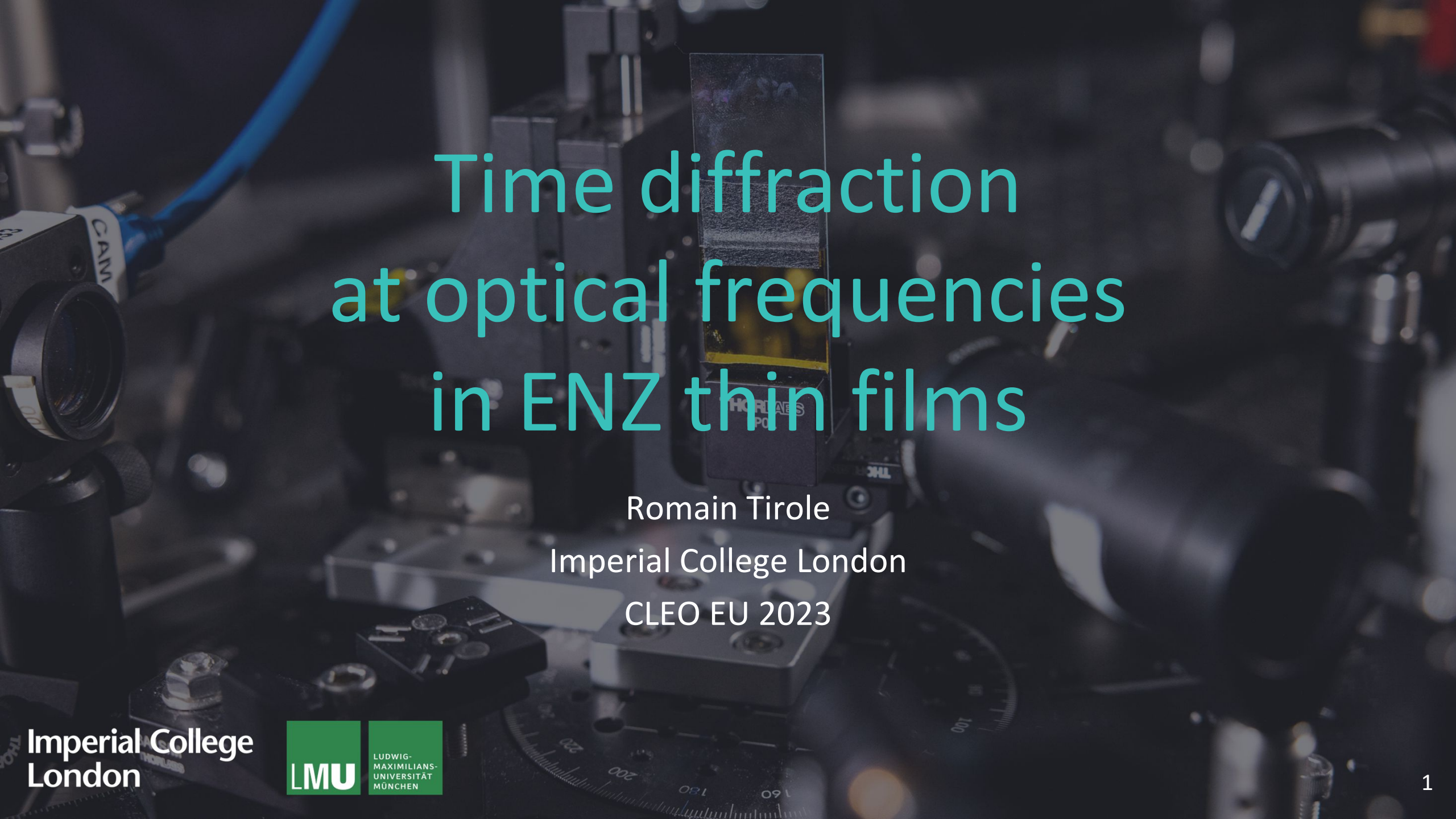


Time diffraction at optical frequencies in ENZ thin films

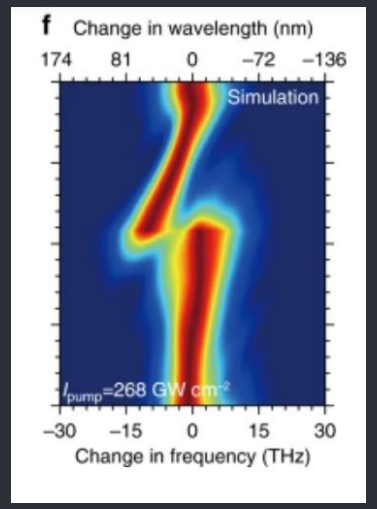
Romain Tirole
Imperial College London
CLEO EU 2023

Imperial College London

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

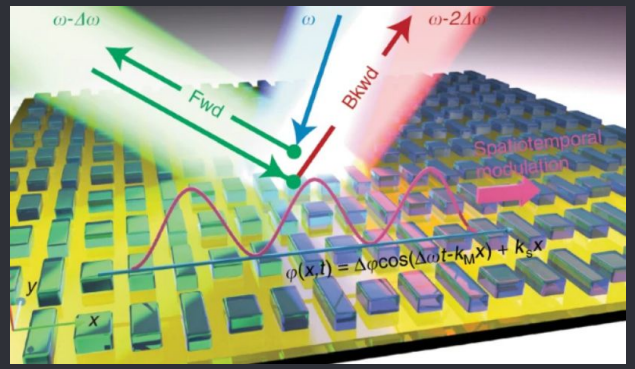
Waves in time-varying media

Waves in time-varying media



Zhou et al. (2020) Nat. Comm.

Frequency control
Time refraction

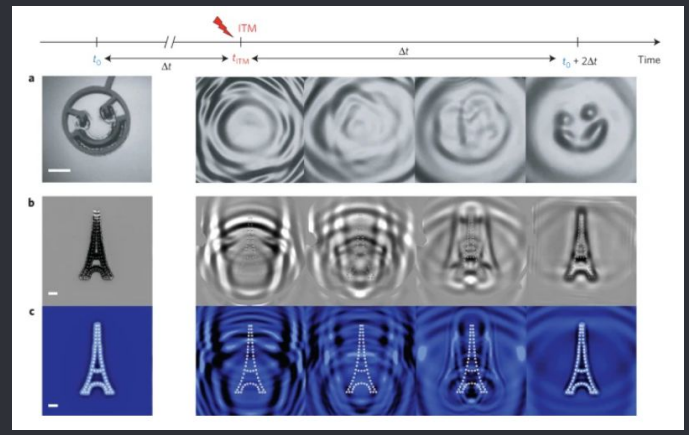


Guo et al. (2019) Light Sci. App.

Nonreciprocal devices

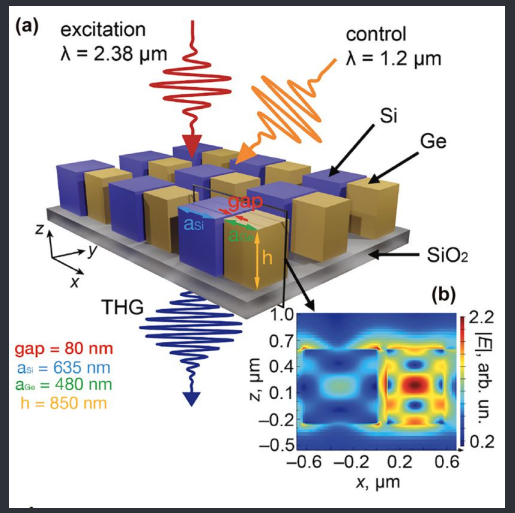
Bacot et al. (2016) Nat. Physics

Time reversal



Shafirin et al. (2022) Nanophotonics

Reconfigurable antennas

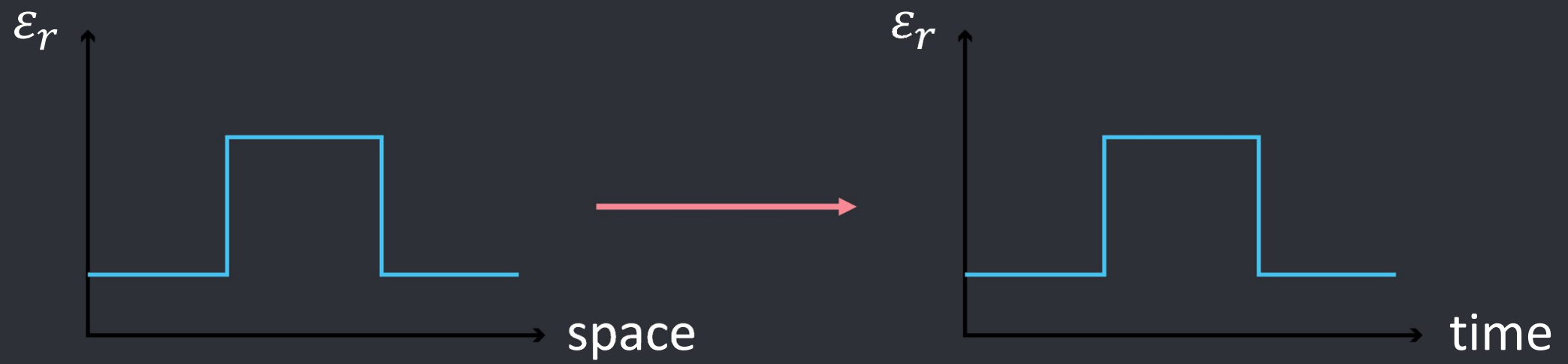


Boyd, Faccio, Hendry, Fan, Shcherbakov, Diaz-Rubio, Caglayan, Fink, Fort, Shalaev, Boltasseva, Daraio, Nassar, Li, Engheta, Atwater and others…

Towards spacetime metamaterials

Moving on from purely spatial structures to **time-structured metasurfaces**:

