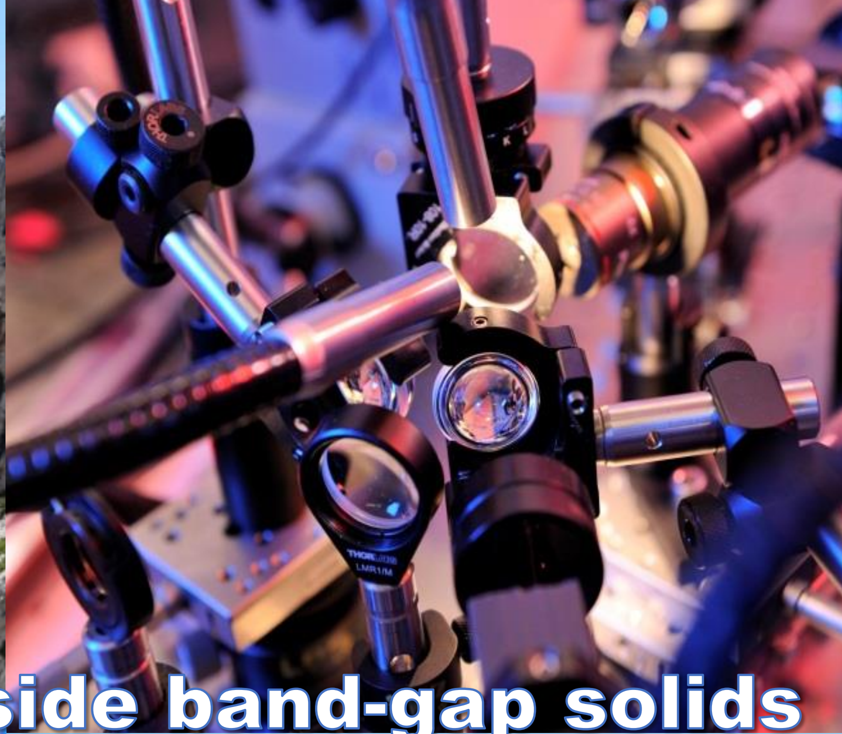



# Ultrafast laser-induced microplasmas inside band-gap solids

## Precision and controllability over the spectrum

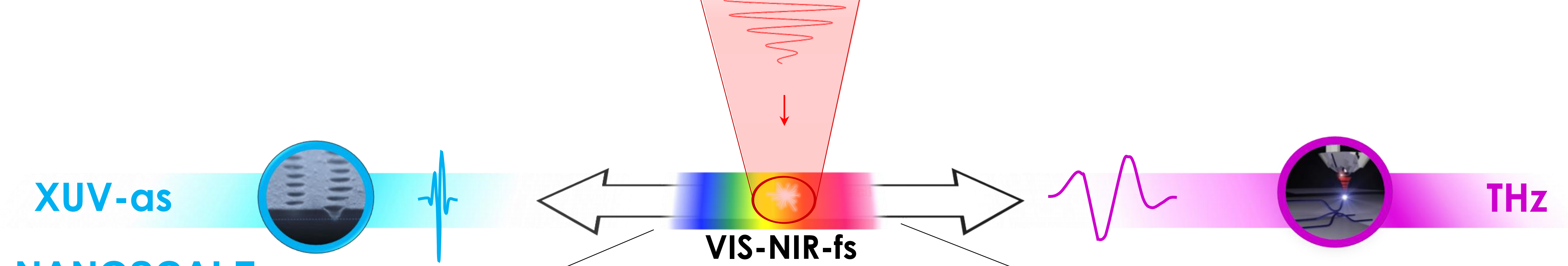
David Grojo



25 Octobre 2021
GDR Emili– Journées 2021, Palaiseau

LP3, Marseille, France
CNRS
Aix Marseille université

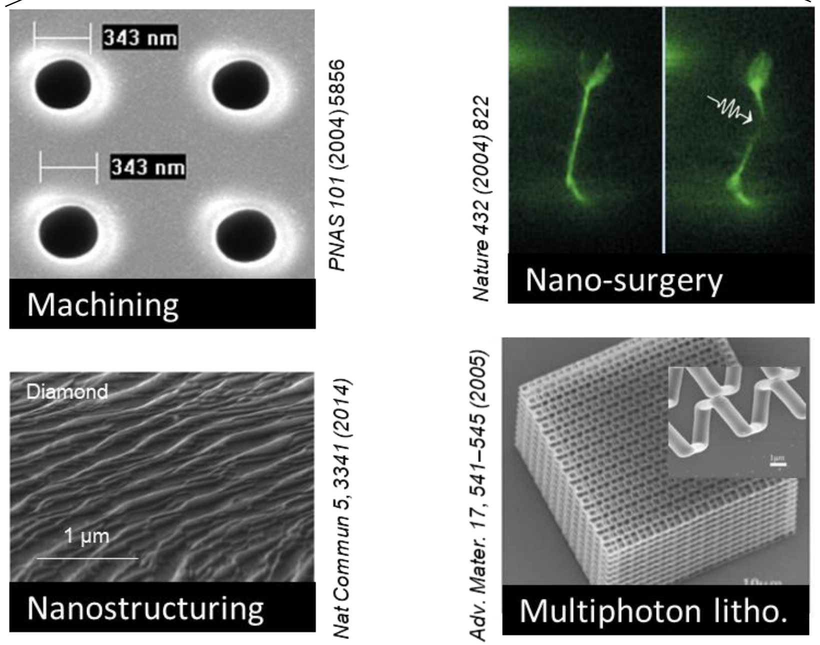
# Broadening the spectrum of ultrafast laser processing ?




**NANOSCALE**
PRECISION GUIDING

**3D IN SILICON**
BREAKDOWN IGNITION

## Ultra-precision
Sub-diffraction
Low thermal budget

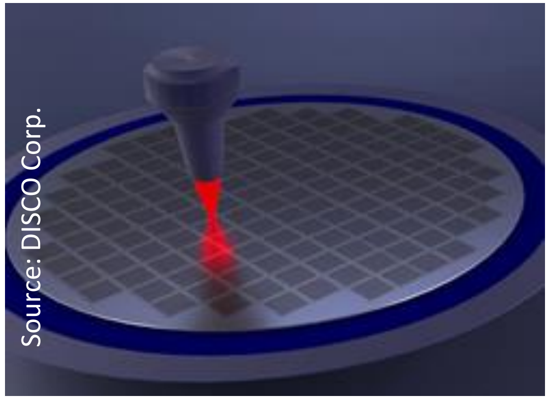



## Three-dimension
NL/Breakdown processing
in transparent matter

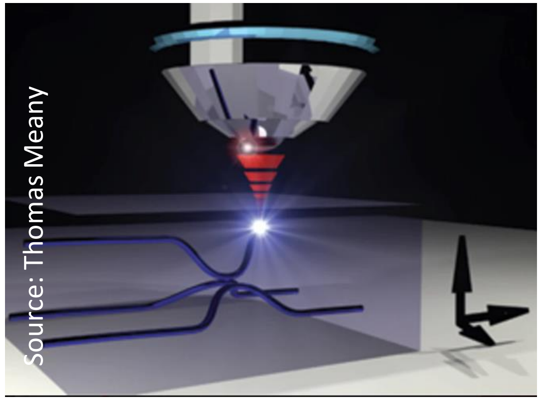
erc | EXSEED

Simple and robust method for determination of laser fluence thresholds for material modifications **Open Research Europe** 2021, **1**:7
Evidencing the nonlinearity independence of resolution in femtosecond laser ablation, **Optics Letters** 45 (2020) 952
Assessing the limits of determinism and precision in ultrafast laser ablation, **Applied Physics Letters** 117 (2020) 171604.

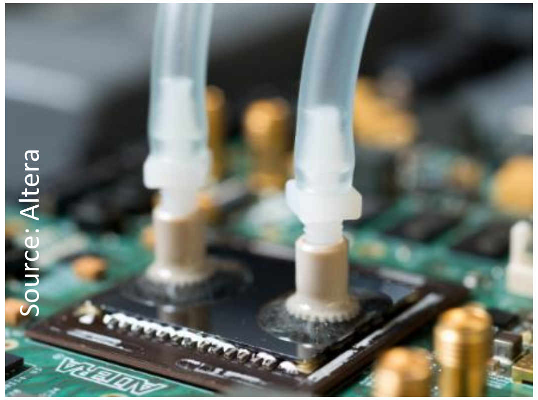
# Internal structuring of Silicon using **infrared** ultrafast lasers ?

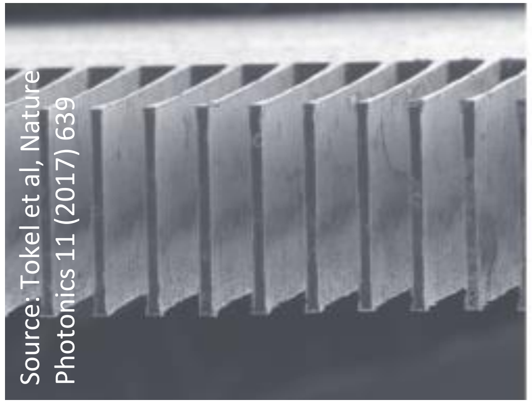

Laser **chips cutting**




Waveguide writing

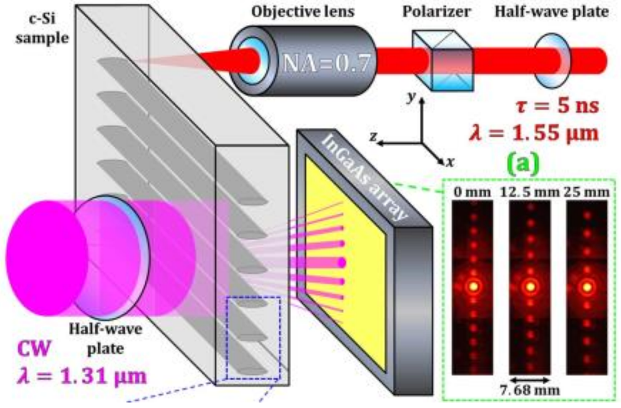



Cooling **microfluidic channels**




Complex **MEMS structures**

+ Optics Lett. 44 (2019) 1619-1622




Index engineering

Optics Lett. 43 (2018) 6069-6072

+ Optics Lett. 41 (2016) 4875

3D Silicon photonics

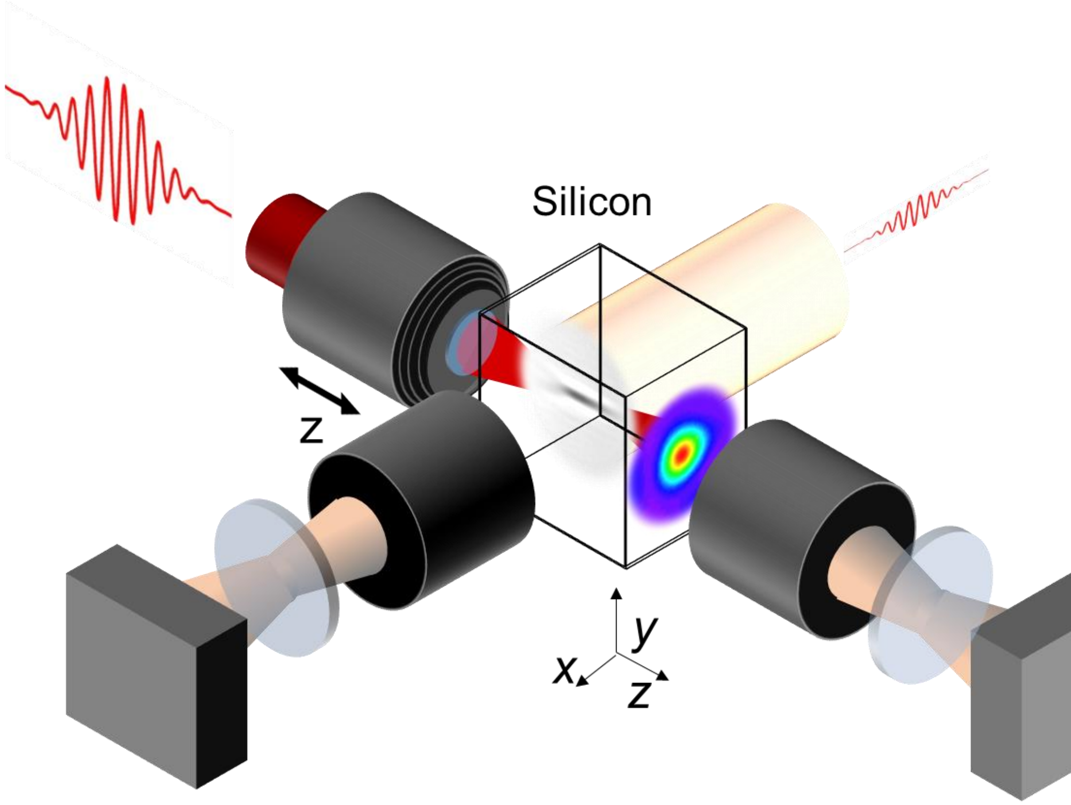
Applications similar to those in transparent dielectrics but much more challenging in Si…

