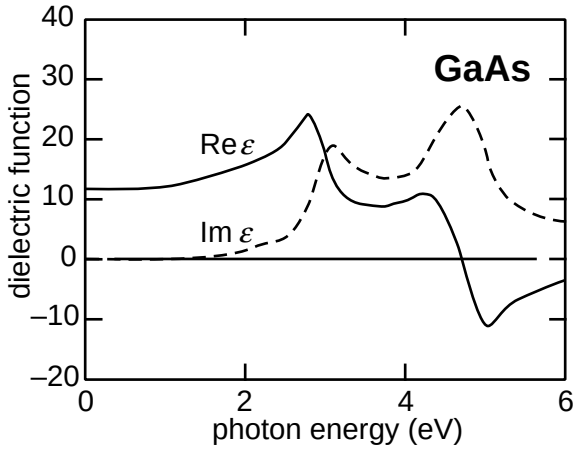
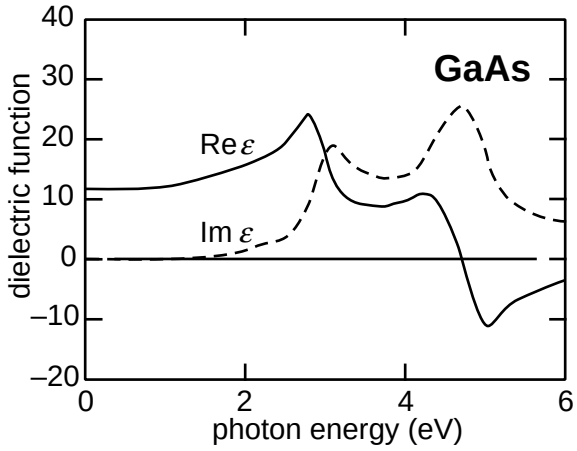
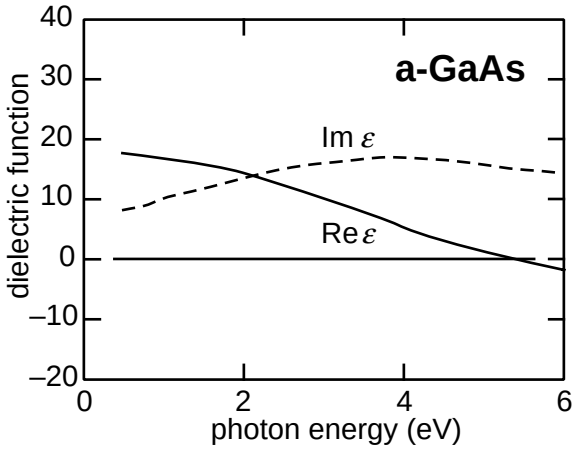


Introduction





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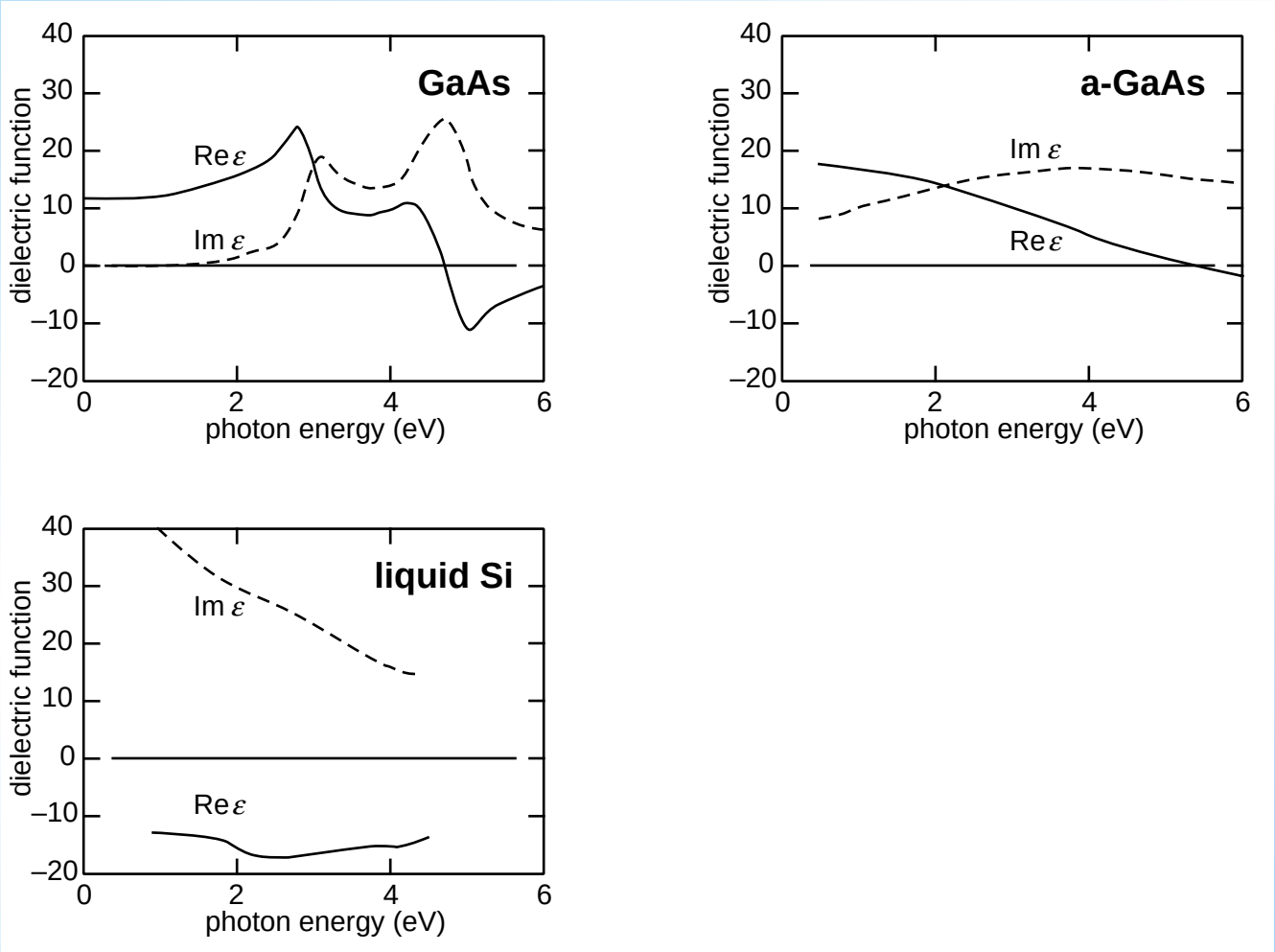

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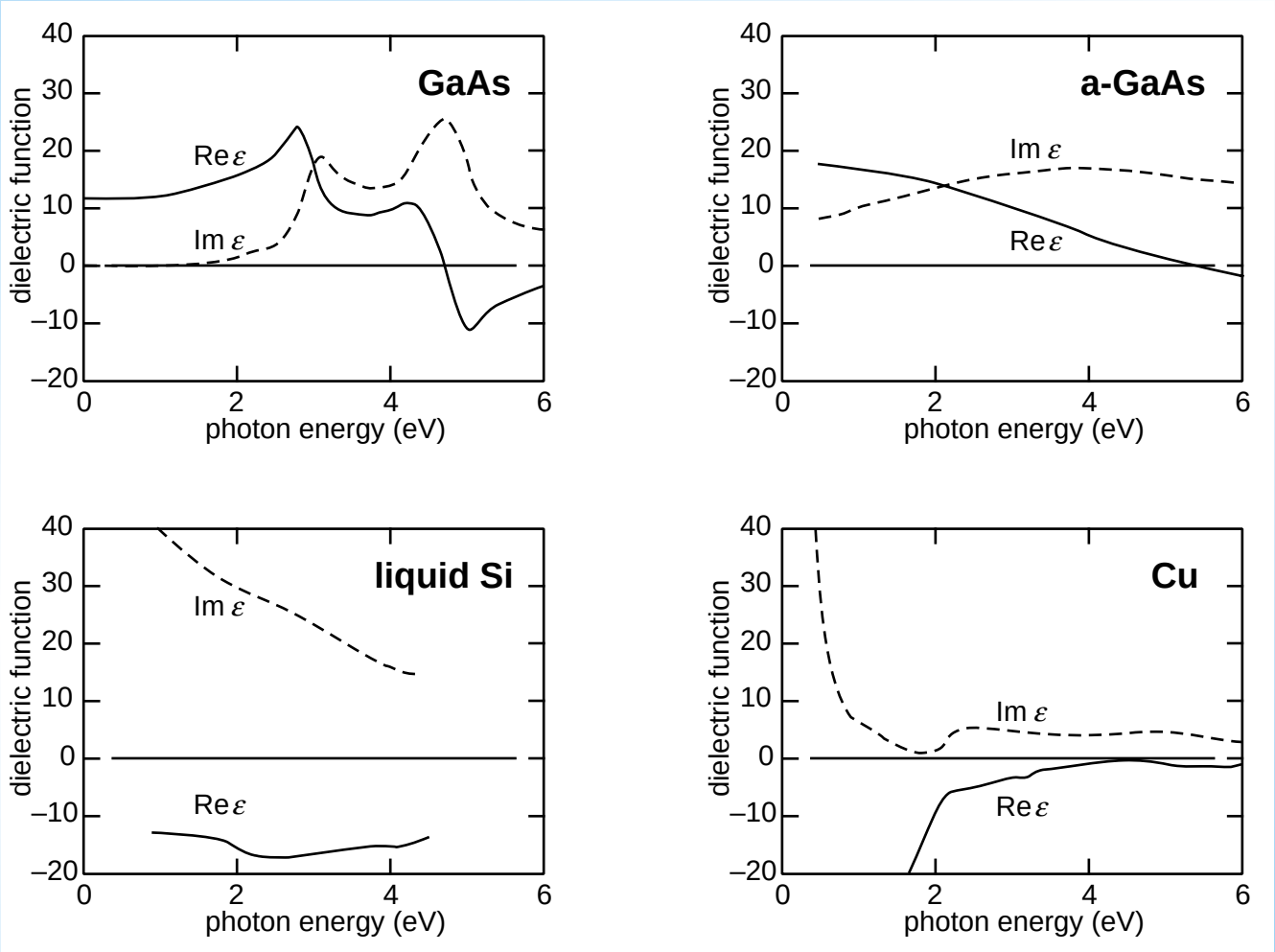

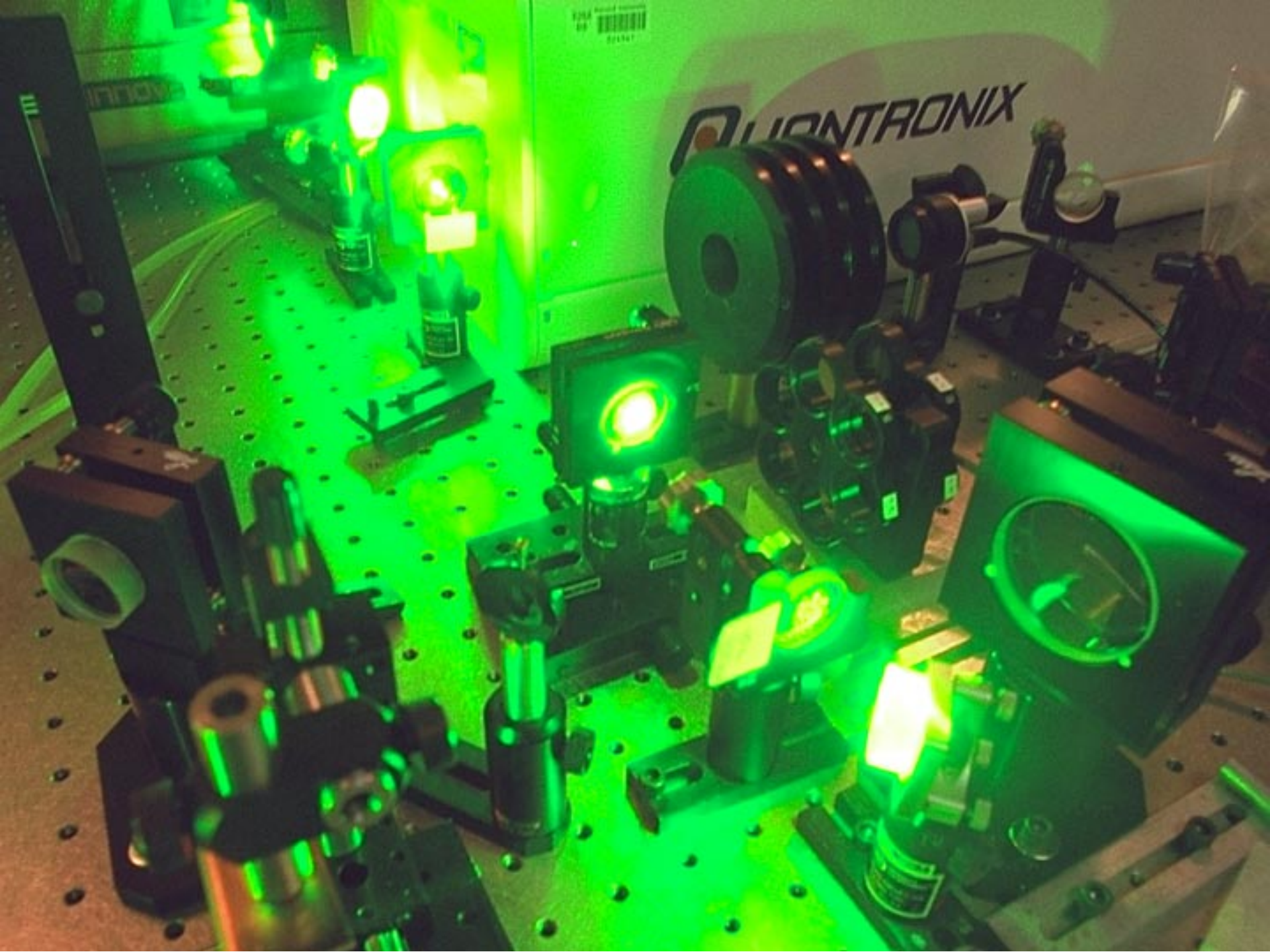
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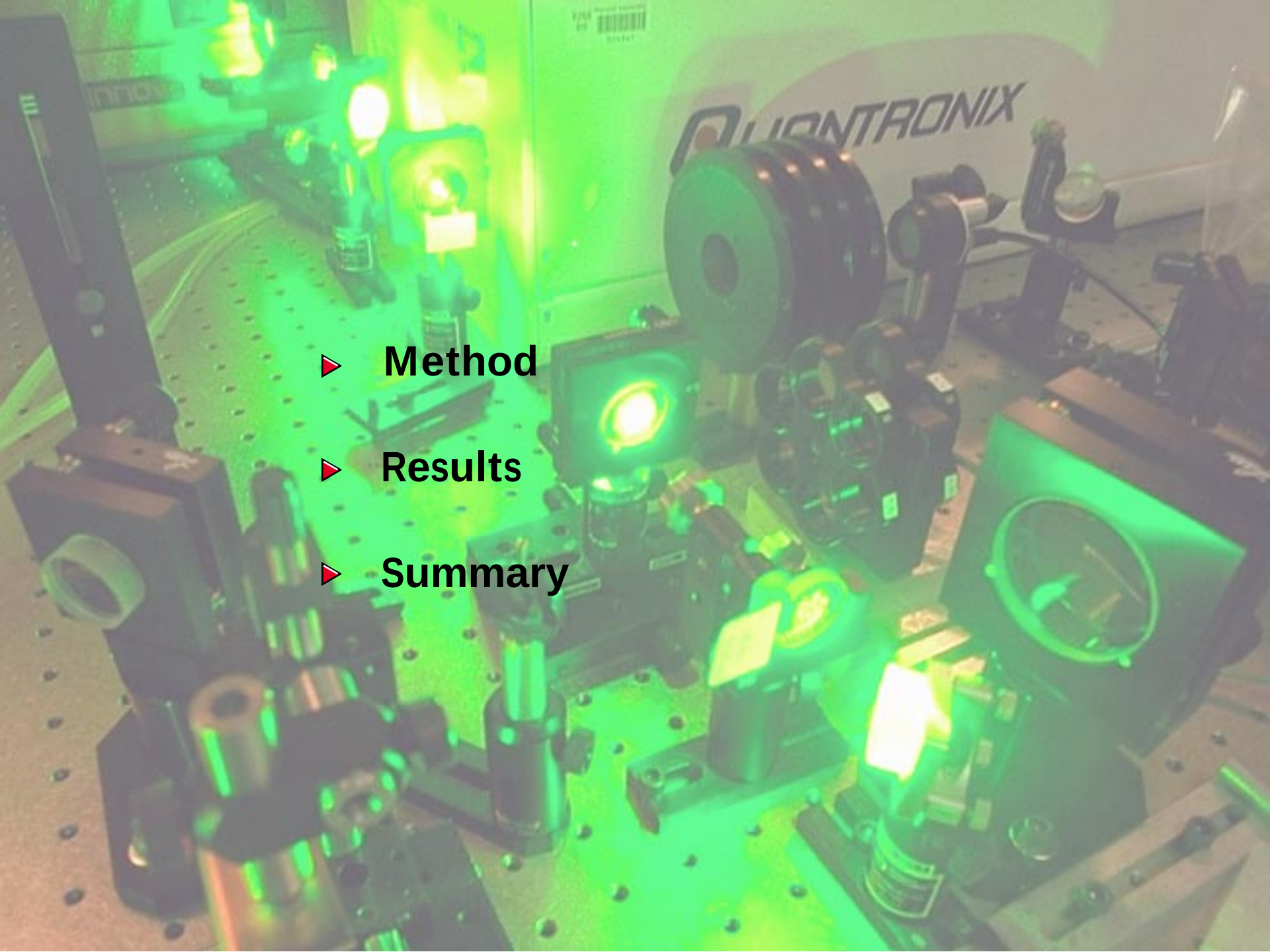
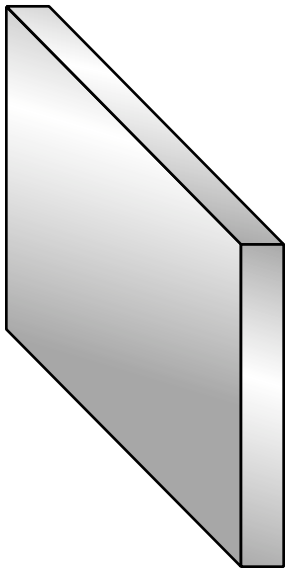


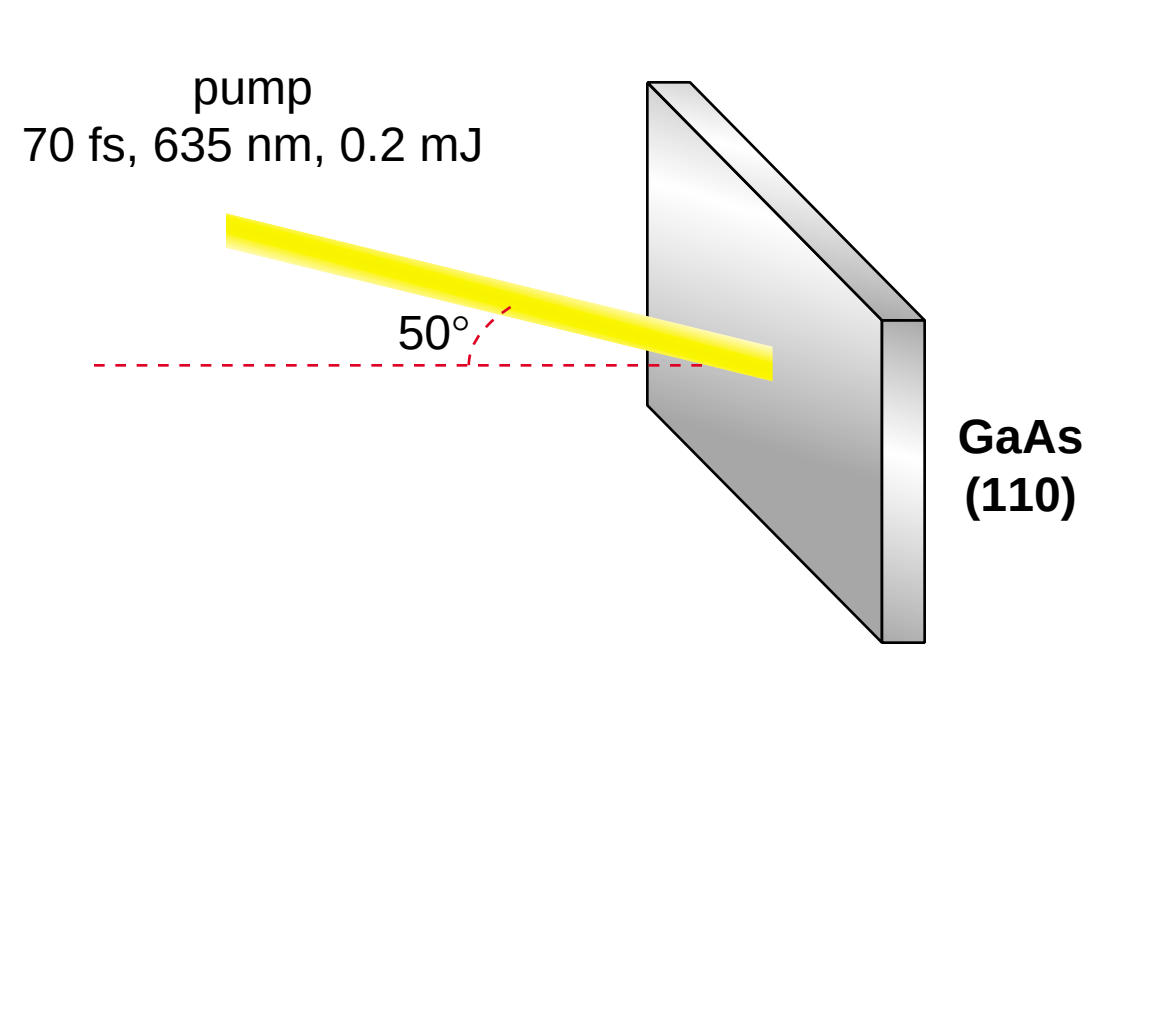
- Method
- Results
- Summary

Method



GaAs
(110)

Method



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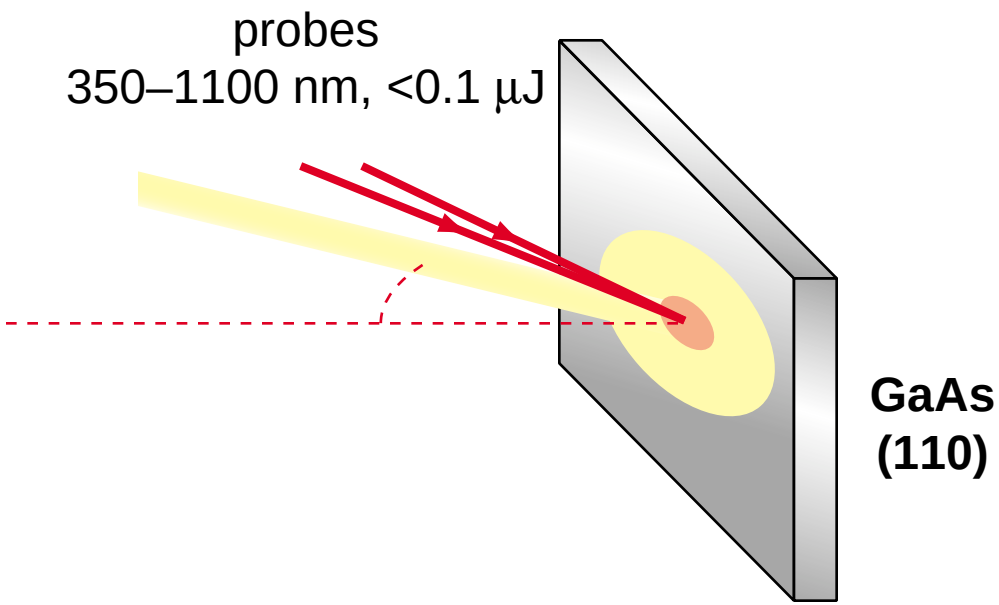

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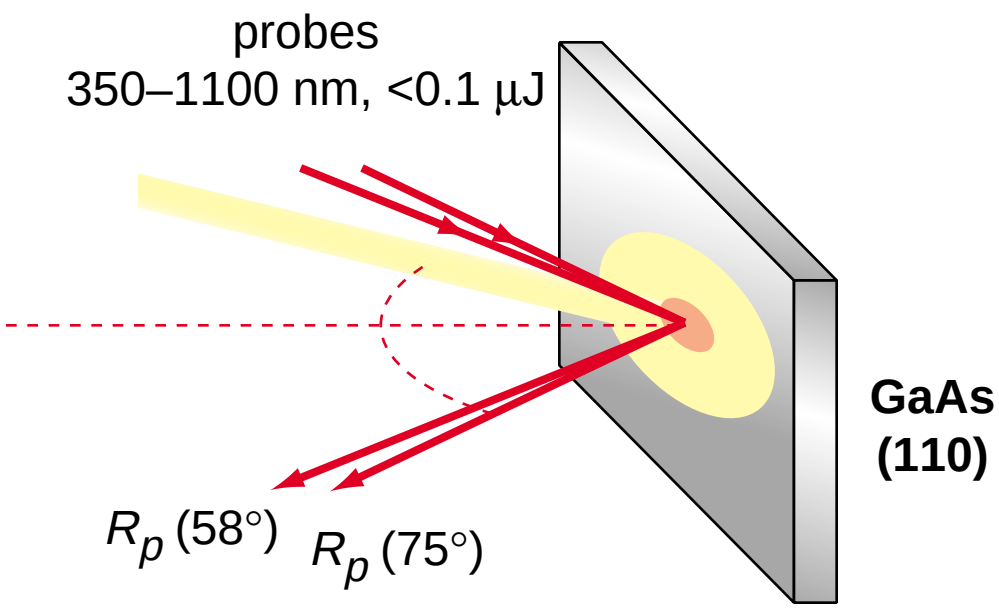
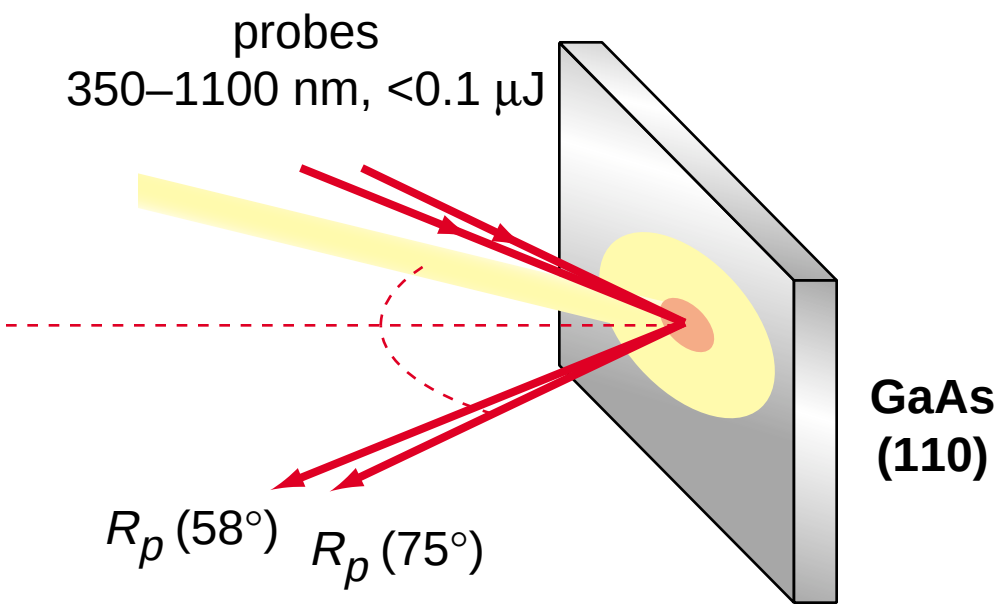
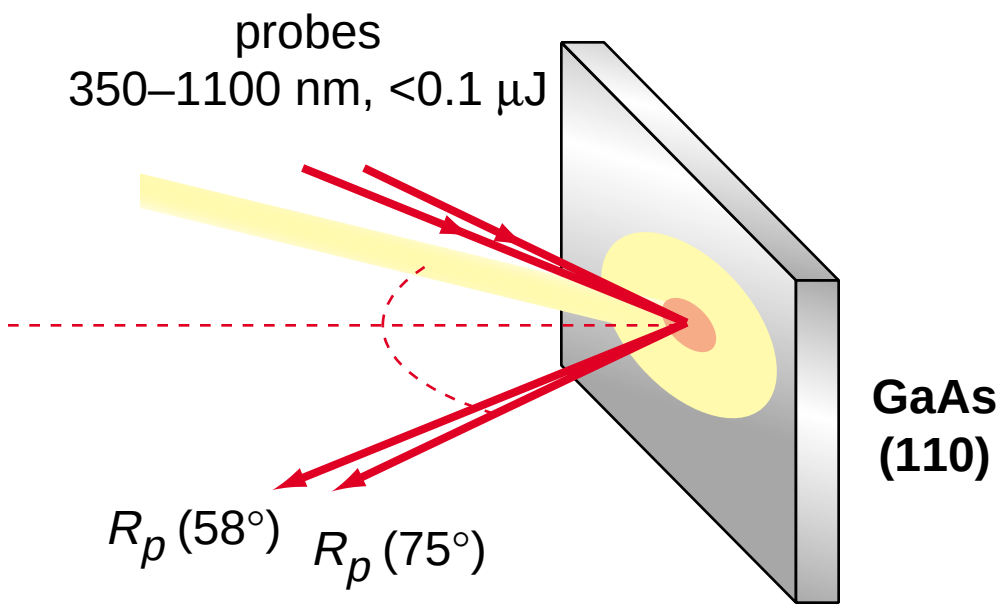


Method

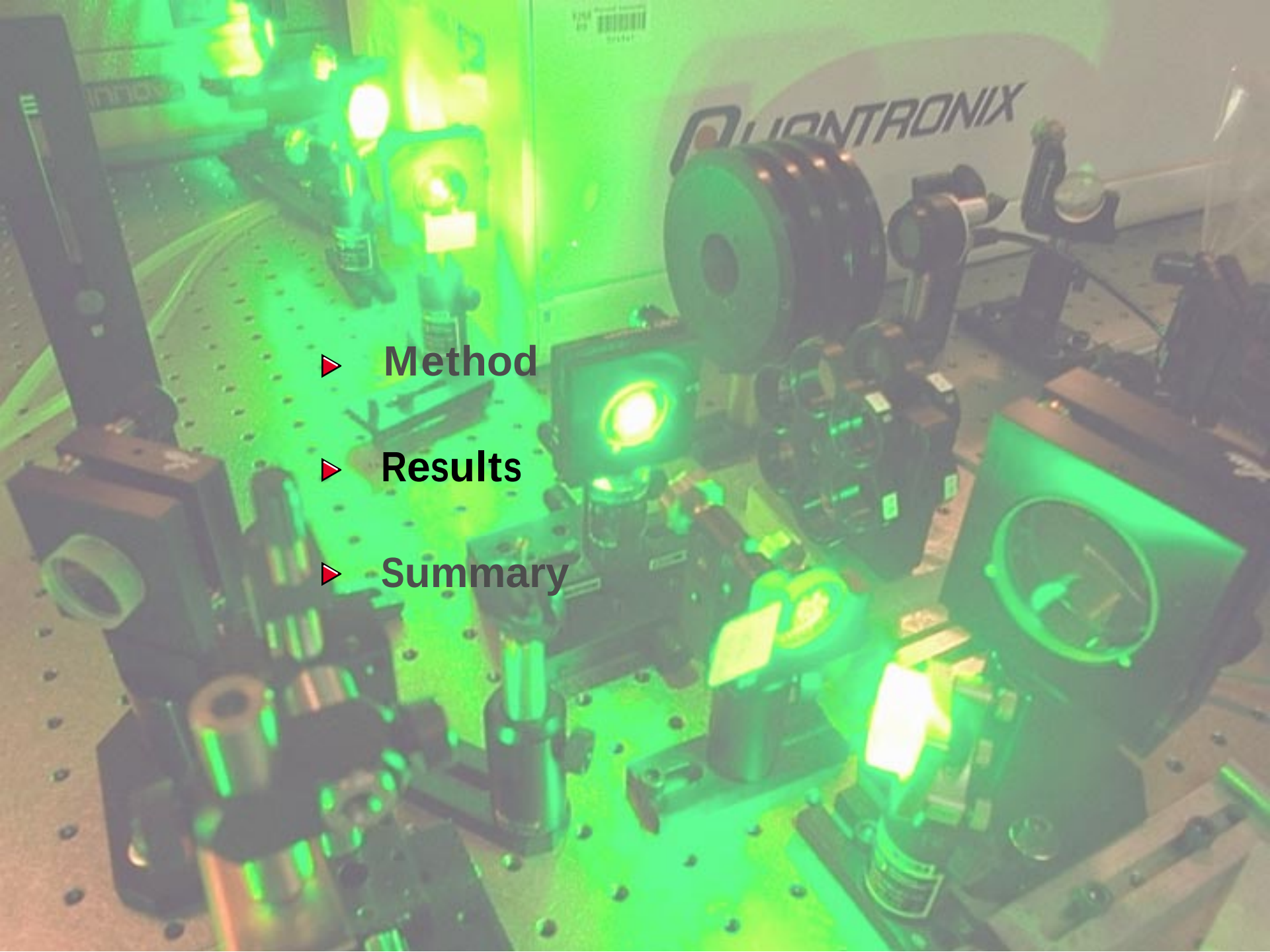


Fresnel
equations

Method



Fresnel equations → Re ε(ω), Im ε(ω)



- Method
- Results
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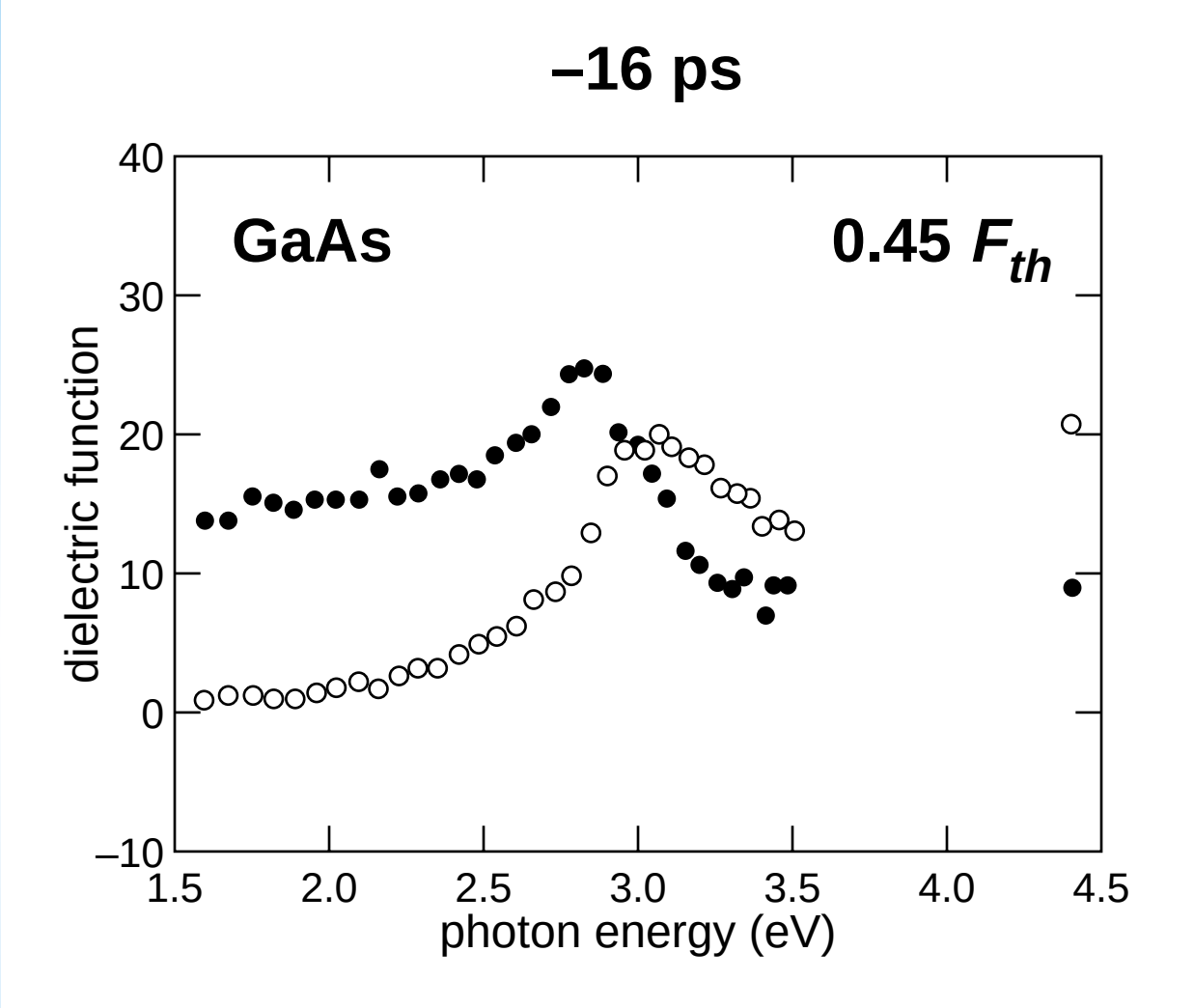
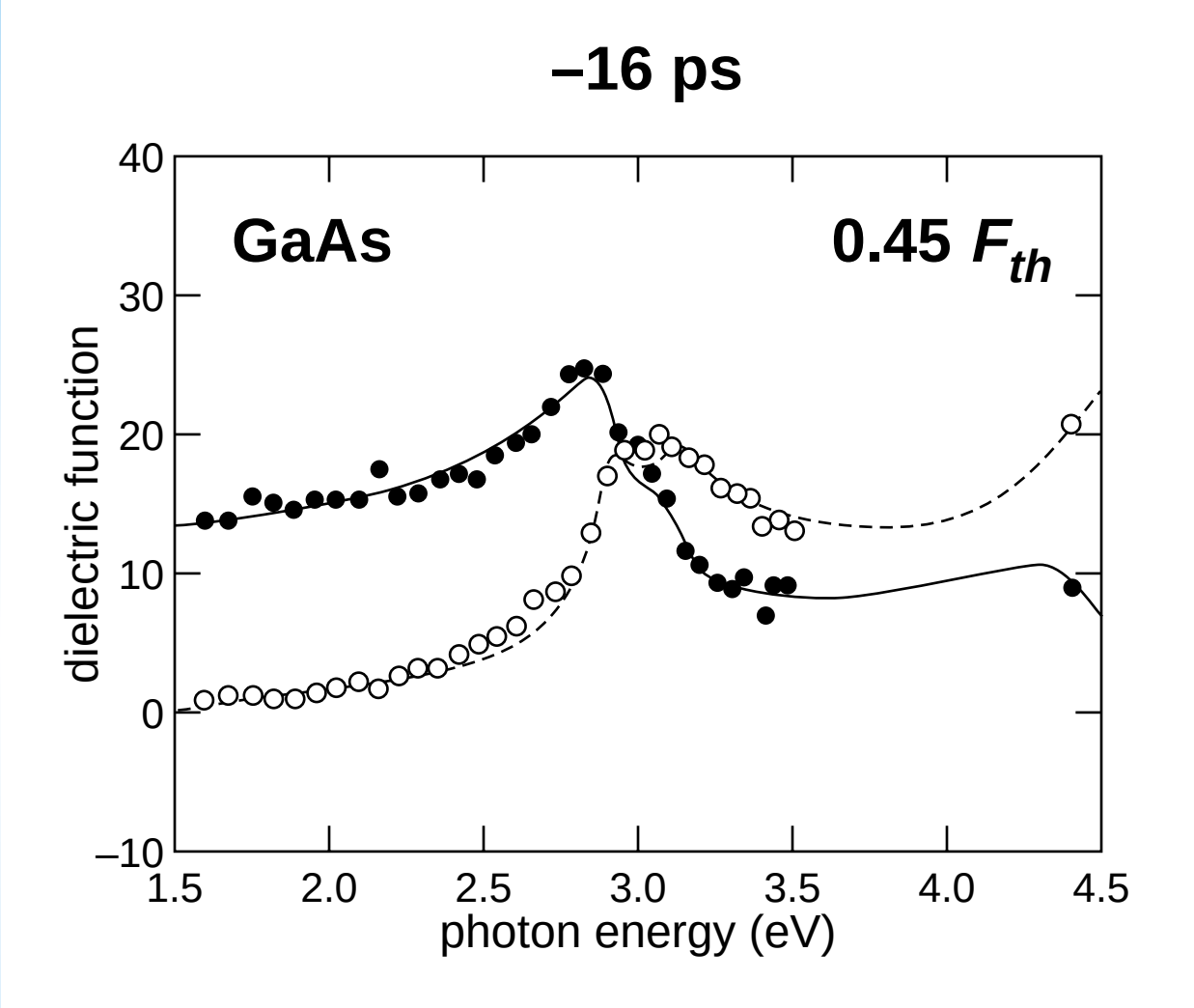
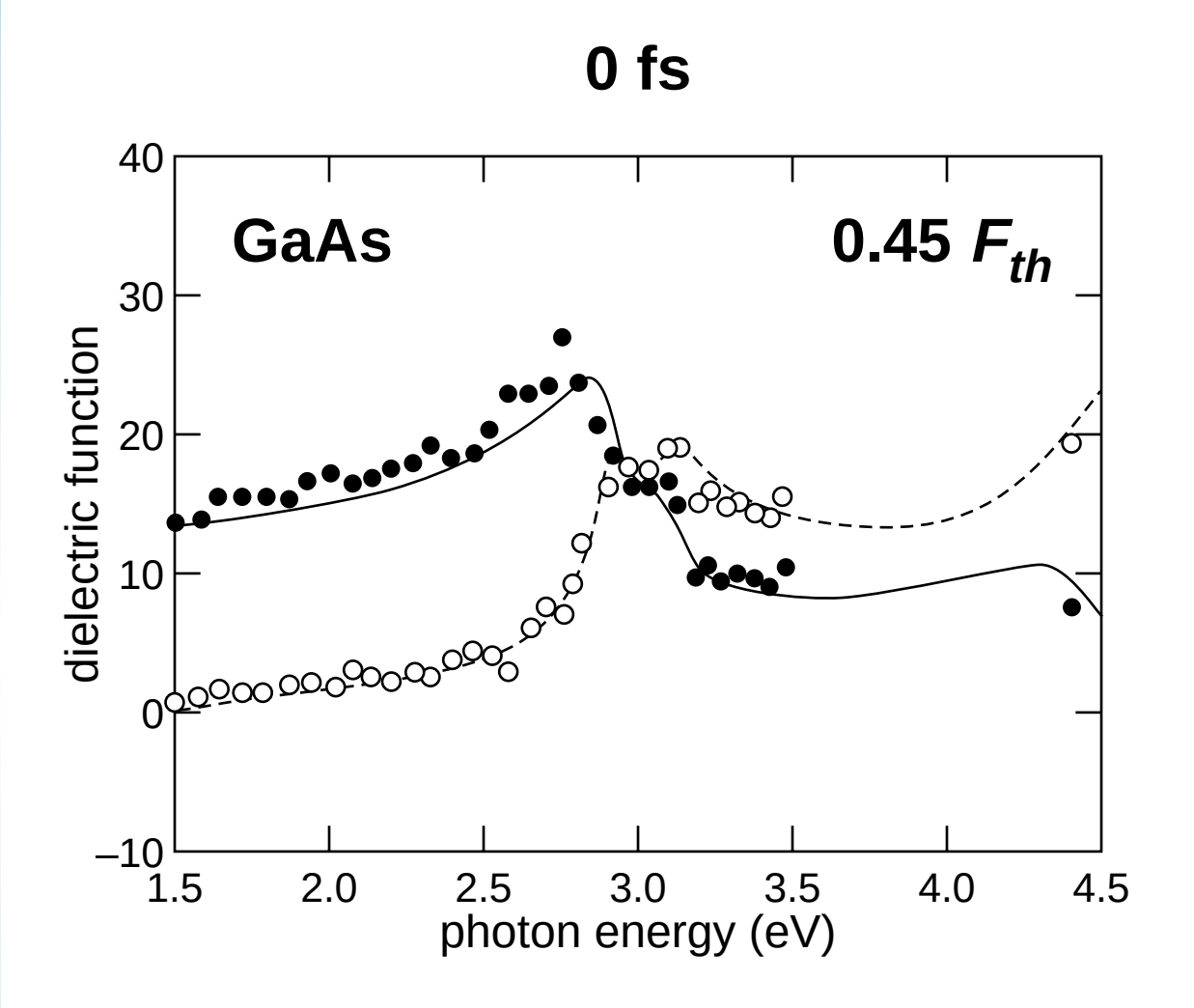
Results


–16 ps
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

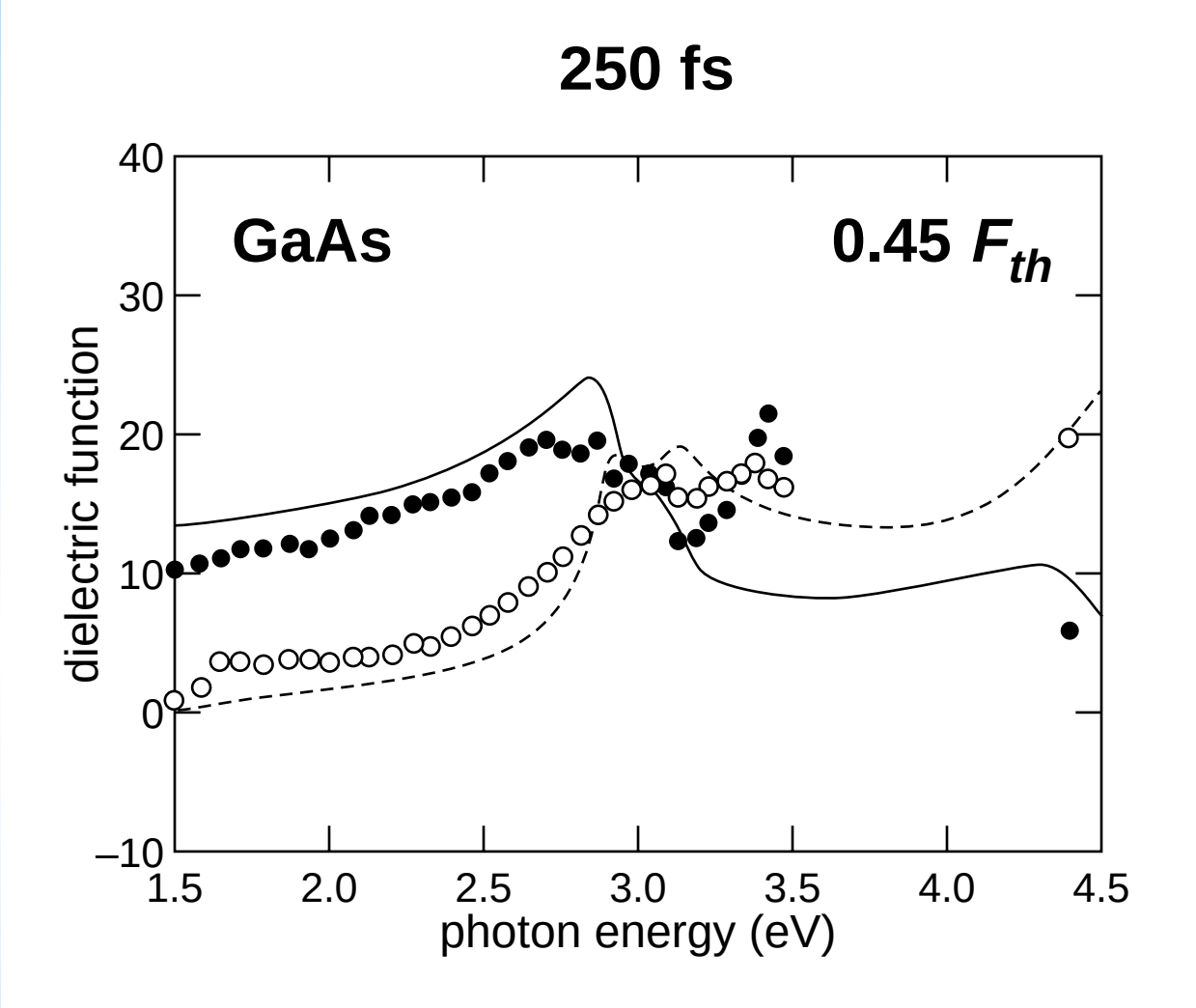
Results


–16 ps
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

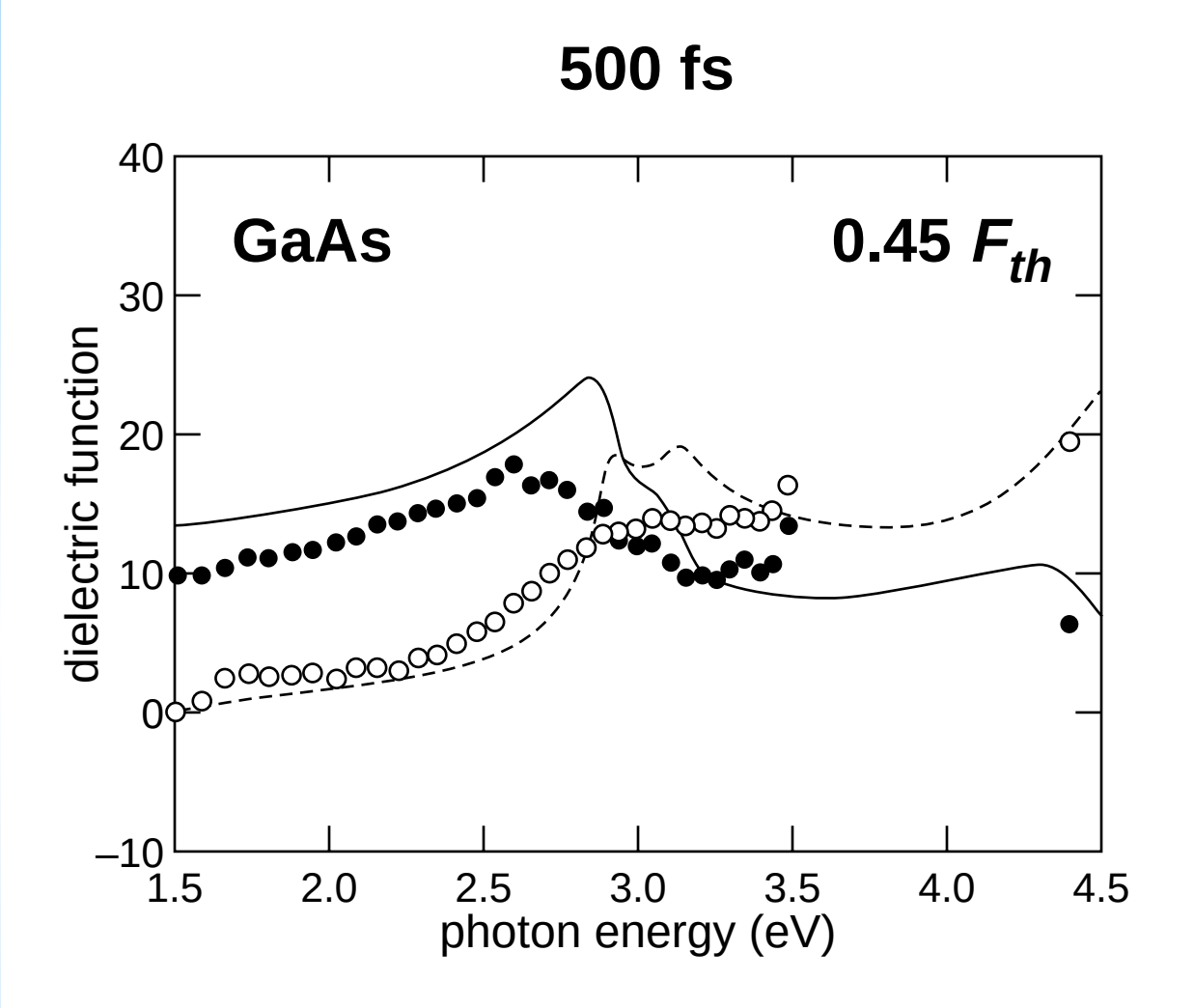
Results


0 fs
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

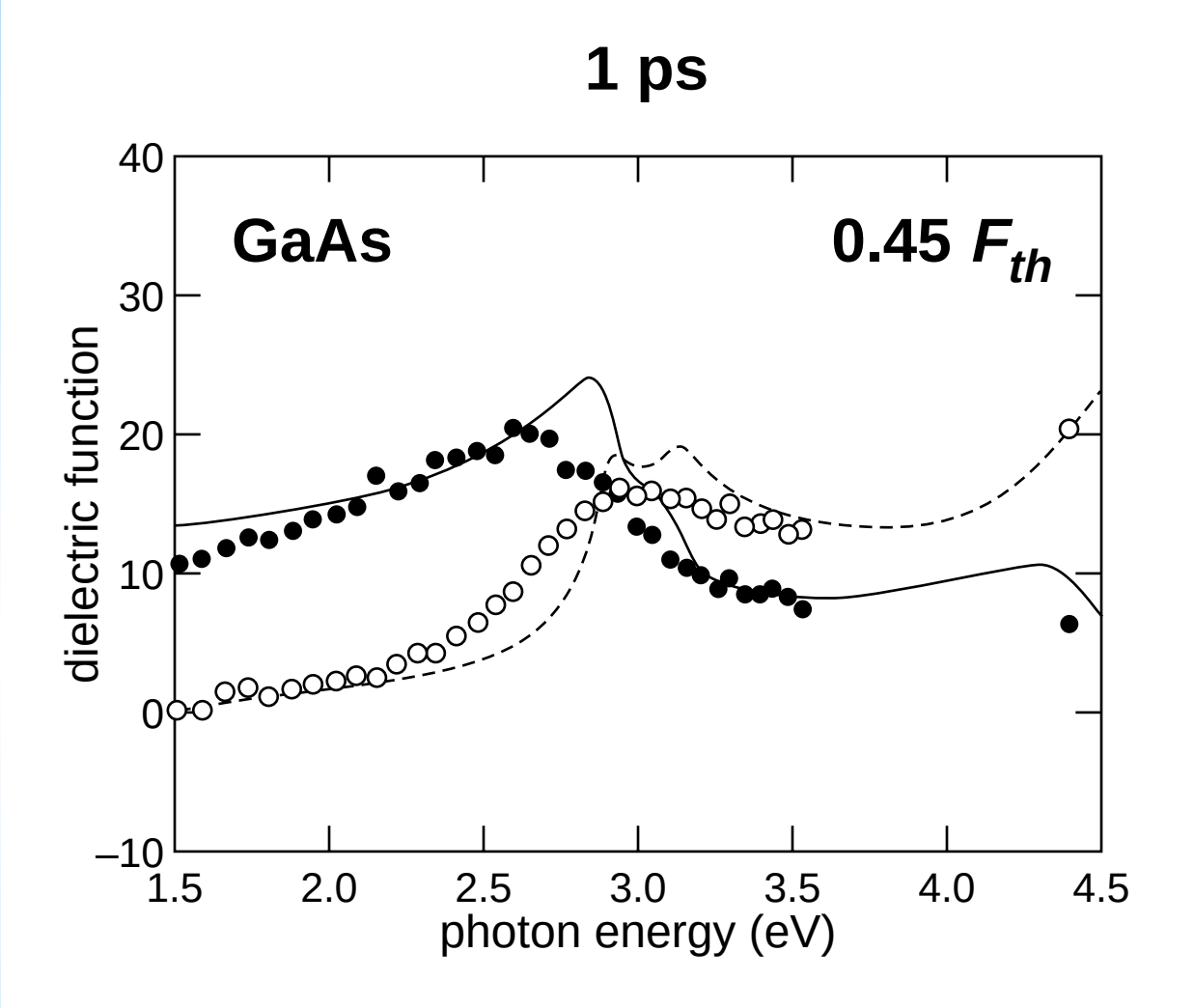
Results


250 fs
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

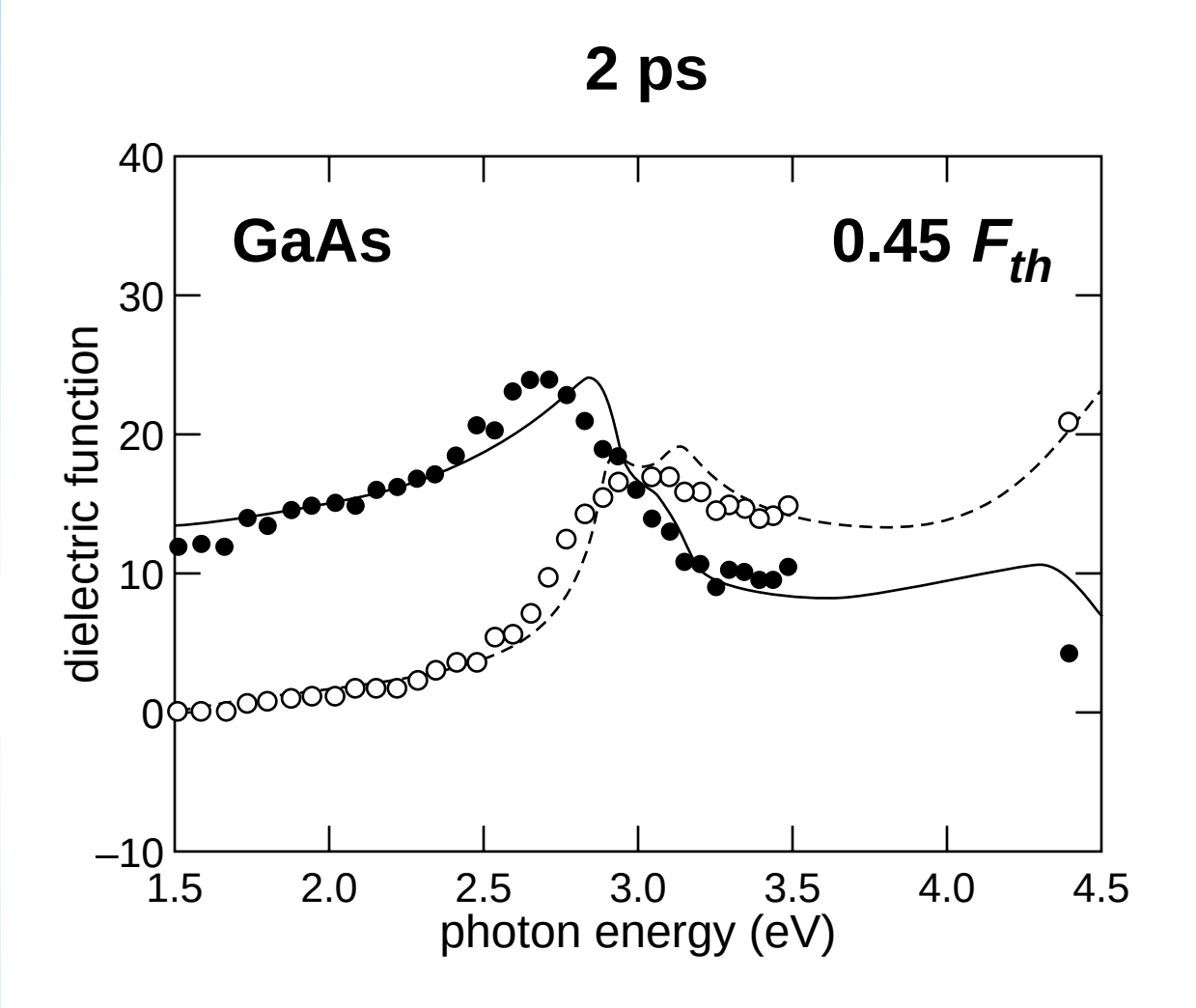
Results


500 fs
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

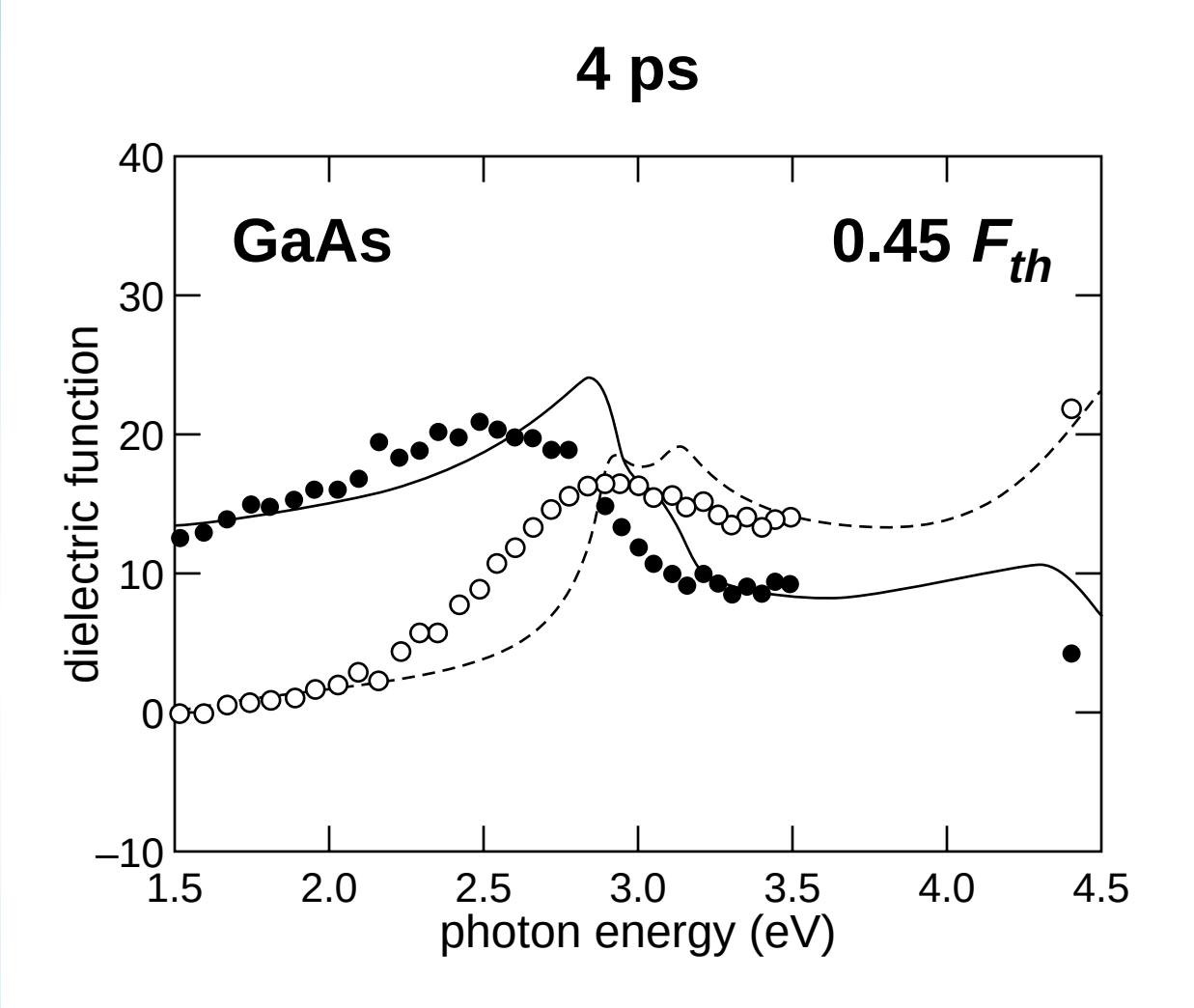
Results


1 ps
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Results


2 ps
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Results


4 ps
GaAs
0.45 F_{th}
dielectric function
photon energy (eV)
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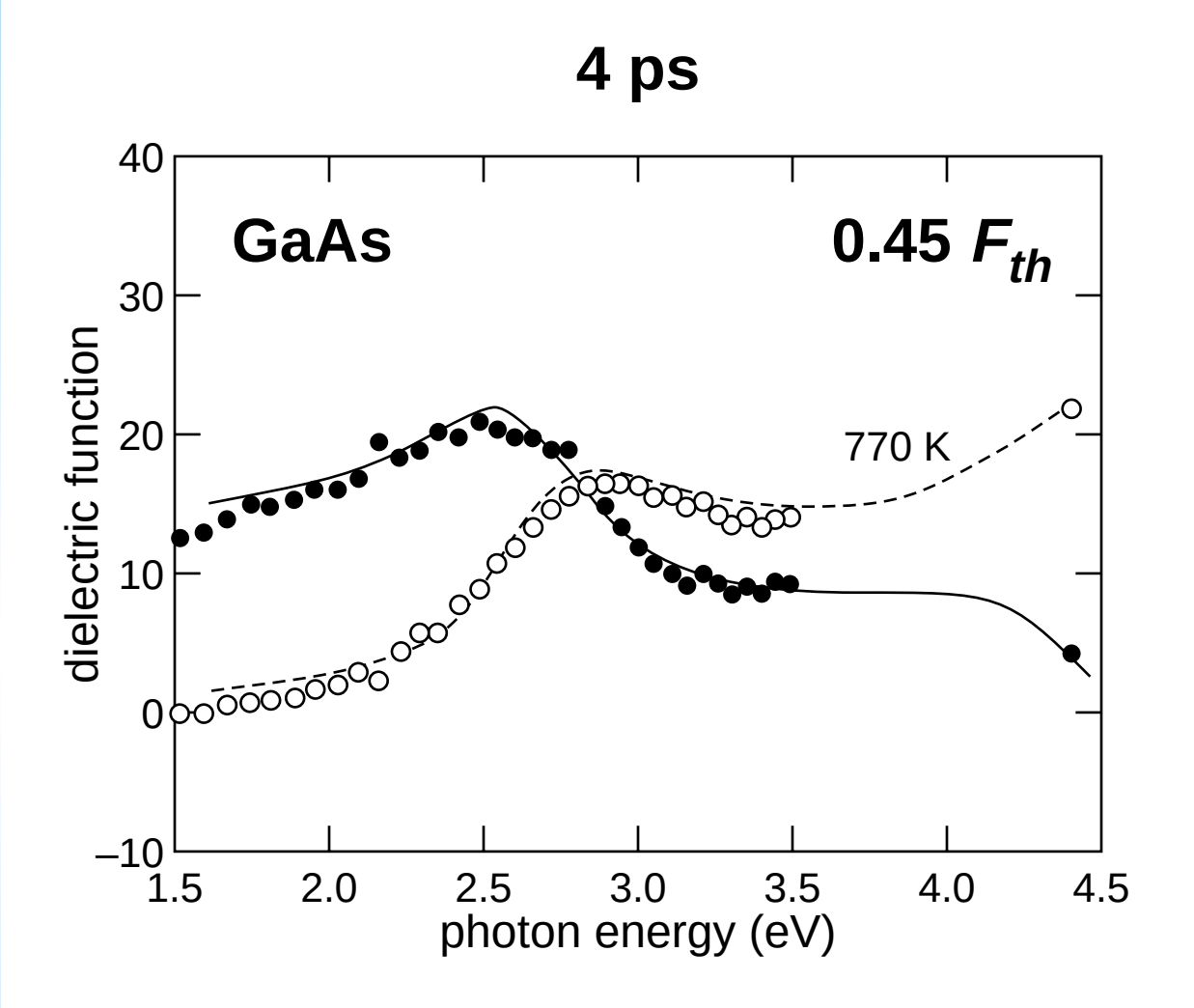
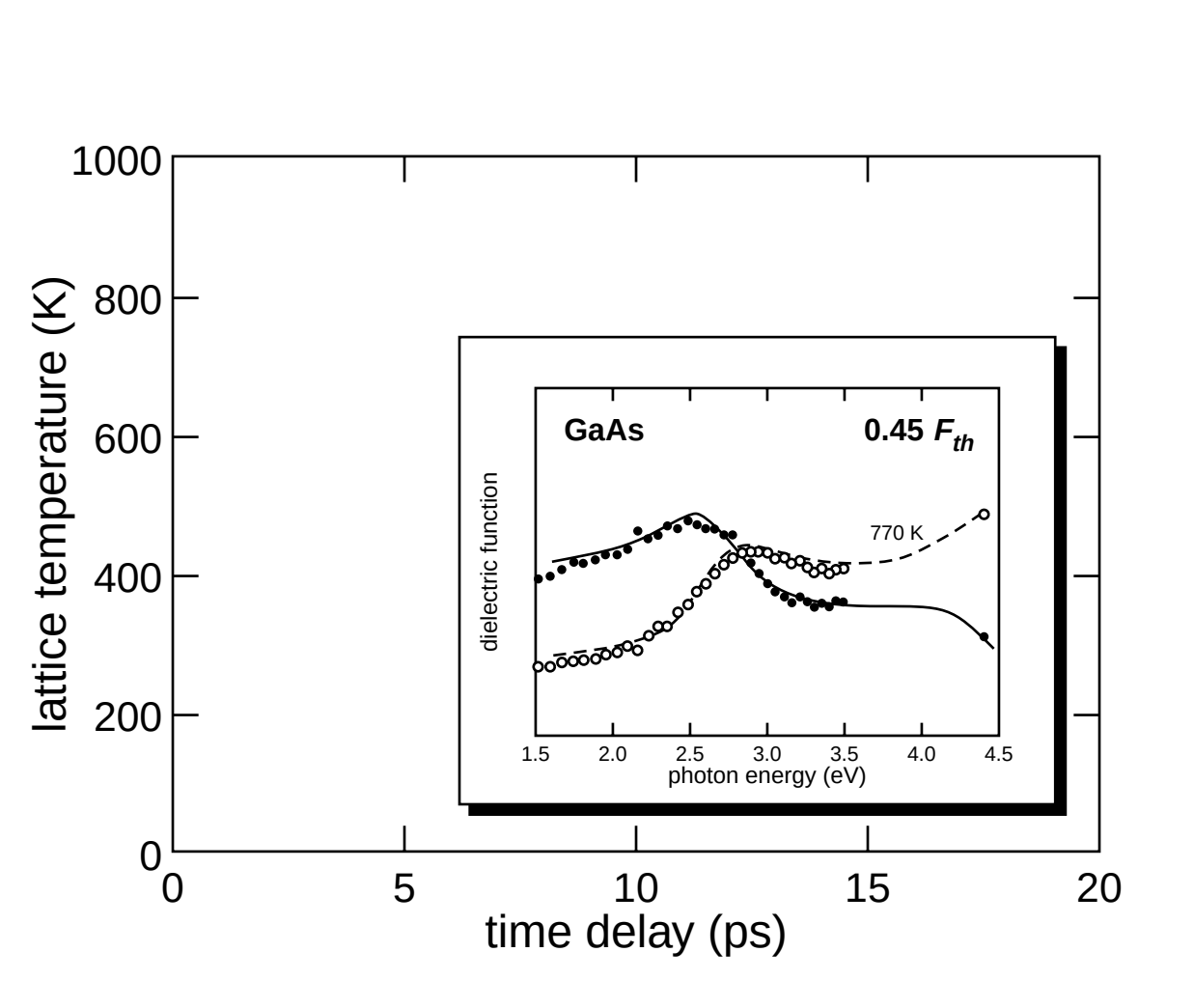
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

