Femtoscopy for the NAPLIFE nano-fusion project?

52nd International Symposium
on Multiparticle Dynamics,
Aug. 24, 2023, Gyöngyös, Hungary

Laszlo P. Csernai, for the
NAPLIFE Collaboration
Univ. of Bergen, Norway

How to remedy the problems of present Laser Fusion trials of NIF@Livermore & OMEGA@Rochester

Two ideas are combined by L.P. Csernai, N. Kroo, I. Papp:

[Patent # P1700278/3] (2017)

Problems:

- Rayleigh-Taylor instability
- Slow propagation of burning from central hot-spot

Solution:

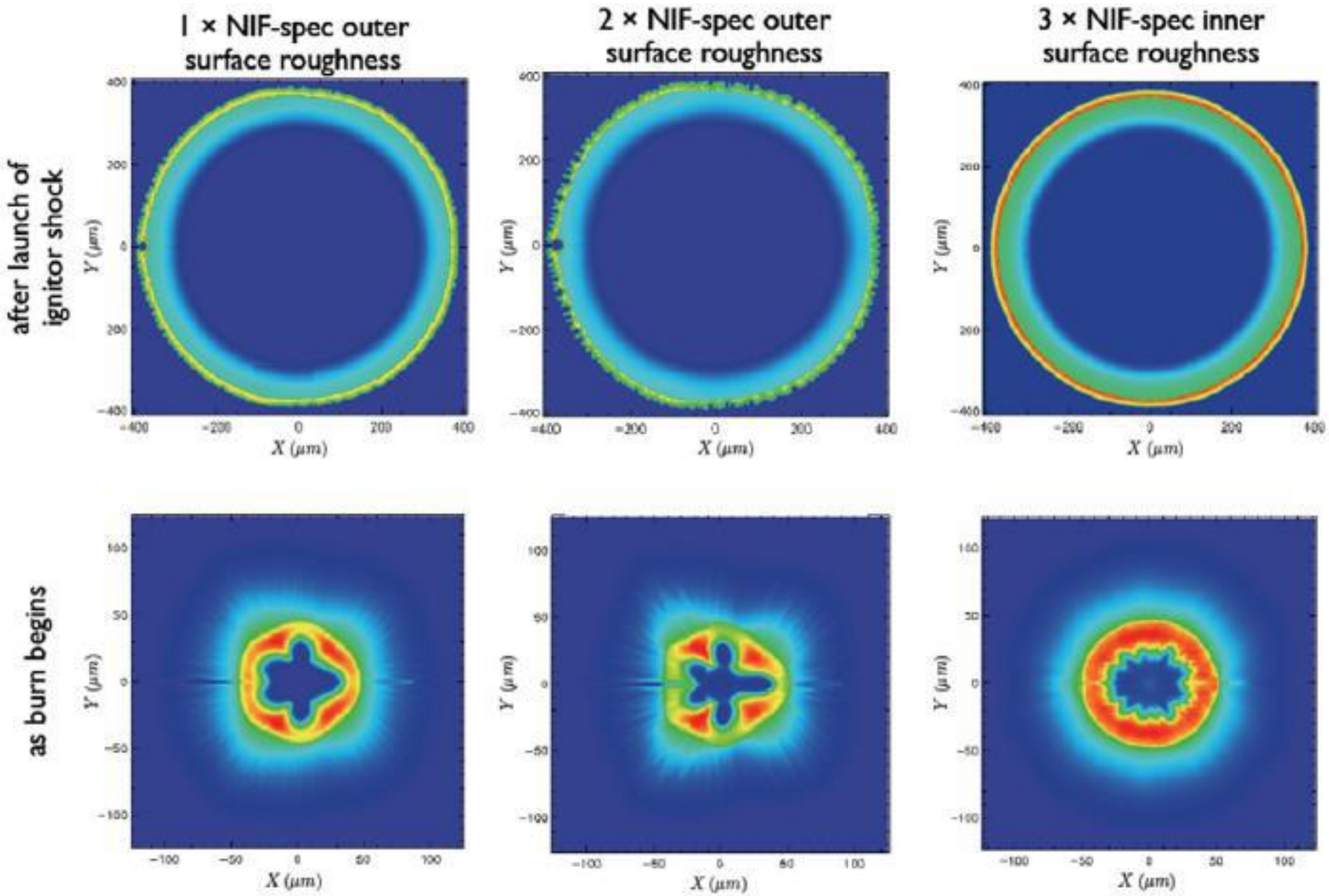
- **Heat the system uniformly by radiation with RFD (1)**
- **Achieve uniform heating by Nano-Technology (2)**

[L.P. Csernai, N. Kroo, I. Papp, ***Laser and Particle Beams,*** **LPB, 36(2), (2018) 171-178.** .
https://doi.org/10.1017/S0263034618000149]

But let us go back in history ➔

Rayleigh-Taylor Instability

NIF – RT instability

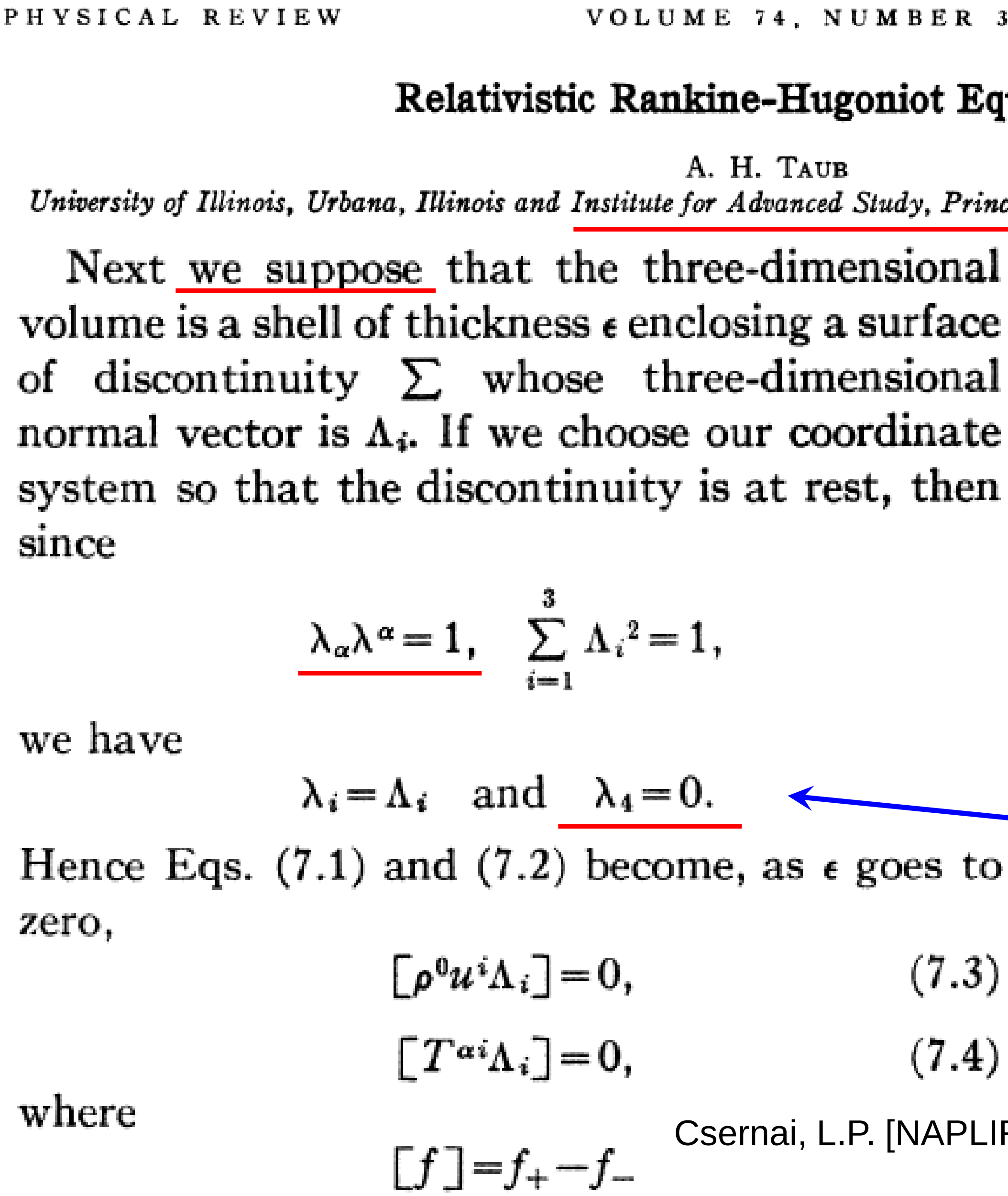


The target is compressed to density ~ 700 g/cm^3.

But, although an ablator layer is used, only ~ **10%-of the target** is ignited. Elsewhere the surface protruded as “potato from the potato press”: **RT- instability.**

How can we prevent it
Idea - #1

[A.H. Taub (1948)]



PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

Relativistic Rankine-Hugoniot Equations

A. H. TAUB

*University of Illinois, Urbana, Illinois and Institute for Advanced Study, Princeton University, Princeton, New Jersey**

Next we suppose that the three-dimensional volume is a shell of thickness ϵ enclosing a surface of discontinuity Σ whose three-dimensional normal vector is Λ_i. If we choose our coordinate system so that the discontinuity is at rest, then since

$$\lambda_\alpha\lambda^\alpha = 1, \quad \sum_{i=1}^{3} \Lambda_i^2 = 1,$$

we have

$$\lambda_i = \Lambda_i \quad \text{and} \quad \lambda_4 = 0.$$

Hence Eqs. (7.1) and (7.2) become, as ϵ goes to zero,

$$[\rho^0 u^i \Lambda_i] = 0, \tag{7.3}$$

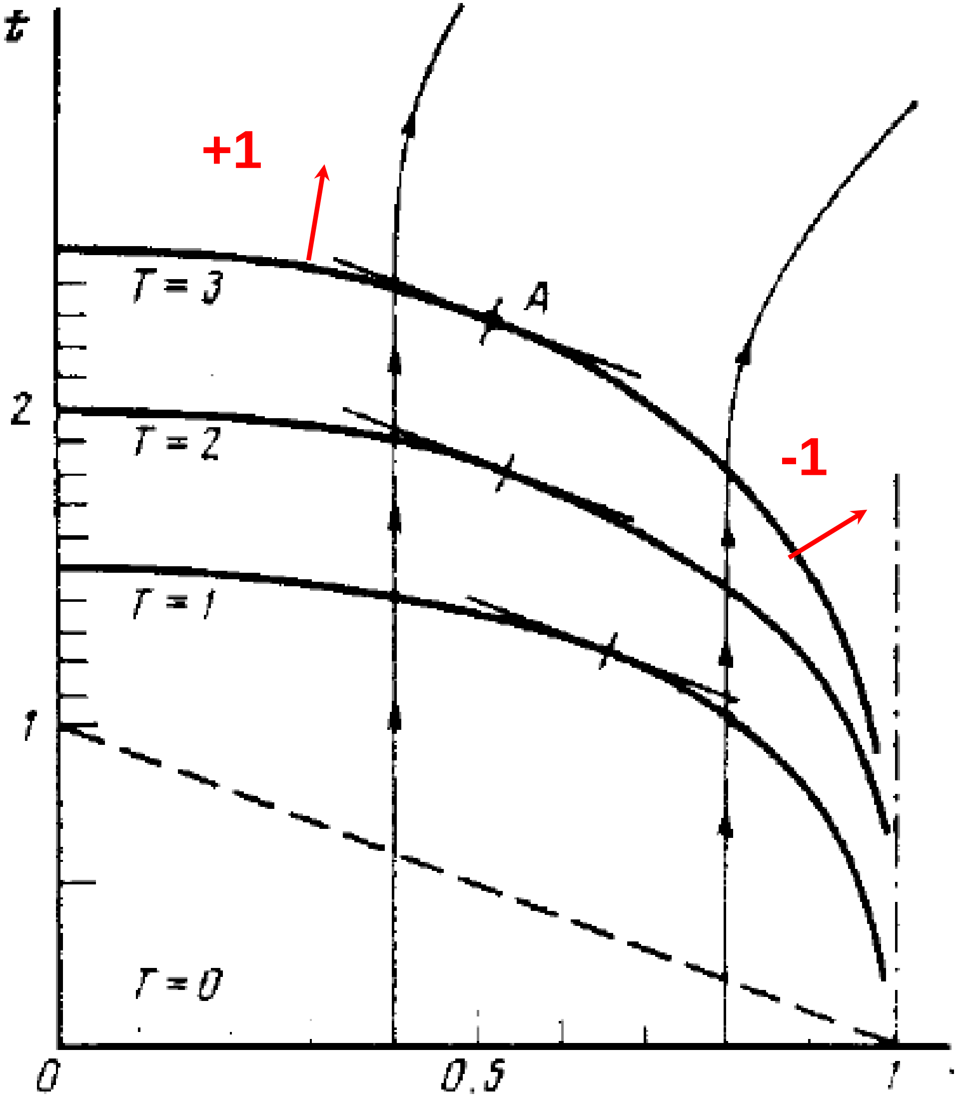
$$[T^{\alpha i}\Lambda_i] = 0, \tag{7.4}$$

where

$$[f] = f_+ - f_-$$

Taub assumed that (physically) only slow space-like shocks or discontinuities may occur (with space-like normal, λ_4=0).