# Outline – Ultrafast Laser Writing Deep inside Silicon

1. A challenging problem

2. *Optimizations in the time domain*

3. *Today's performance with introduction multi-timescale control*



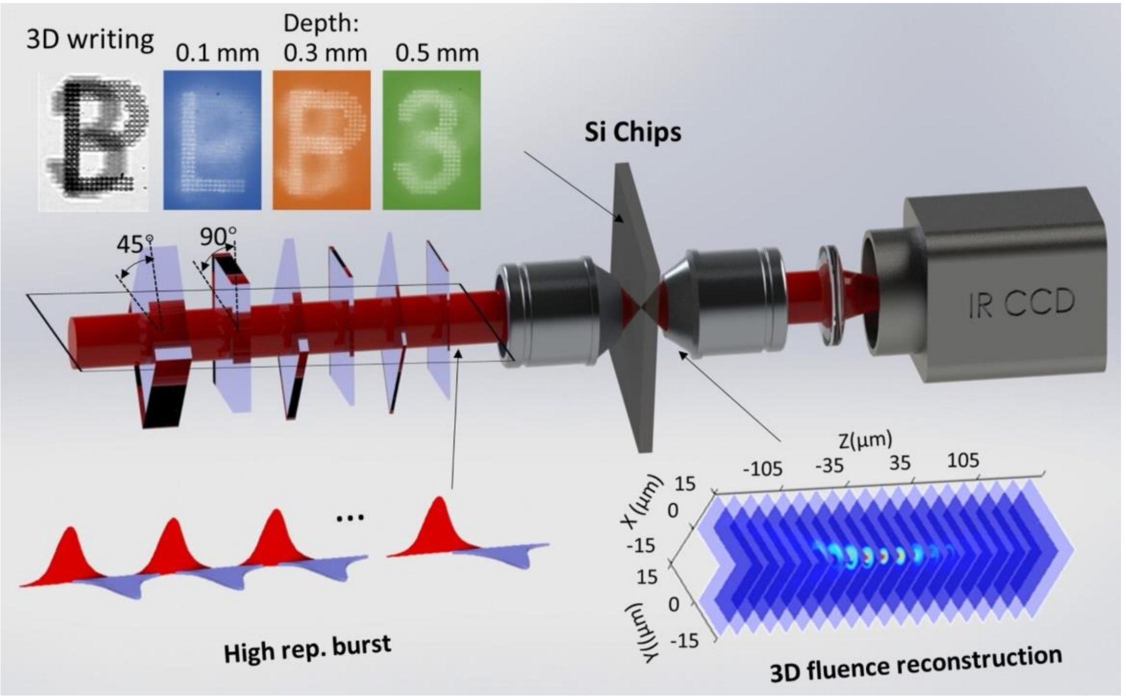
# Outline – Ultrafast Laser Writing Deep inside Silicon

2

*1. A challenging problem*

2. Optimizations in the time domain

*3. Today's performance introduction multi-timescale control*



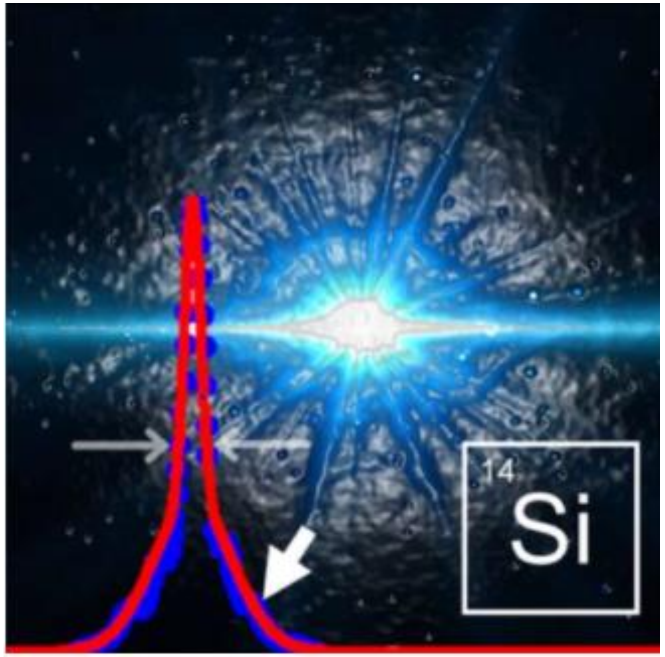
# Outline – Ultrafast Laser Writing Deep inside Silicon

3

*1. A challenging problem*

*2. Optimizations in the time domain*

3. Today's performance introducing multi-timescale control



# Outline – Ultrafast Laser Writing Deep inside Silicon

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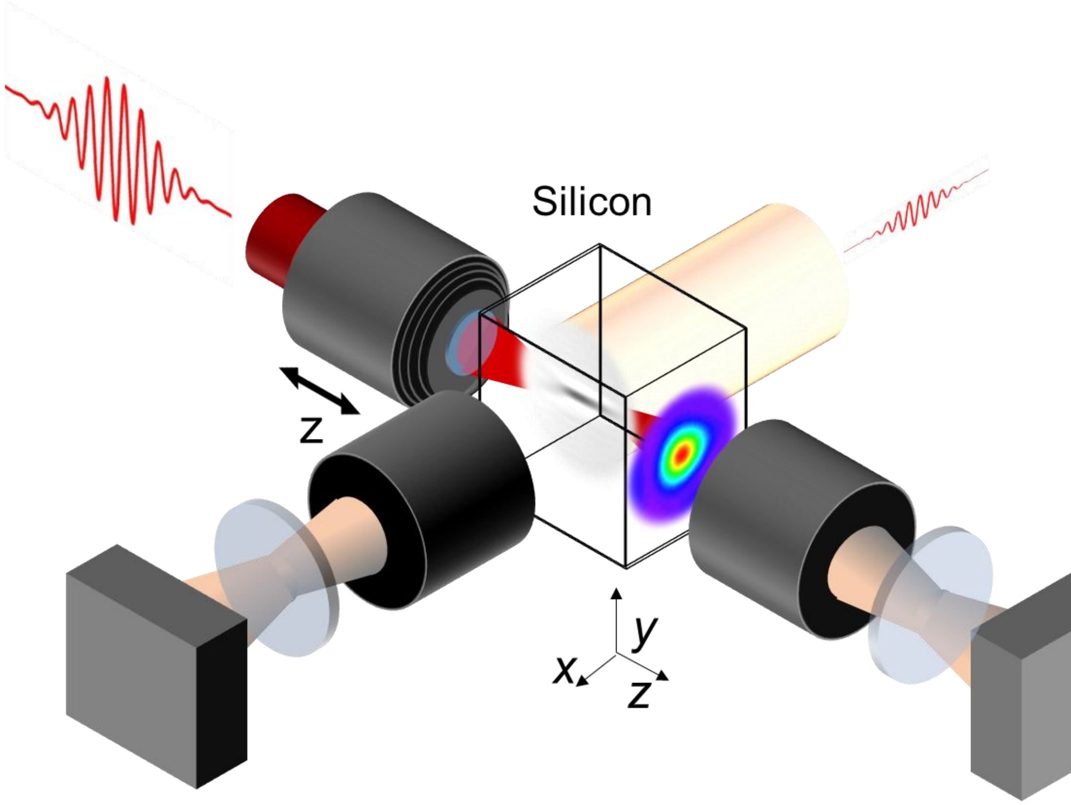


# Challenges for high space-time energy localization in Si

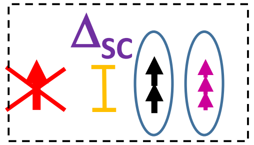

- Indirect band Gap: **1.1 eV**

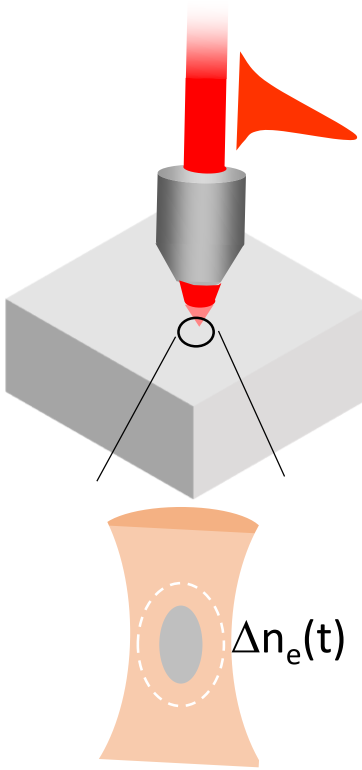
**- h$\nu_{las}$ < band gap**

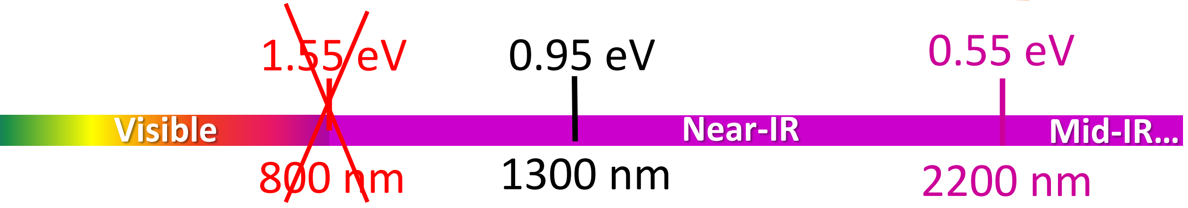
**- Optical Parametric Amp. (OPA)**

$\lambda_{las}$ > 1.2µm (h$\nu_{las}$ <1 eV)

-Tu: or Er: doped fiber lasers




Need for SWIR fs pulses...

**Narrow gap**

high index n=3.5

*.. and associated refraction*

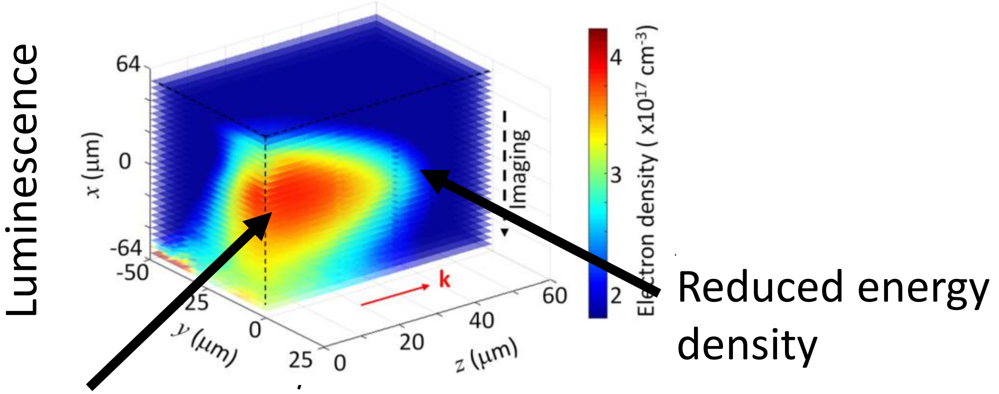
Increased 2PA aborption coef. *(≈dielectics x100)*

**Stronger nonlinearities**

**Long wavelengths**

Reduced critical plasma densities *(≈visible/10-100)*

**Stronger plasma effects**




**Detrimental pre-focal plasmas**

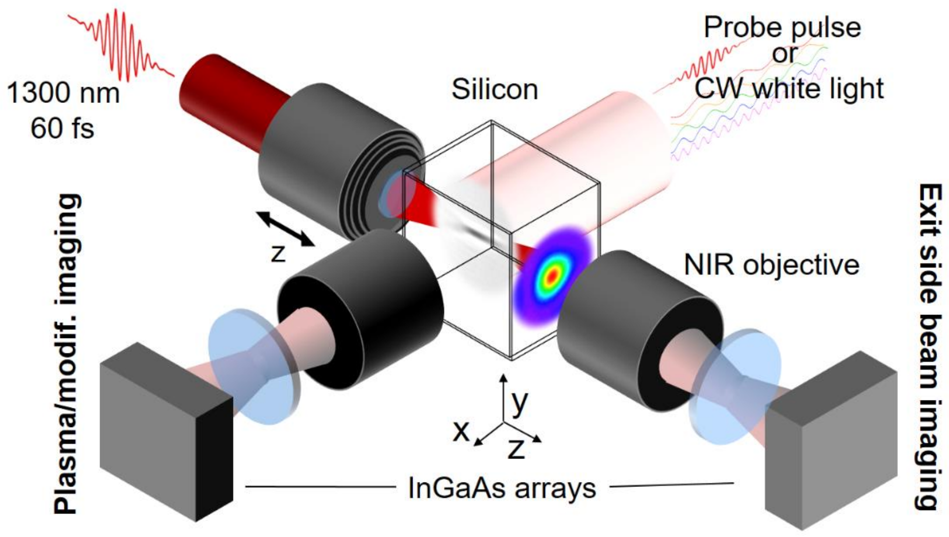
**Applied Physics Letters 119** (2021) 041108

Delocalization preventing excitation ...