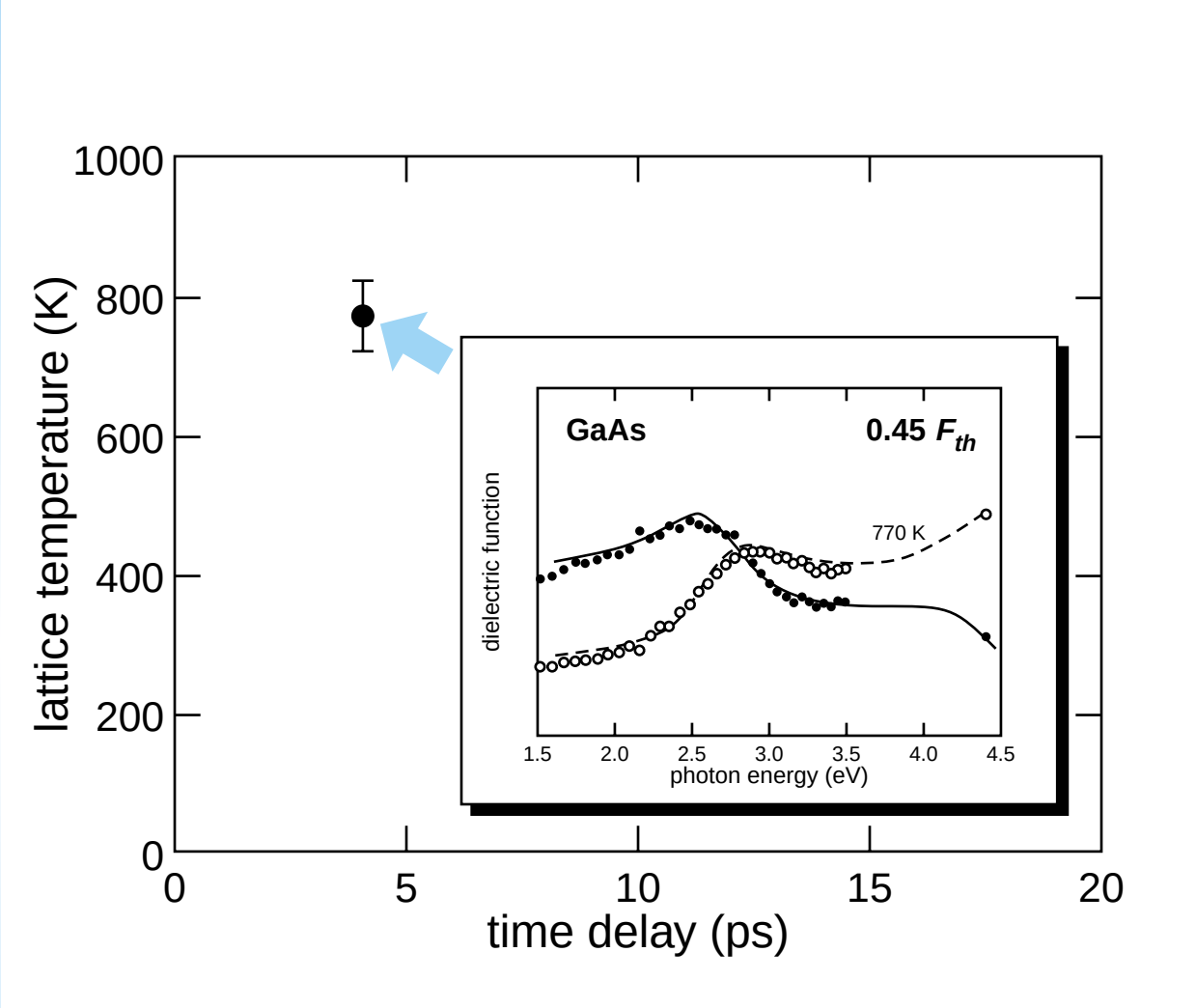
Results


4 ps
GaAs
0.45 F_{th}
770 K
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

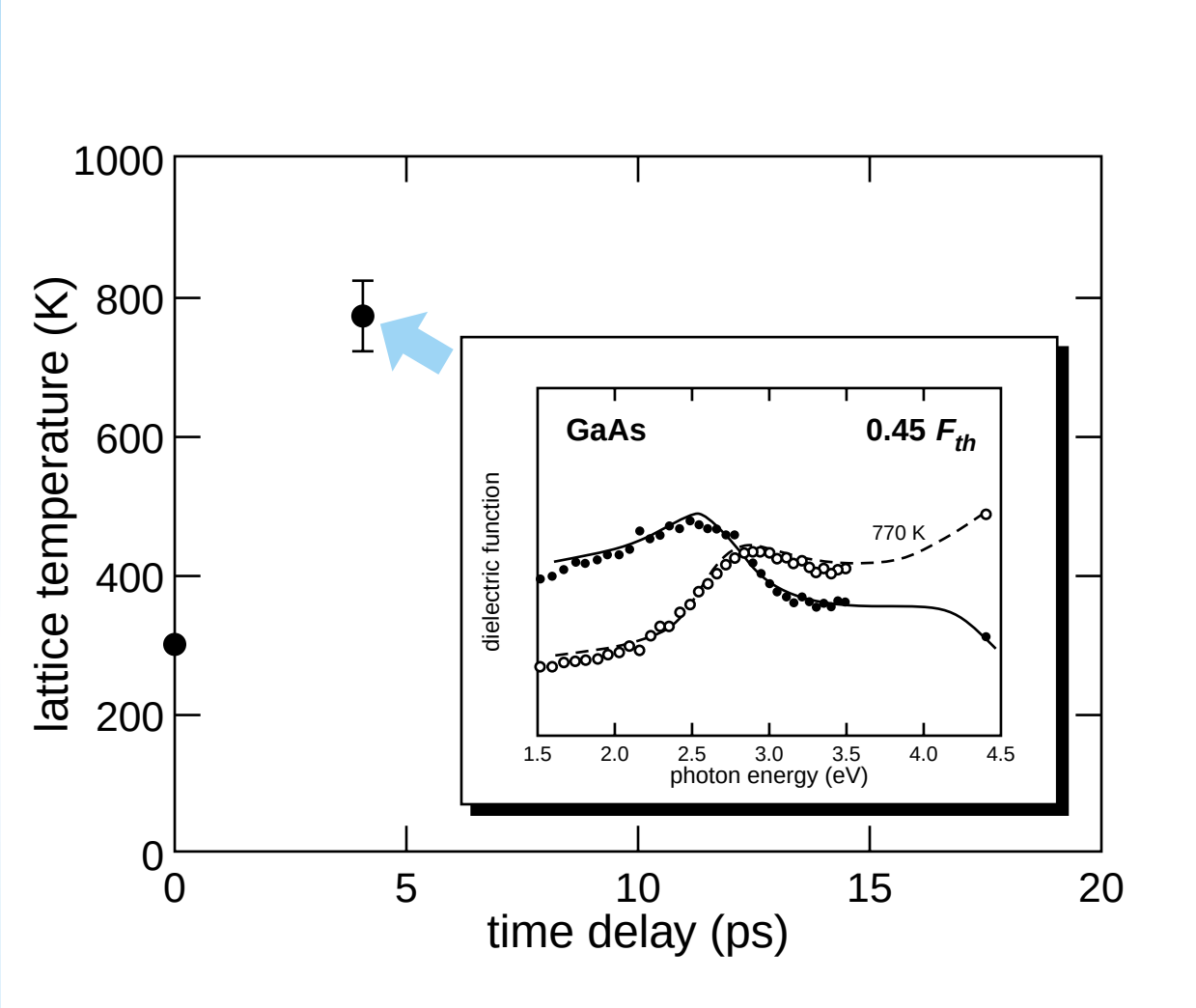
Results


1000
800
600
400
200
0
lattice temperature (K)
0
5
10
15
20
time delay (ps)
GaAs
0.45 F_{th}
770 K
dielectric function
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

Results


1000
800
600
400
200
0
lattice temperature (K)
0
5
10
15
20
time delay (ps)
GaAs
0.45 F_{th}
770 K
dielectric function
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

Results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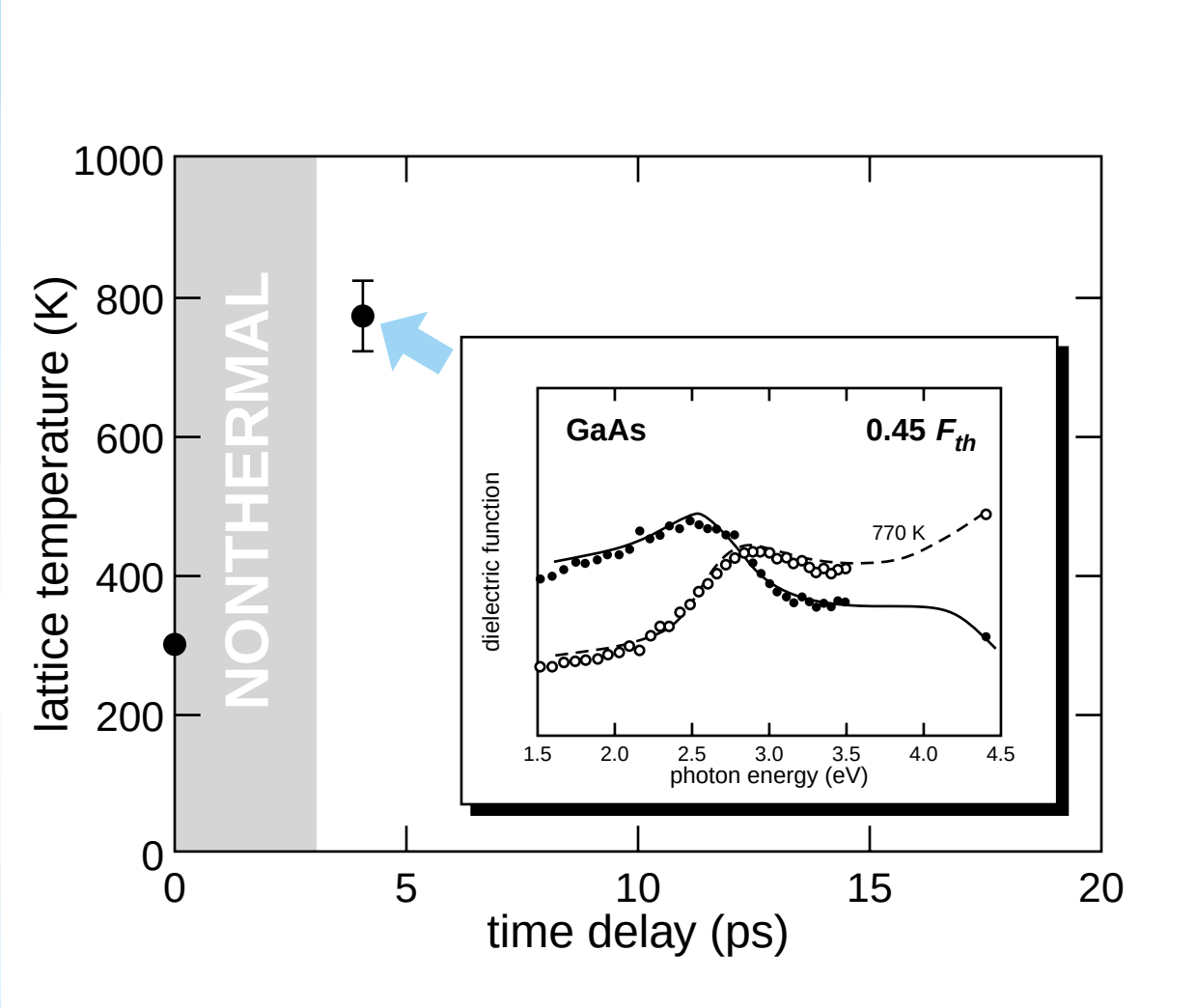
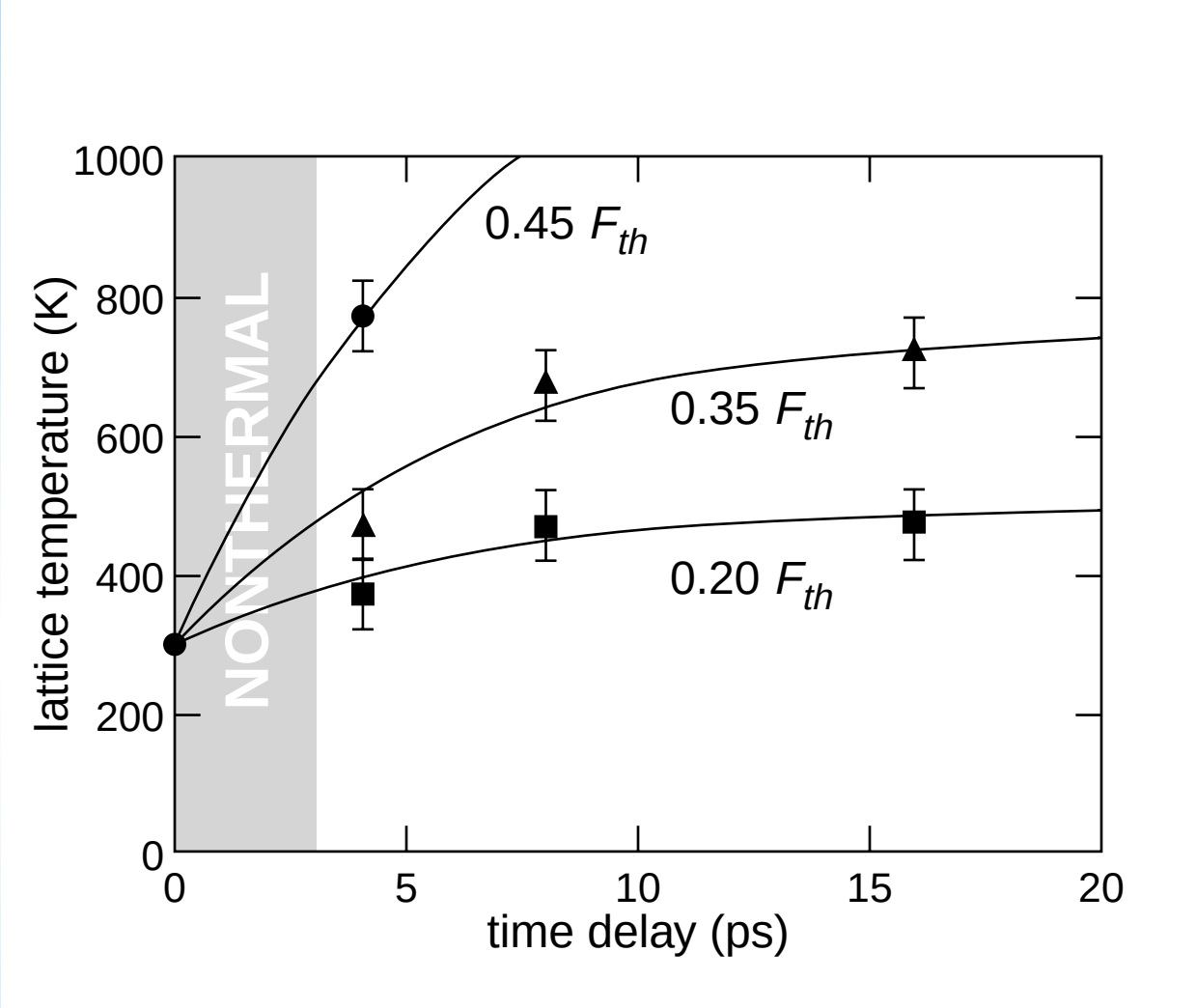
800
600
400
200
0
lattice temperature (K)
0
5
10
15
20
time delay (ps)
GaAs
0.45 F_{th}
770 K
dielectric function
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

Results


1000
800
600
400
200
0
lattice temperature (K)
NONTHERMAL
0
5
10
15
20
time delay (ps)
GaAs
0.45 F_{th}
770 K
dielectric function
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

Results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800
600
400
200
0
lattice temperature (K)
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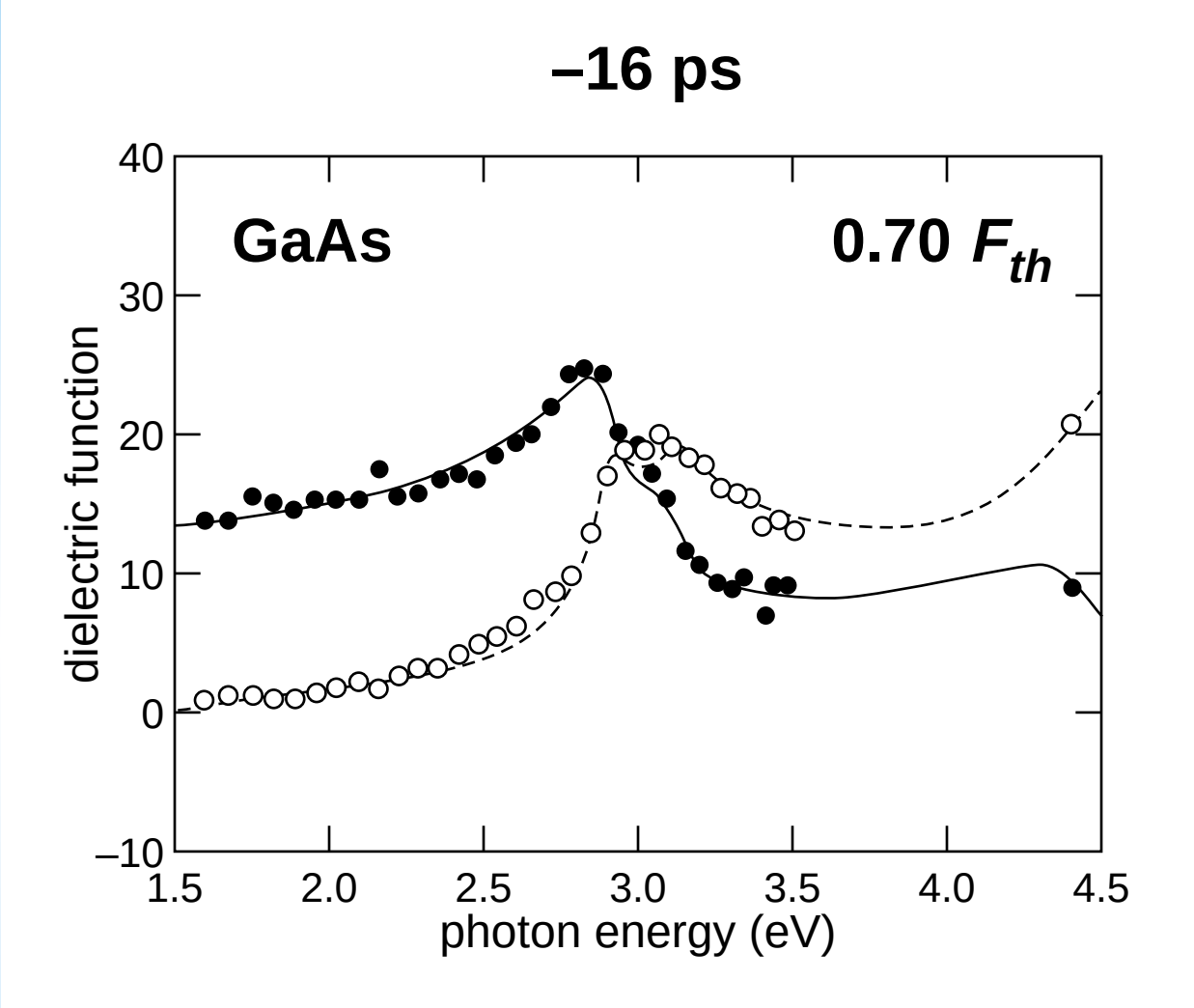
0.35 F_{th}
0.20 F_{th}
0
5
10
15
20
time delay (ps)

Results


–16 ps
GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
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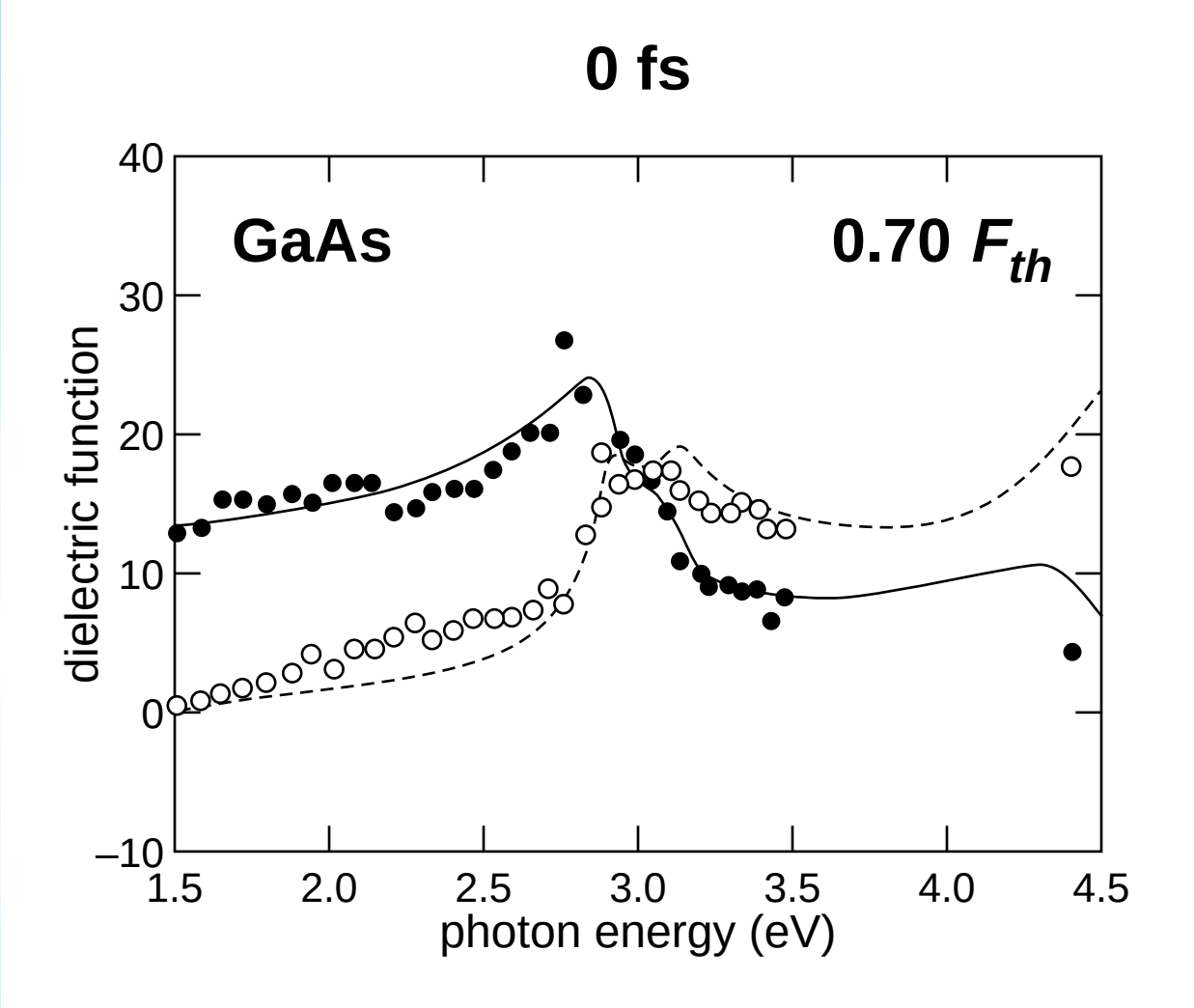
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Results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GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
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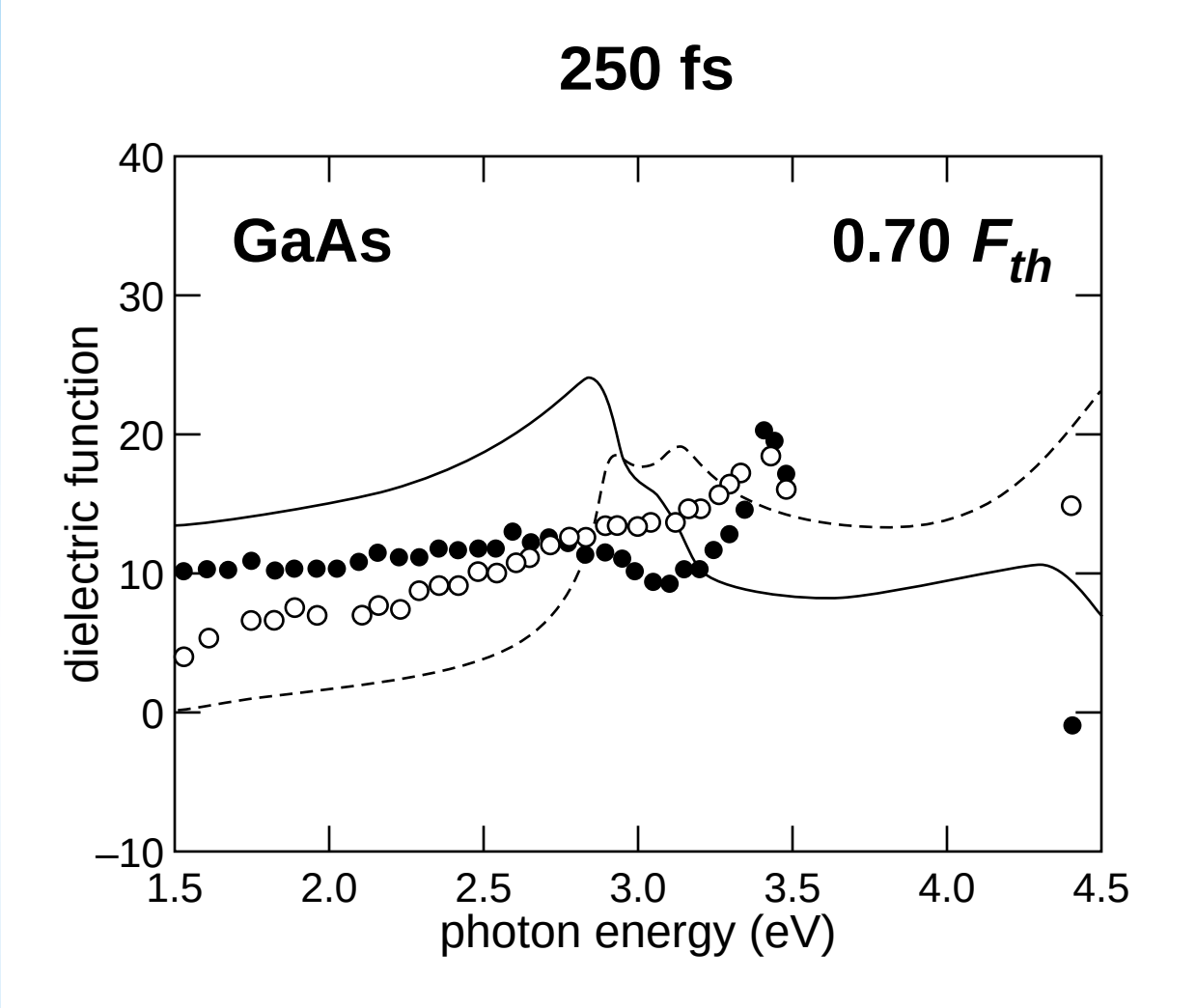
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Results


250 fs
GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
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10
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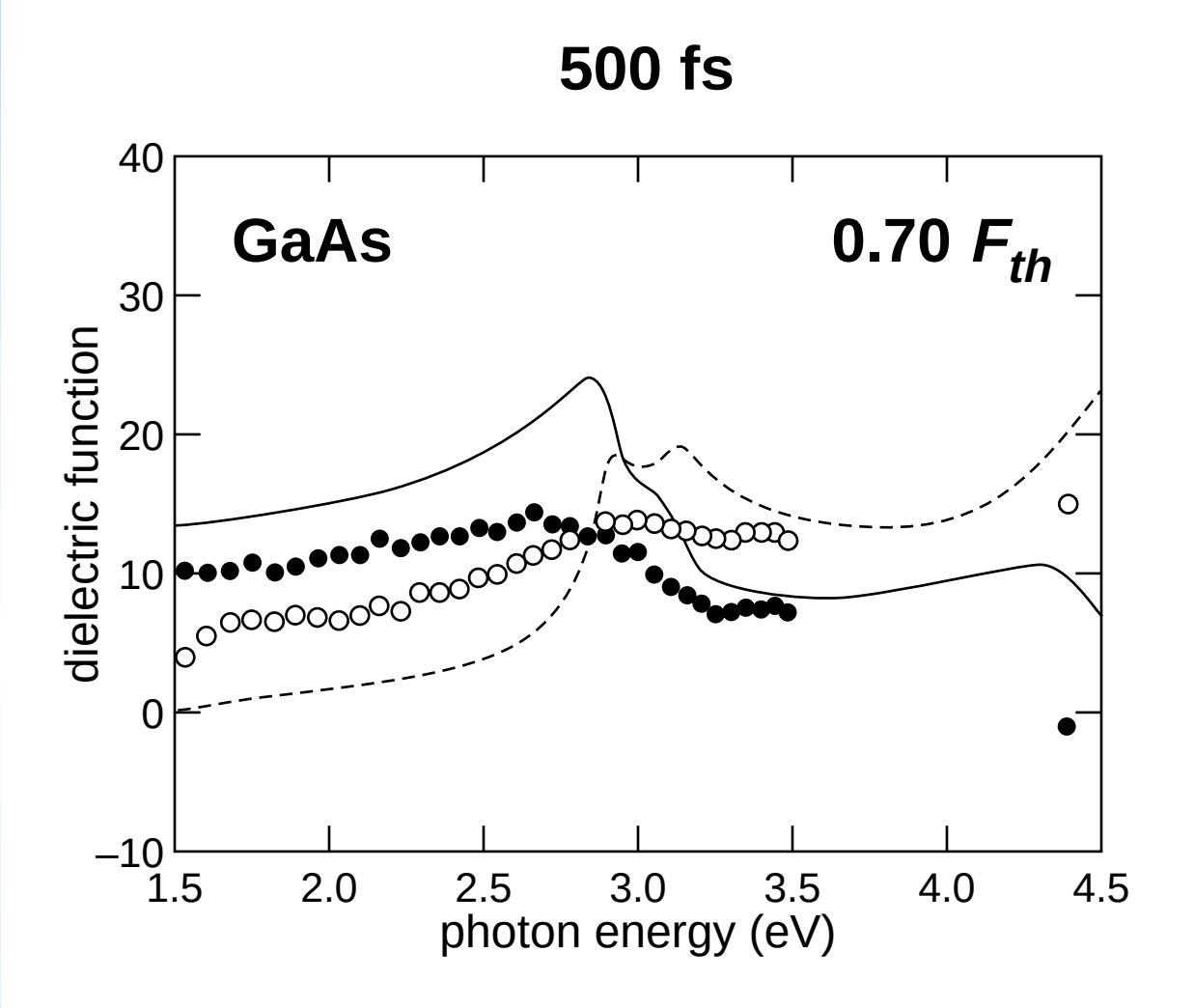
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Results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GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
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2.0
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4.0
4.5

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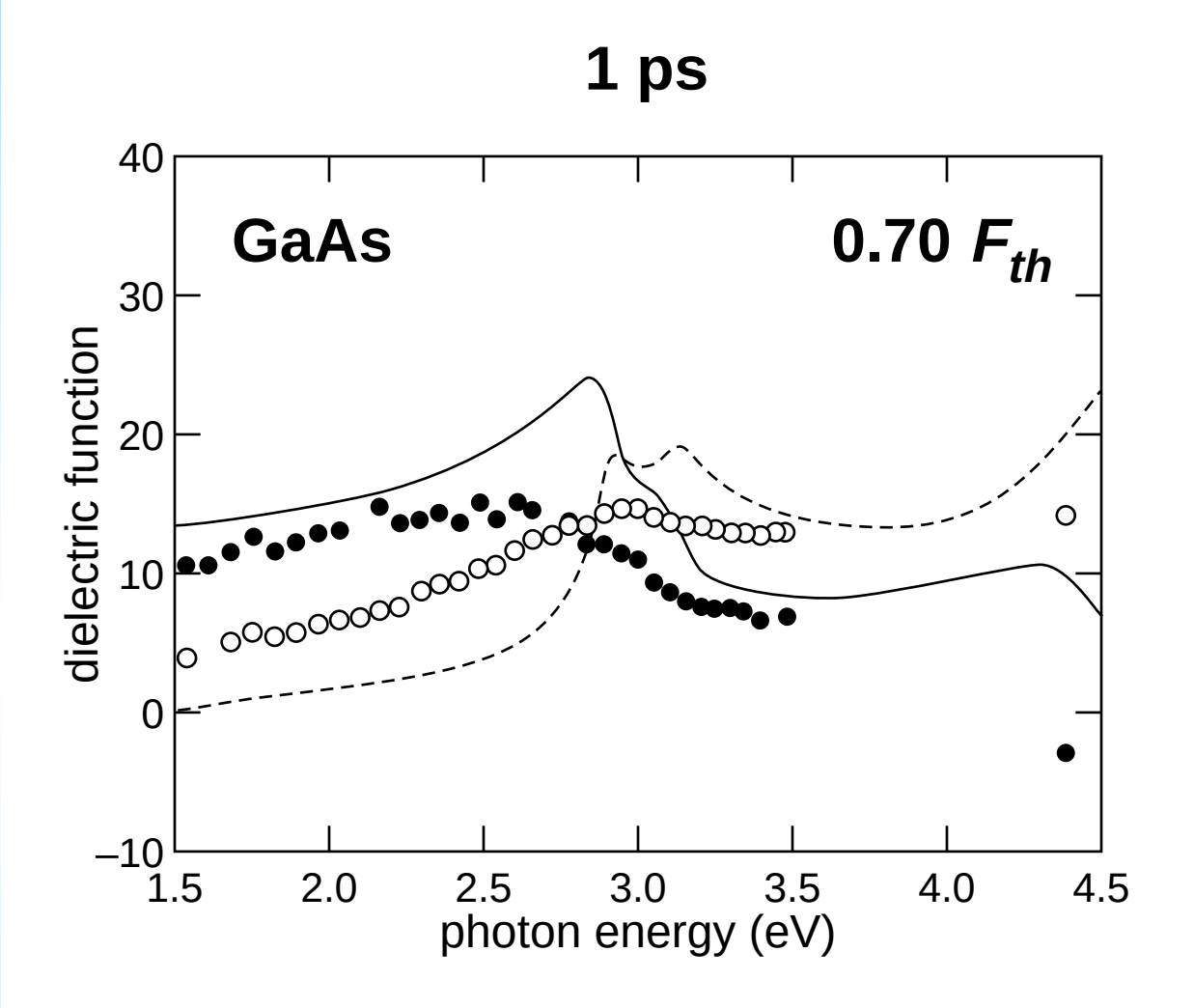
1 ps
GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
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0
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1.5
2.0
2.5
3.0
3.5
4.0
4.5

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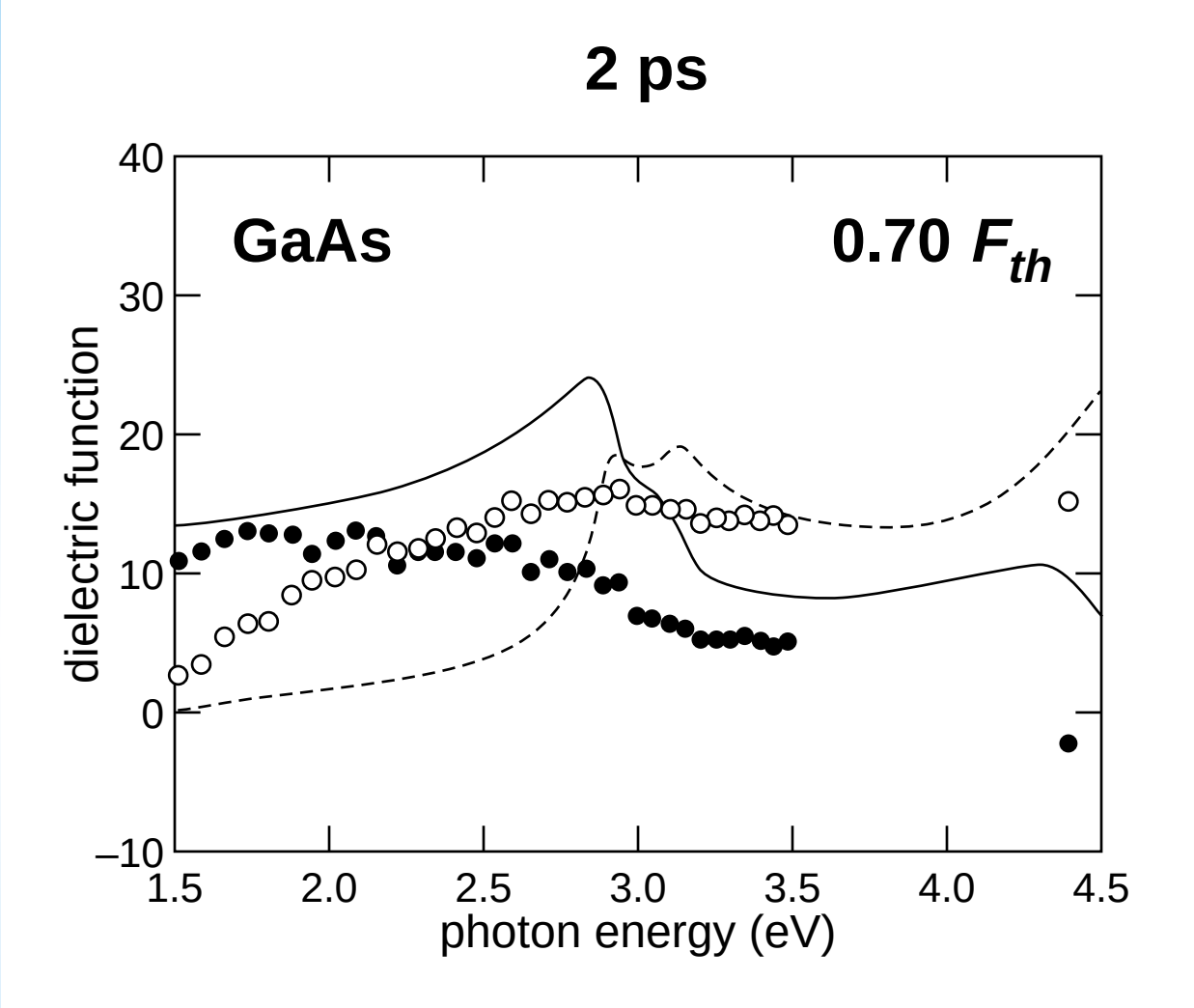
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GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
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0
–10
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3.0
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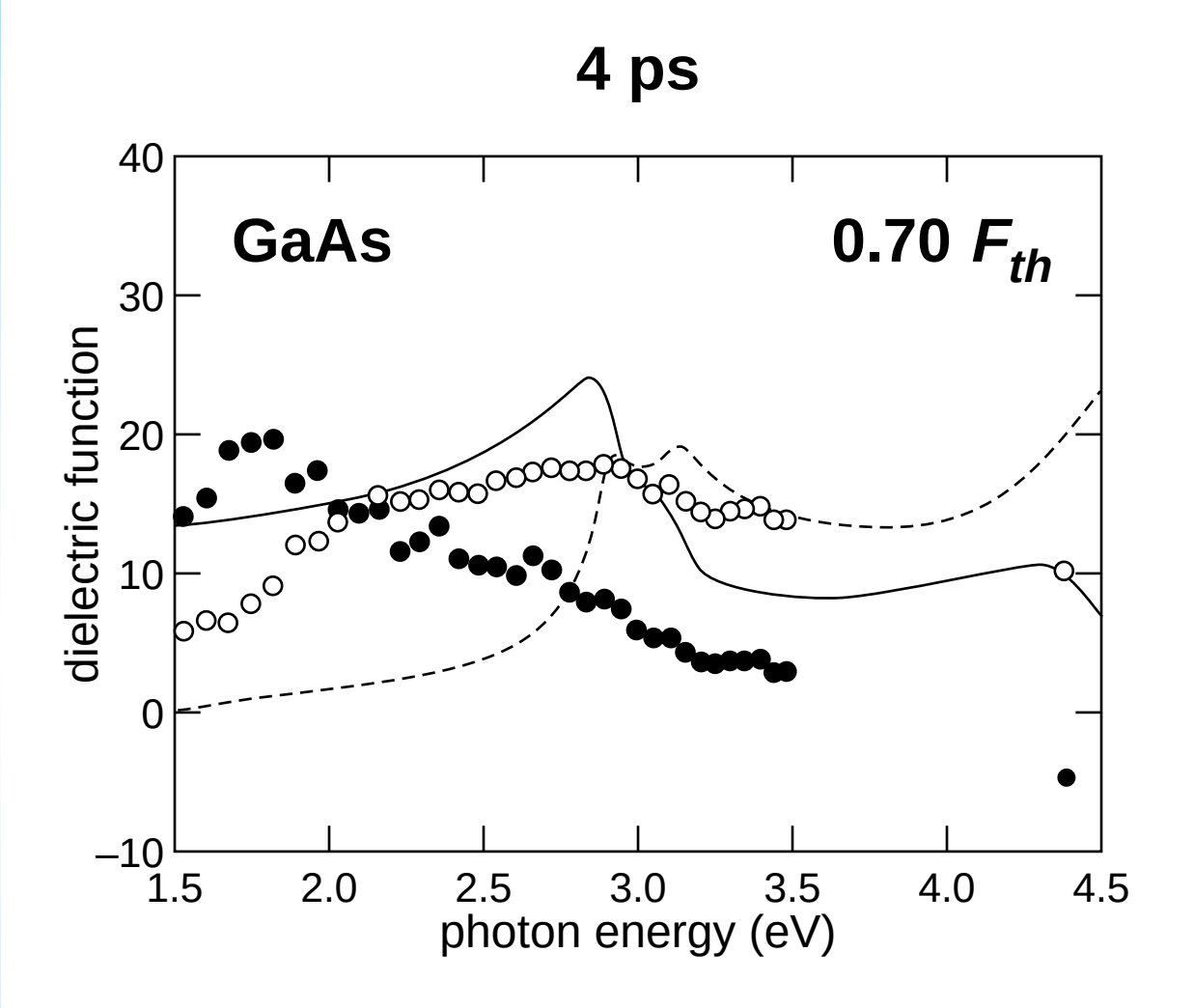
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GaAs
0.70 F_{th}
dielectric function
photon energy (eV)
40
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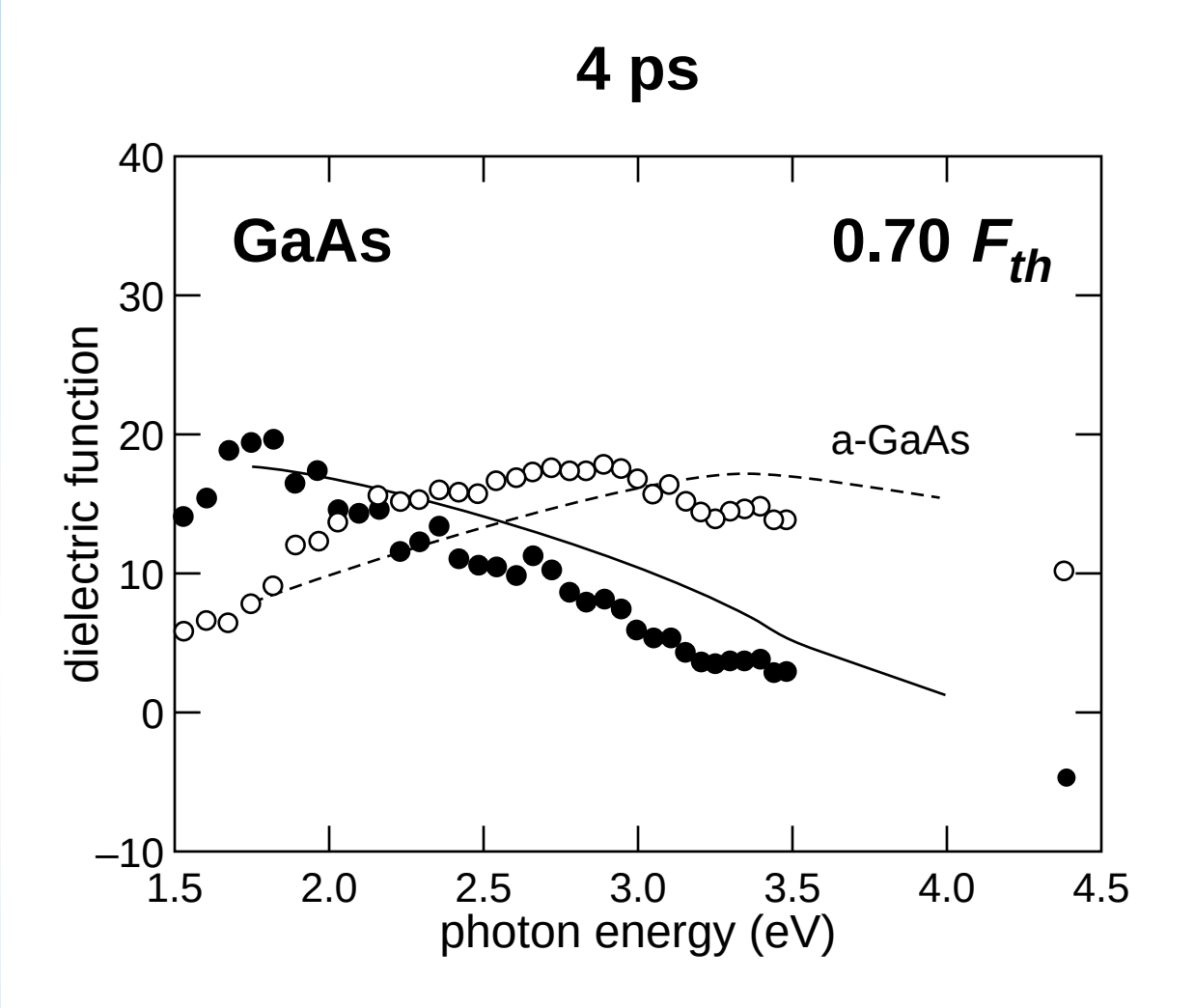
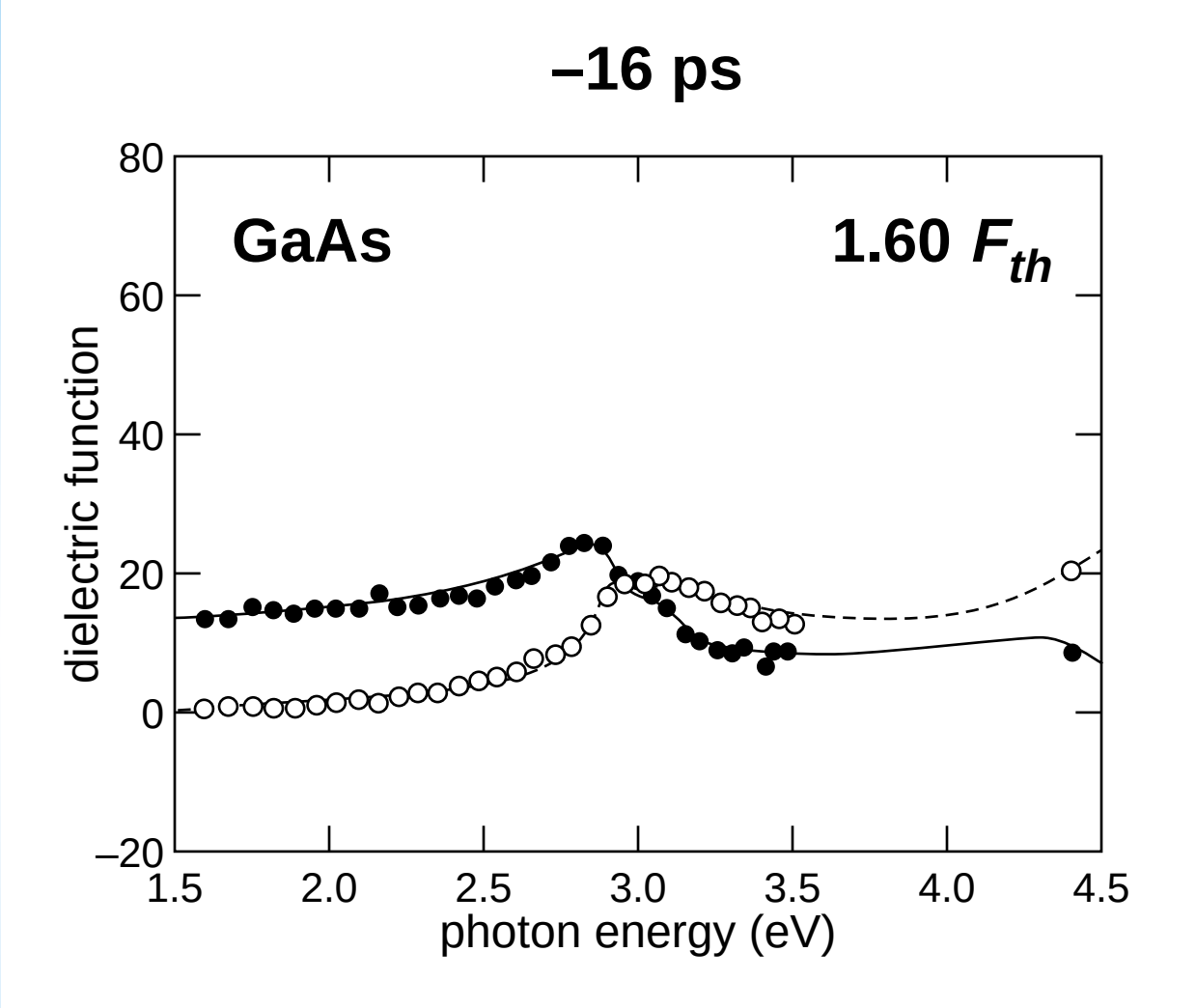
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

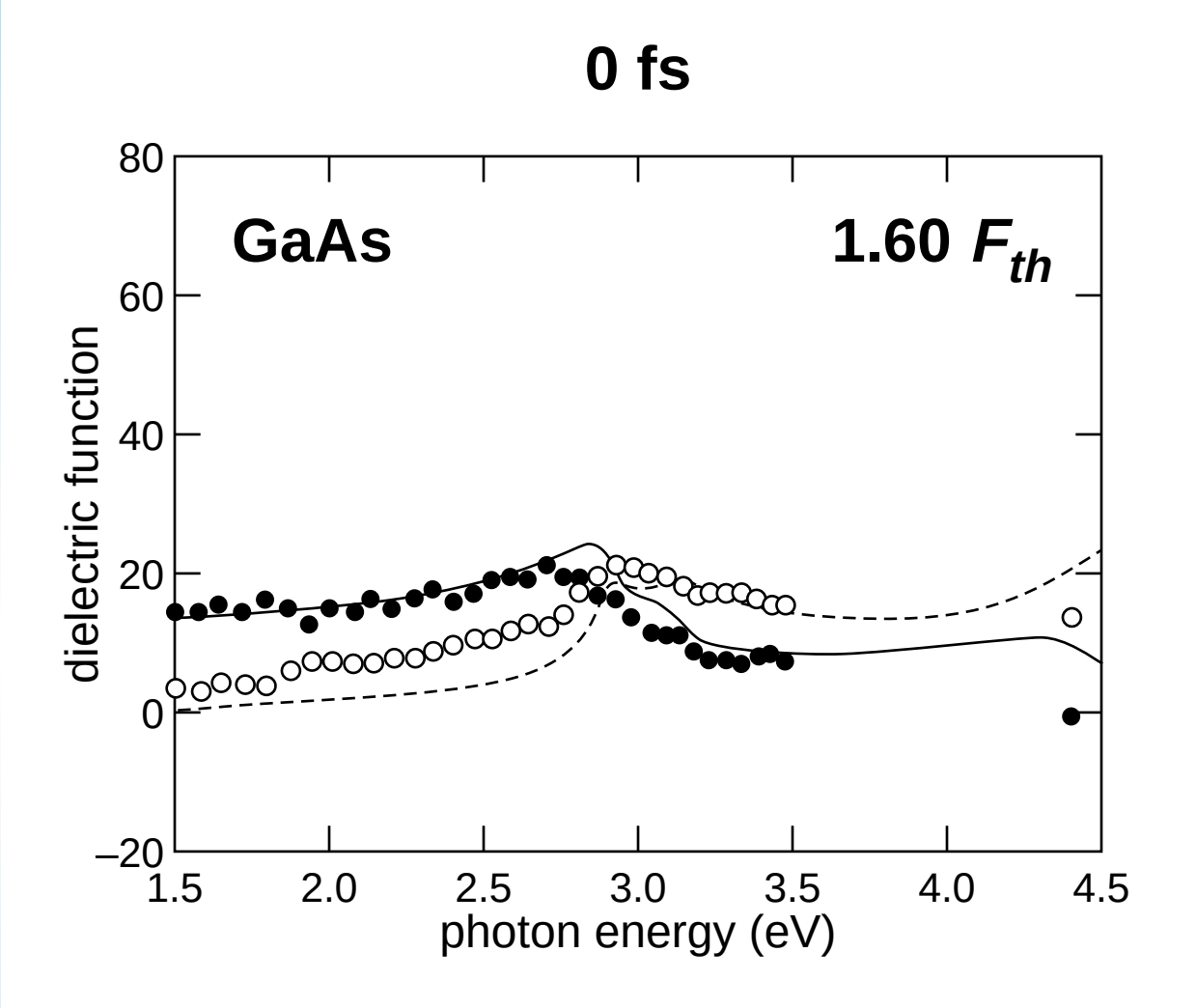
Results


4 ps
GaAs
0.70 F_{th}
a-GaAs
dielectric function
photon energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5
4.0
4.5