This was then taken as standard, since then (e.g. LL 1954-)



[L. P. Csernai, Zh. Eksp. Teor. Fiz. 92, 379-386 (**1987**) & Sov. Phys. JETP 65, 216-220 (1987)]

corrected the work of [**A. Taub**, Phys. Rev. 74, 328 (**1948**)]

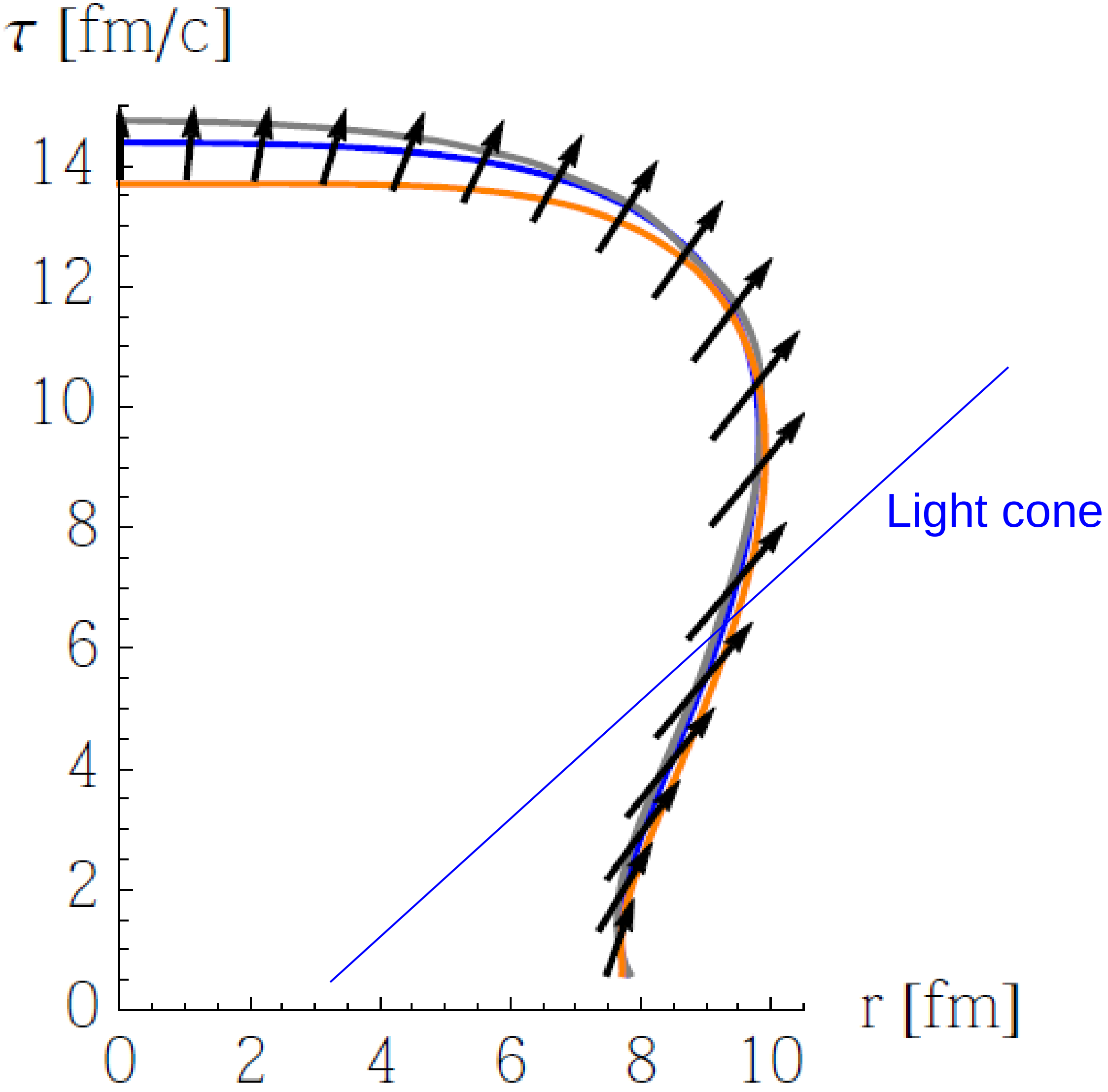
$$\lambda_\alpha \lambda^\alpha = \pm 1$$

Л. П. Чернаи

ДЕТОНАЦИЯ НА ВРЕМЕНИПОДОБНОМ ФРОНТЕ ДЛЯ РЕЛЯТИВИСТСКИХ СИСТЕМ

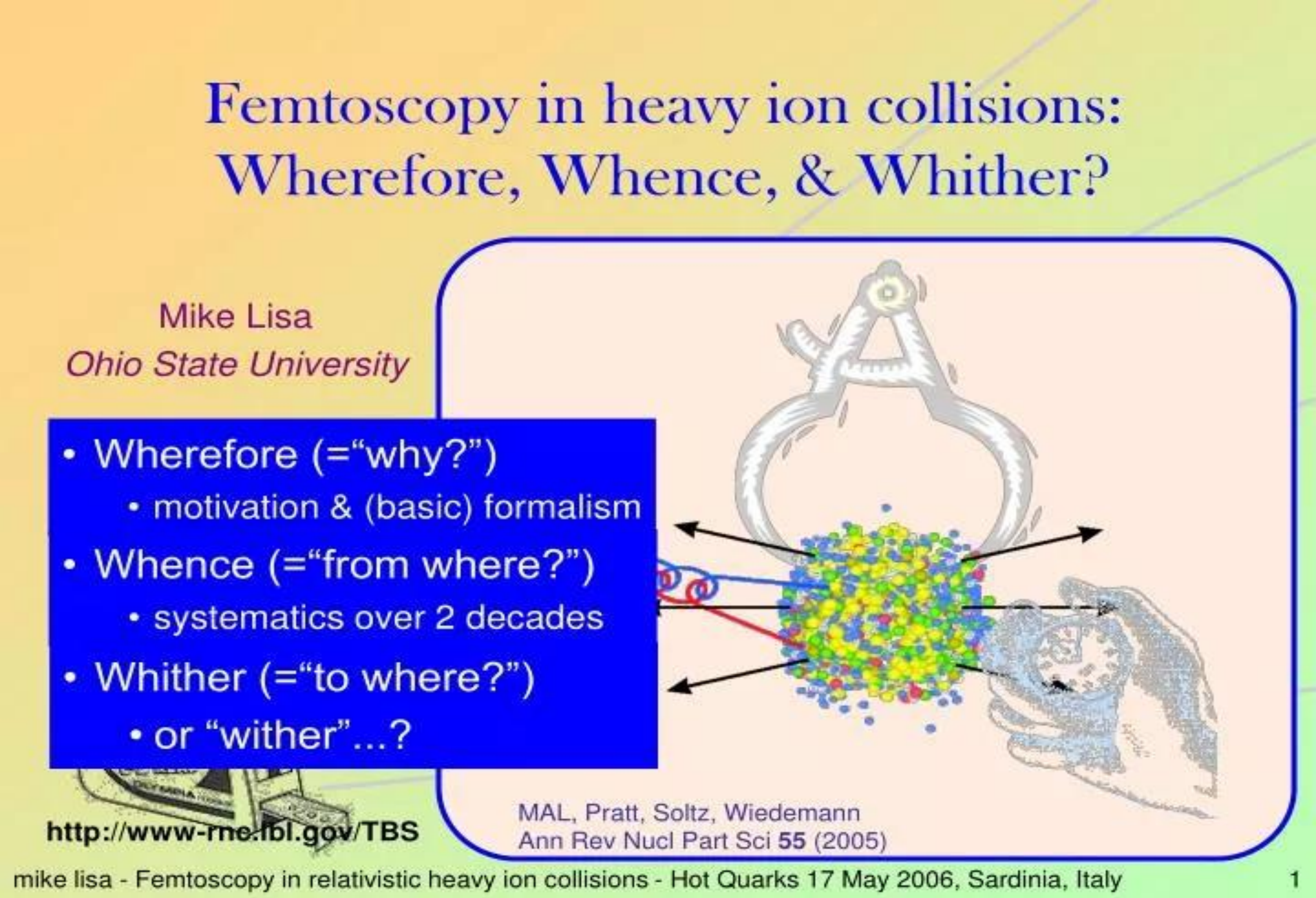
Журнал экспериментальной и теоретической физики

1987



@ CERN in High energy heavy ion collisions

[Stefan Floerchinger, and Urs Achim Wiedemann, Phys. Rev. C 89, 034914 (2014)]



Femtoscopy in heavy ion collisions: Wherefore, Whence, & Whither?

Mike Lisa

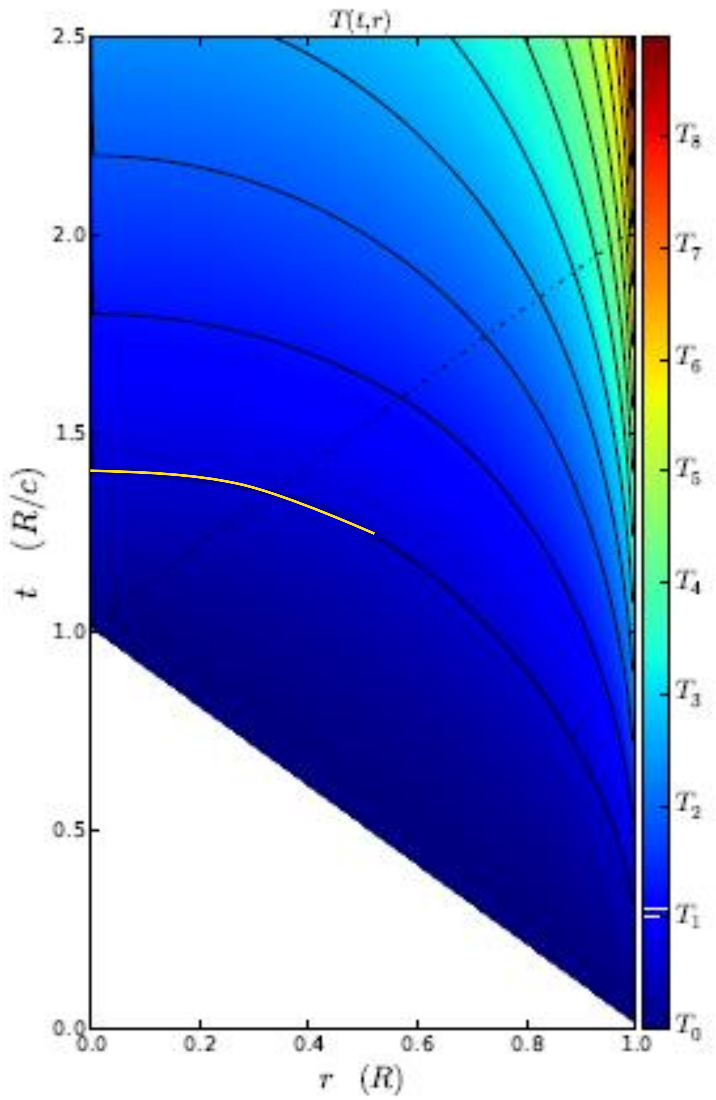
Ohio State University

- Wherefore (="why?")
  - motivation & (basic) formalism
- Whence (="from where?")
  - systematics over 2 decades
- Whither (="to where?")
  - or "wither"...?

http://www-rnc.lbl.gov/TBS

MAL, Pratt, Soltz, Wiedemann
Ann Rev Nucl Part Sci **55** (2005)

mike lisa - Femtoscopy in relativistic heavy ion collisions - Hot Quarks 17 May 2006, Sardinia, Italy 1



[L.P. Csernai & D.D. Strottman,
Laser and Particle Beams 33, 279 (2015).]