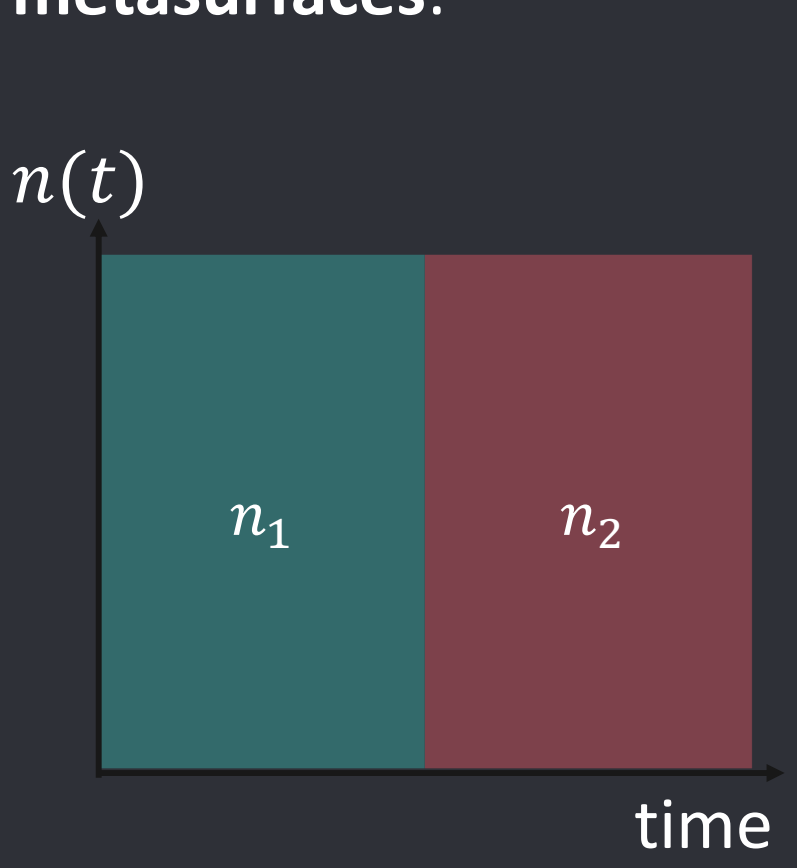
$$\varepsilon_r(\boldsymbol{r}, t)$$

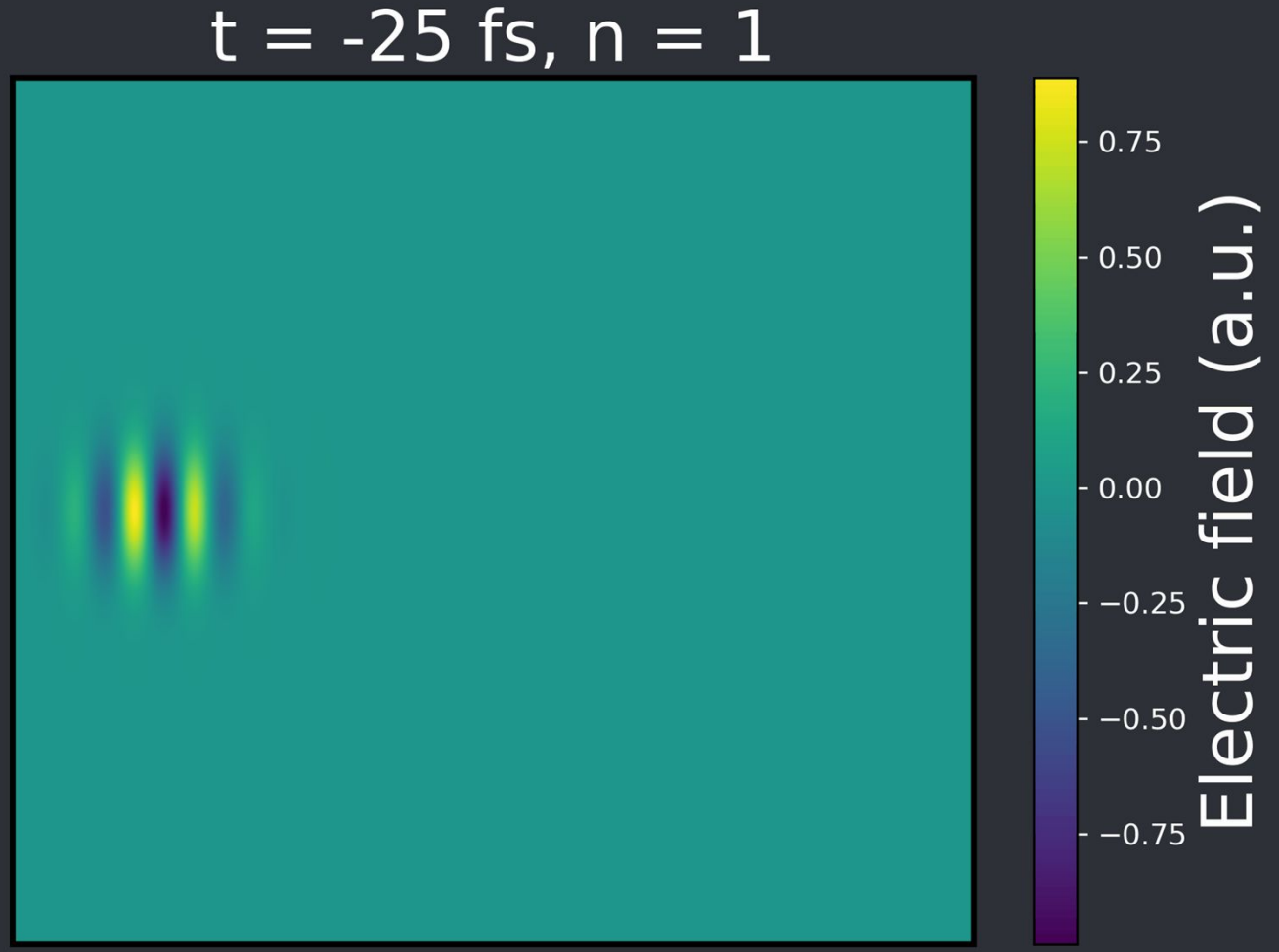


e.g. refraction: $k_2 = \frac{n_2}{n_1} k_1$ $\omega_2 = \frac{n_1}{n_2} \omega_1$

Towards spacetime metamaterials

Moving on from purely spatial structures to **time-structured metasurfaces**:

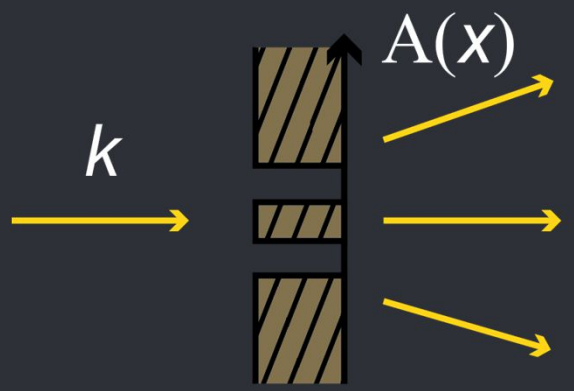




Our objective: time diffraction

e.g. Young's double slit experiment in space ⇒ Young's double slit in **time**

Space:



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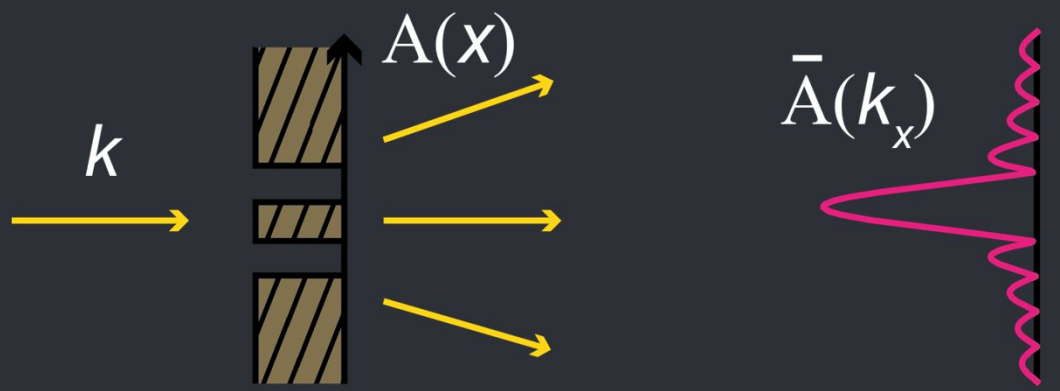

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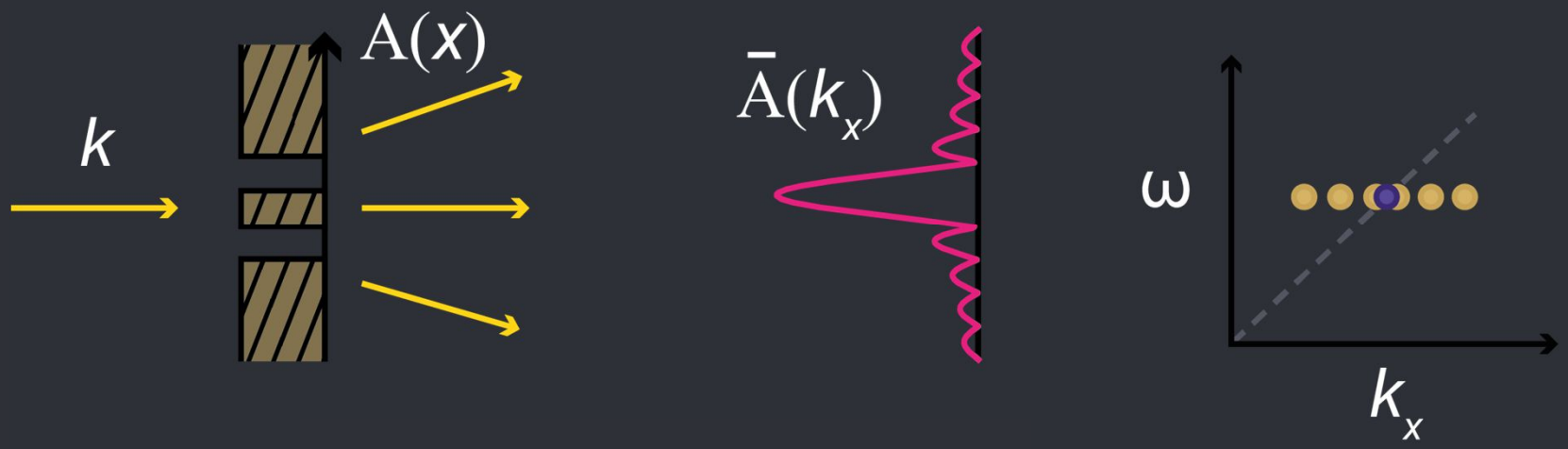

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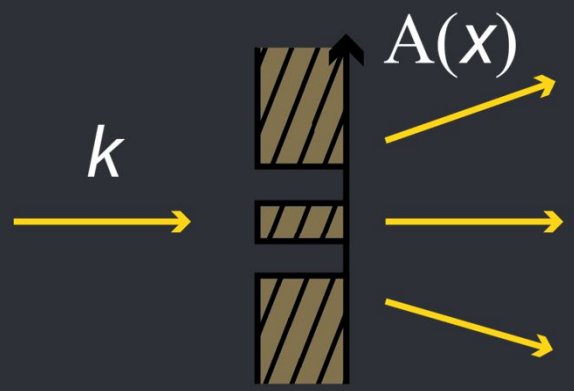
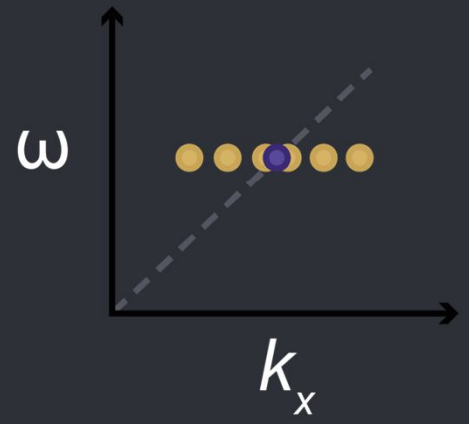
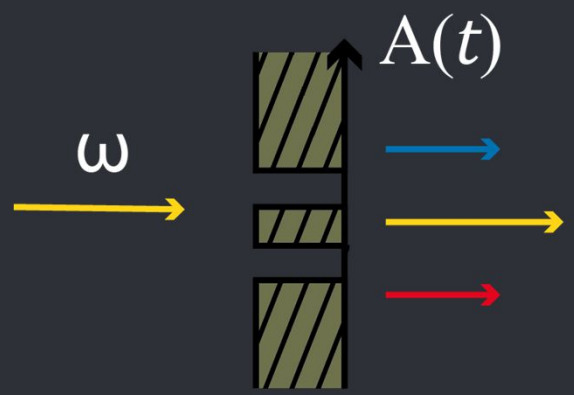




Time:



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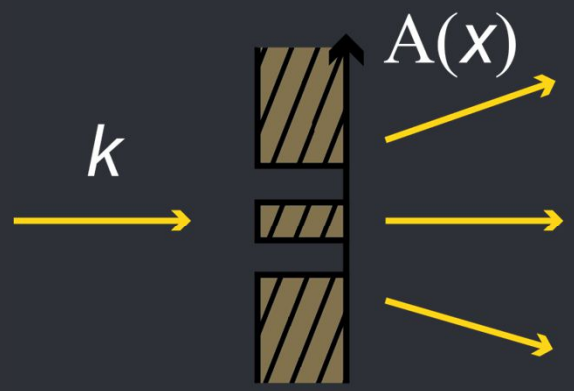
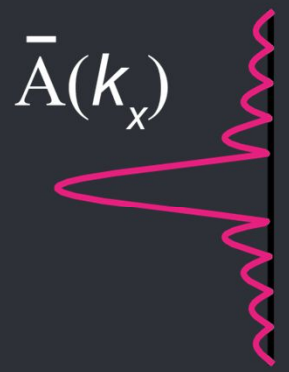
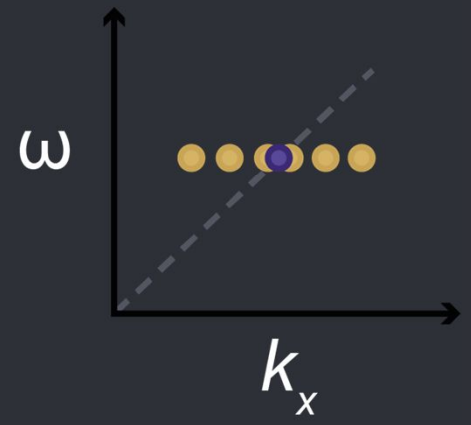
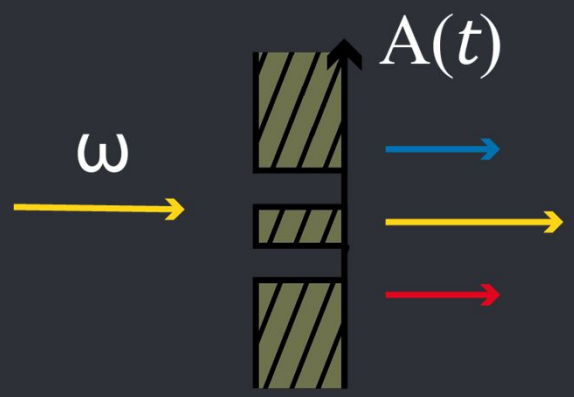
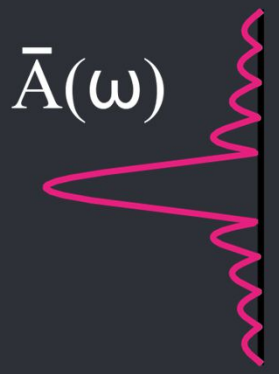