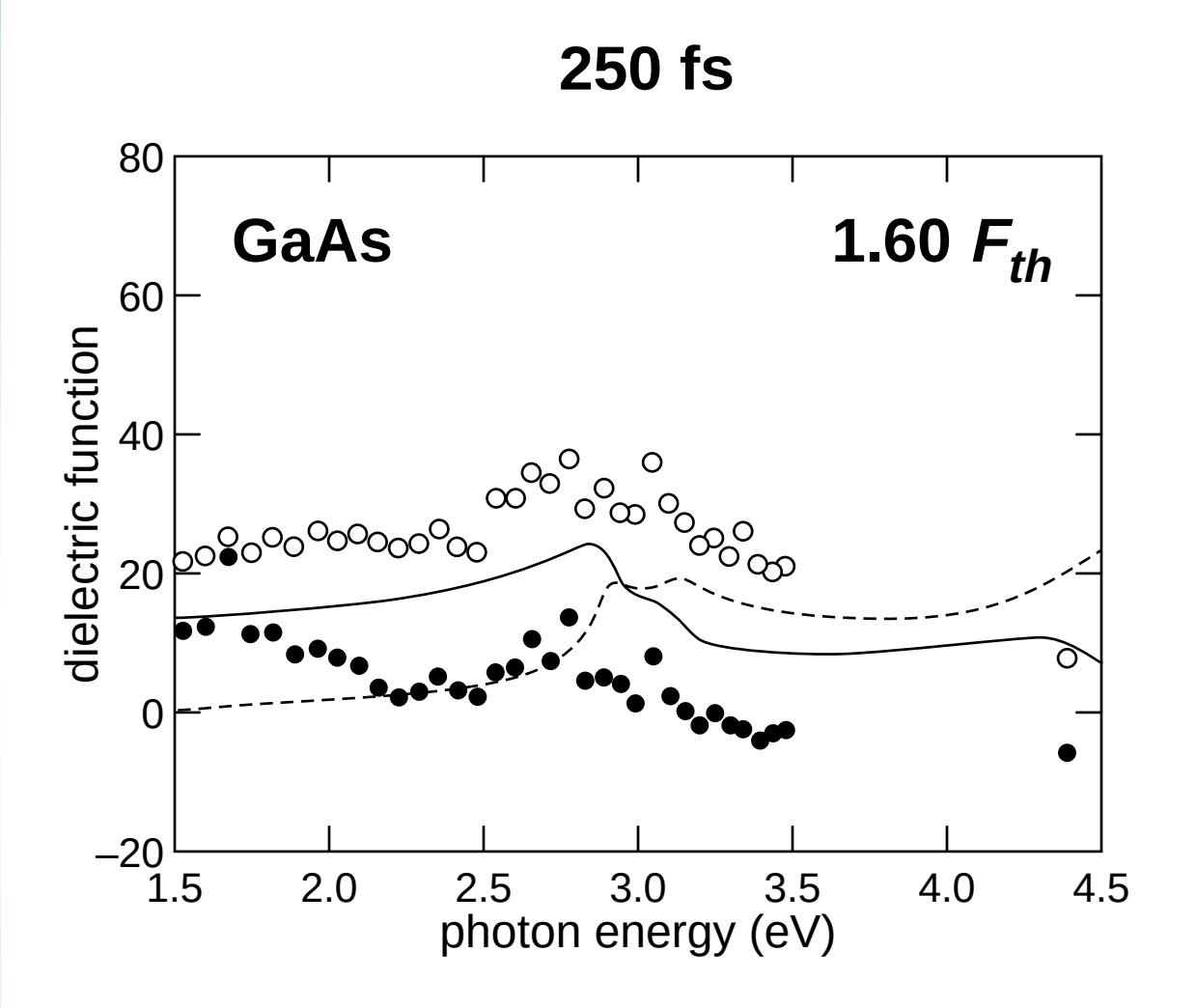
Results


–16 ps
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

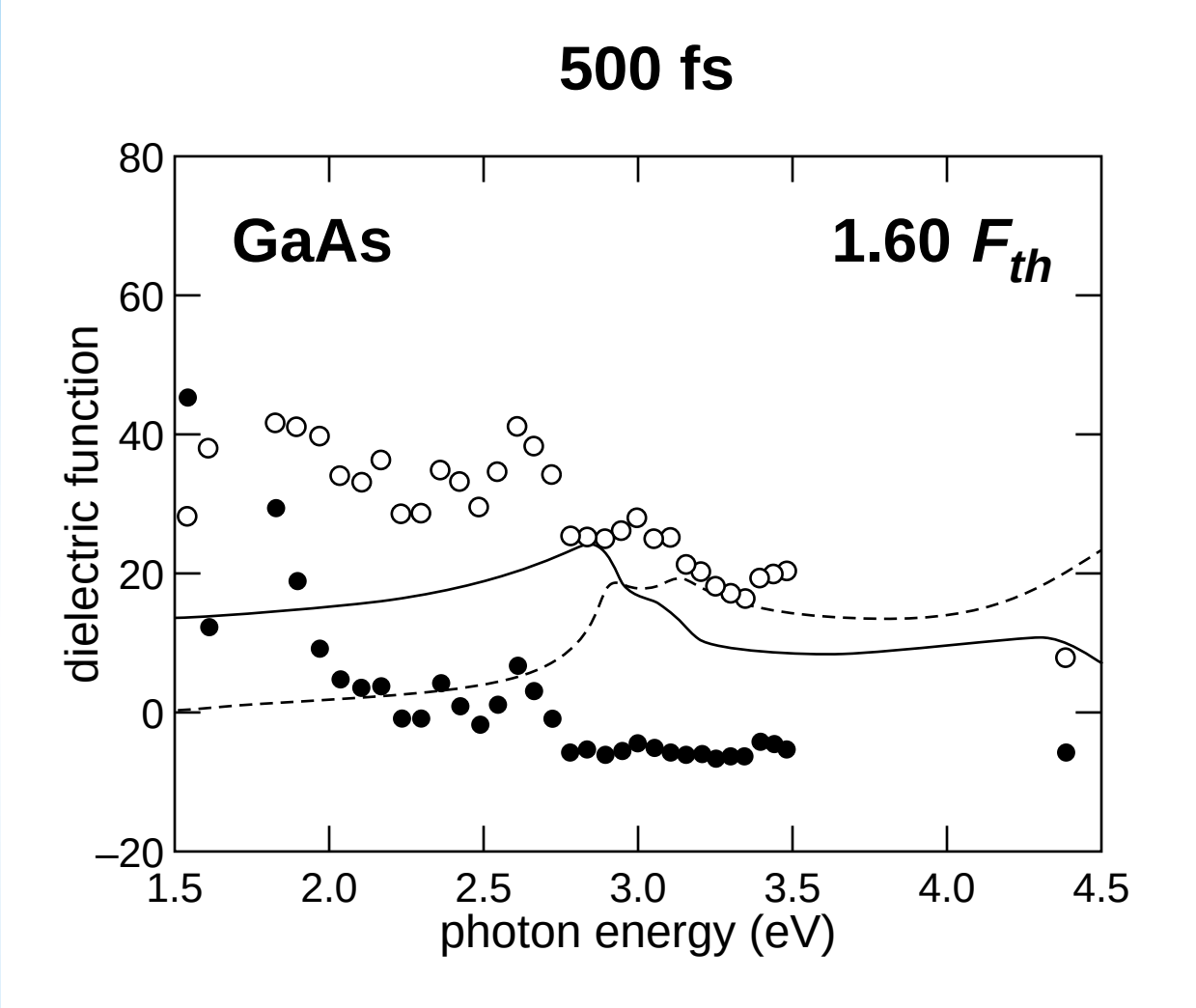
Results


0 fs
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

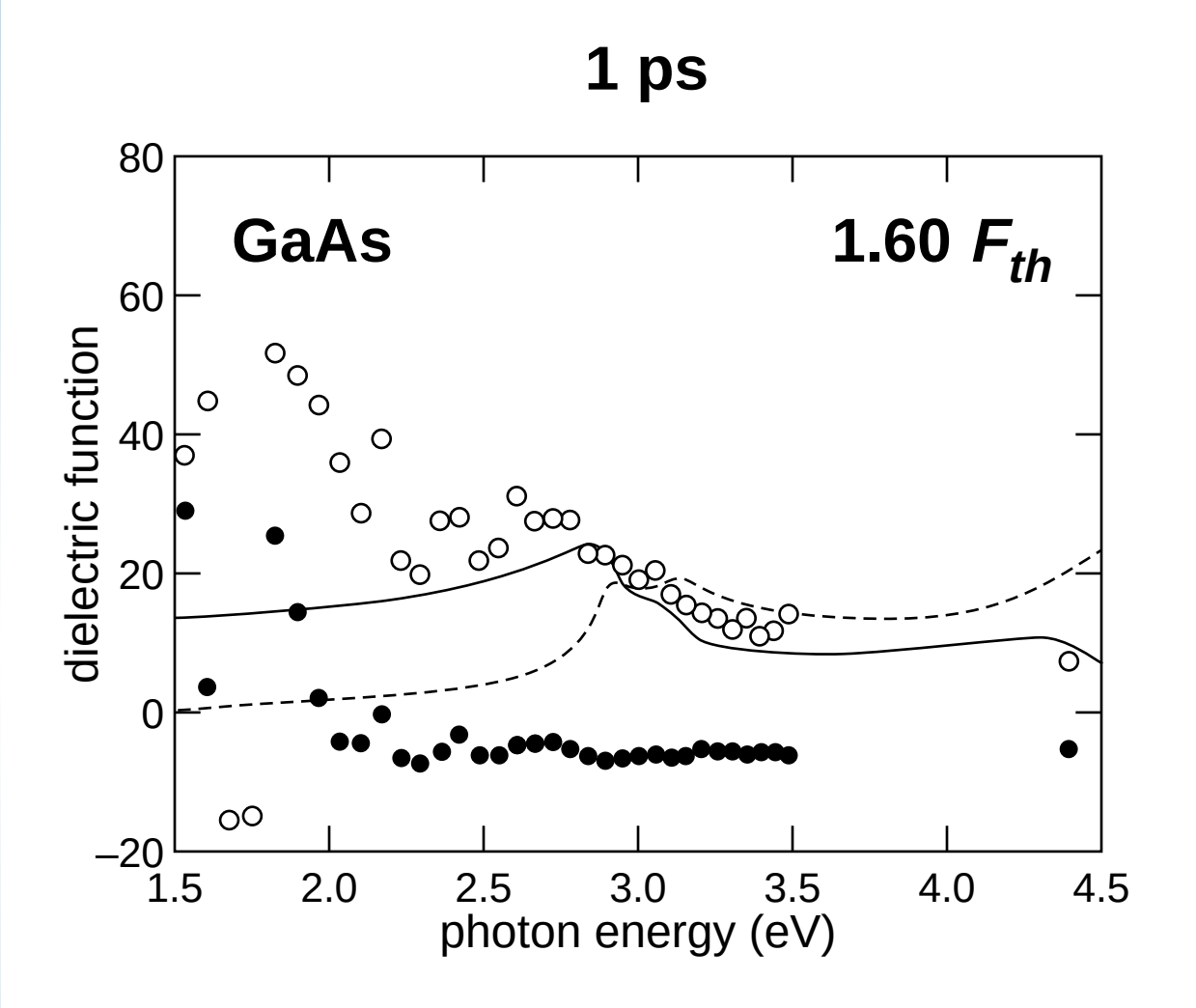
Results


250 fs
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

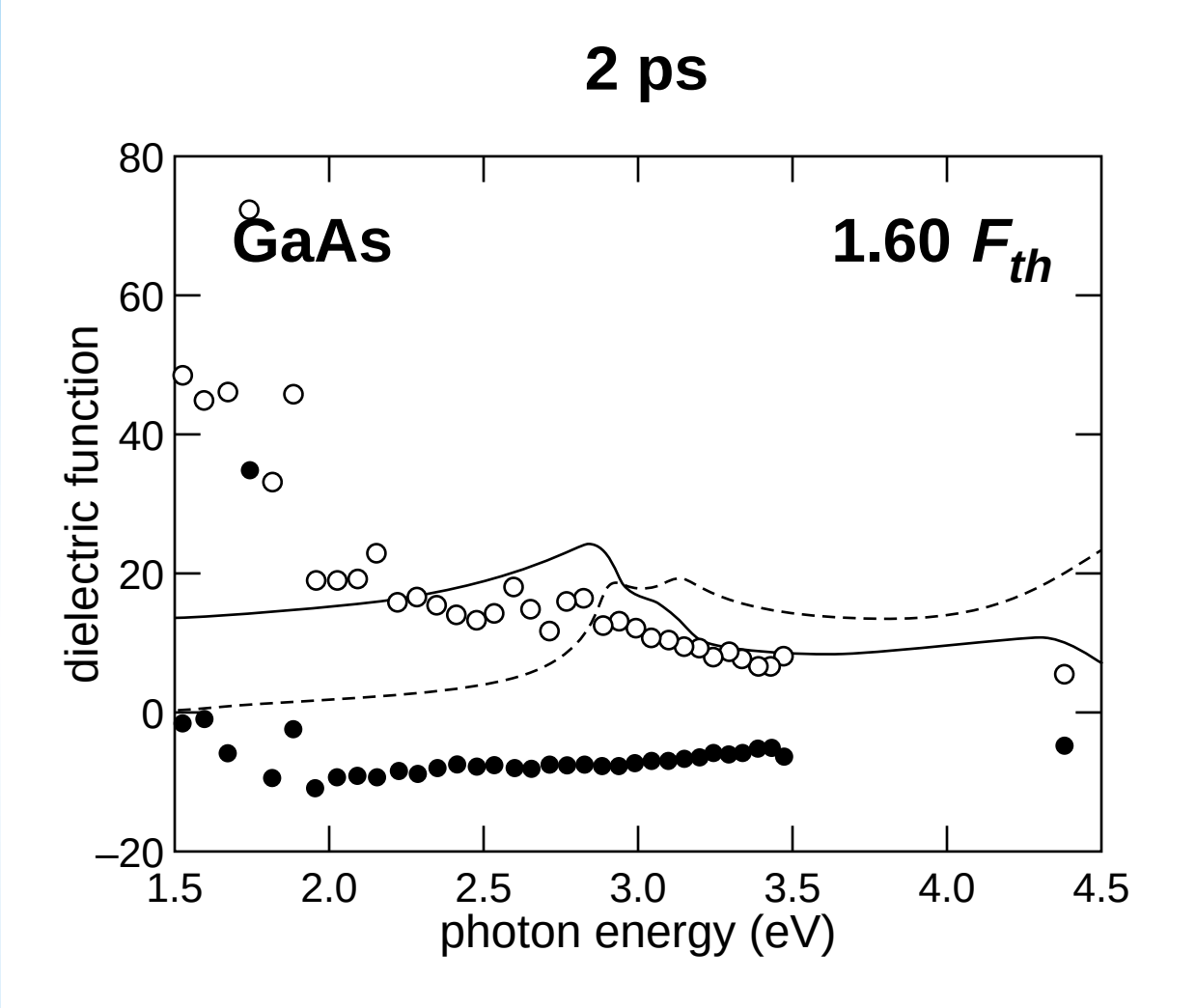
Results


500 fs
GaAs
1.60 F_{th}
dielectric function
photon energy (eV)
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5

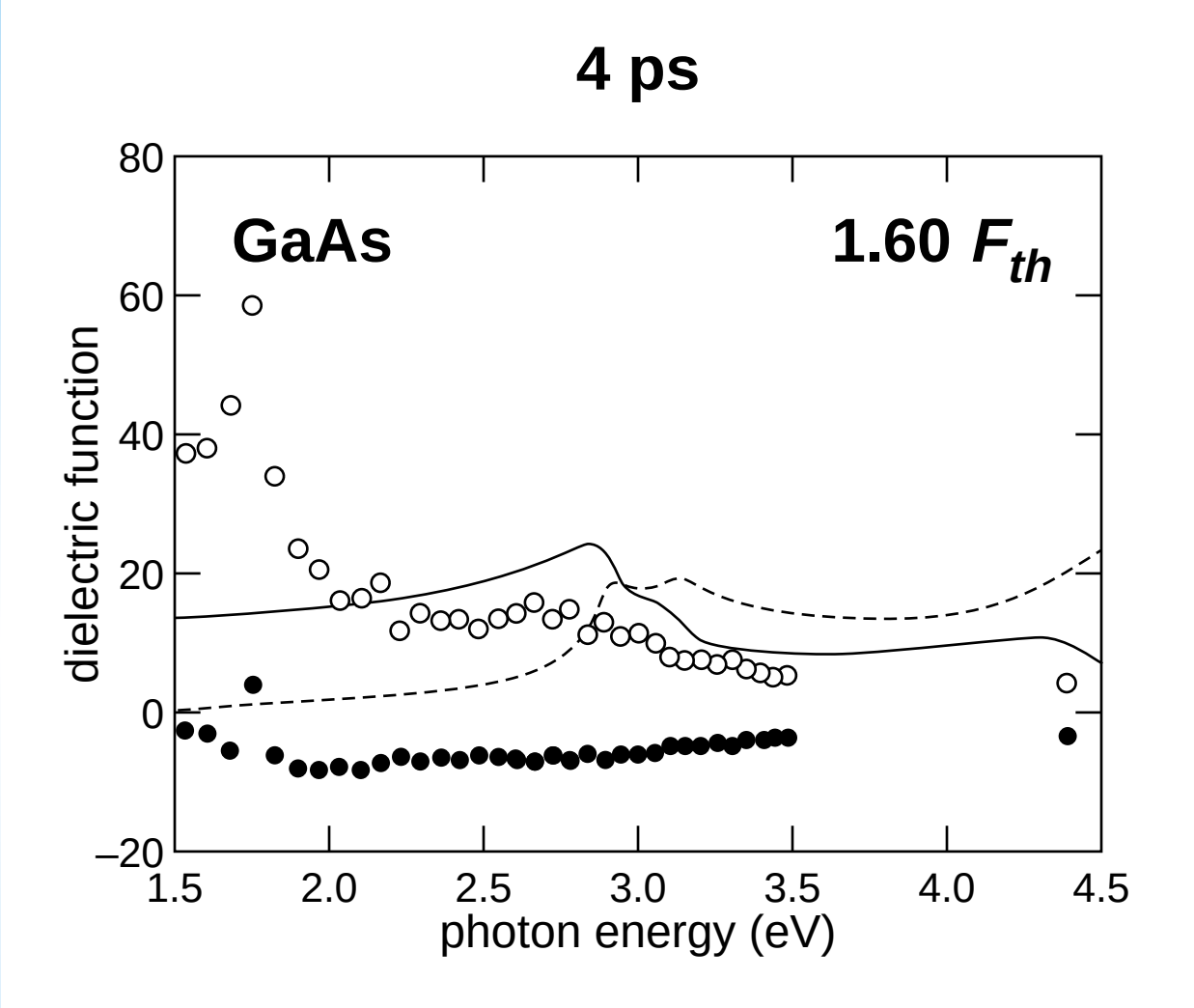
Results


1 ps
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

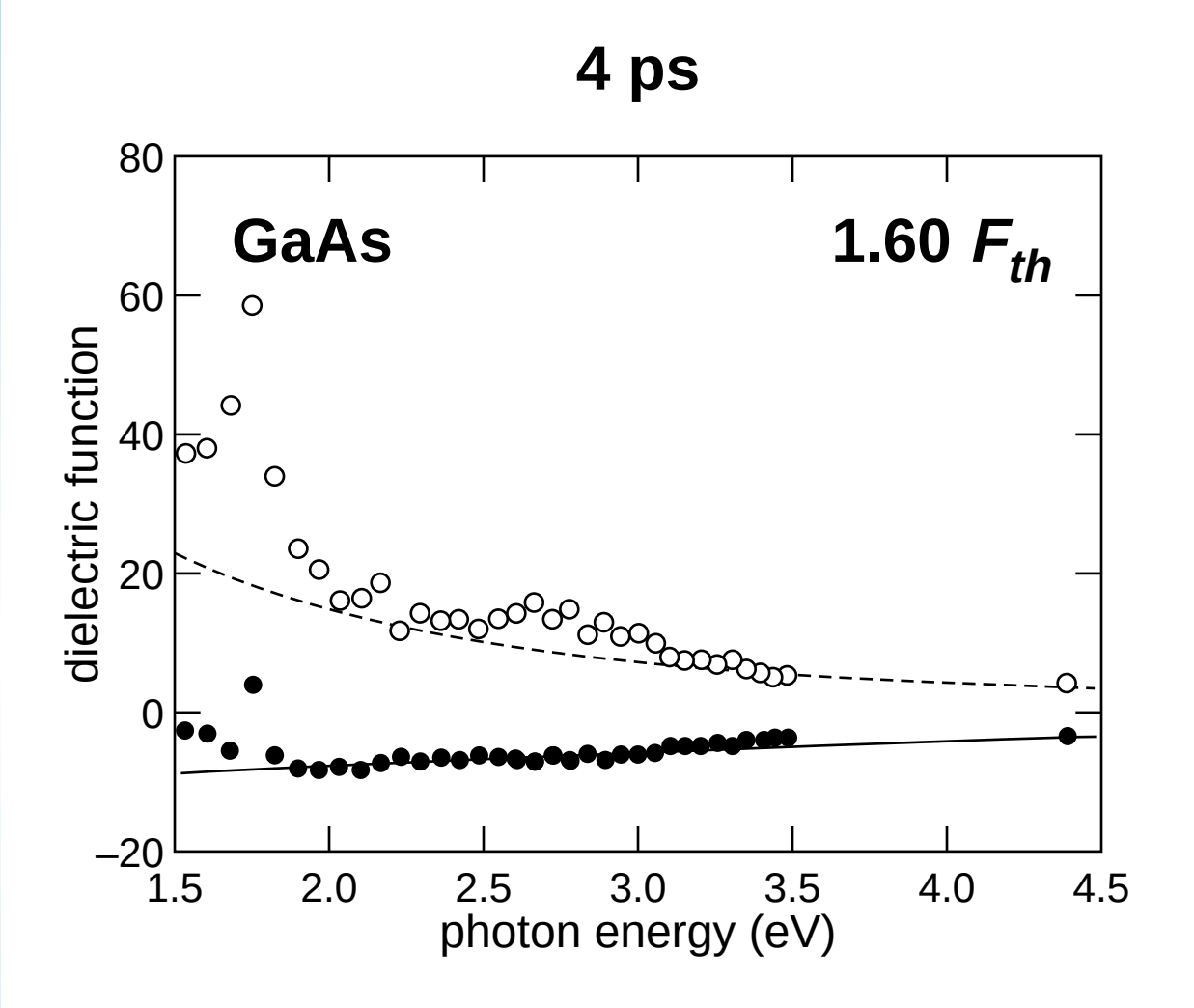
Results


2 ps
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

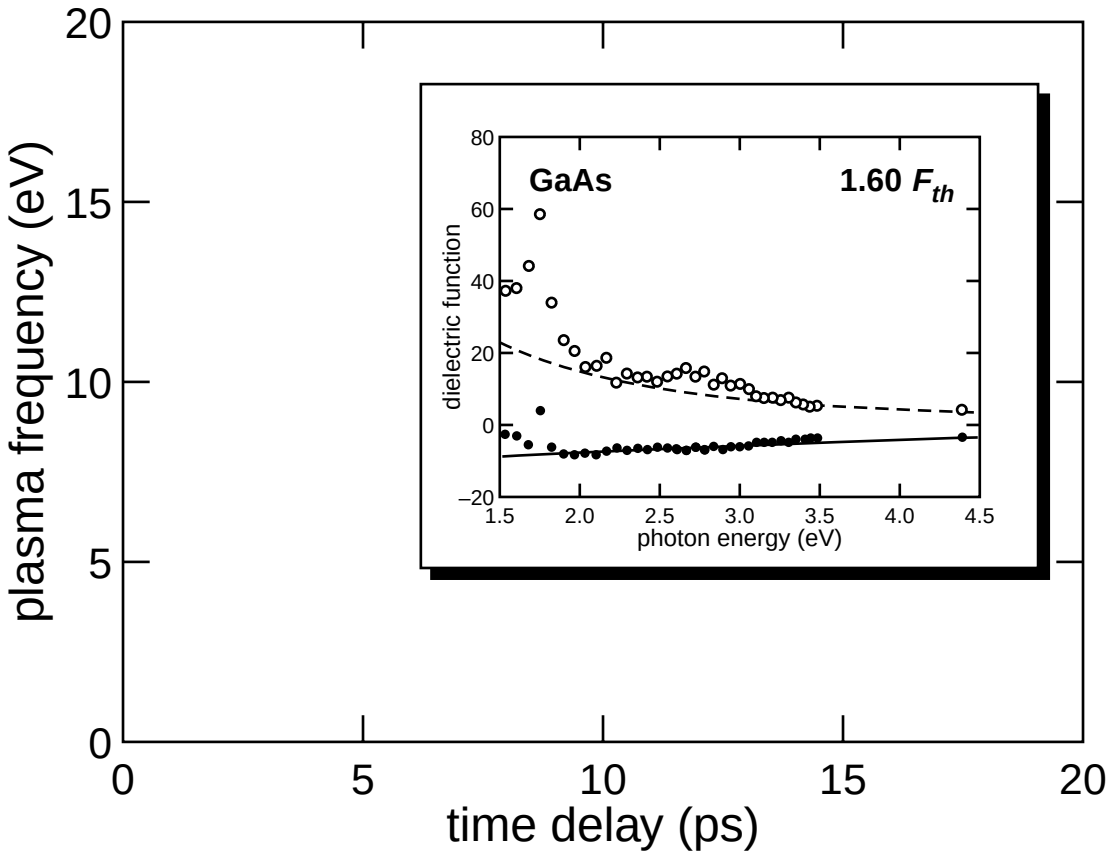
Results


4 ps
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

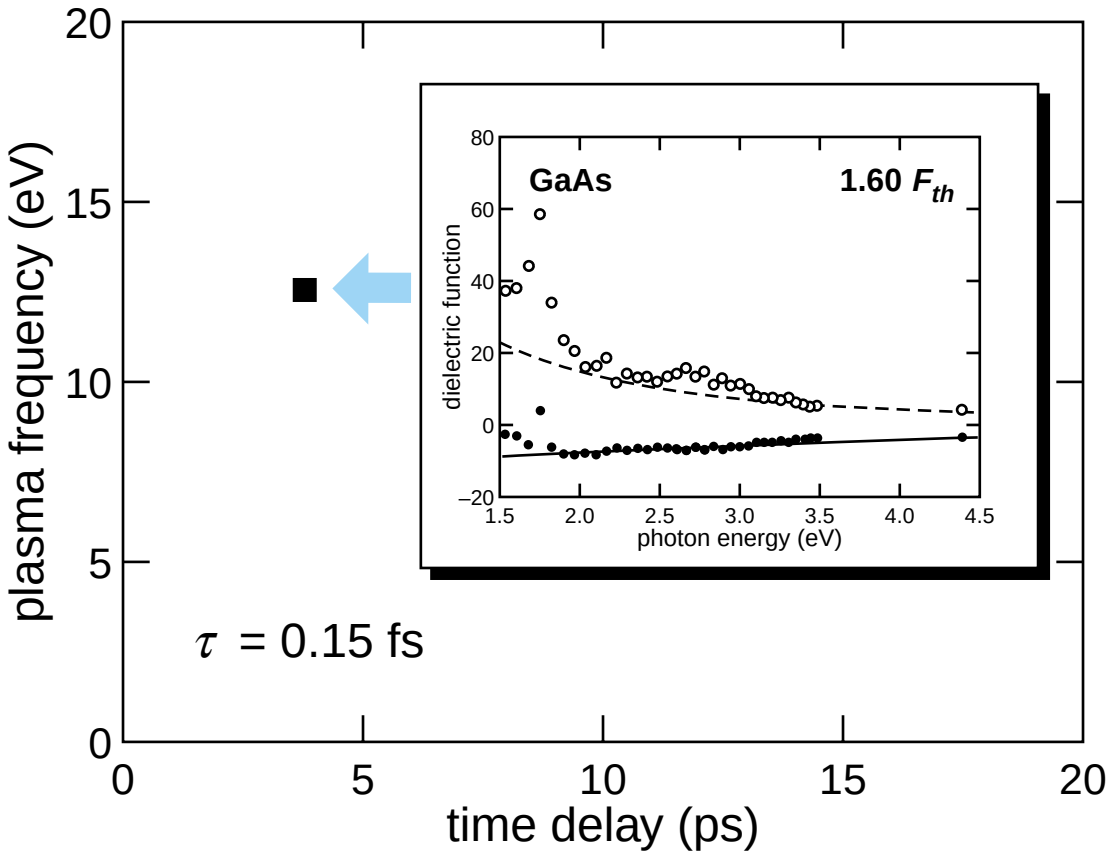
Results


4 ps
GaAs
1.60 F_{th}
dielectric function
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5
photon energy (eV)

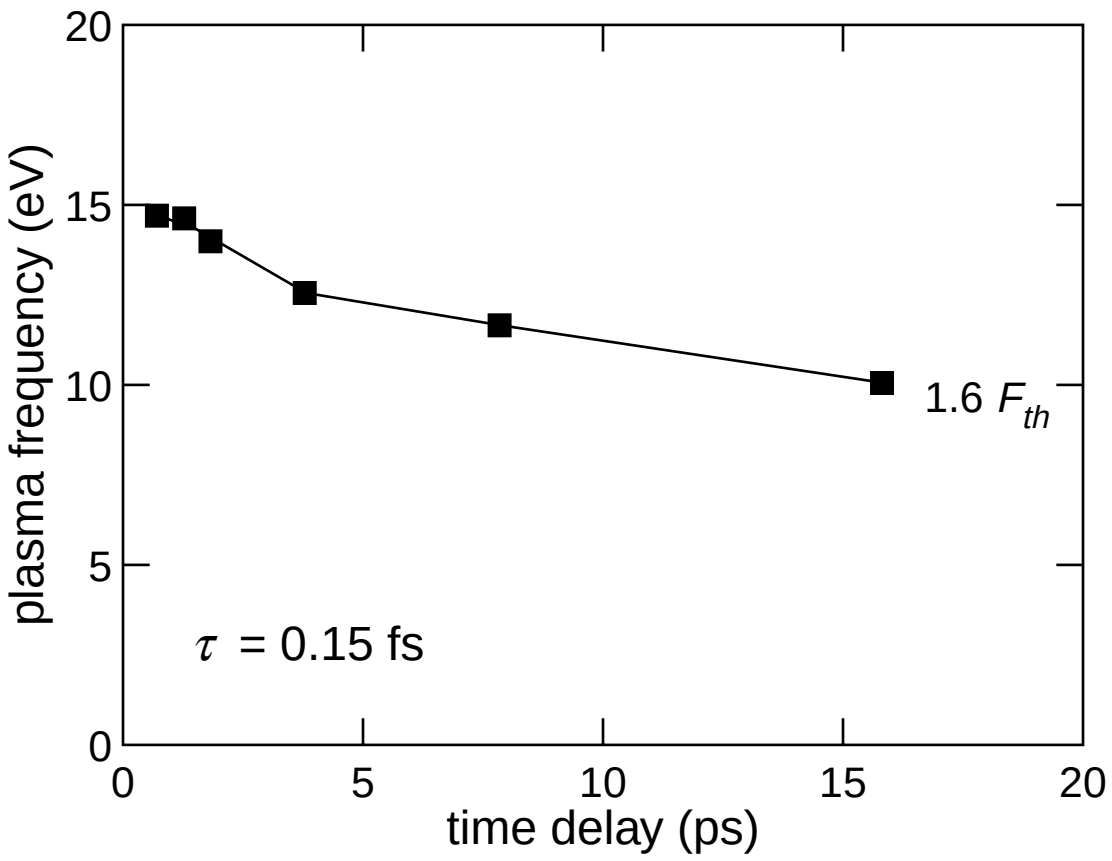
Results


plasma frequency (eV)
time delay (ps)
0
5
10
15
20
GaAs
1.60 F_{th}
dielectric function
photon energy (eV)
80
60
40
20
0
–20
1.5
2.0
2.5
3.0
3.5
4.0
4.5

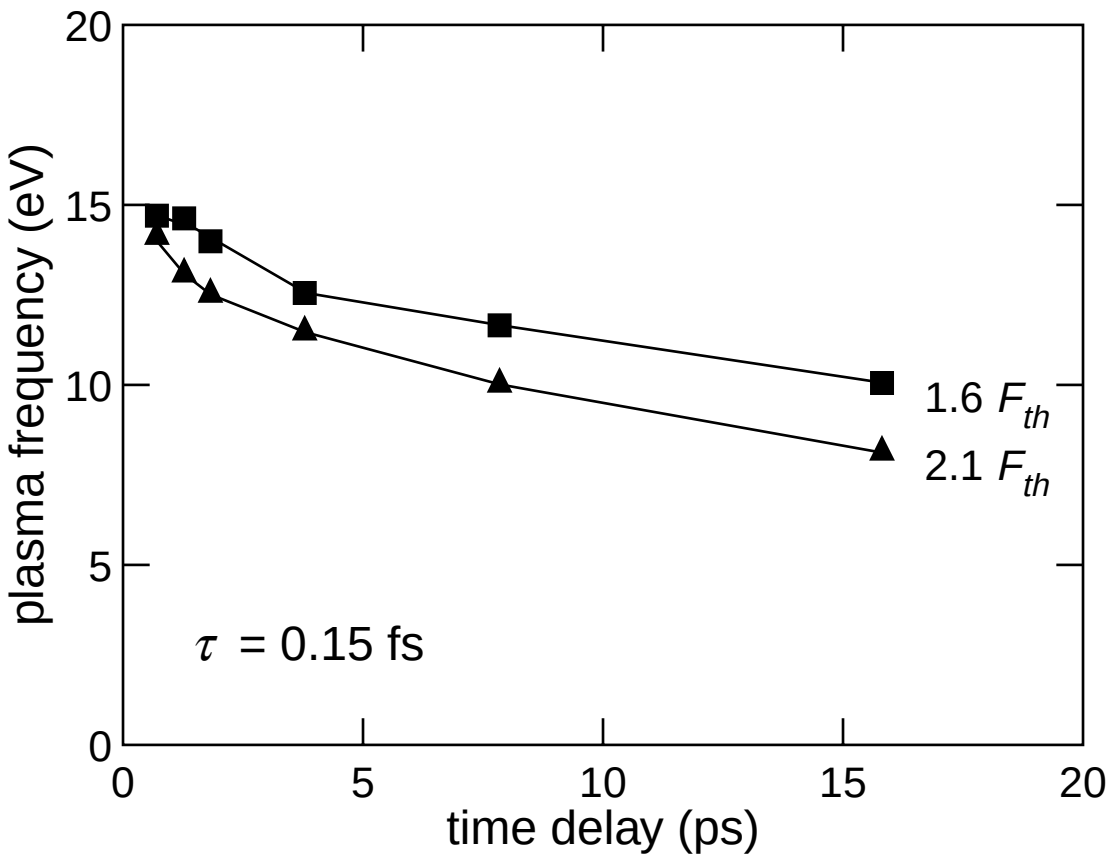
Results


plasma frequency (eV)
time delay (ps)
0
5
10
15
20
τ = 0.15 fs
GaAs
1.60 F_{th}
dielectric function
photon energy (eV)
80
60
40
20
0
−20
1.5
2.0
2.5
3.0
3.5
4.0
4.5

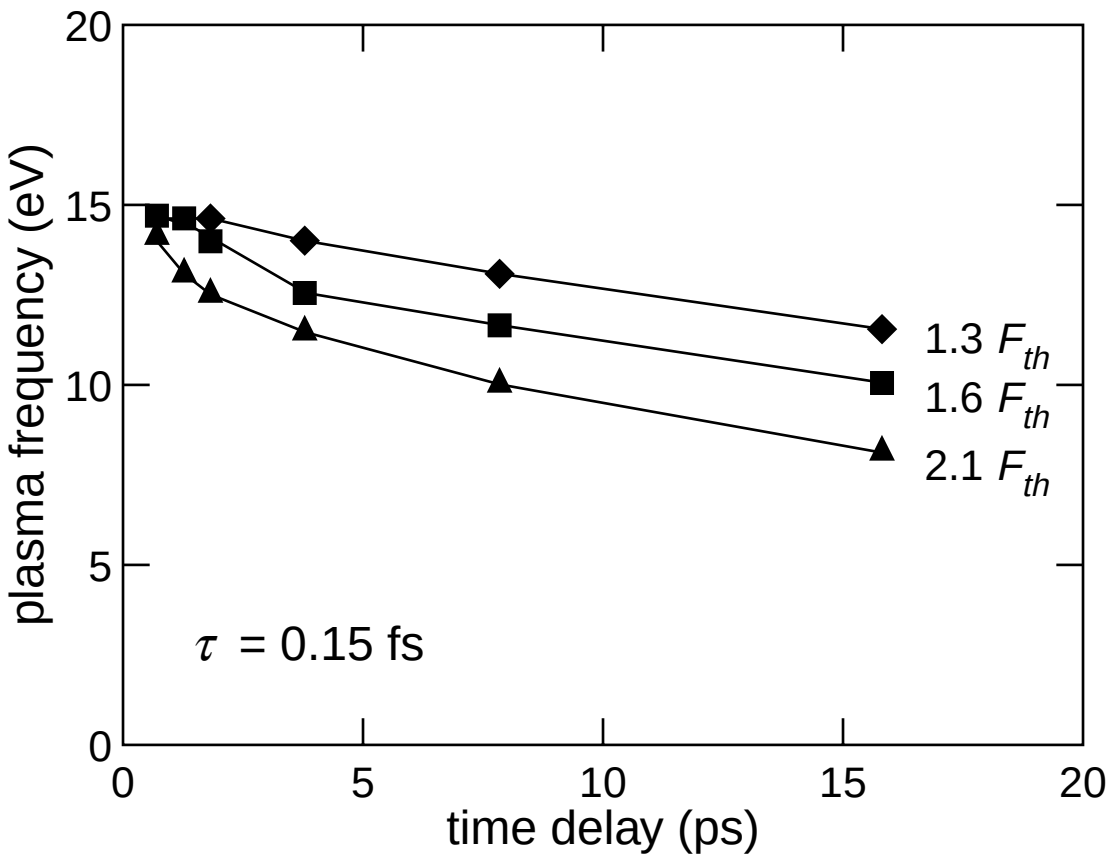
Results


20
15
10
5
0
plasma frequency (eV)
0
5
10
15
20
time delay (ps)
1.6 F_{th}
τ = 0.15 fs

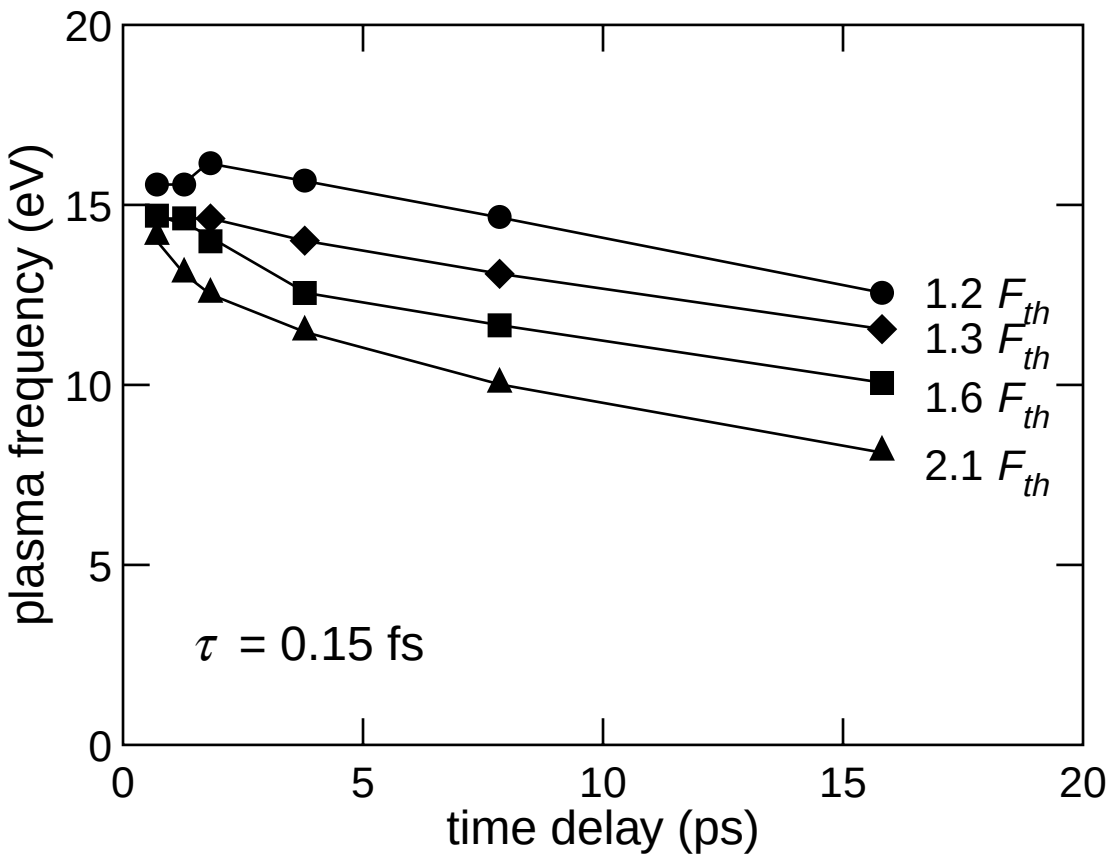
Results


20
15
10
5
0
plasma frequency (eV)
0
5
10
15
20
time delay (ps)
1.6 F_{th}
2.1 F_{th}
τ = 0.15 fs

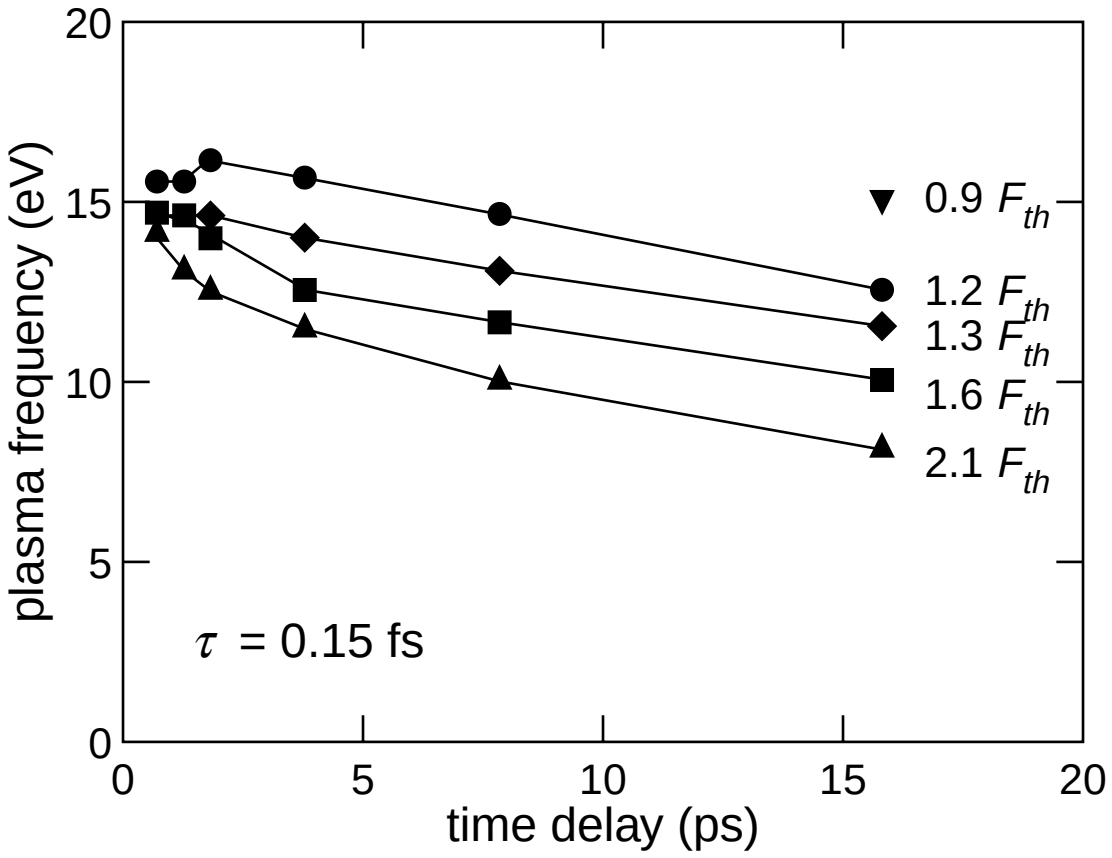
Results


20
15
10
5
0
plasma frequency (eV)
0
5
10
15
20
time delay (ps)
1.3 F_{th}
1.6 F_{th}
2.1 F_{th}
τ = 0.15 fs

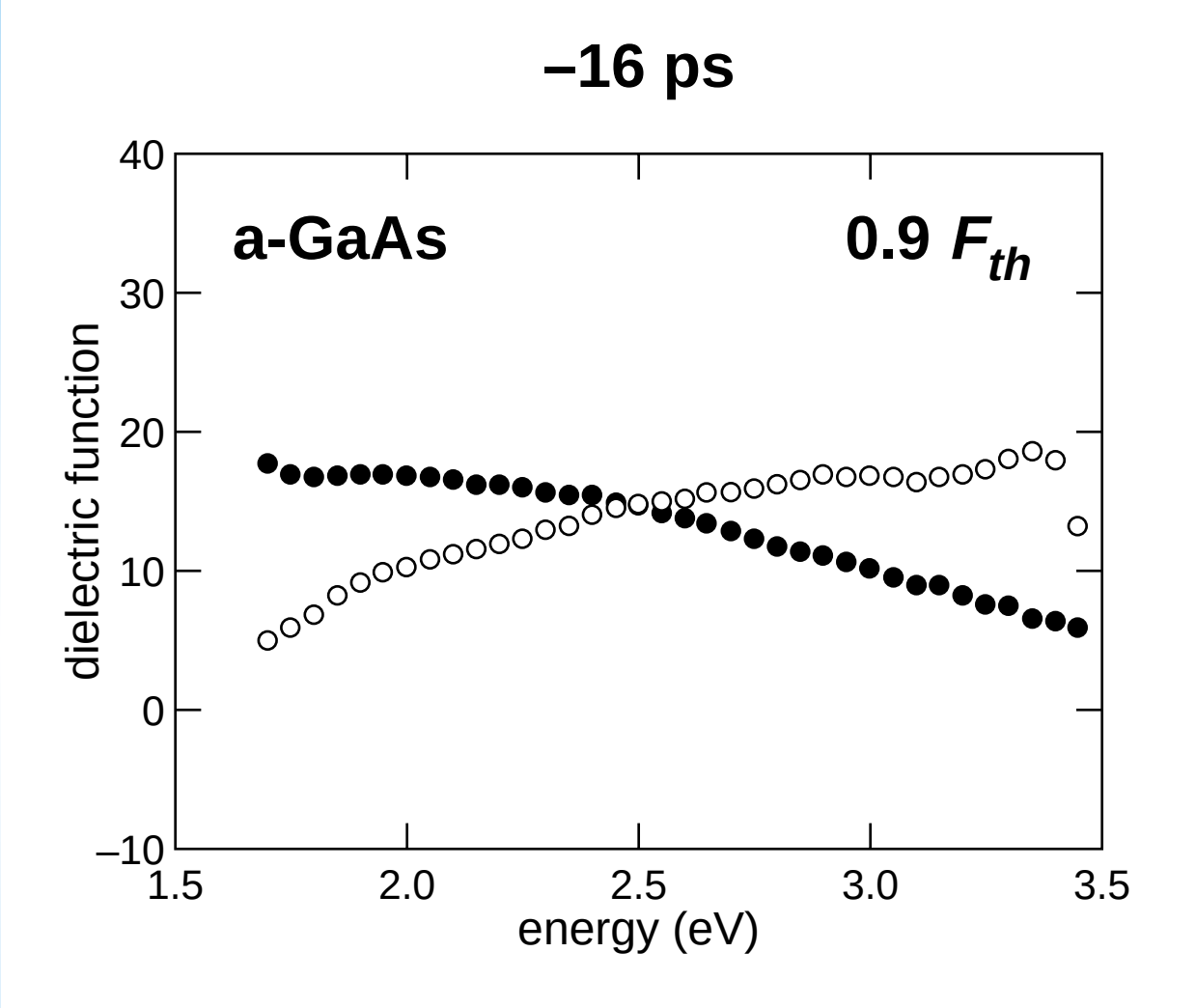
Results


20
15
10
5
0
0
5
10
15
20
plasma frequency (eV)
time delay (ps)
1.2 F_{th}
1.3 F_{th}
1.6 F_{th}
2.1 F_{th}
τ = 0.15 fs

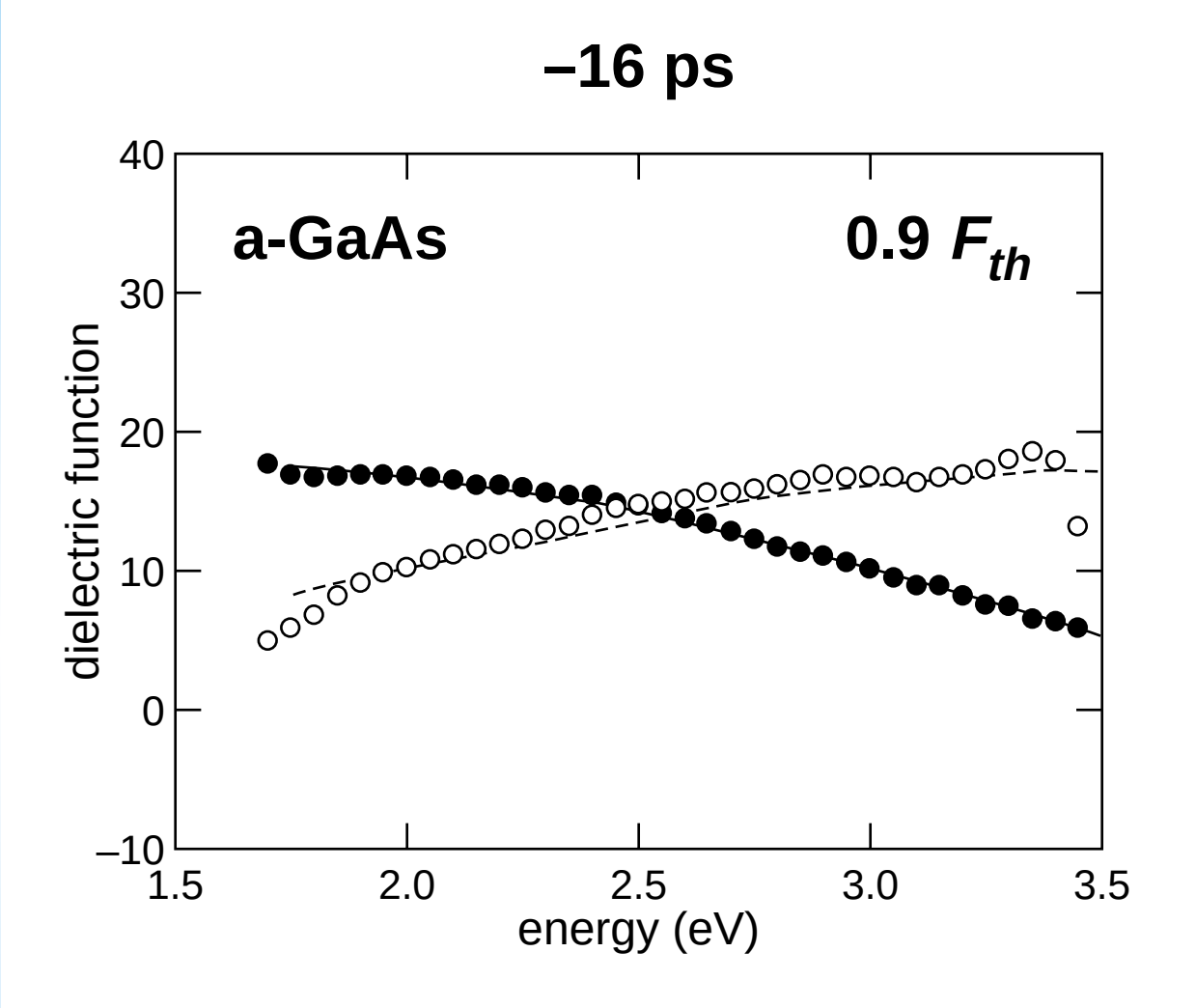
Results


20
15
10
5
0
0
5
10
15
20
plasma frequency (eV)
time delay (ps)
0.9 F_{th}
1.2 F_{th}
1.3 F_{th}
1.6 F_{th}
2.1 F_{th}
τ = 0.15 fs

