Relativistic Fluid Dynamics in heavy-ion physics and in laser-driven pellet fusion

L.P. Csernai - FIAS Colloquium, Frankfurt am Main, SEP. 28, 2017

Burning of Quark Gluon Plasma in Relativistic, Radiation Dominated Systems according to Relativistic Fluid Dynamics

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Applications to Pellet Fusion

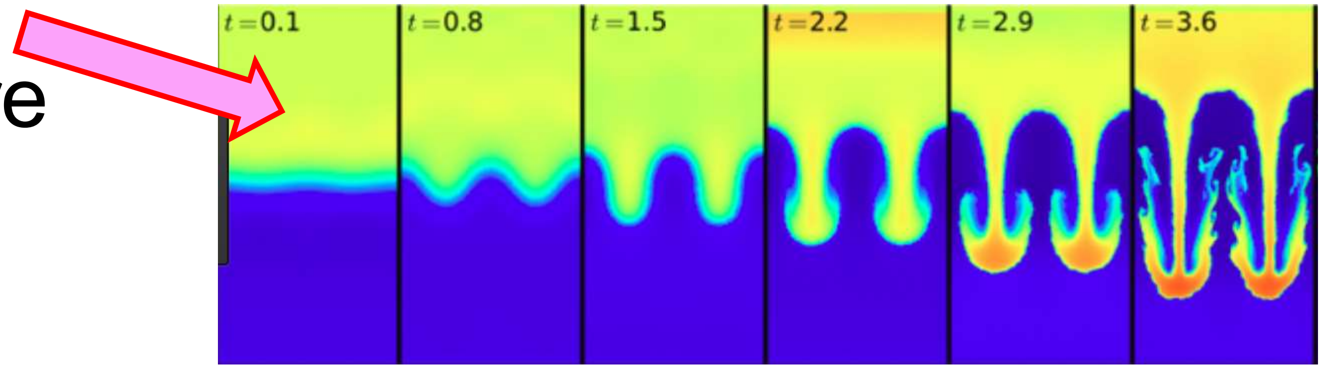
Classical Fluid Dynamics (CFD) does assumes that all dynamical processes, including shocks and detonations, are having speeds which are slower than the speed of light, c. (Note, however: Einstein's GR: Synchronizing watches)

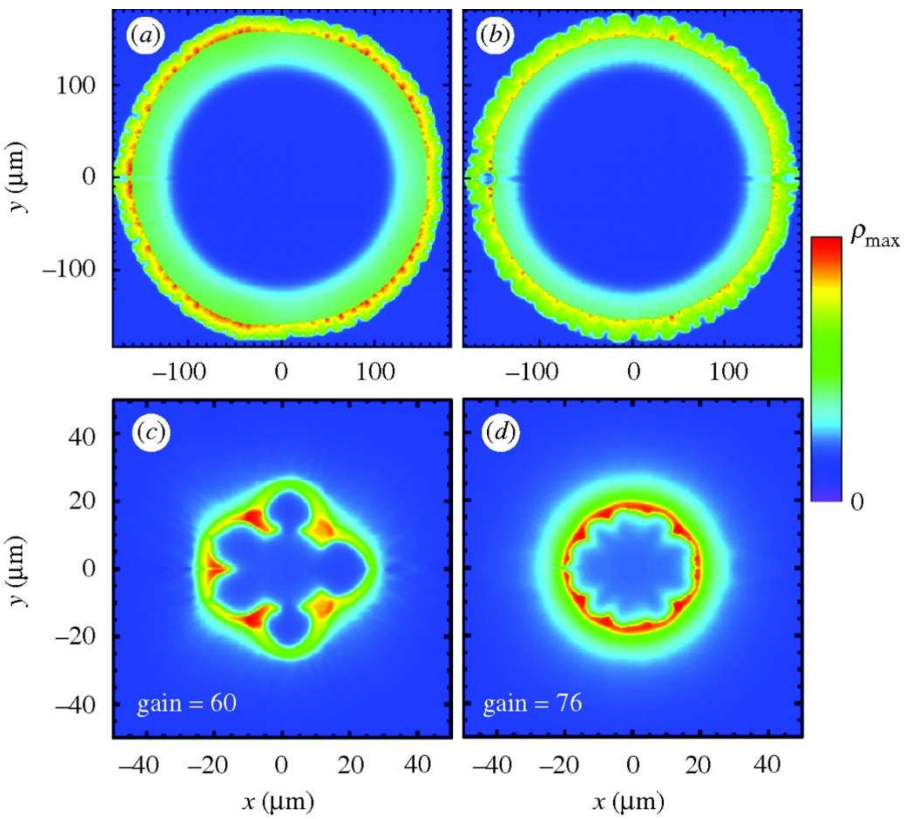
Engineering books keep this assumption even today!

In ICF attempts the mechanical Rayleigh – Taylor instability is the major obstacle to reach ignition in the whole volume of the target fuel.

Rayleigh – Taylor Instability

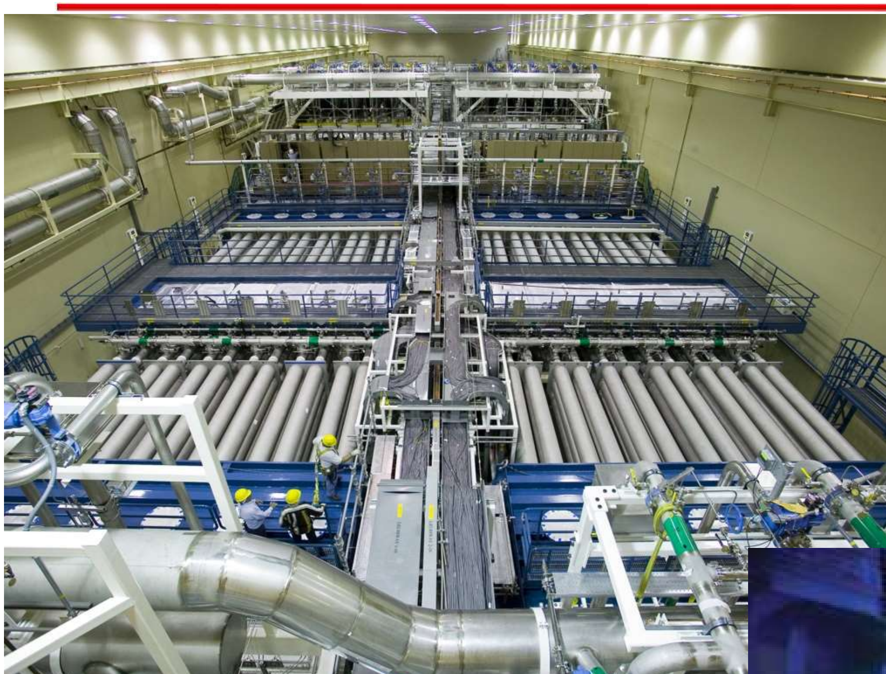
High pressure

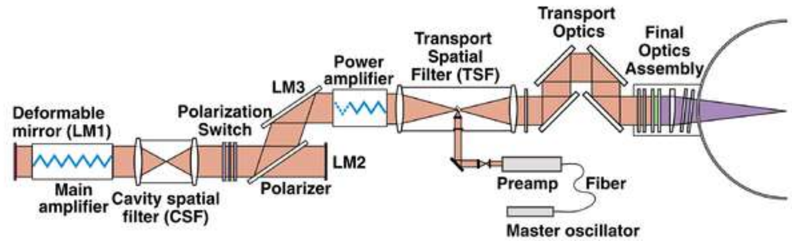




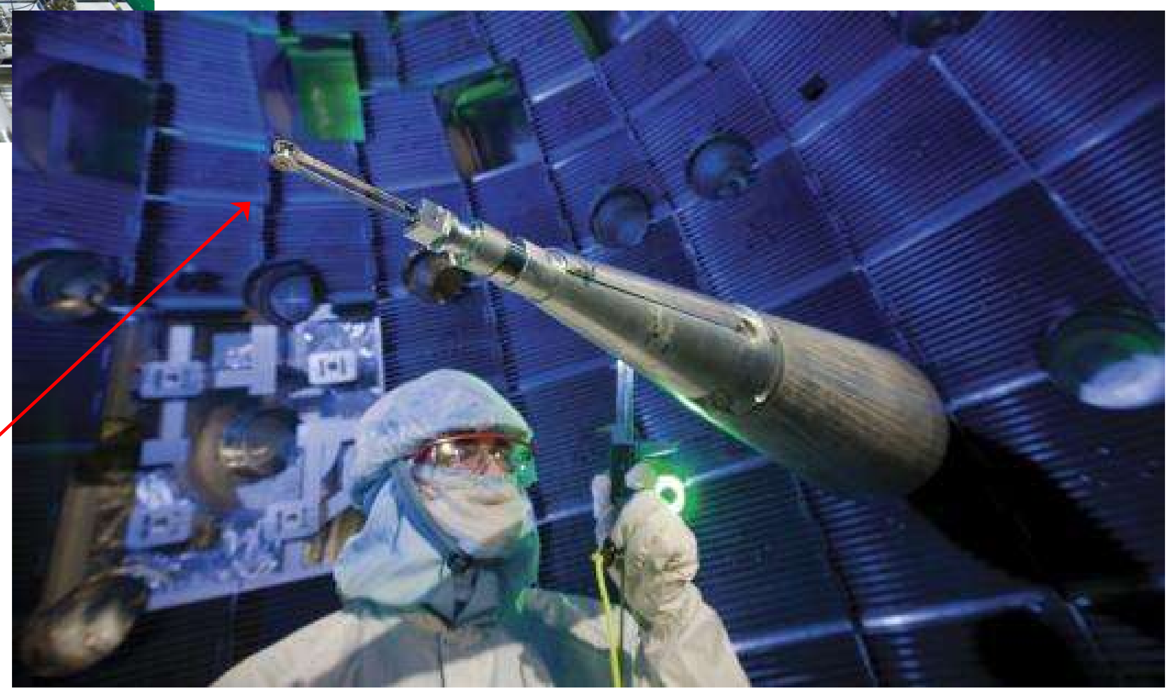
Spherical compression [LLNL]