# Accessing extreme spatio-temporal energy localizations in Si

**Experimental**

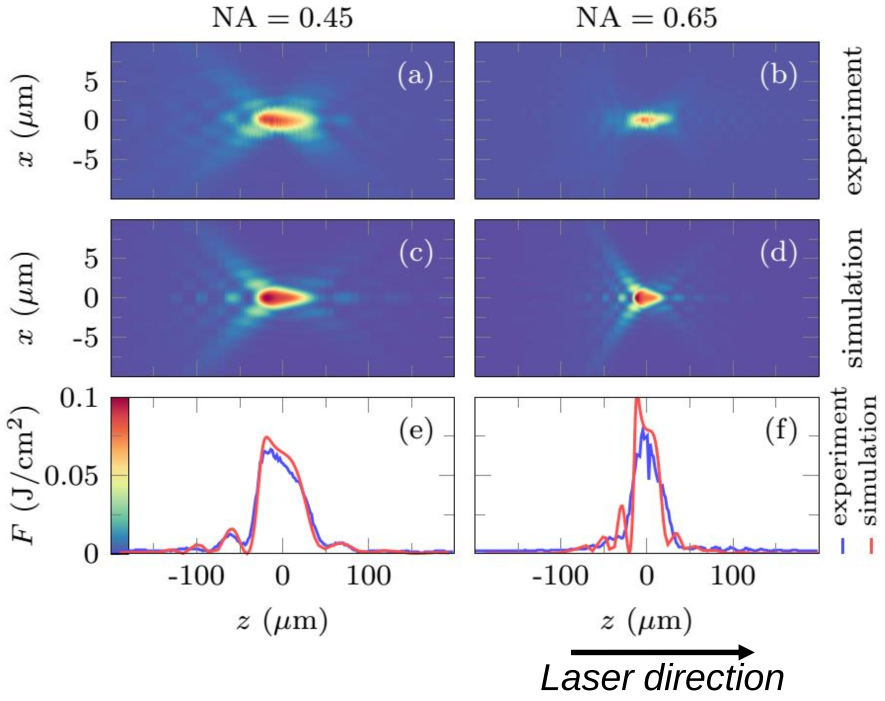
Full space-time IR microscopy of the **beam (3D)** and matter




Nature Communications 8 (2017) 773

**Modeling**

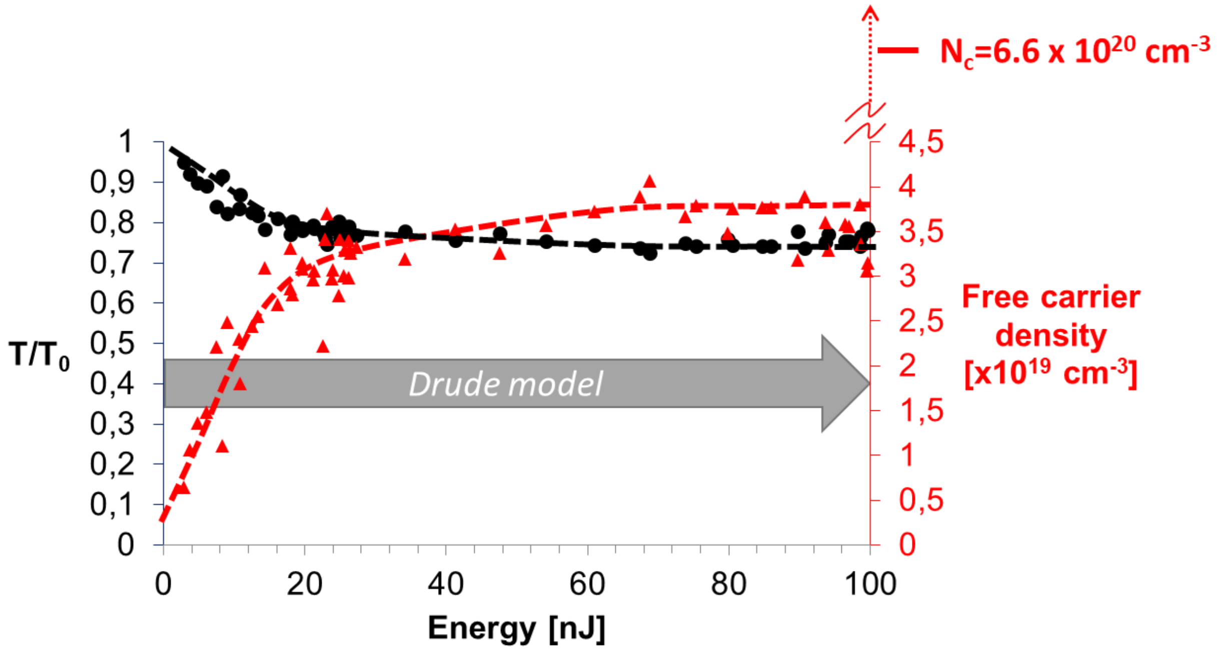
Transformation optics enabling the use of scalar equations for **non-paraxial** propagation problems



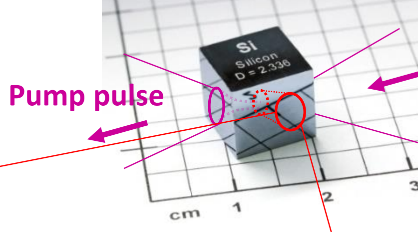

Physical Review Letters 117 (2016) 043902

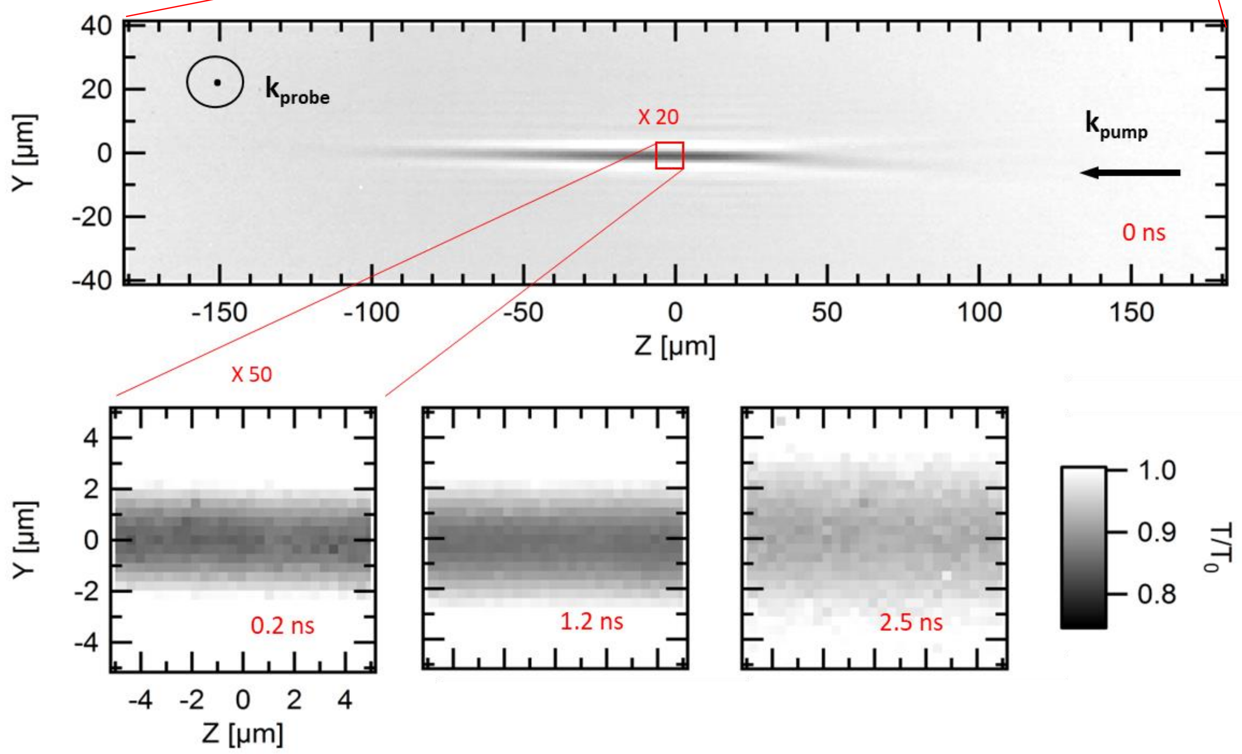
Experimental and numerical tools for studying the physical mechanisms taking place in the nonlinear interactions (propagation, ionization, plasma, etc..)

# Ultrafast microscopy of plasmas inside Si




Appl. Phys. Lett. 105, 191103 (2014)

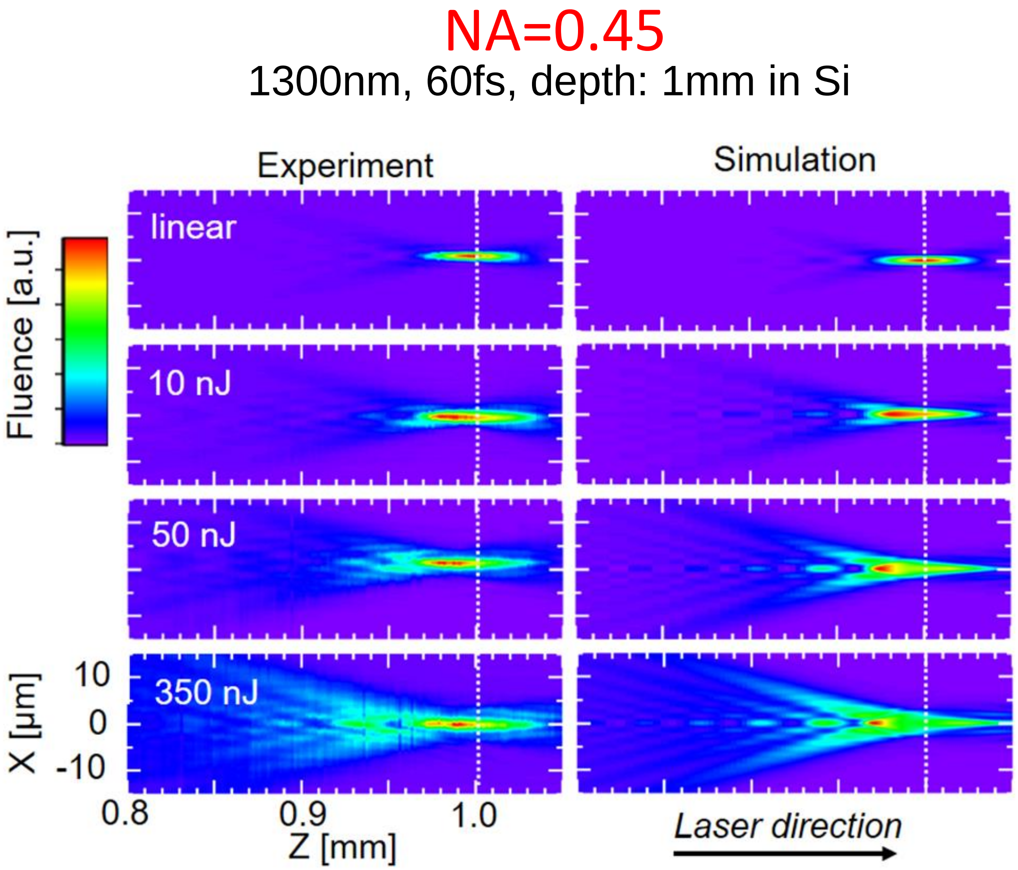


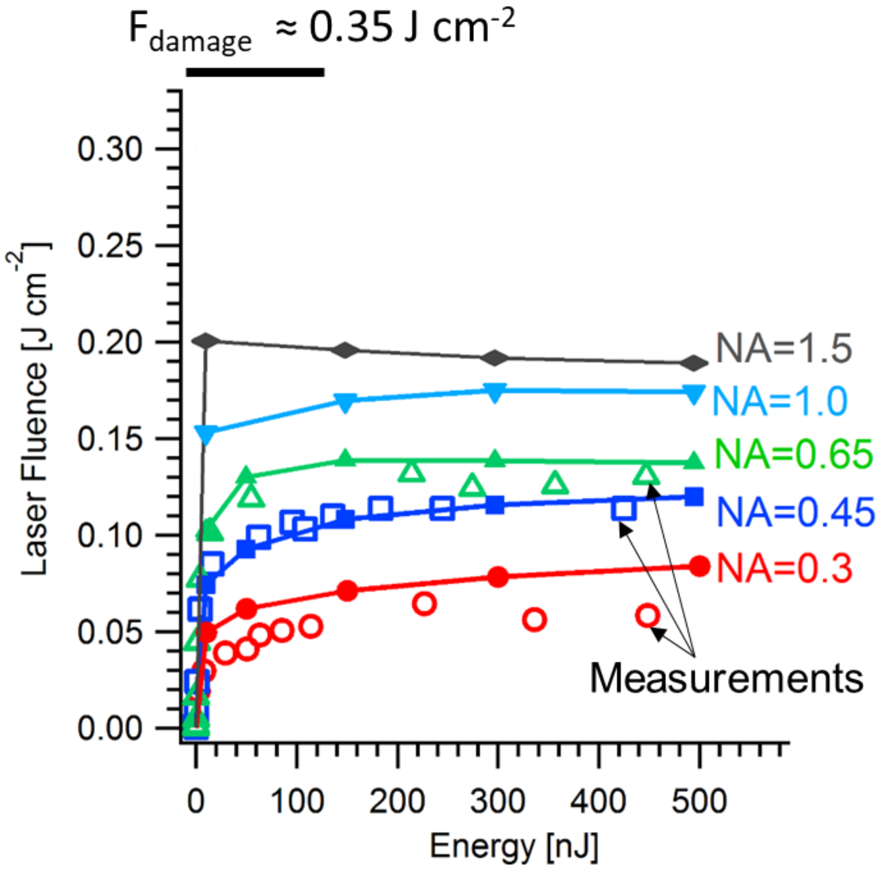




Appl. Phys. Lett. 108 (2016) 041107

**Self-limited nonlinear excitation** but **no evidence of ultrafast dissipation** (ns carrier diffusion) which could limit the achievable energy density!