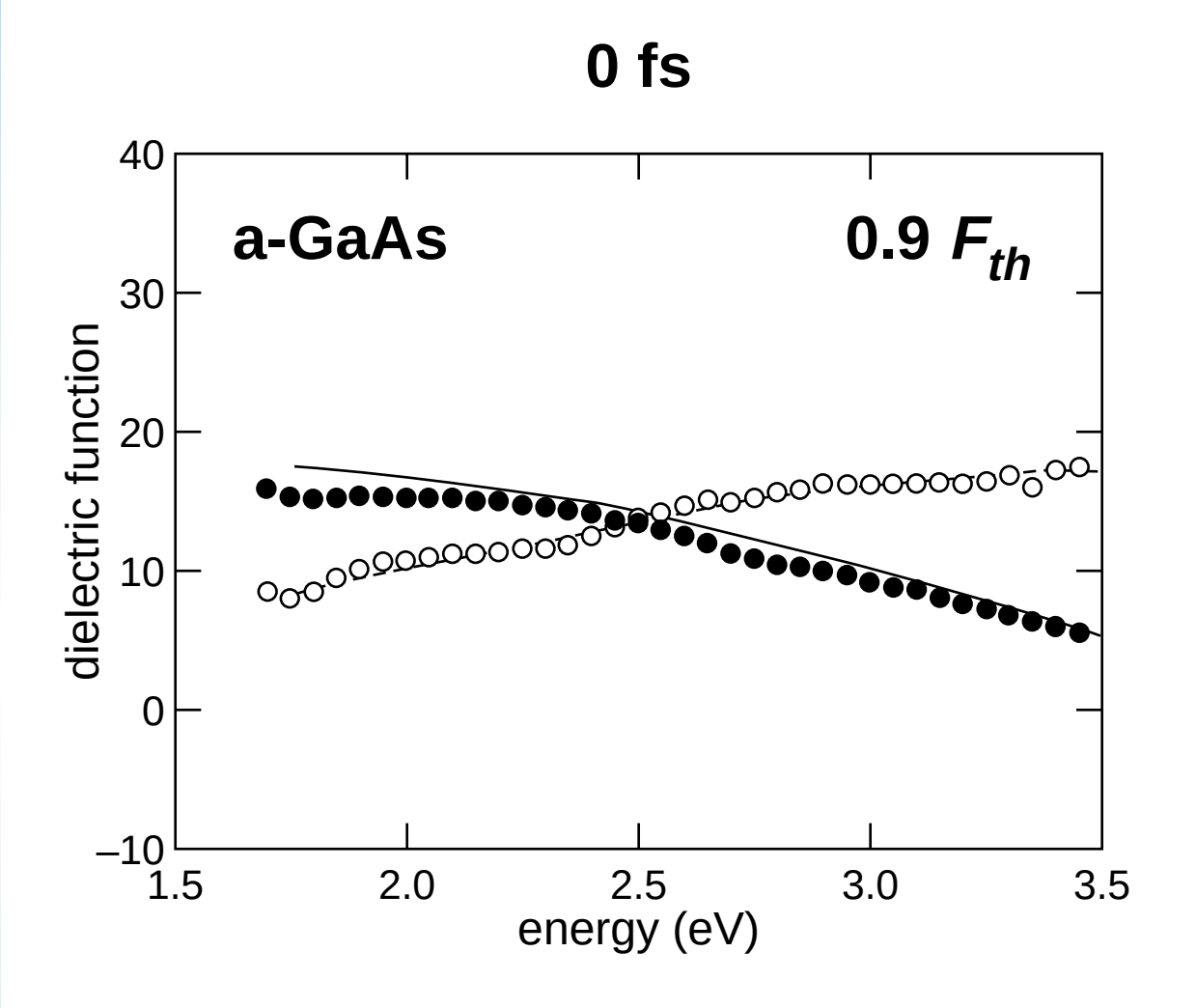
Results


–16 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

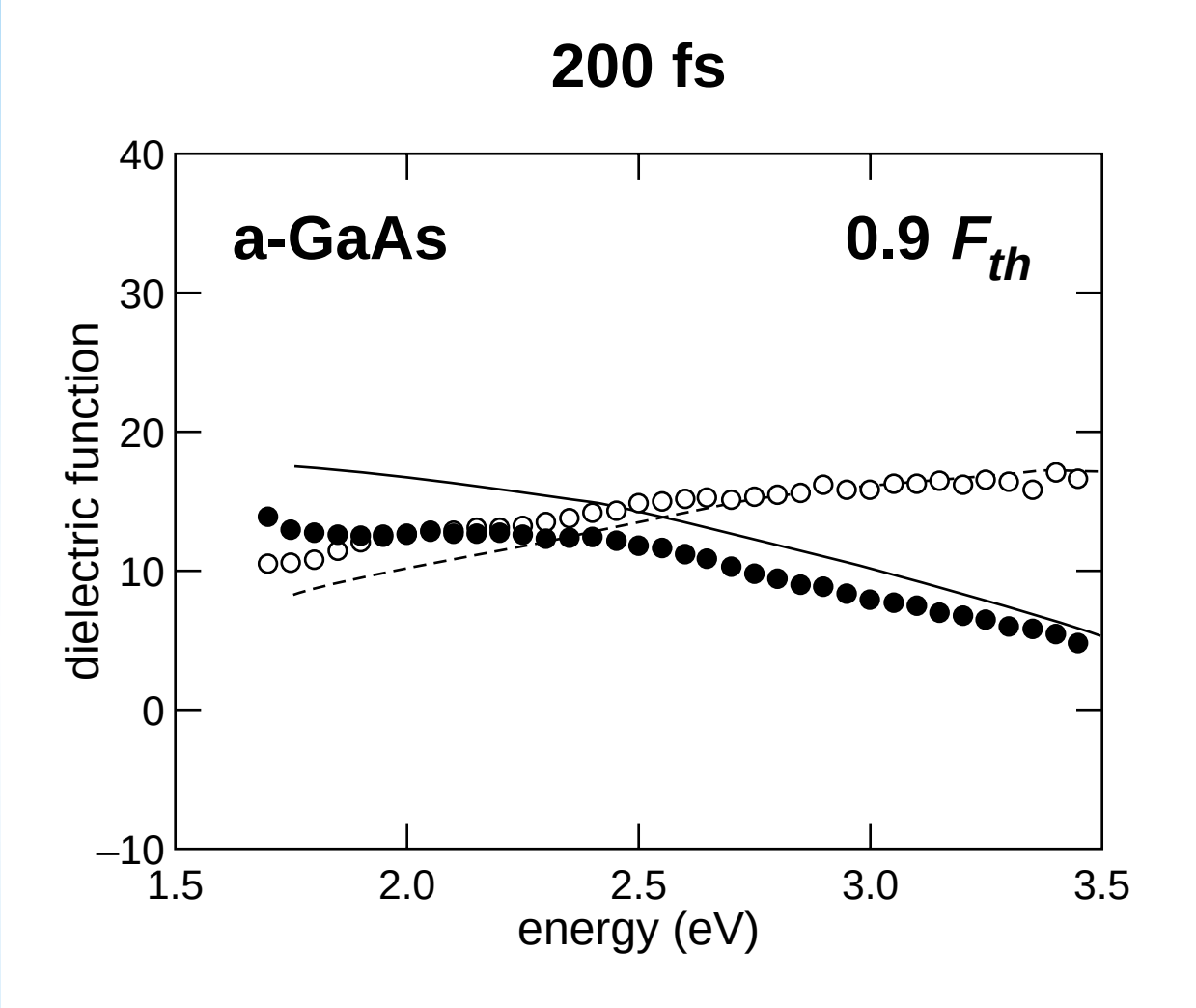
Results


–16 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

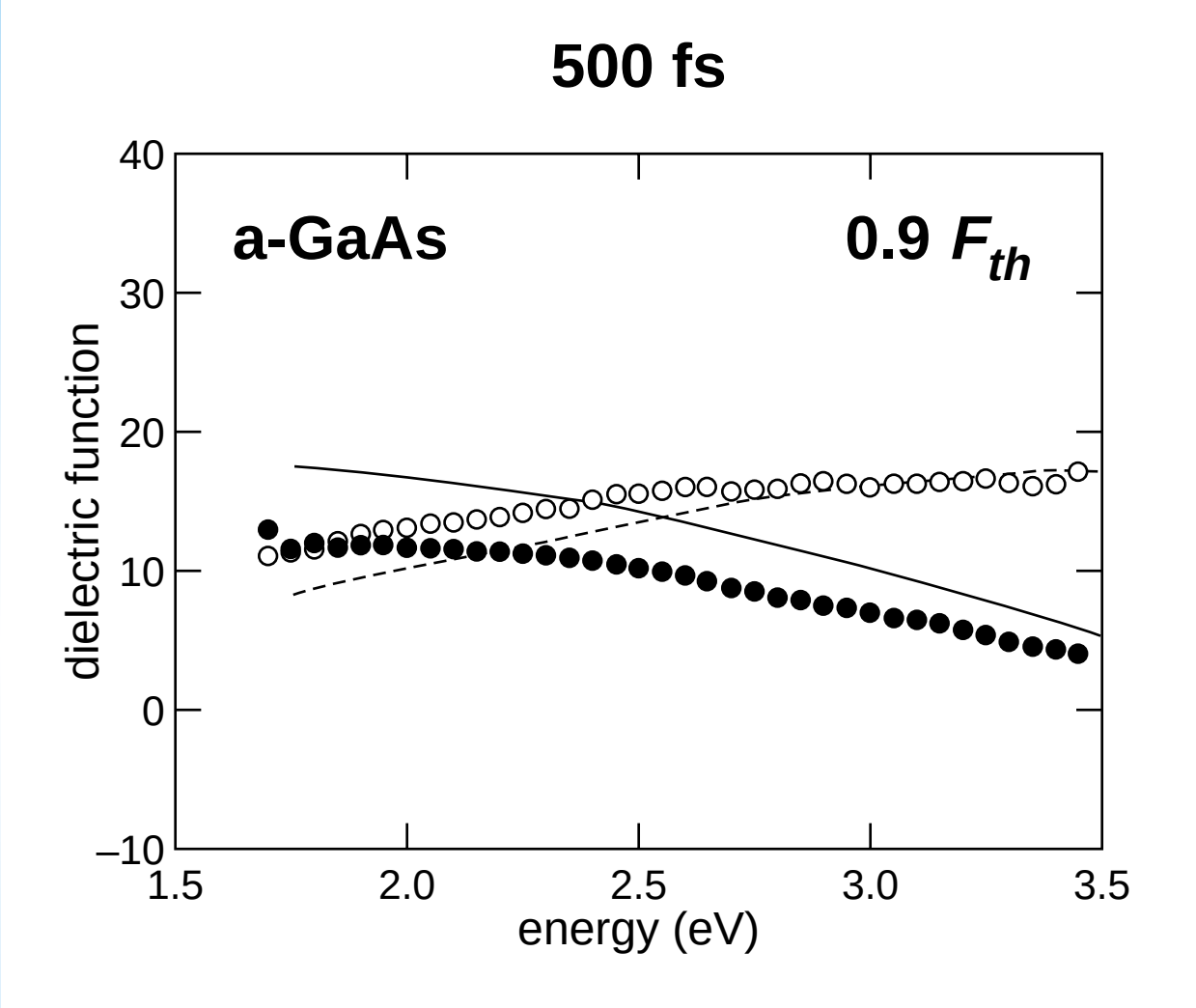
Results


0 fs
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

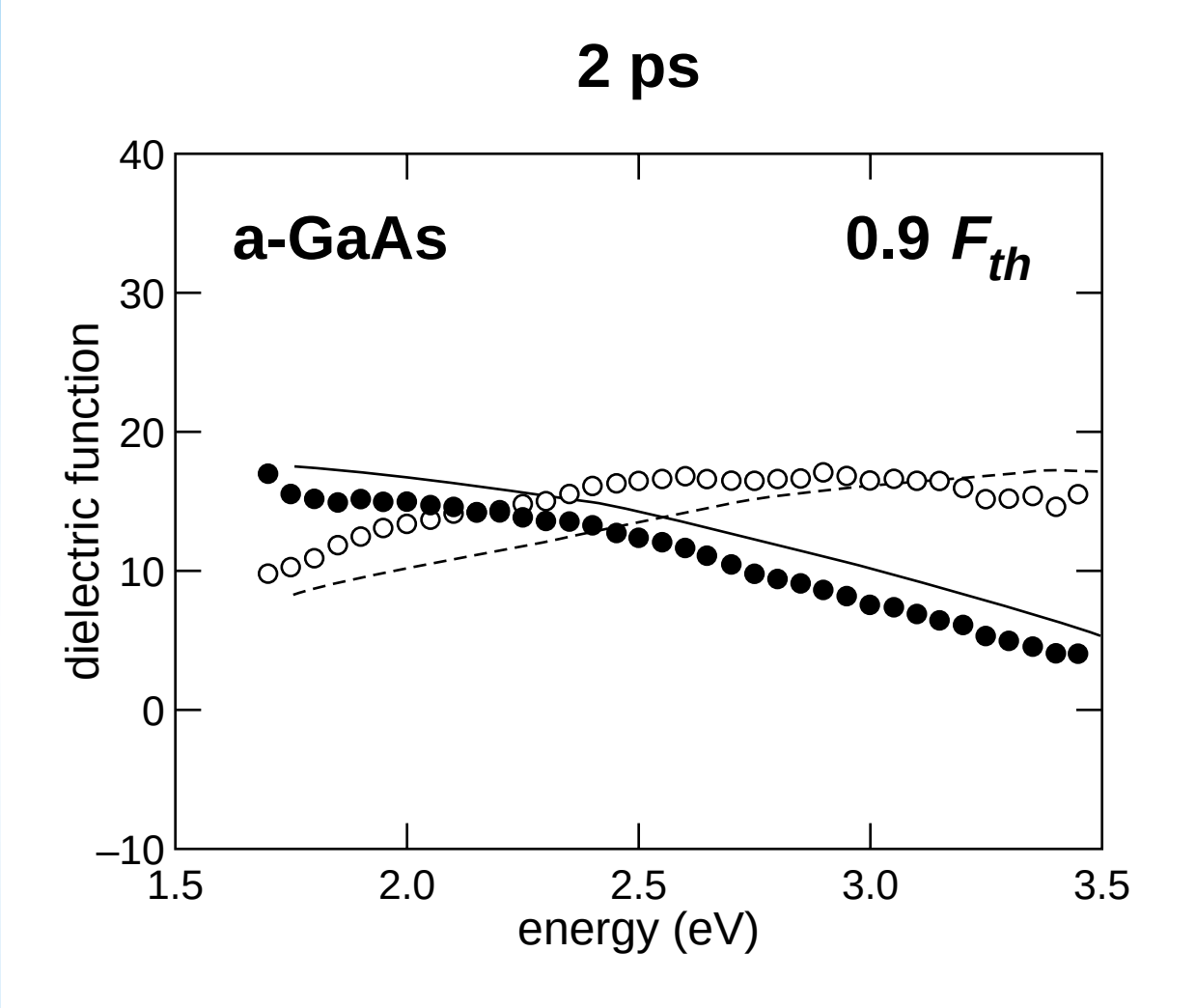
Results


200 fs
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

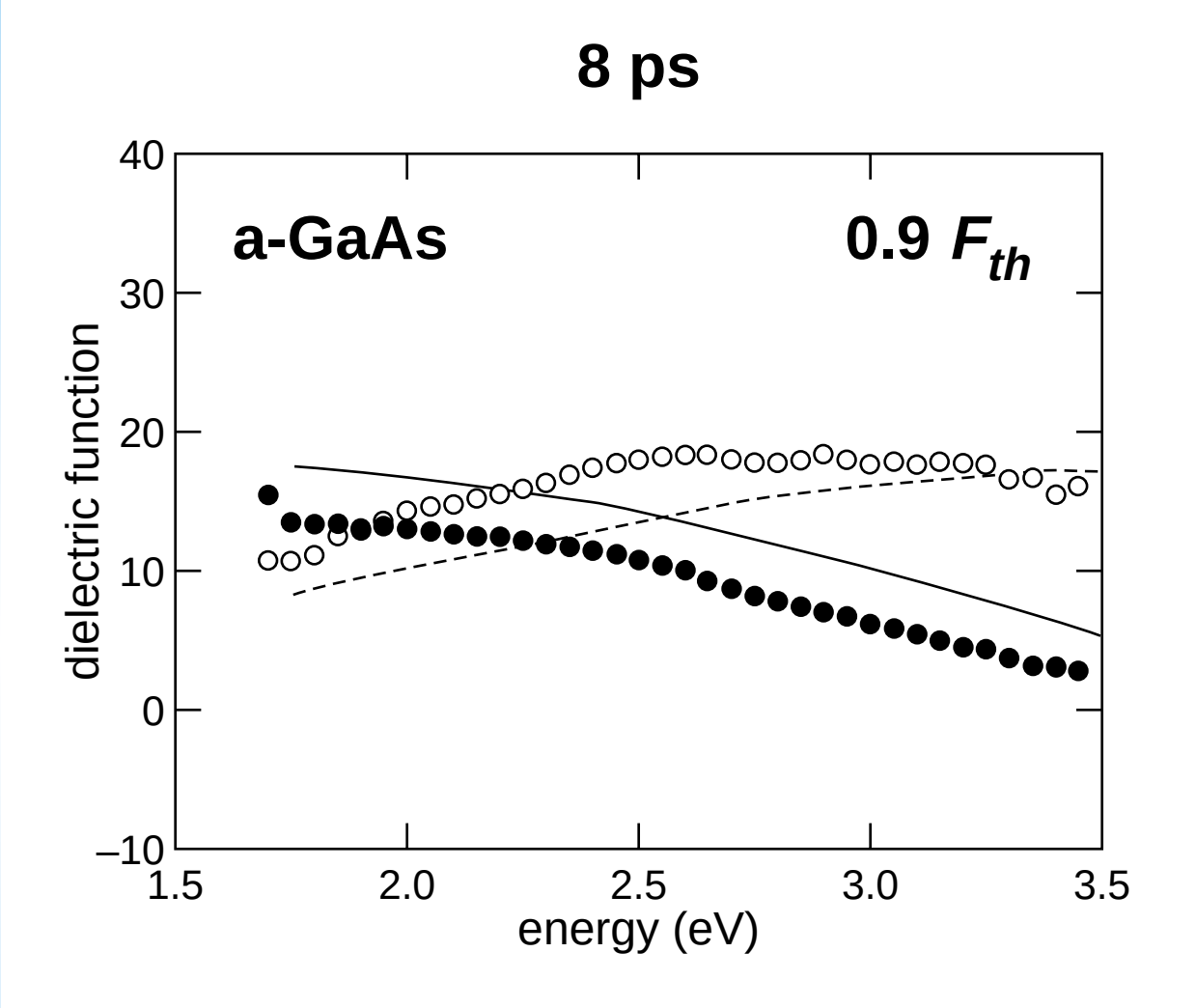
Results


500 fs
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

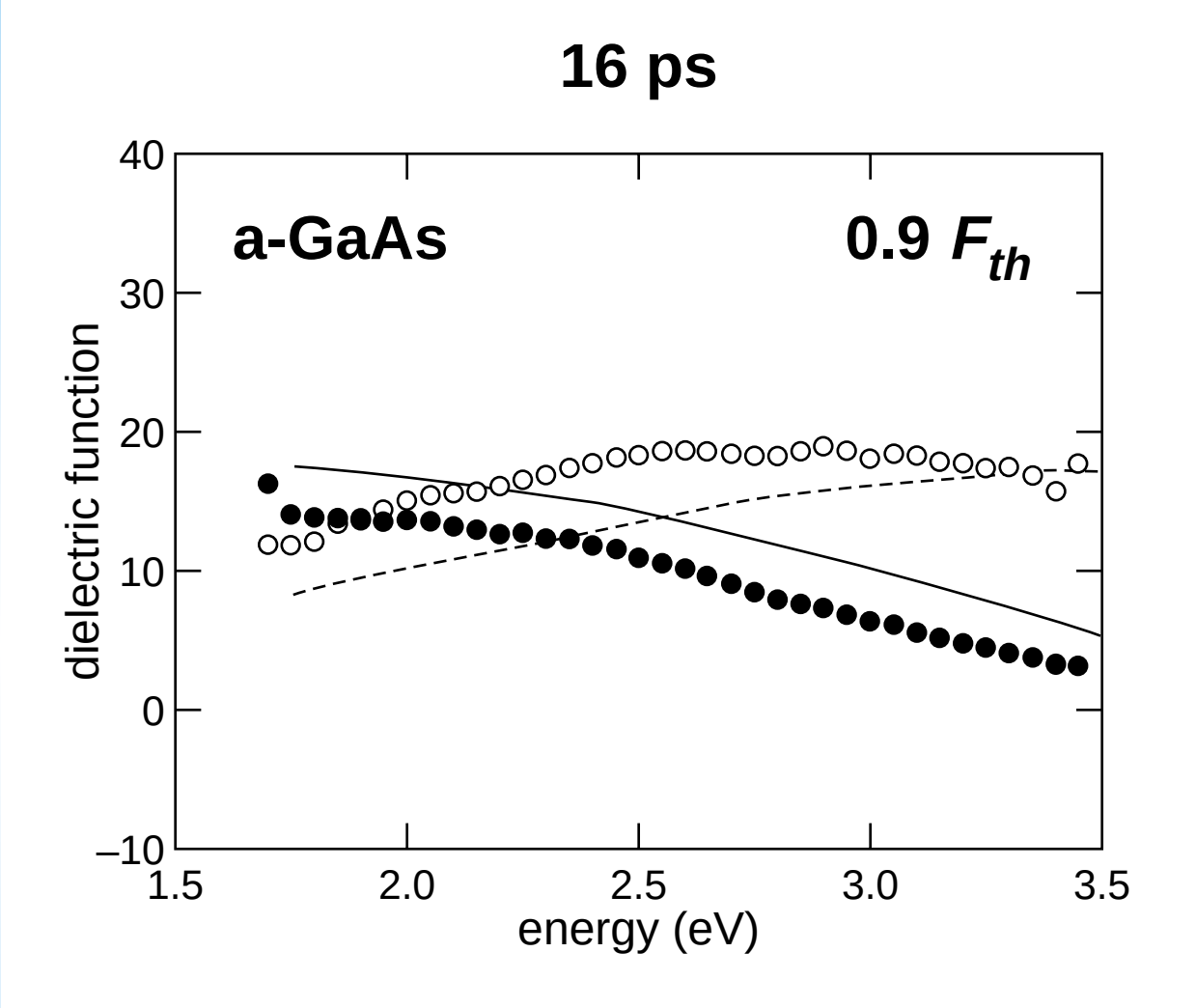
Results


2 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

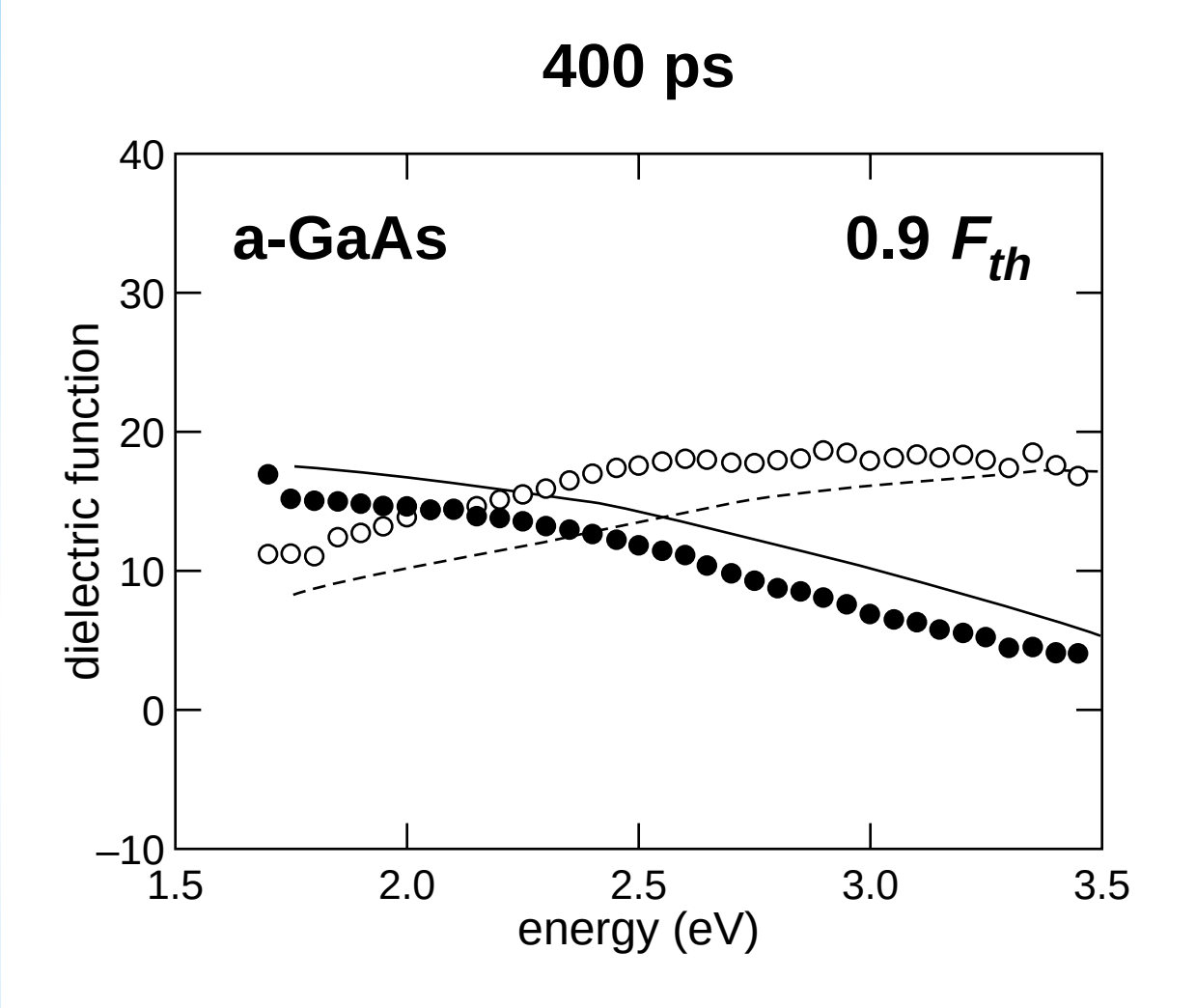
Results


8 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

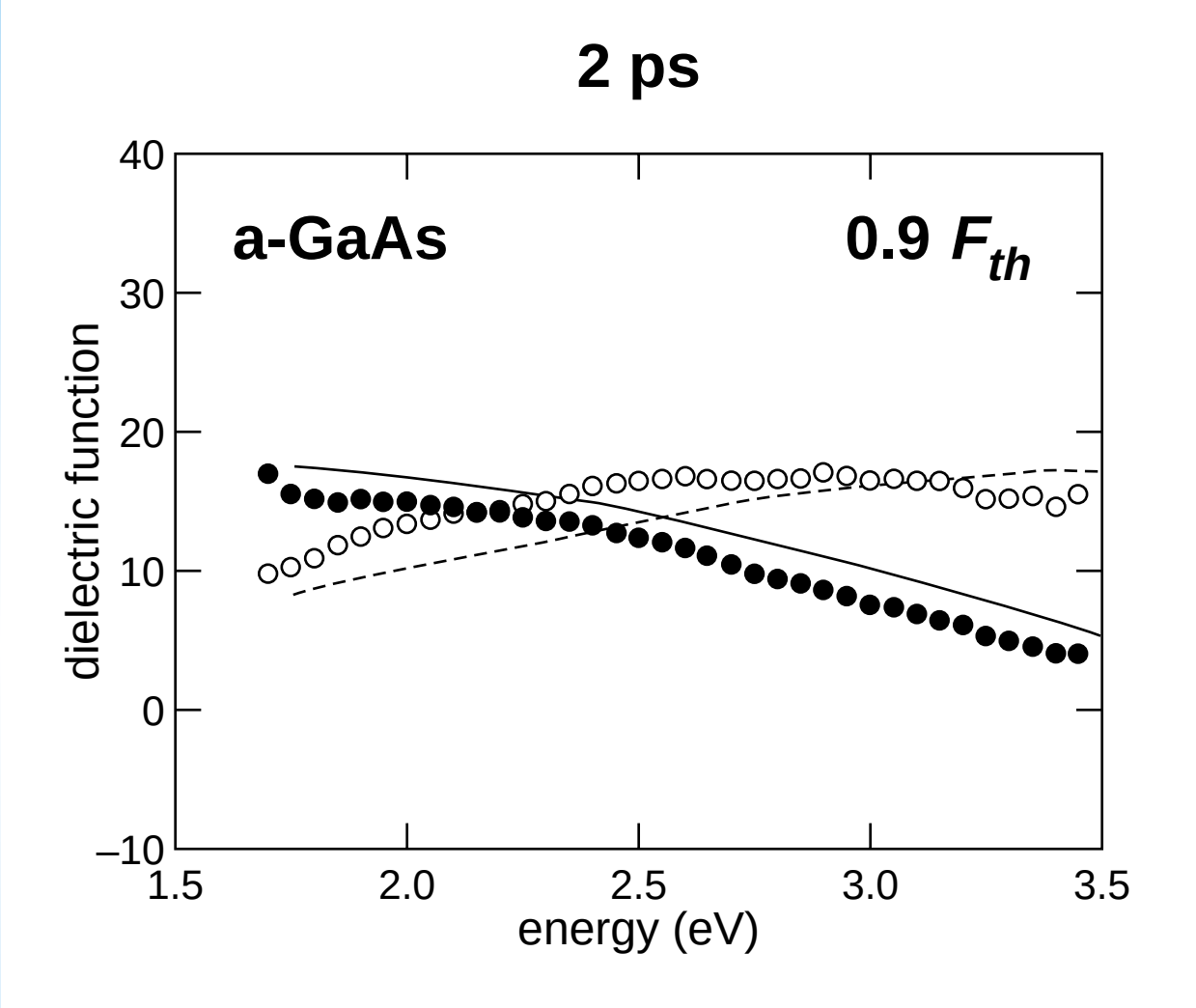
Results


16 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

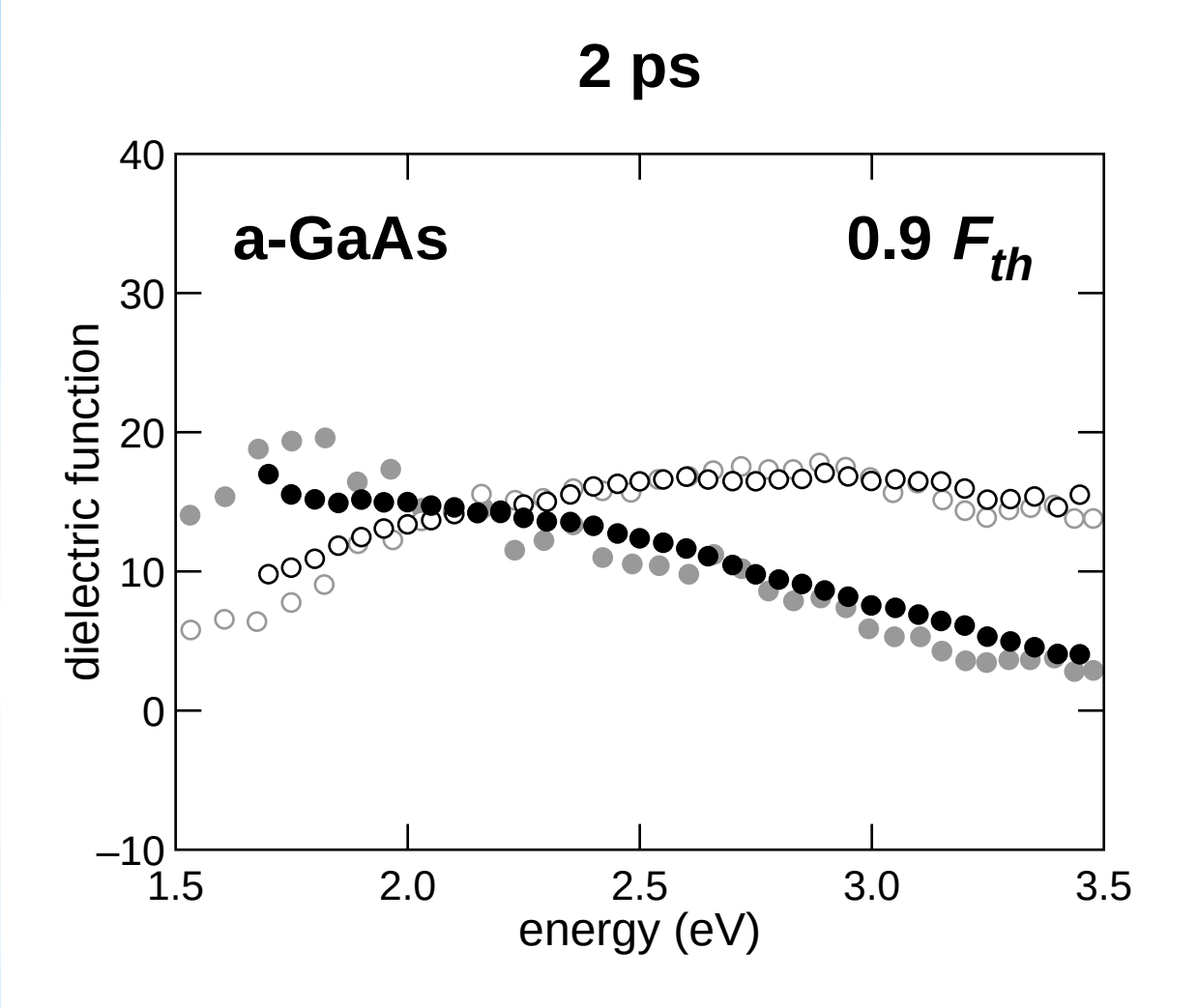
Results


400 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

Results

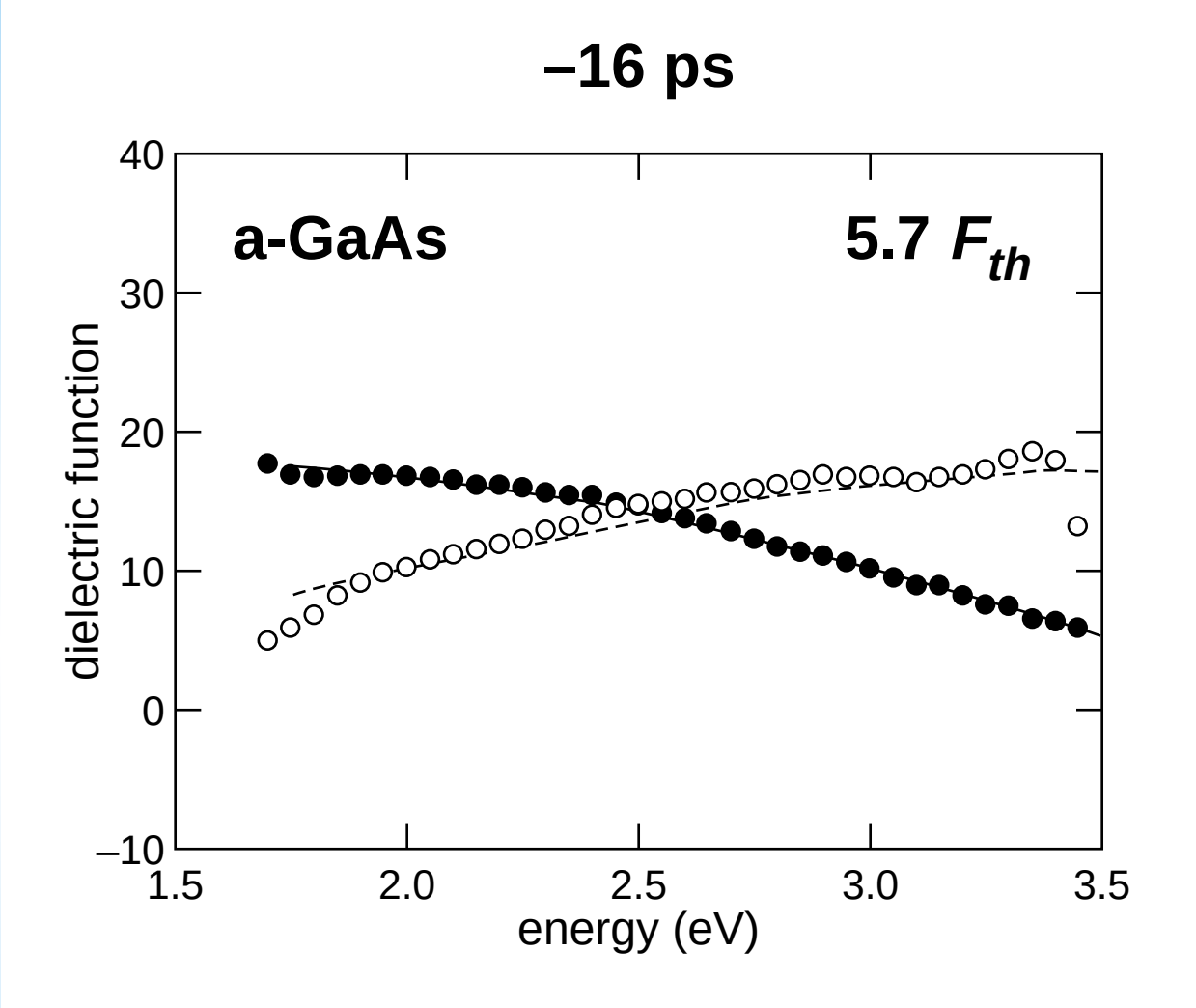

2 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

Results

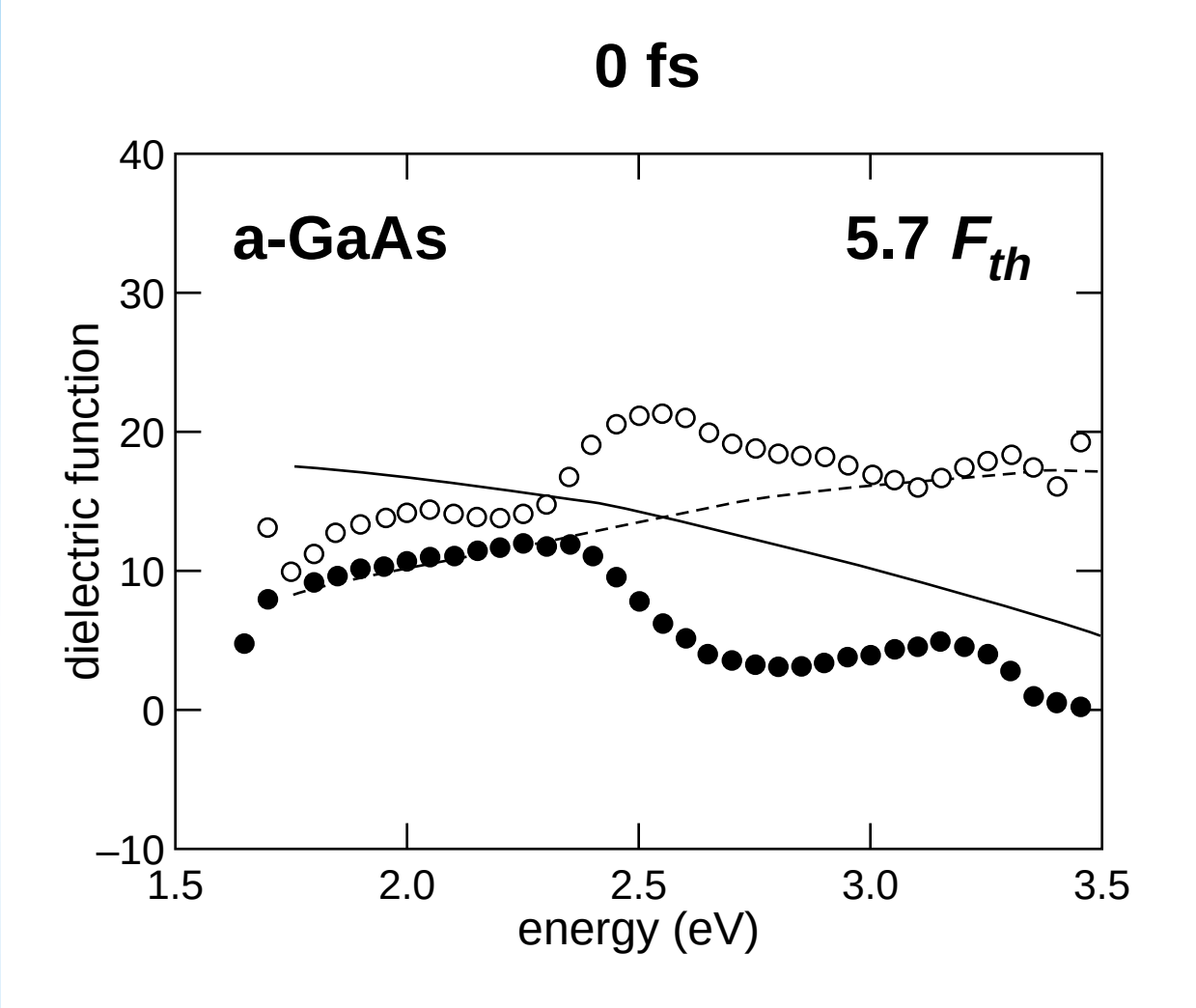


matches disordered c-GaAs

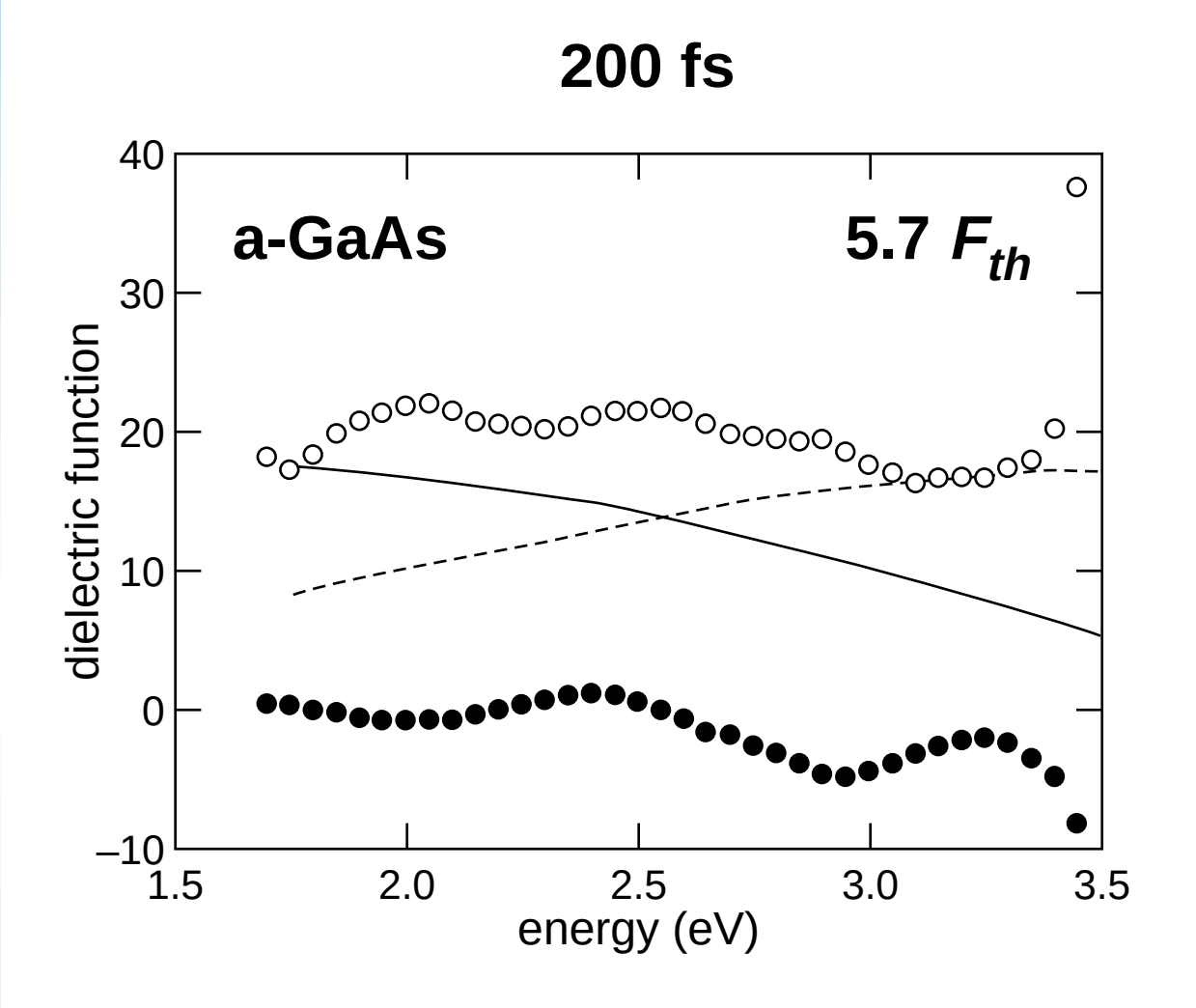
Results


–16 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

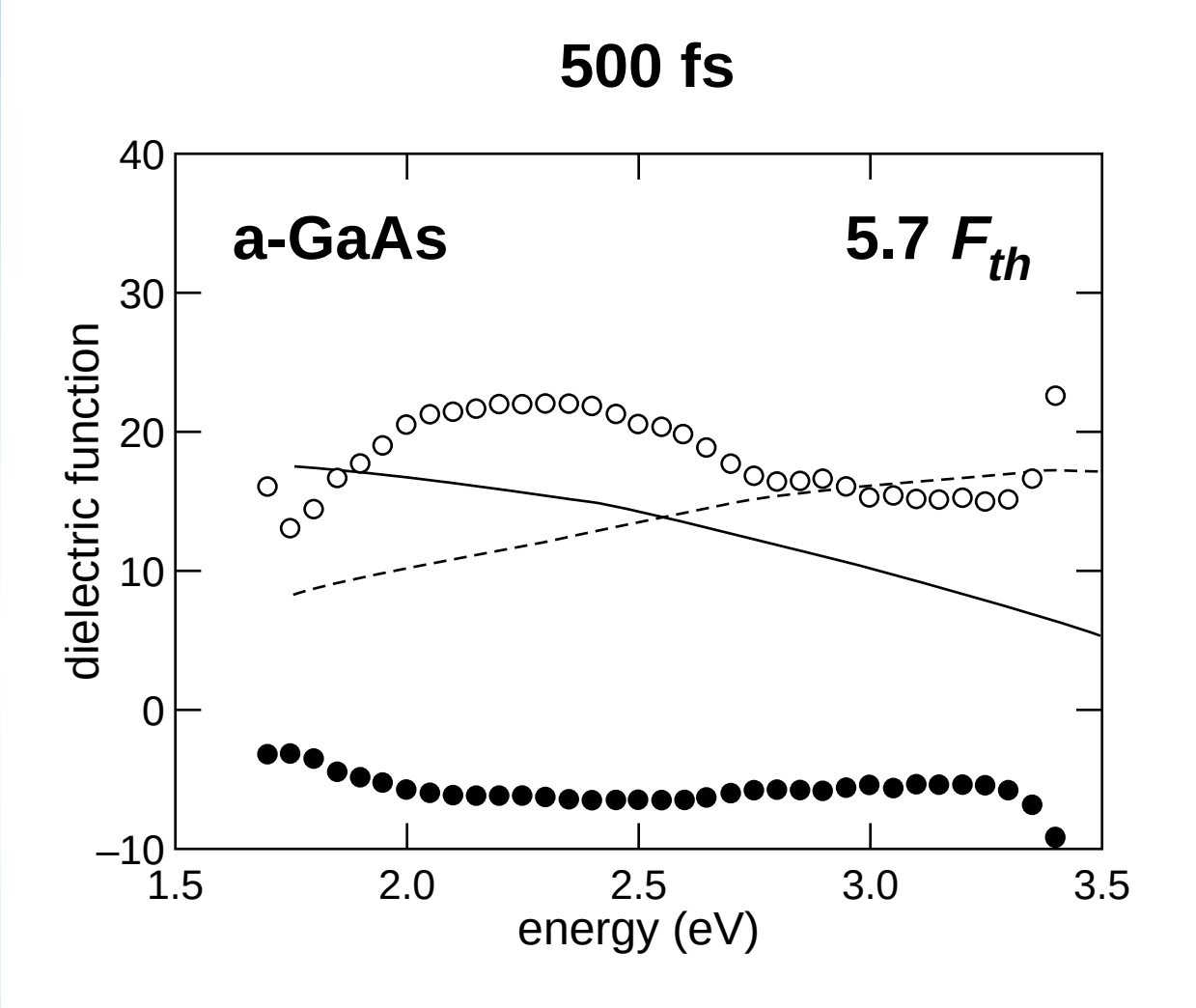
Results


0 fs
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

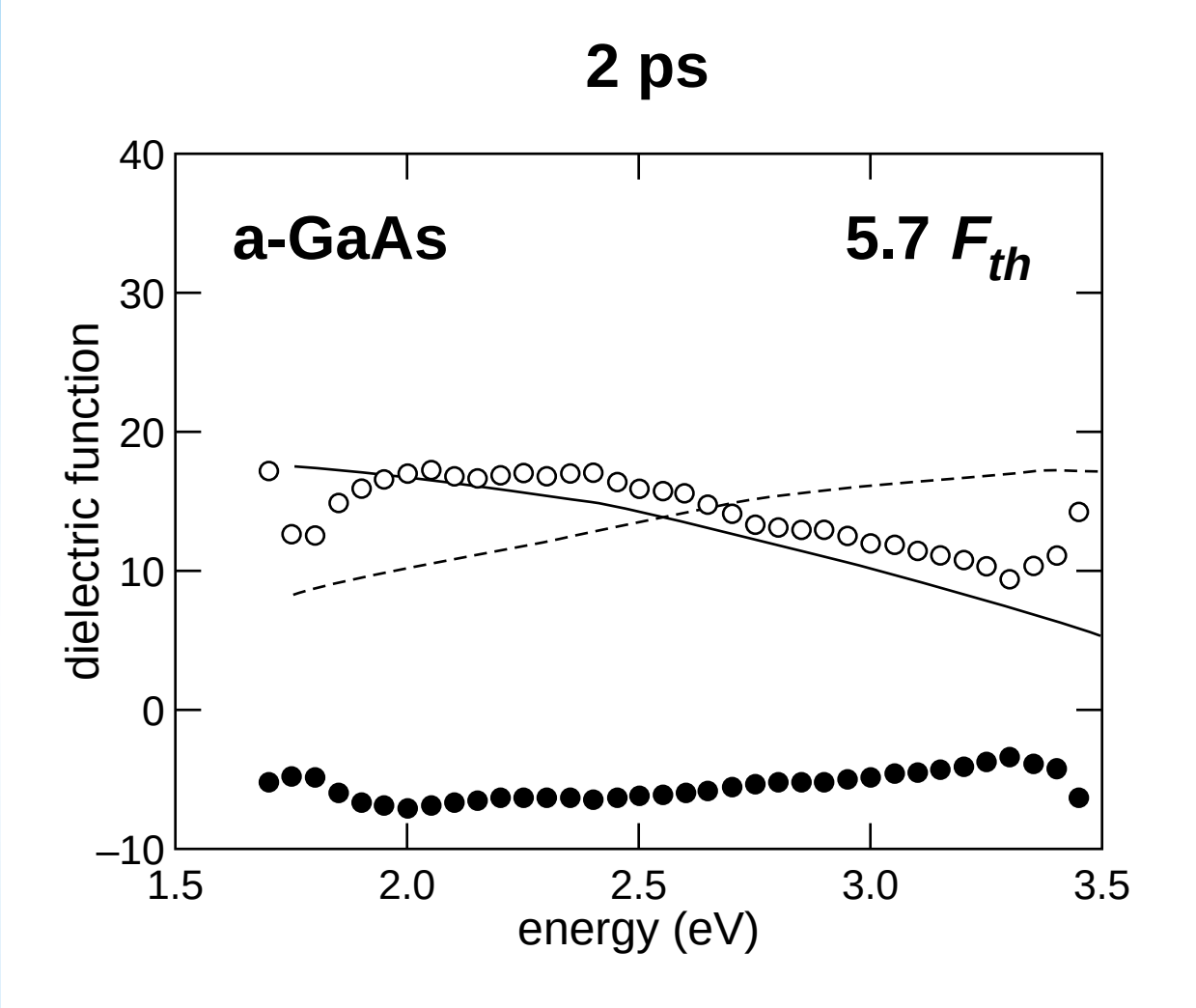
Results


200 fs
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

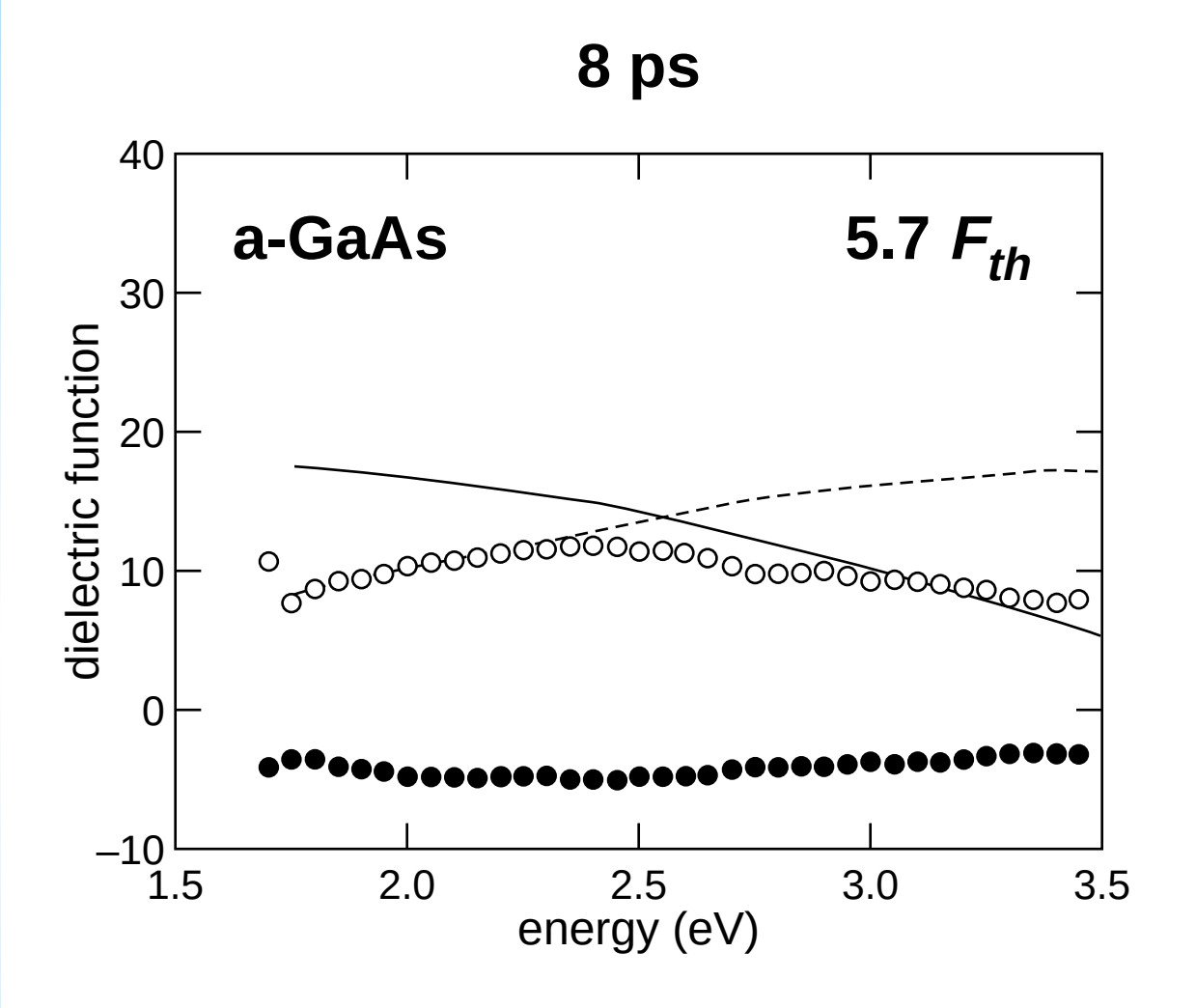
Results


500 fs
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

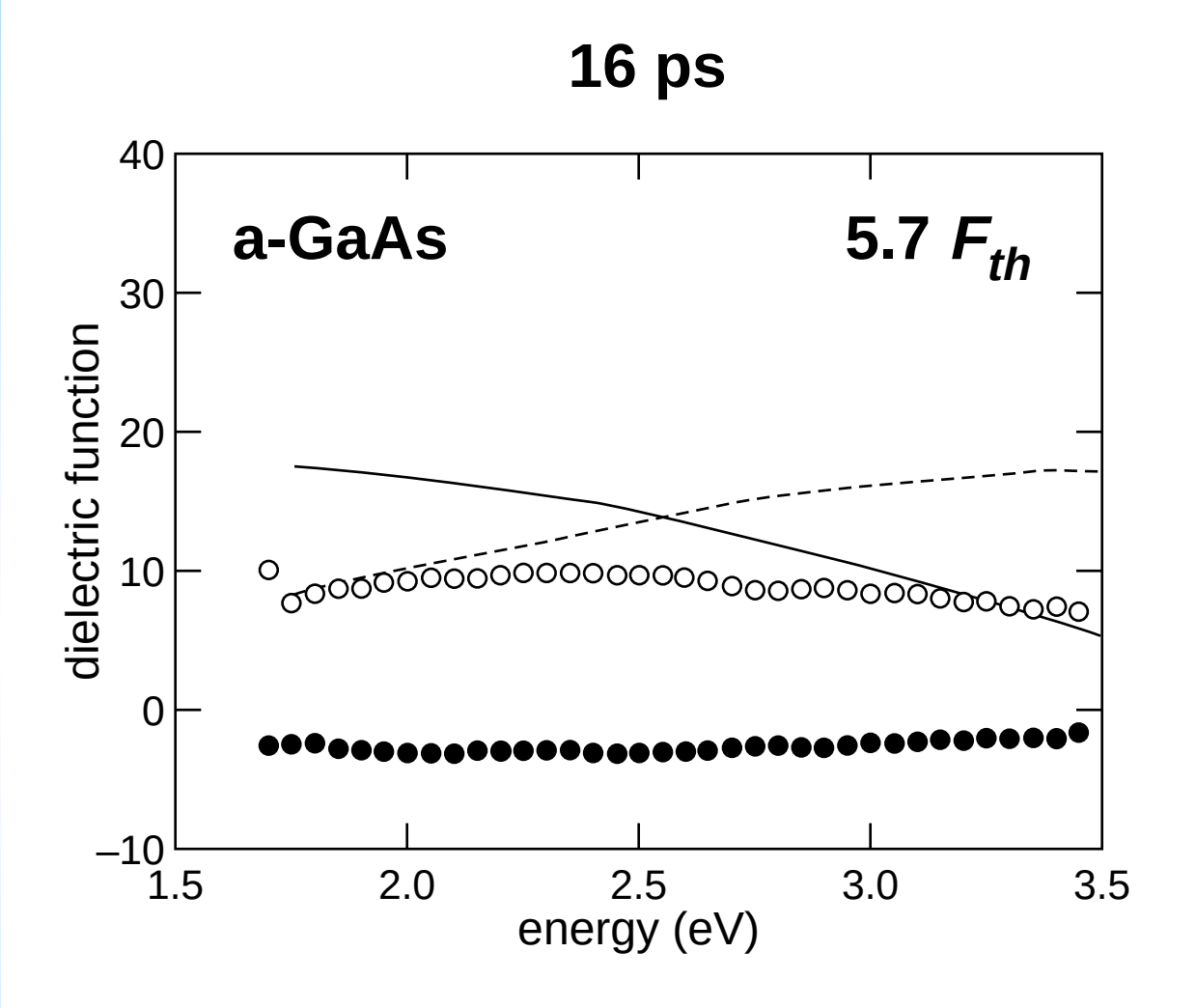
Results


2 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

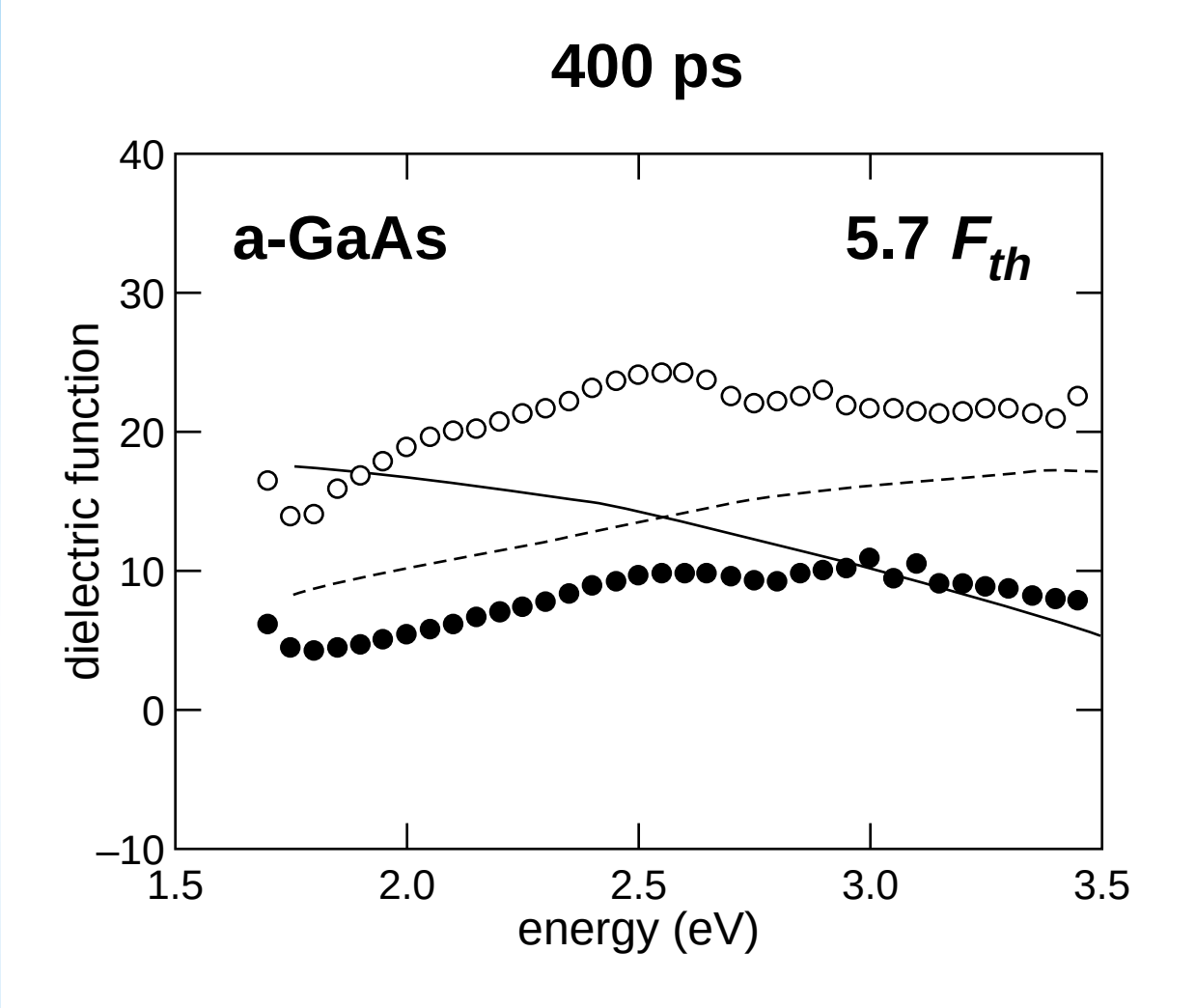
Results


8 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

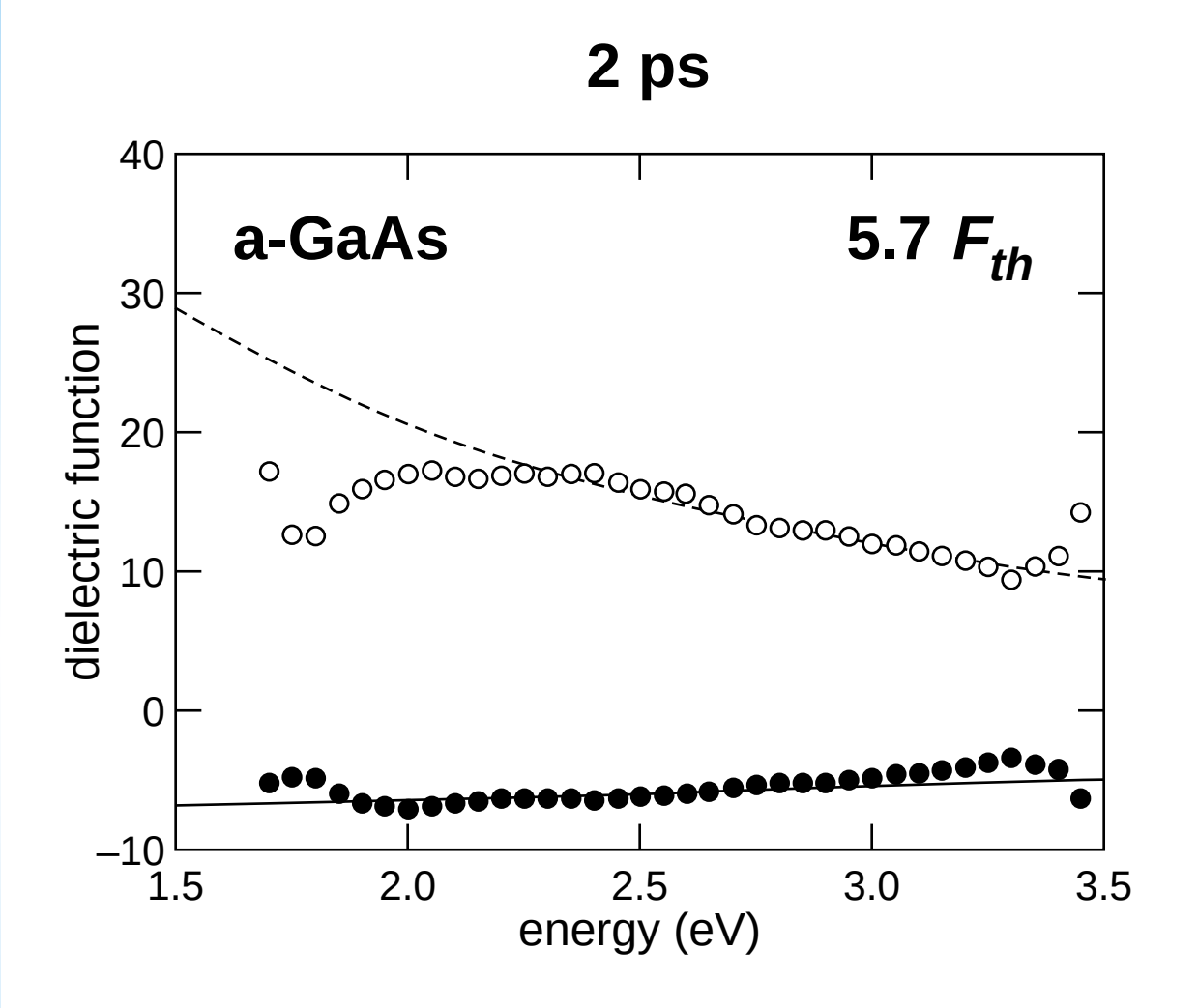
Results


16 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

Results

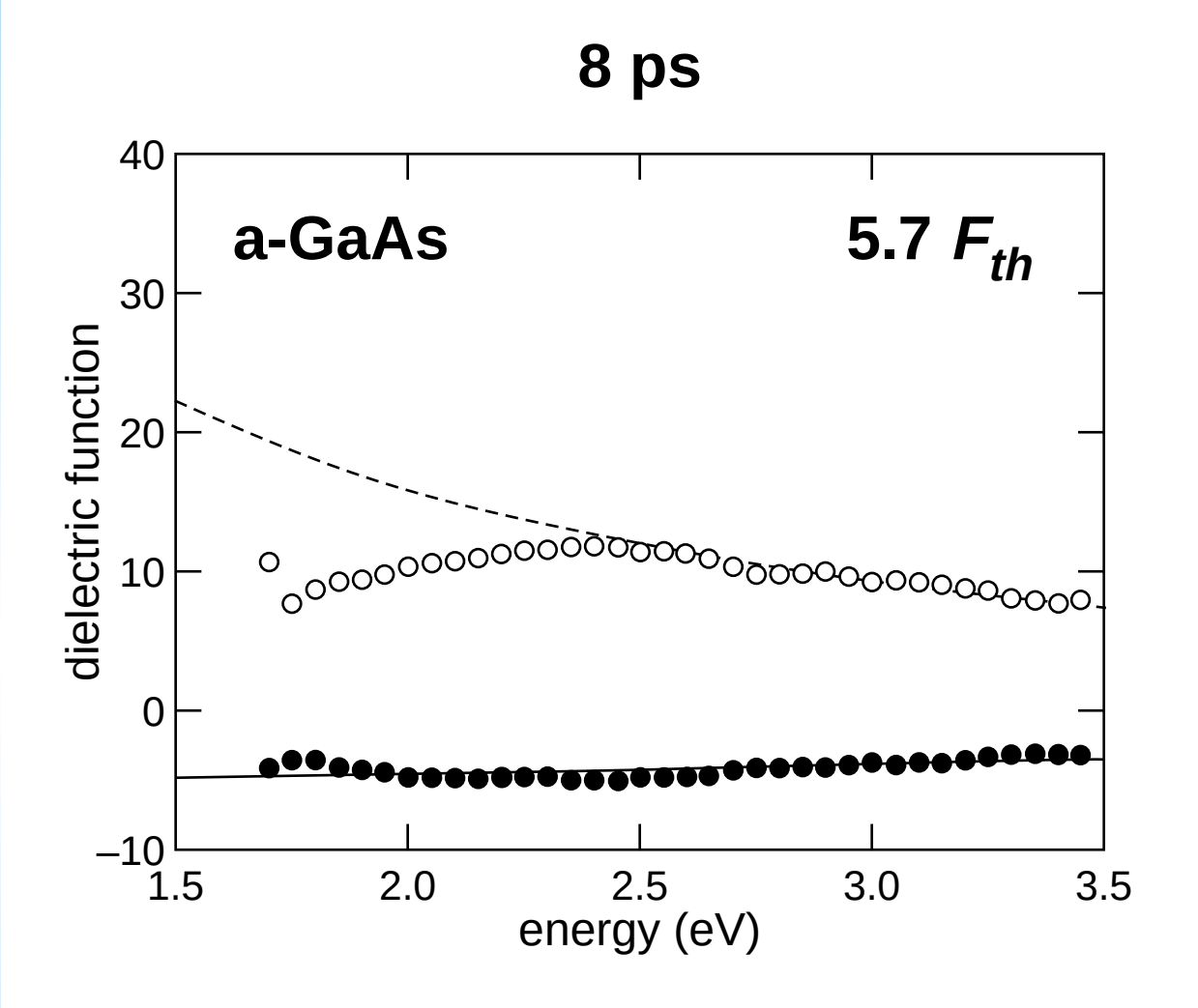

400 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

Results



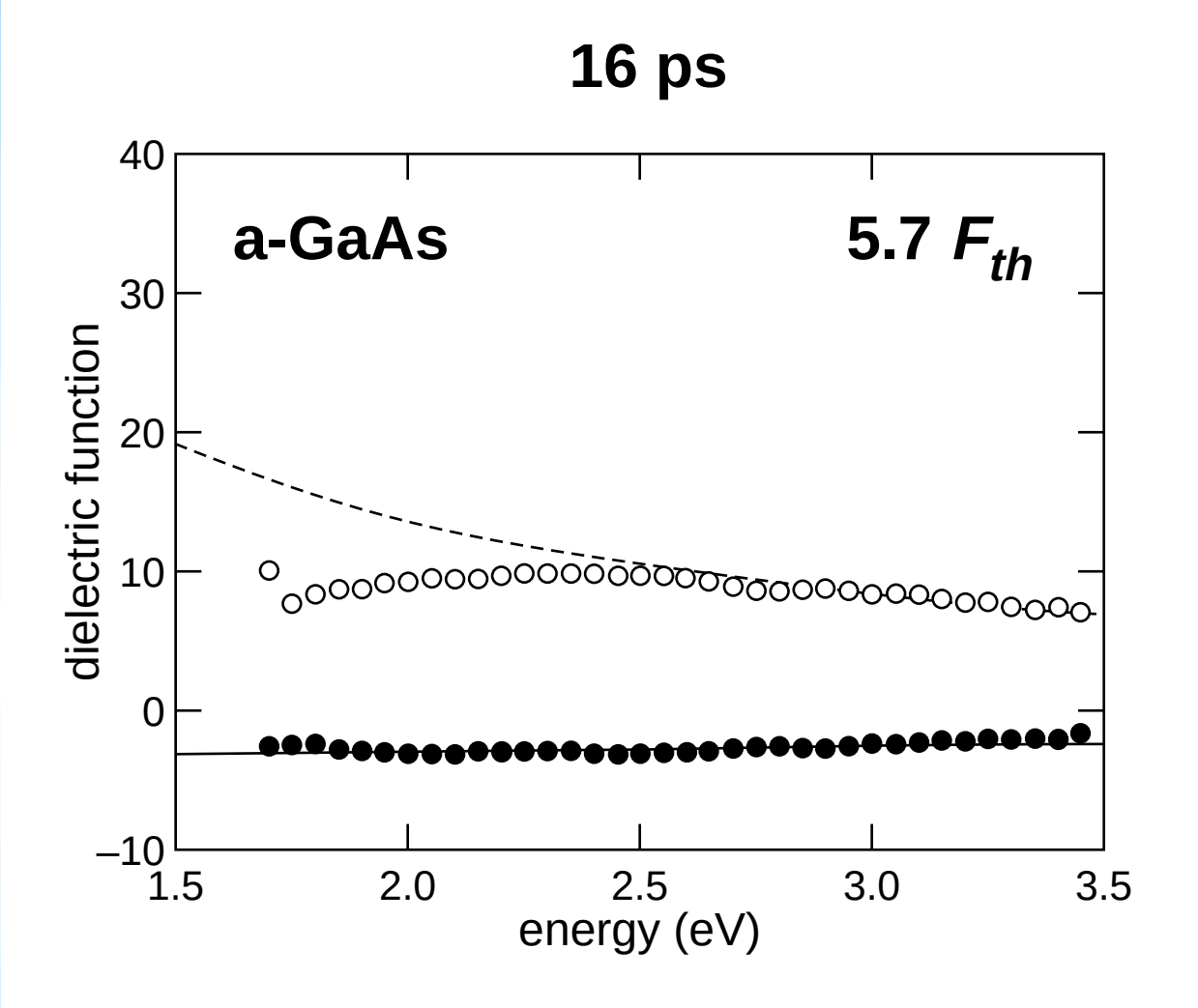
Drude-like after 2 ps

Results



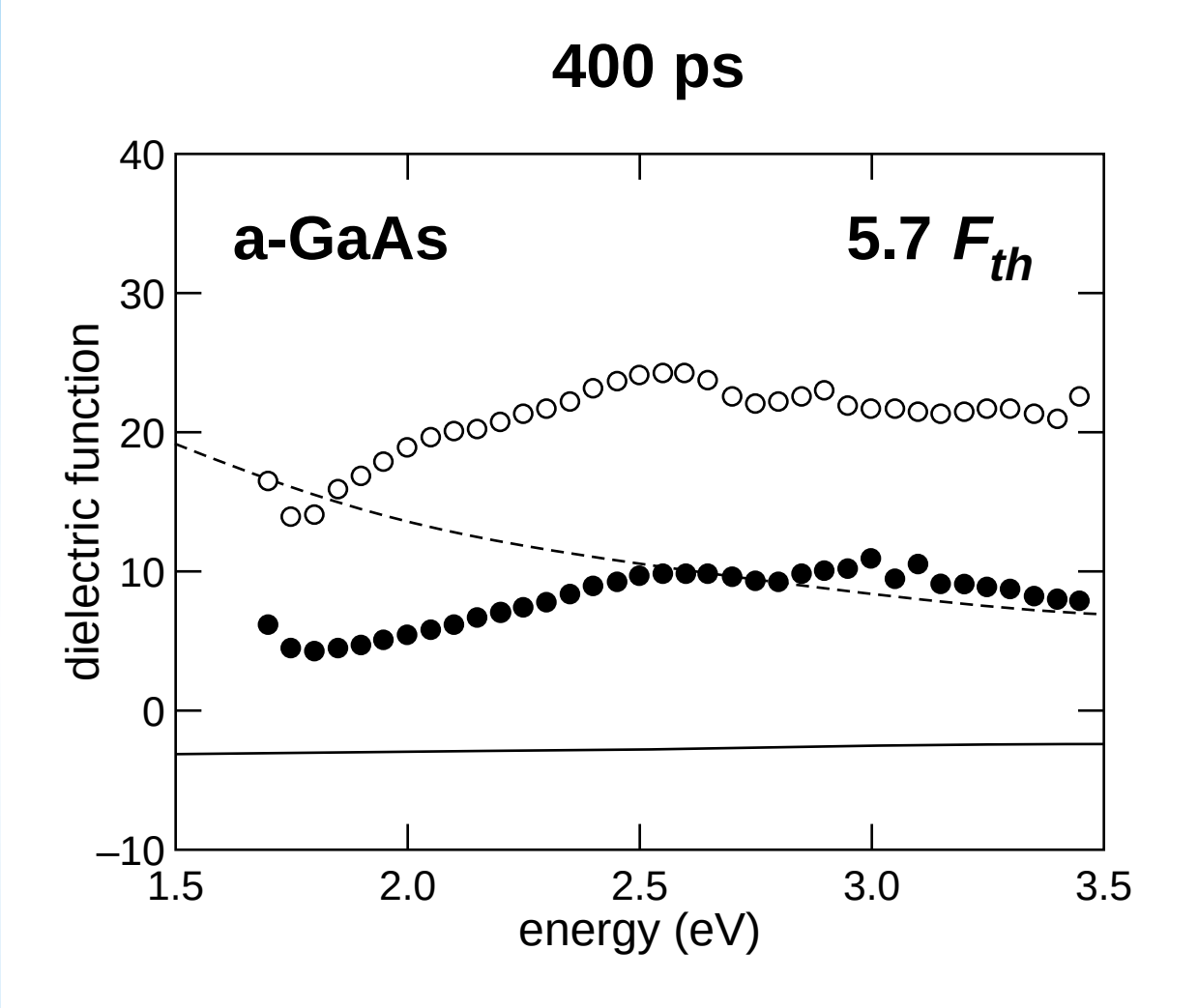
plasma frequency decreases

Results



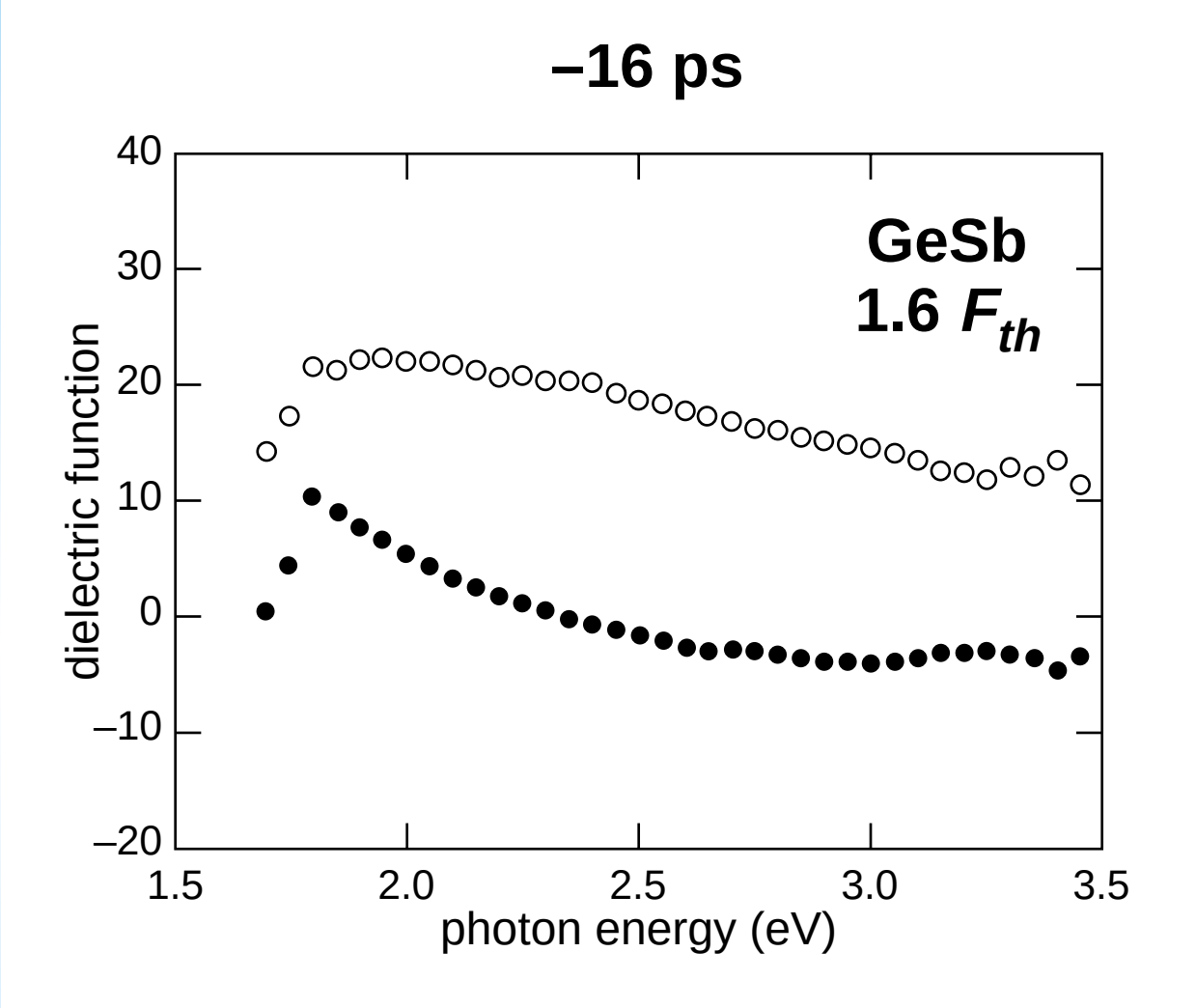