Time:





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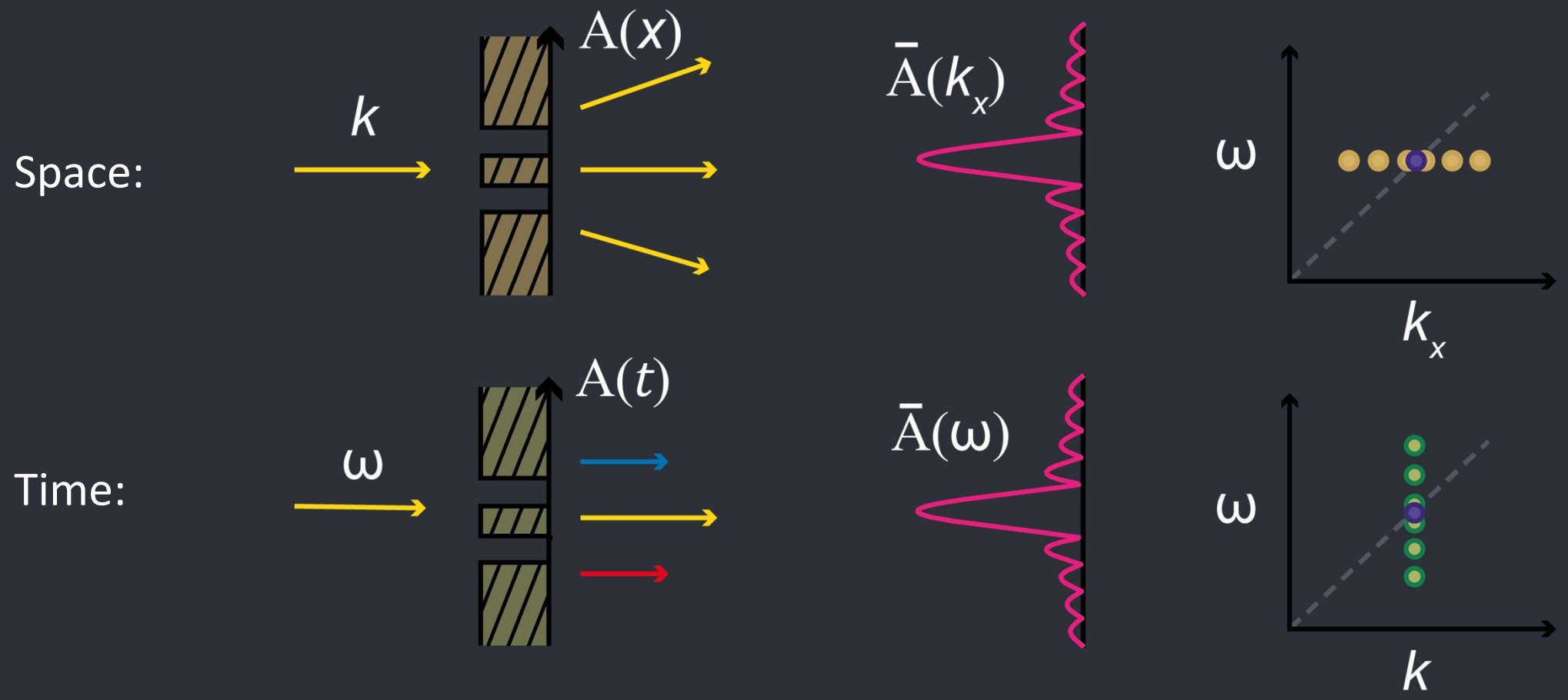

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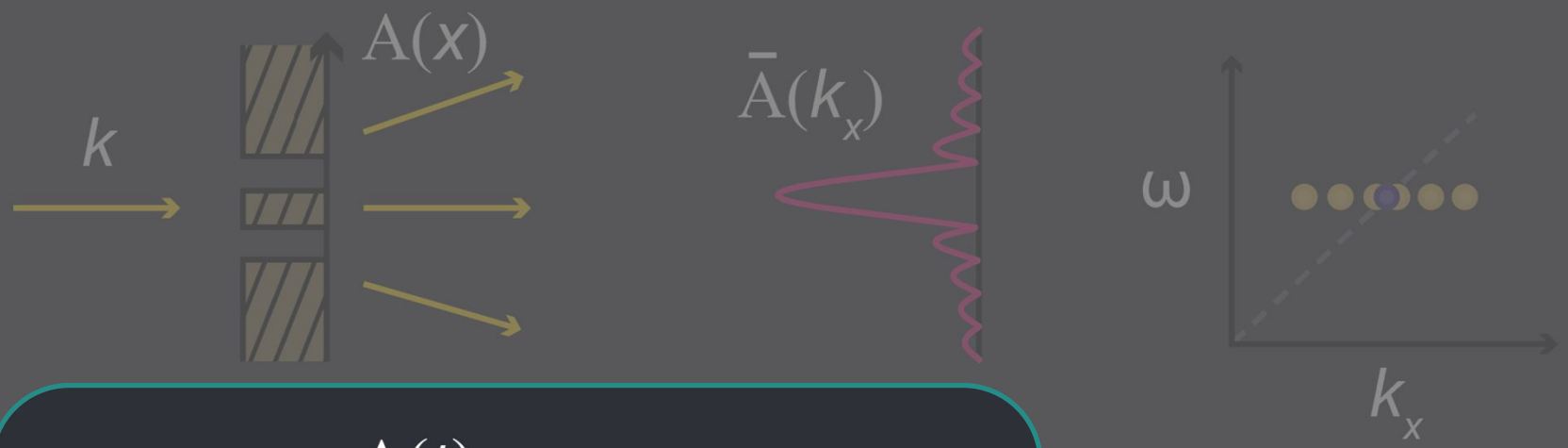

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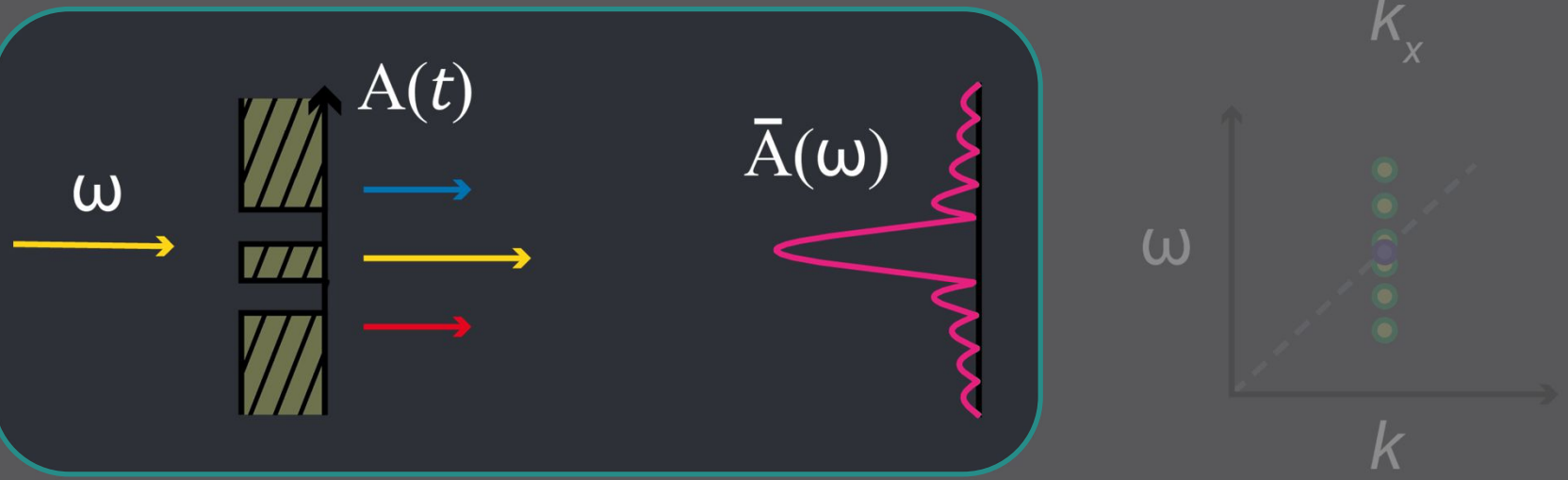
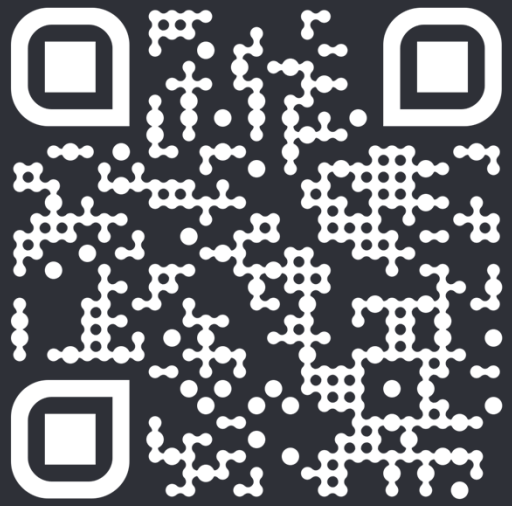
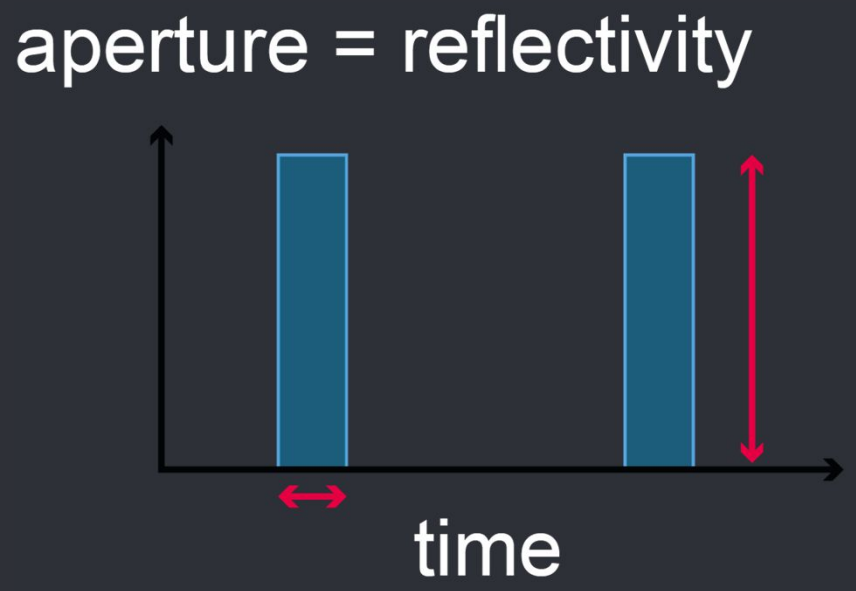