The ICF research

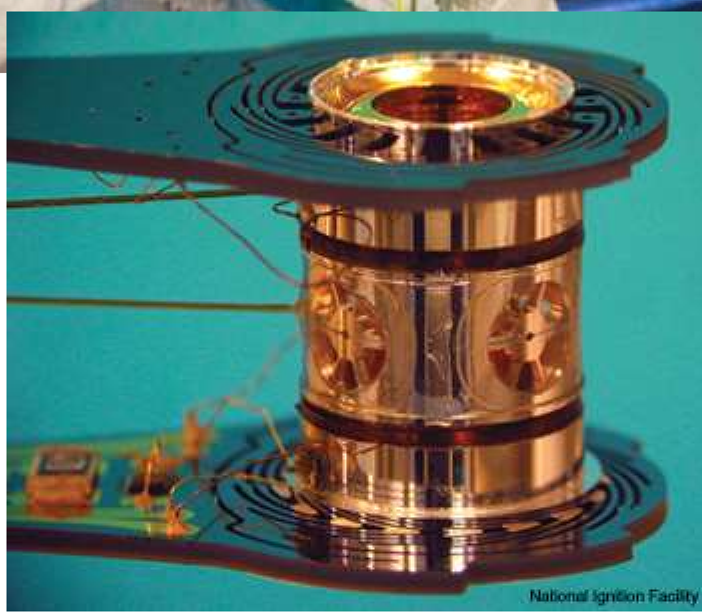


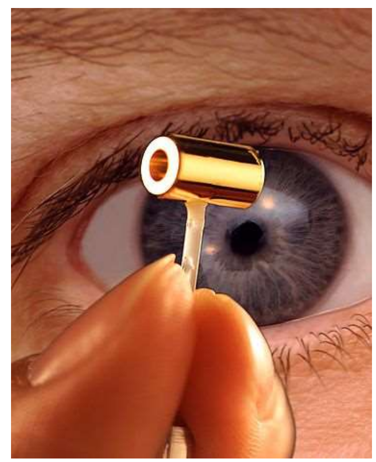


Lasers at NIF

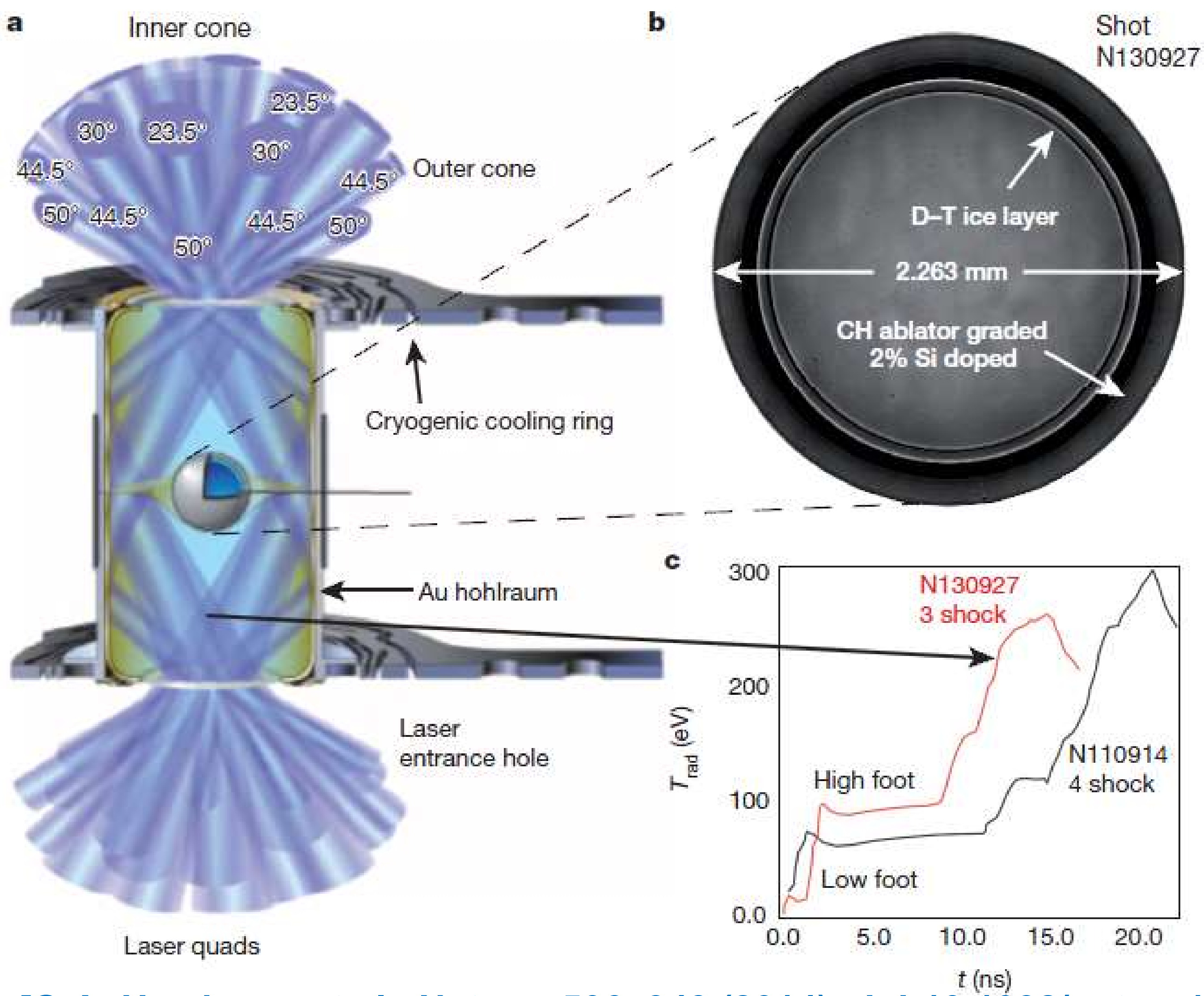


The Au Hohlraum at NIF


National Ignition Facility



Indirectly Driven, ICF target for NIF



Time profile of the laser beam:

Initial pre-compression of ~ 10 ns,

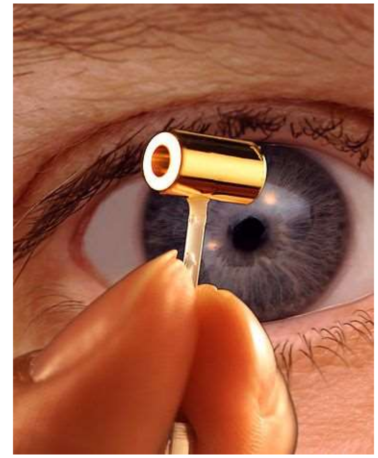
→ Stable compression

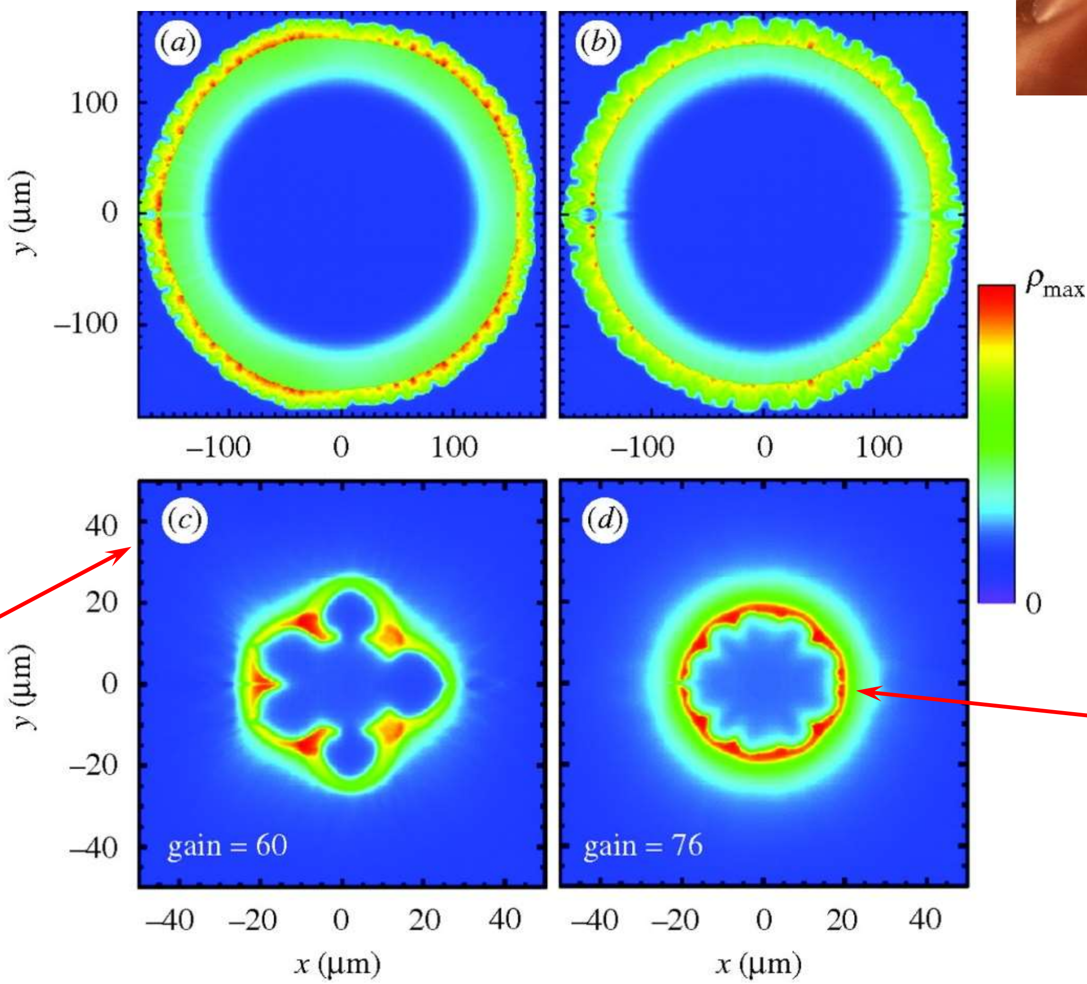
→ Then 3,4 "shocks" of 3-5 ns to ignite

[O.A. Hurricane et al., Nature, 506, 343 (2014), doi:10.1038/nature13008]