# 3D fluence distributions inside Si



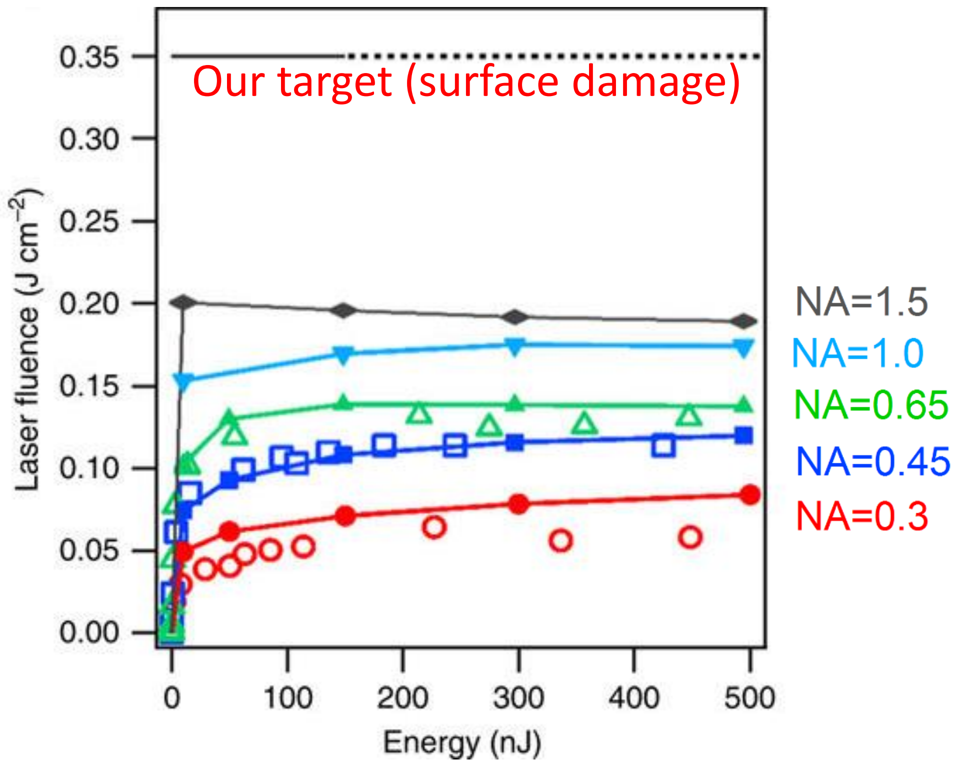

Attempt to deliver a high fluence by **increasing the pulse energy**

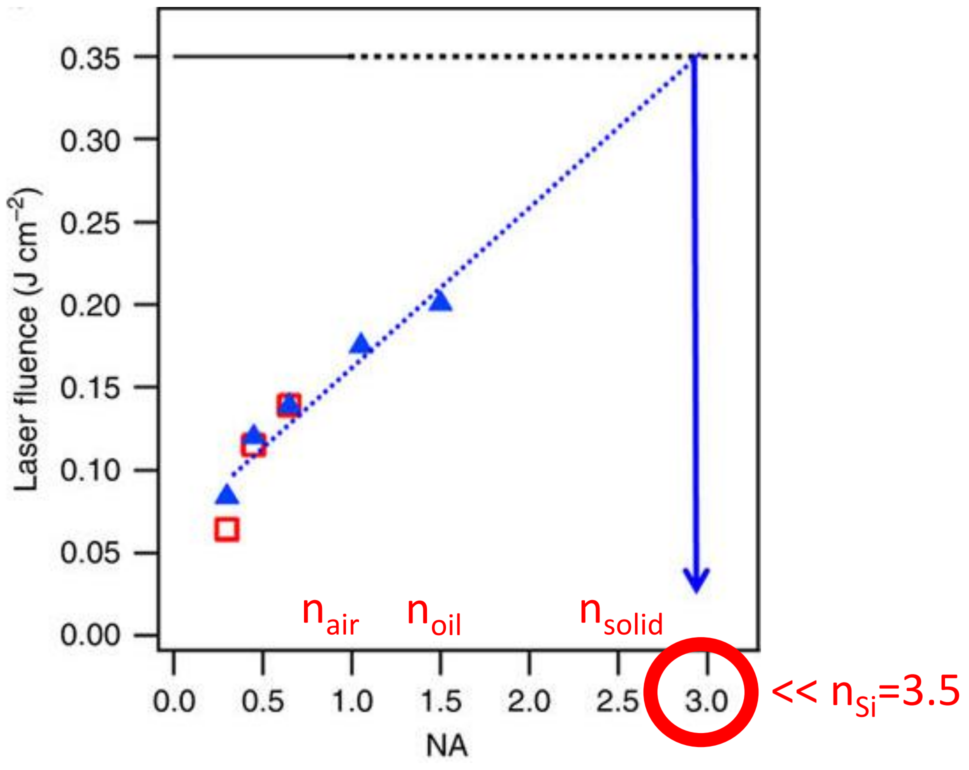
**energy fails and degrades resolution**

Nature Communications 8 (2017) 773

# Solid immersion for increased delivered fluence

1300nm, 60fs




Extrapolating simulations and measurements, **hyper-NA values are required** to circumvent sufficiently detrimental TPA and plasma pre-focal effects…

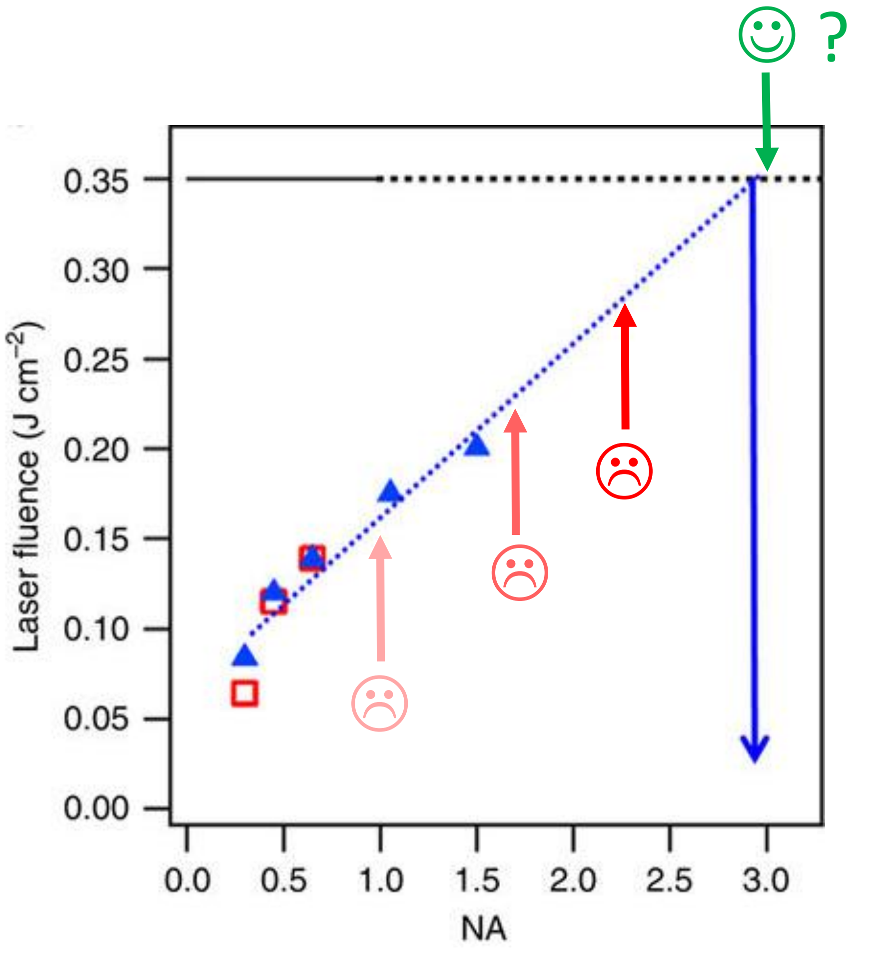
Nature Communications 8 (2017) 773

# Hyper-NA focusing as a solution ?


NA=sinθ    NA'=n.sin θ' =sinθ=NA

NA=sinθ    NA'=n.sinθ =n.NA = 3.5 x NA

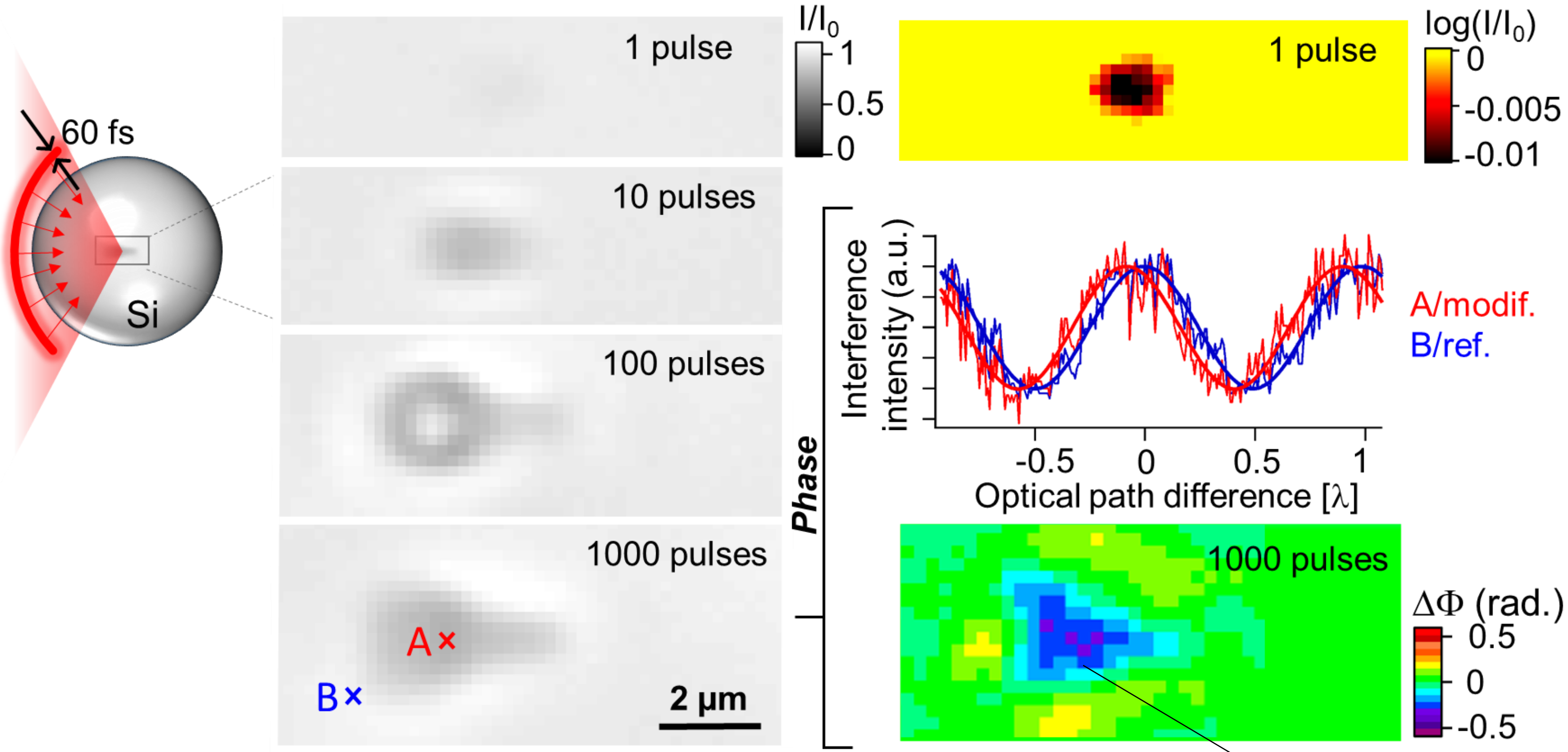
| NA | $\theta_{air}$ (°) | $\theta_{Si,flat}$ (°) | $\theta_{Si,sphere}$ (°) | $NA_{Si,sphere}$ | Test |
|---|---|---|---|---|---|
| **0.3** | 18 | 5 | 18 | 1.05 | ☹ |
| **0.45** | 27 | 7 | 27 | 1.57 | ☹ |
| **0.65** | 40.5 | 11 | 40.5 | 2.27 | ☹ |
| **0.85** | 58 | 17 | 58 | 2.97 | ☺ |