plasma frequency decreases

Results

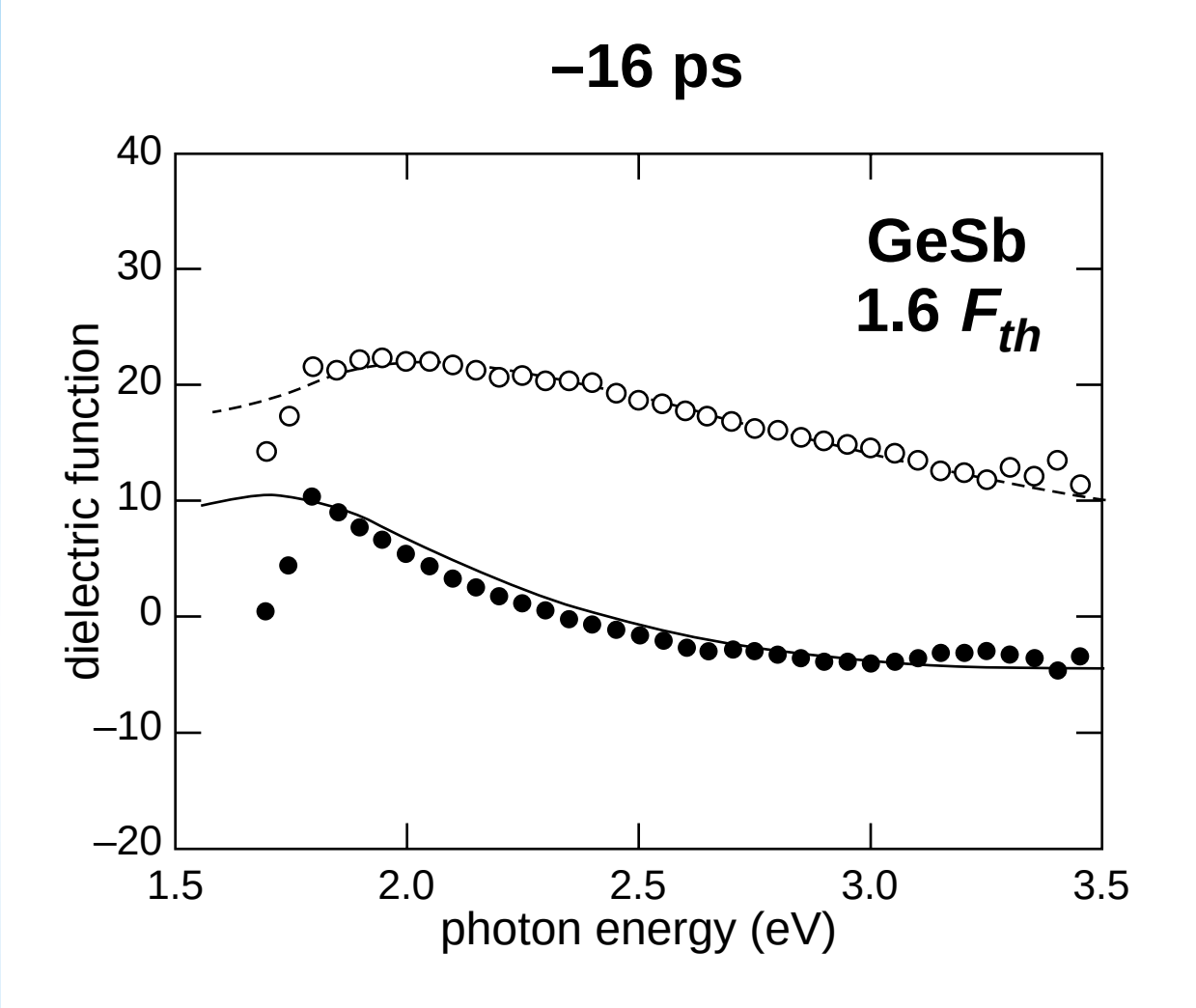


resolidification

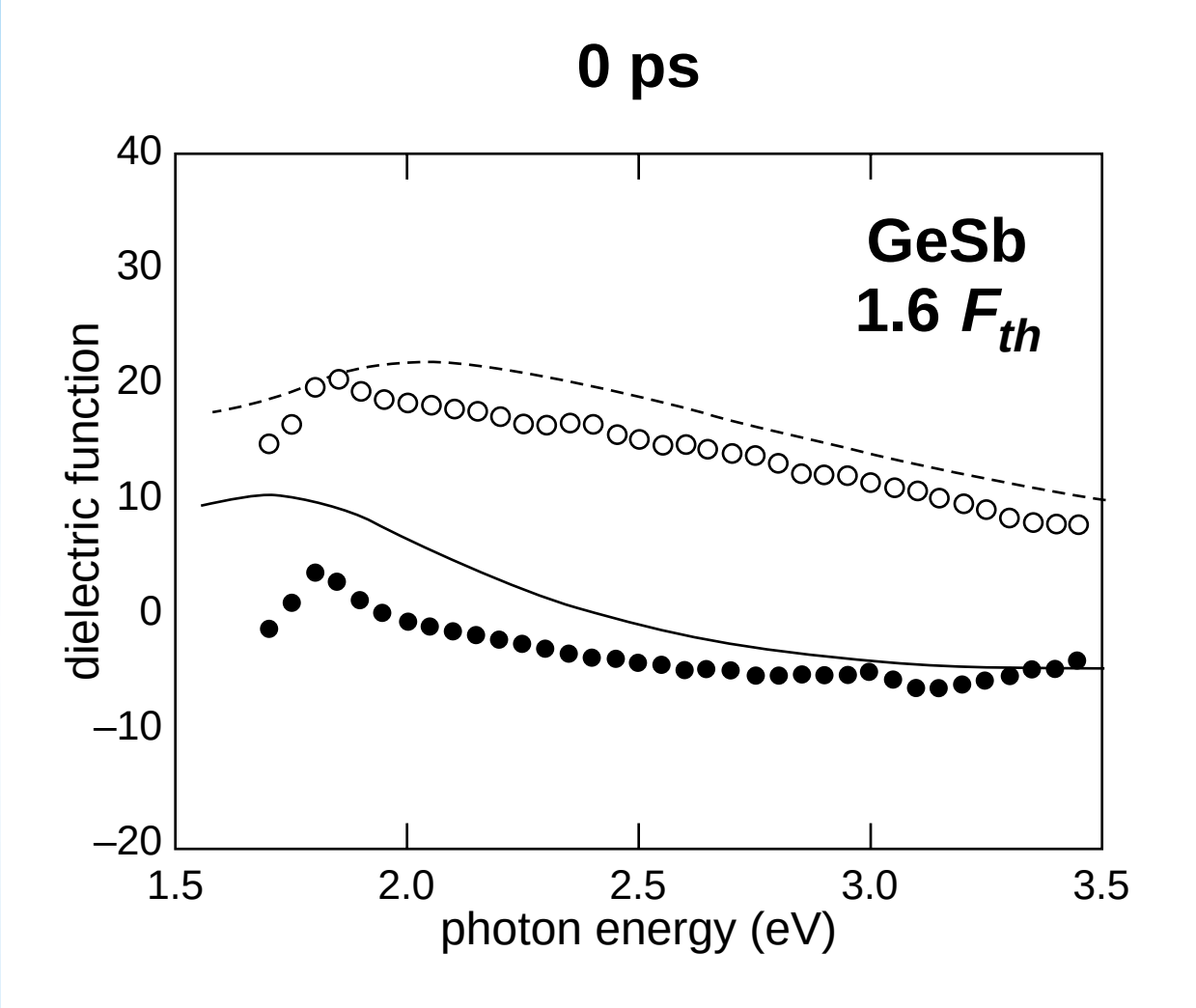
Results


–16 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

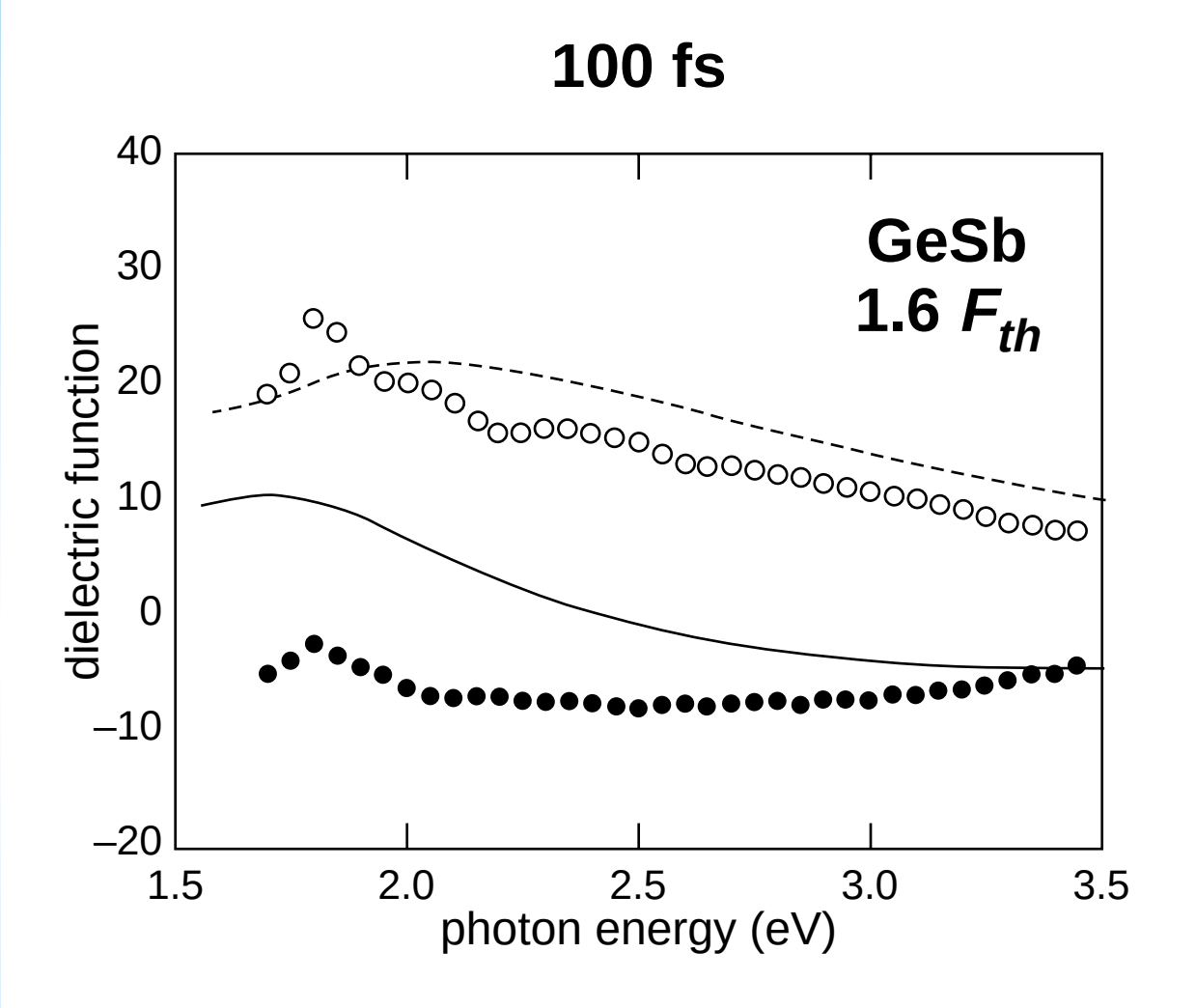
Results


–16 ps
GeSb
1.6 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5

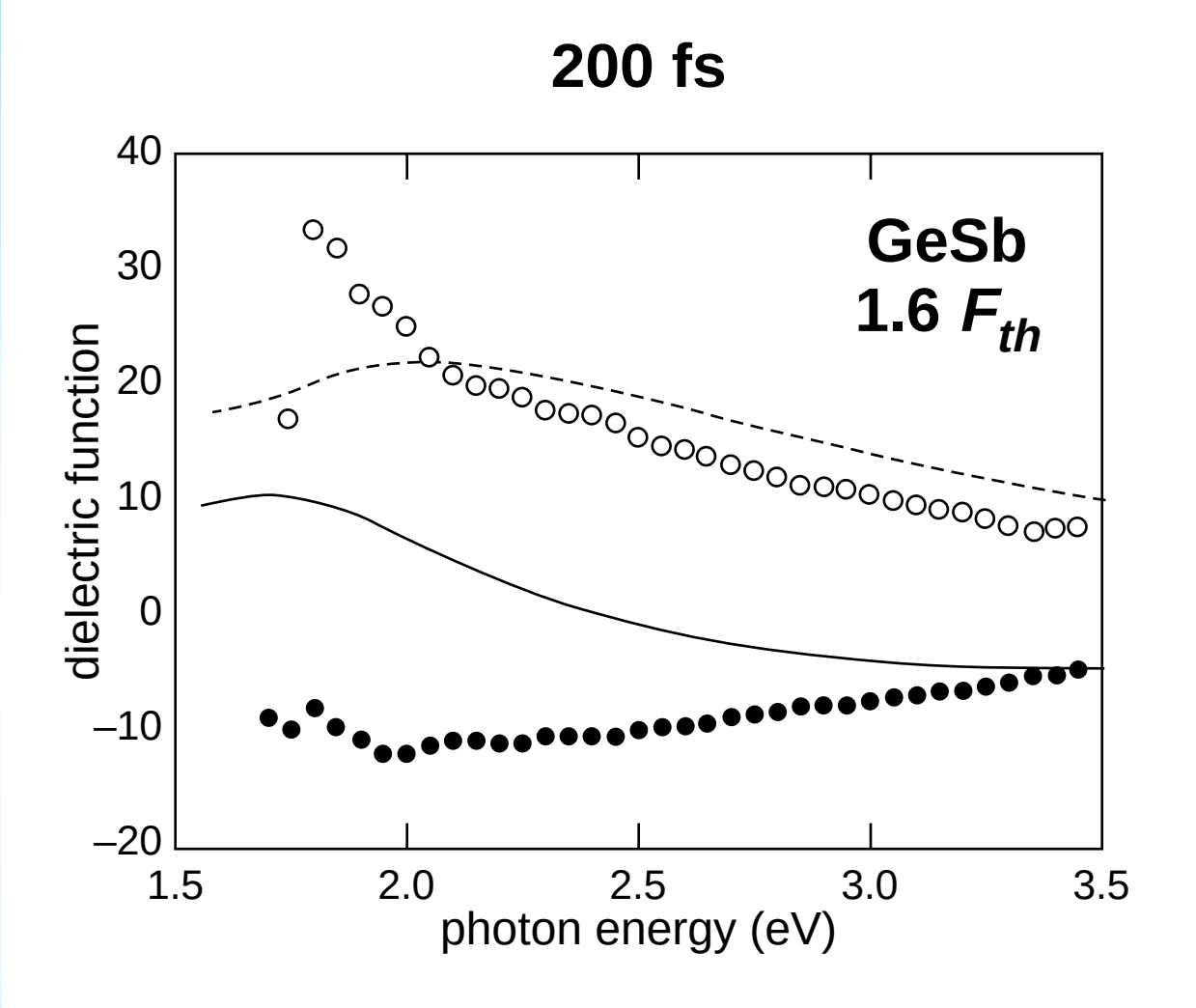
Results


0 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

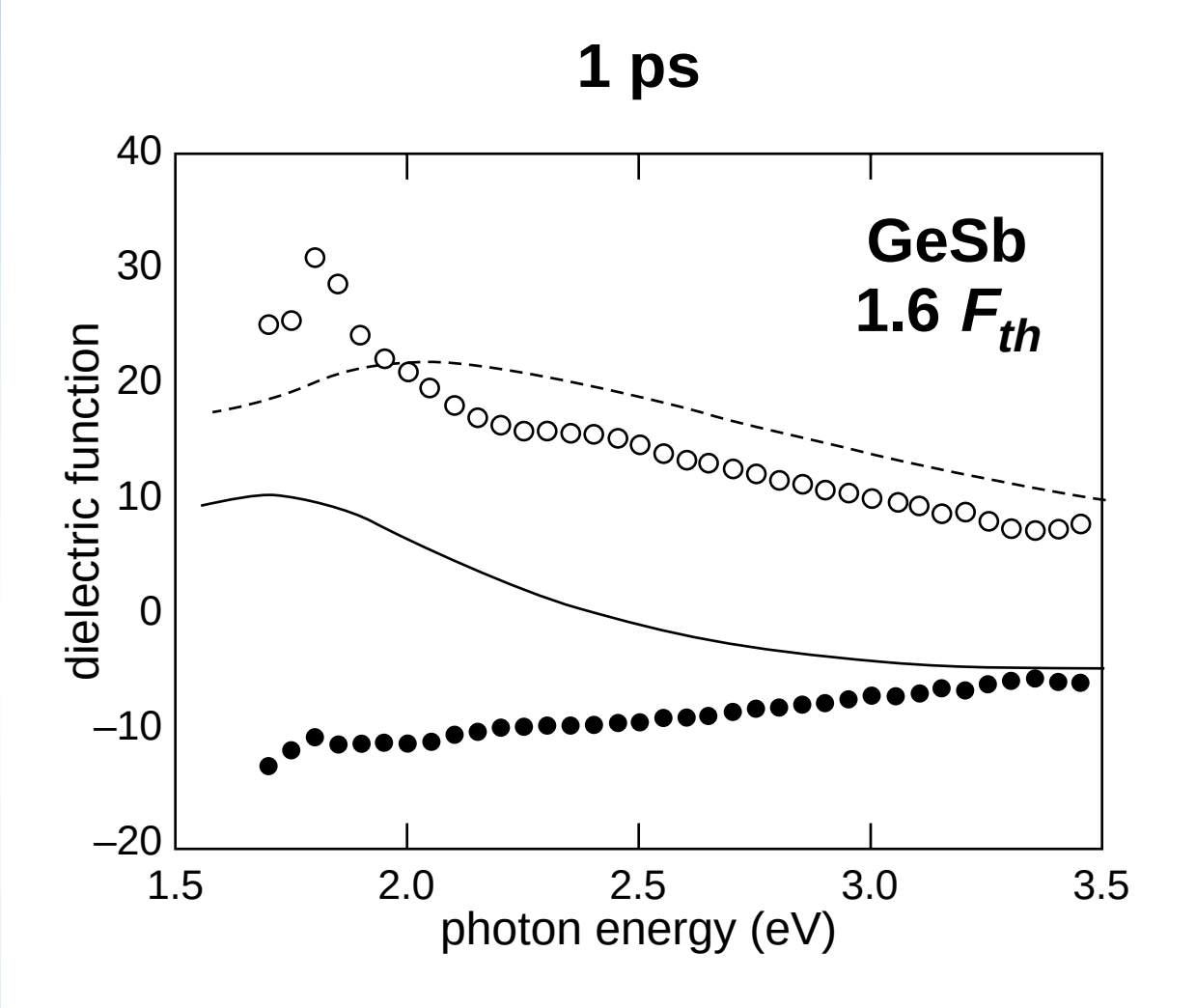
Results


100 fs
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

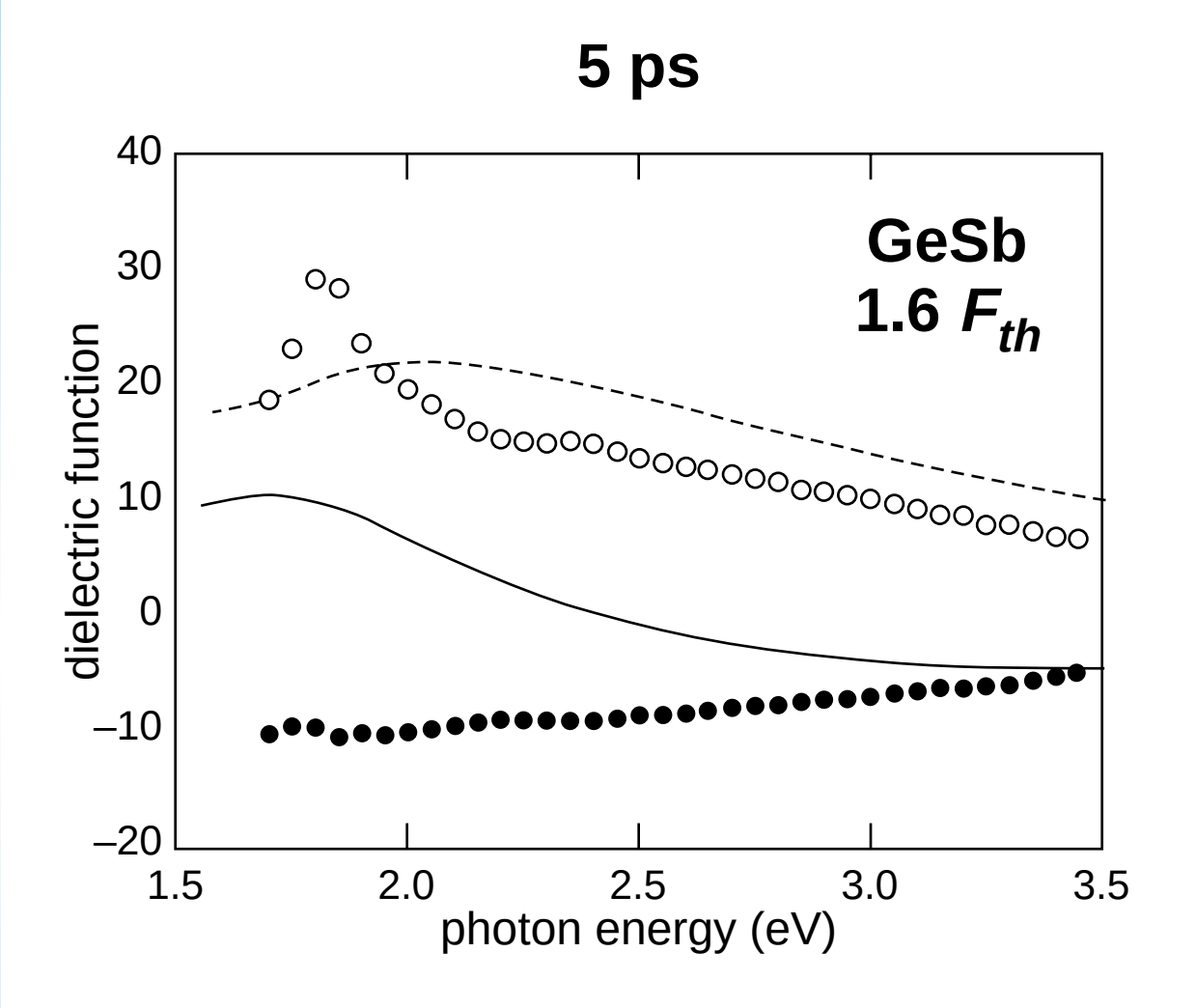
Results


200 fs
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

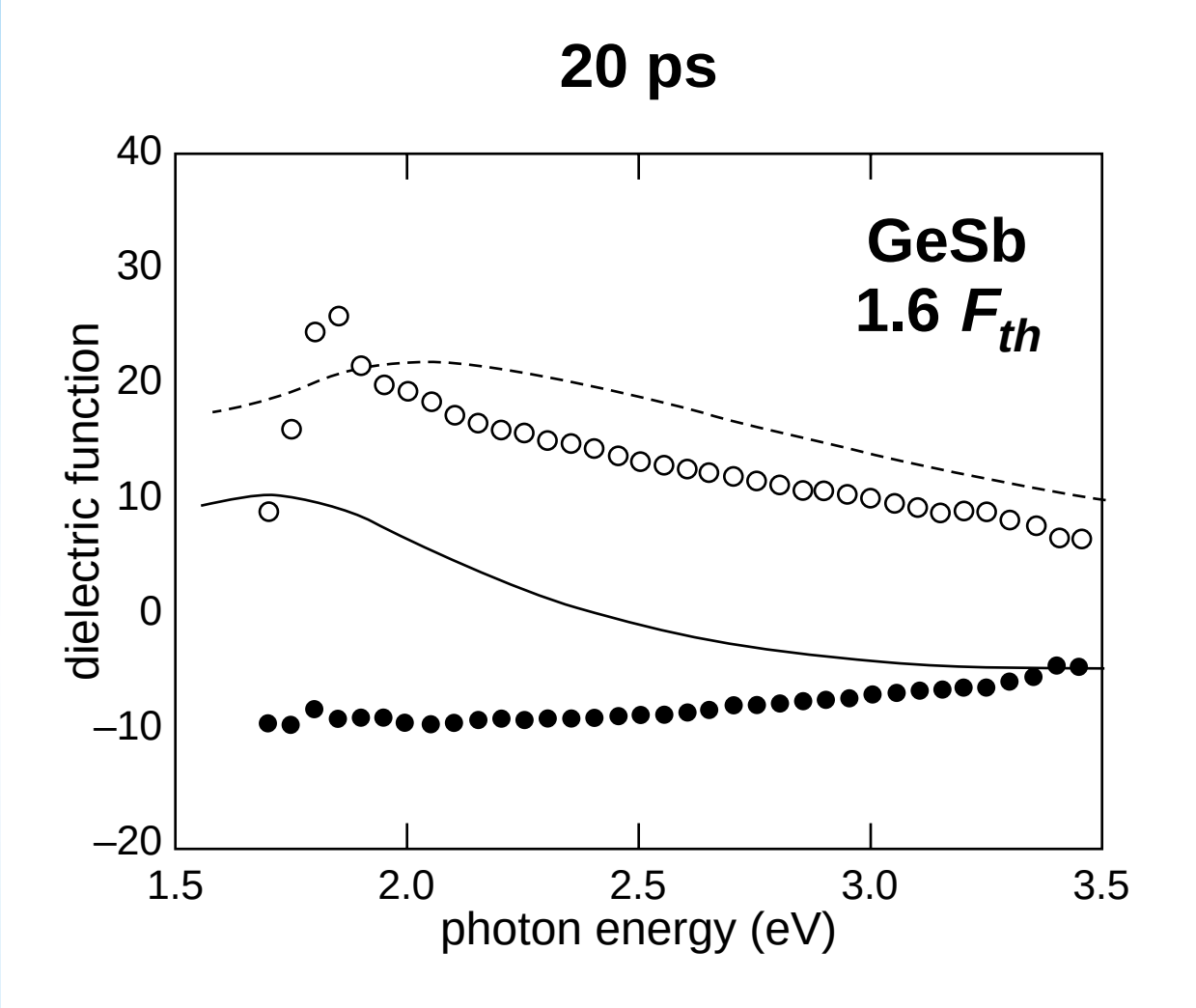
Results


1 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

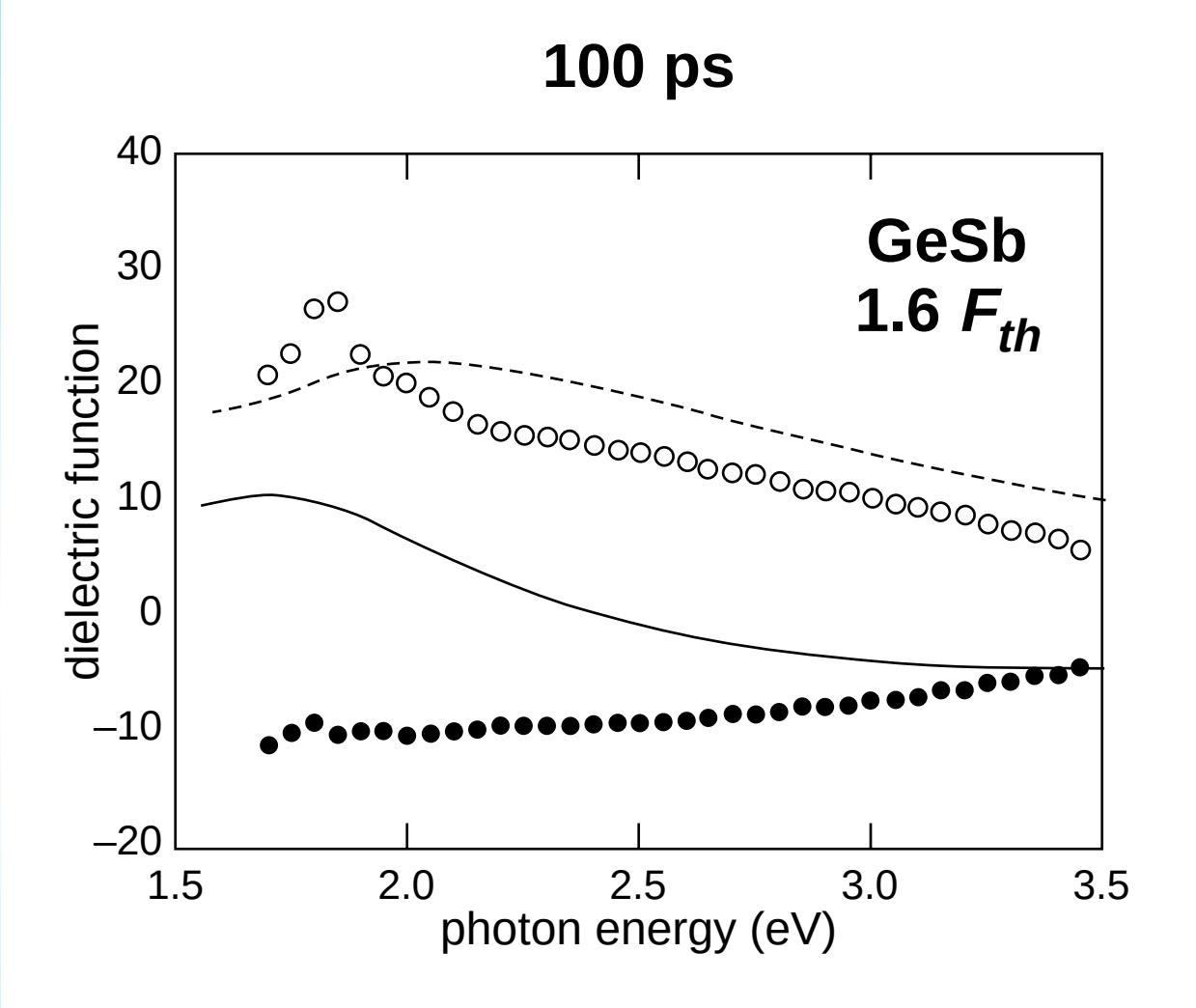
Results


5 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

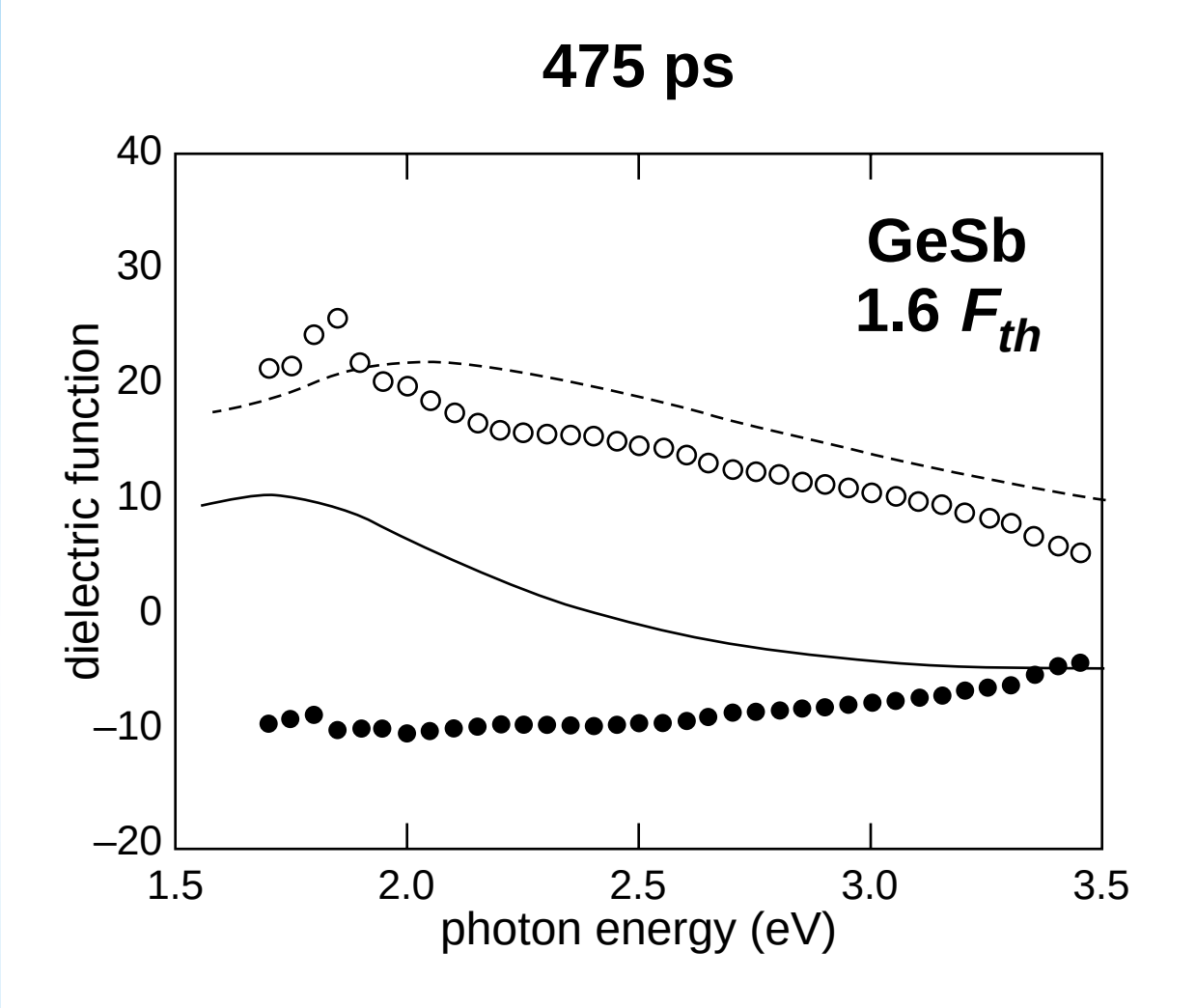
Results


20 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

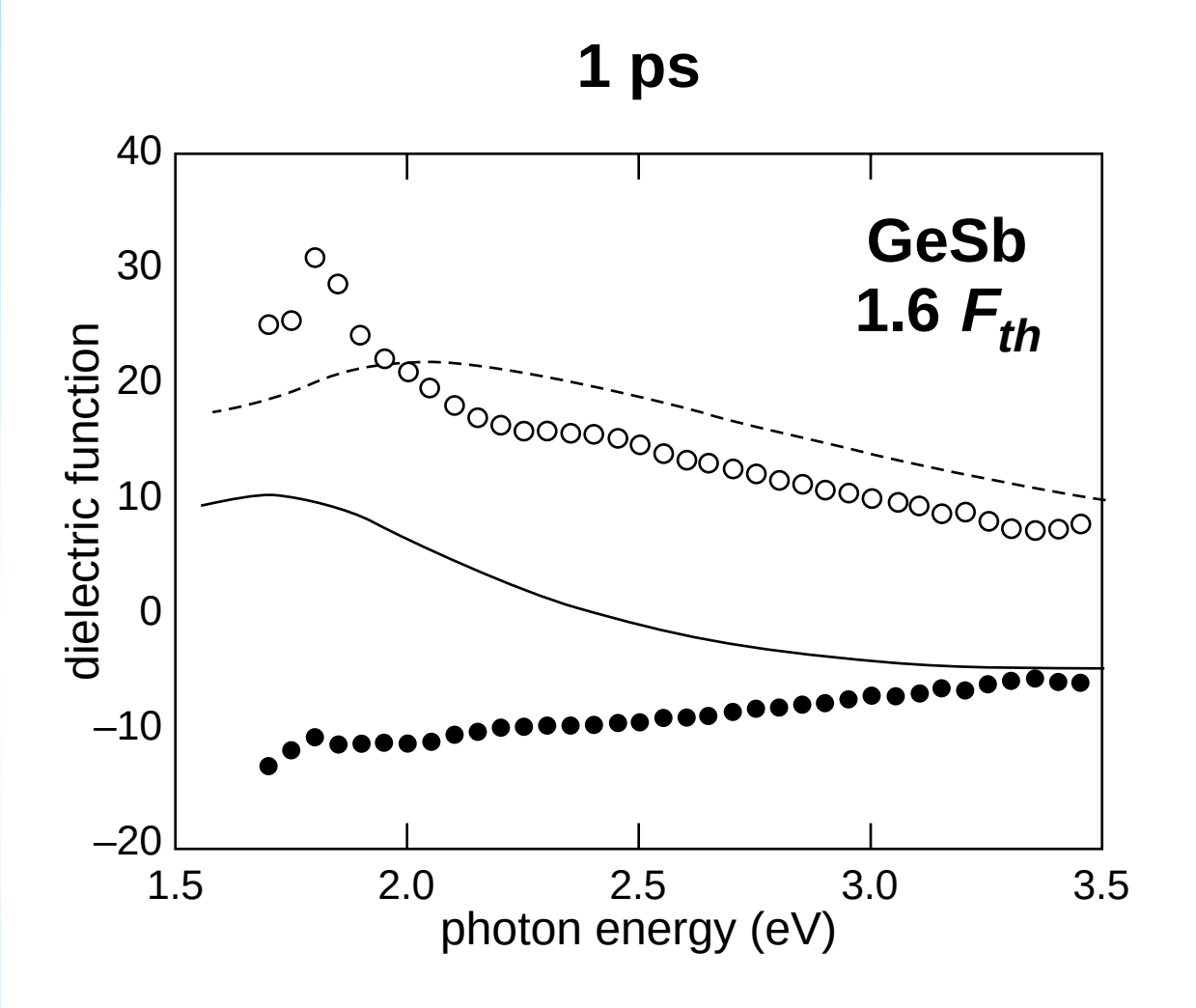
Results


100 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

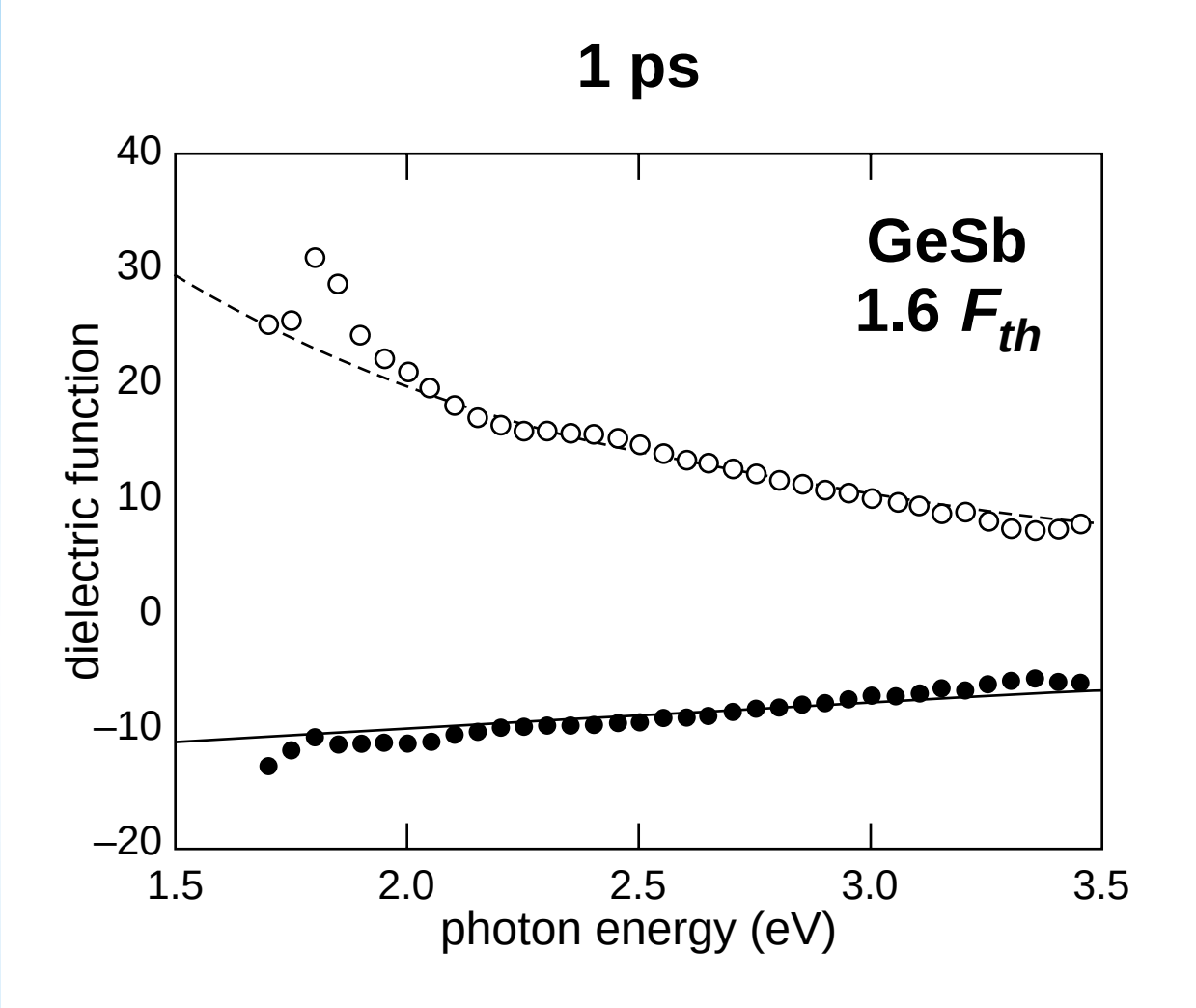
Results


475 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results

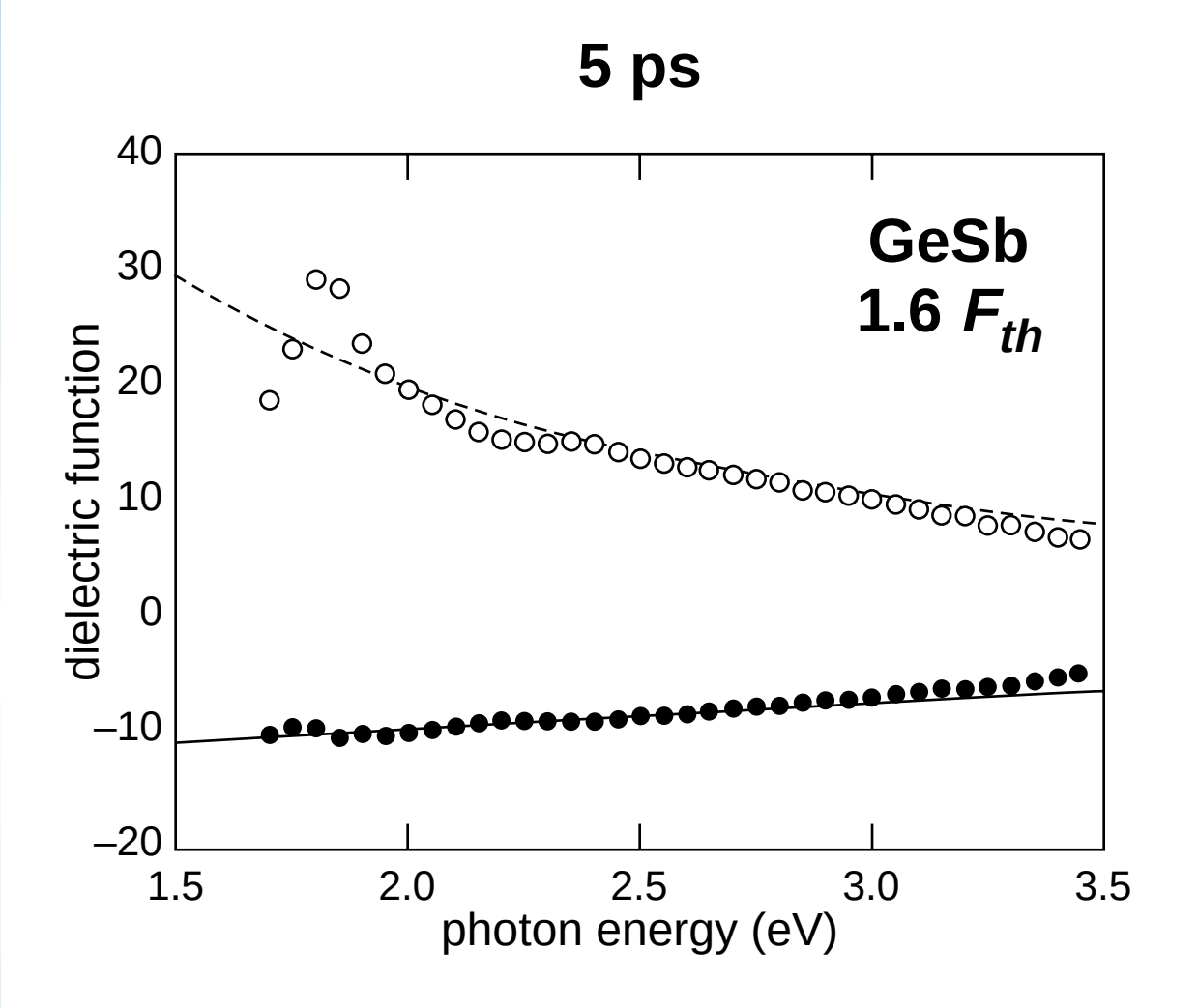

1 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results



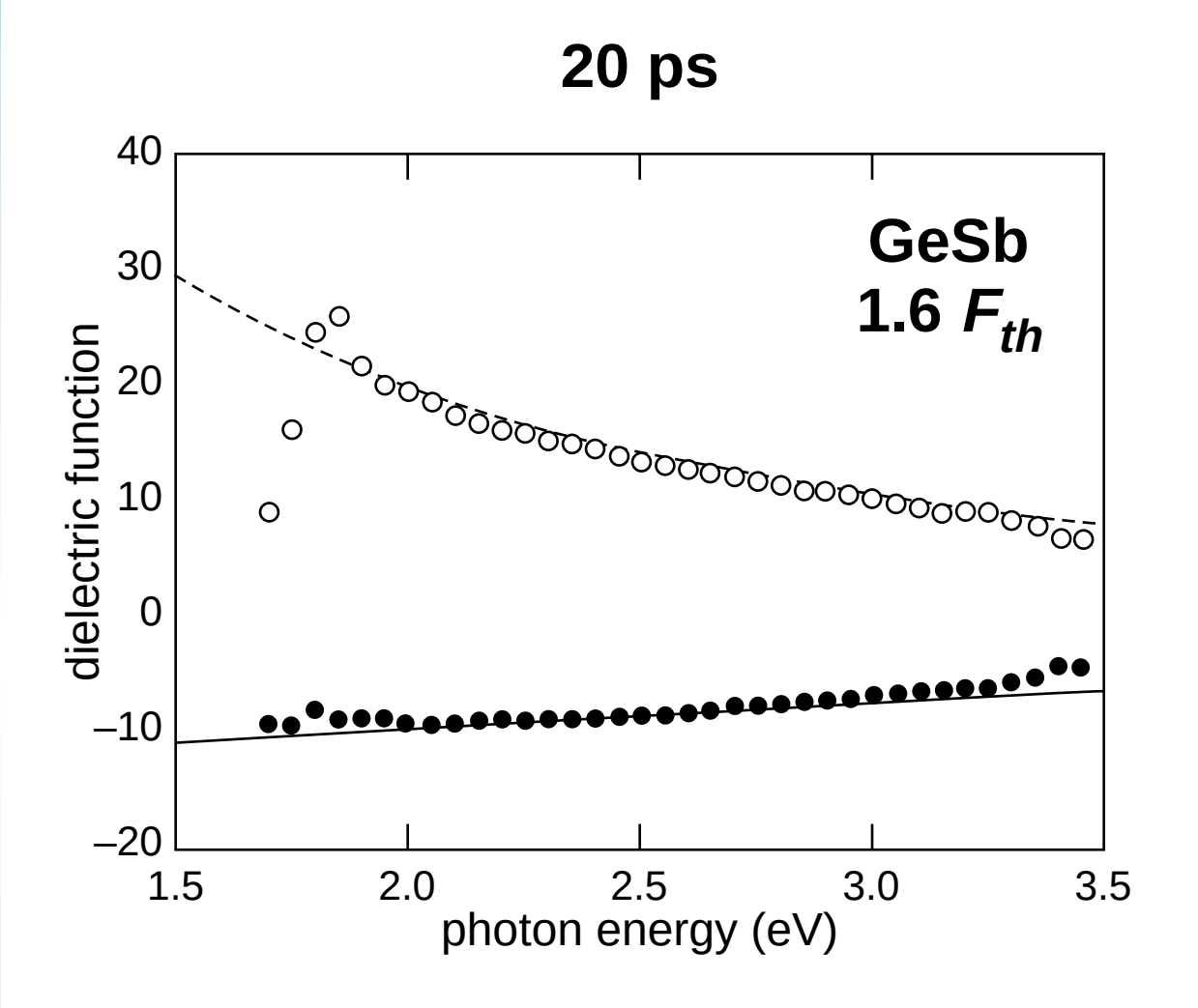
Drude-like after 1 ps

Results



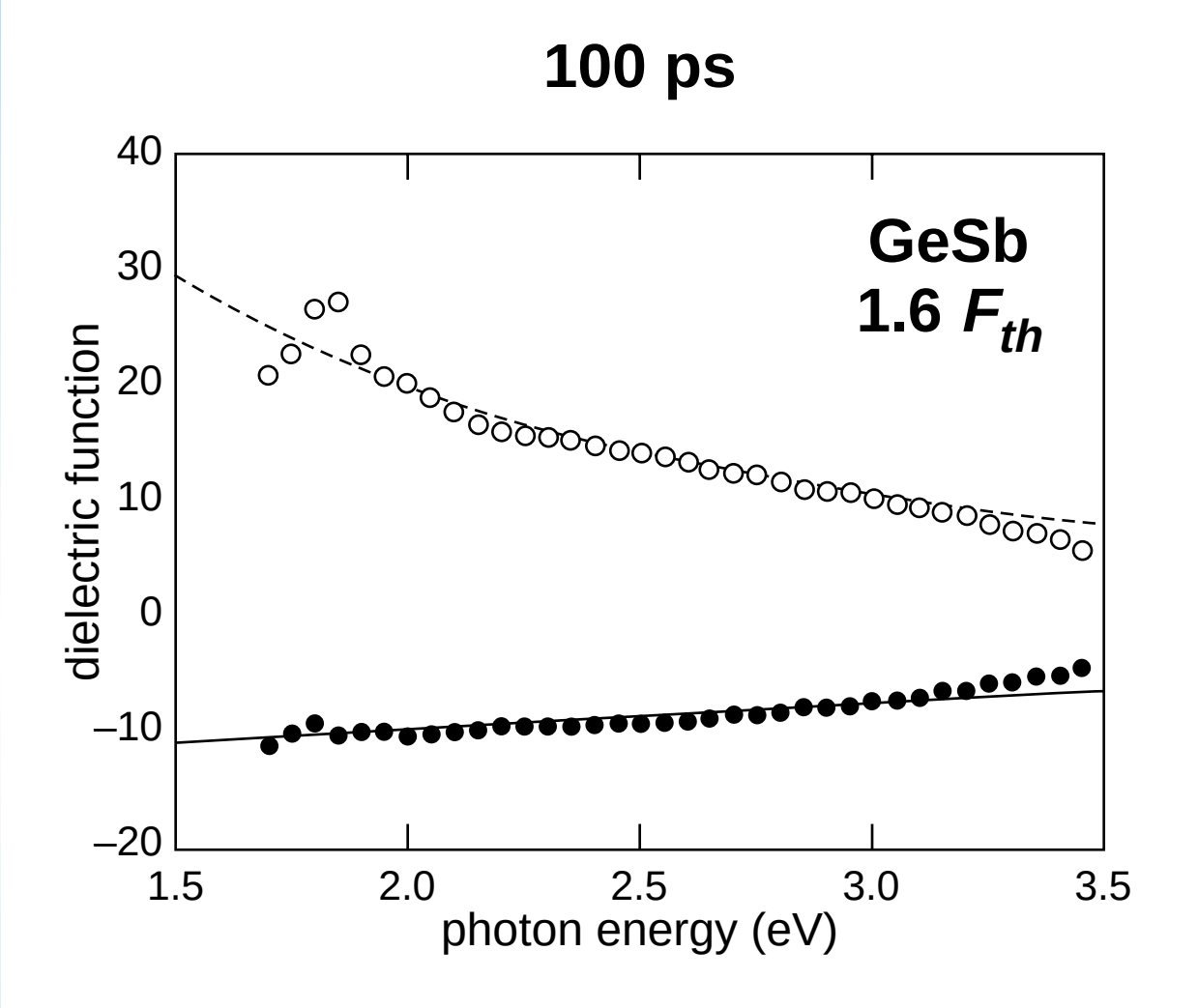
Drude-like after 1 ps

Results



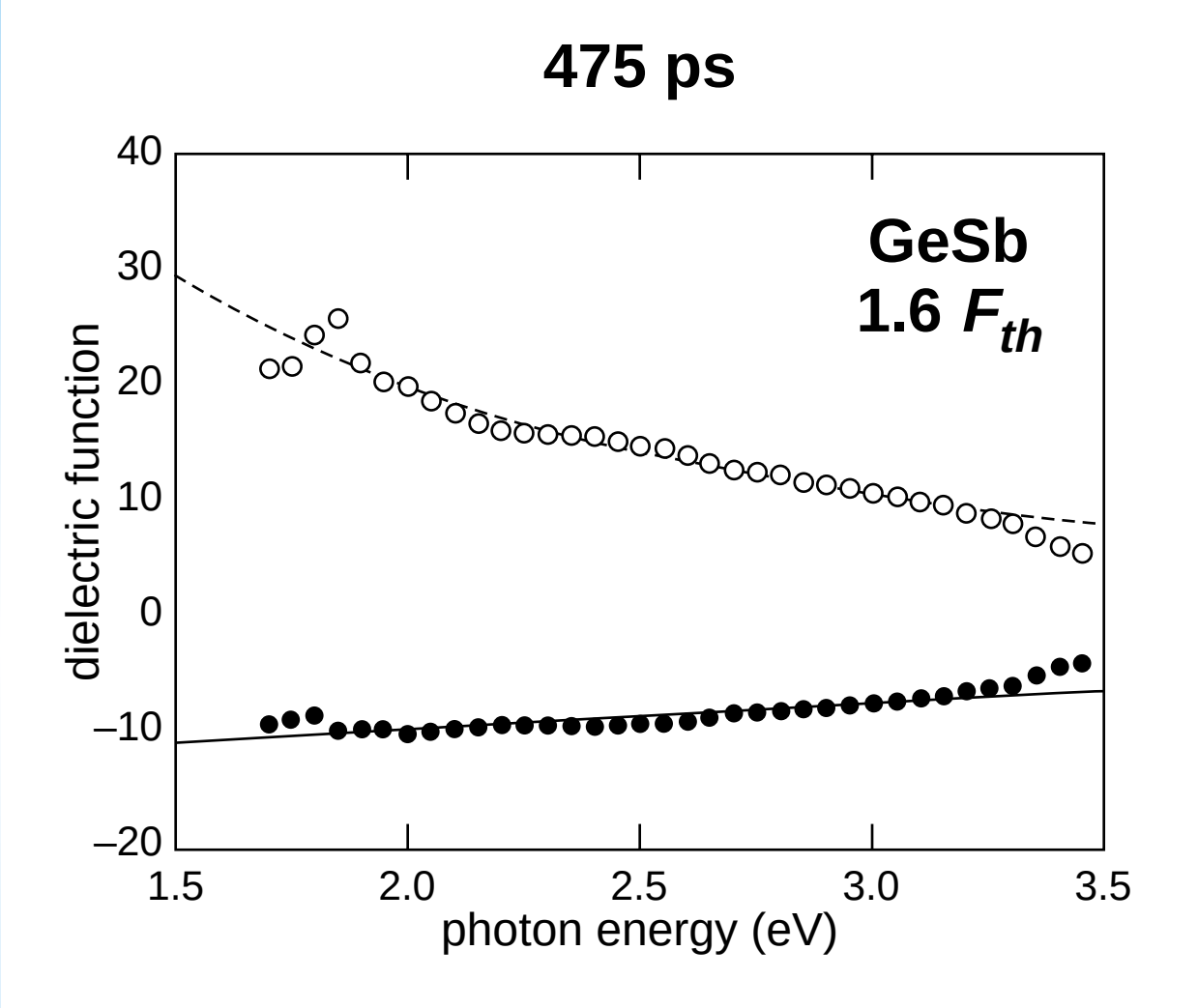
Drude-like after 1 ps

Results



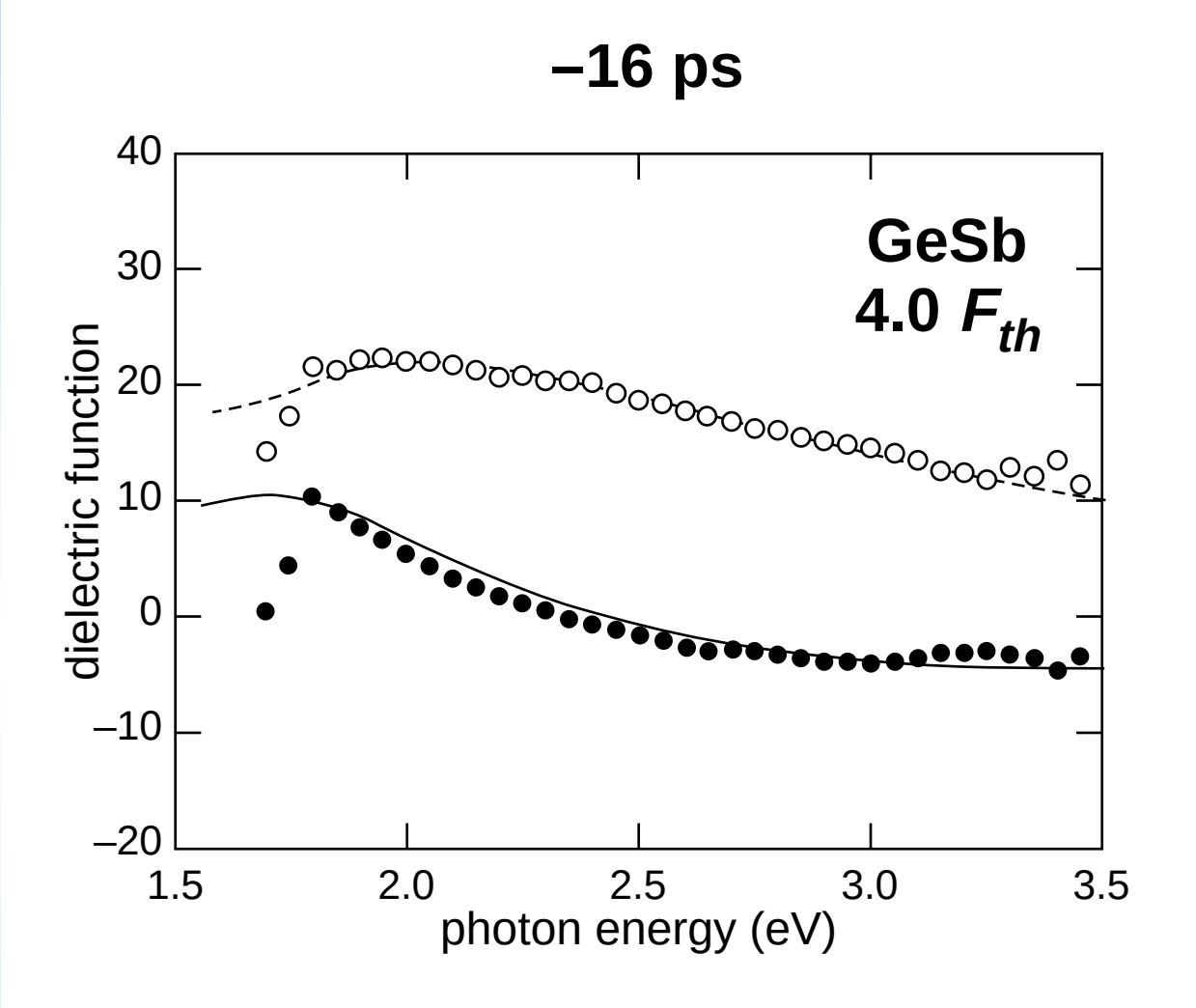
Drude-like after 1 ps

Results

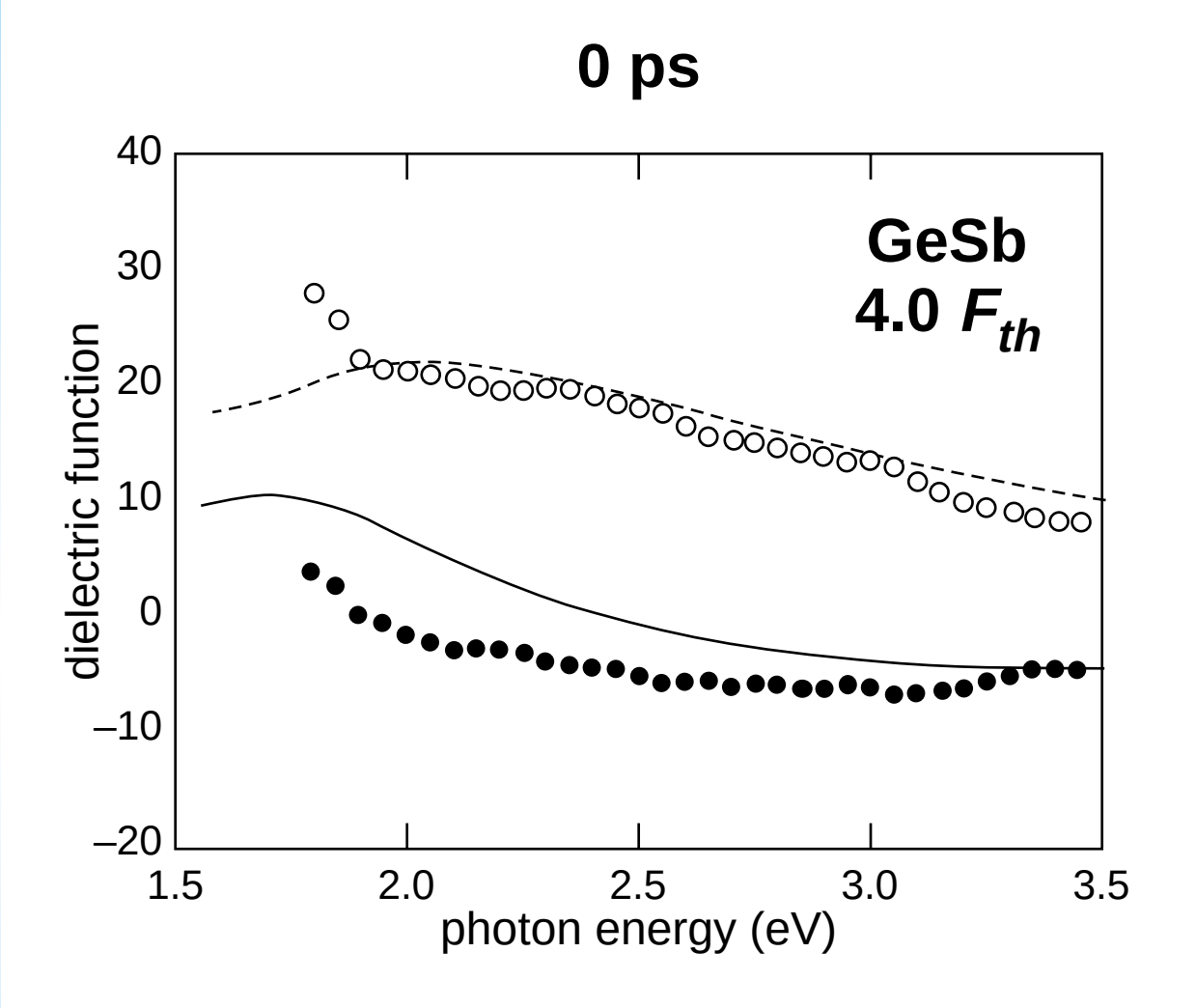


Drude-like after 1 ps

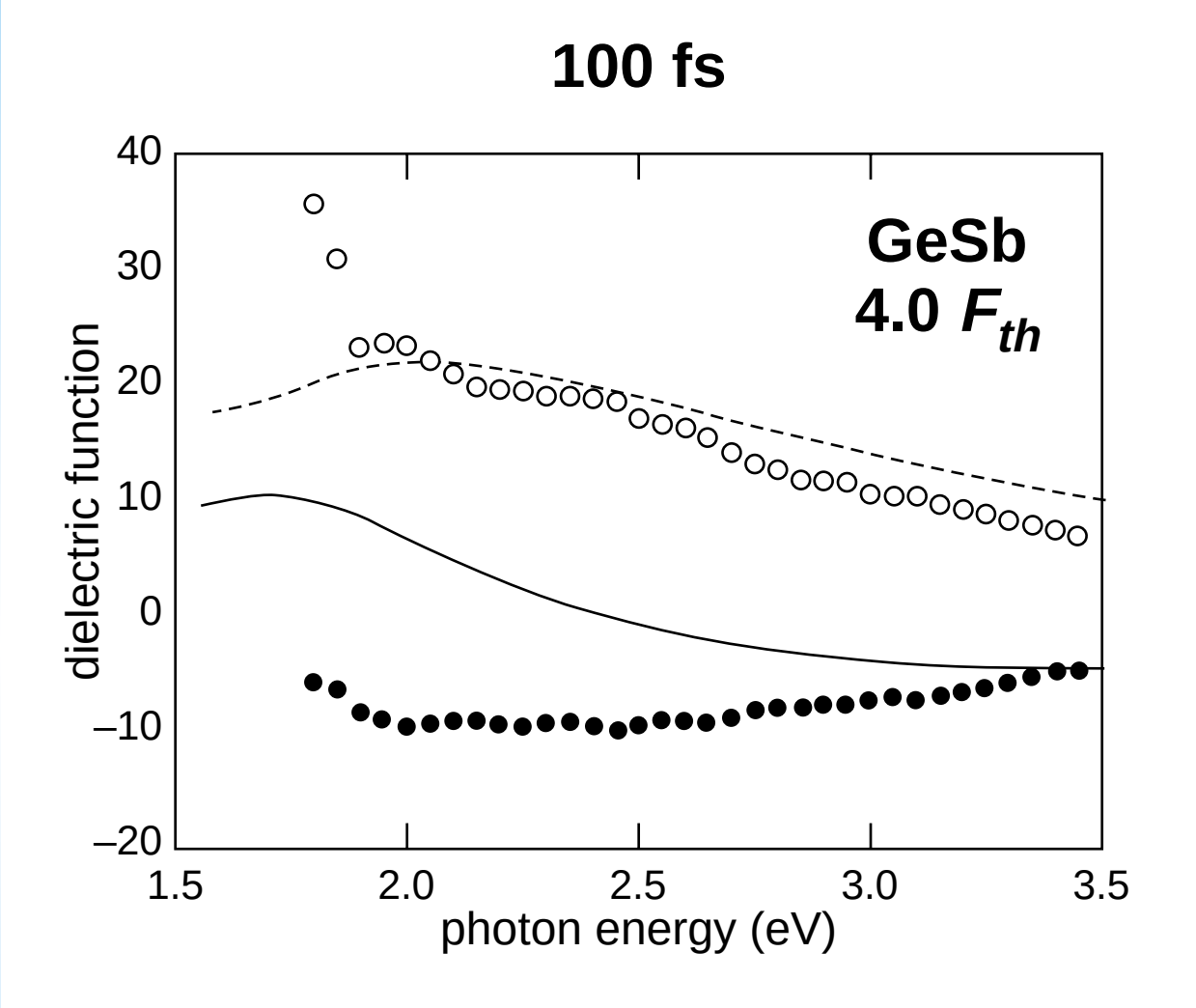
Results


–16 ps
GeSb
4.0 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5

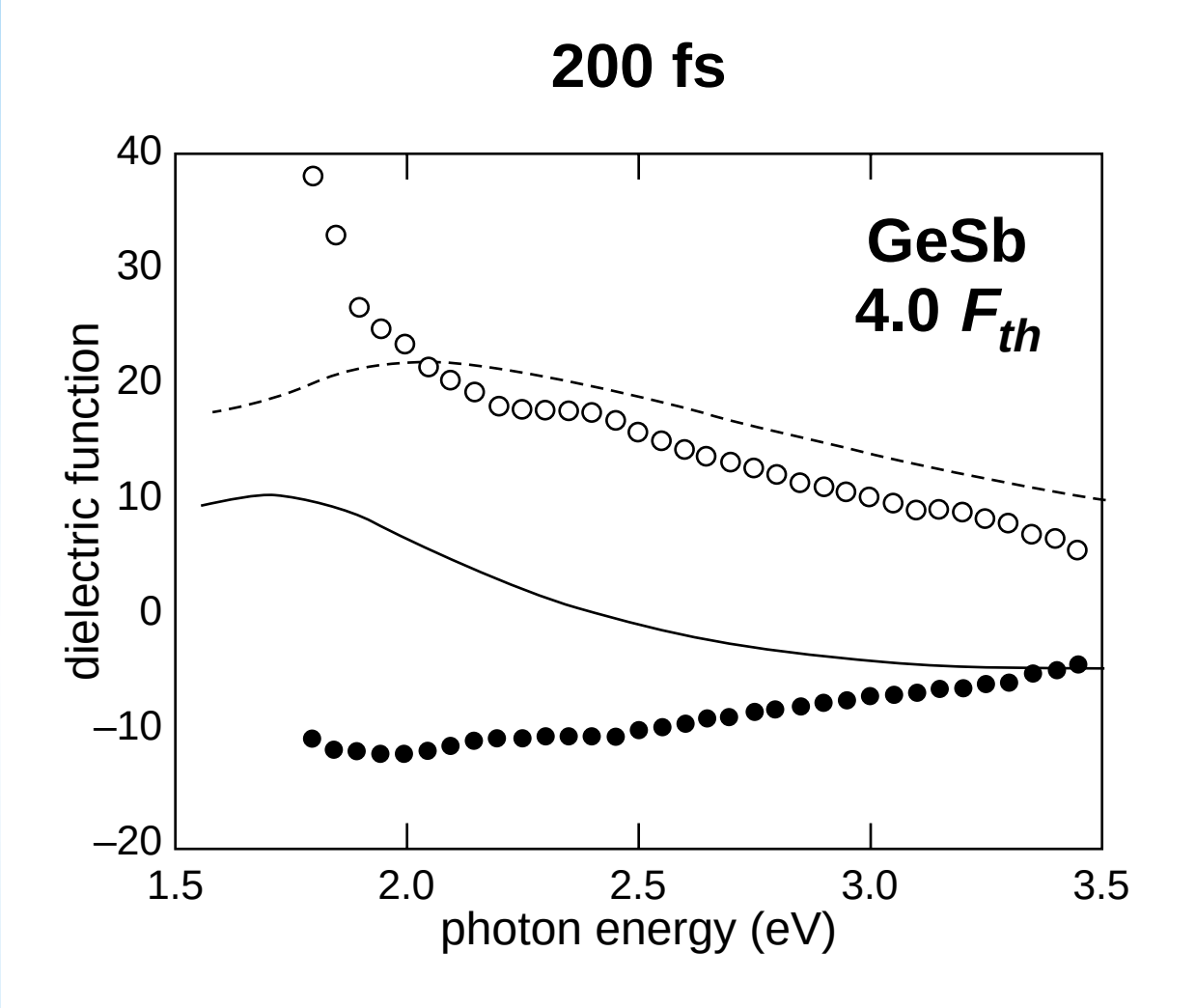
Results


0 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

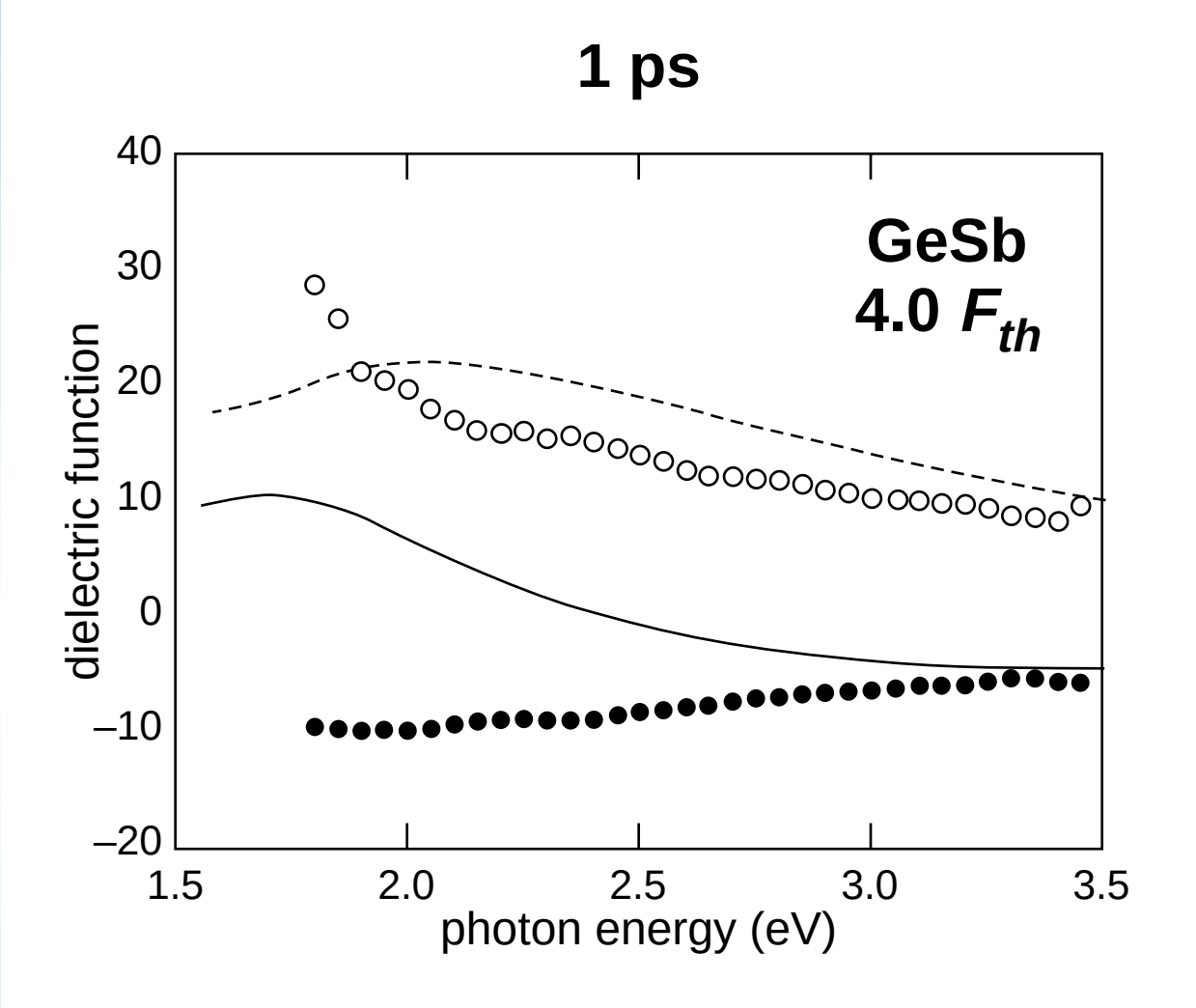
Results


100 fs
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

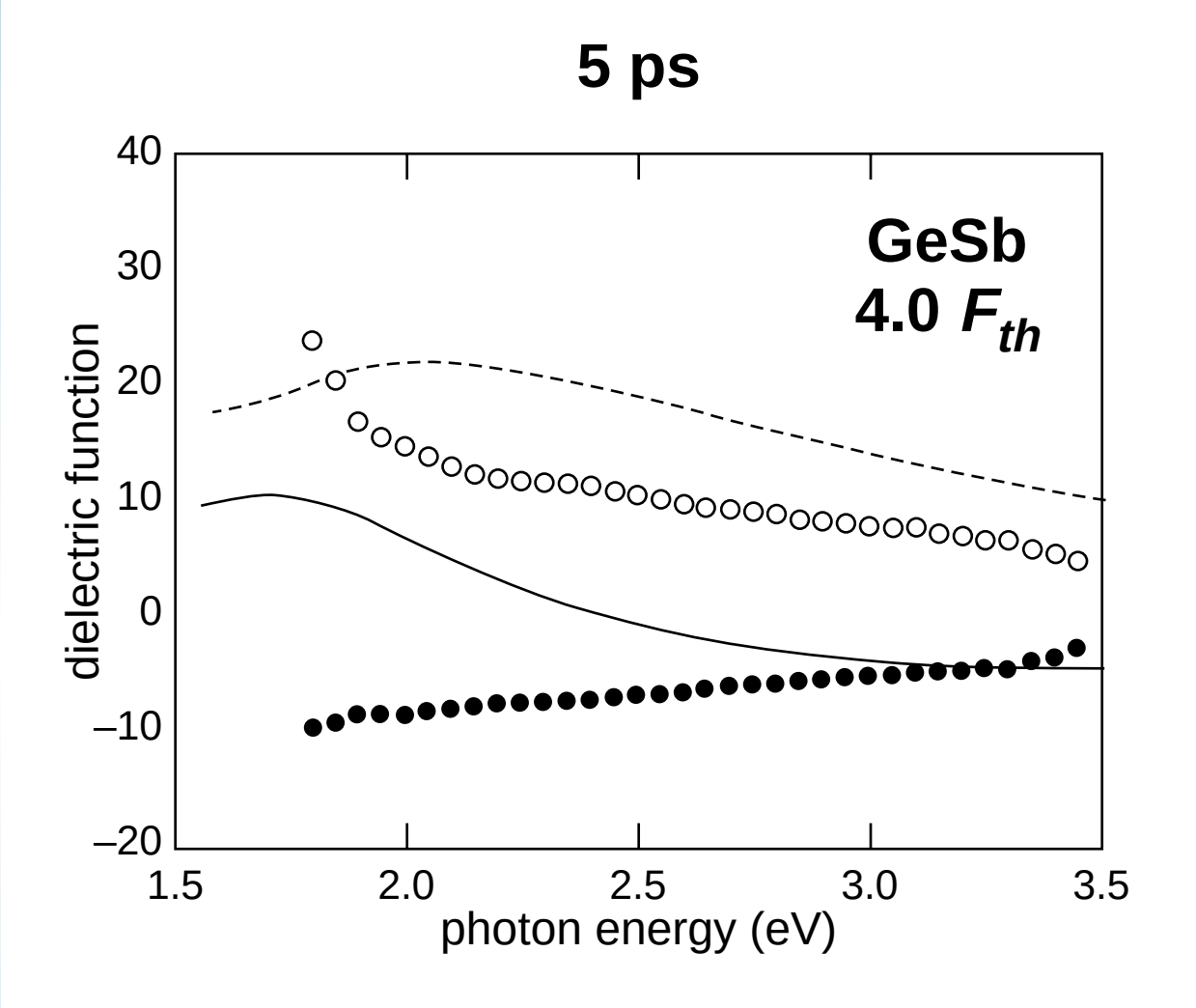
Results


200 fs
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results


1 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results


5 ps
GeSb
4.0 F_{th}
dielectric function