- The hohlraum

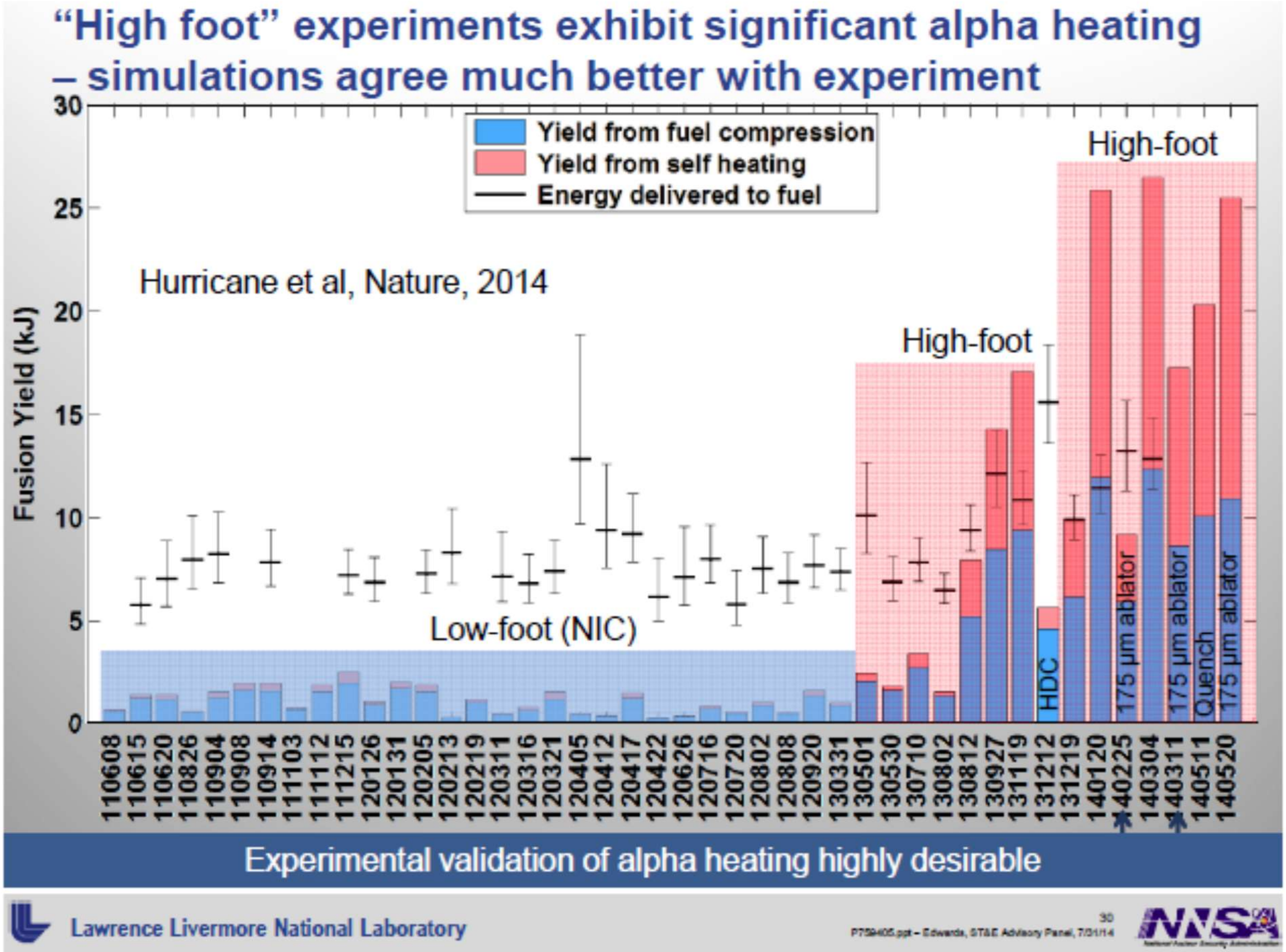
  The reconstructed size & shape of ignited source
  (~ 30x)





Max. compression

Re - expansion



"High foot" experiments exhibit significant alpha heating
– simulations agree much better with experiment
Yield from fuel compression
Yield from self heating
Energy delivered to fuel
Hurricane et al, Nature, 2014
Fusion Yield (kJ)
30
25
20
15
10
5
0
High-foot
High-foot
Low-foot (NIC)
HDC
175 µm ablator
175 µm ablator
Quench
175 µm ablator
110608
110615
110620
110826
110904
110908
110914
111103
111112
111215
120126
120131
120205
120213
120219
120311
120316
120321
120405
120412
120417
120422
120626
120716
120720
120802
120808
120920
130331
130501
130530
130710
130802
130812
130927
131119
131212
131219
140120
140225
140304
140311
140511
140520
Experimental validation of alpha heating highly desirable
Lawrence Livermore National Laboratory
30
NNSA

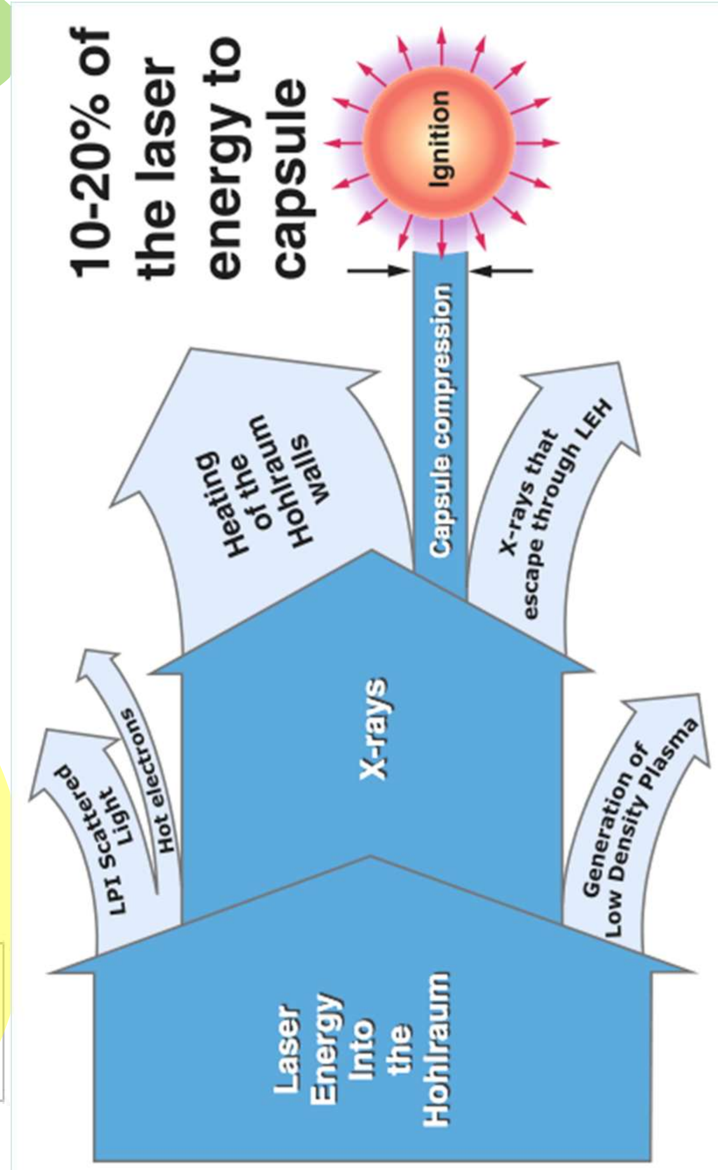
Approximate energy efficiency of diff. process steps of NIF:

Input energy of the laser (xenon lamps are powered by a capacitor bank)	422 MJ
Laser Infrared output (amplified IR light of the laser)	3.6 MJ
Laser UV output (about 50% is left after conversion to UV)	1.8 MJ
Laser energy absorbed by the hohlraum (theoretical prediction: about 85% is left after the X-ray conversion in the hohlraum)	<1.5 MJ
Laser energy absorbed by the outer layers of the DT target pellet (theoretical prediction: about 15% of the X-rays are absorbed by the outer layers of the target)	<220 kJ
Actual energy absorbed by the DT target pellet (based on report that more energy for this shot was released than UV-energy that is absorbed in the DT-target).	<14 kJ

Energy out

Energy released by fusion reactions (fraction 3.3×10^{-5} of input energy of the laser)	~14 kJ

0.003318% !



Burning of Quark Gluon Plasma in Relativistic, Radiation Dominated Systems according to Relativistic Fluid Dynamics

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Applications to Pellet Fusion

Classical Fluid Dynamics (CFD) does assumes that all dynamical processes, including shocks and detonations, are having speeds which are slower than the speed of light, c. (Note, however: Einstein's GR: Synchronizing watches)

Initial Relativistic FD (RFD) maintained this assumption based on the requirement of causality [A.Taub, 1948].→

Engineering books keep this assumption even today!

Relativistic Heavy Ion Physics proved the opposite!