Extrapolating simulations and measurements, **hyper-NA values are required** to circumvent sufficiently detrimental TPA and plasma pre-focal effects…

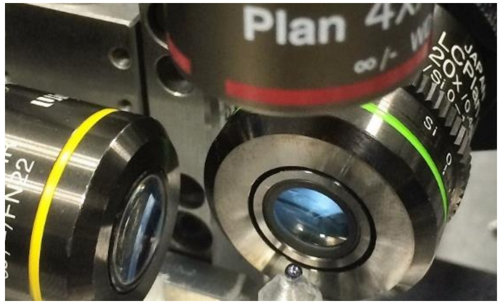
Nature Communications 8 (2017) 773

# Femtosecond laser refractive index modification




Δn<0 ≠ amorphization

Infrared phase microscope: **Applied Optics** 55 (2016) 9577




λ=1300nm

**NA=2.97**

60 fs

20nJ/pulse

NA≅3 leads to spot of
λ/6≅220 nm for λ=1.3µm

## Perspectives for ultrafast laser 3D writing with complex solid immersion lens (SIL) techniques ?

Crossing the threshold of ultrafast laser writing in bulk silicon, **Nature Communications** 8 (2017) 773

# Outline – Ultrafast Laser Writing Deep inside Silicon

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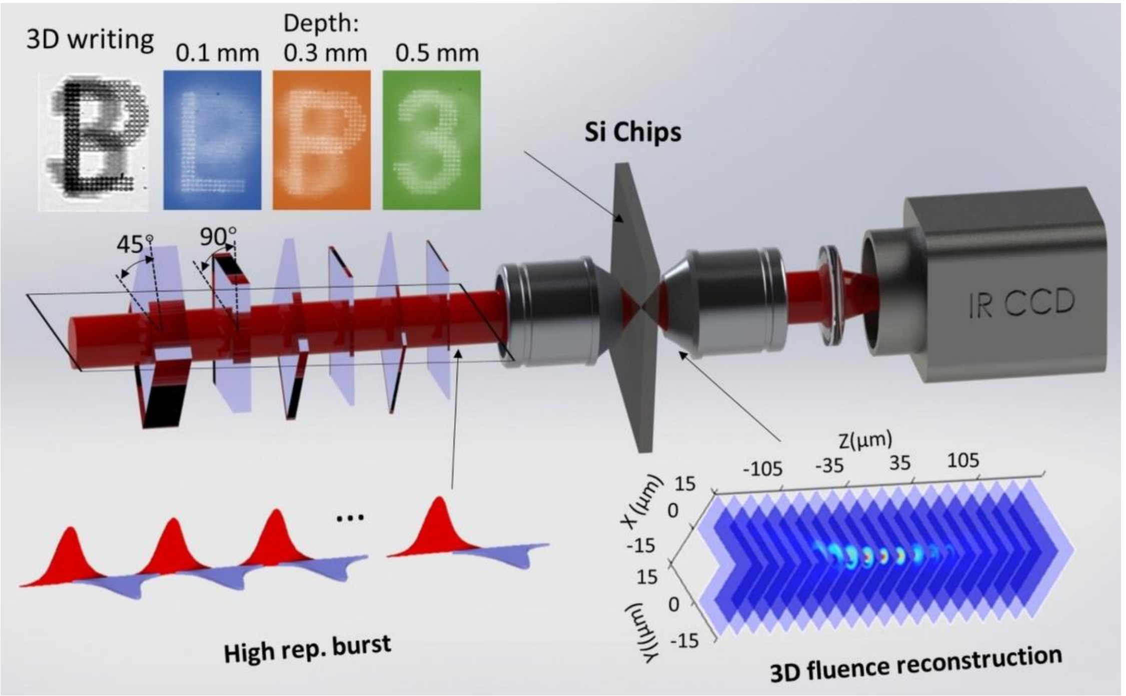
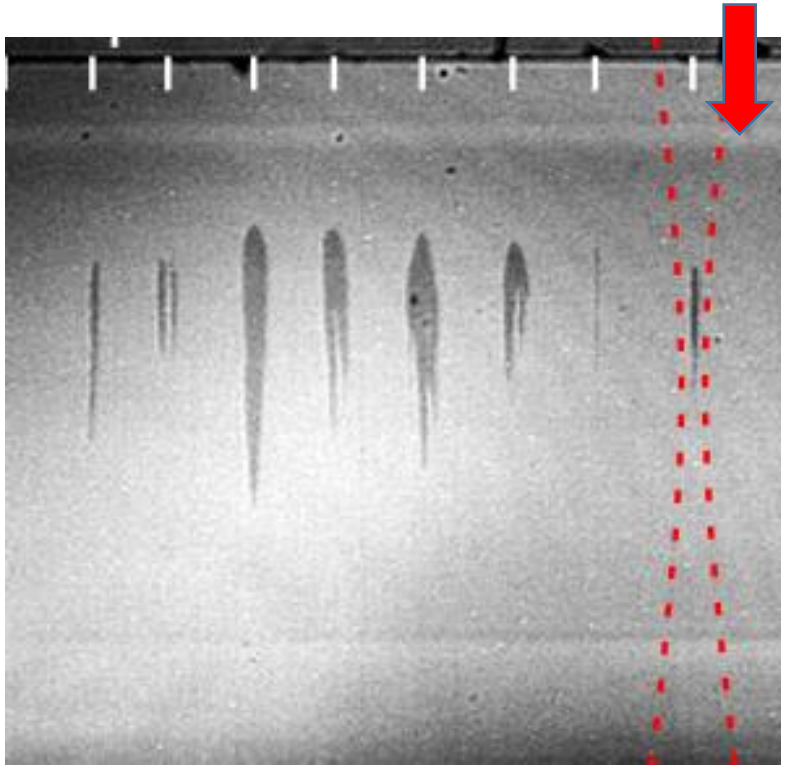
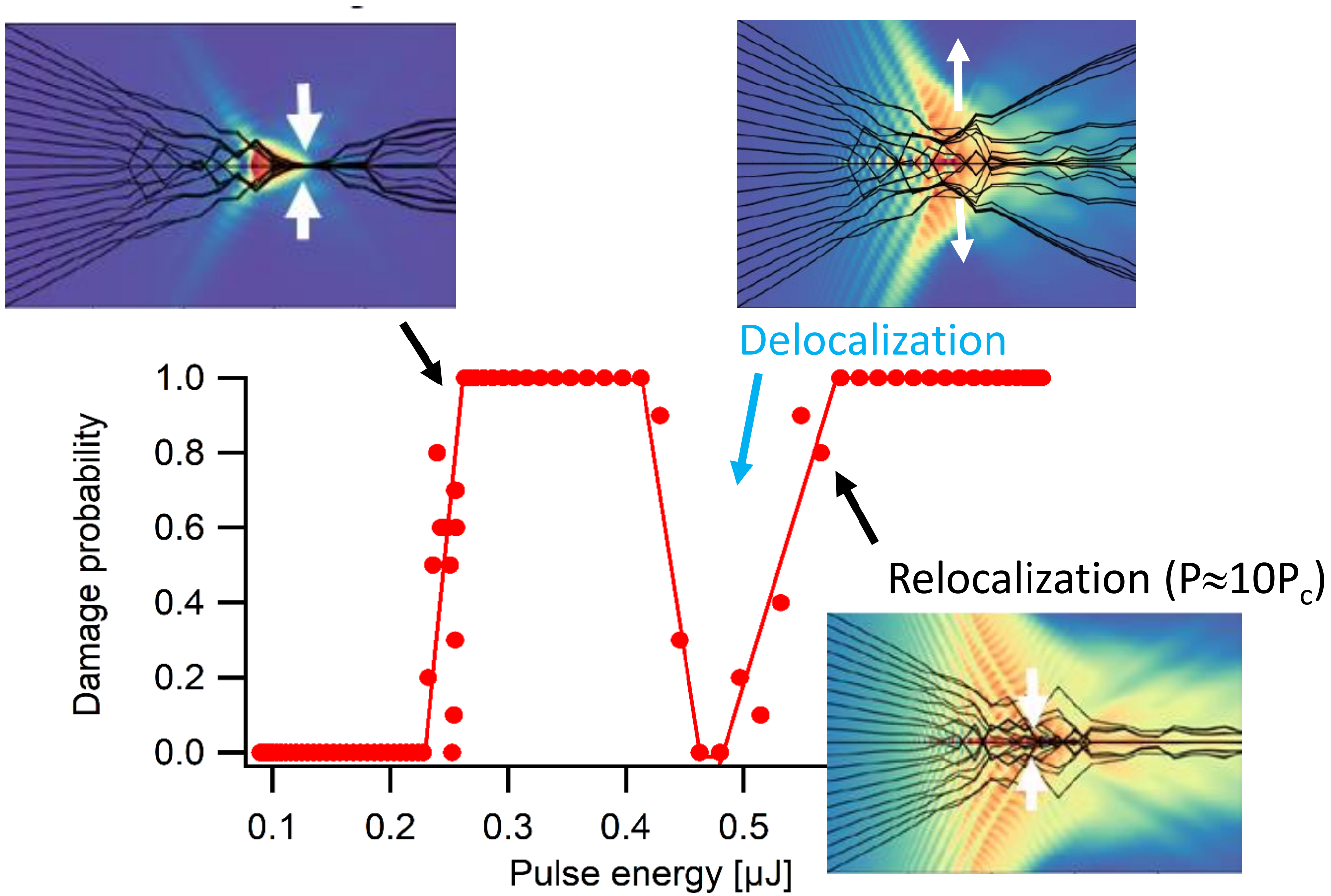