40
30
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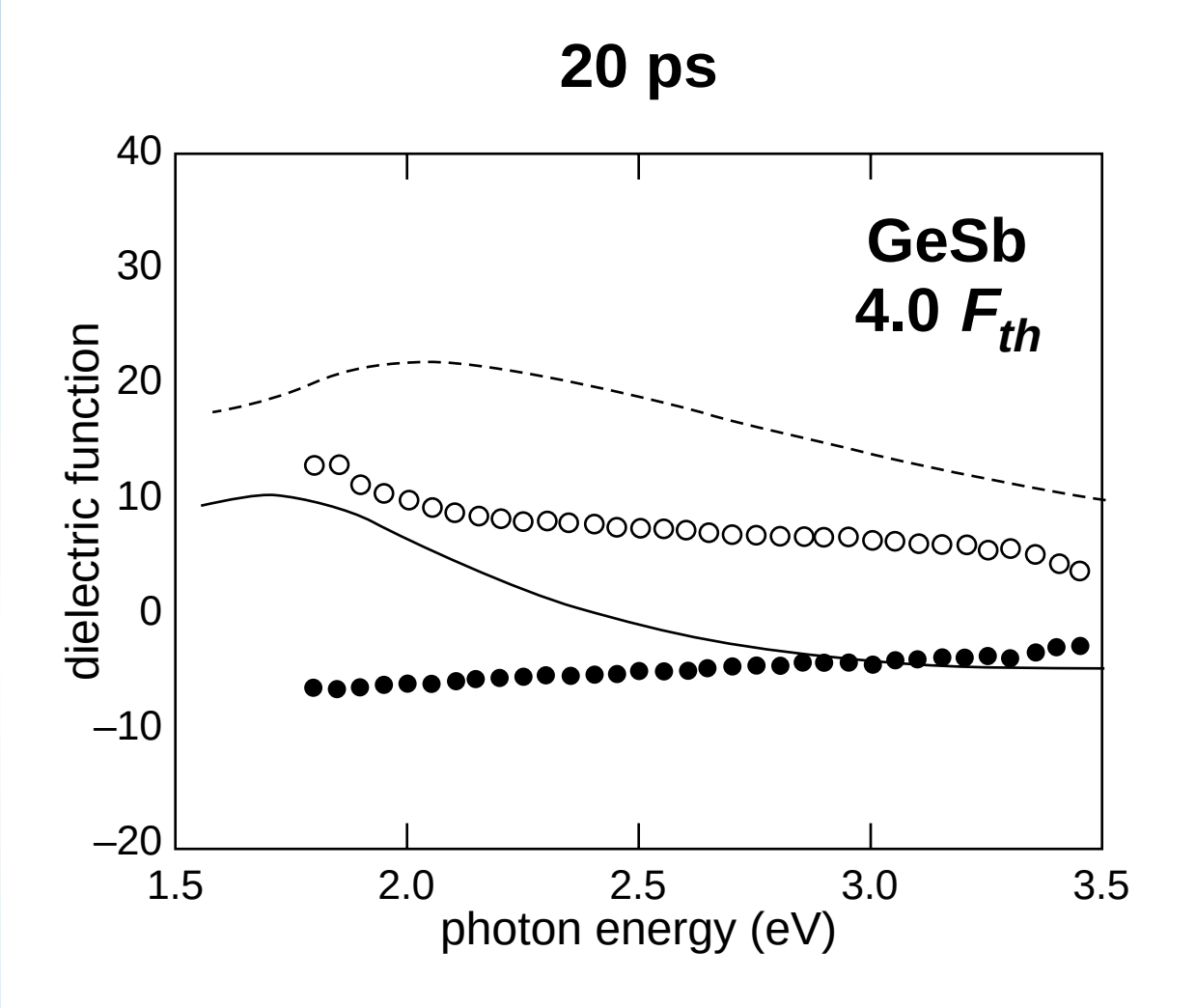
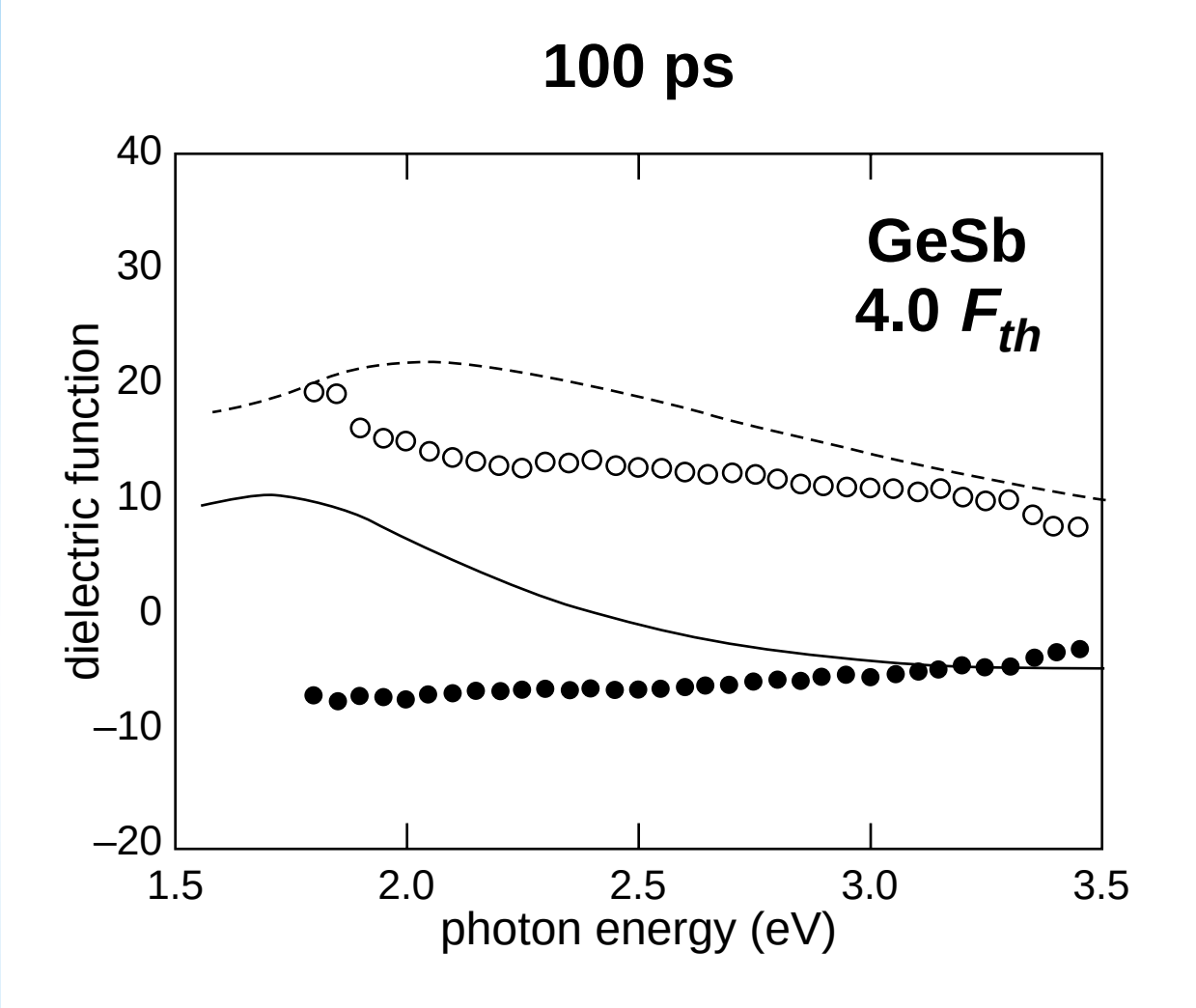
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

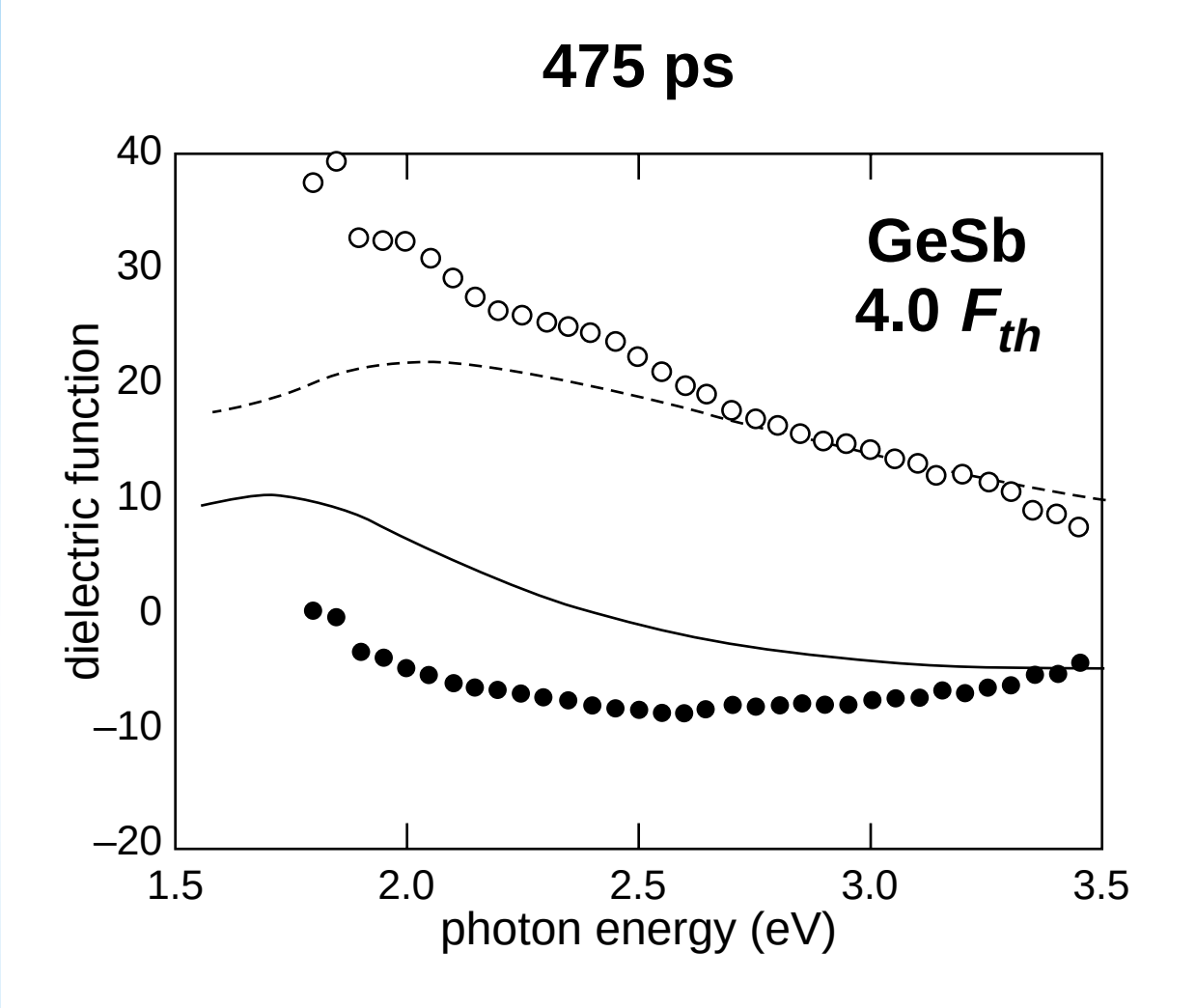
Results


20 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

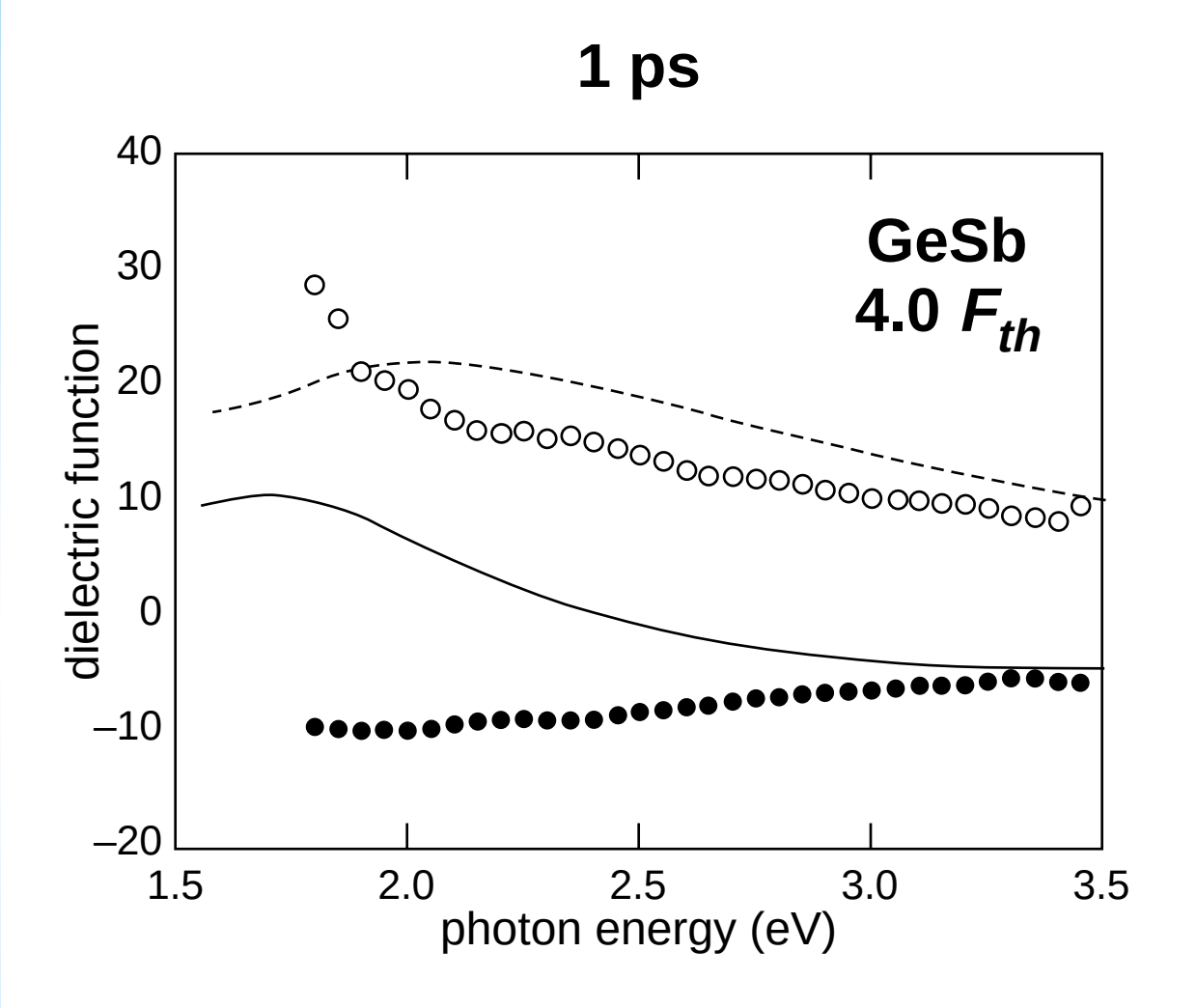
Results


100 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

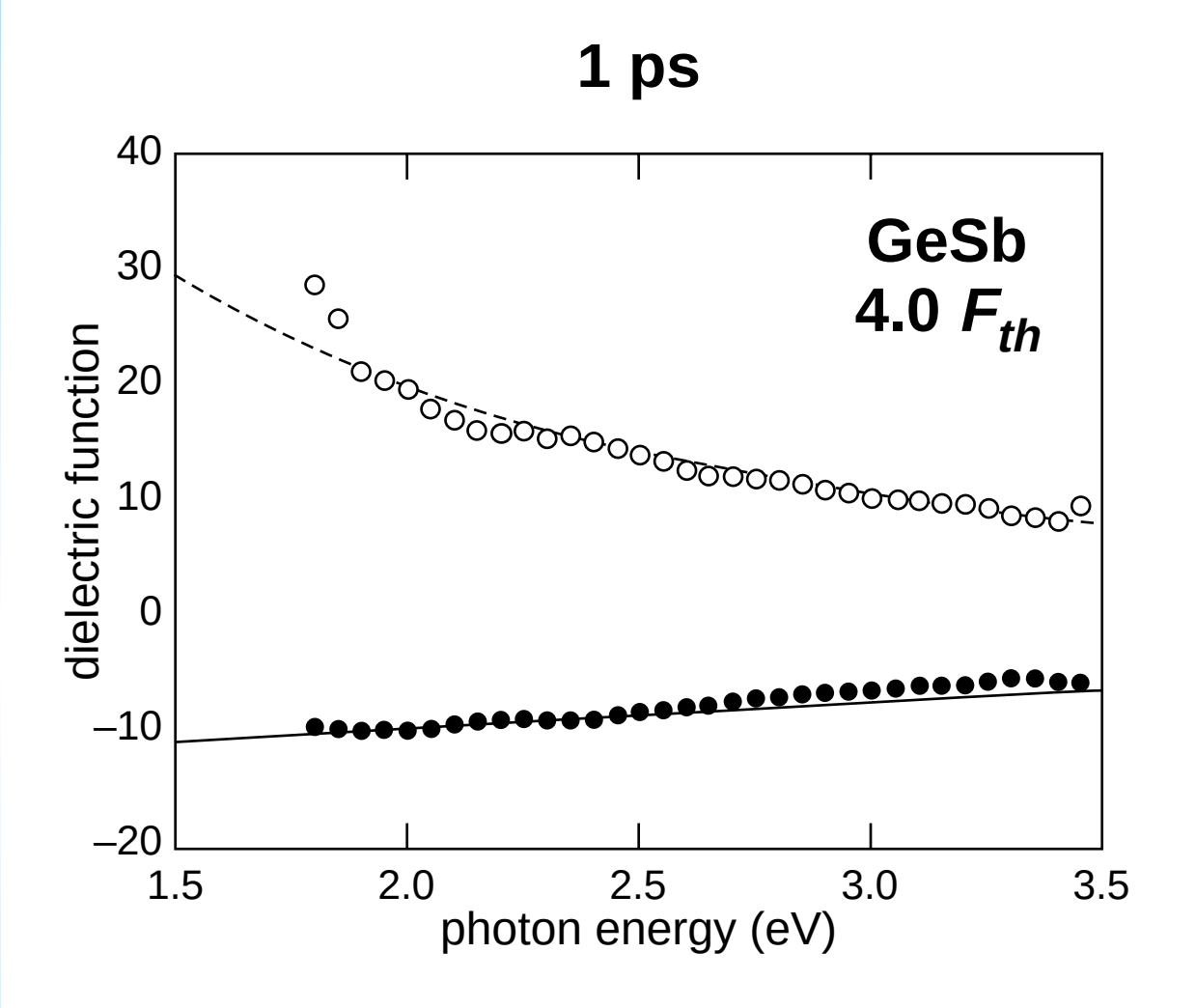
Results


475 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results

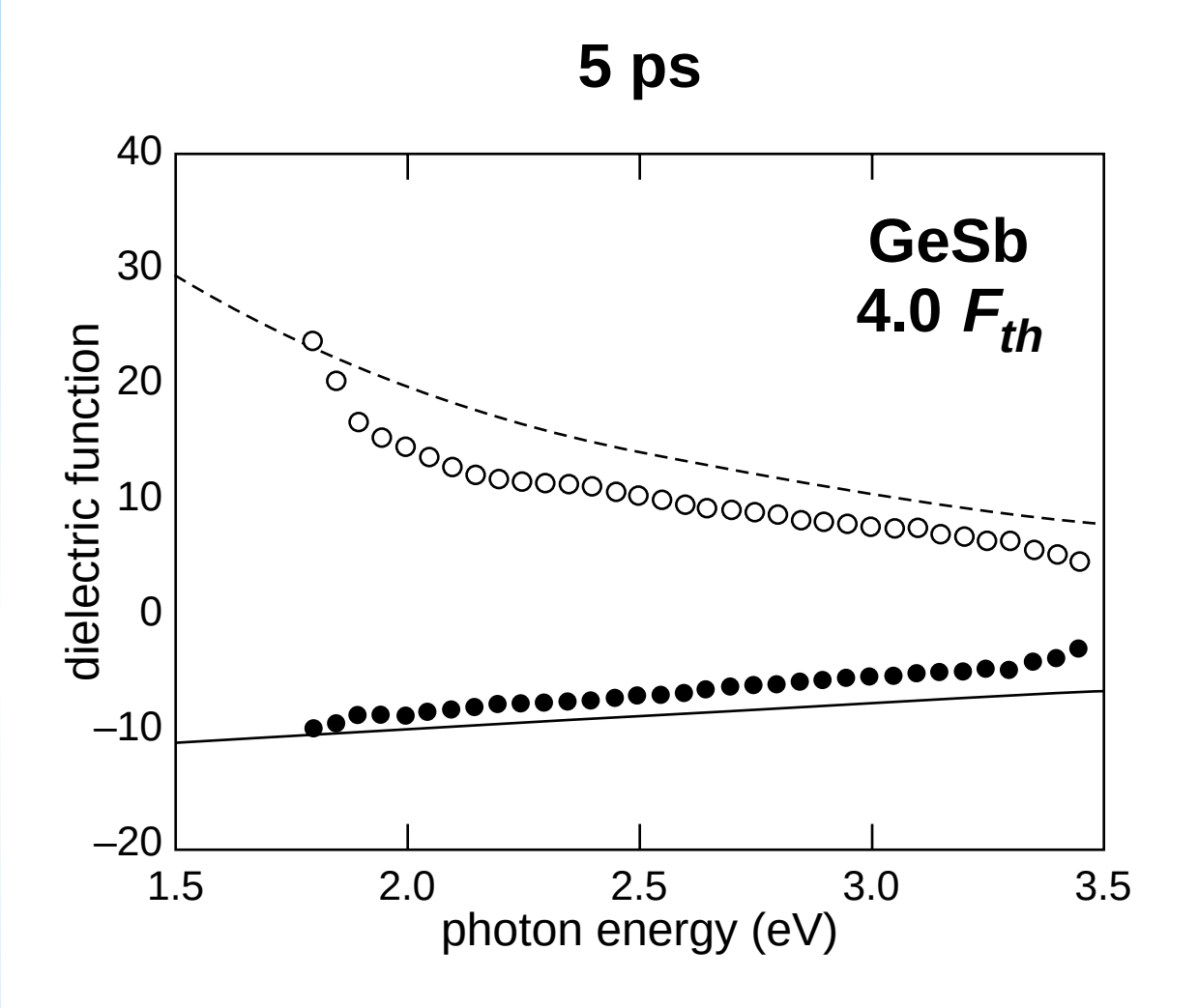

1 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results



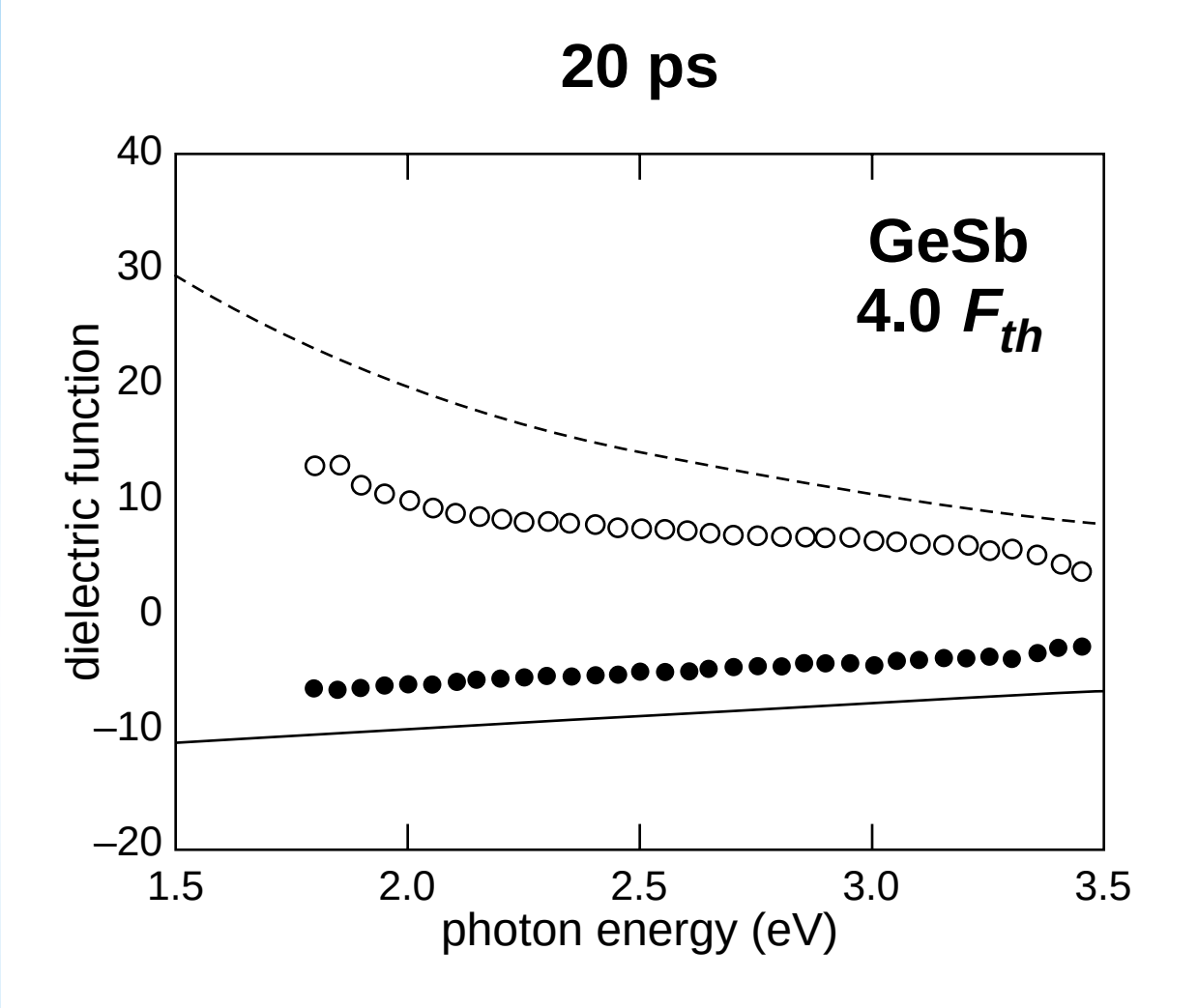
Drude-like after 1 ps

Results



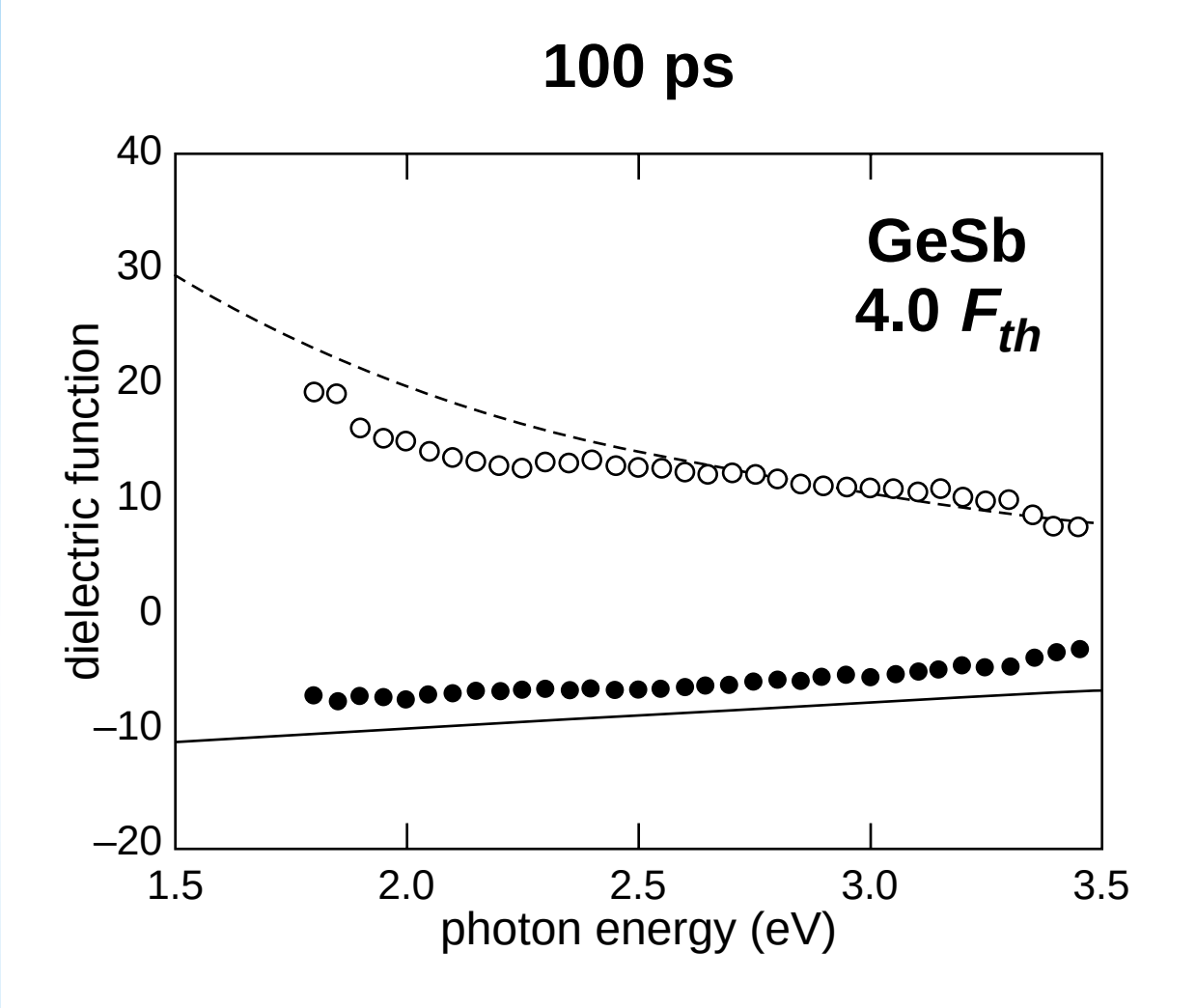
plasma frequency decreases

Results

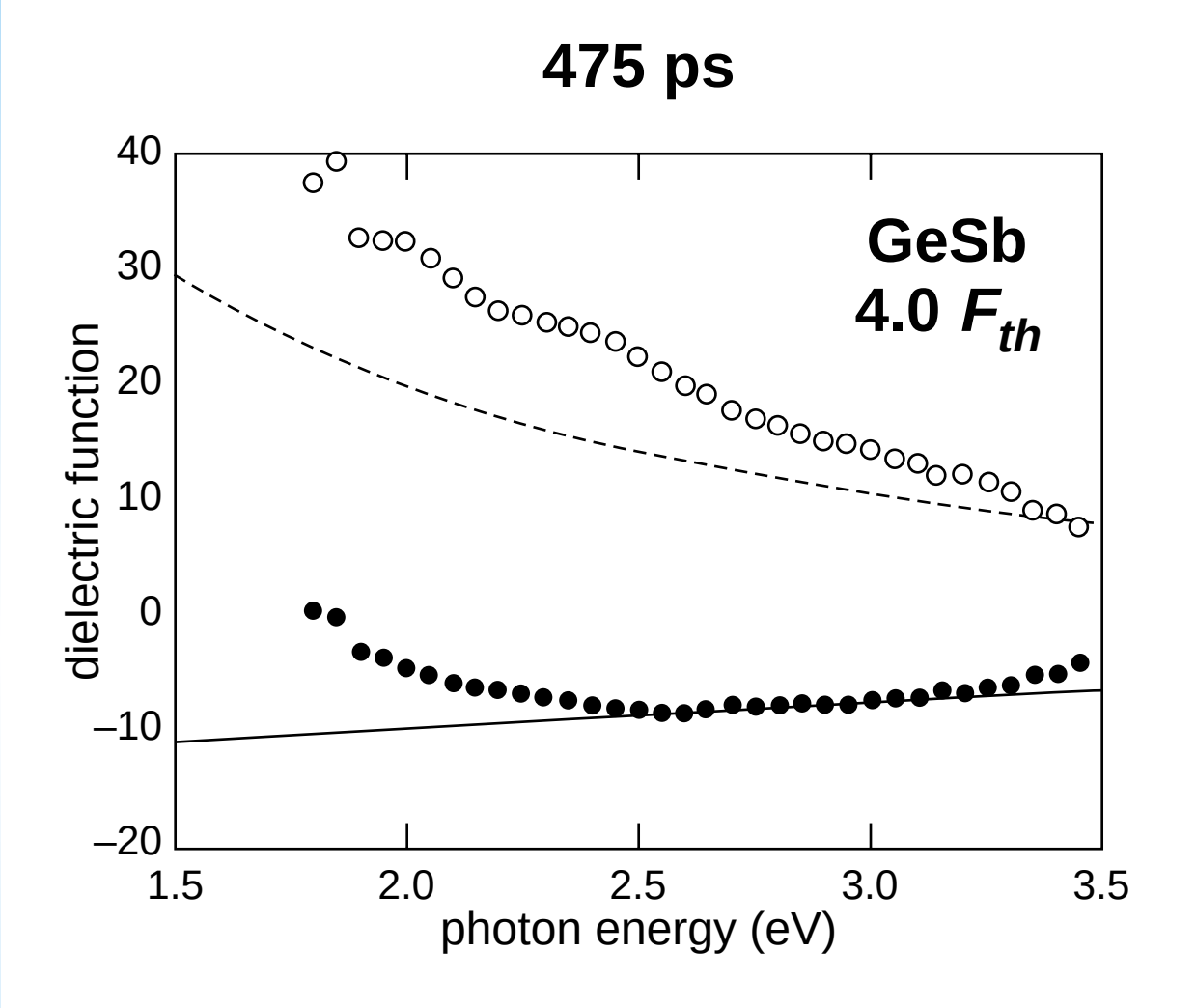


plasma frequency decreases

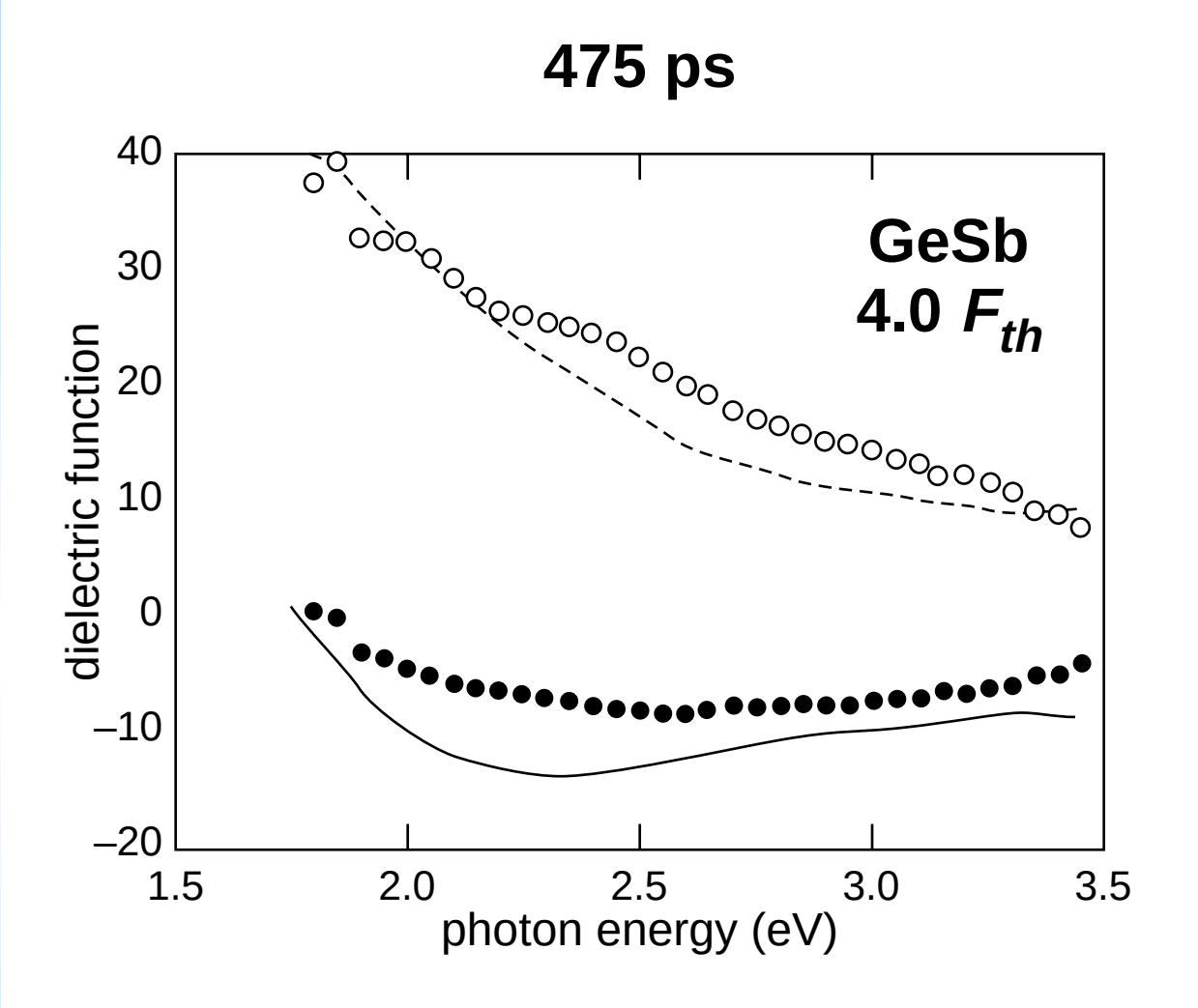
Results


100 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

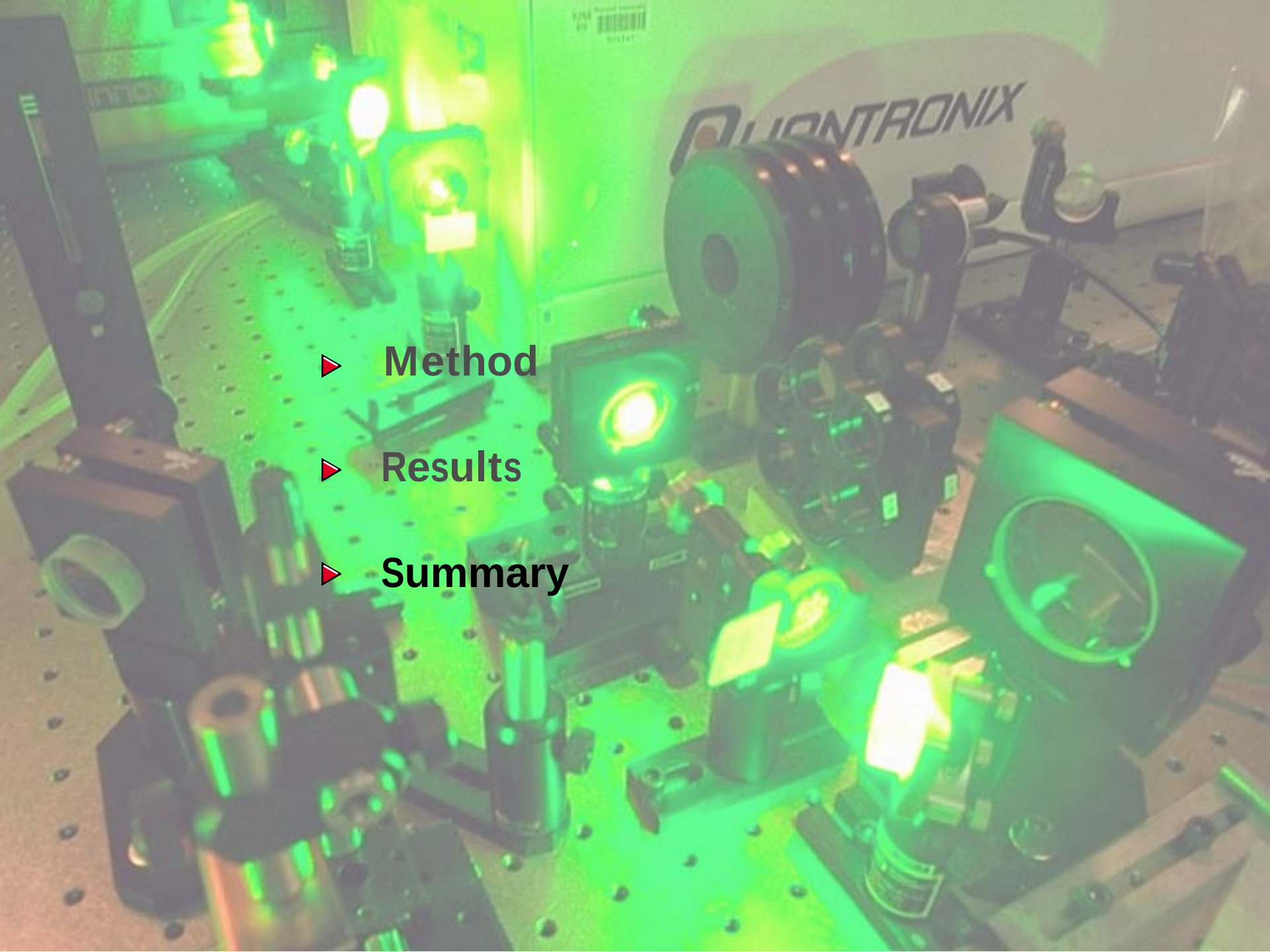
Results


475 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results



laser-induced recrystallization



- Method
- Results
- Summary

Summary

Universal features:

Summary

Universal features:

- **semiconductor-to-metal transition**

Summary

Universal features:

- **semiconductor-to-metal transition**
- **decrease in bonding-antibonding splitting takes picoseconds**

Summary

Universal features:

- **semiconductor-to-metal transition**
- **decrease in bonding-antibonding splitting takes picoseconds**
- **plasma frequency decreases with time**

Summary

Universal features:

- **semiconductor-to-metal transition**
- **decrease in bonding-antibonding splitting takes picoseconds**
- **plasma frequency decreases with time**
- **plasma frequency decreases with increasing fluence**

Summary

Femtosecond time-resolved ellipsometry

- **powerful tool for tracking ultrafast electron and lattice dynamics in highly excited solids**
- **helps uncover unexplored terrain on the boundary between condensed matter and plasma physics**


GORDON McKAY
LABORATORY OF
APPLIED SCIENCE

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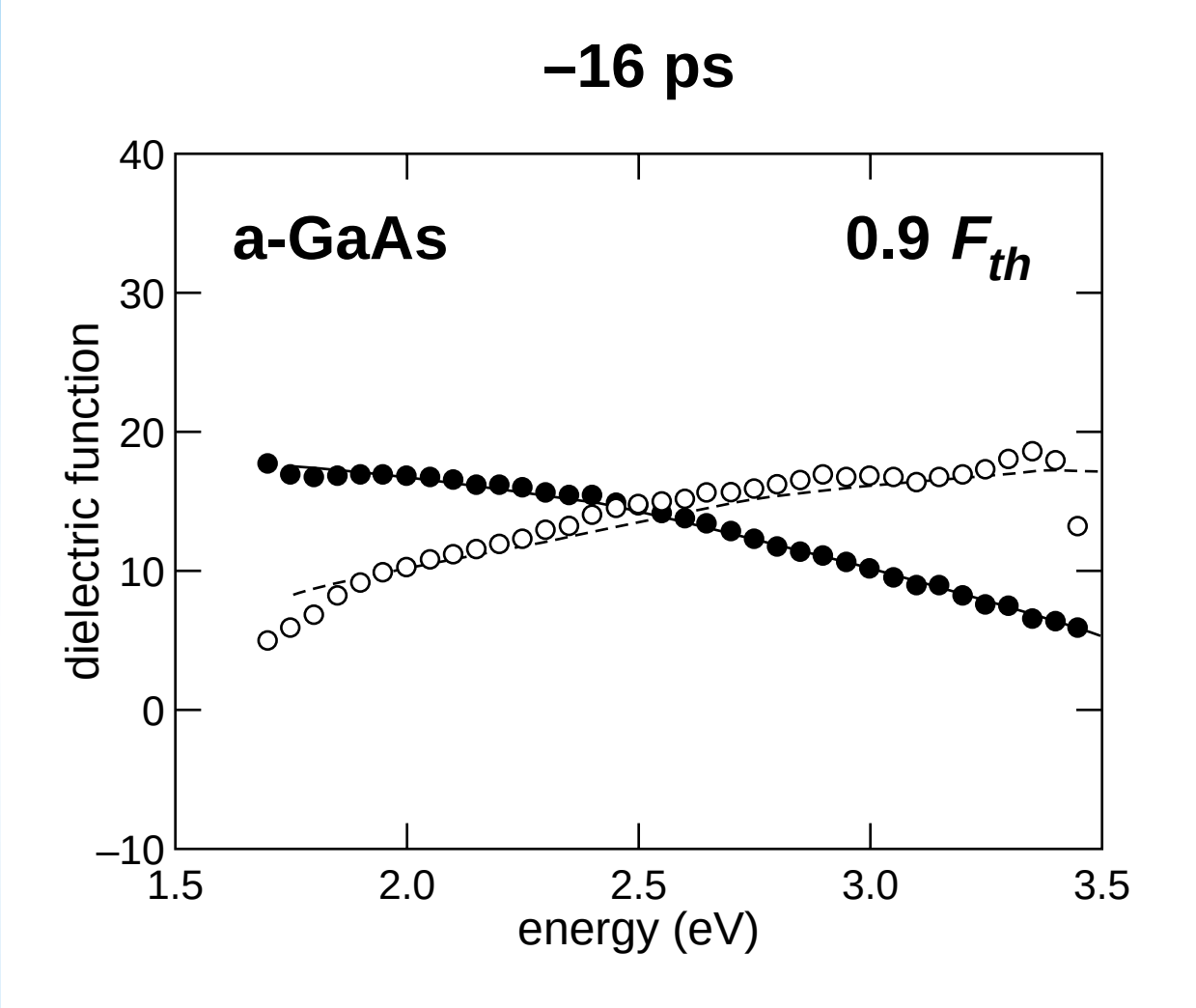
Prof. H. Ehrenreich
Prof. T. Kaxiras
Prof. C. Klingshirn