[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,

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

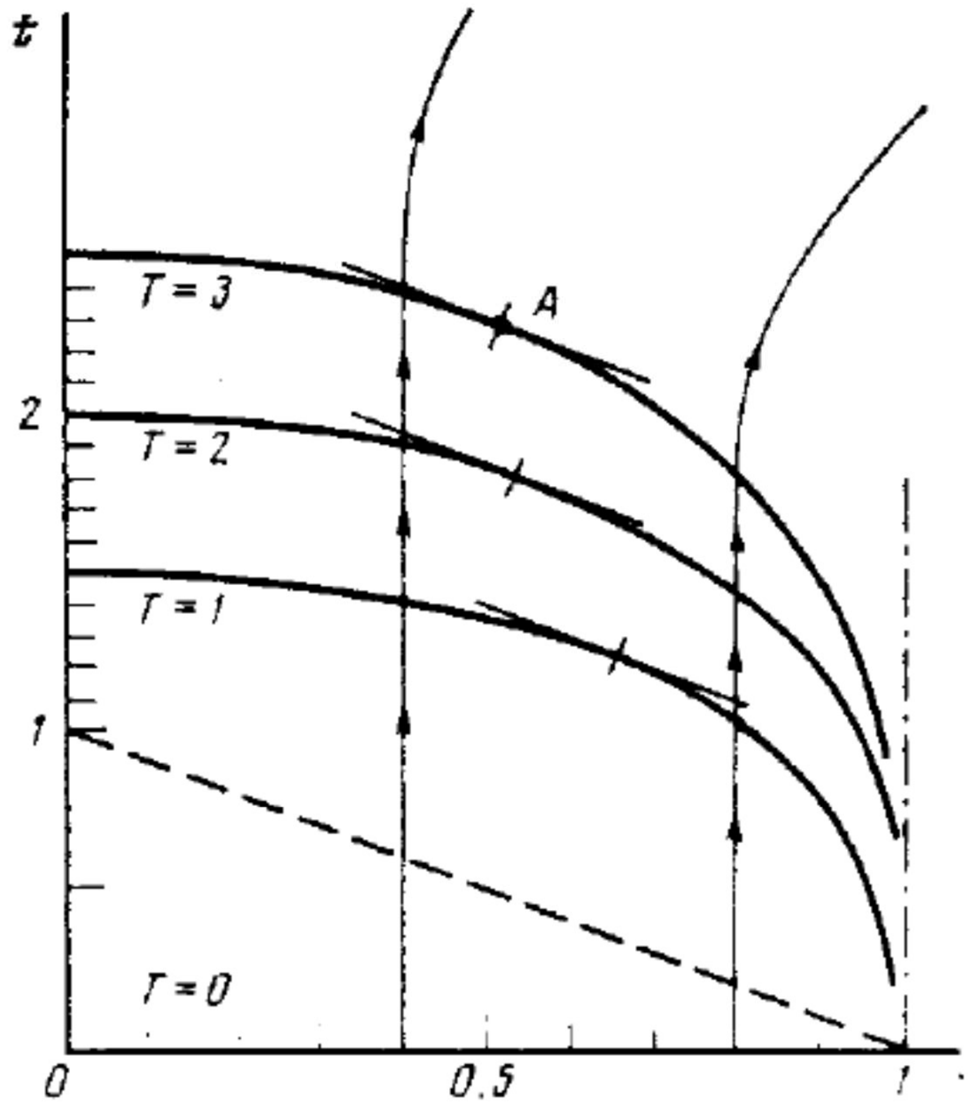
$$[T^{\alpha i} \Lambda_i] = 0, \tag{7.4}$$

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)]

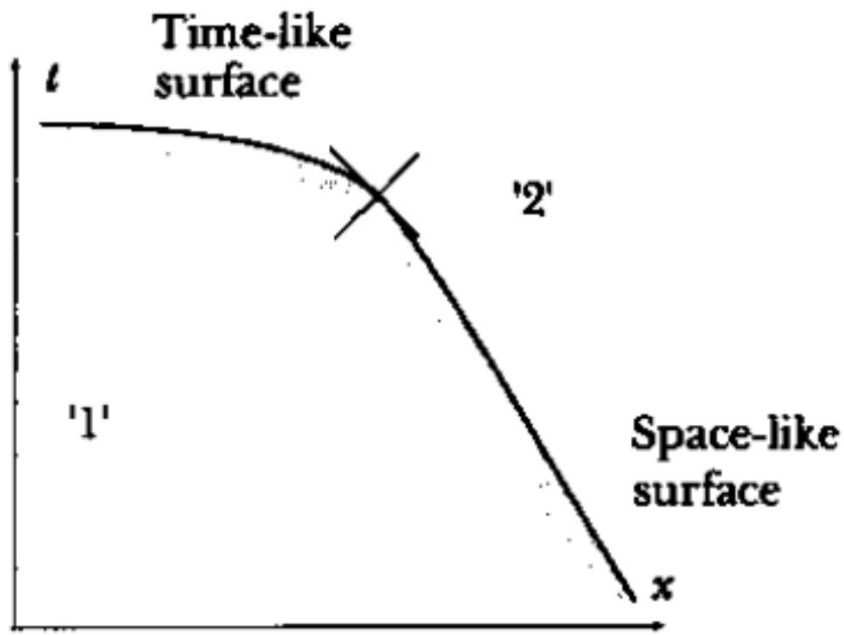
corrected the work of [**A. Taub**, Phys. Rev. 74, 328 (**1948**)]