# Controllability of the picosecond regime ?



1550 nm, **NA=0.45**, 10 ps

**Applied Physics A** 124 (2018) 302



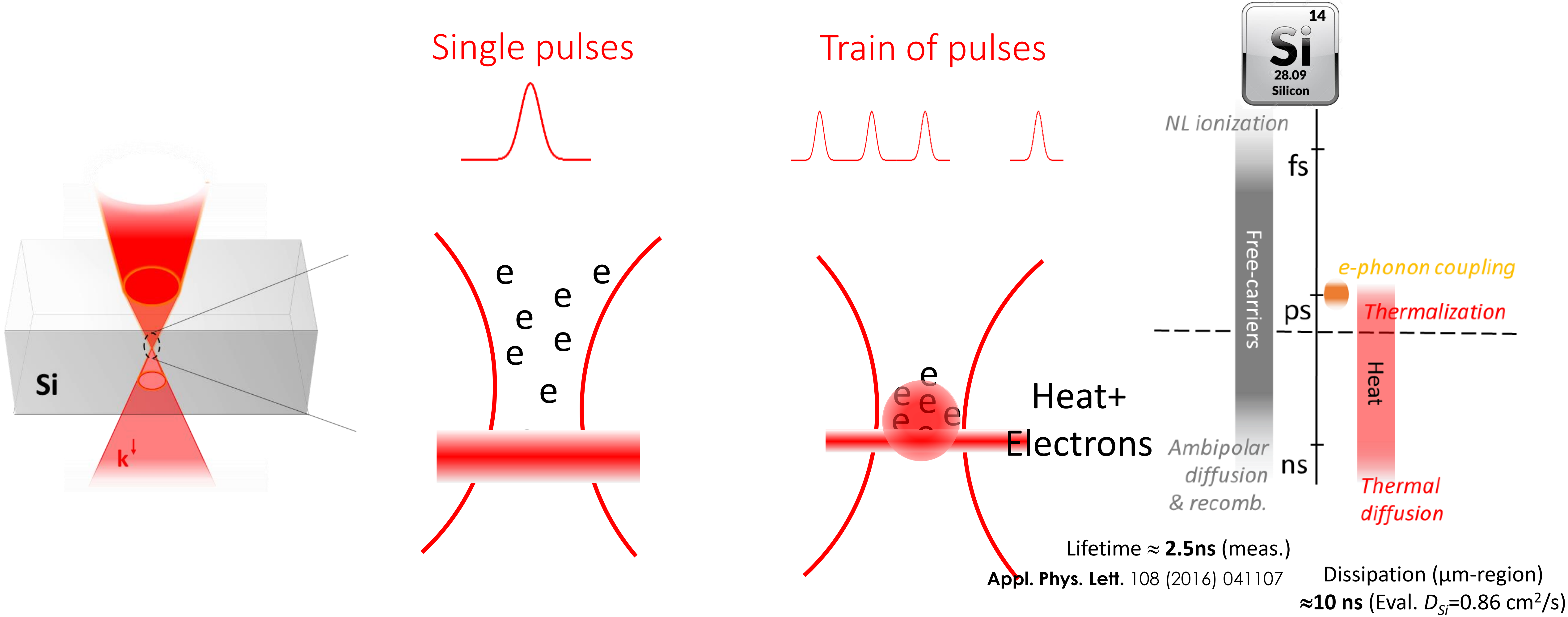

2000 nm, **NA=0.85**, 2 ps

**Physical Review Applied** 12 (2019) 024009

Competing nonlinear delocalization persists leading to hardly repeatable writing

+ Pulse duration depence study: **Optics Express** 28 (2020) 26623

# ‘Accumulation’ strategy by ultrafast pulse trains

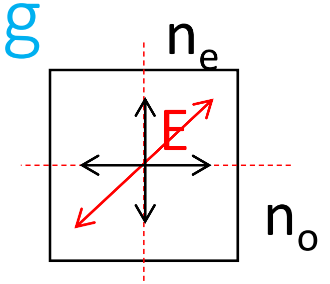


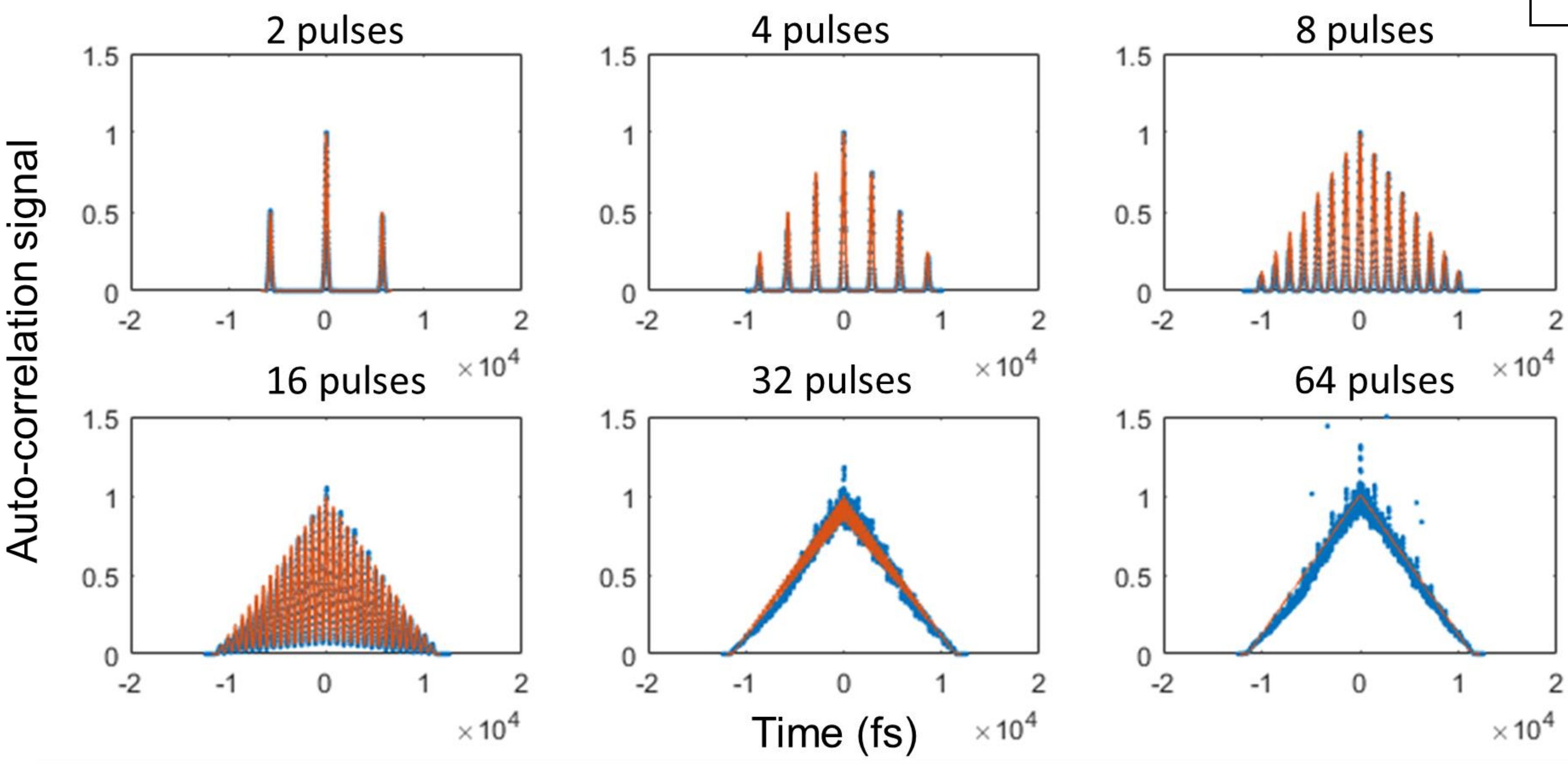

**>GHz pulses** must enable localized accumulation of heat and electrons near focus

Ultrafast Laser Writing Deep Inside Silicon with THz-repetition-rate Trains of Pulses, **Research** 2020 (2020) 8149764, https://doi.org/10.34133/2020/8149764

# Ultrafast trains of pulses by polarization splitting

$\lambda$=1550nm
$\tau_{pulse}$=200fs

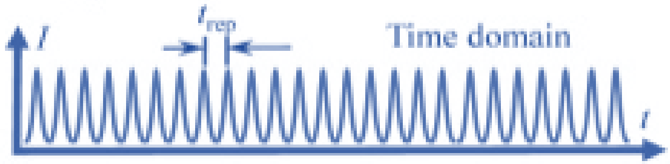



**Delay determined by thickness**

| $YVO_4$ Crystal Thickness(mm) | Theoretical Delay(ps) |
|---|---|
| 0.25 | 0.17 |
| 0.5 | 0.34 |
| 1 | 0.68 |
| 2 | 1.36 |
| 4 | 2.73 |
| 8 | 5.47 |

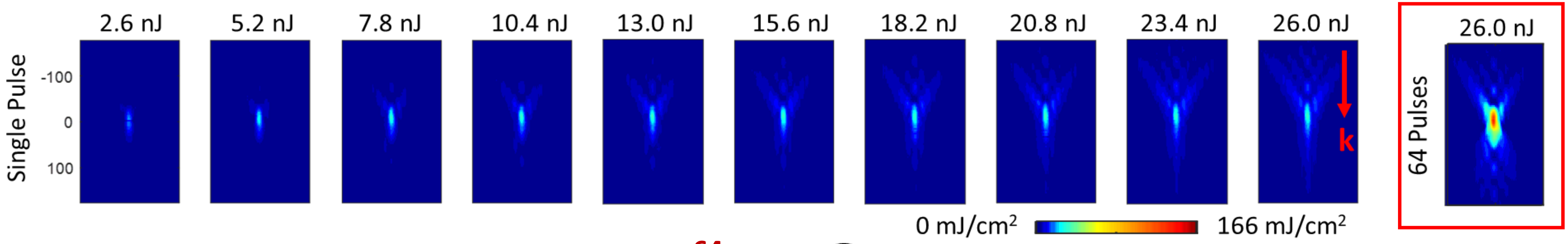
$2^6$=64 pulses

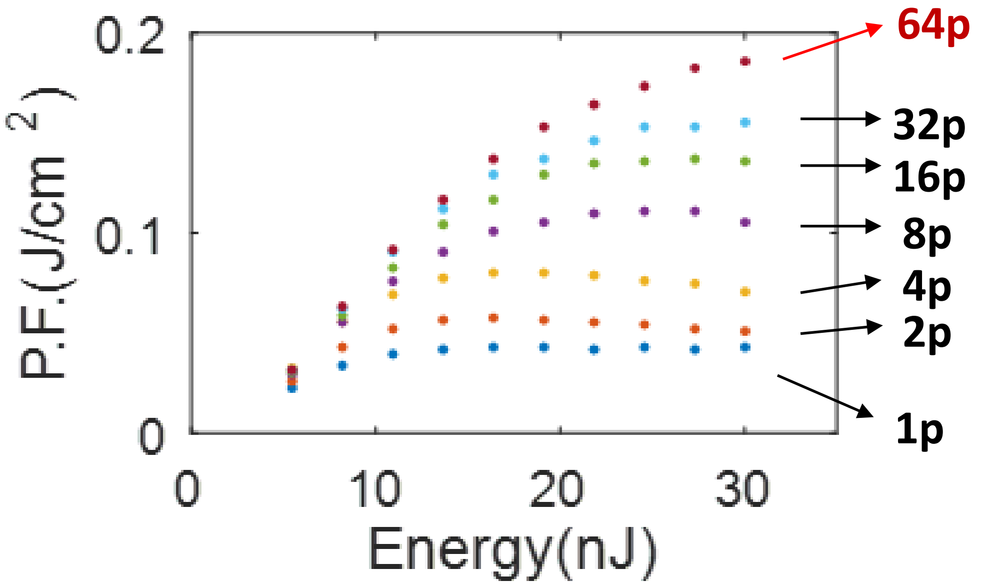


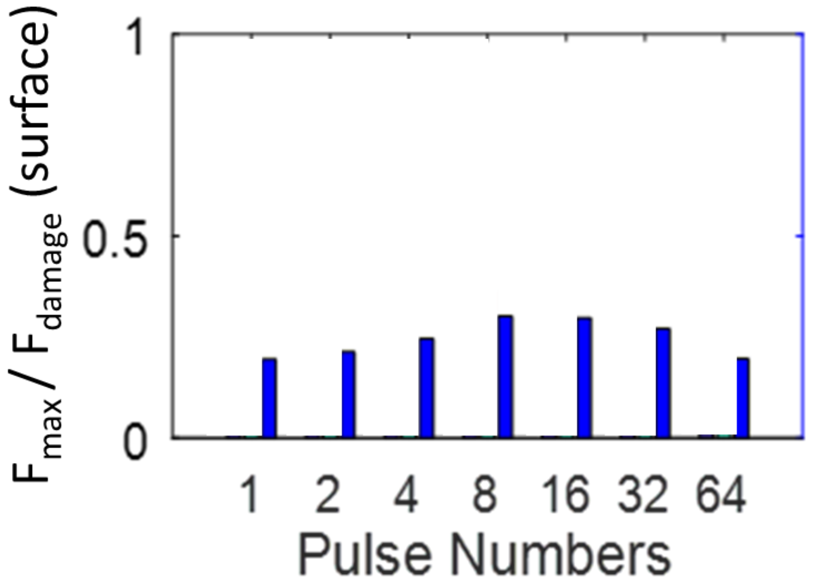

5.8 THz rep. rate trains of up to 64 pulses by passive propagation in a stack of crystals

Ultrafast Laser Writing Deep Inside Silicon with THz-repetition-rate Trains of Pulses, **Research** 2020 (2020) 8149764, https://doi.org/10.34133/2020/8149764

# Improved energy densities to achieve writing



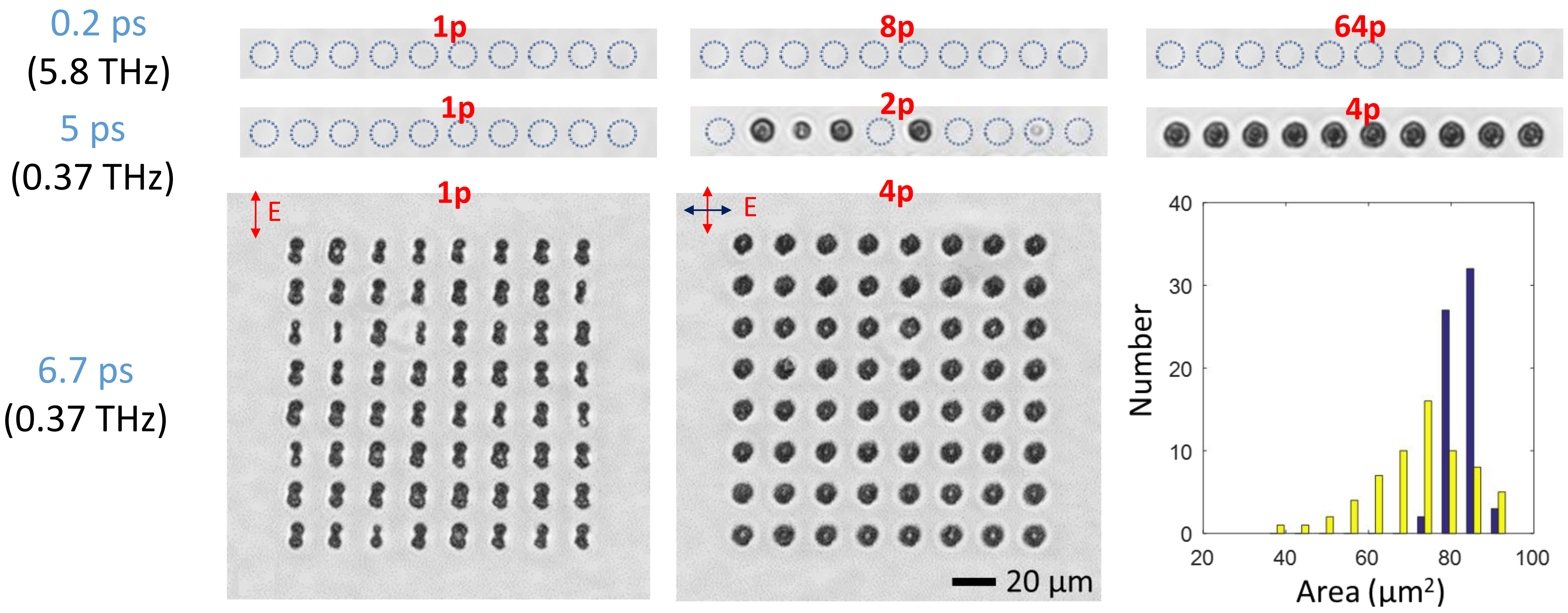

$\lambda$=1550nm
$\tau_{pulse}$=200fs
5.8 THz r.r.