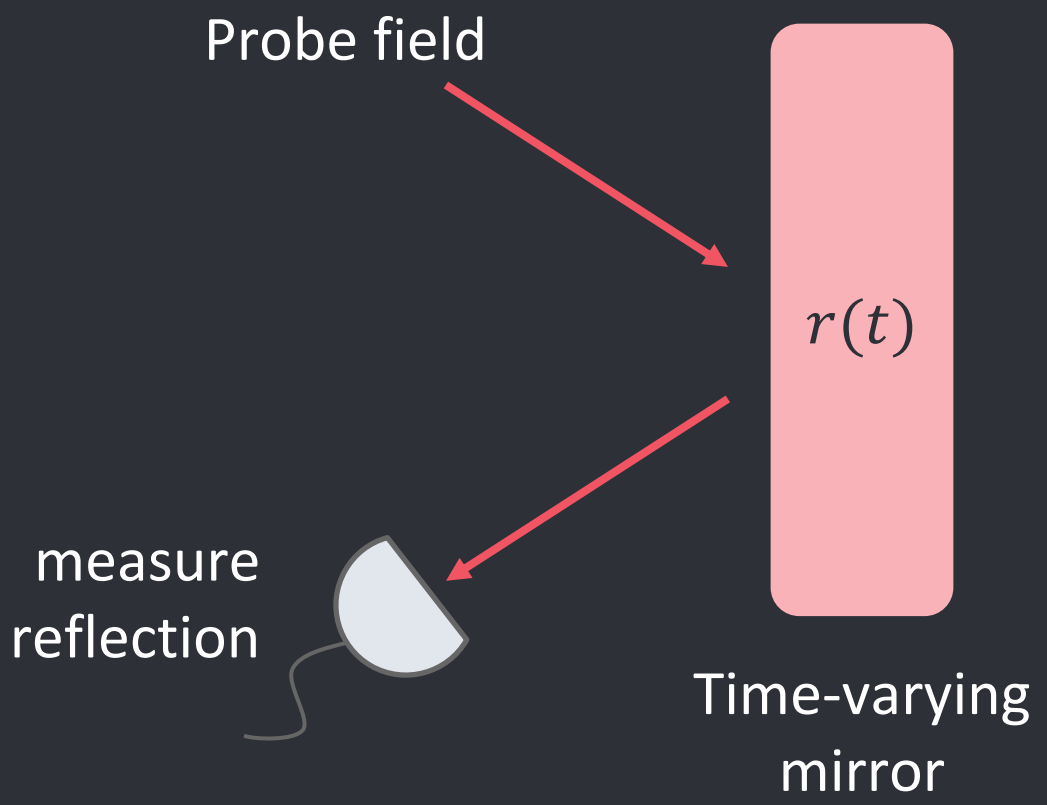


Single slit diffraction in time

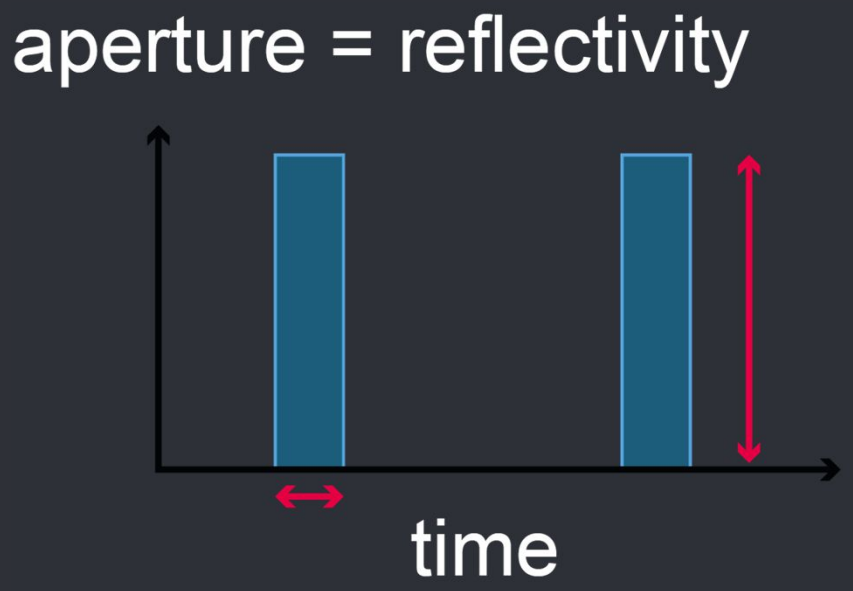
Tirole et al., "Saturable Time Varying Mirror Based on an Epsilon-Near-Zero Material", Physical Review Applied (2022)

All-optical modulation of Indium Tin Oxide





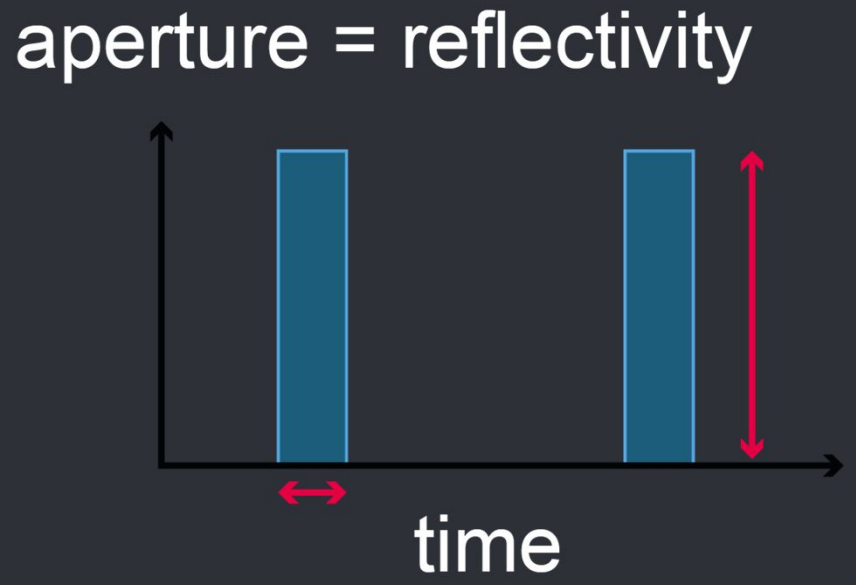
All-optical modulation of Indium Tin Oxide

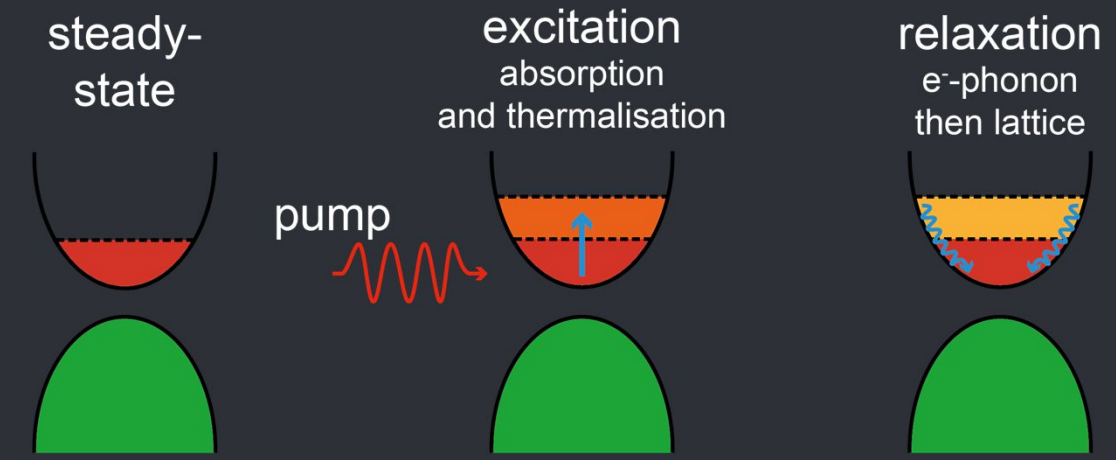


- Amplitude: large change of permittivity of ITO in near-infrared [1]
- Speed: nonlinear optics with short pulses drive material at fast scale

Alam et al., "Large optical nonlinearity of indium tin oxide in its epsilon-near-zero region", Science (2016)

All-optical modulation of Indium Tin Oxide





Non parabolicity of the band ⇒ **redshift** of the **permittivity**

- Amplitude: large change of permittivity of ITO in near-infrared [1]
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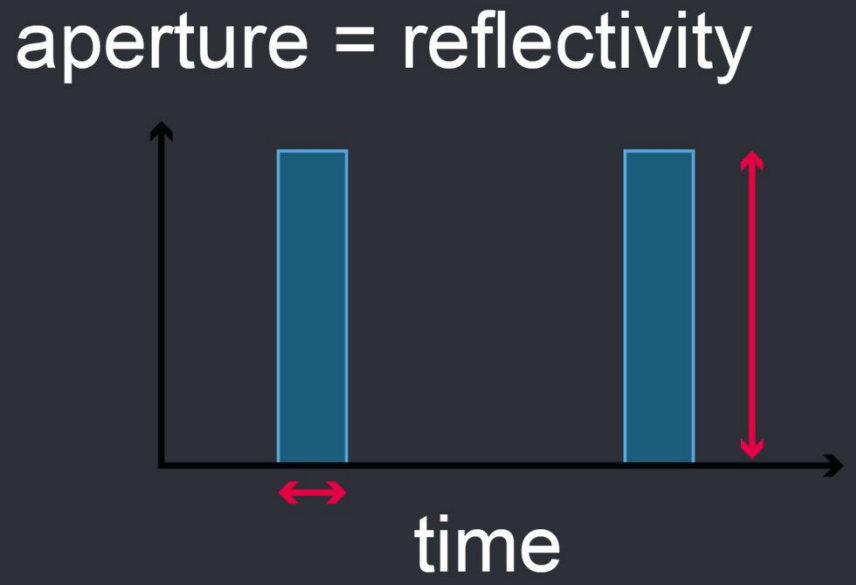