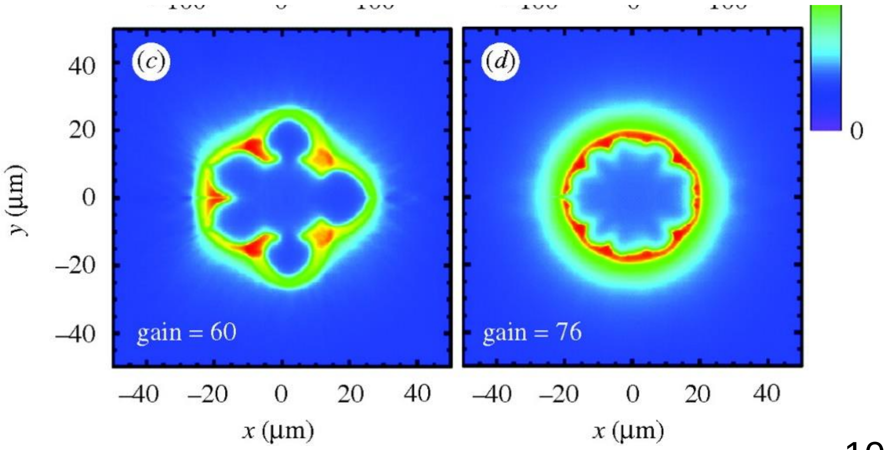
Fusion reaction:

D + T ➔ n(14.1 MeV) + 4He (3.5 MeV)

Constant absorptivity,
Spherical irradiation
Ignition temperature = T1 ➔

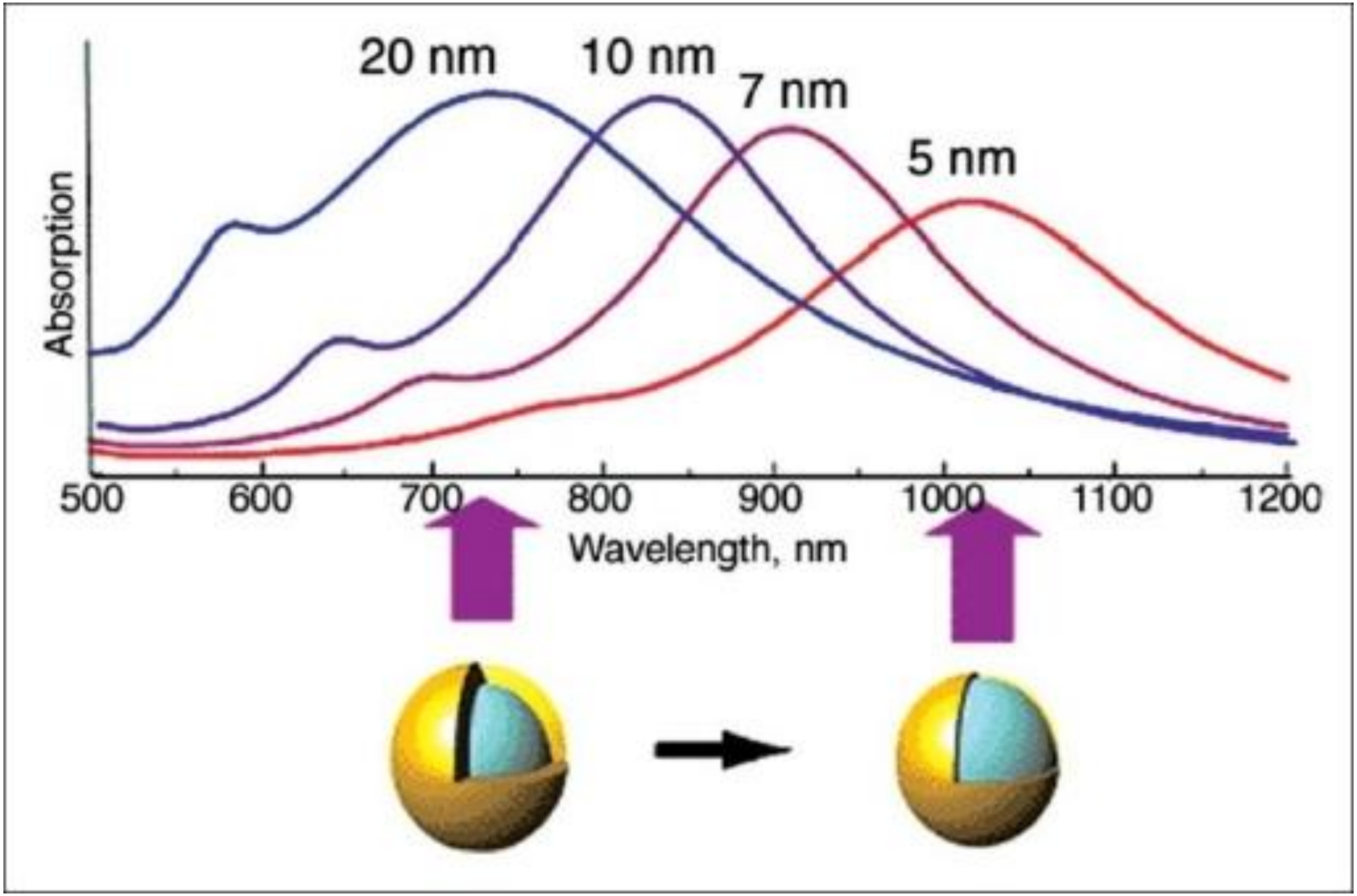
Simultaneous, volume ignition up to 0.5 R (i.e. **12%** of the volume).

Not too good, but better than:



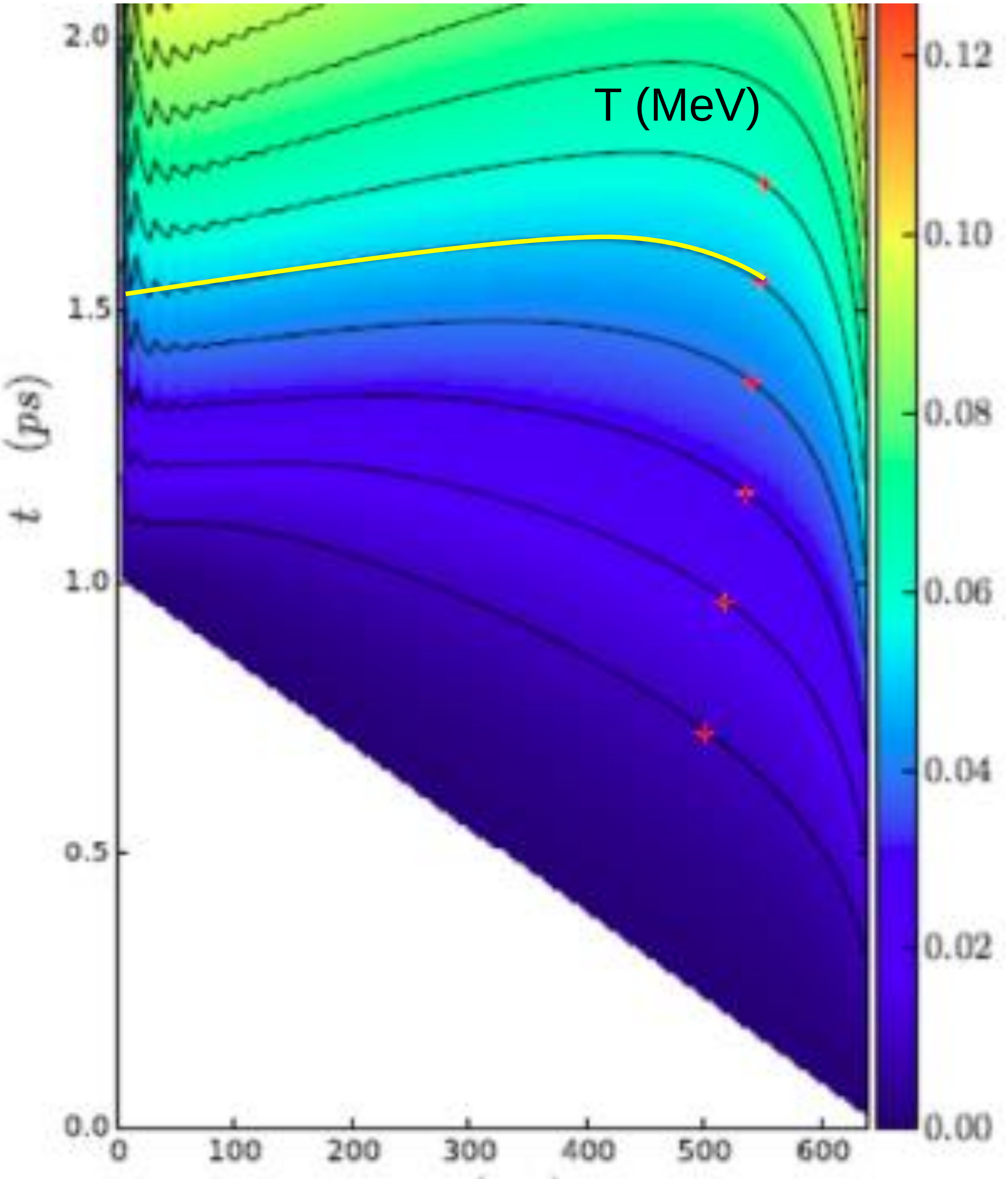
How can we realize it
Idea - #2

Golden Nano-Shells – Resonant Light Absorption



Csernai, L.P. [NAPLIFE]

L.P. Csernai, N. Kroo, I. Papp [Patent # P1700278/3]
Laser &Particle Beams , 36(2), (2018) 171-178.