Improved conditions (+60%) in Si for burst irradiation

.... optimum **with ≈ 8-16 pulses but still below bulk damage threshold**

Ultrafast Laser Writing Deep Inside Silicon with THz-repetition-rate Trains of Pulses, **Research** 2020 (2020) 8149764, https://doi.org/10.34133/2020/8149764

# Burst-induced modifications deep inside Si




'Accumulation' burst strategy is **beneficial for crossing threshold and/or stabilize writing**

Ultrafast Laser Writing Deep Inside Silicon with THz-repetition-rate Trains of Pulses, **Research** 2020 (2020) 8149764, https://doi.org/10.34133/2020/8149764

# Outline – Ultrafast Laser Writing Deep inside Silicon

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*1. A challenging problem*

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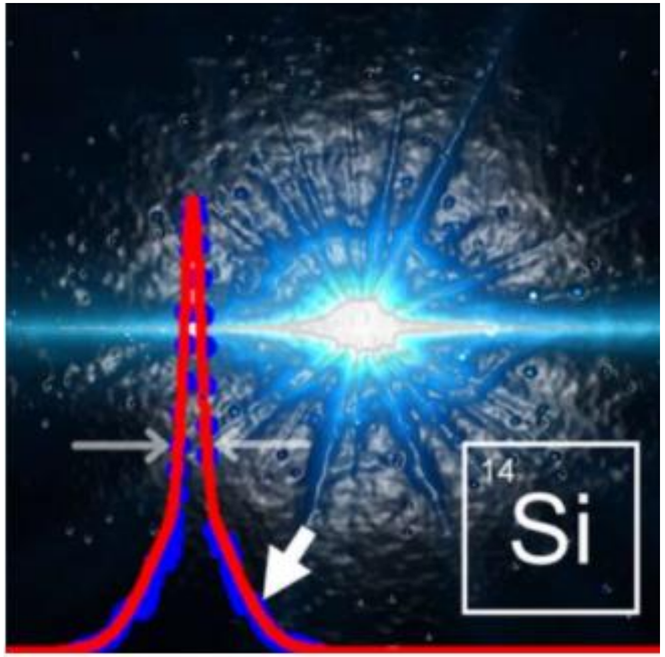
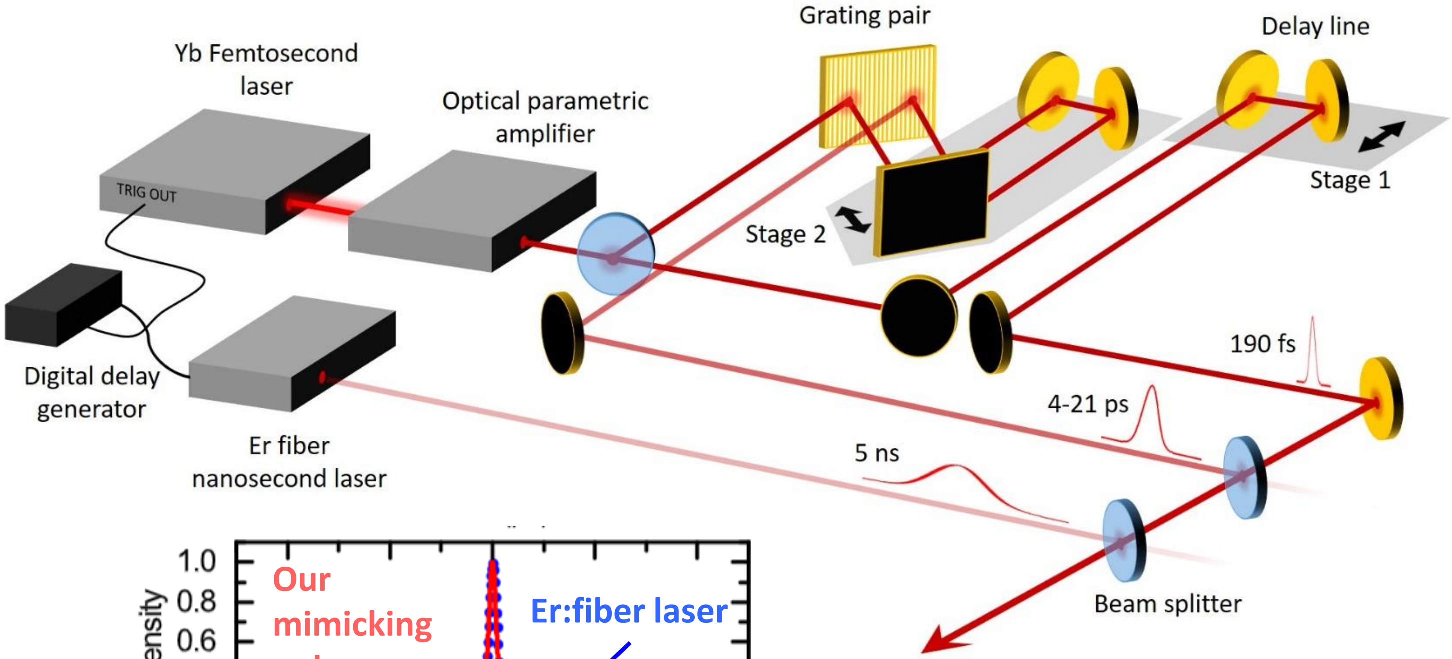
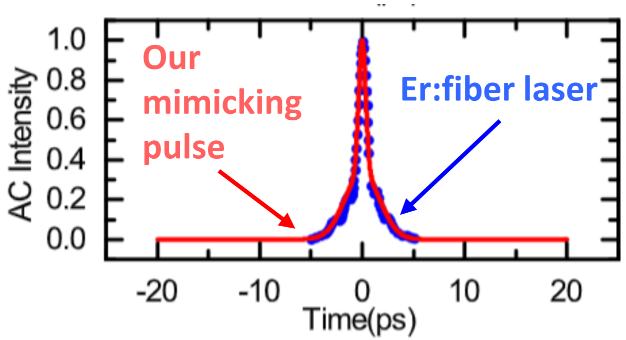
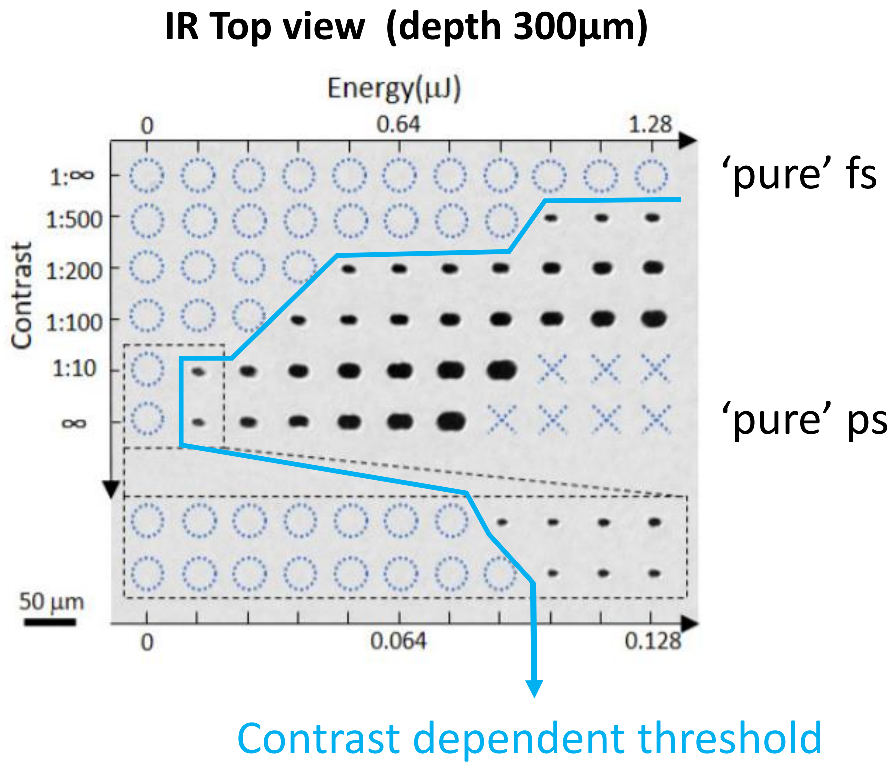


# Multi-time scale control of the temporal contrast




NA=0.85
1550nm

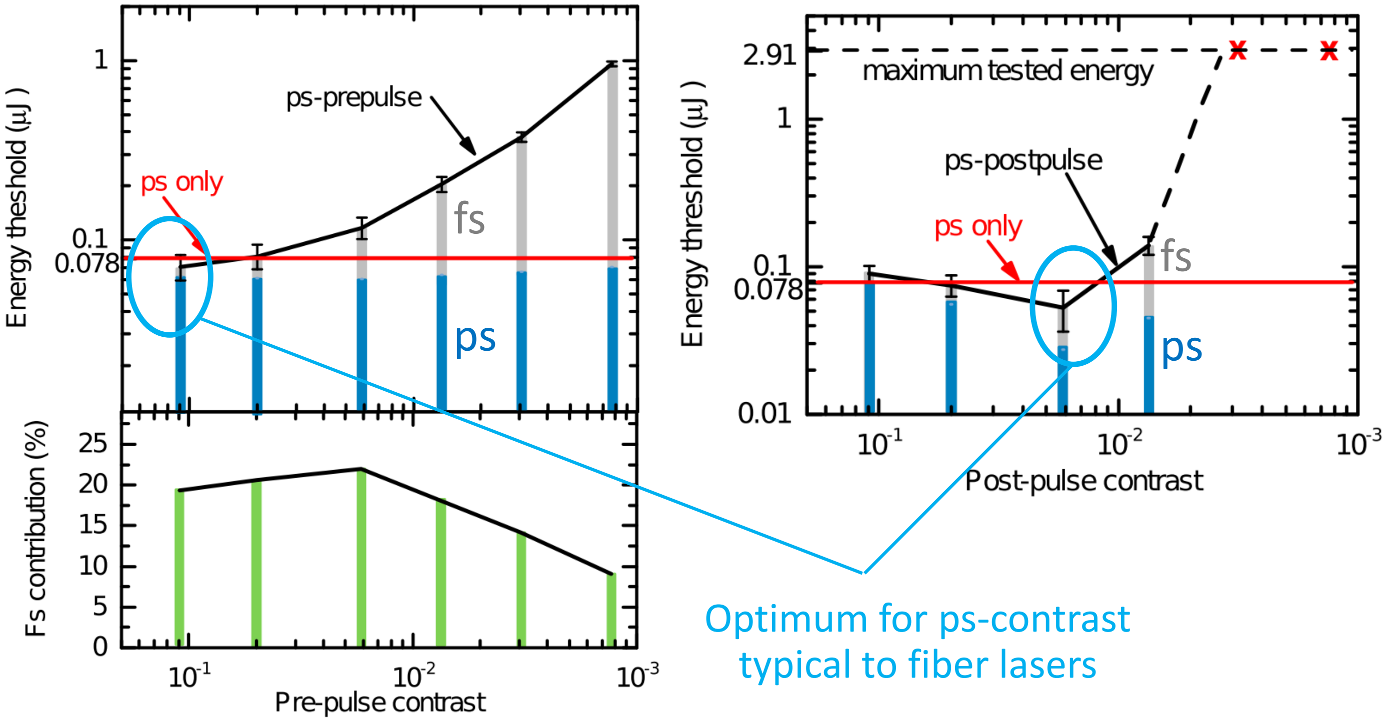



Imperfect contrast (e.g. fiber lasers) leading to **modifications inaccessible with highly contrasted pulses (eg. OPA)**