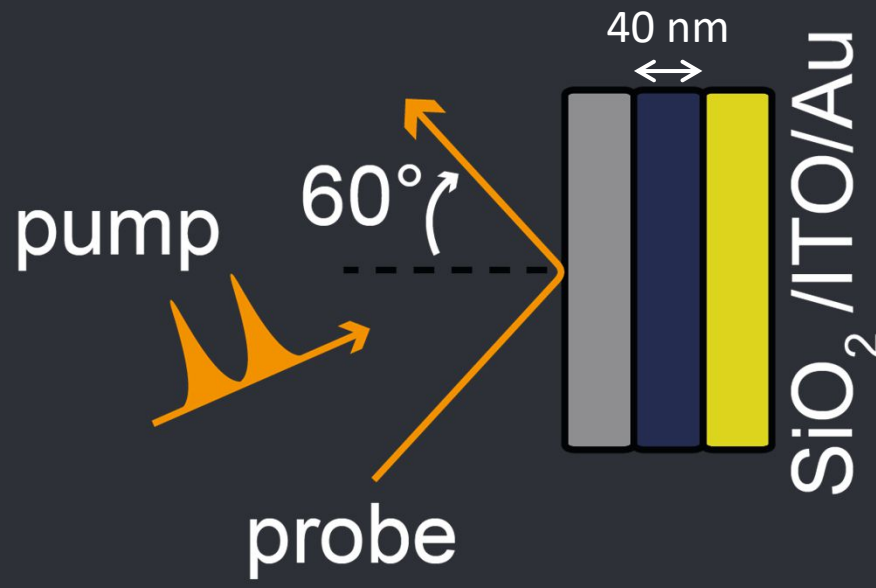

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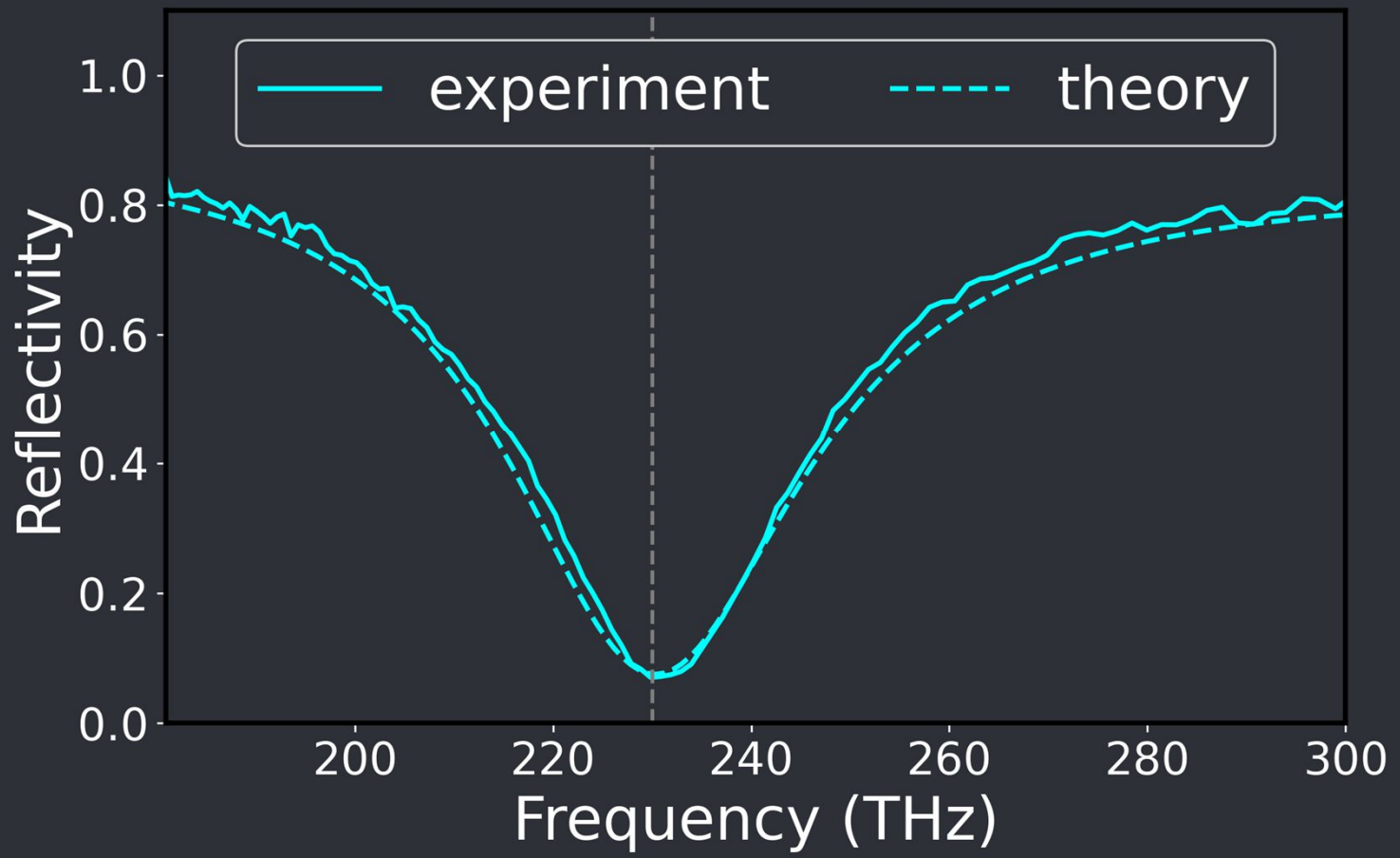
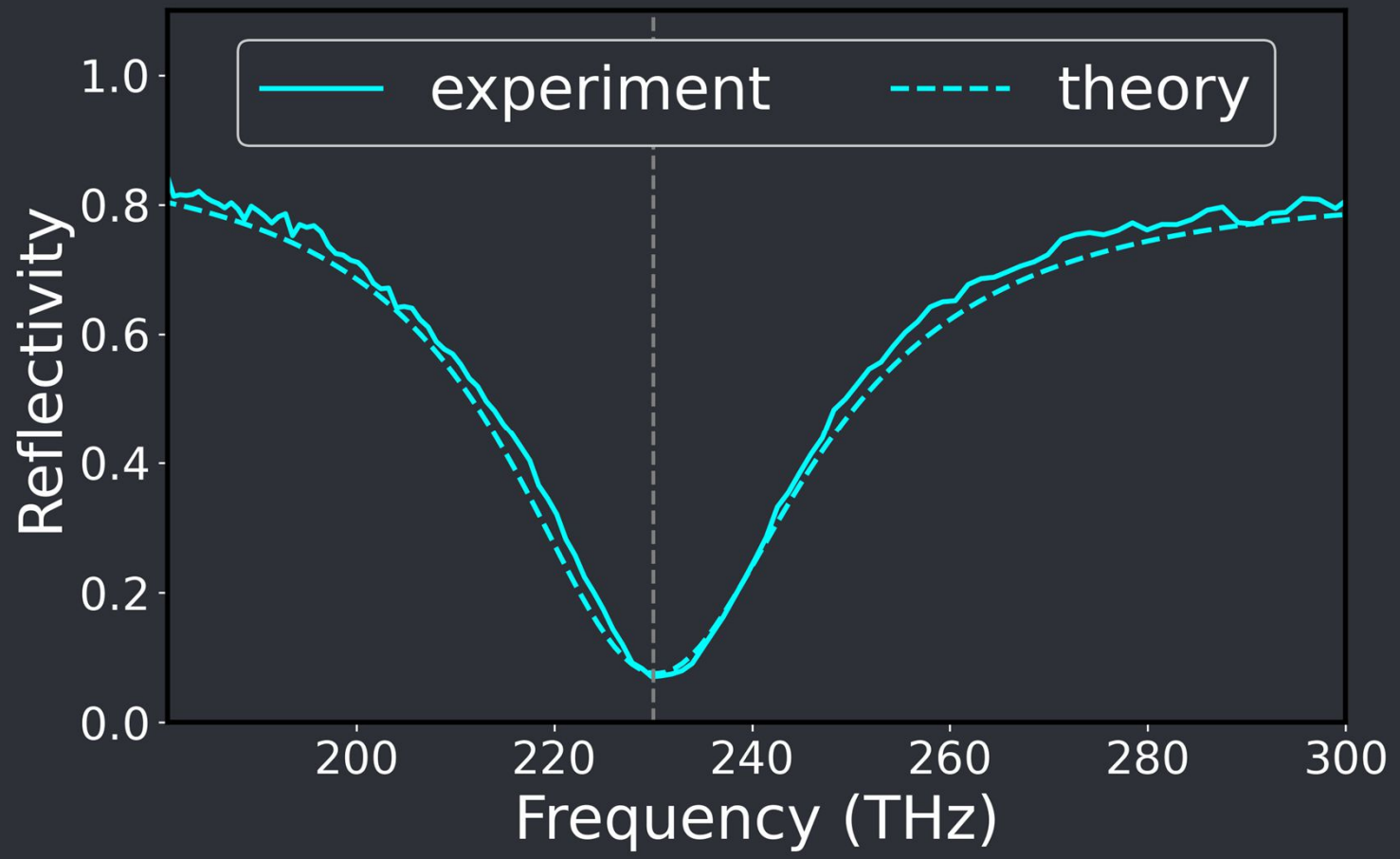
All-optical modulation of Indium Tin Oxide



Exploit resonance at 230 THz / 1300 nm

All-optical modulation of Indium Tin Oxide



Exploit resonance at 230 THz / 1300 nm

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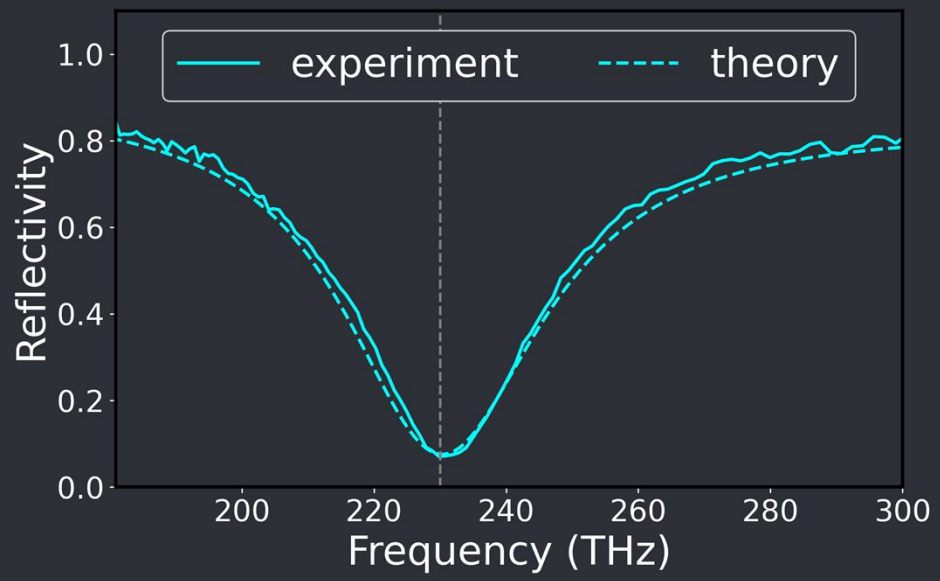
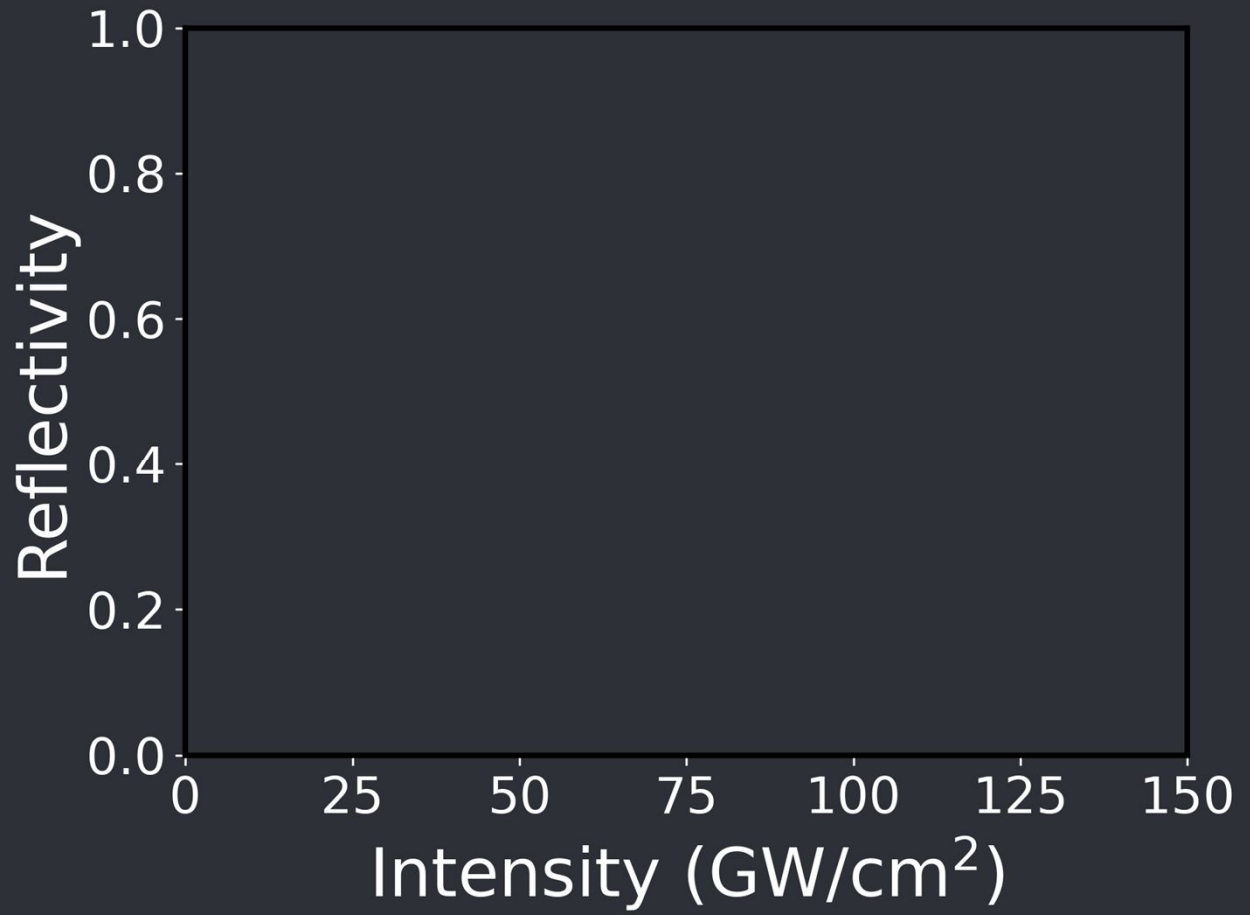
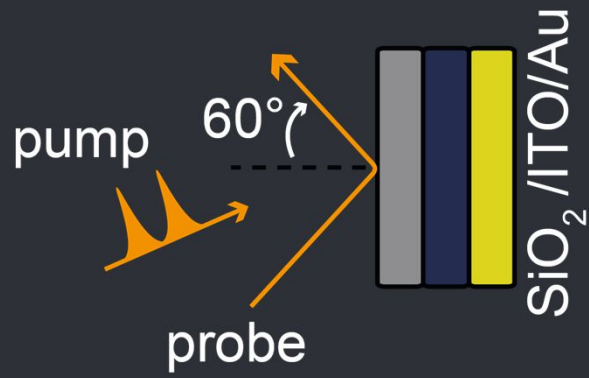
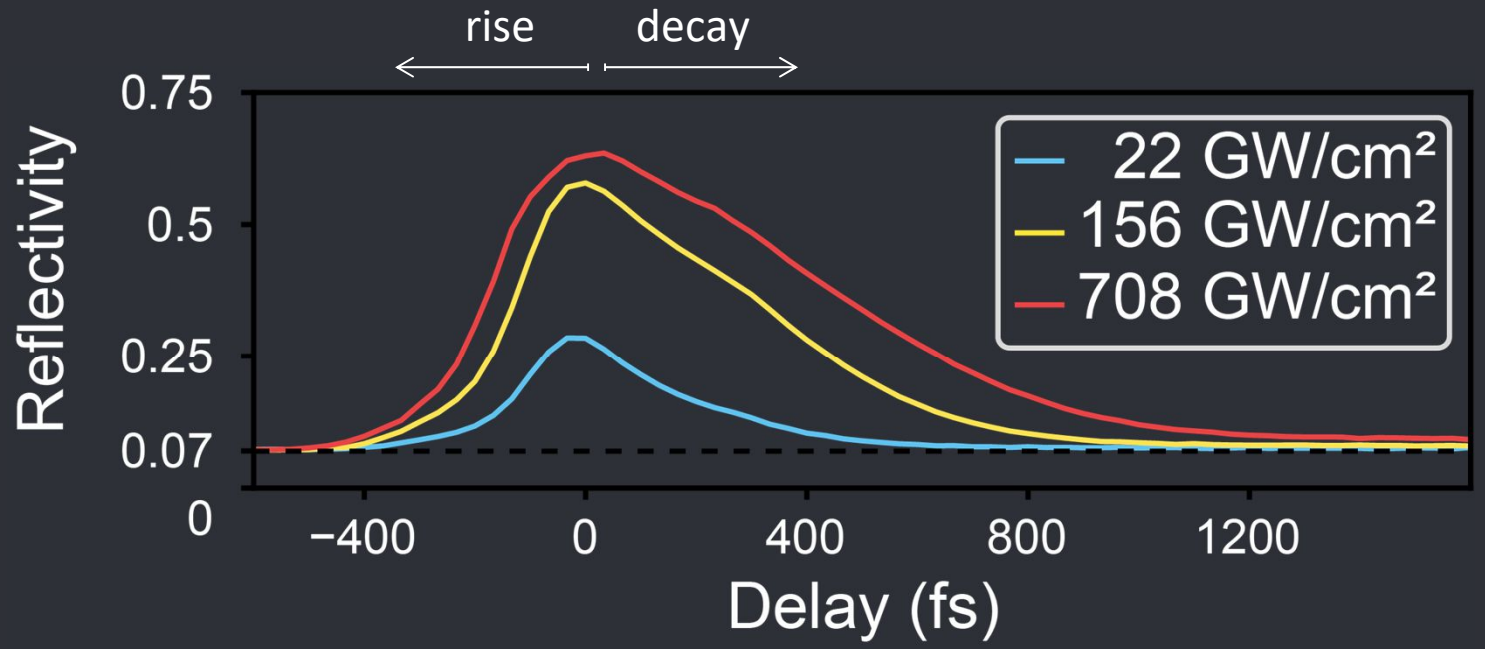