Л. П. Чернаи

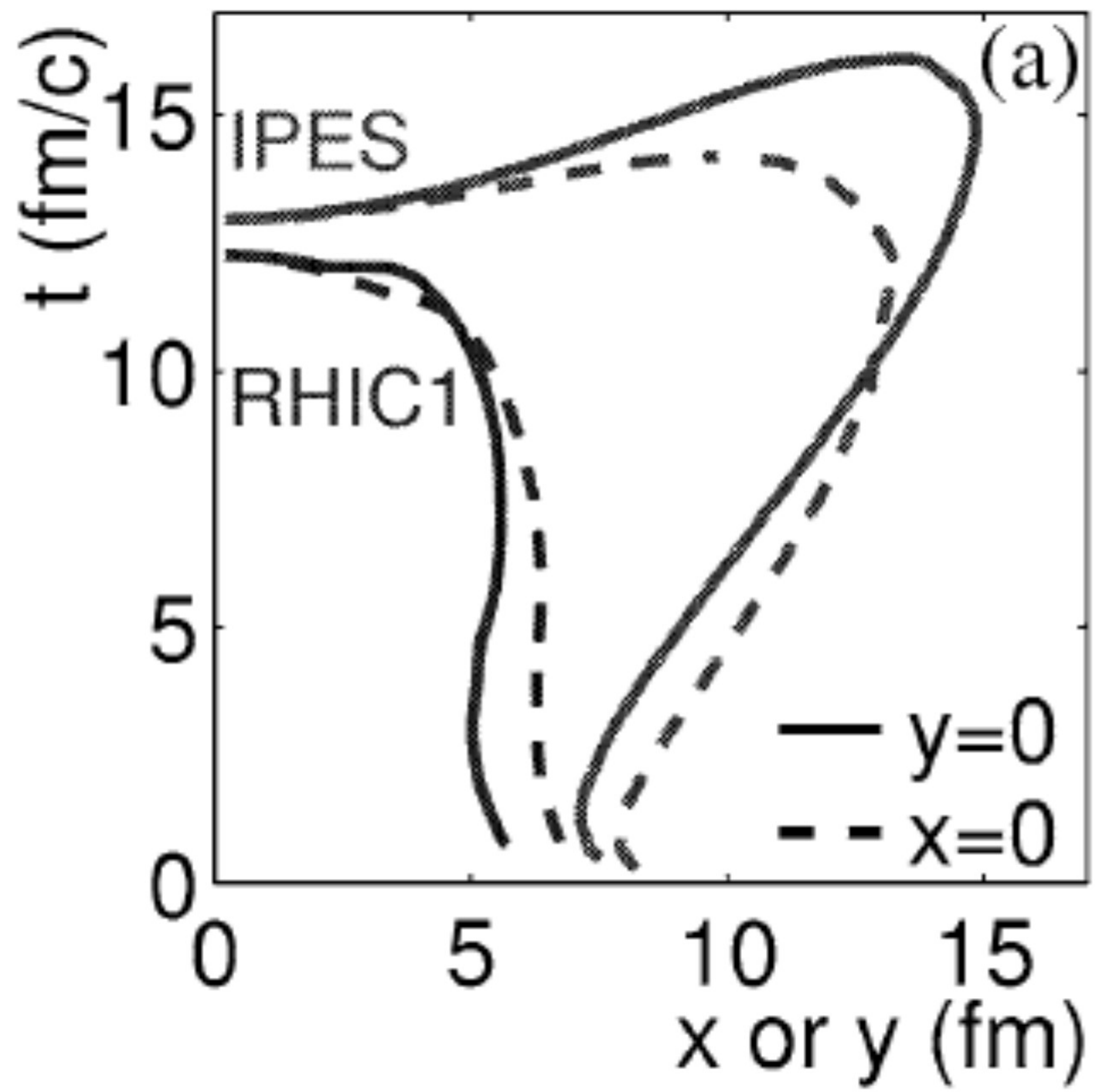
ДЕТОНАЦИЯ НА ВРЕМЕНИПОДОБНОМ ФРОНТЕ ДЛЯ РЕЛЯТИВИСТСКИХ СИСТЕМ

Журнал экспериментальной и теоретической физики

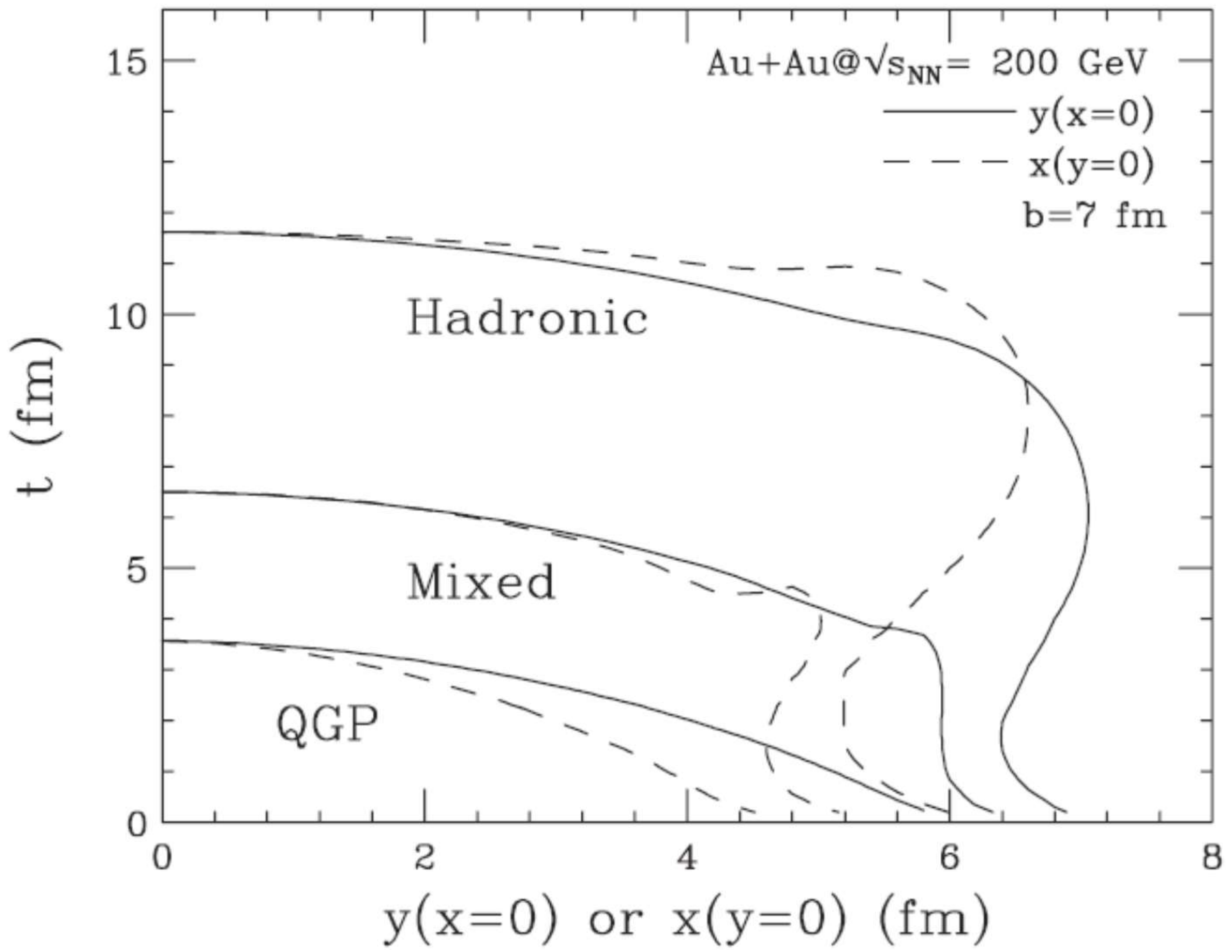
1987



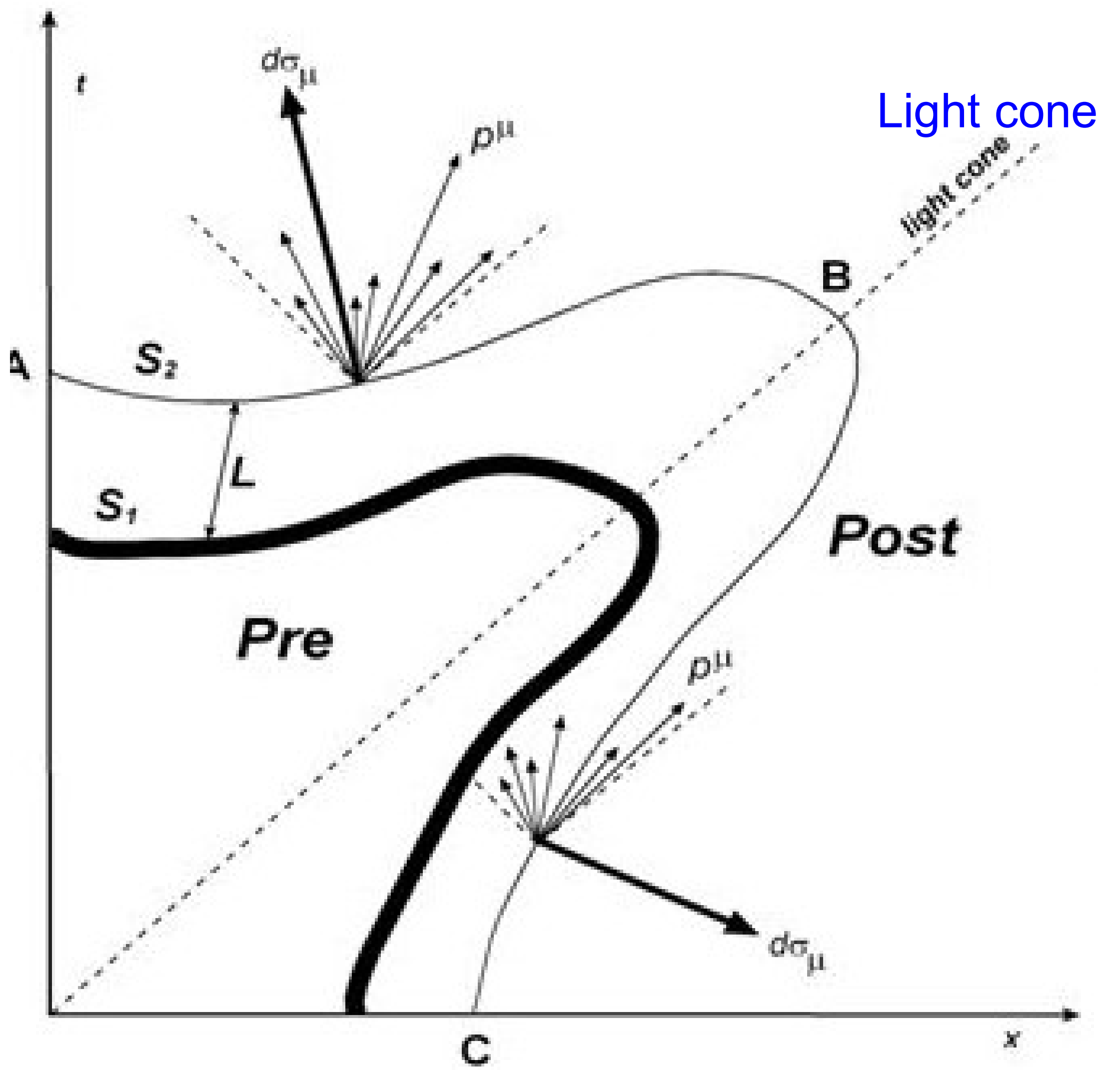
[L.P. Csernai:
Introduction to Relativistic Heavy Ion Collisions,
(**1994**, John Wiley & Sons, Cichester, England)]



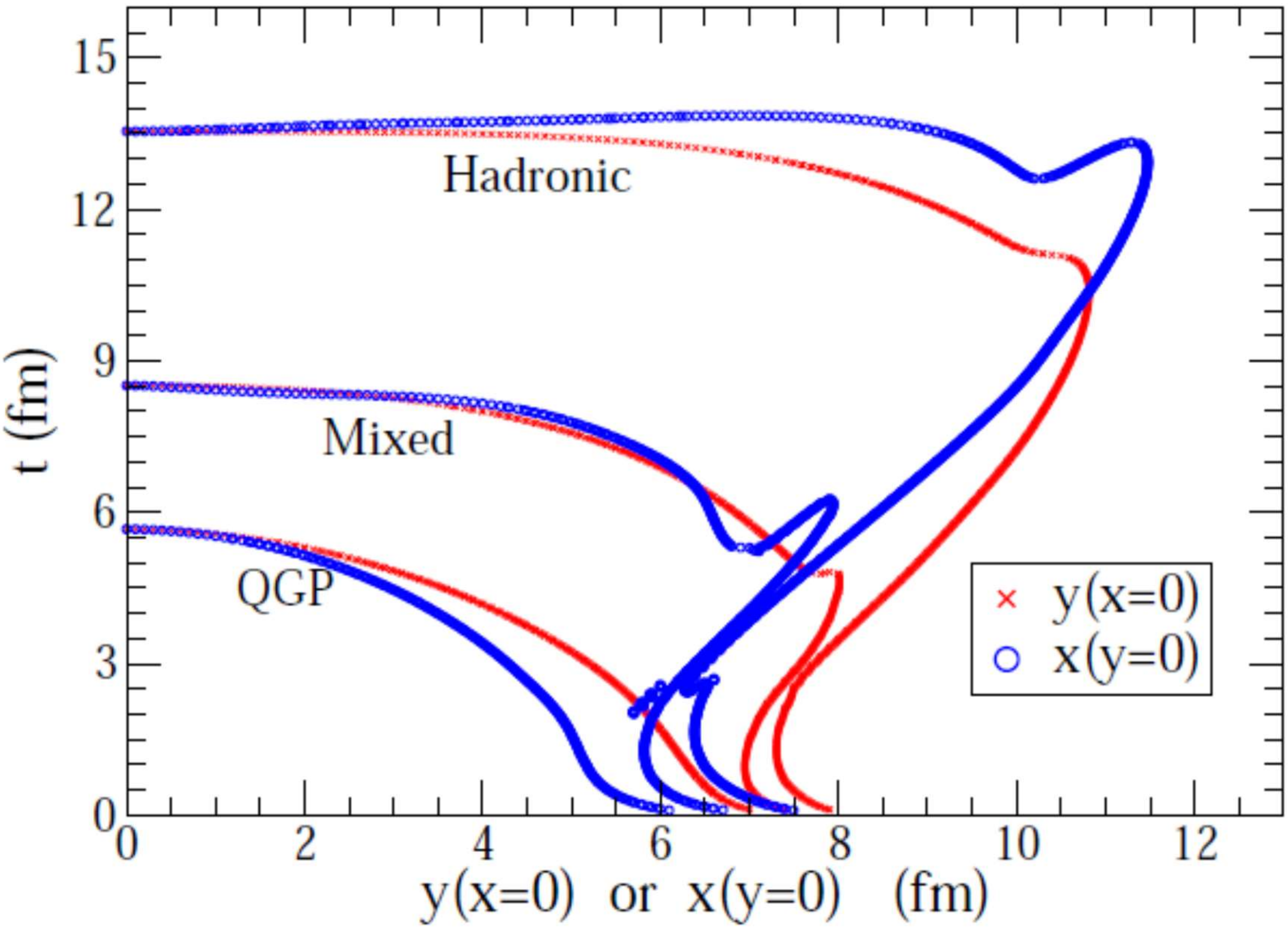
[U.W. Heinz and P.F. Kolb, Phys. Lett. B 542, 216 (2002)]



[R. Chatterjee, et al., Phys. Rev. Lett. 96, 202302 (2006)]



[E. Molnar, et al., J. Phys. G 34 (2007) 1901]



[E. Frodemann, et al., J.Phys. G 34, 2249-2254 (2007)]