Temporal Contrast Imperfections as Drivers for Ultrafast Laser Modifications in Bulk Silicon, **Physical Review Research** 2 (2020) 033023

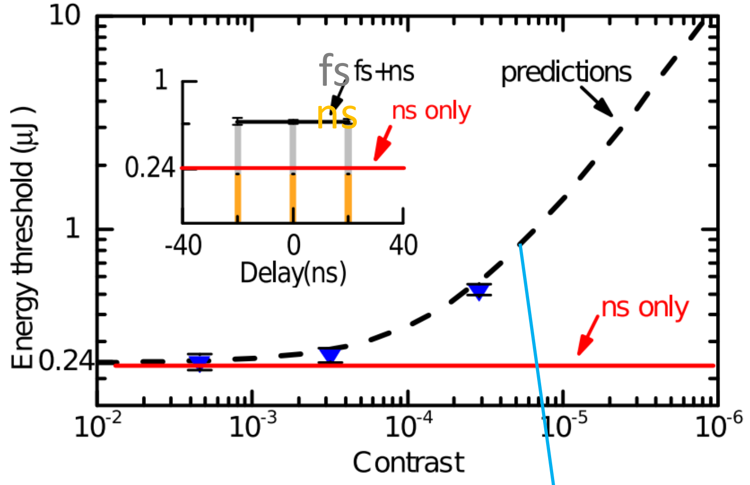
# Multiscale temporal contrast study

## Picosecond contrast (190 fs **+ 11ps, delay ±20ps**)




Optimum for ps-contrast typical to fiber lasers

## ns contrast (190 fs **+ 5ns**)




Pure ns modification in all cases indicating typical ns ASE in fs lasers can always induce modification… without any ultrafast contribution

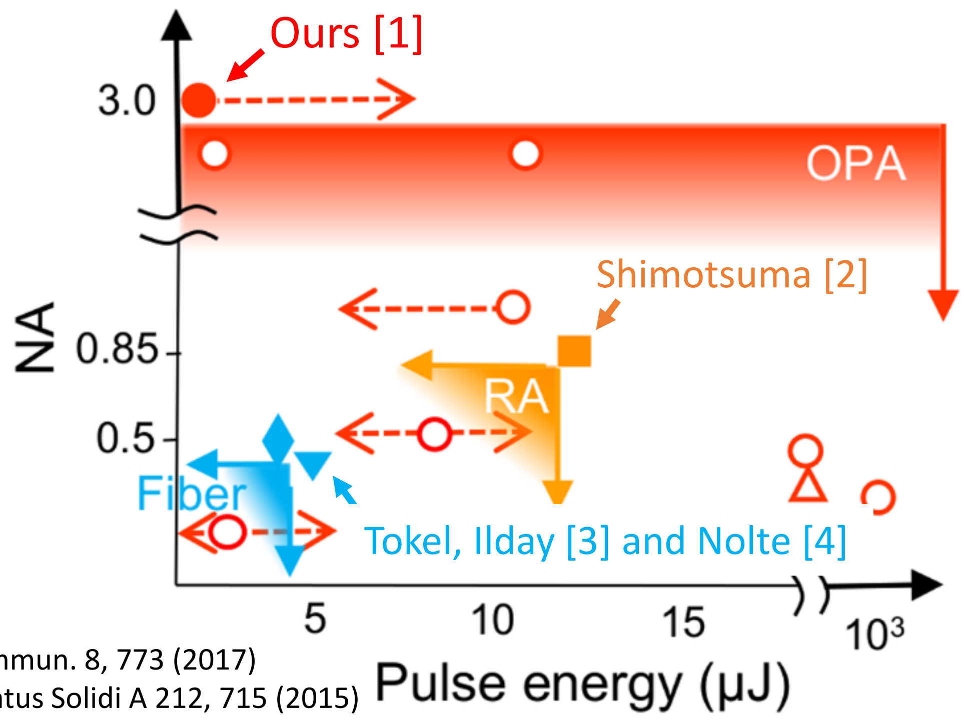
**An unusually high sensitivity to the temporal contrast**

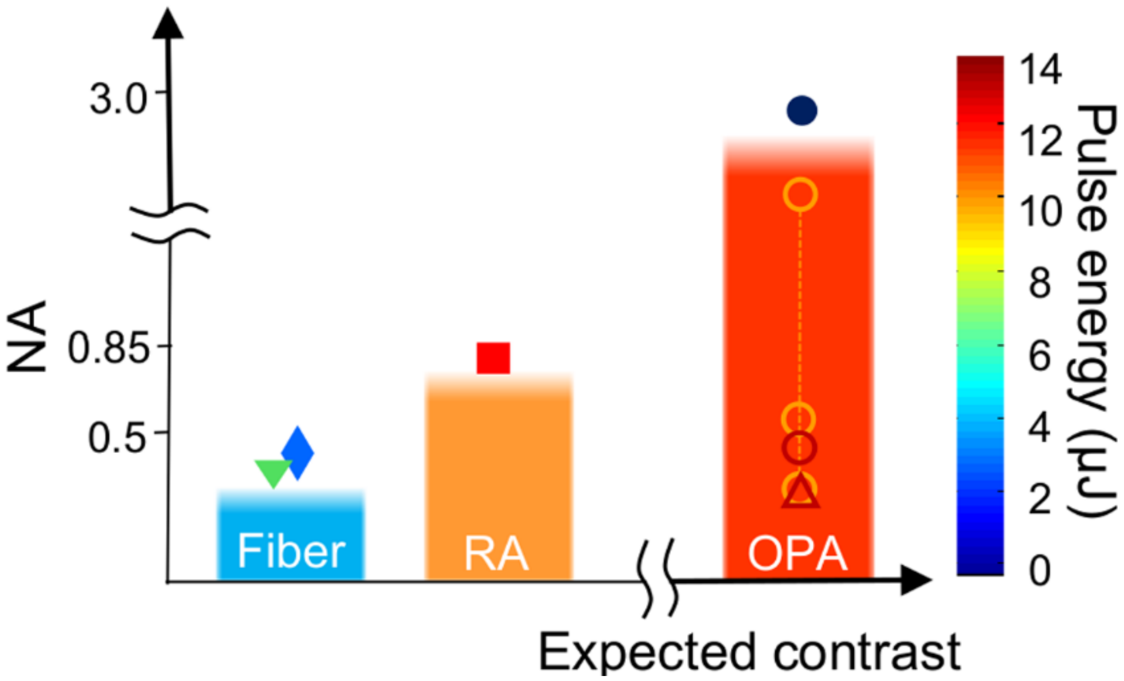
… leading to a laser technology dependent problem ?

Temporal Contrast Imperfections as Drivers for Ultrafast Laser Modifications in Bulk Silicon, **Physical Review Research** 2 (2020) 033023

# Solving contradictions between previous work

**Si Bulk Modifications attempts (sub-ps)**
Solid symbol: Successful ☺
Empty symbols: Unsuccessful ☹





[1] Nat. Commun. 8, 773 (2017)
[2] Phys. Status Solidi A 212, 715 (2015)
[3] Appl. Phys. A-Mater. 124, 302 (2018)
[4] Opt. Lett. 42, 3028 (2017)


A laser-technology dependent problem: **contrast imperfections are drivers for modifications**

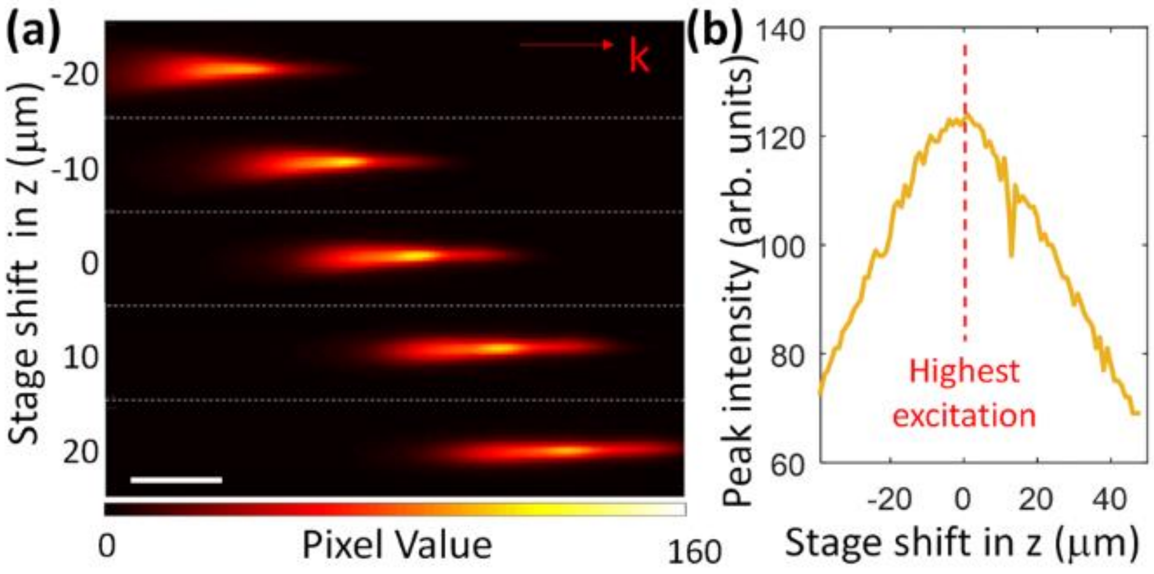
… inspiring new developments based on temporal shaping for reliable 3D writing in Si

Temporal Contrast Imperfections as Drivers for Ultrafast Laser Modifications in Bulk Silicon, **Physical Review Research** 2 (2020) 033023
In-volume laser direct writing of silicon – Challenges and Opportunities, **Laser and Photonics Reviews** (2021) 2100140

# Today’s performance with multi-time scale control

Image removed

***Real time monitoring of ionization by luminescence***




… Quantitative plasma characterization in bulk semiconductors,
**Applied Physics Letters 119** (2021) 041108

**Improved resolution and controlability** (incl. progressivity and erasure)

….using pre-ionization pulses and giving new perspectives !

Patent Application EP21184898.1 (2021)

# Acknowledgements…

LP3

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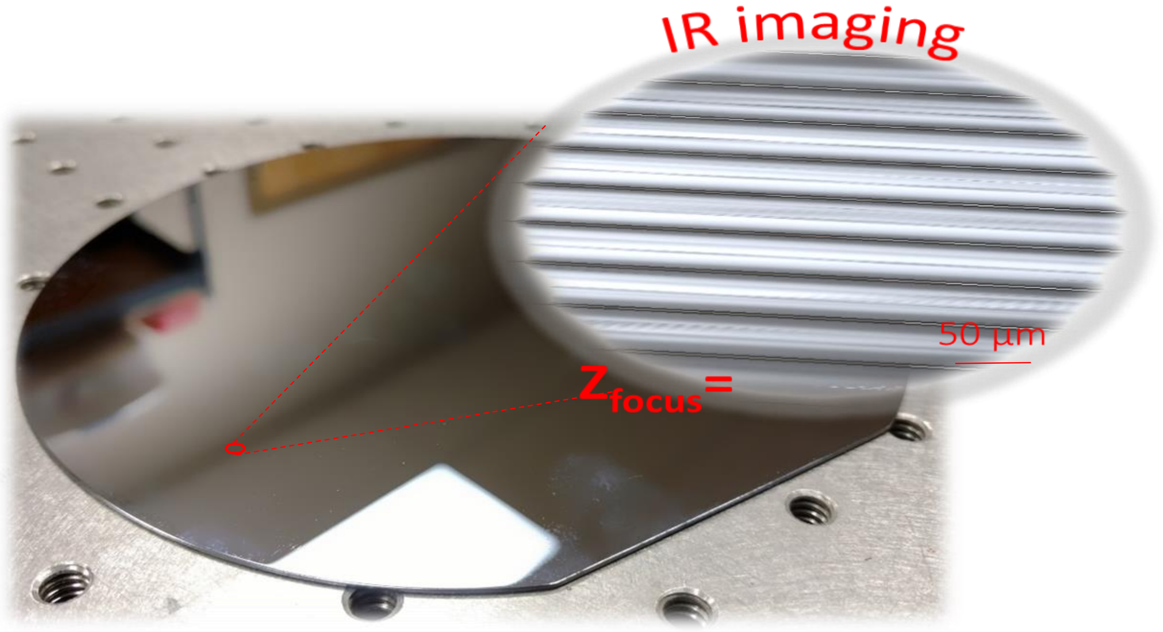
Pol Martinez Sopena
Haoqing Ning
Qingfeng Li (MSc, Europhotonics)
Sambit Mitra (MSc, KIT Germany)
Raphaël Clady
Philippe Delaporte
Marc Sentis
Nicolas Sanner
Olivier Utéza
Jörg Hermann

Int'l Associated Laboratory
MINOS LAB

FORTH Institute of Electronic Structure and Laser
Stelios Tzortzakis
Vladimir Fedorov




This research has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 724480)