Single slit diffraction in time

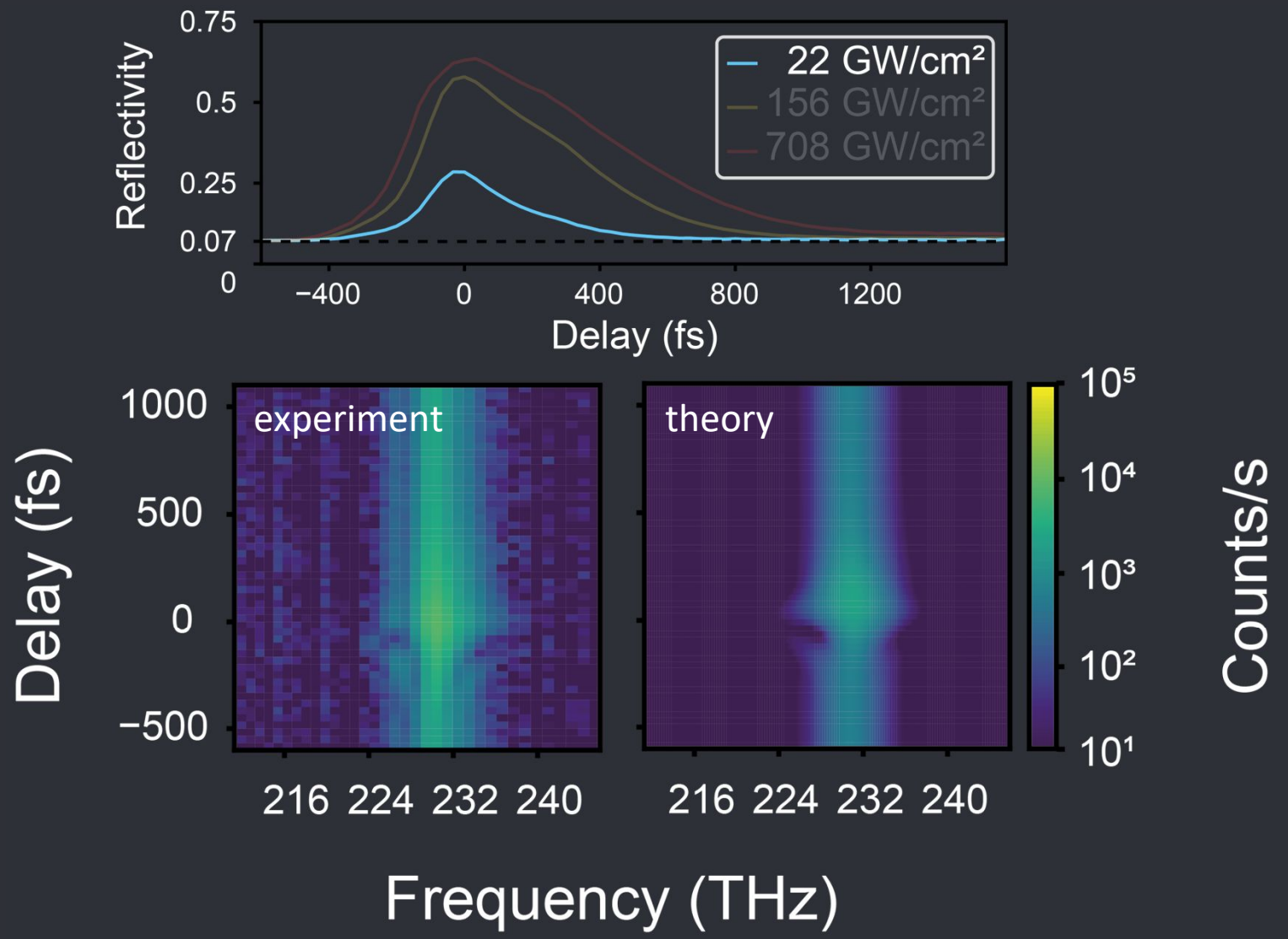


- Rise time? Hidden by probe duration
- Decay time: increases at higher intensities due to electron heat capacity dependence on temperature