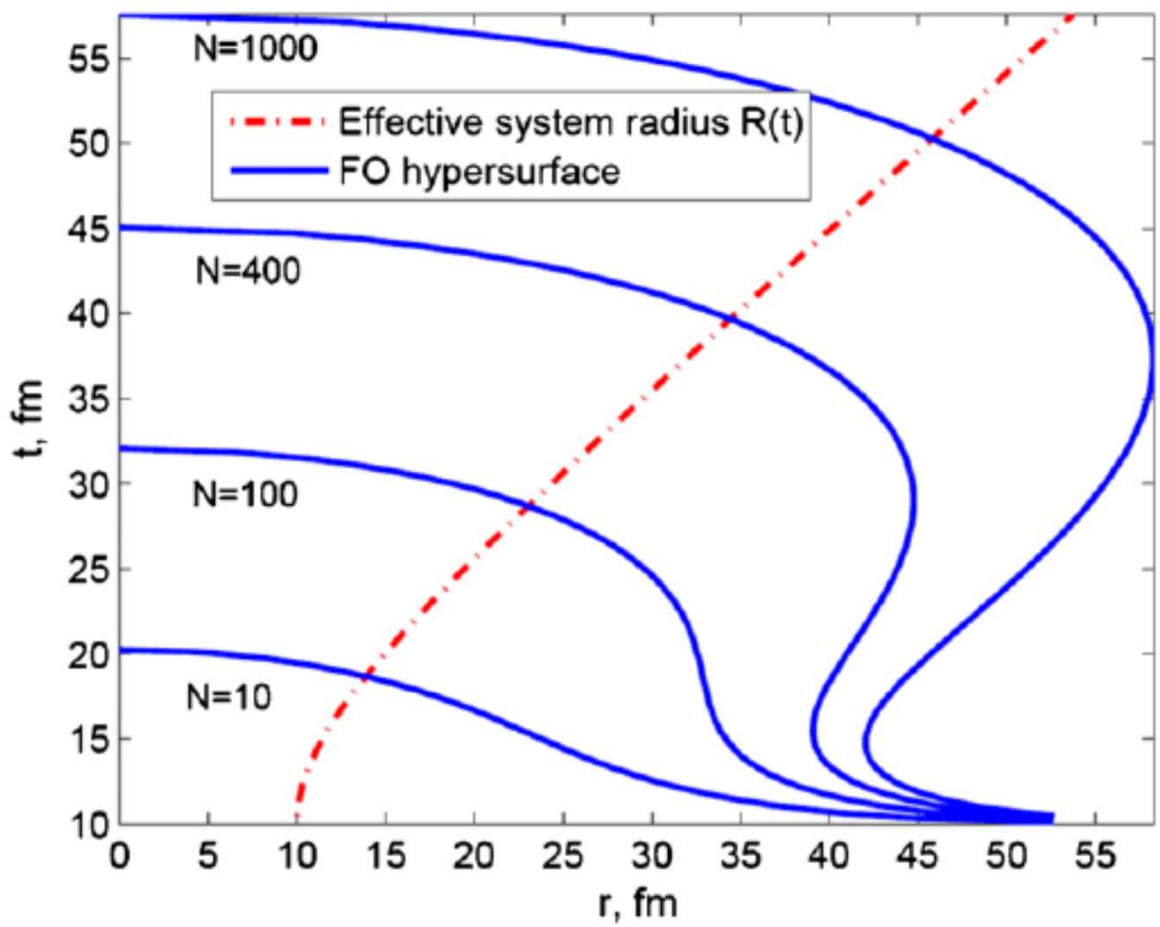
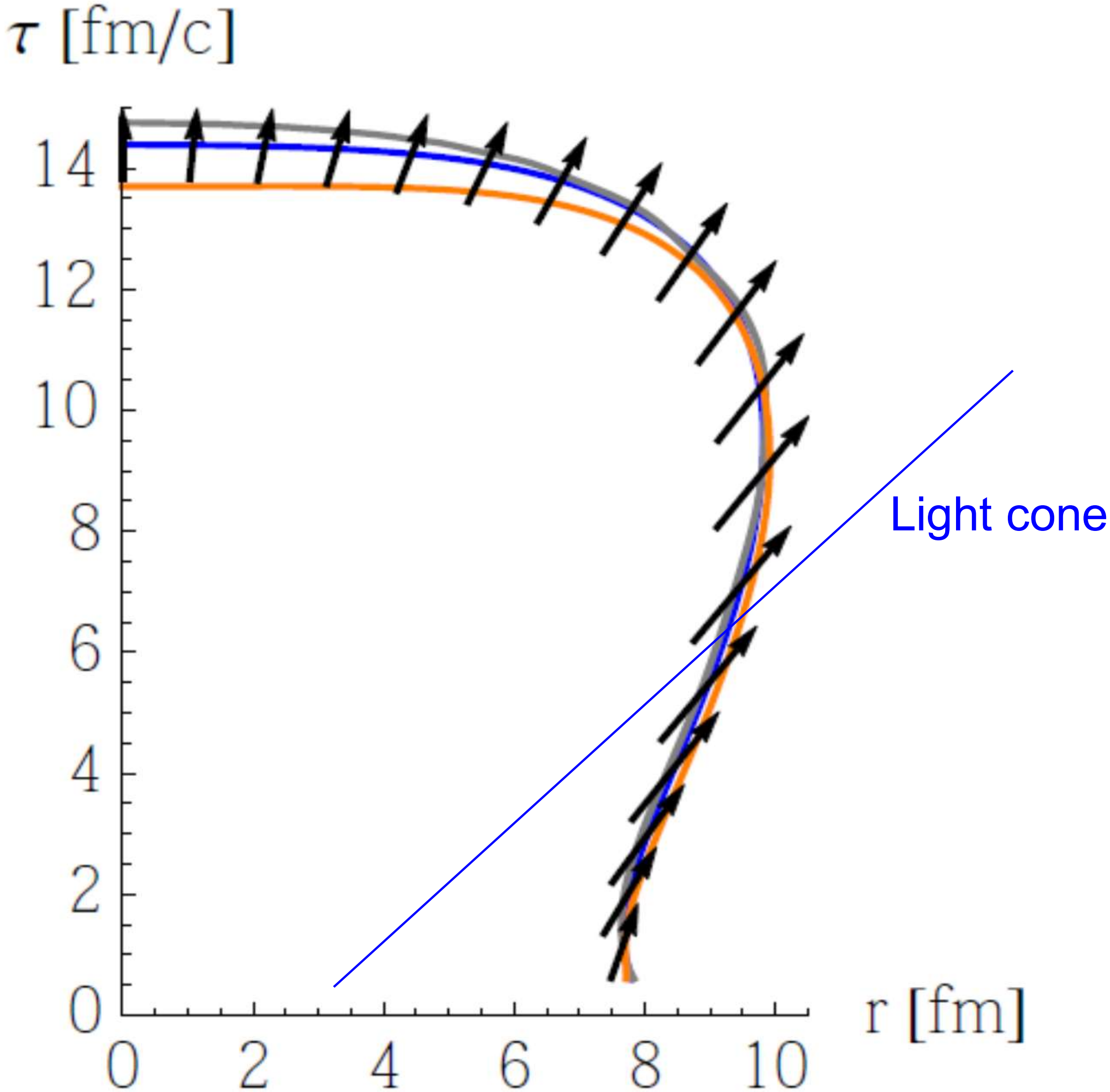
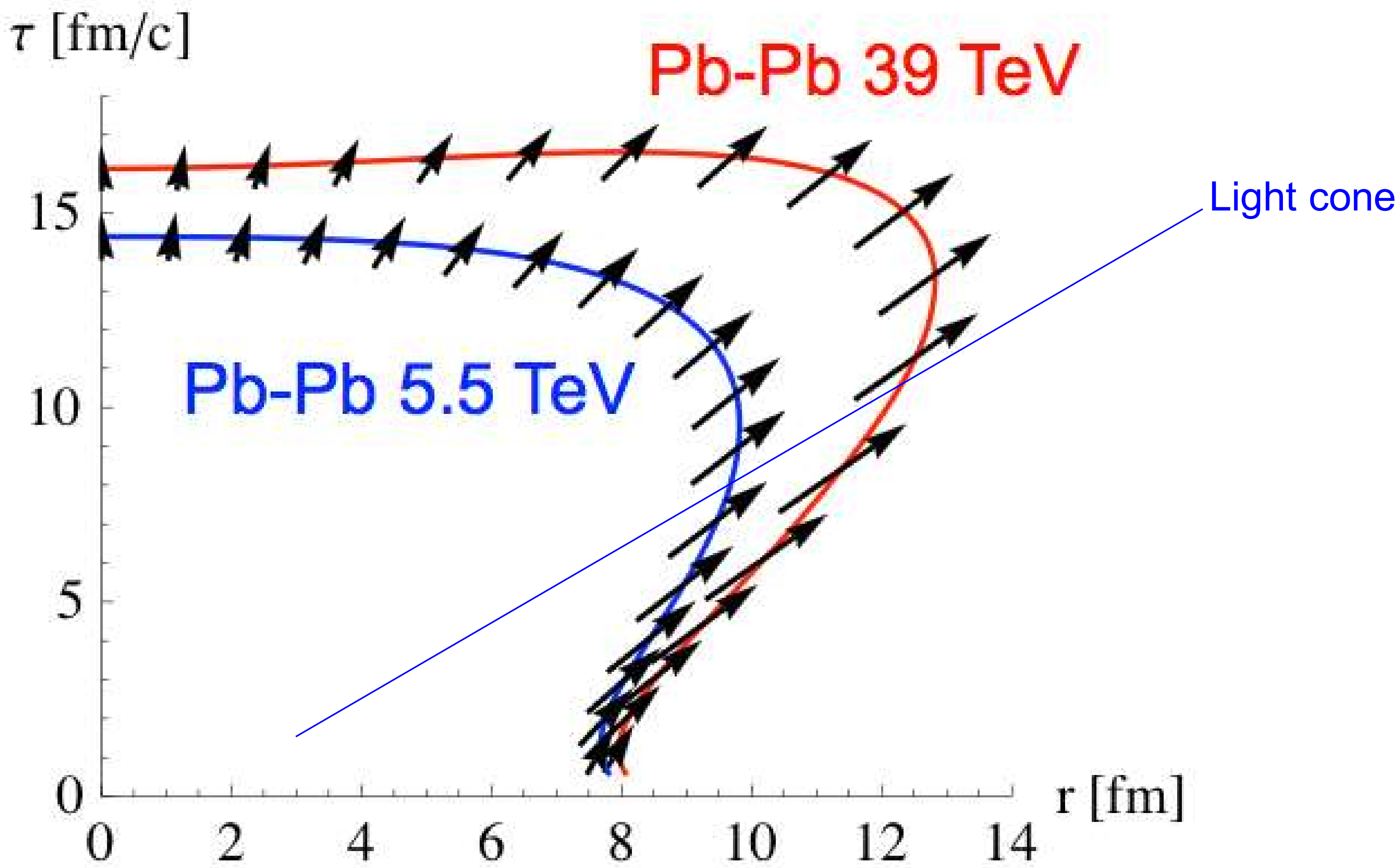


Figure 4. Freeze-out surfaces calculated from the Bondorf condition (see the text) for various particle numbers N.