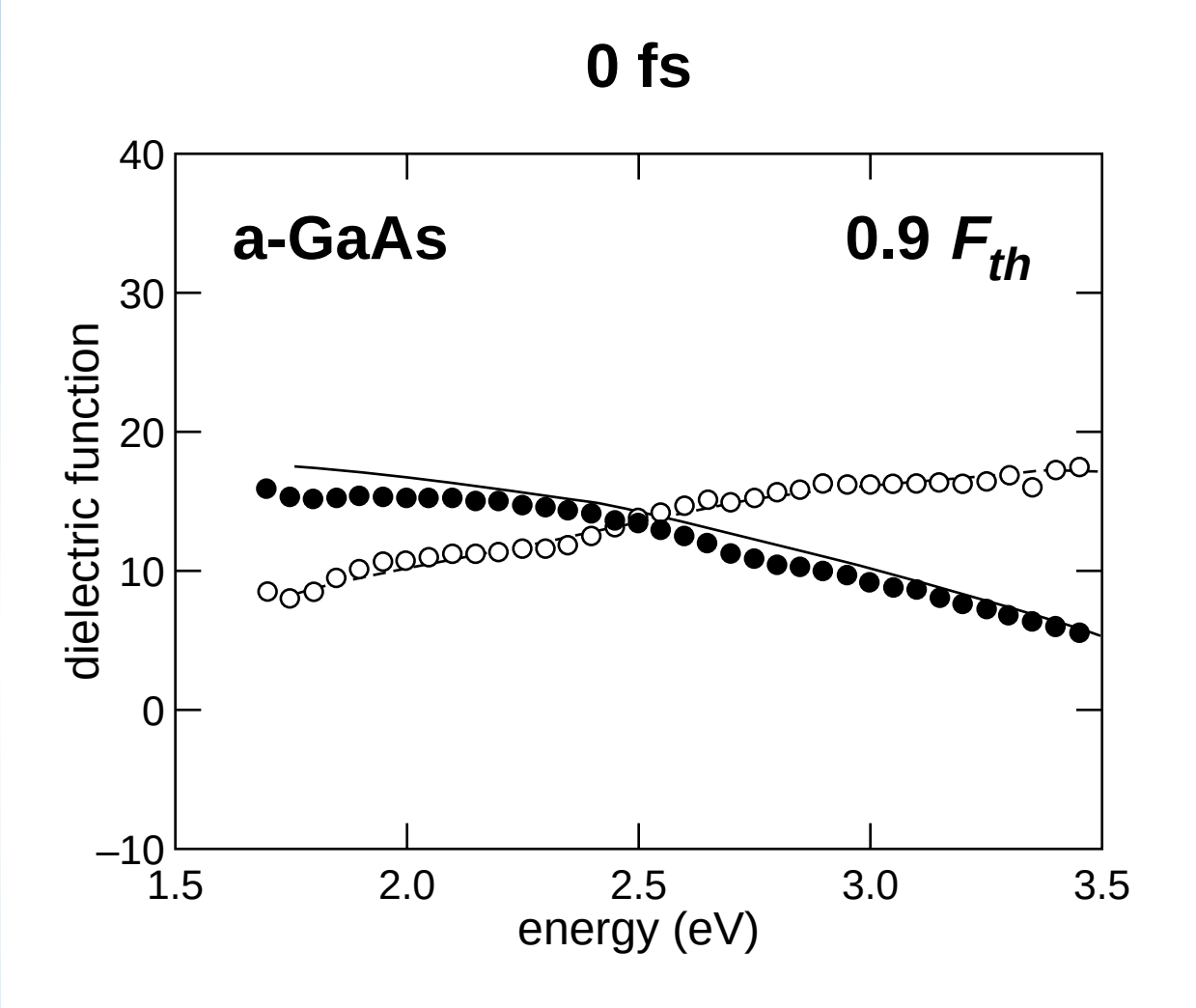
For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu

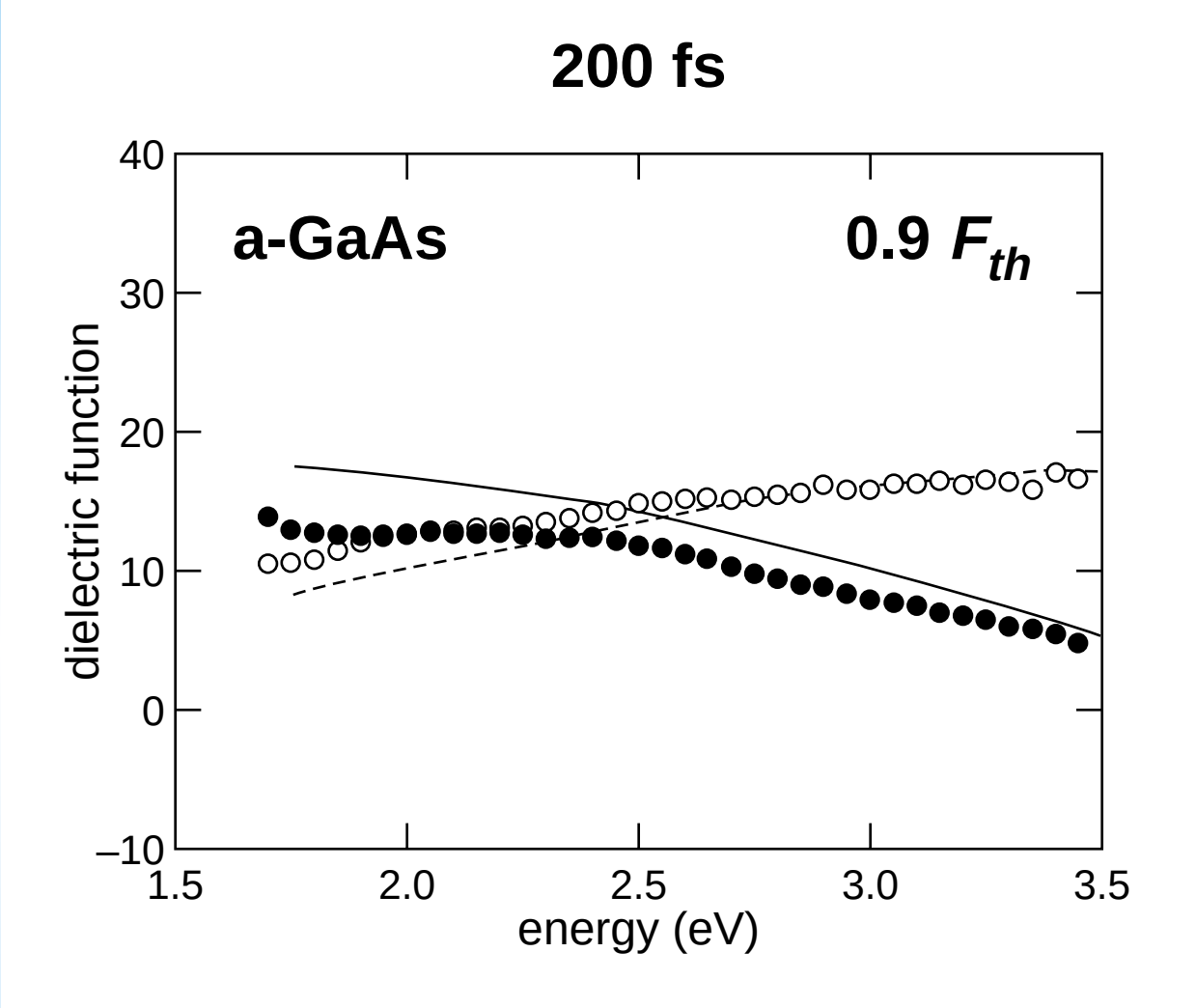
Results


–16 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

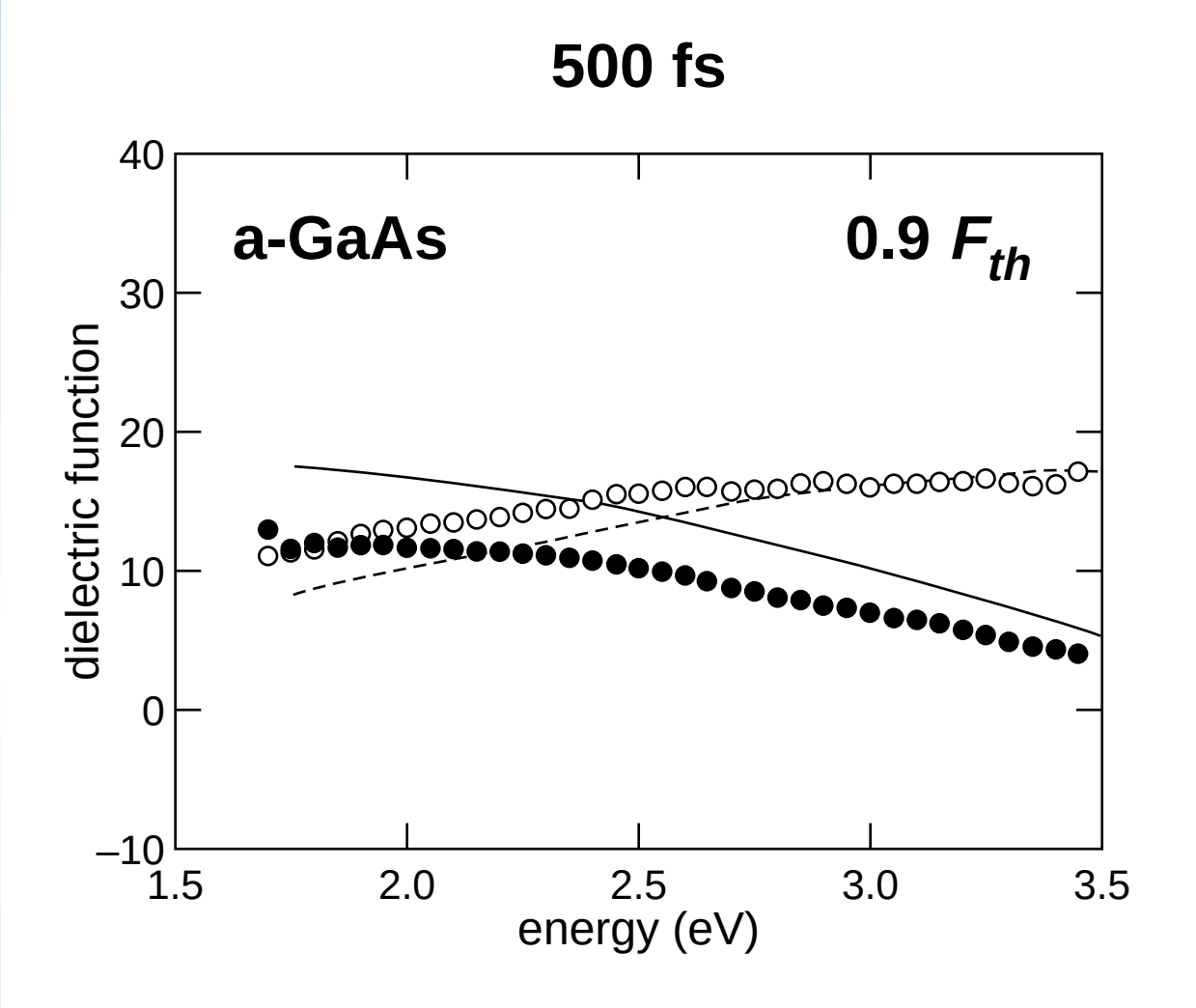
Results


0 fs
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

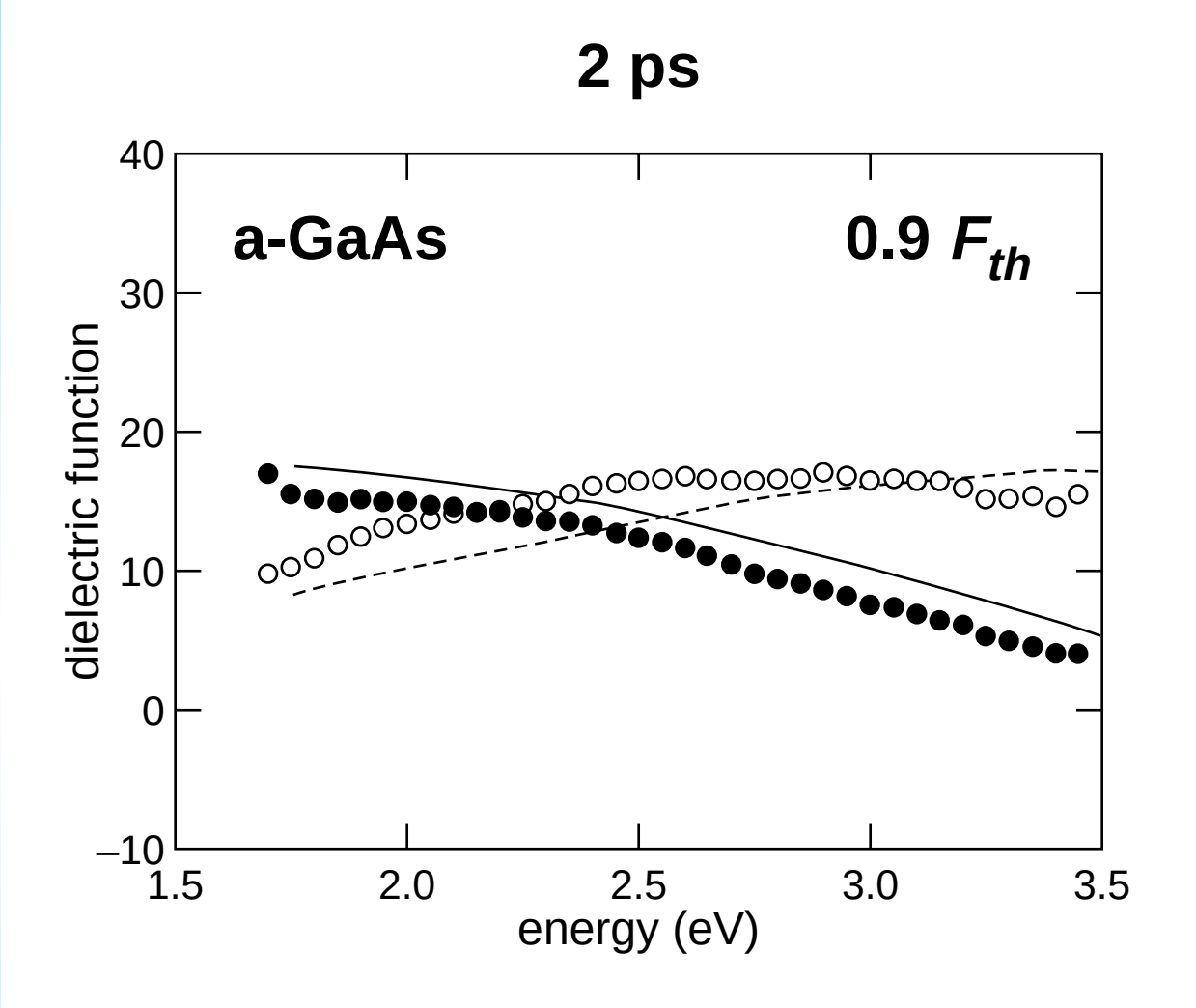
Results


200 fs
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

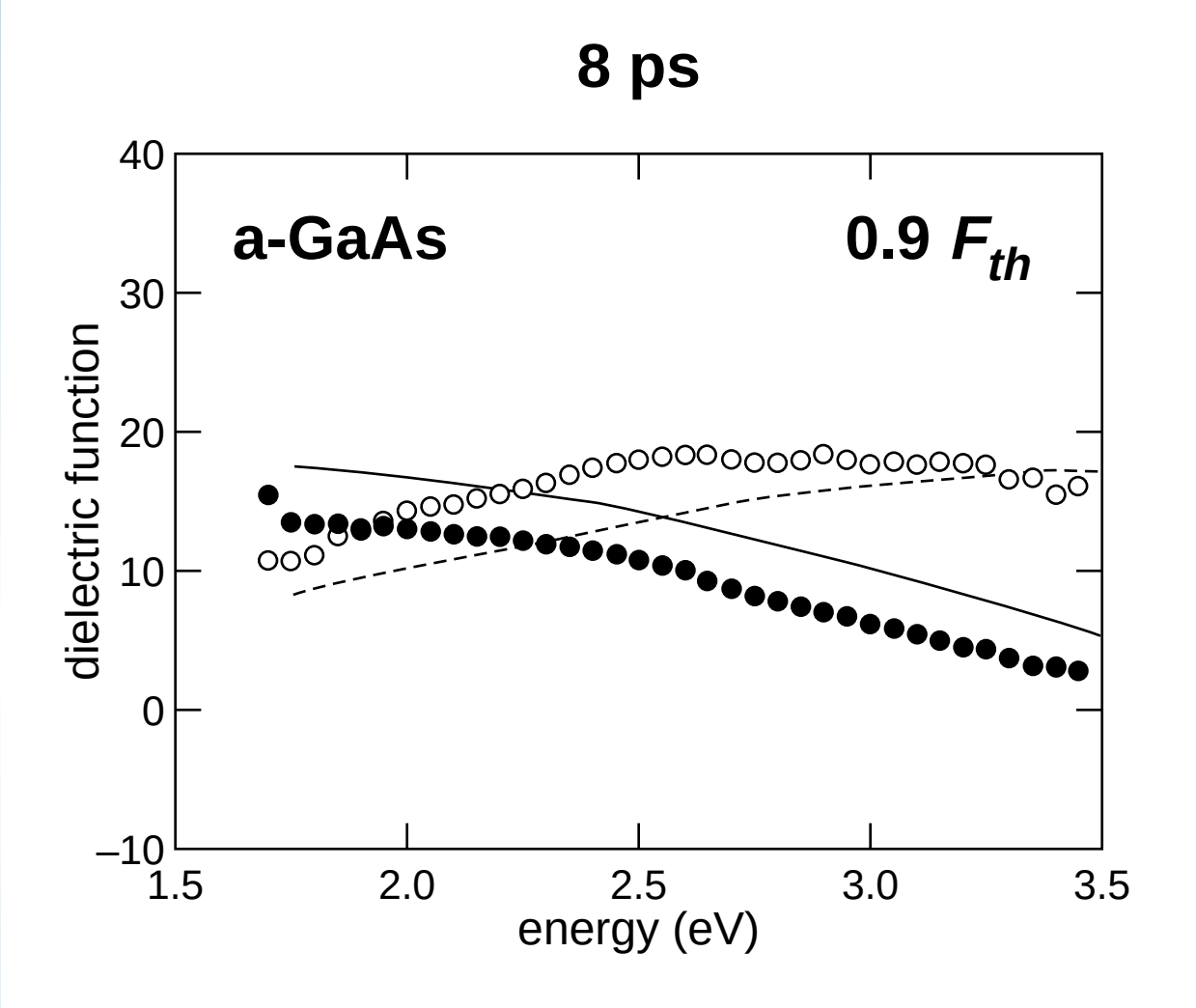
Results


500 fs
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

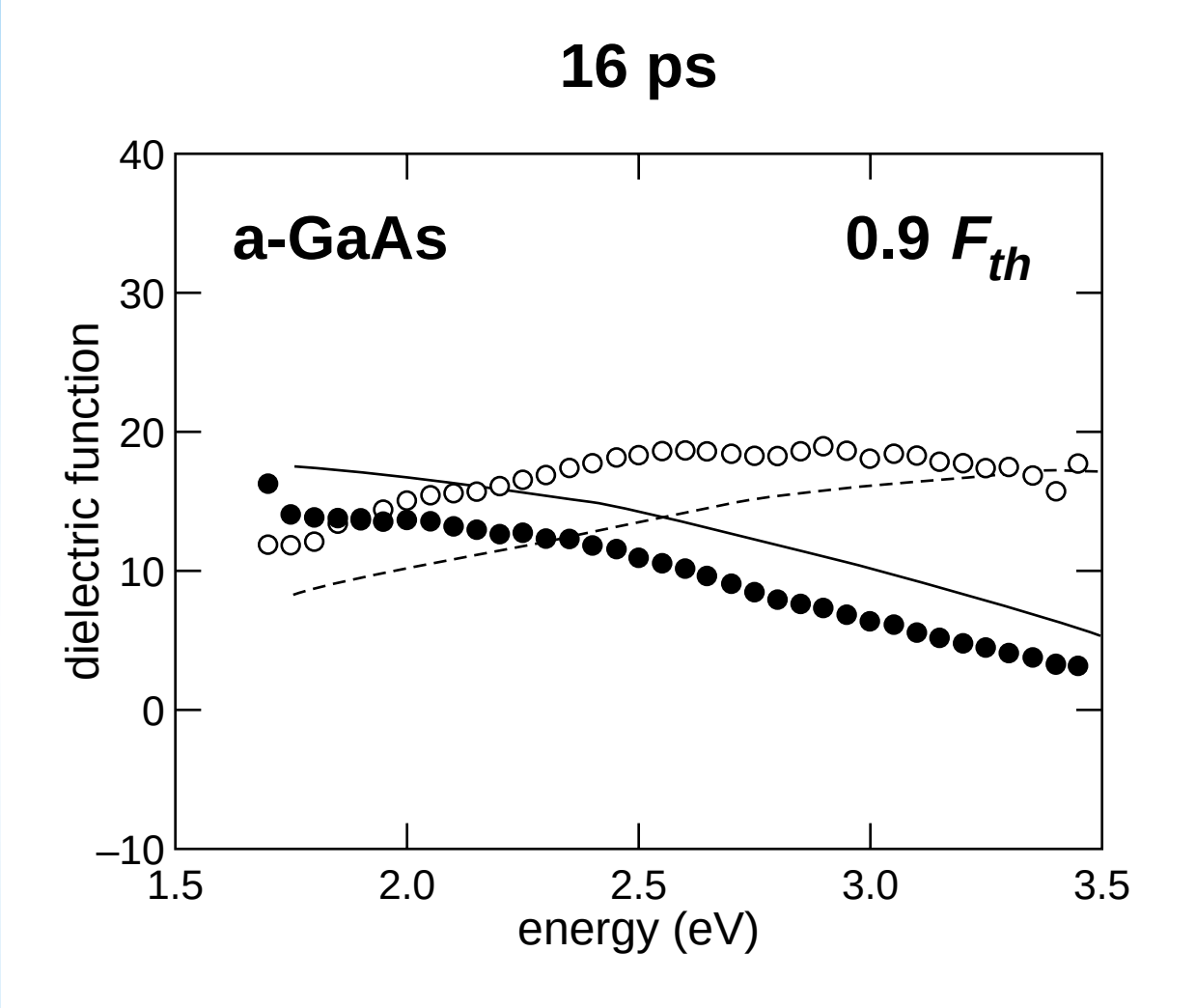
Results


2 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

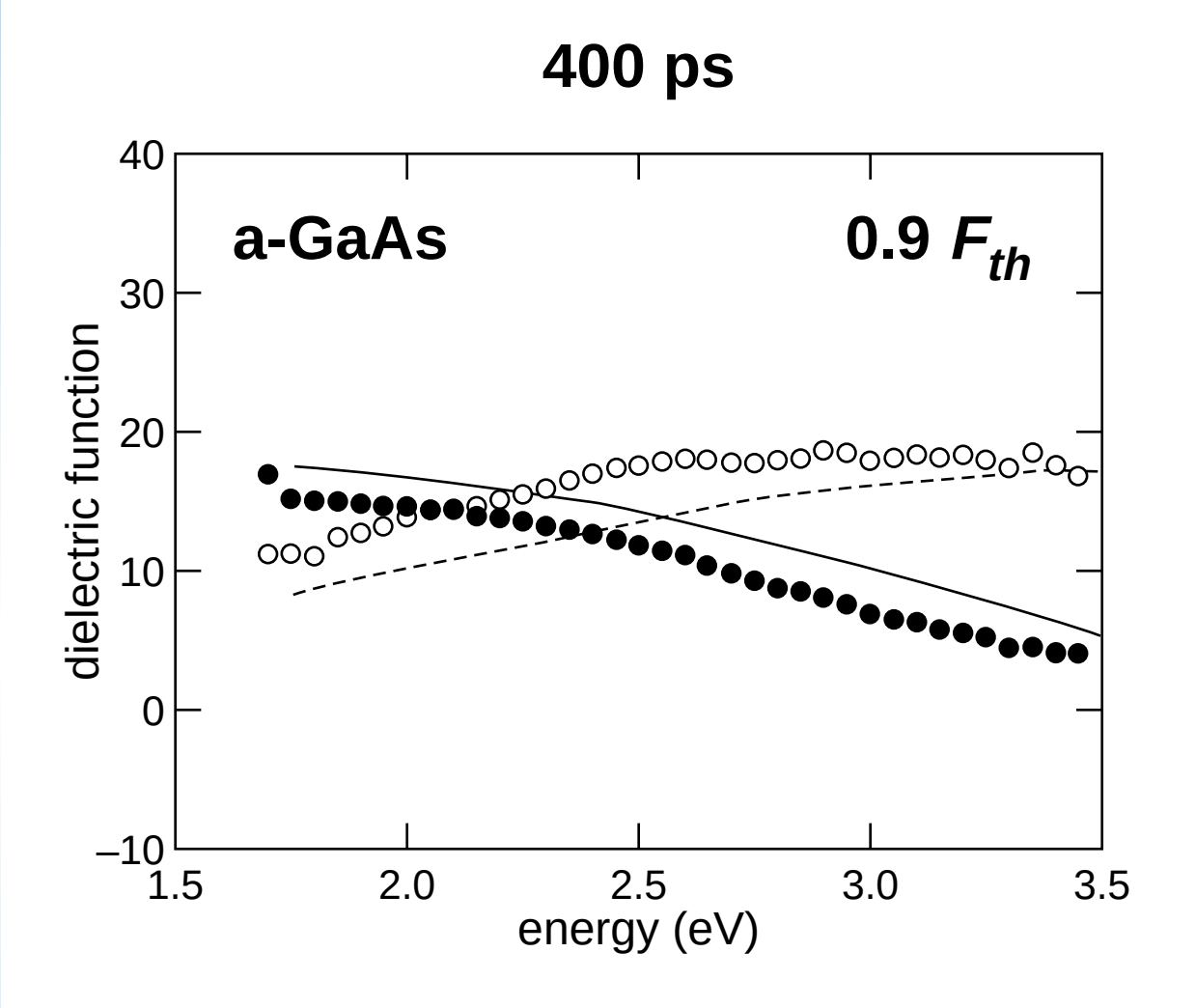
Results


8 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

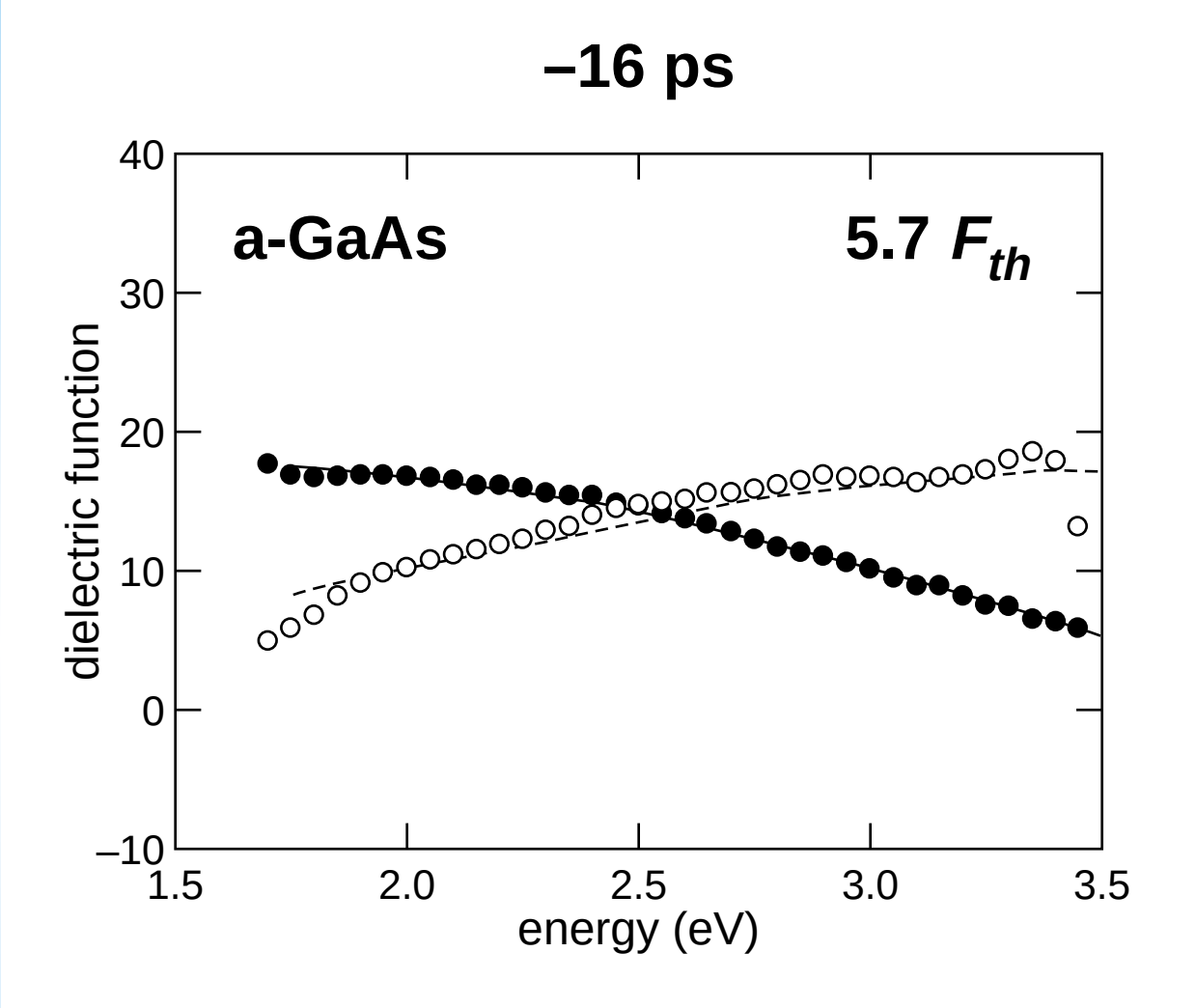
Results


16 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

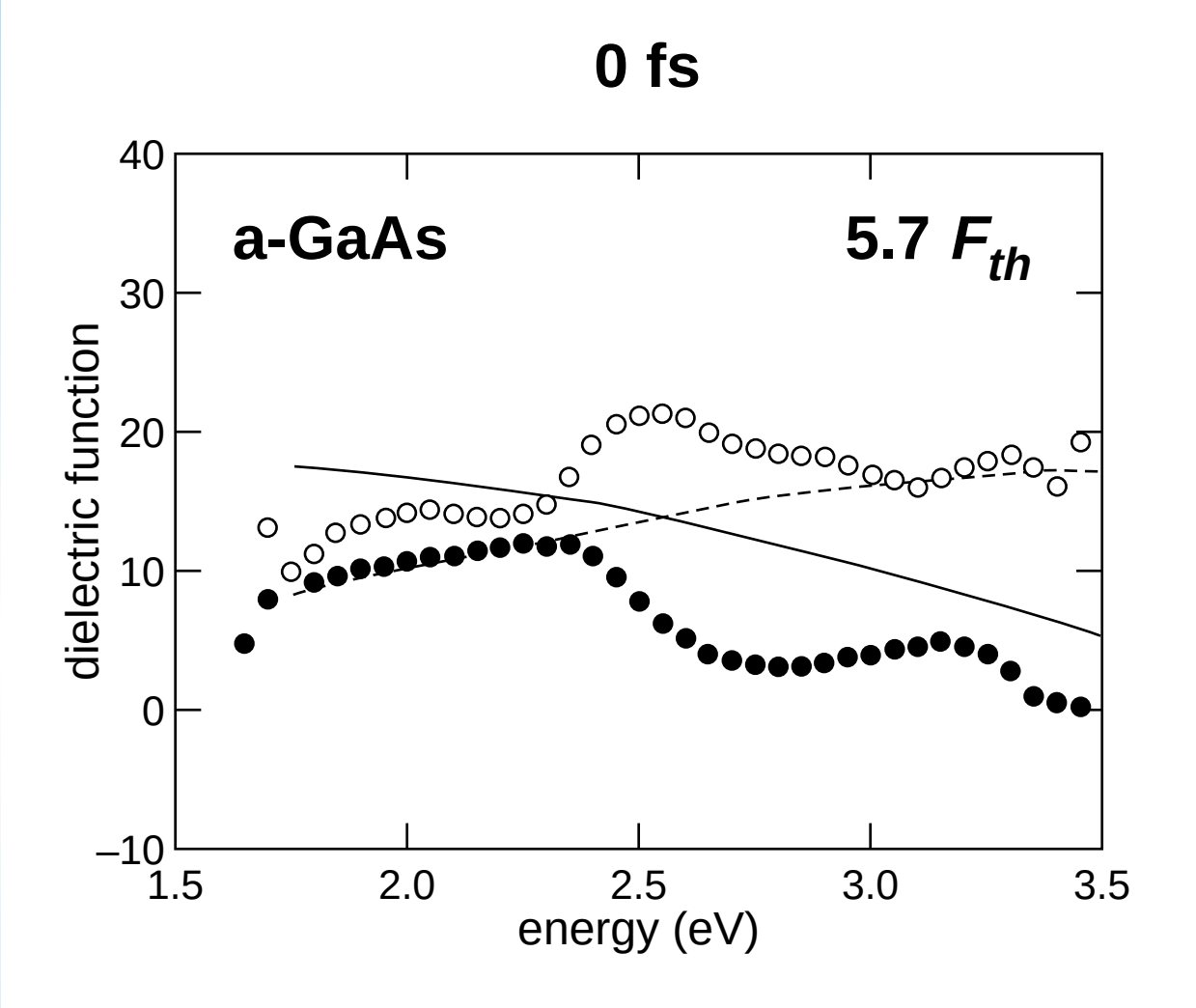
Results


400 ps
a-GaAs
0.9 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

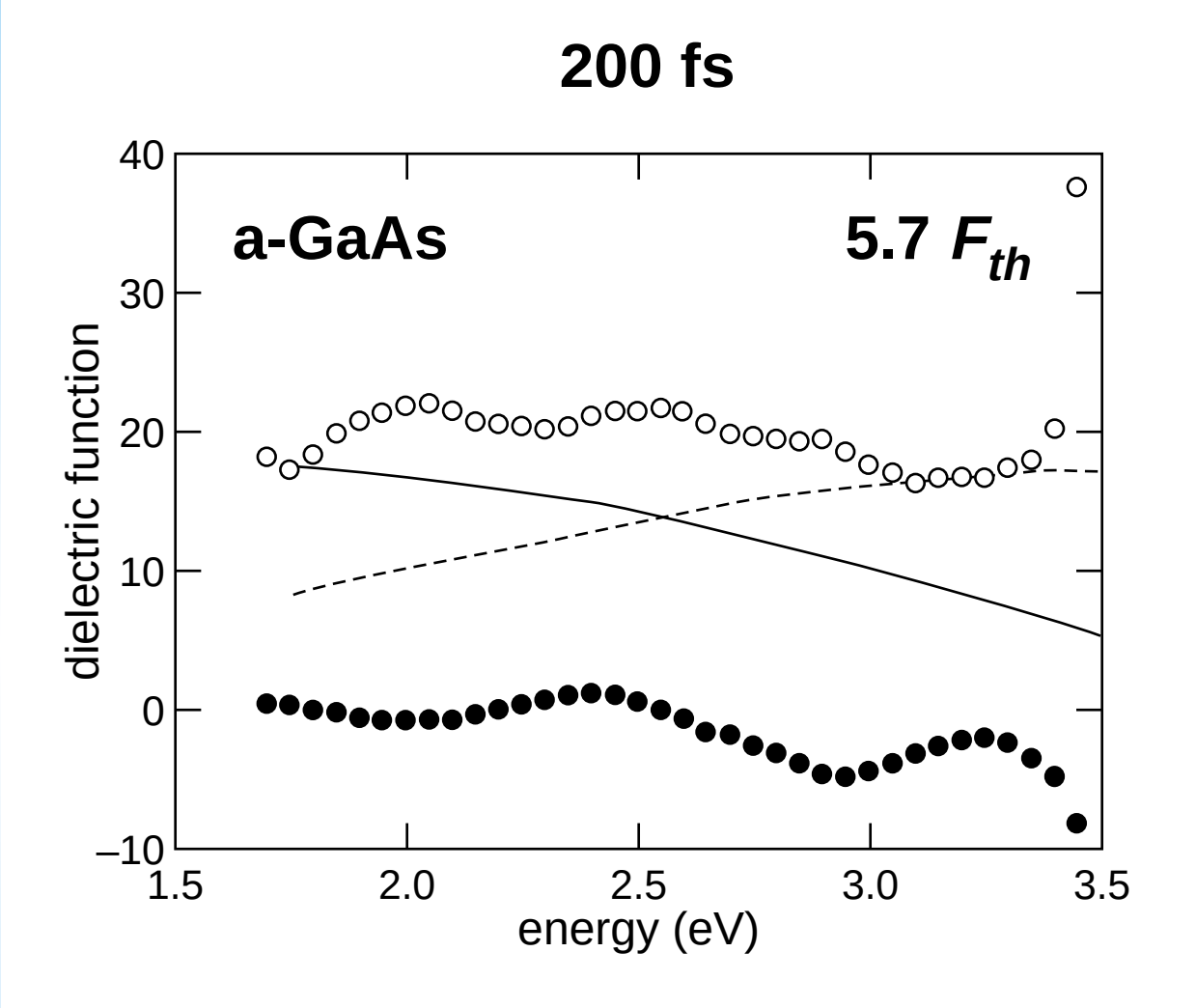
Results


–16 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

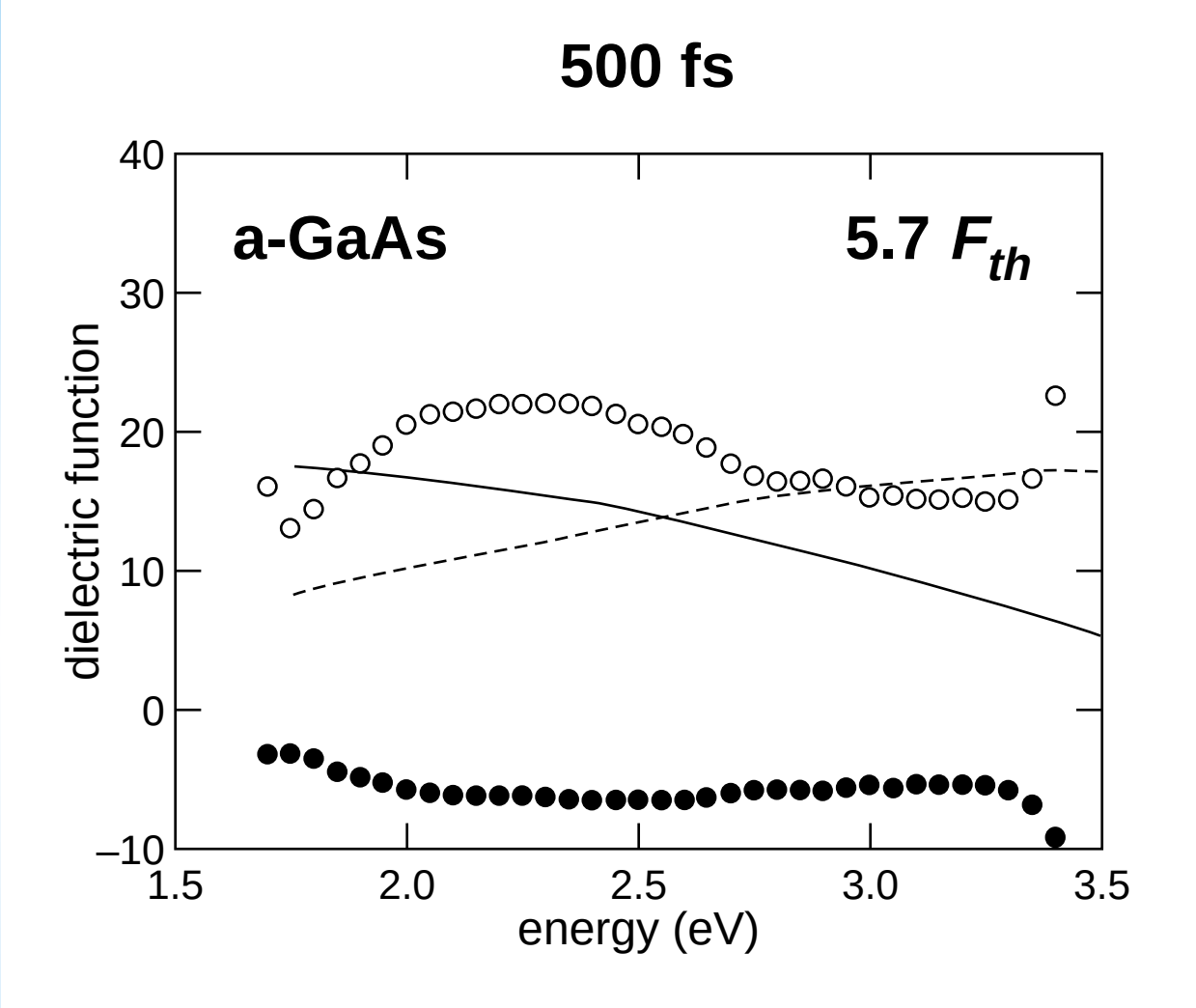
Results


0 fs
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

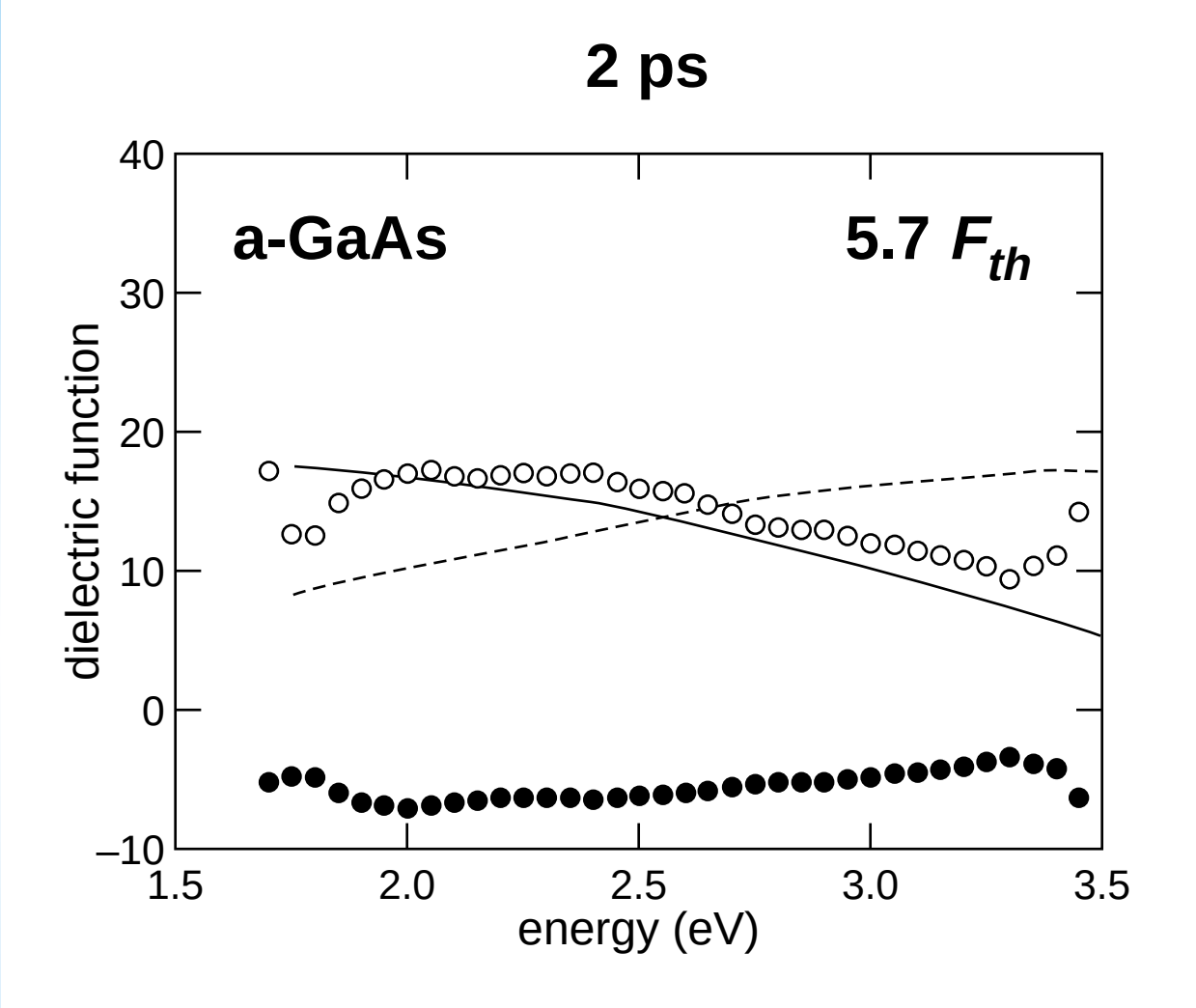
Results


200 fs
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

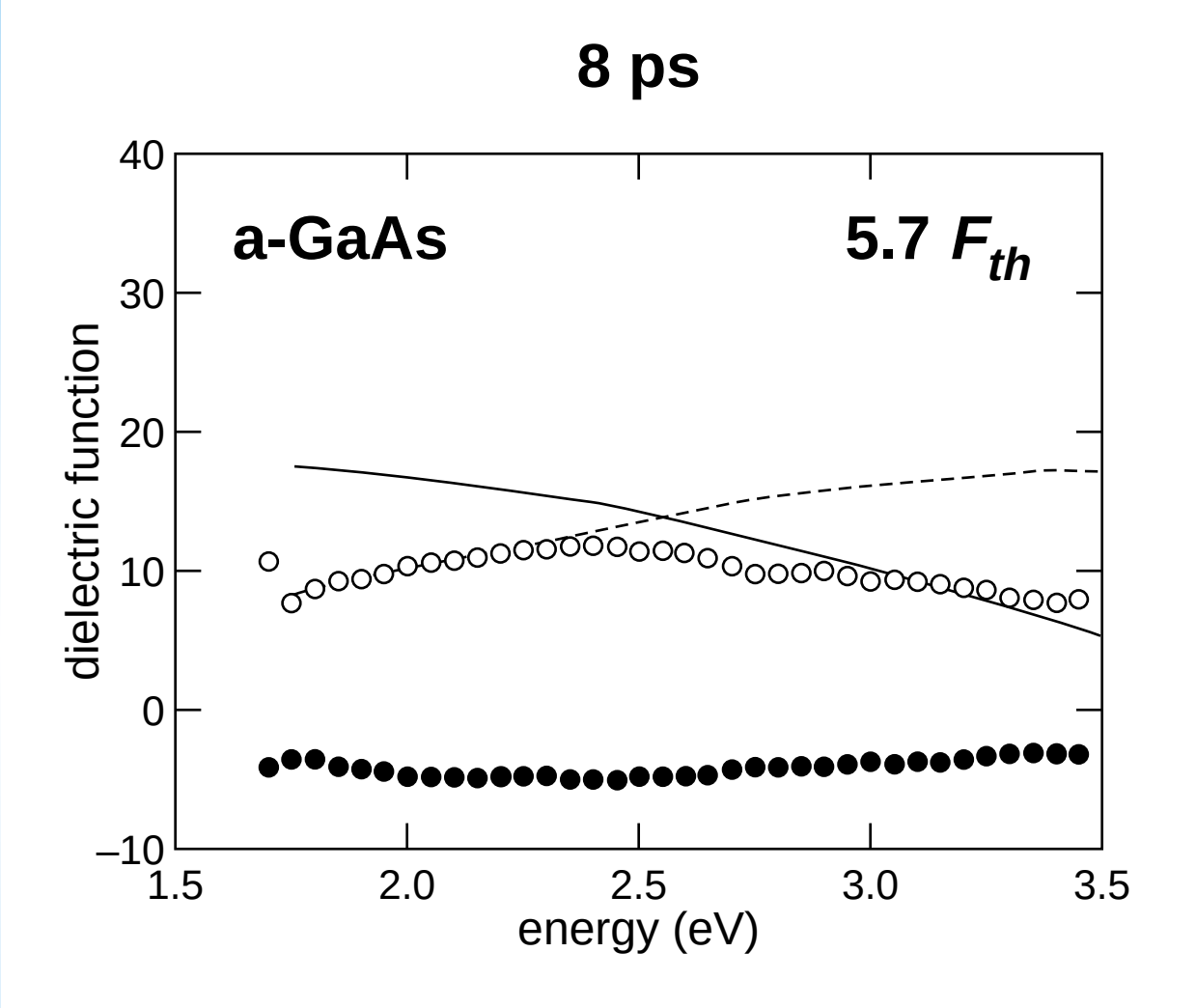
Results


500 fs
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

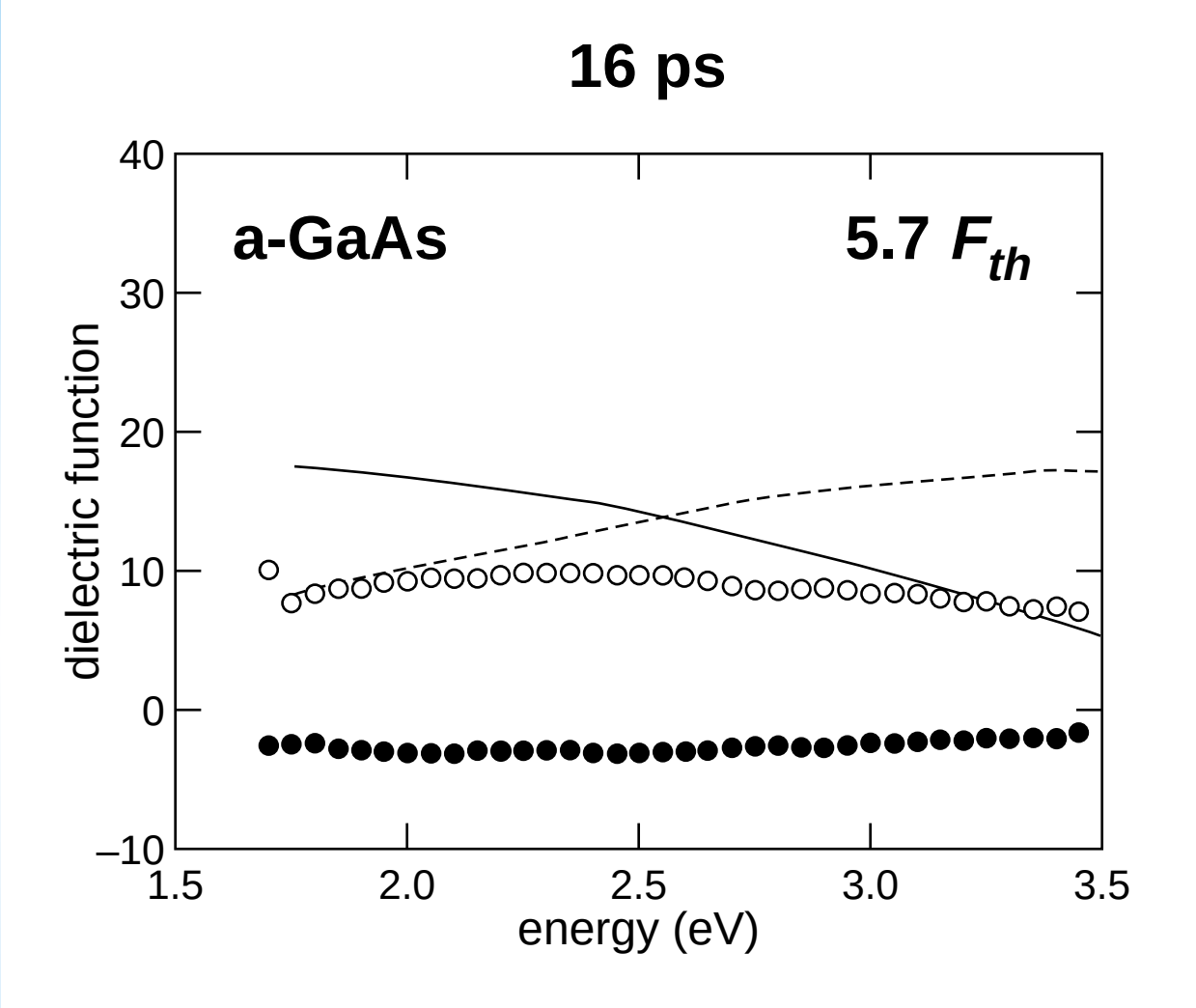
Results


2 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

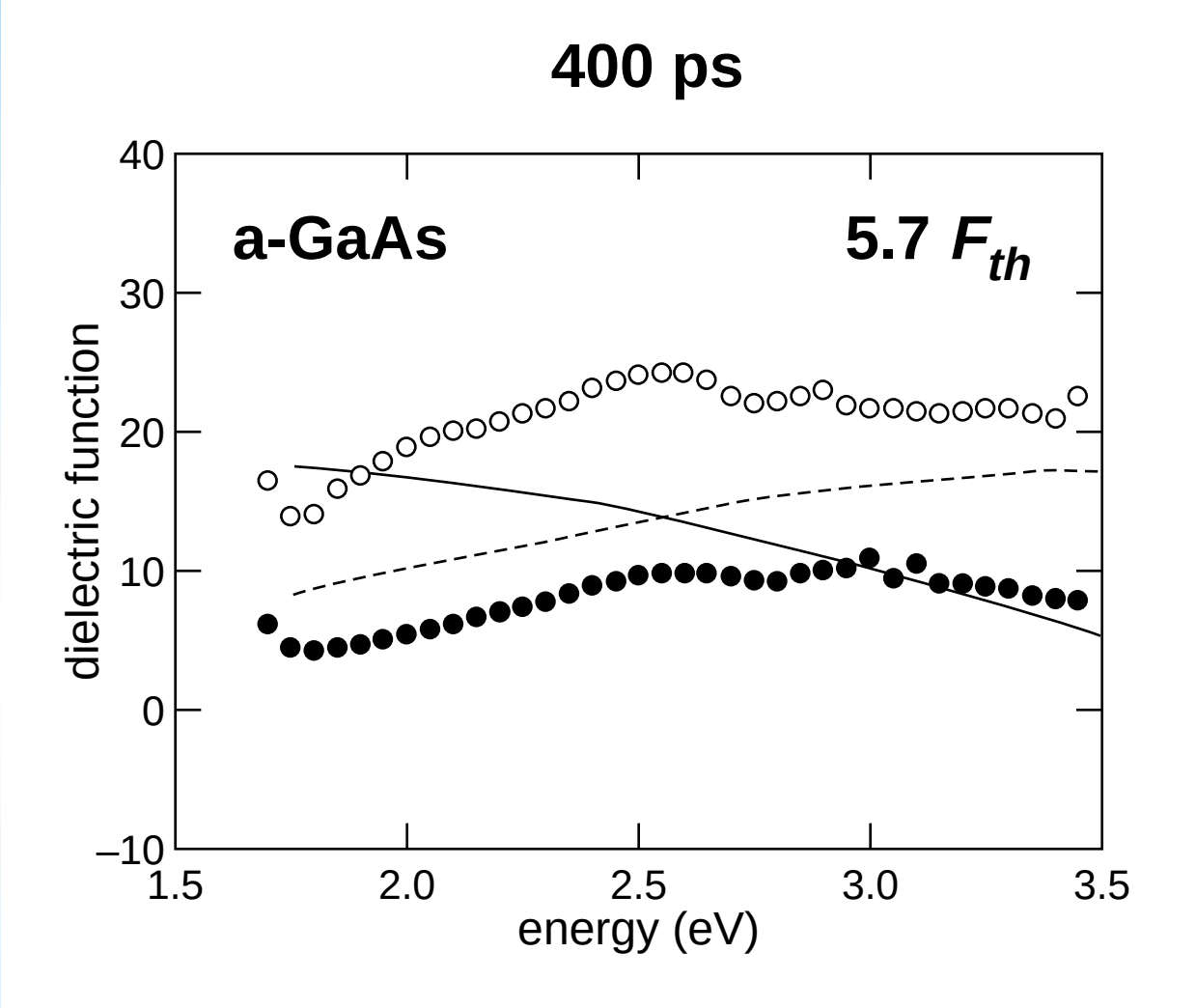
Results


8 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

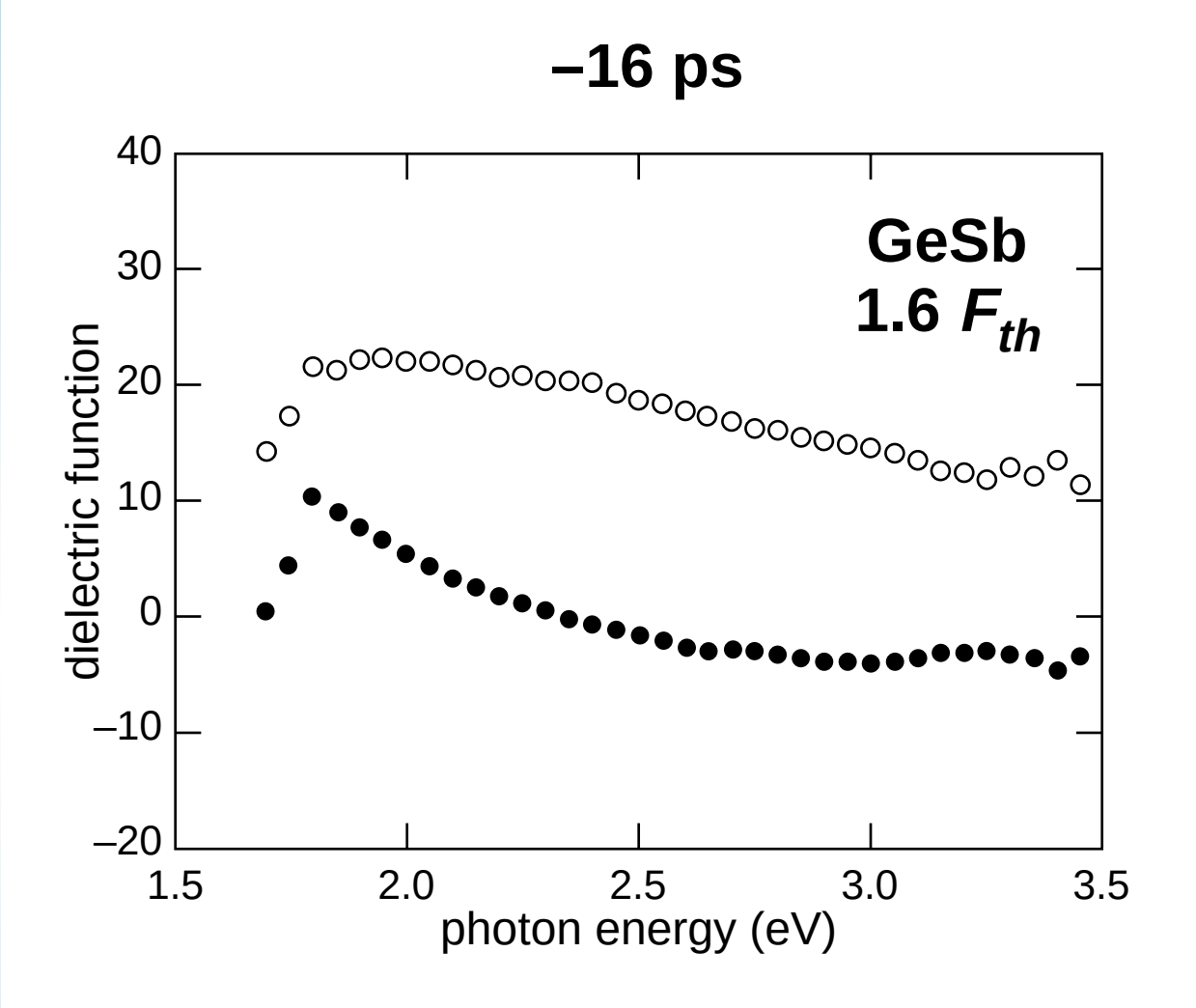
Results


16 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

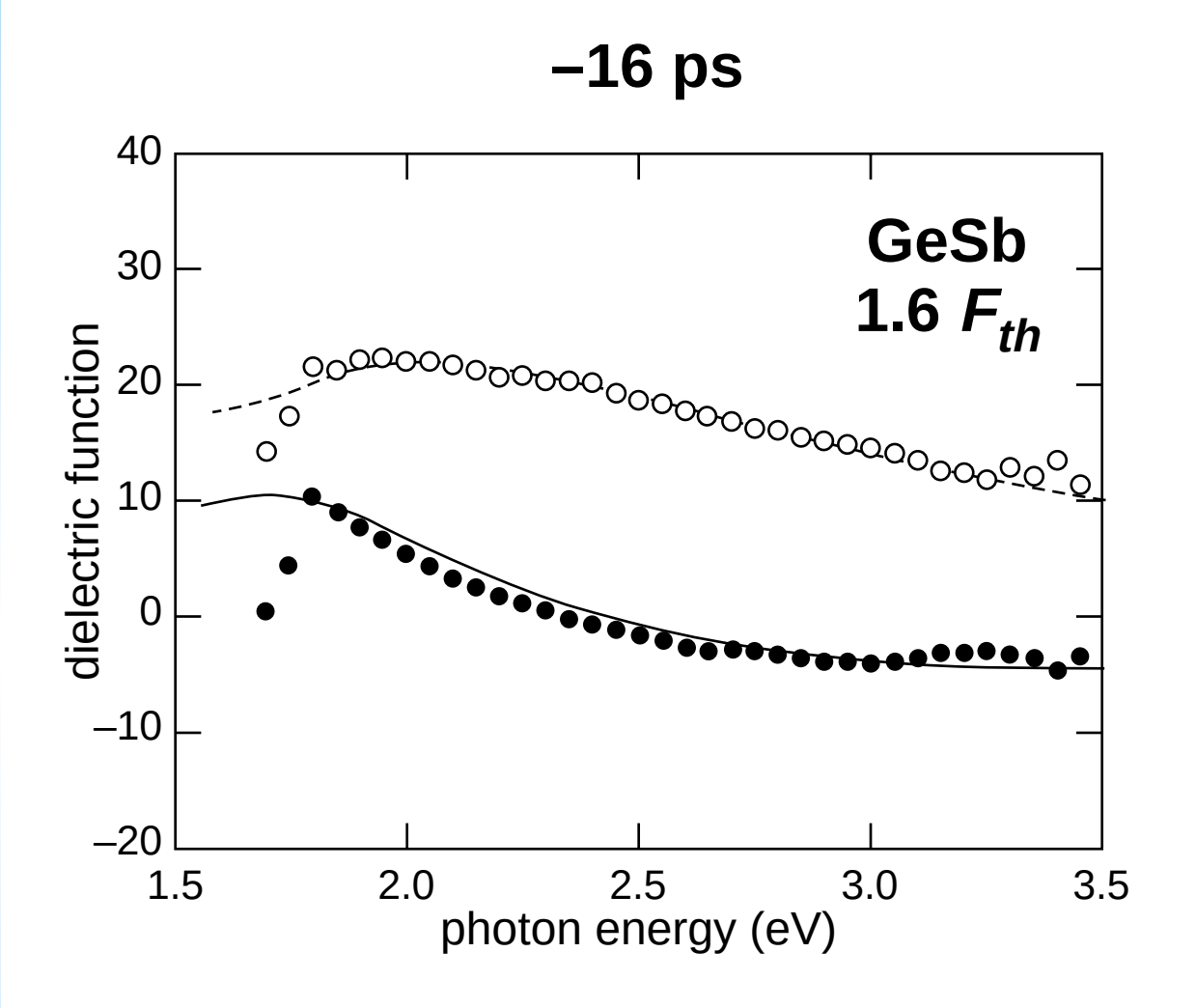
Results


400 ps
a-GaAs
5.7 F_{th}
dielectric function
energy (eV)
40
30
20
10
0
–10
1.5
2.0
2.5
3.0
3.5