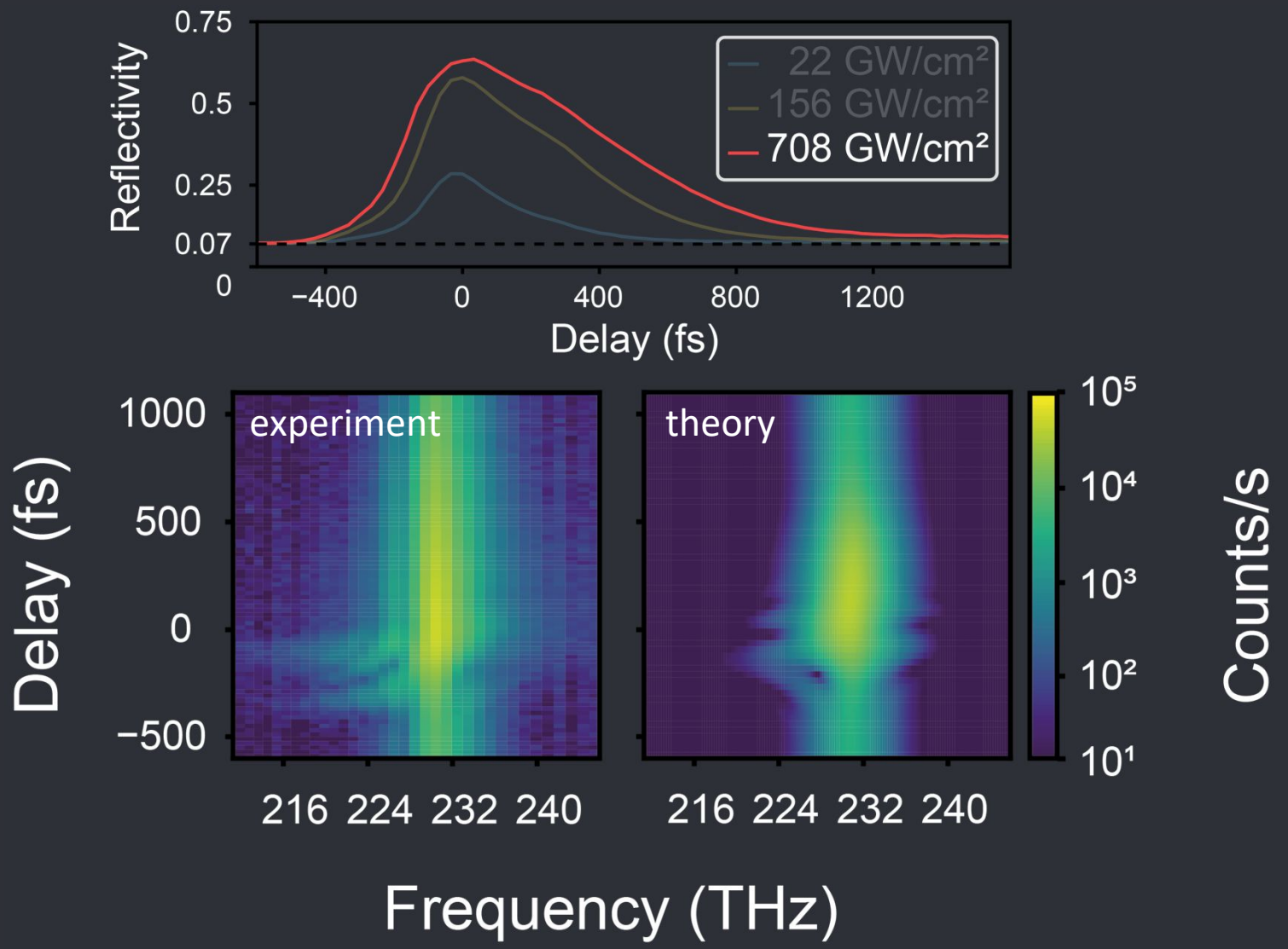


Rise time ≤ 110 fs

Single slit diffraction in time

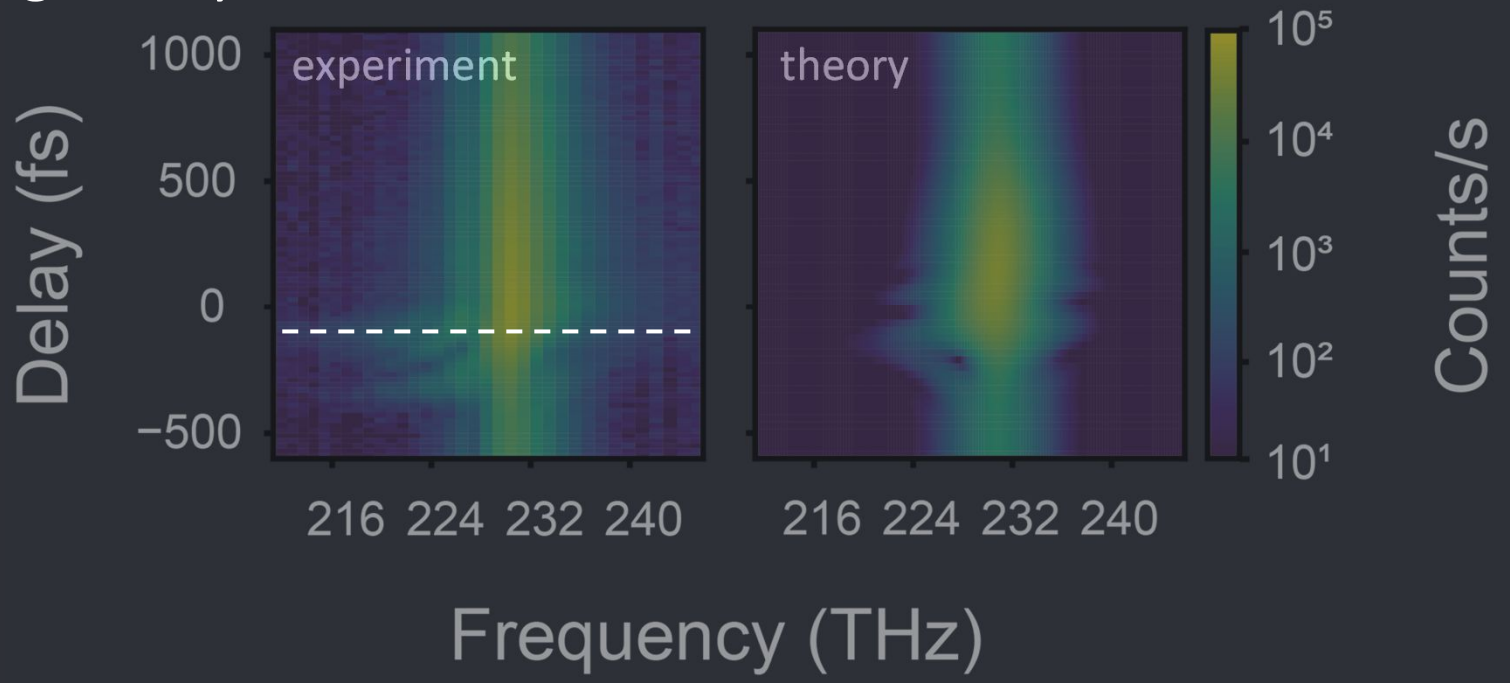


Single slit diffraction in time



Single slit diffraction in time

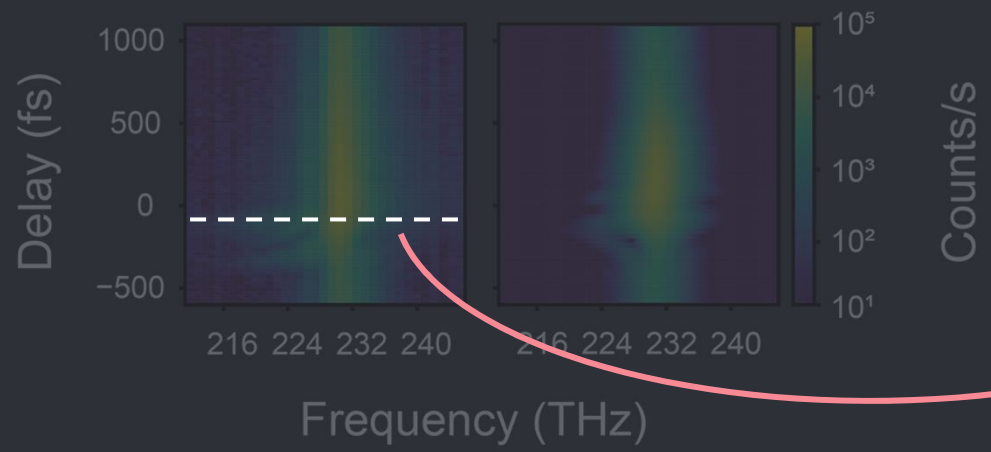
Spectral width given by rise time!

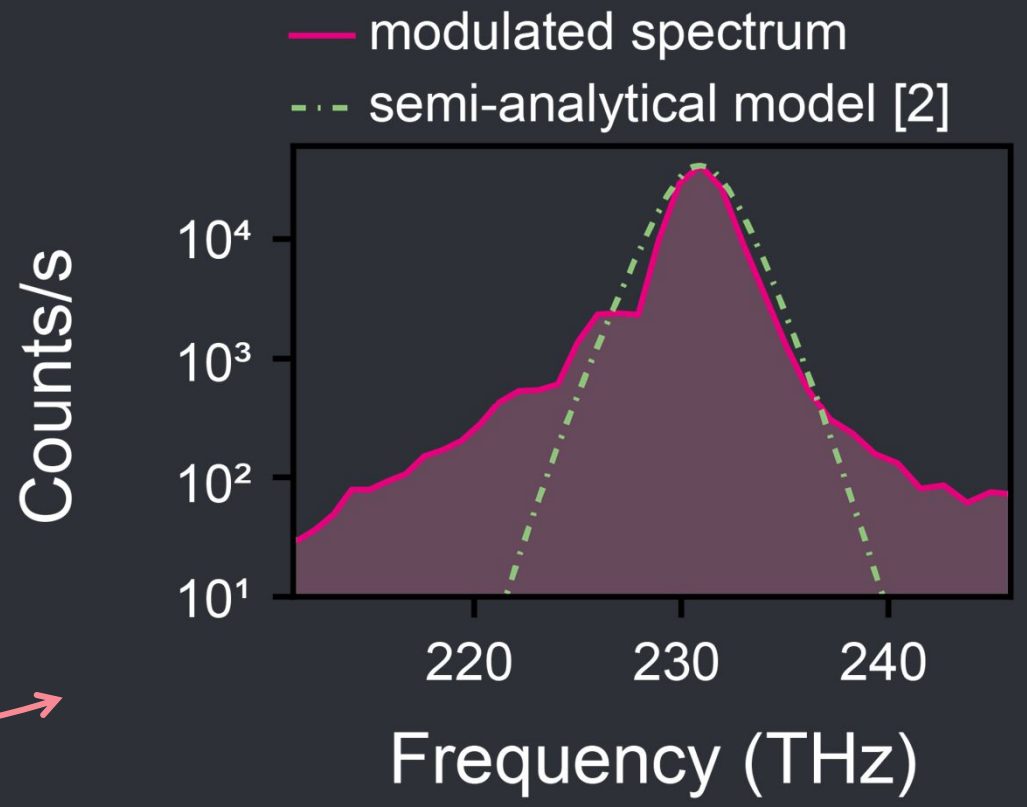


Single slit diffraction in time

Rise time $<$ 30 fs
for a pump pulse of 225 fs

Spectral width given by rise time!



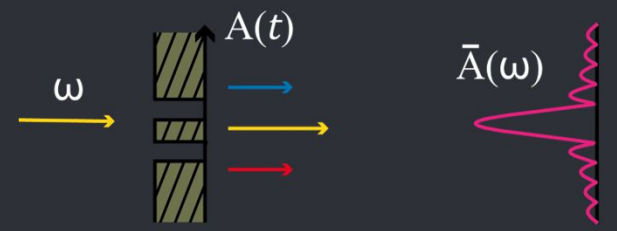


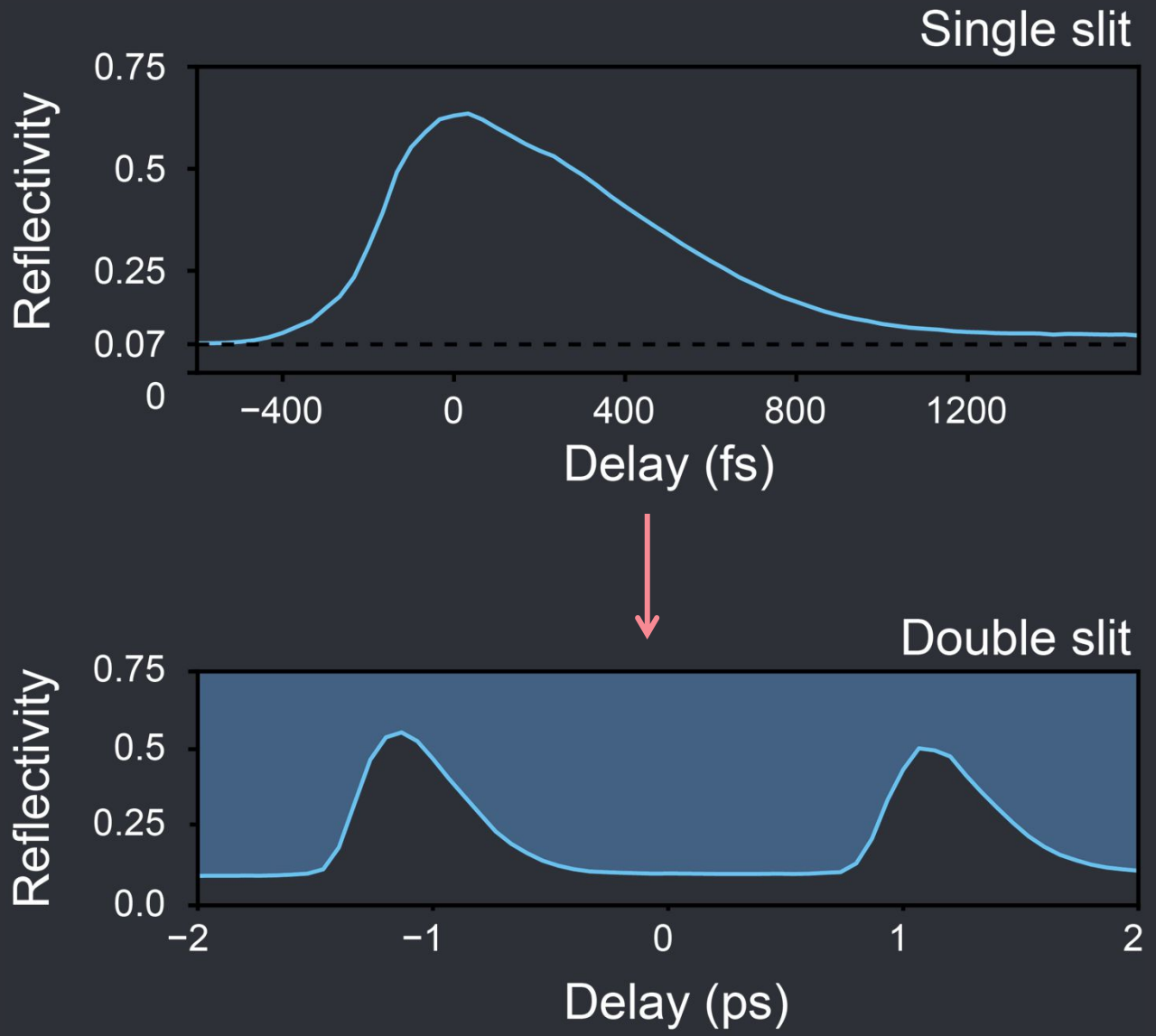
Bohn et al., All-optical switching of an epsilon-near-zero plasmon resonance in indium tin oxide", Nature Communications (2021)

Double slit diffraction in time

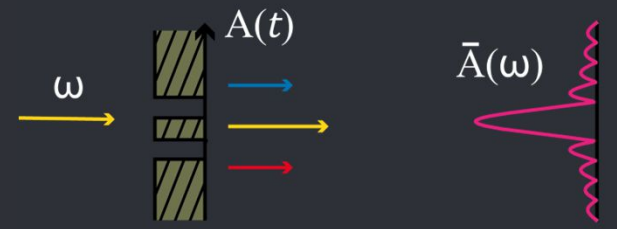
Tirole et al., "Double-slit time diffraction at optical frequencies", Nature Physics (2023)