Csernai, L.P. [NAPLIFE]

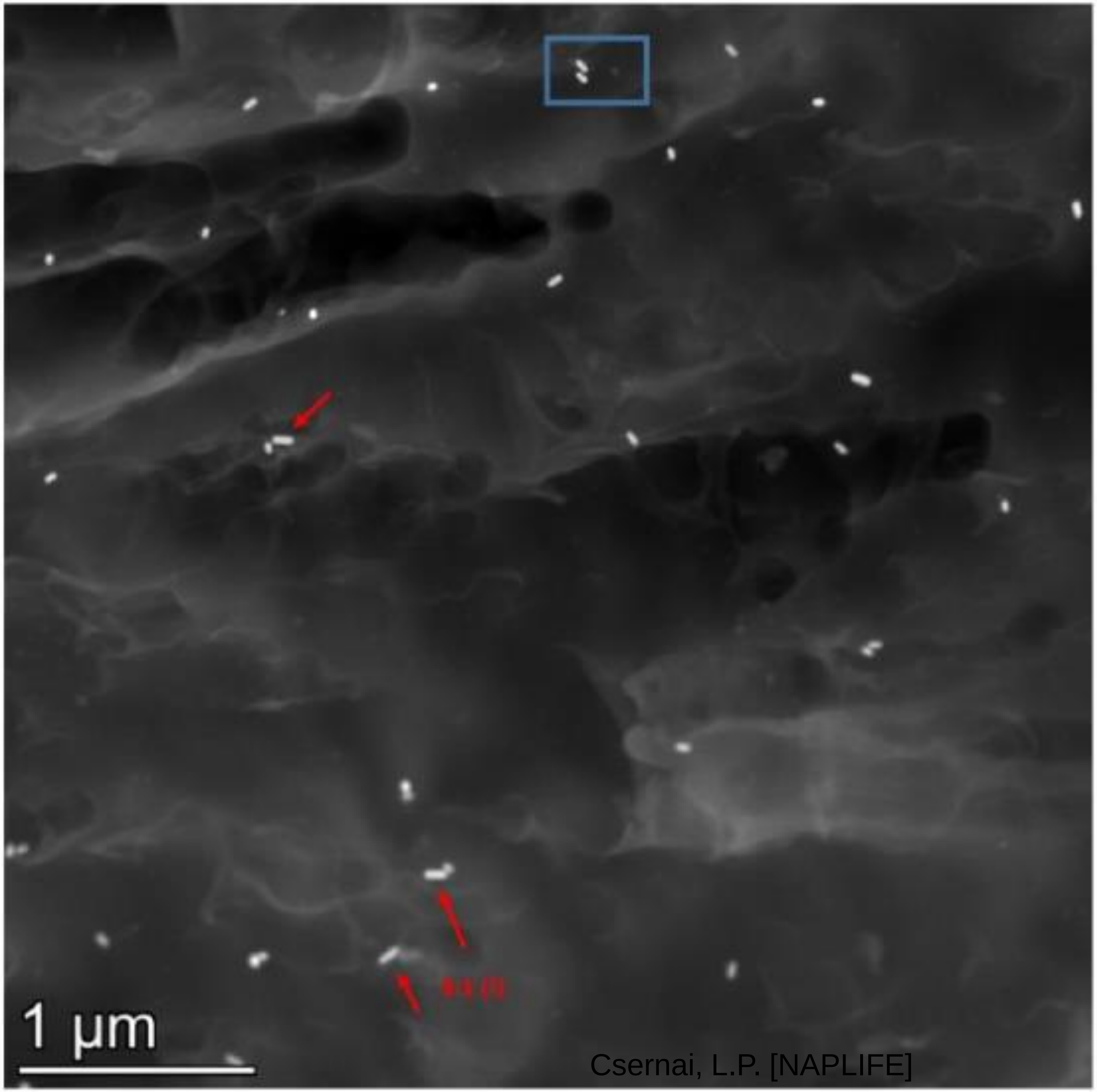
The absorption coefficient is **linearly** changing with the radius: In the center,

r = 0, $\alpha_K = 30\ \mathrm{cm}^{-1}$ while at the outside

edge $\alpha_K = 8\ \mathrm{cm}^{-1}$.

The temperature is measured in units of $T_1 = 272$ keV, and $T_n = n\, T_1$.

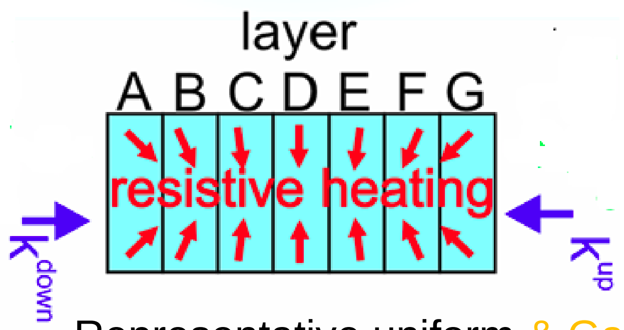
Simultaneous, volume ignition is up to 0.9 R, so **73% of the fuel target!**



TEM Photo of ~uniformly implanted 85x25 nm nanorod antennas in UDMA target polymer. The density is 9-20 / µm^3

[Judit Kámán, A. Bonyár et al. (NAPLIFE Collab.)., Gold nanorods …, 10th ICNFP 2021, K**olymbari**, Crete, Greece, 30 August 2021.**]**

Layered target with variable light absorption

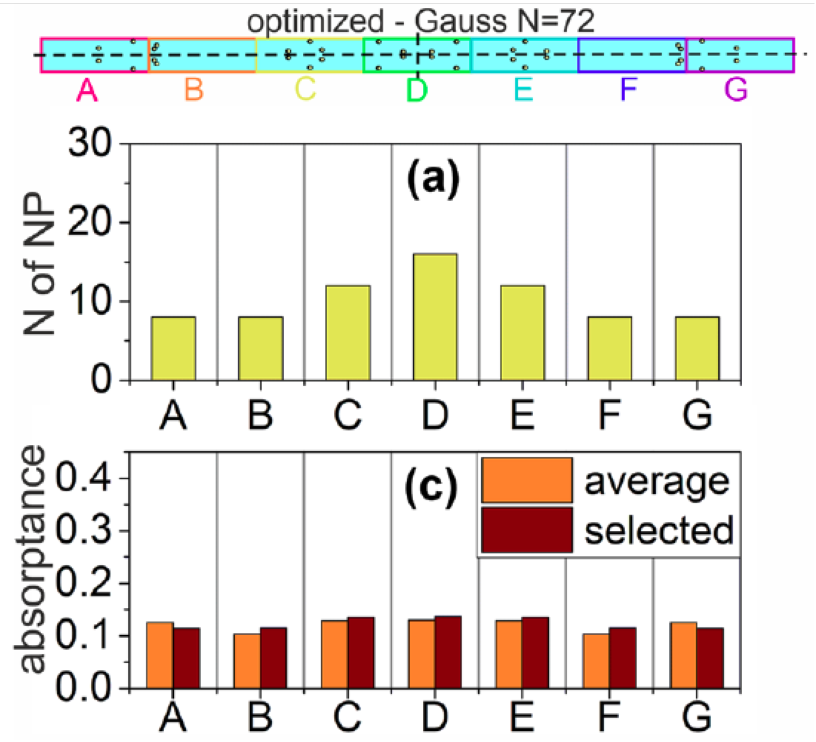


Representative uniform & Gaussian number density distributions of (d) 70 oriented nanorods, in a 1 × 1 × 21 µm3 supercell of UDMA polymer target, with random location distribution.

Plasmonics (2022) 17:775–787
https://doi.org/10.1007/s11468-021-01571-x

Comparative Study on the Uniform Energy Deposition Achievable via Optimized Plasmonic Nanoresonator Distributions

Mária Csete[1] · András Szenes[1] · Emese Tóth[1] · Dávid Vass[1] · Olivér Fekete[1] · Balázs Bánhelyi[2] · István Papp[3,4] · Tamás Bíró[3] · László P. Csernai[3,4,5] · Norbert Kroó[3,6]



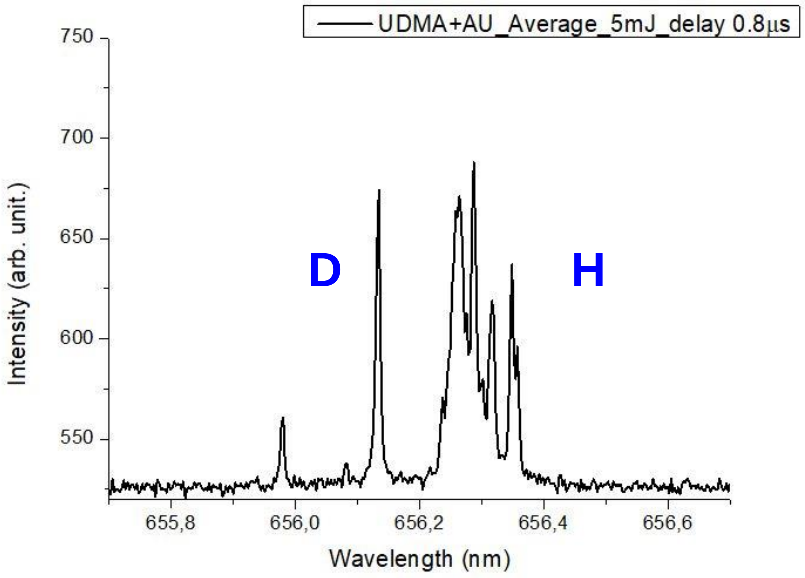
[M. Csete, A. Szenes, E. Tóth, D. Vass, O. Fekete, B. Bánhelyi, T. S. Bíró, L. P. Csernai, N. Kroó: *„Comparative study on the uniform energy deposition achievable via optimized plasmonic nanoresonator distributions“*, Plasmonics (2022), 17: 775-787; https://doi.org/10.1007/s11468-021-01571-x.]

Validation tests ➔

Laser Induced Fusion with Nanoantennas

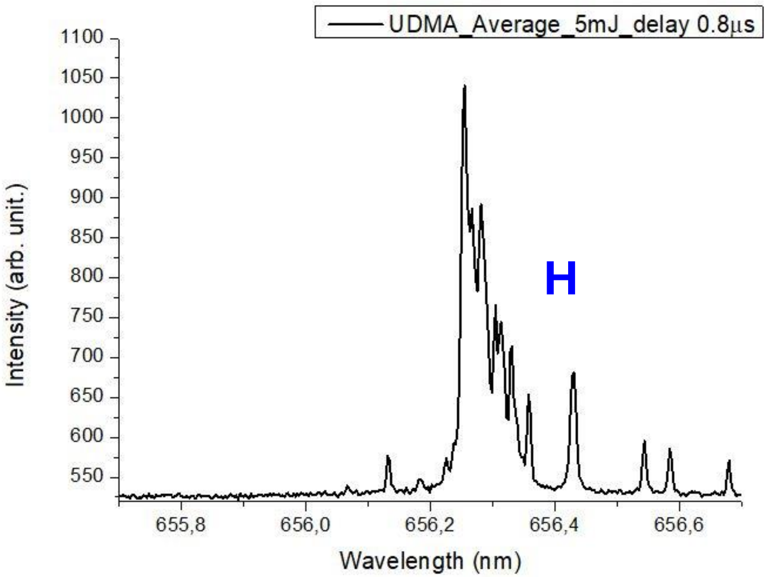
Deuterium production (PRELIMINARY !)