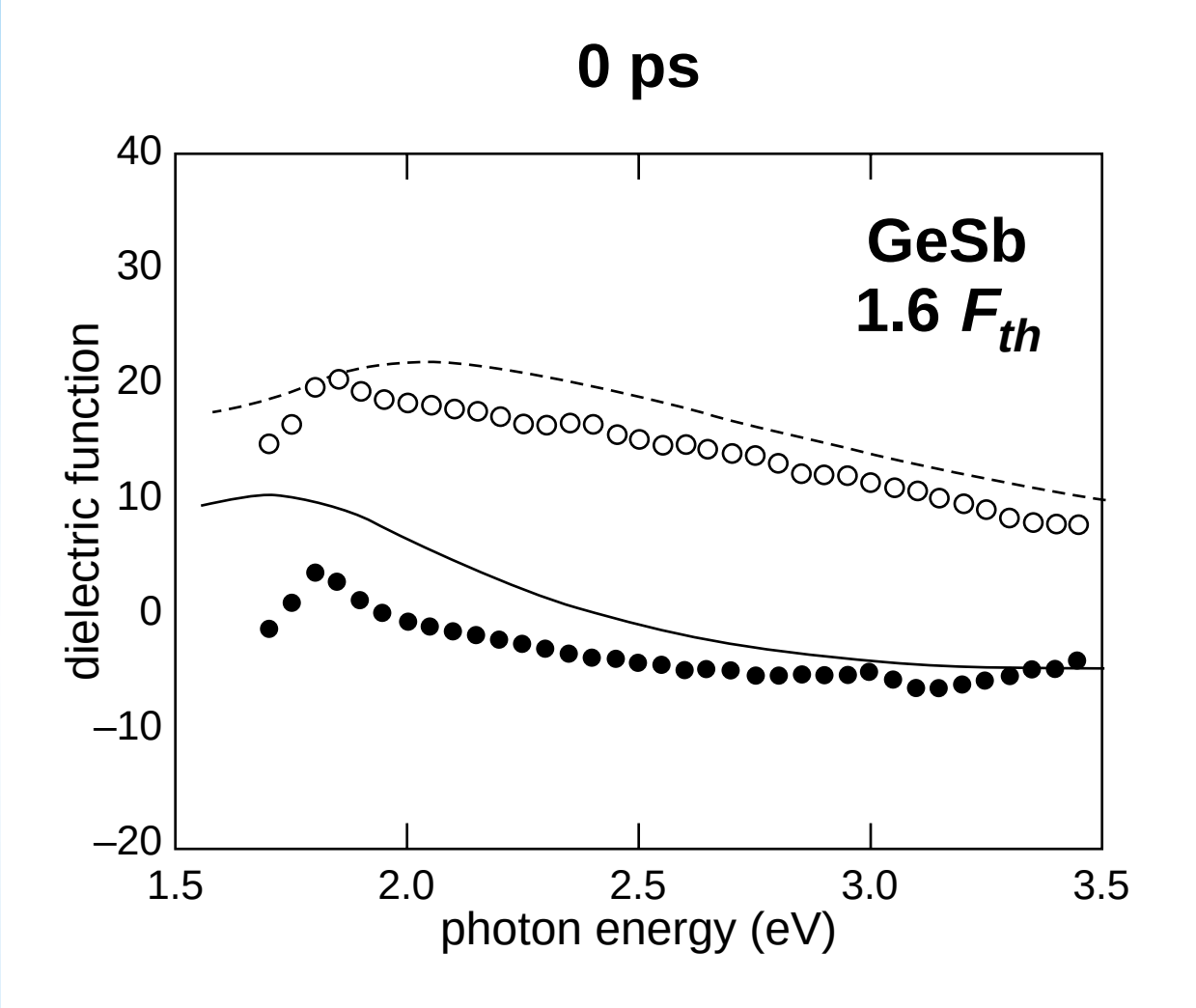
Results


–16 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

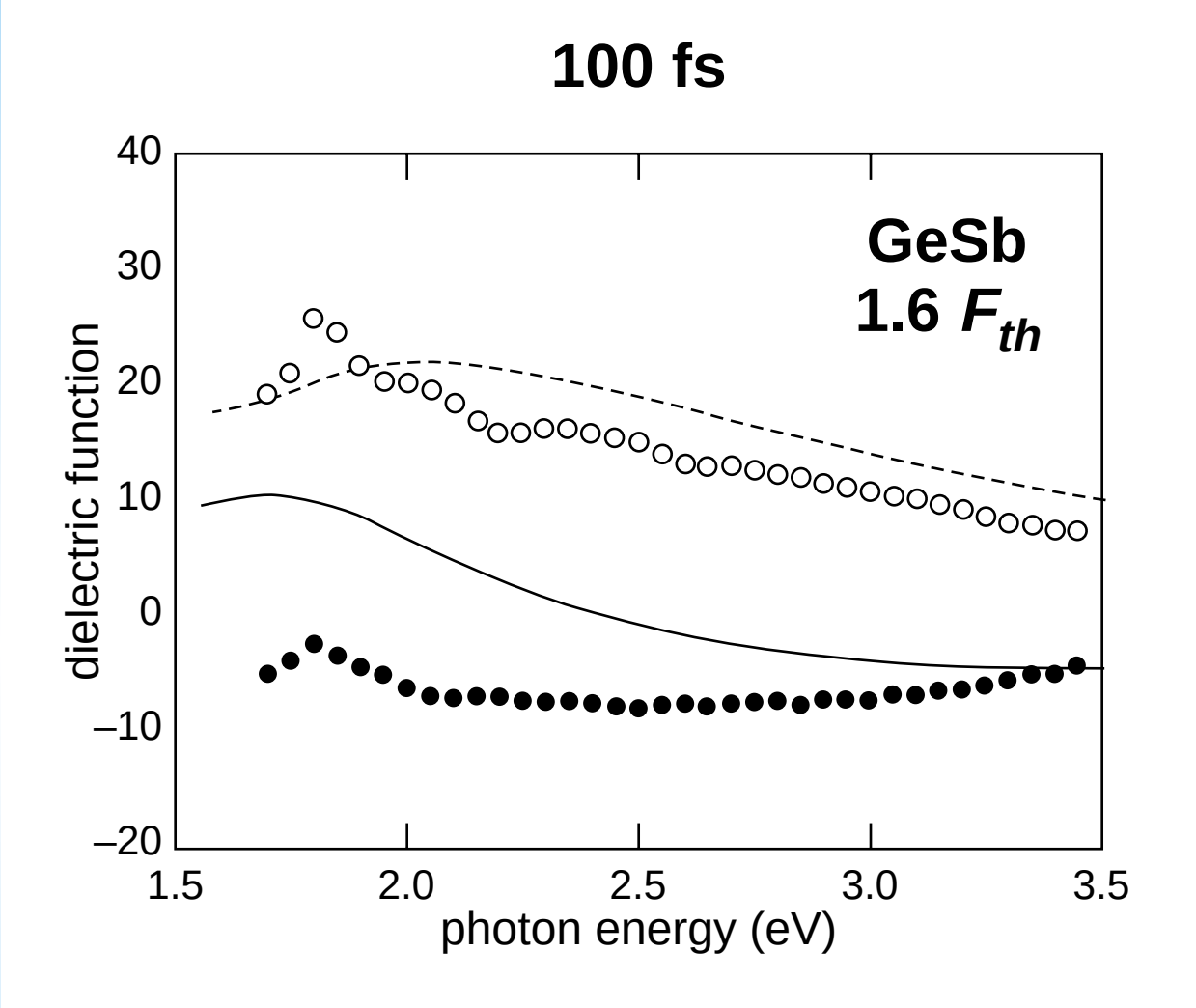
Results


–16 ps
GeSb
1.6 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5

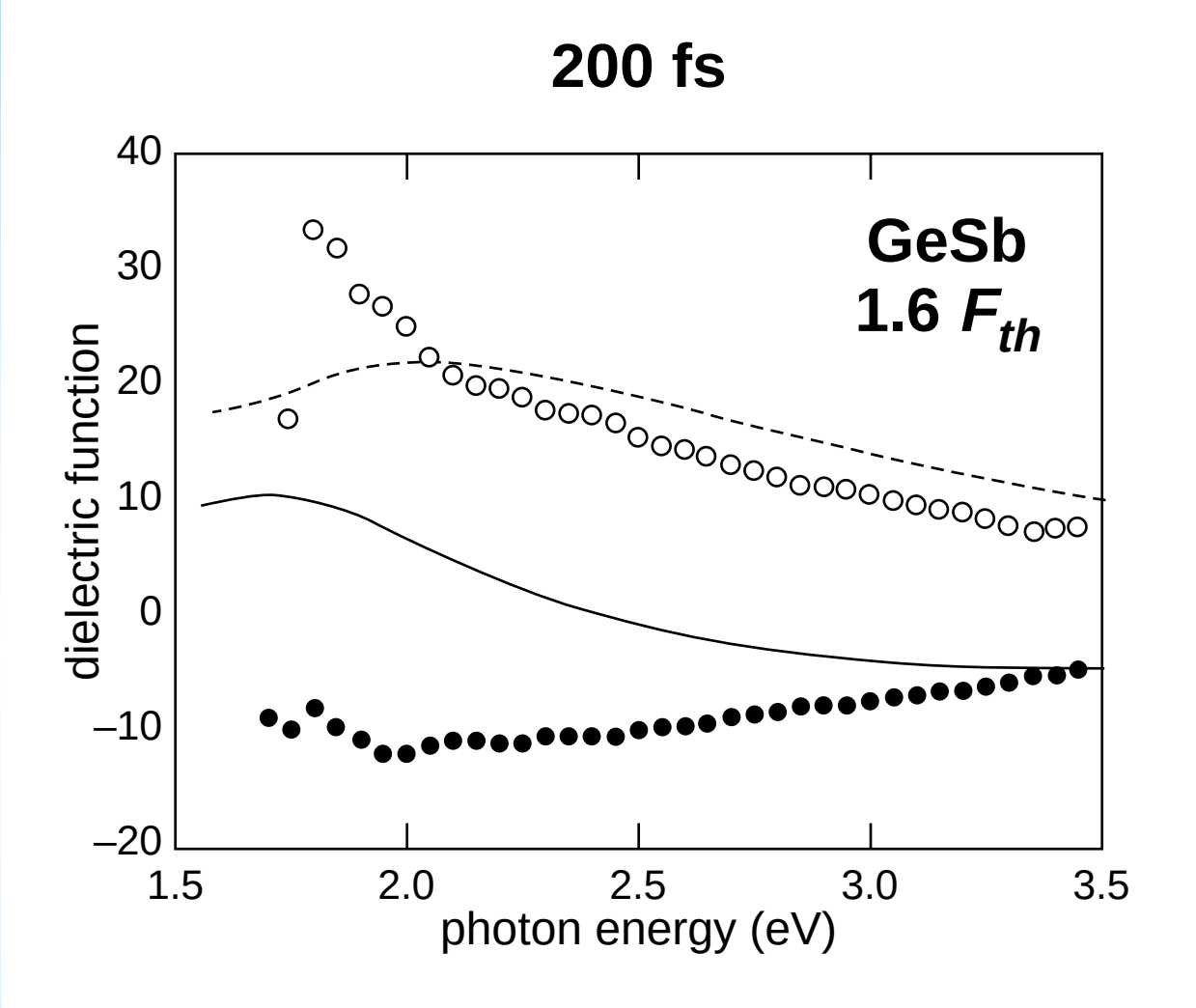
Results


0 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

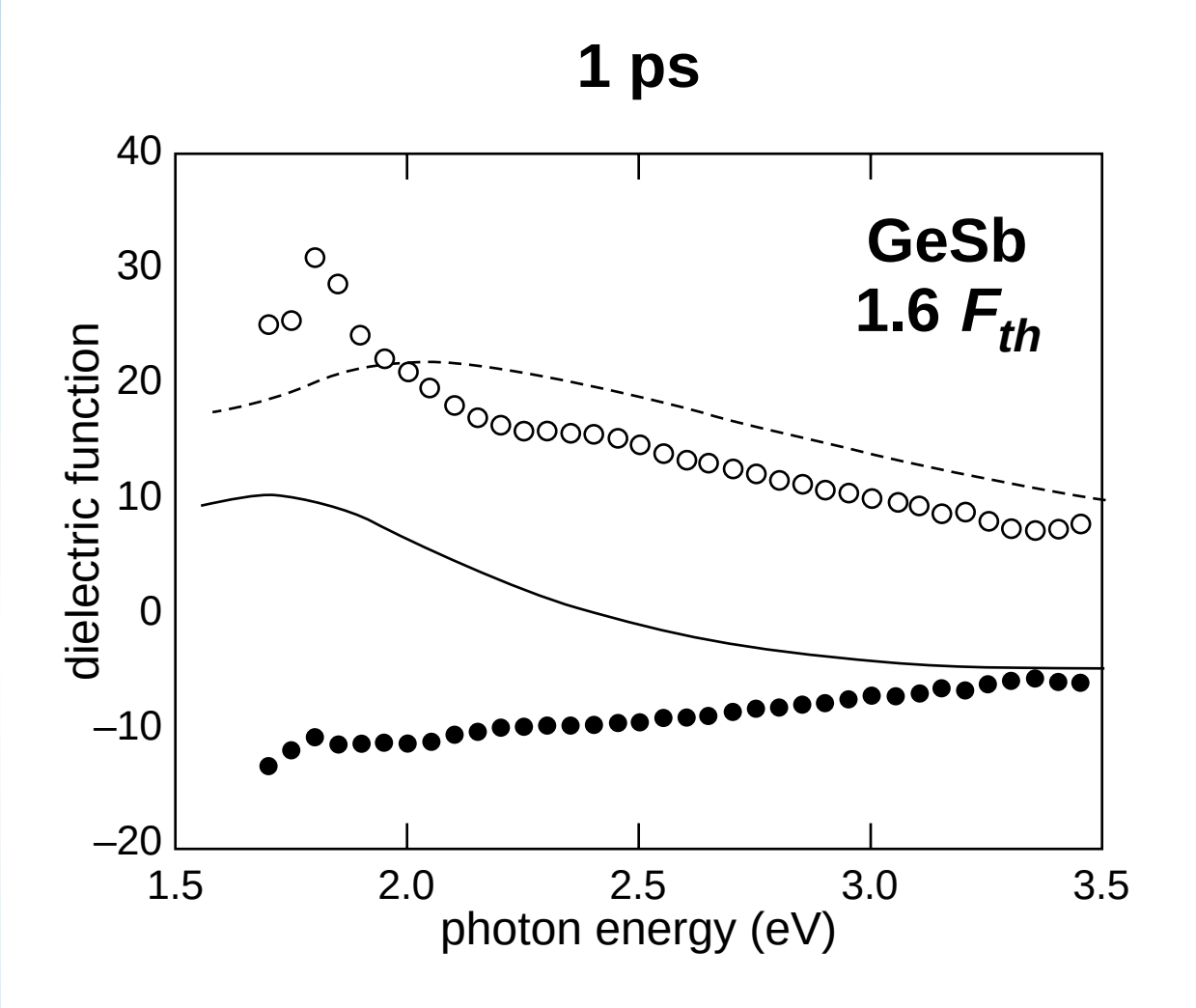
Results


100 fs
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

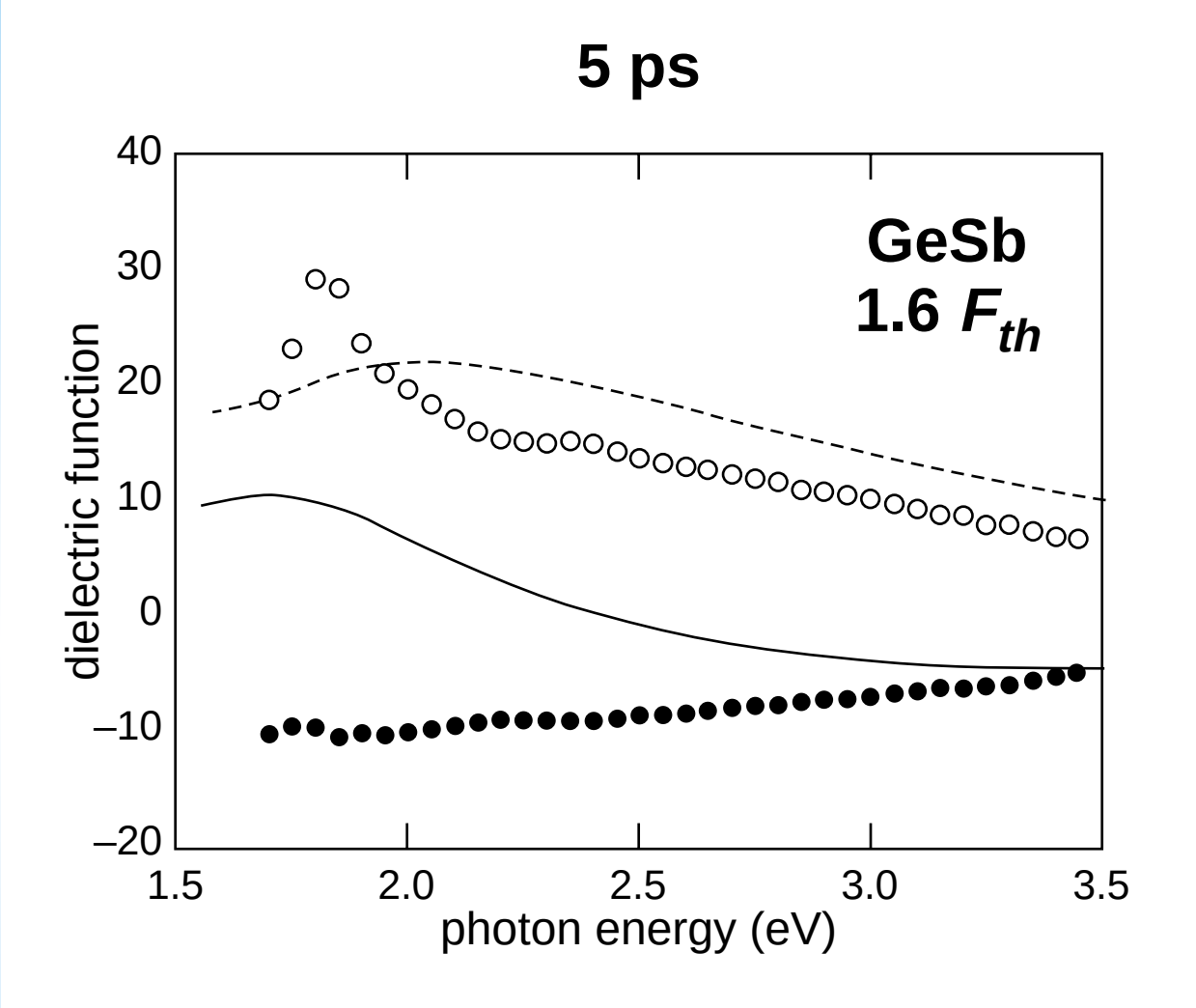
Results


200 fs
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

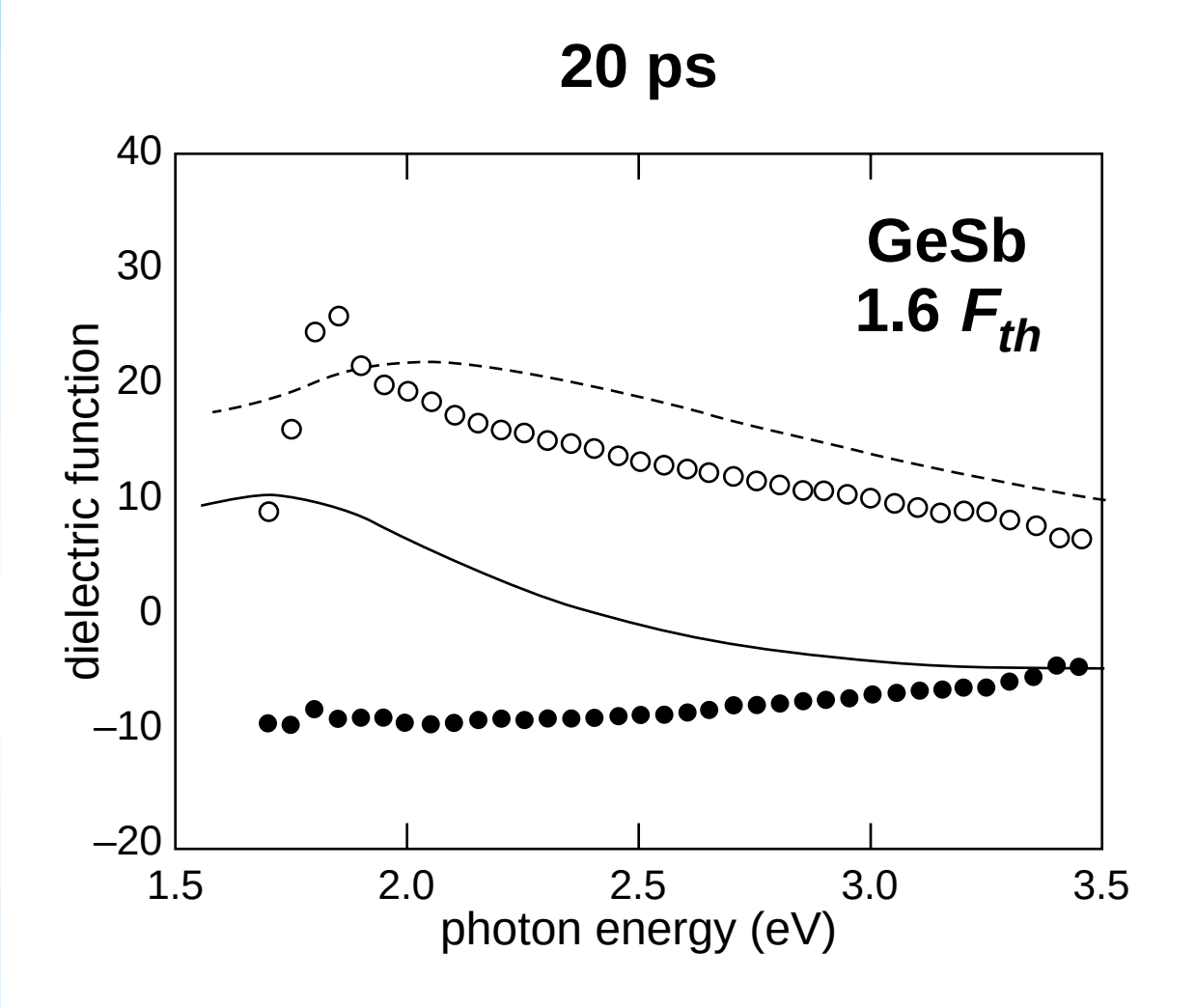
Results


1 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

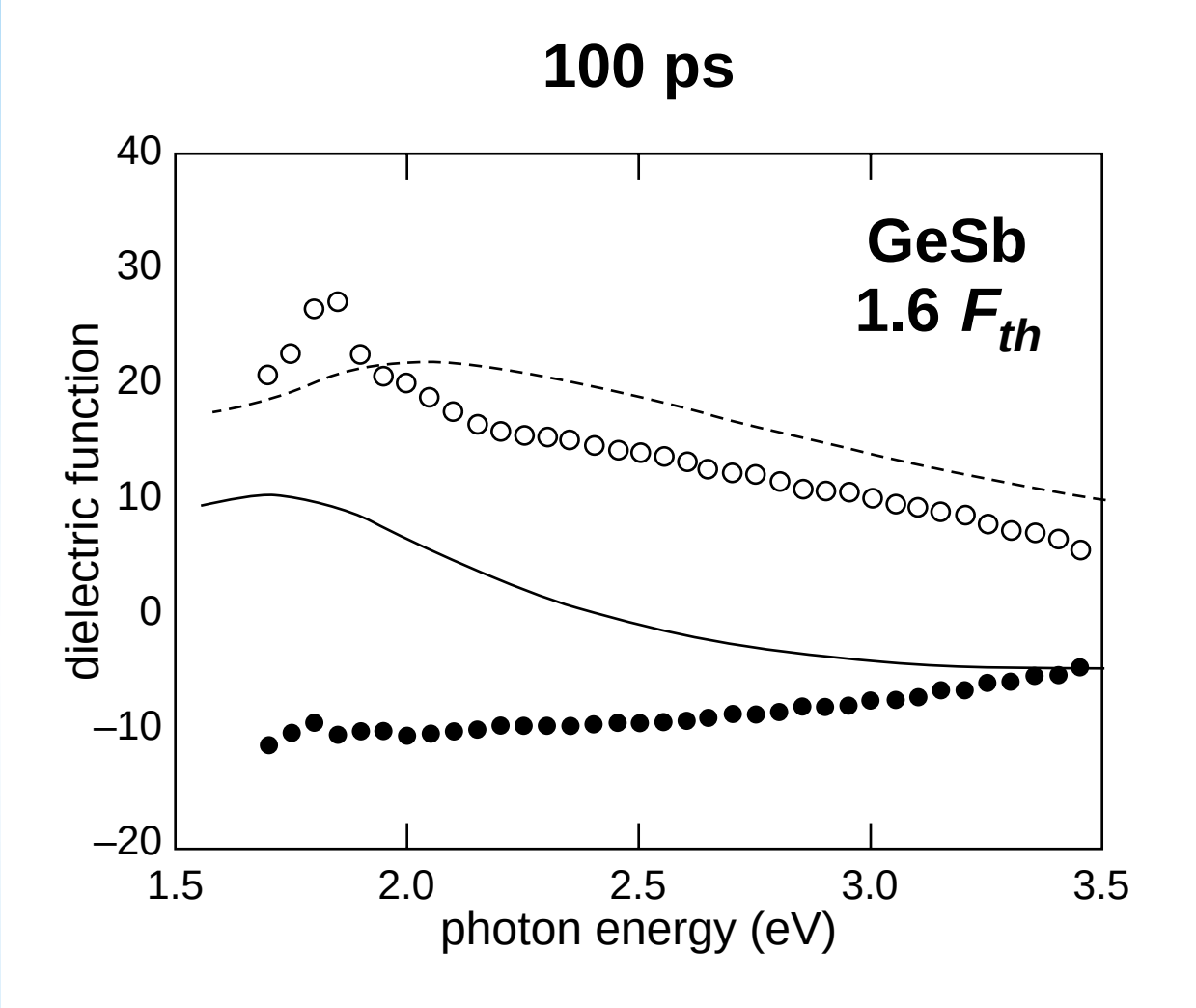
Results


5 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

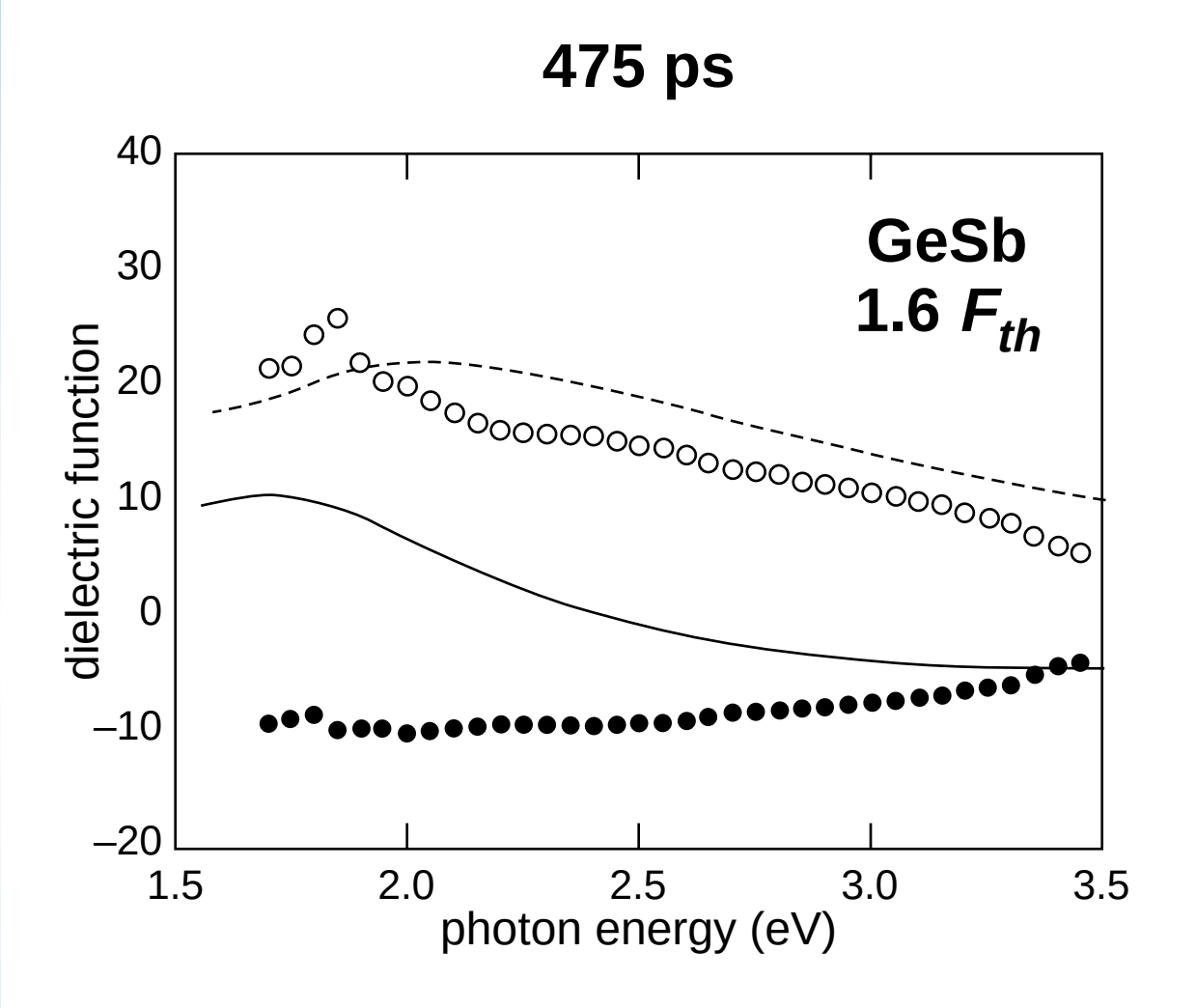
Results


20 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

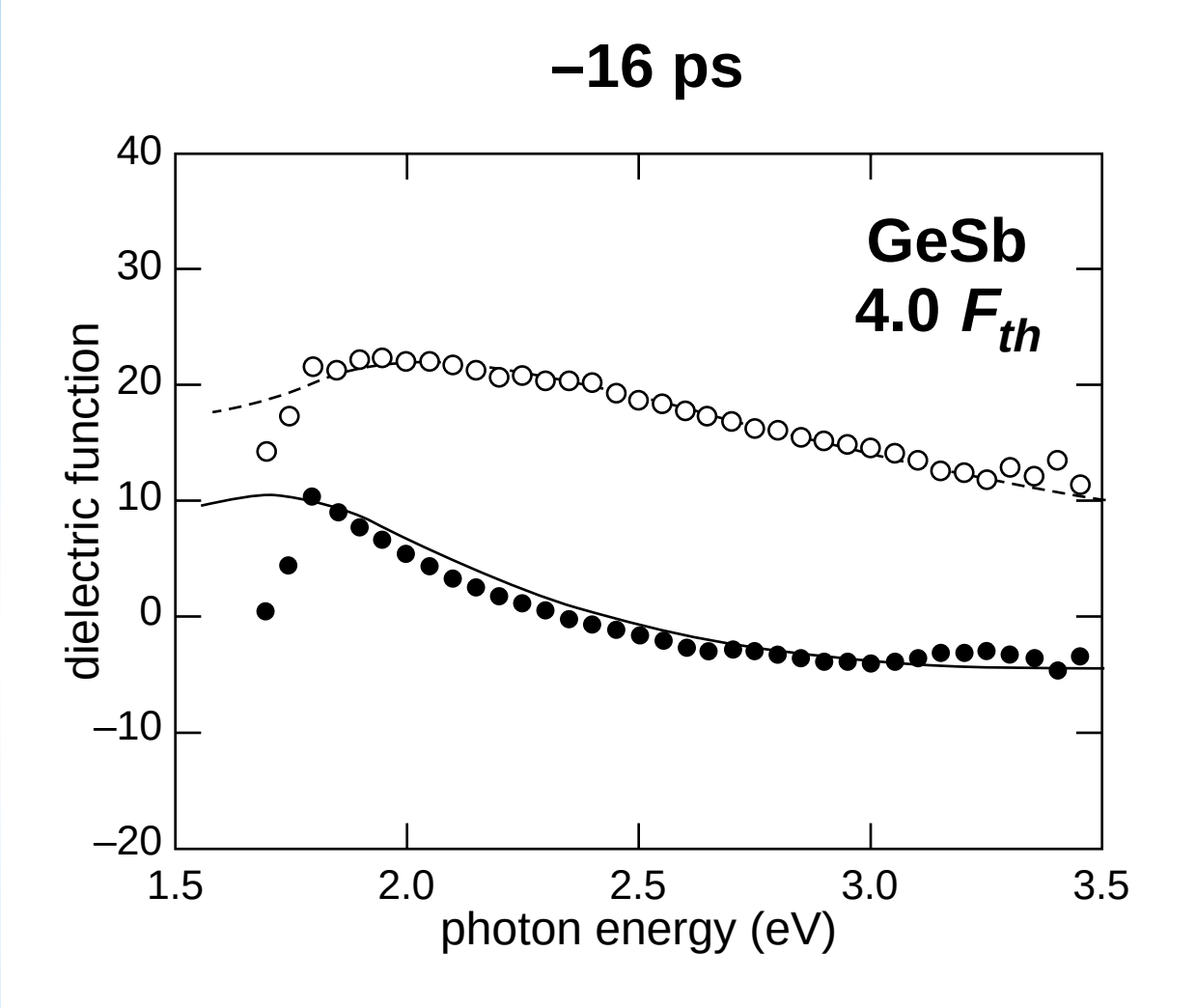
Results


100 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

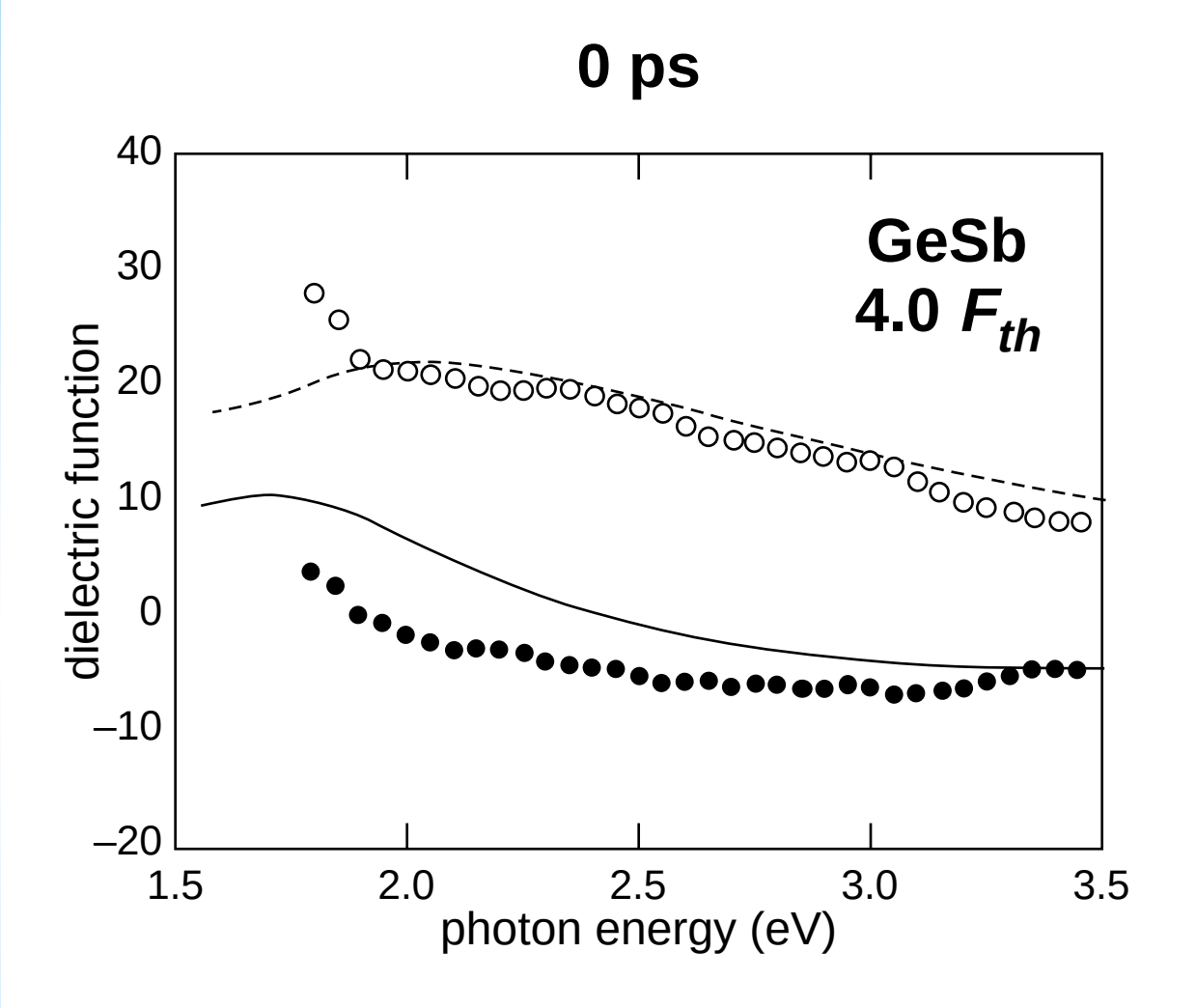
Results


475 ps
GeSb
1.6 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

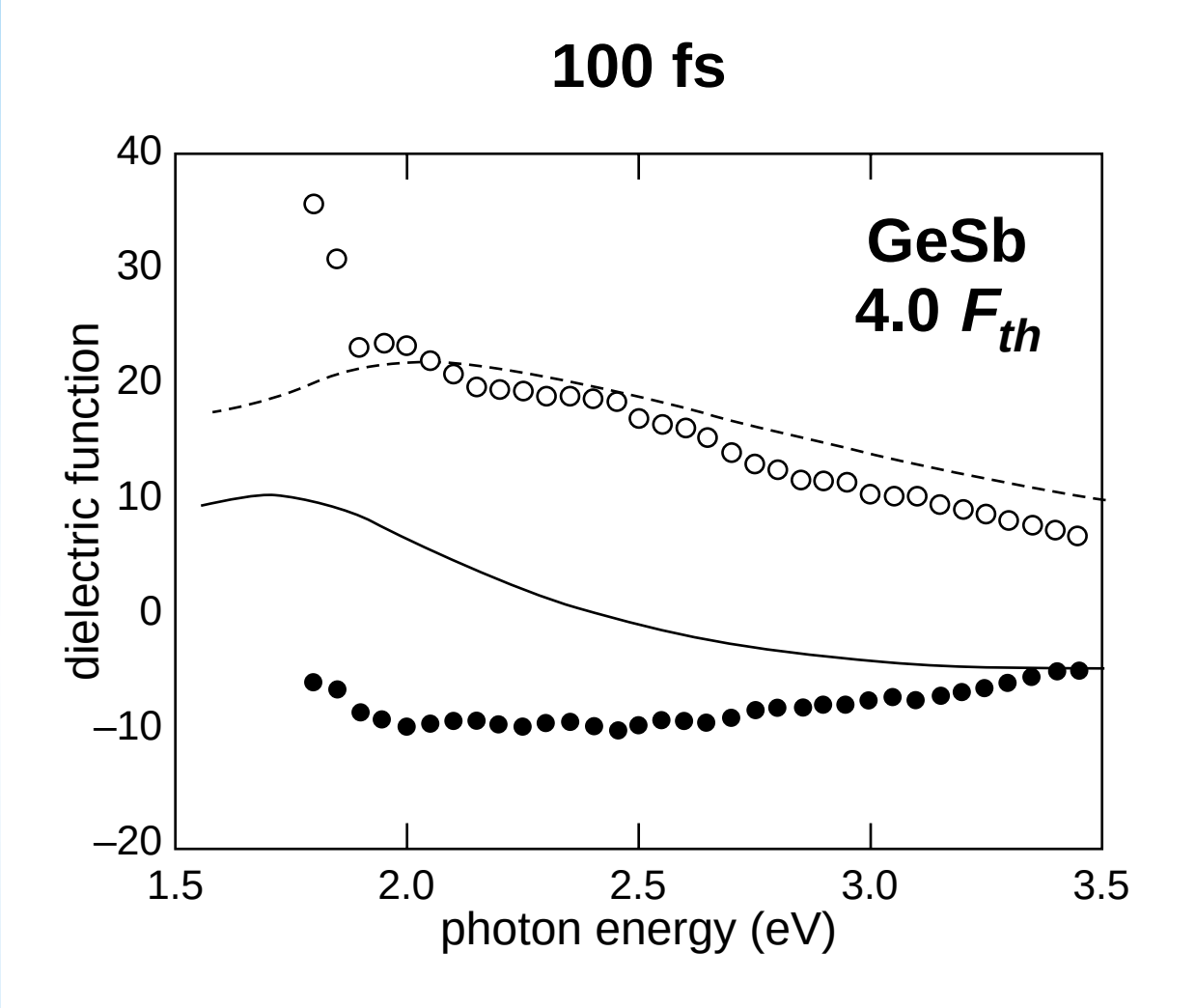
Results


–16 ps
GeSb
4.0 F_{th}
dielectric function
photon energy (eV)
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5

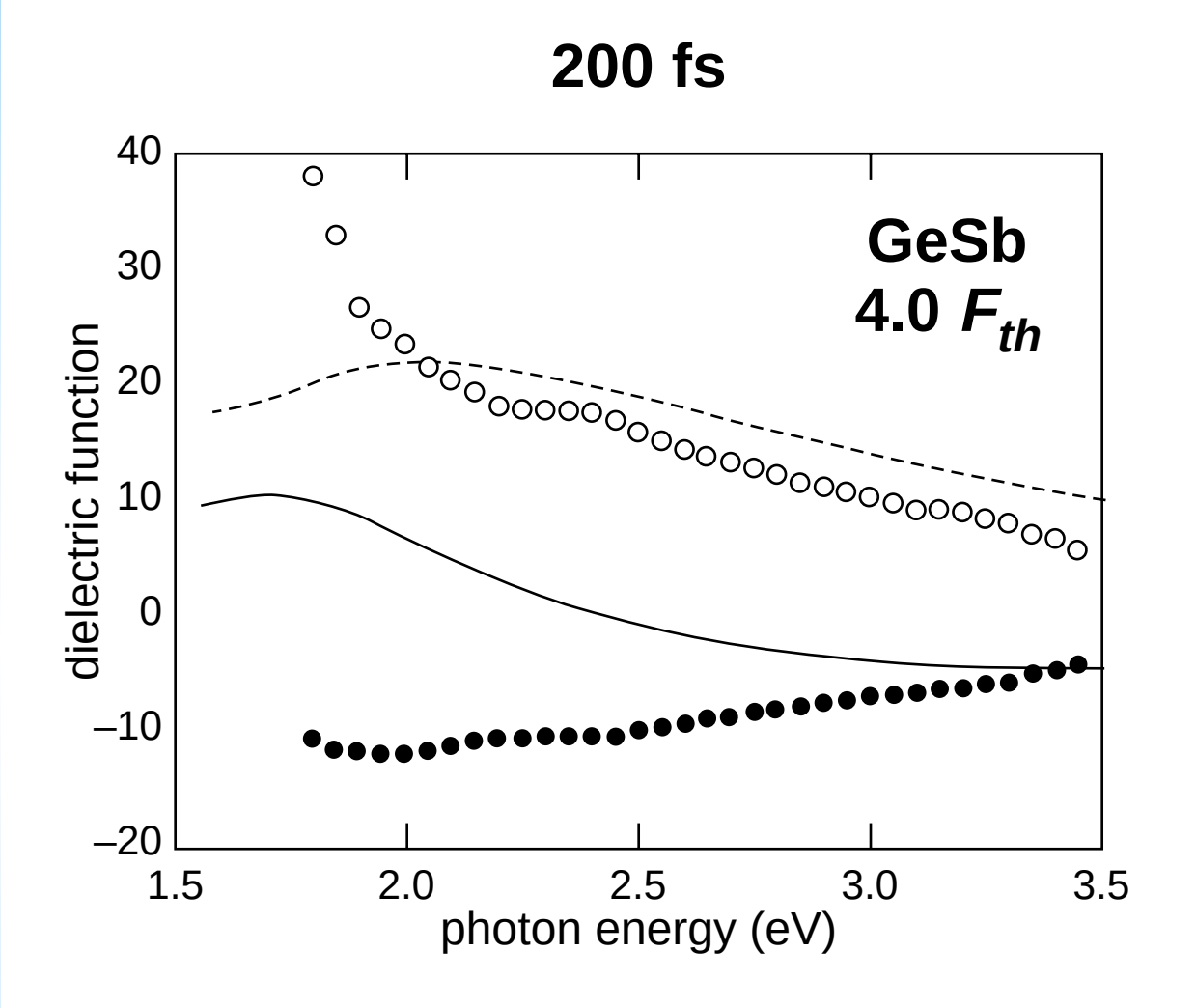
Results


0 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

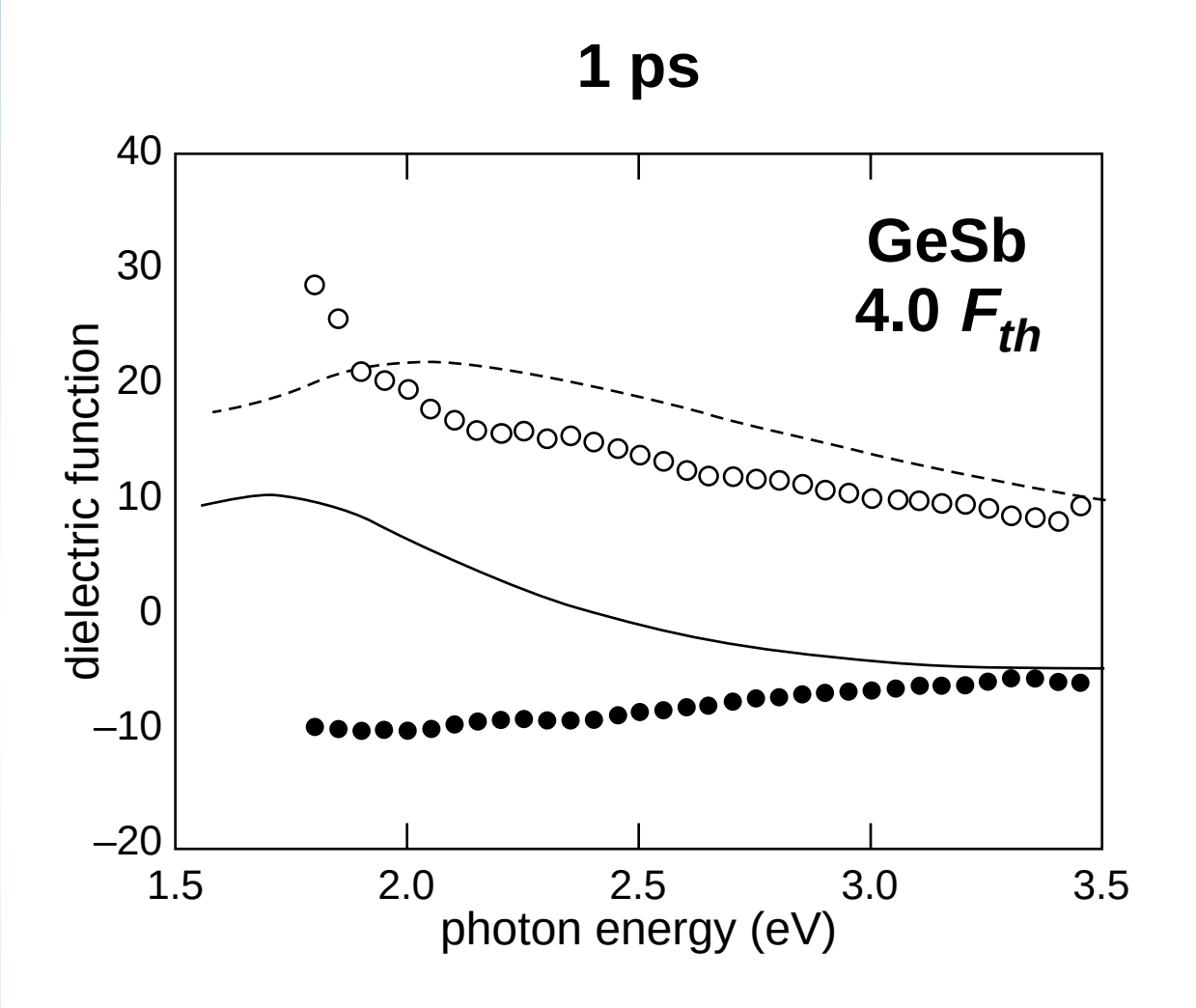
Results


100 fs
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

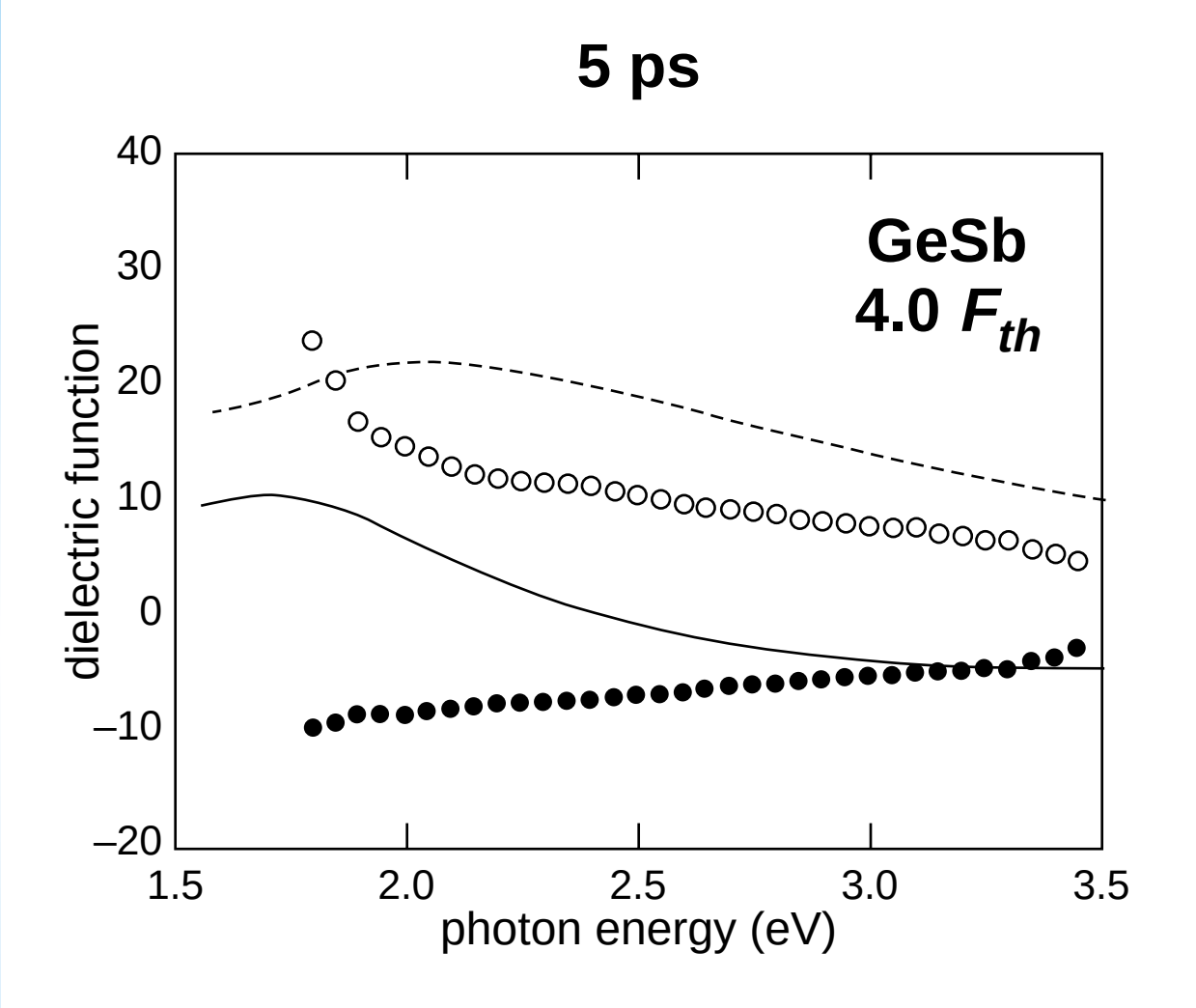
Results


200 fs
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

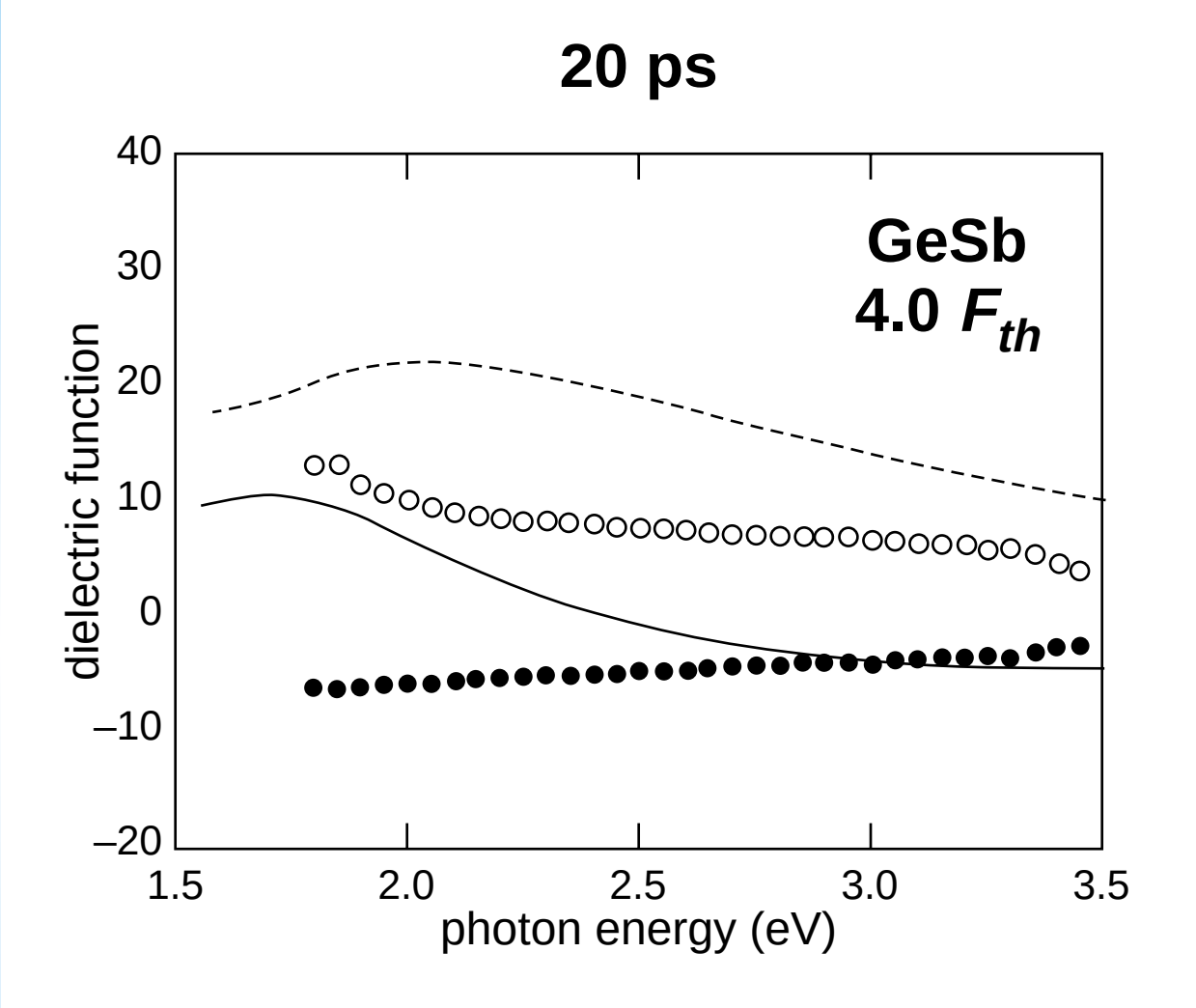
Results


1 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

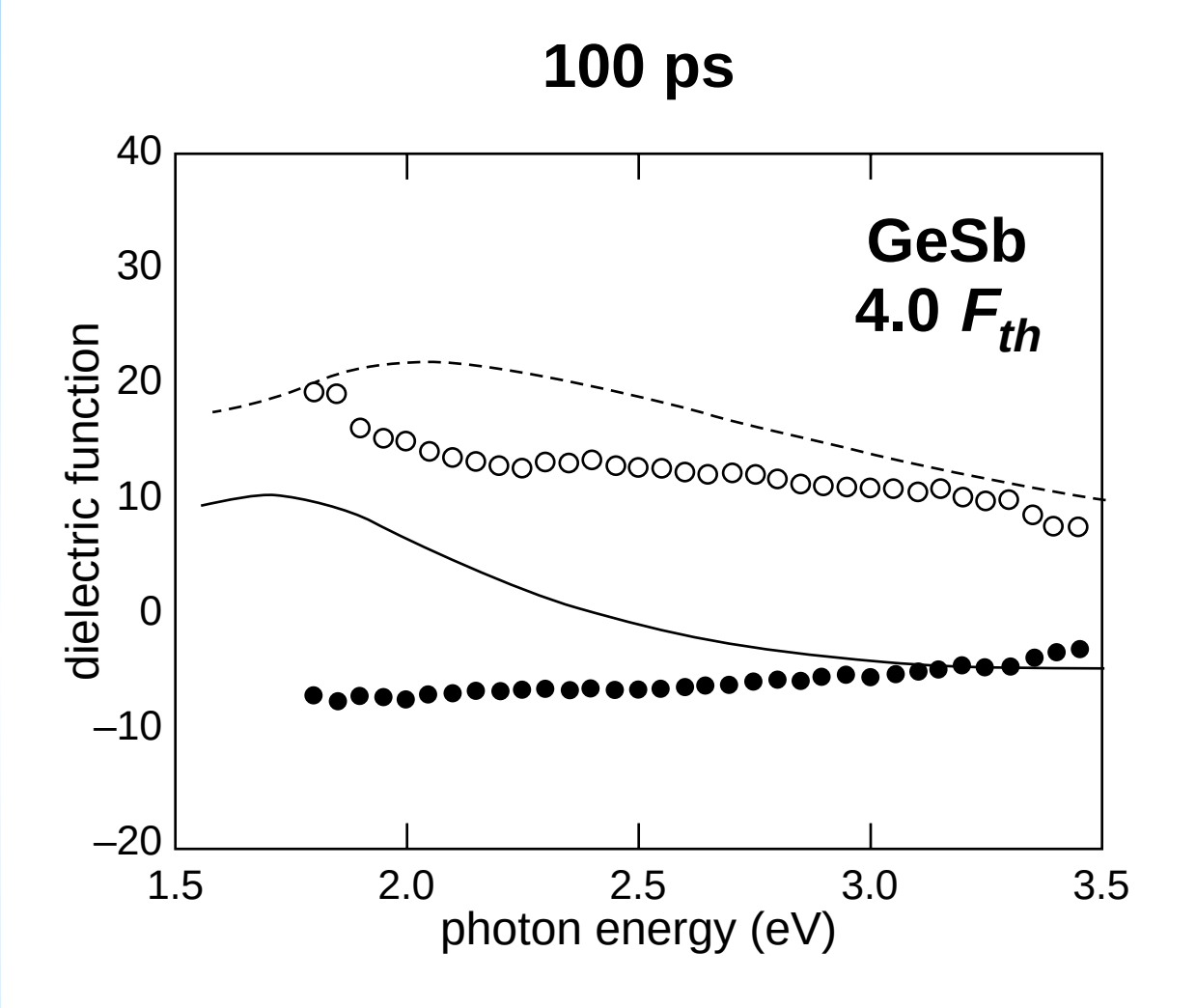
Results


5 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

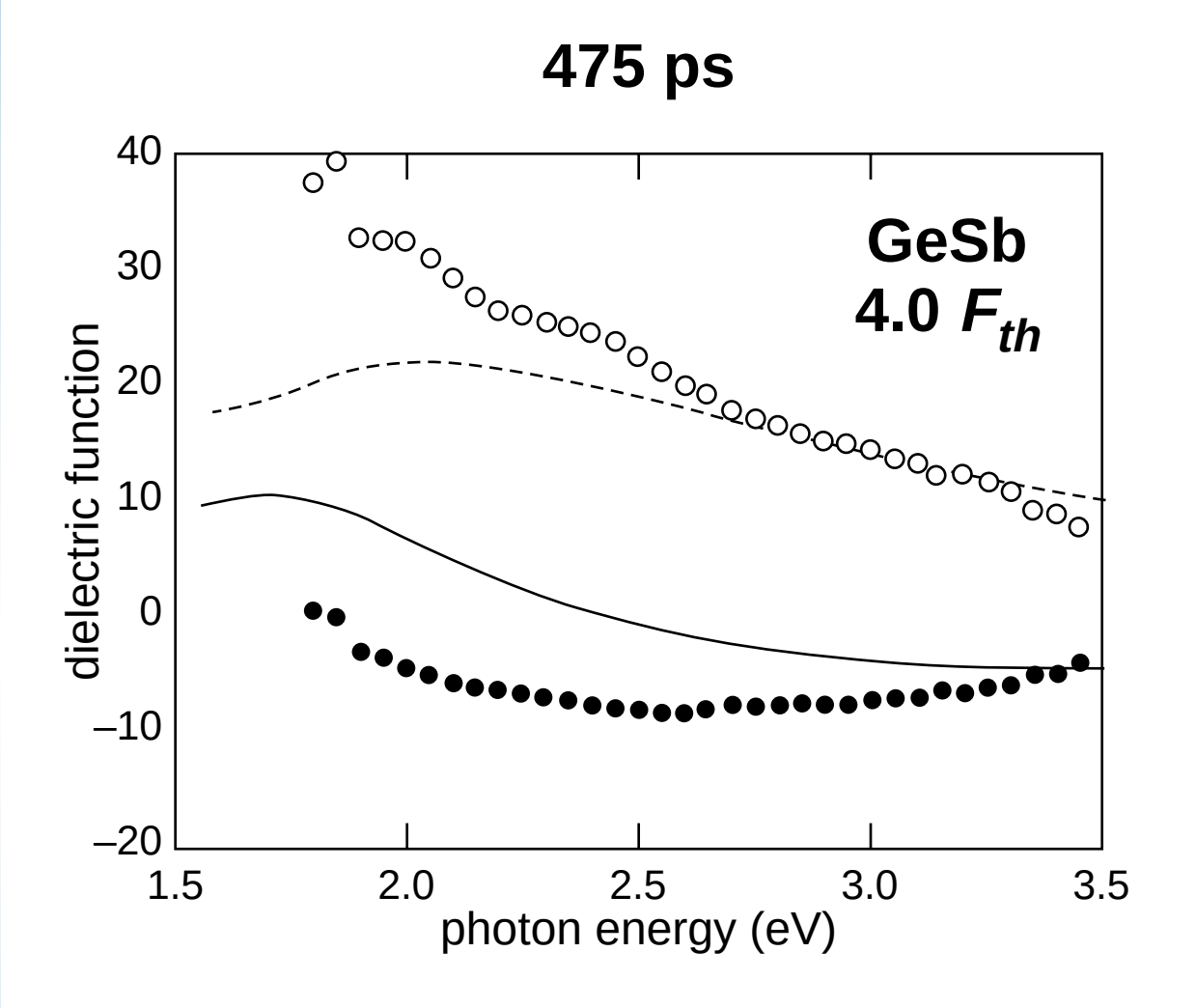
Results


20 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results


100 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)

Results


475 ps
GeSb
4.0 F_{th}
dielectric function
40
30
20
10
0
–10
–20
1.5
2.0
2.5
3.0
3.5
photon energy (eV)