Double slit diffraction in time

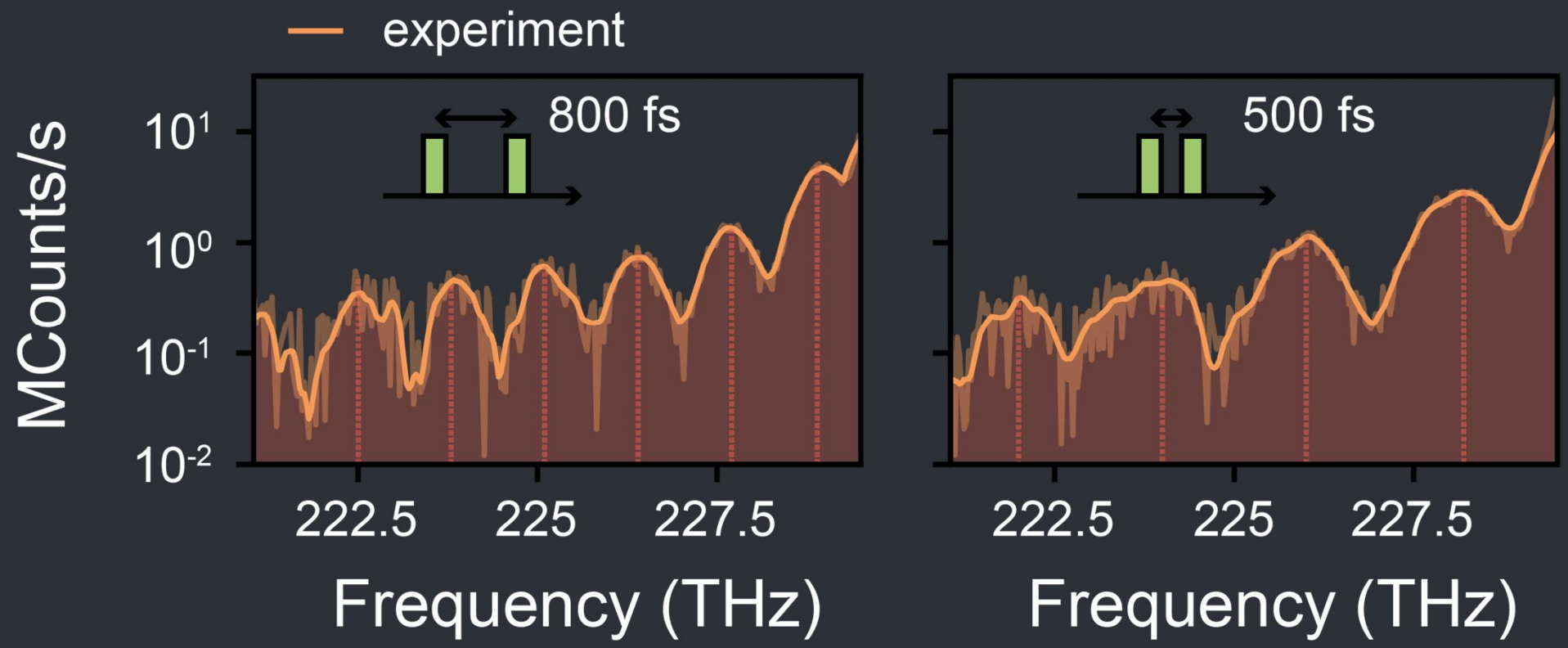




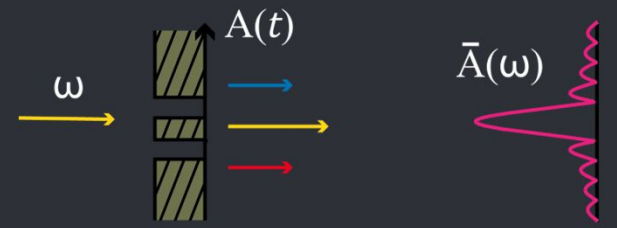
Double slit diffraction in time

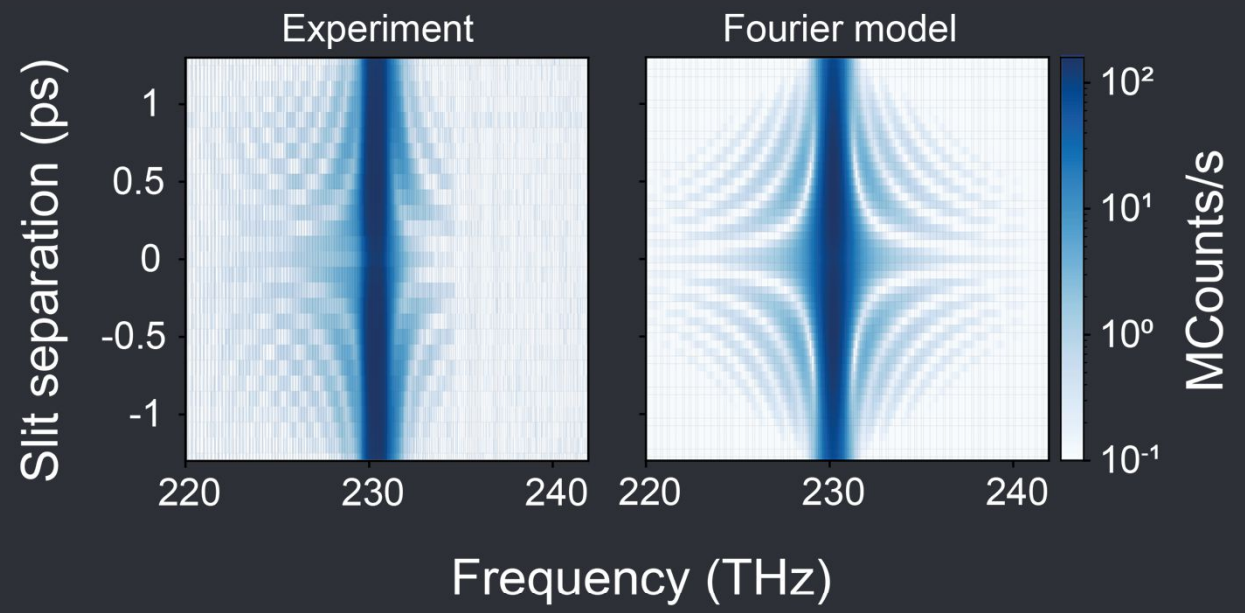


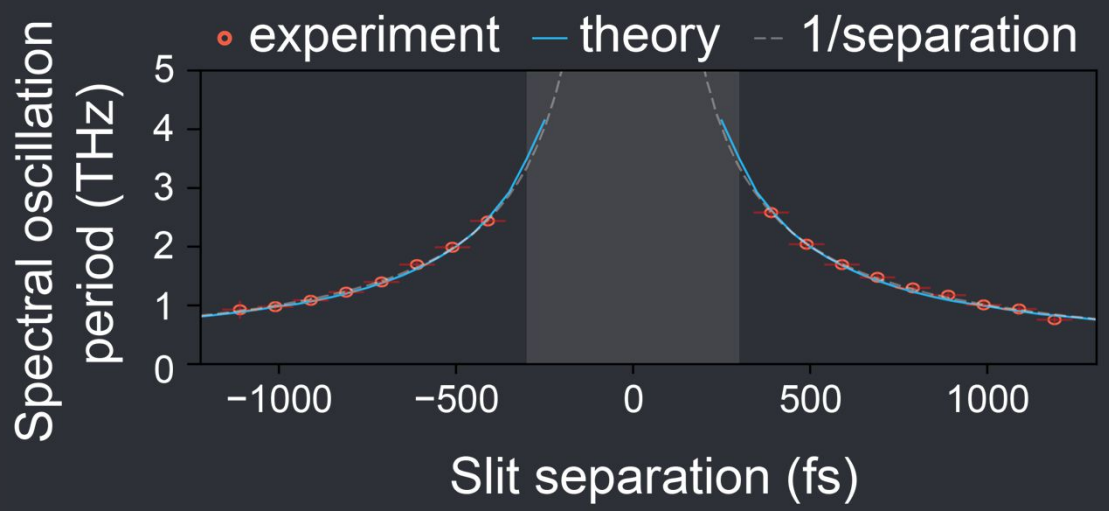
- Proof we have diffraction in time – see oscillations! (main peak at 230 THz)
- First time demonstration at optical frequencies



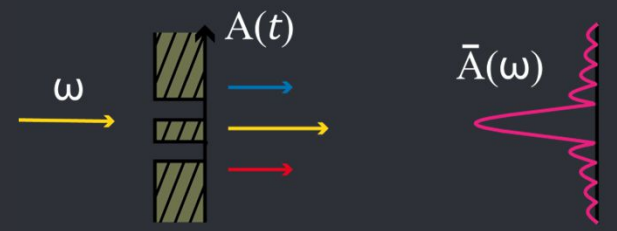
Double slit diffraction in time



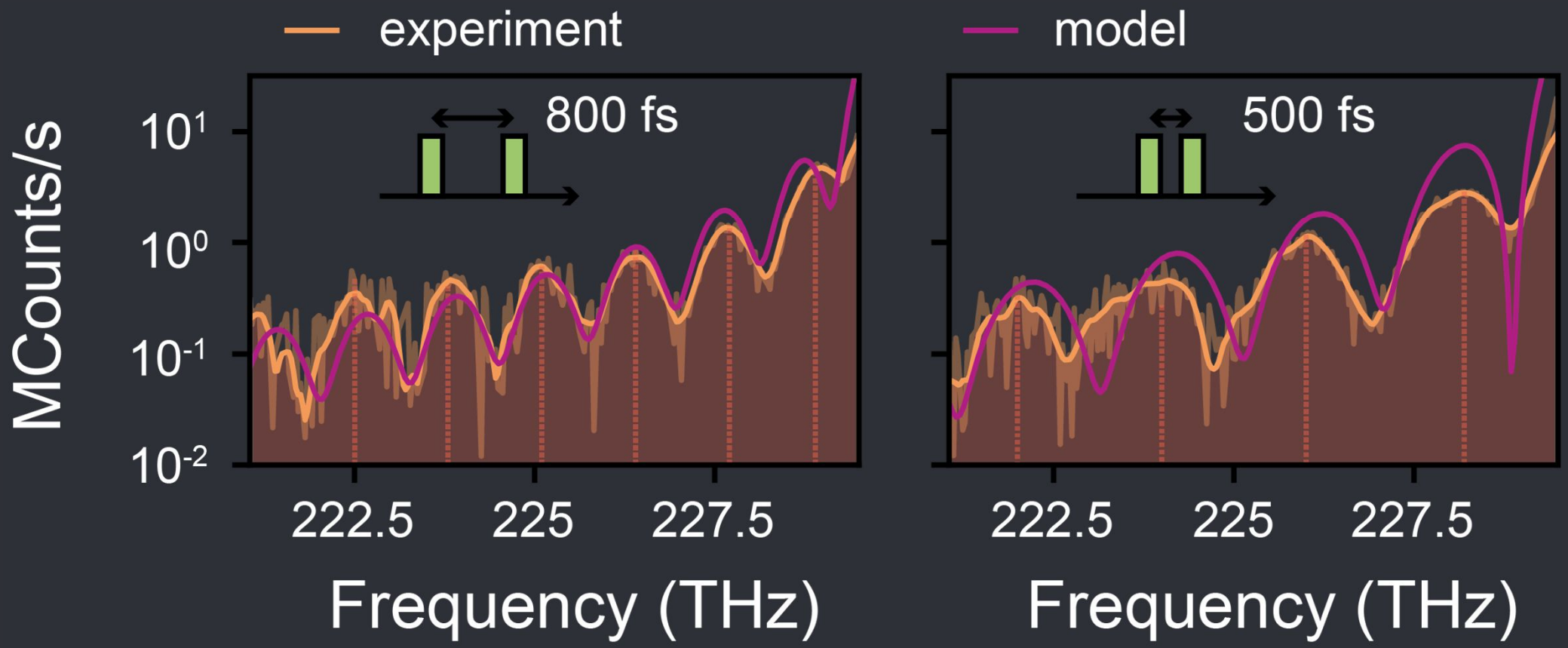




Double slit diffraction in time



Rise time 1~10 fs!



Conclusion and main take-away

- An ENZ time-varying mirror can act as a temporal interface for time diffraction
- Demonstrated single and double slit diffraction from a time-varying mirror
- Shortening of the rise time at high intensities, in the range $1\sim10$ fs

Thanks to everyone on the project:

Thank you for listening!

Stefano Vezzoli
Emanuele Galiffi
Benjamin Tilmann

Riccardo Sapienza
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Stefan A. Maier
Paloma A. Huidobro
Andrea Alù

Jakub Dranczewski
Taran Attavar
Dries Maurice
Iain Robertson
Shu Yang

Imperial College London

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

UKRI UK Research and Innovation