(N.K.*)



5-12% **D + 88-95% H**

~ **10^{17} D** / pulse (10Hz)



100% **H**

Balmer-α line

Two step process (average of 20 shots):

p + e* → n + ν \ electron capture (-1.24 MeV)

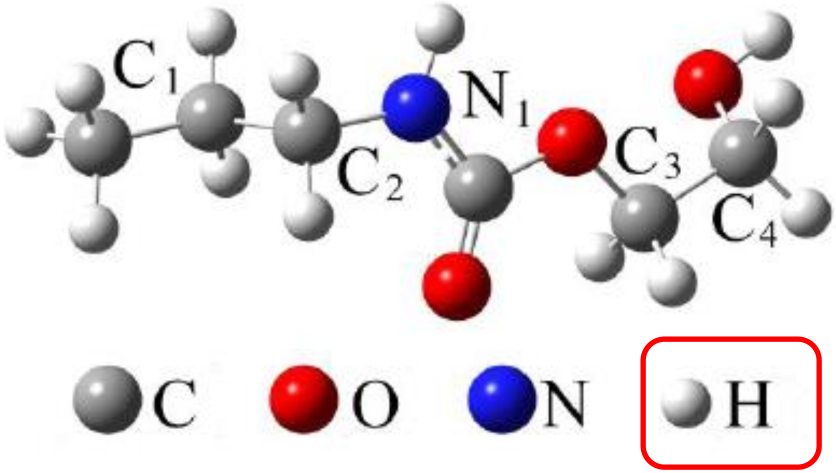
n + p → d + γ \ neutron capture (+2.22 MeV)

Electron capture may happen spontaneously in heavy nuclei,

here laser light and resonant nanorods act similarly, high e density

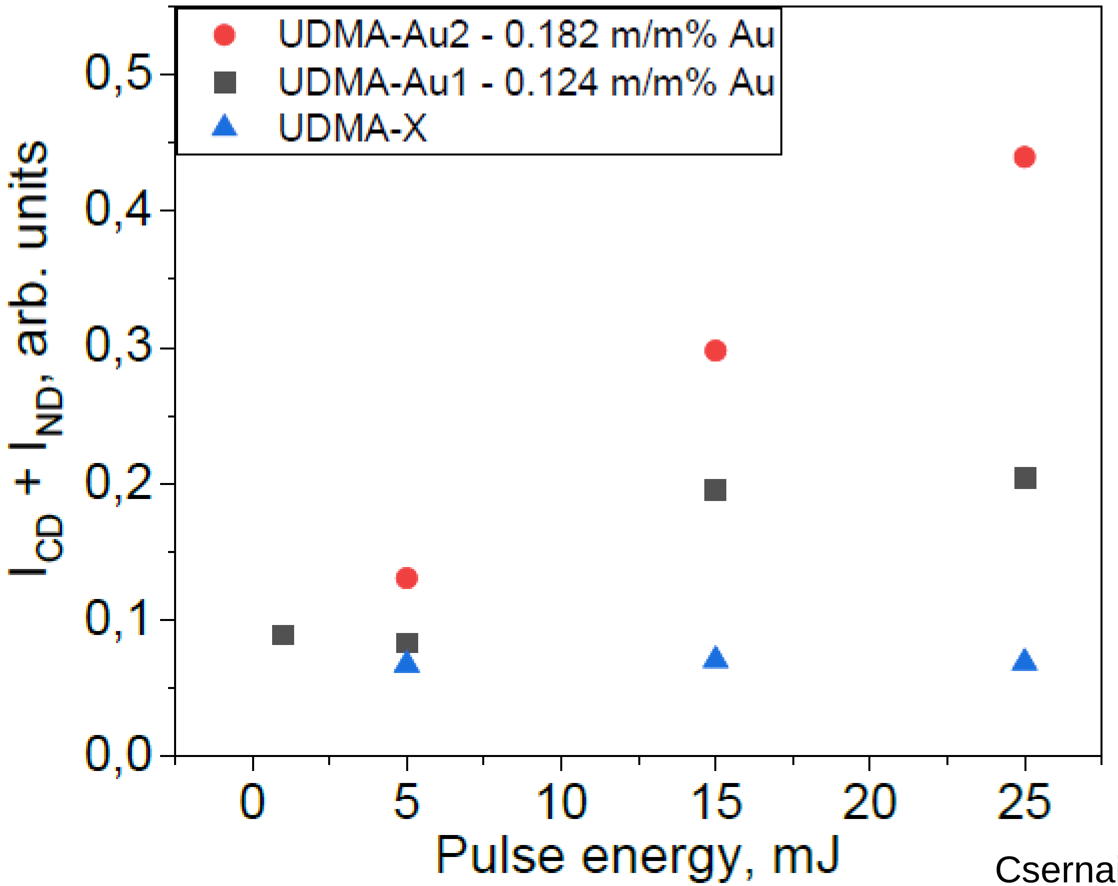
UDMA (470: H38, C23, O8, N2)

[P. Rácz, A. Kumar et al. 2021 ICNFP, Kolymbari]



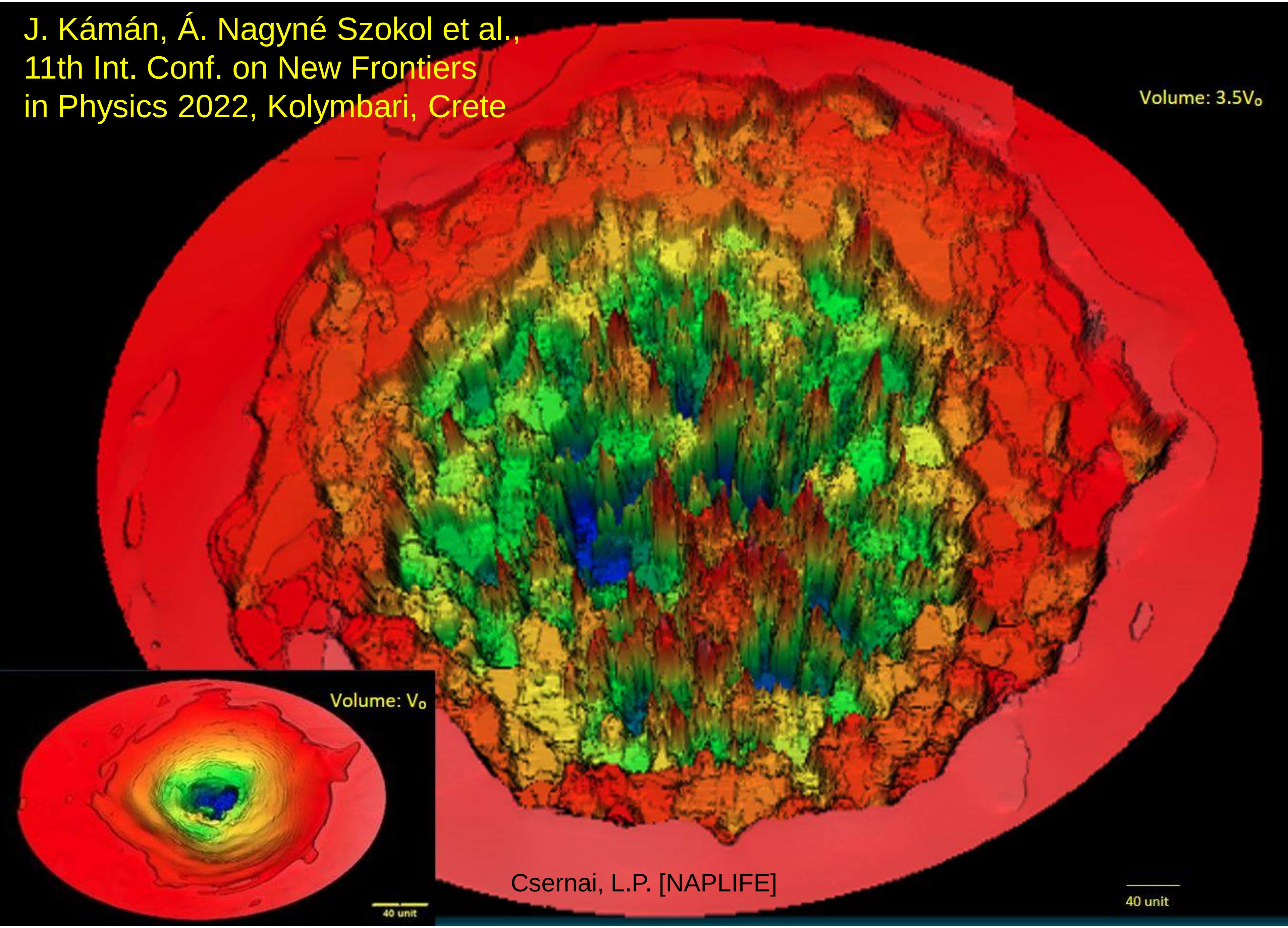
[I. Rigo et al., arXiv 2022]

With Nanorods (Au2)
at 25 mJ laser pulse
~4 times increased D
production, compared
to 1 mJ pulse



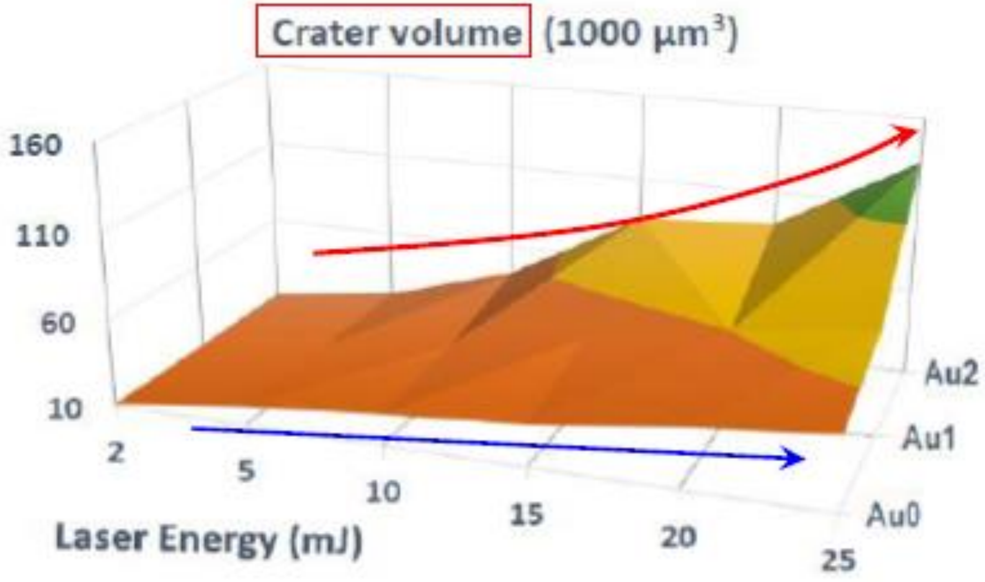
Csernai, L.P. [NAPLIFE]

J. Kámán, Á. Nagyné Szokol et al.,
11th Int. Conf. on New Frontiers
in Physics 2022, Kolymbari, Crete



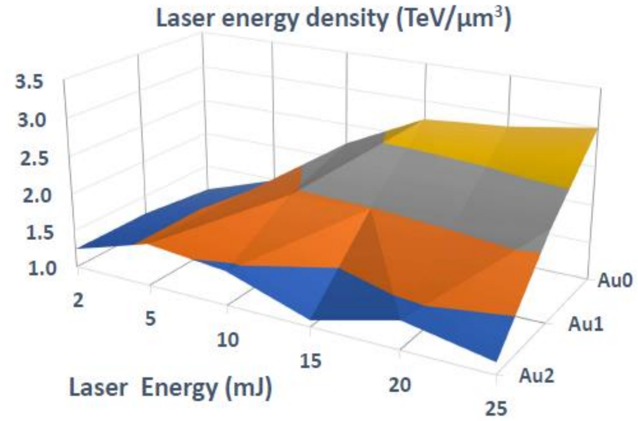
Csernai, L.P. [NAPLIFE]

Theoretical analyzis of Crater & Deuterium production



Crater Formation and Deuterium Production in
Laser Irradiation of Polymers with Implanted Nano-antennas

László P. Csernai[1,2,3], Igor N. Mishustin[3], Leonid M. Satarov[3], Horst Stöcker[3,7,8], Larissa Bravina[4], Mária Csete[5,6], Judit Kámán[1,5], Archana Kumari[1,5], Anton Motornenko[3], István Papp[1,5], Péter Rácz[1,5], Daniel D. Strottman[9], András Szenes[5,6], Ágnes Szokol[1,5], Dávid Vass[5,6], Miklós Veres[1,5], Tamás S. Biró[1,5], Norbert Kroó[1,5,10]
(NAPLIFE Collaboration)



Puzzle ?