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



[N. Armesto, et al., Nucl.Phys. A931 (2014) 1163]

Applications to Pellet Fusion

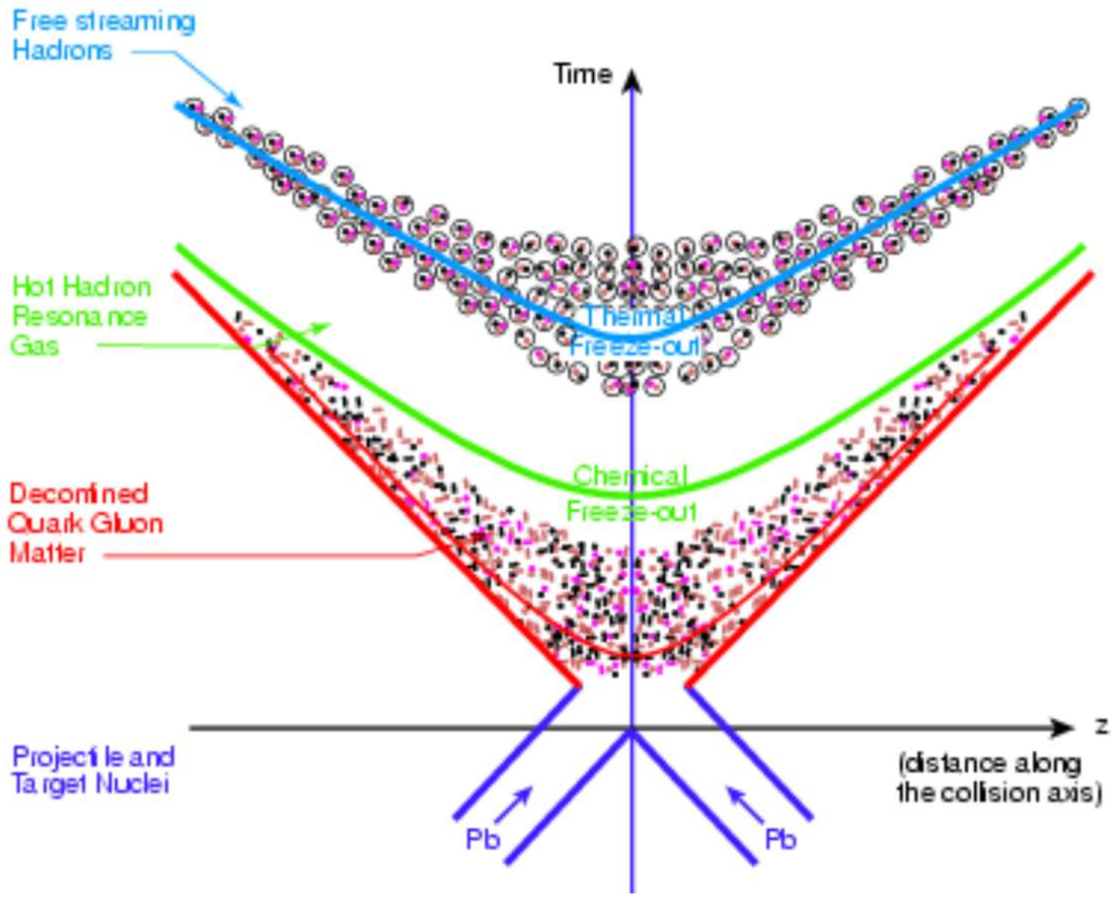
Up to now all theoretical studies of Internal Confinement fusion are based on Classical Fluid Dynamics (CFD).

Still the aim is to

- achieve Volume Ignition
- achieve Rapid Ignition
- but within CFD!

Relativistic Heavy Ion Physics proves that simultaneous ignition and burning is possible, both theoretically and experimentally!

This is not against causality, as the burning front is within the light cone of the initial state (i.e. the initial ST configuration).



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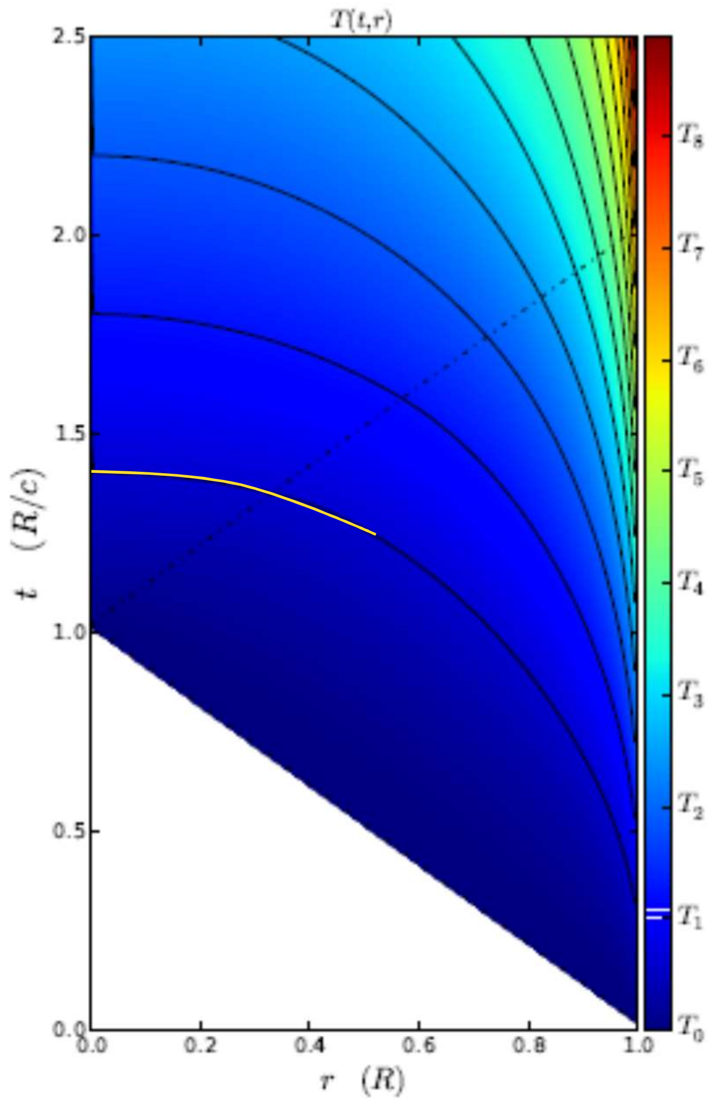


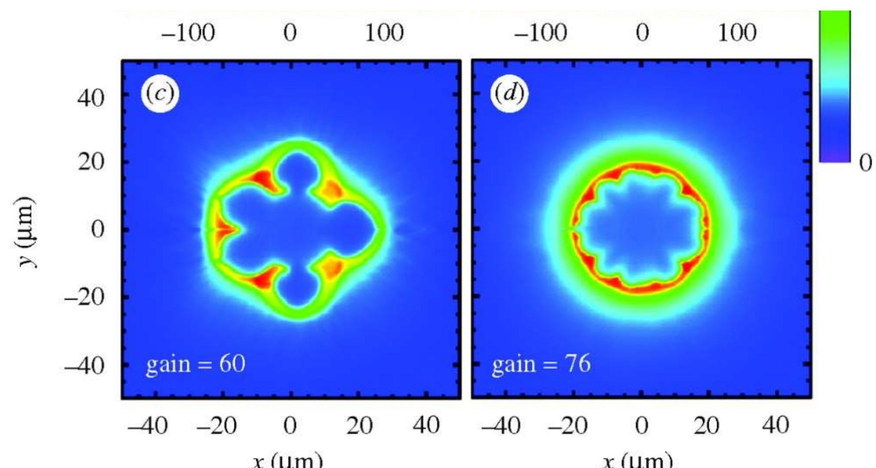
Fusion reaction:

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:



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

Can we achieve better volume ignition, and how?

Two ideas are combined by
L.P. Csernai, N. Kroo, I. Papp **[Patent # P1700278/3](*)**

- **Heat the system uniformly by radiation with RFD**
- **Achieve uniform heating by Nano-Technology**

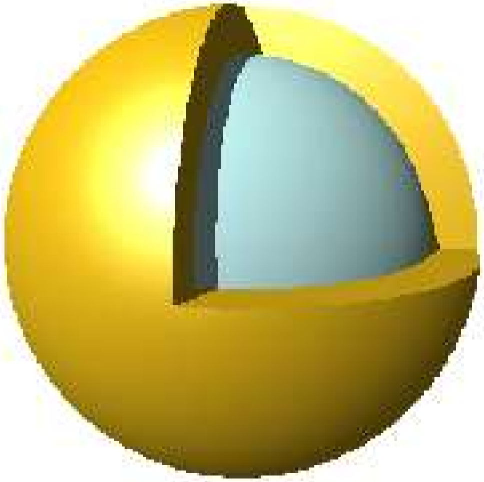
Mechanical compression and adiabatic heating should be avoided, because it is slow and leads to Rayleigh-Taylor instabilities. Similarly outside ablator surface should be avoided.