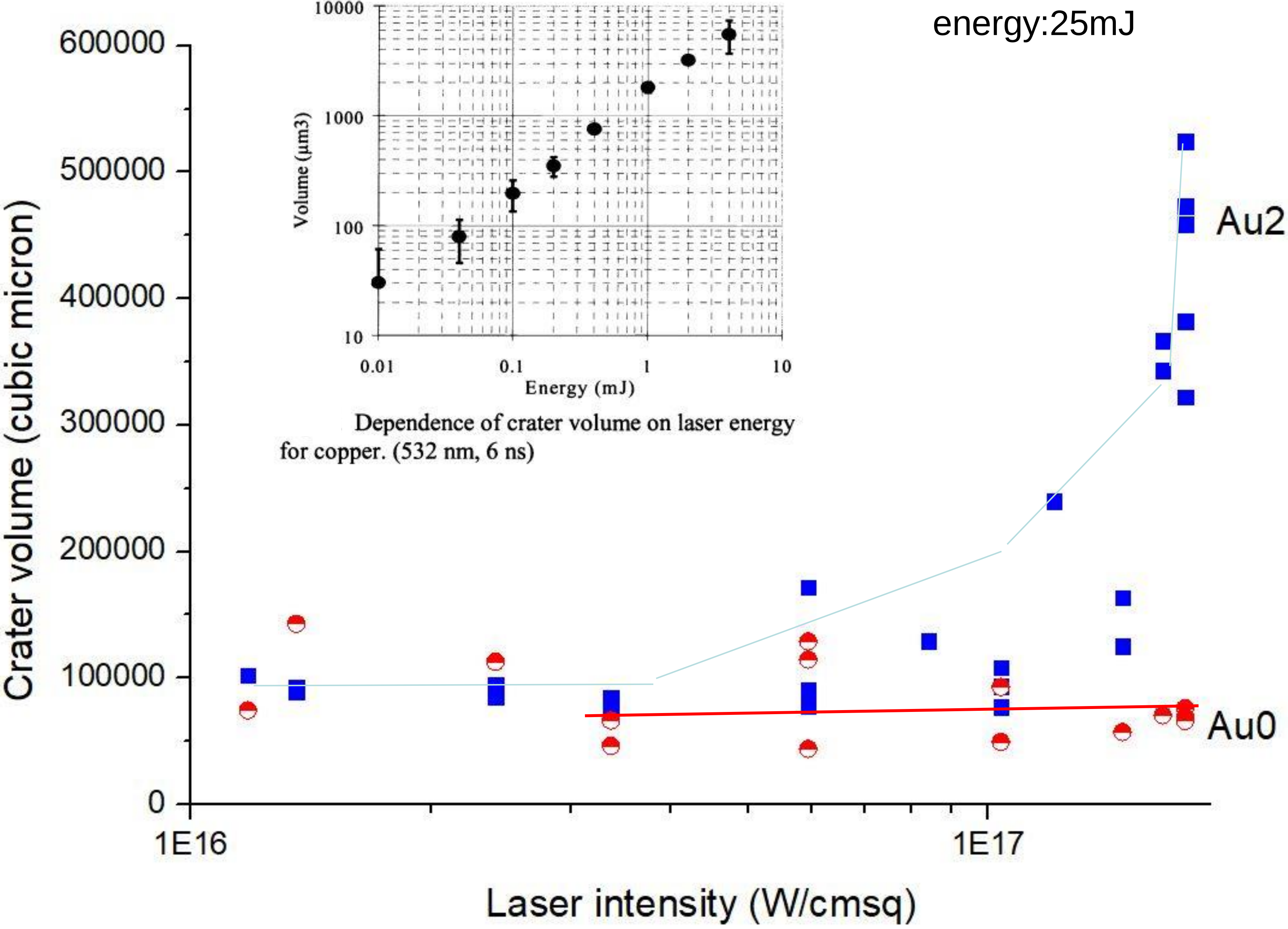
With nanorods V grows non-linearly. Increasing energy deposition. Several types of targets are considered: Au1 and Au2 with implanted nano-rod antennas, and Au0 without implantation. The mass concentrations of implanted particles in UDMA are 0.126% and 0.182% for targets Au1 and Au2, respectively.

With nanorods, Au2, deposited energy into the crater increases non-linearly (!?)

Origin of this extra energy (?)

[LP. Csernai et al., Phys. Rev. E, 108(2) 025205 (2023)]

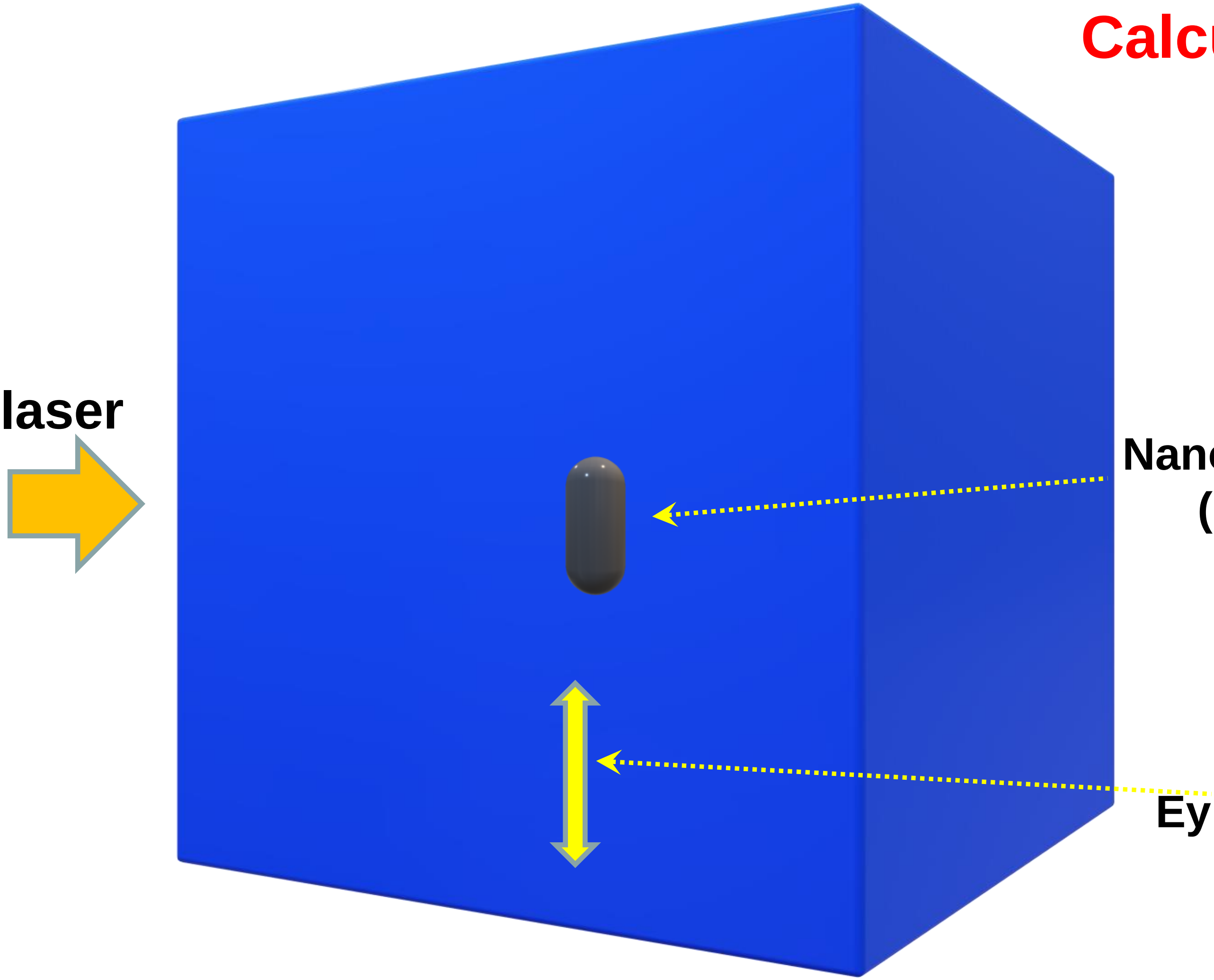
Laser pulse energy:25mJ



Dependence of crater volume on laser energy for copper. (532 nm, 6 ns)

Calculational Box (CB)

(530 nm)^3



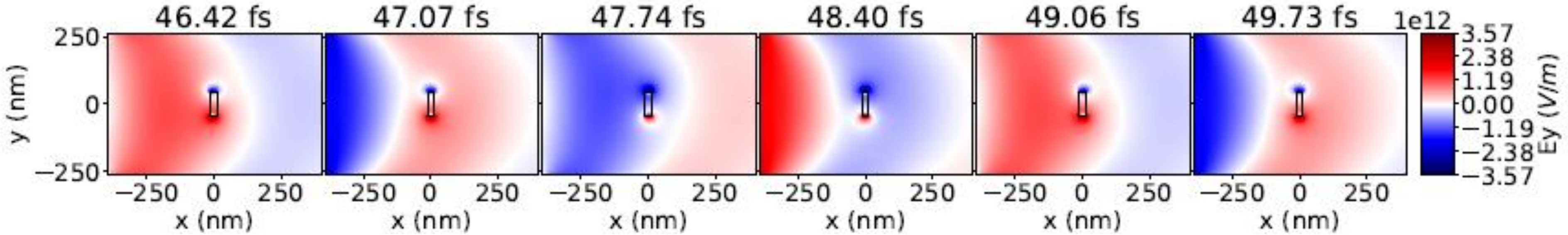
laser

Nano-rod antenna
(~ 85x25 nm)

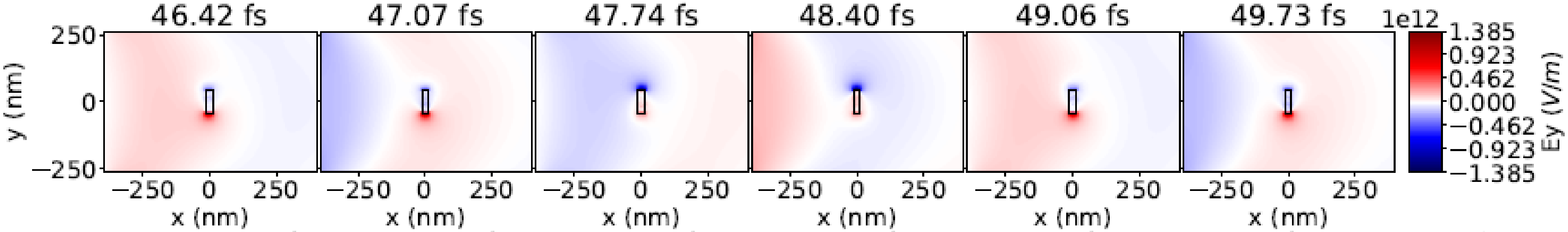
Ey Ffield

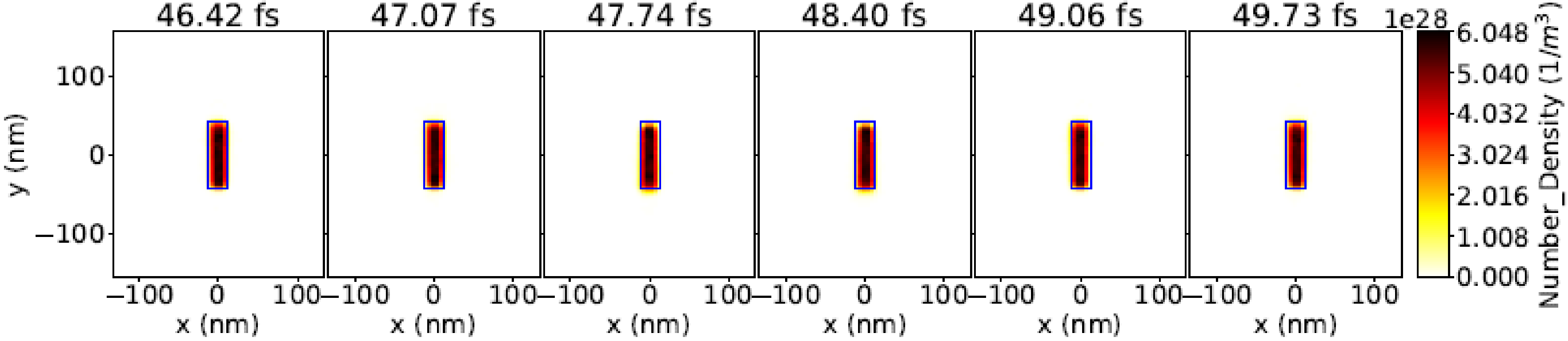
Laser

$I = 4 \cdot 10^{17}$ W/cm^2 $V \sim 7.1 \cdot 10^{12}$ V/m

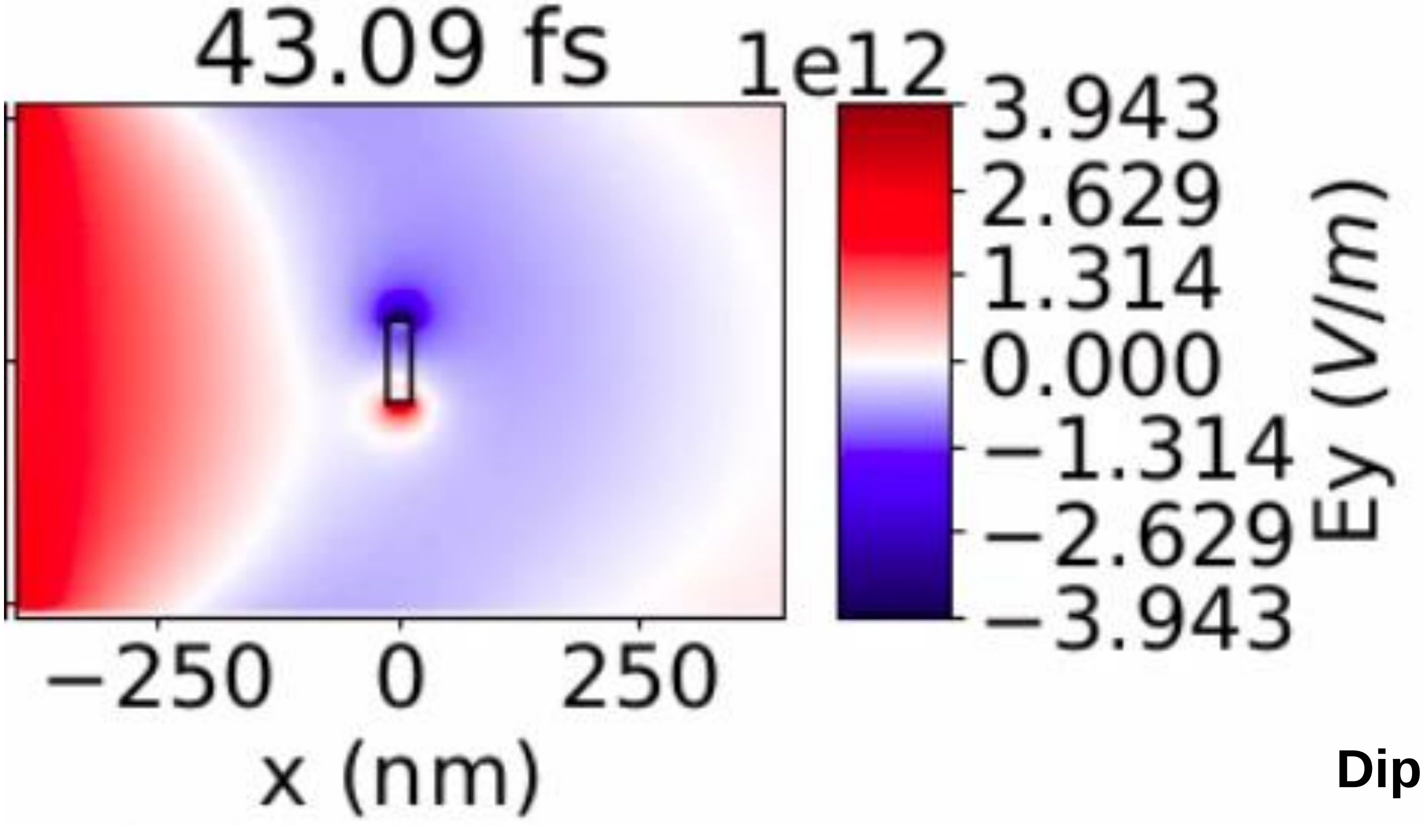


$I = 4 \cdot 10^{15}$ W/cm^2 $V \sim 2.6 \cdot 10^{12}$ V/m





[I. Papp et al., *arXiv:* 2306.13445]

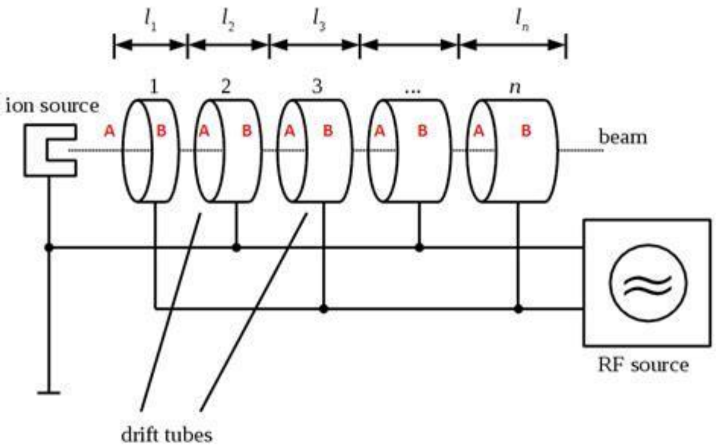


Neighboring protons are accelerated (100-200 nm)

Dipole L = 85 nm

I = 4 · 10^{17} W/cm^2

dV ~ 8 · 10^{12} V/m



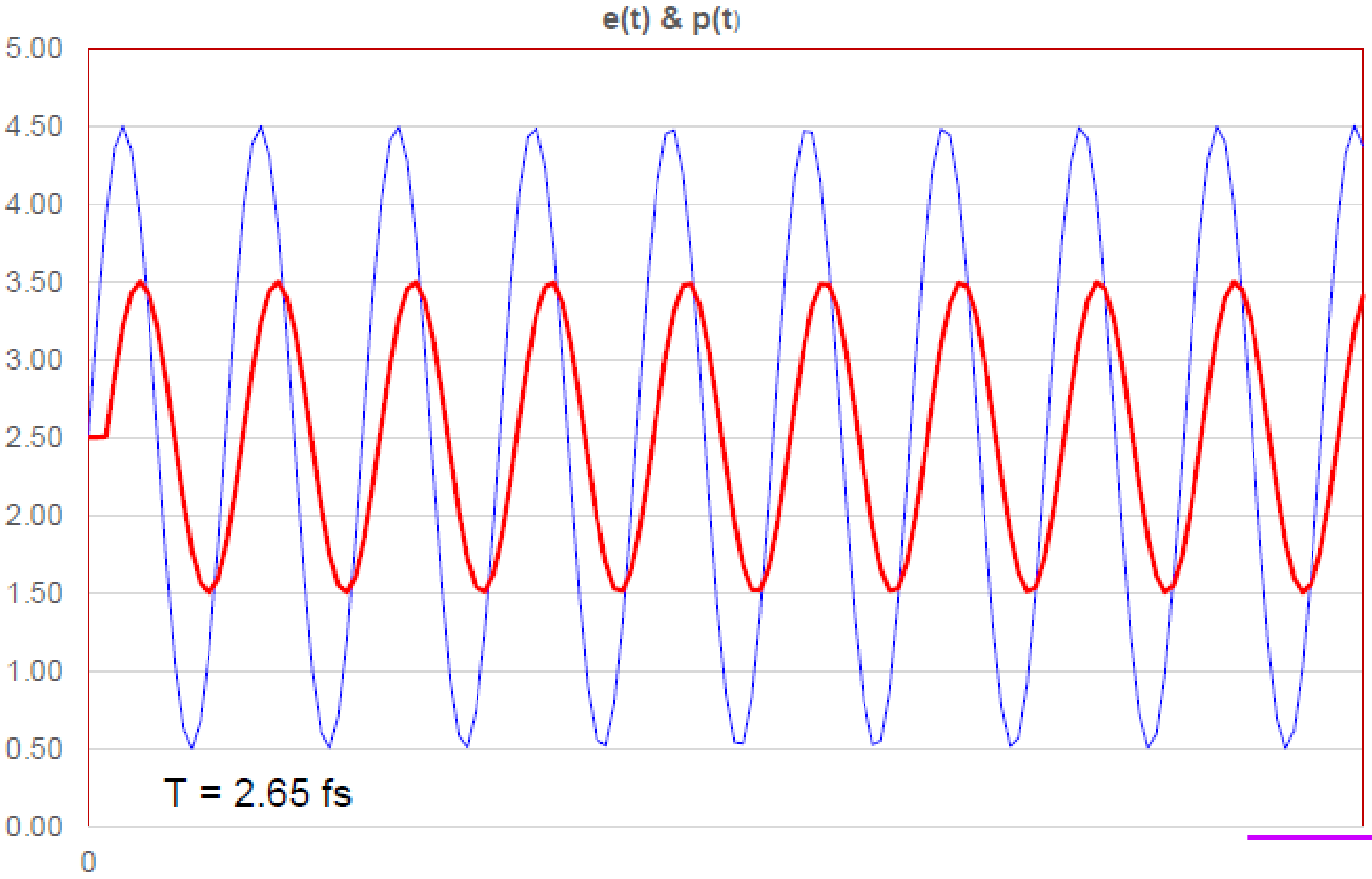
LHC

dV ~ 1 · 10^6 V/m

Dipole L ~ 16 cm

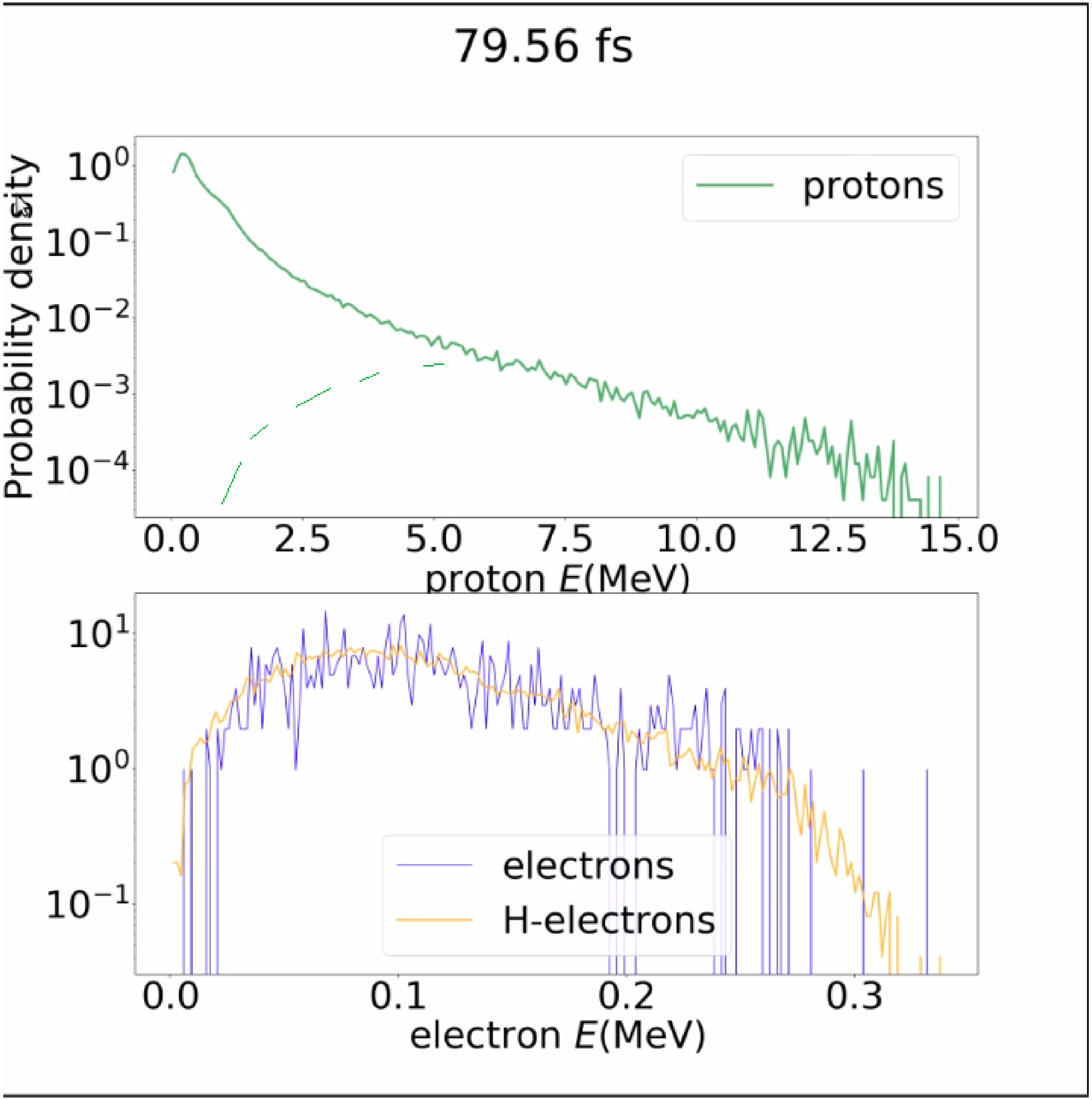
Csernai, L.P. [NAPLIFE]