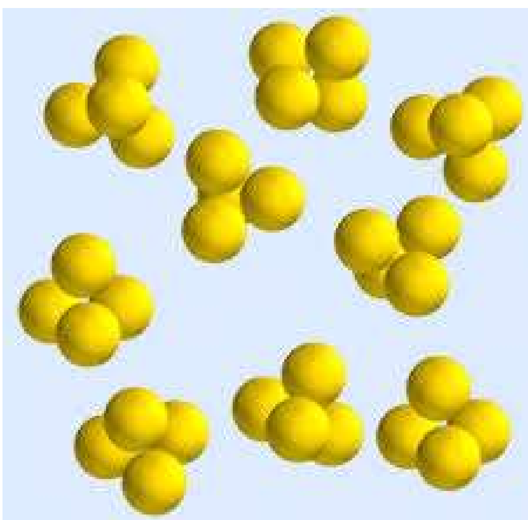
Uniform, 4π radiation should heat the target to ignition within the light penetration time (i.e. ~ 10-20 ps). This follows from RFD!

How can we achieve uniform heating?

- **Optimize the light absorptivity of the target by imbedding golden nano-shells of resonant size into the DT pellet.**
- **Nano-shells can increase light absorption by up to a factor of 30 or more.**

- Light heats up 1^{st} the external surface of the pellet and for a longer time. To compensate for this we have to increase the absorptivity of the central domains of the pellet.
- We can optimize the absorptivity by imbedding nano-shells of increasing density towards the center of the pellet.
- This way we can achieve near uniform, simultaneous, volume ignition.



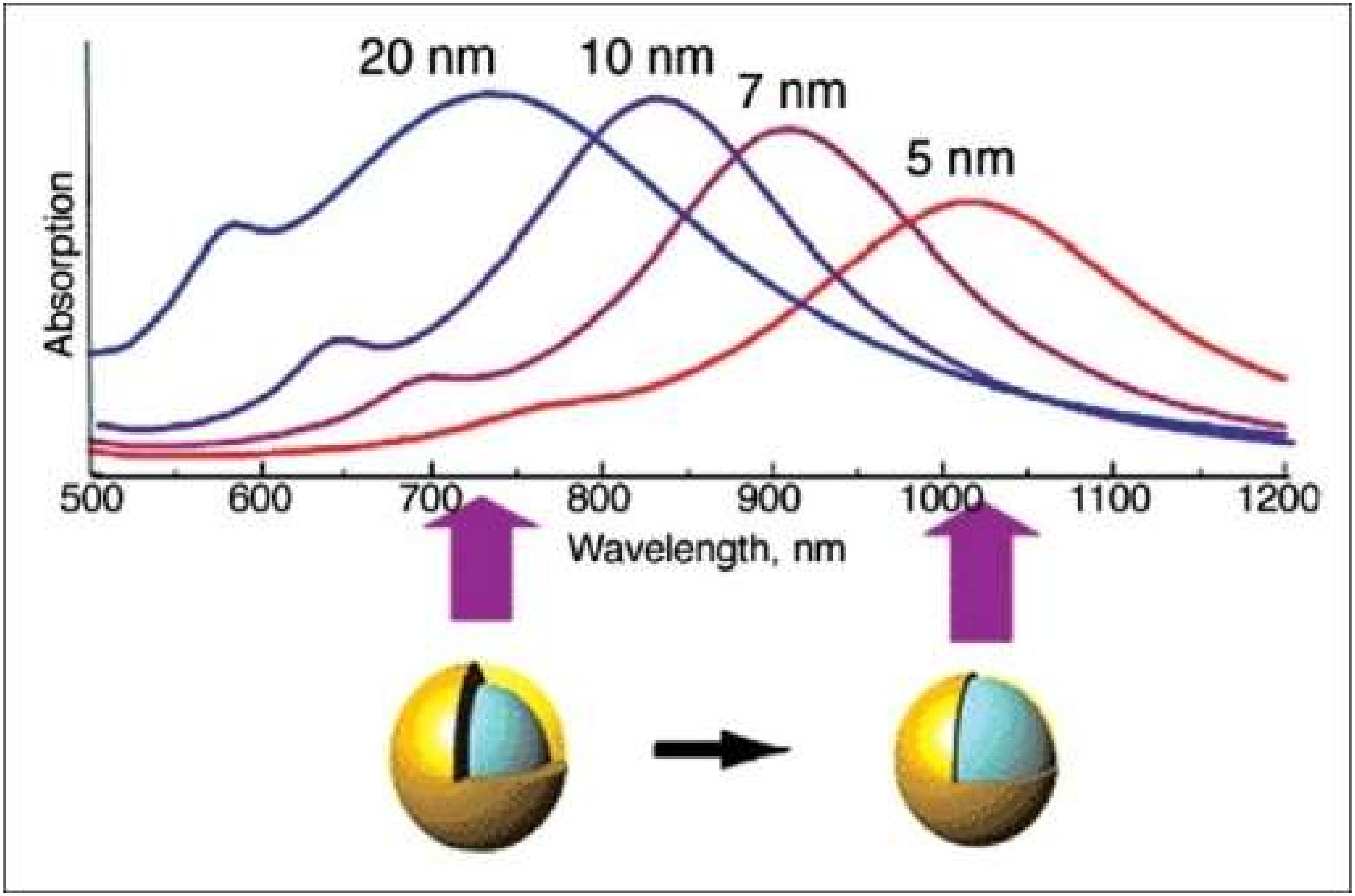


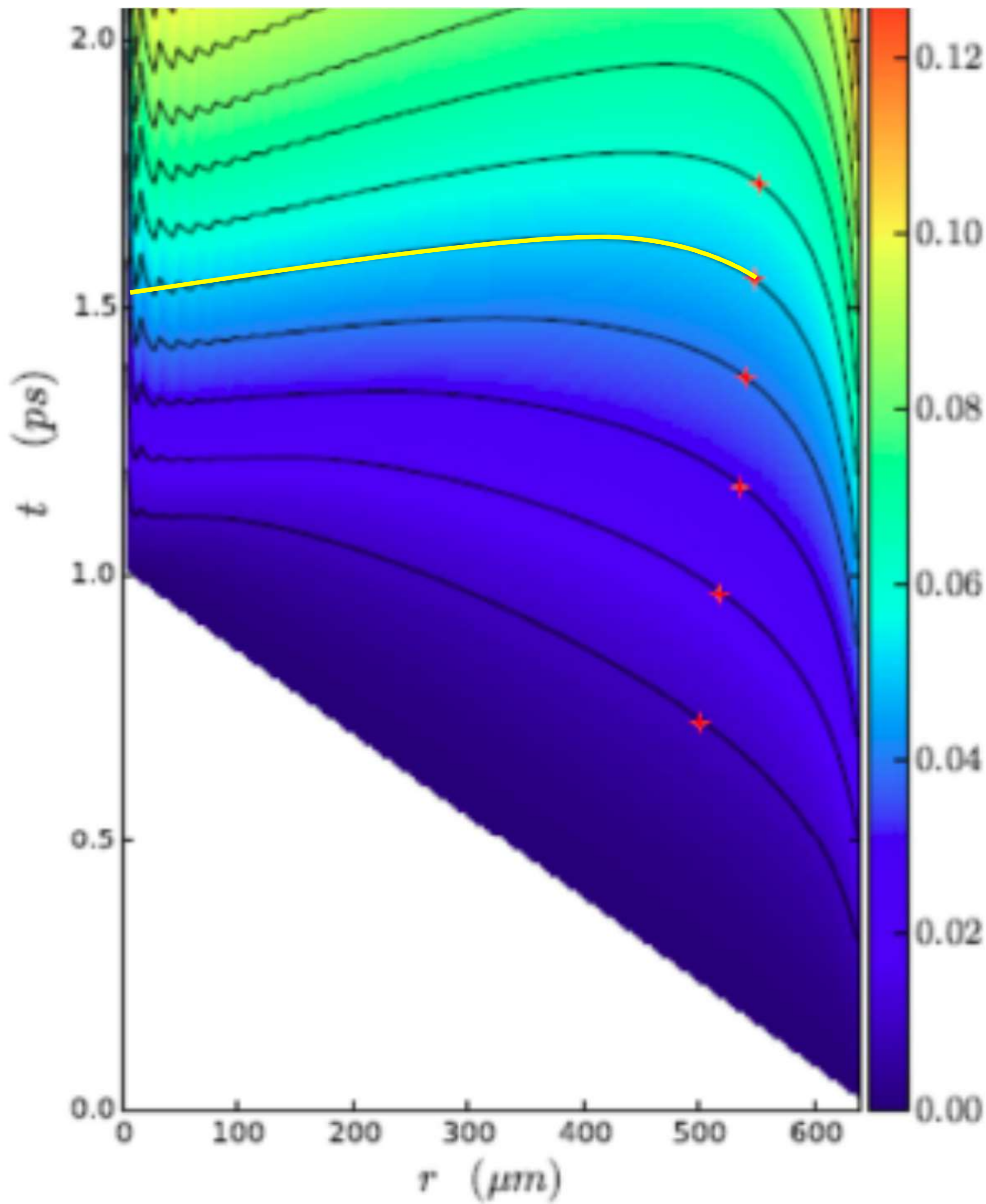
The reflectivity of the target can be made negligible, and the **absorptivity can be increased by one to two orders of magnitude** by the plasmonic nano-shells embedded in the target fuel.

Thus higher ignition temperature can be achieved with no or modest compression. The **short light pulse** can heat the target so that most of the interior will reach the ignition temperature simultaneously.

This **prevents** the development of any kind of mechanical or pressure **instability**, which would prevent complete ignition of the target.

Golden Nano-Shells – Resonant Light Absorption





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

r = 0, α_K = 30 cm^{-1} while at the outside edge α_K = 8 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!**

Another Option to Reach Volume Ignition
Heavy-Ion Beams – FAIR & NICA

- Energy deposition by heavy ion beams – Bragg peak!
- Absorption depth can be tuned! ➔
- Beam bunch energy distribution could be achieved
- Present Bunch length is ~ 70 ns
- Bunch length of 10 ps may be reached [B. Shakov, p.c.]
- ➔ **Proposal(s), Patent(s) ???**

Thus, ultra-relativistic heavy ion physics did not only lead to fundamental discoveries, as the **EoS and transport** properties of Quark Gluon Plasma (QGP),

but also to advances in relativistic fluid dynamics (RFD), which may revolutionize the technological development of **Inertial Confinement Fusion** research and other dynamical radiation dominated processes.

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