Laser wake field acceleration mechanism =>



BUT
Proton
amplitudes
& speeds
are
smaller

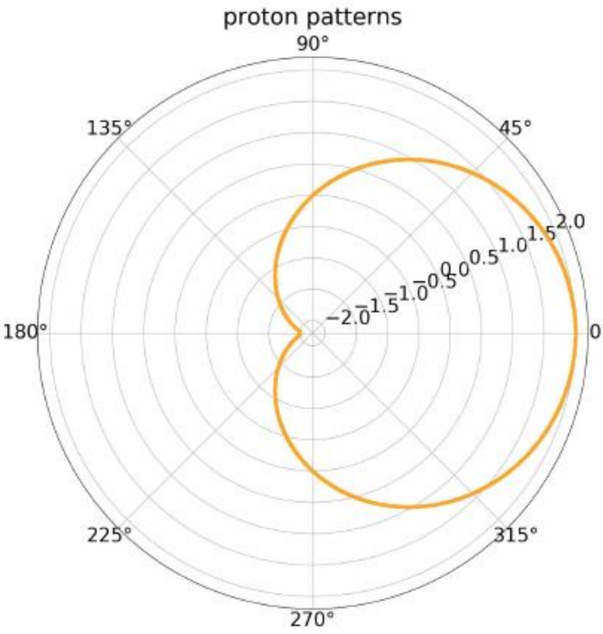
time

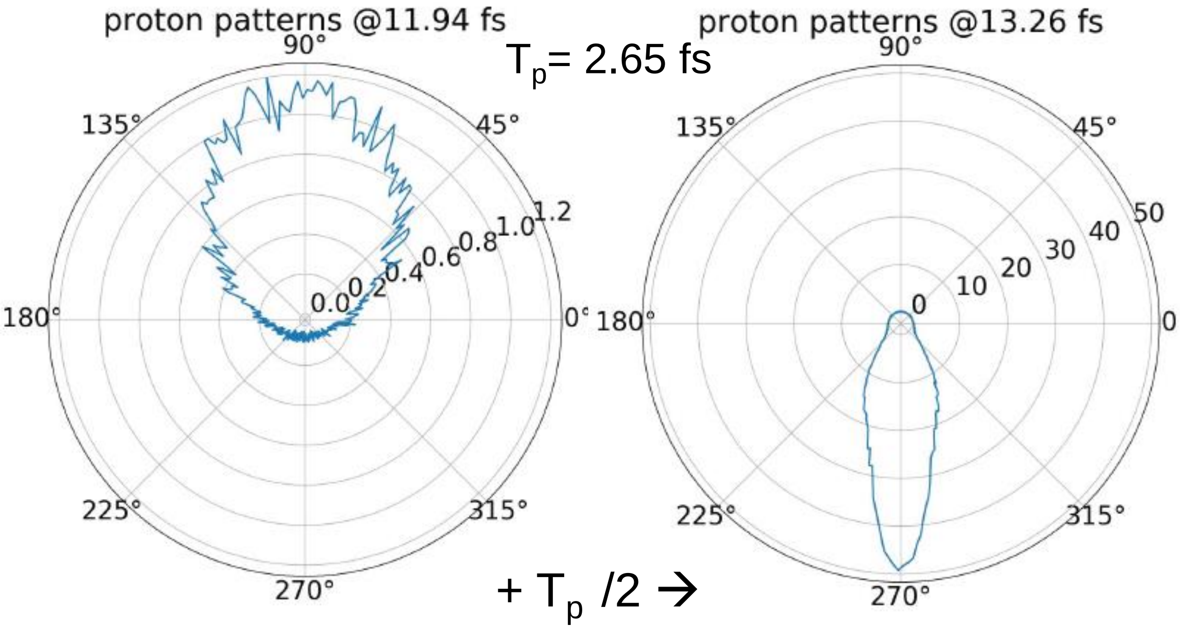


Number of 1-2 MeV protons is about 1-100

=>

small number of Deuterium





T_p= 2.65 fs

+ T_p /2 →

One-sided irradiation

Two-sided irradiation

$$C(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)},$$

$$C(k,q) = 1 + \frac{R(k,q)}{\left|\int d^4x\, S(x,k)\right|^2} \ ,$$

$$R(k,q) = \int d^4x_1\, d^4x_2\, \cos[q(x_1-x_2)]\times$$
$$S(x_1, k+q/2)\, S(x_2, k-q/2)\ .$$

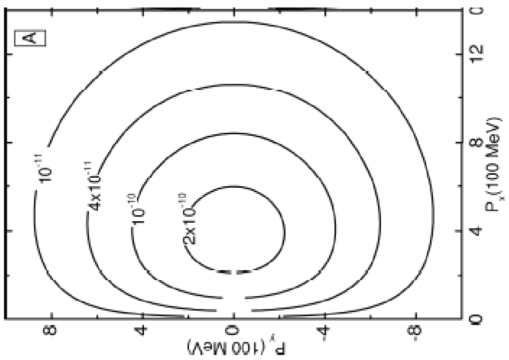
$$J(k,q) = \int d^4x\ S(x, k+q/2)\, \exp(iqx)$$

$$R(k,q) = Re\,[J(k,q)\, J(k,-q)].$$

$$f^J(x,p) = \frac{n(x)}{C_\pi(2\pi\hbar)^3} \exp\left(\frac{-p^\mu u_\mu(x)}{T(x)}\right)$$

$$f_{CJ} = \frac{\Theta(p^\mu d\sigma_\mu)\ n(x)}{C_\pi\ (2\pi\hbar)^3} \ \times$$
$$\left(\exp\frac{-p^\mu u^R_\mu}{T} - \exp\frac{-p^\mu u^L_\mu}{T}\right)$$

Csernai, L.P. [NAPLIFE]



Fluid elements [s] can be represented by Cancelling Jütner distributions, i.e. Cells are not in thermal equilibrium. (protons are accelerated by the nanorods

Then standard procedure like for a spherical, thermal cell.

Cancelling Jüttner distribution (CJ)

$$\gamma n_s \exp\left(-\frac{x^2+y^2+z^2}{2R^2}\right)$$

$$C(k,q) = 1 + \exp\left(-(\Delta\tau)^2(\hat{\sigma}^\mu q_\mu)^2 - R^2 q^2\right)$$

$$C(k,q) = 1 + \exp\left(-R^2 q^2\right)$$

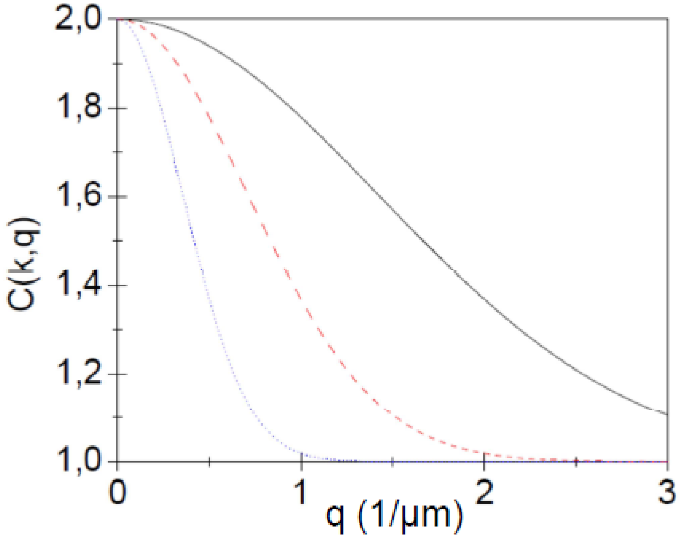


FIG. 6. (color online) The correlation function, $C(k,q)$, for a single, static, spherically symmetric, Gaussian source with different radii, $R = 4, 1$ and $0.25\,\mu$m, (*blue dotted, red dashed,* and *full black lines* respectively), as described by Eq. (16).

For a single spherical source:

[L.P. Csernai, S. Velle, and D.J. Wang PHYSICAL REVIEW C 89, 034916 (2014)]

New fusion mechanism

Traditionally (NIF) after ignition, DT burning is spreading by *alpha particle self heating*. This turns out to be slower than expansion after extreme compression and extreme pressure.

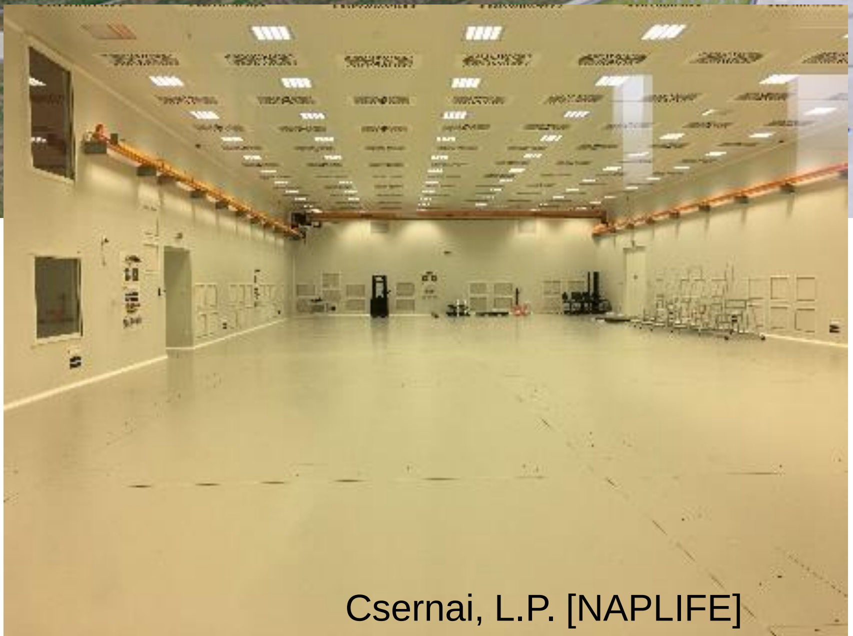
HINT:

Here after simultaneous (time-like) ignition attraction of large number of electrons *collectively accelerate* protons, which can induce nuclear reaction (e.g. transmutation).

We try to verify this mechanism by the Hanbury-Brown and Twiss effect to determine the deuteron and alpha source size, after a laser shot.

High Energy, Short Pulse Laser, unique at ELI – ALPS Szeged

European Laser Infrastructure – Szeged, HU



Csernai, L.P. [NAPLIFE]

ELI-ALPS Szeged:
EU Extr. Light Infrastructure
Attosec. Light Pulse Source

2PW High Field laser
10 Hz, <10fs, **20 J**