Laser-driven inertial confinement fusion: principles, status and perspective for energy production after the achievement of ignition at the NIF

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23 gennaio 2023

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The New York Times

December 13, 2022

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

The advancement by Lawrence Livermore National Laboratory researchers will be built on to further develop fusion energy research.

https://www.nytimes.com/2022/12/13/science/nuclear-fusion-energy-breakthrough.html

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THE TIMES OF INDIA

December 13, 2022

Here comes the Sun: Breakthrough in nuclear fusion

https://timesofindia.indiatimes.com/world/rest-of-world/here-comes-the-sun-breakthrough-in-nuclear-fusion/articleshow/96180155.cms https://www.lastampa.it/esteri/2022/12/13/news/gli_usa_annunciano_la_svolta_storica_sulla_fusione_nucleare-12410485/

Gli Usa annunciano la "svolta storica" sulla fusione nucleare. Il fisico Atzeni: "Ci vorranno 30 anni perché diventi realtà"

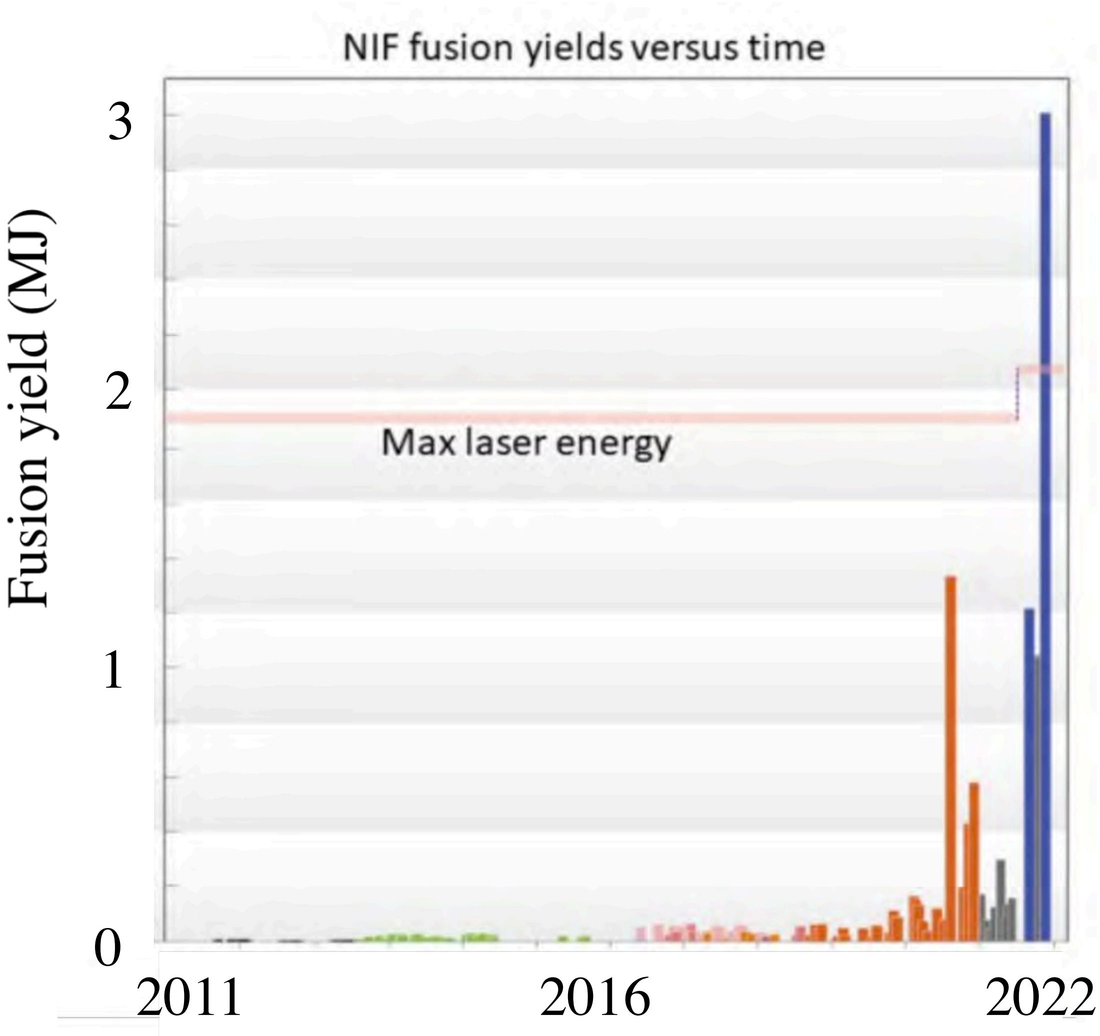
> "Last week at the Lawrence Livermore National Laboratory in California, scientists at the National Ignition Facility achieved fusion ignition. And that is creating more energy from fusion reactions than the energy used to start the process. It's the first time it has ever been done in a laboratory anywhere in the world. Simply put, this is one of the most impressive scientific feats of the 21st century."

U.S. Secretary of Energy Jennifer Granholm
DOE Press Conference Announcing Major Nuclear Fusion Breakthrough
December 13, 2022

Aug. 8, 2021: Fusion yield = 1.3 MJ

Dec. 5, 2022: Fusion yield = 3.1 MJ

	Up to 2020	**2021**	**2022**
Target gain	< 0.07	0.7	1.5
Peak T	4.5 keV	9 keV	
Fuel burn-up	0.2%	2%	3%



From:
Inertial Fusion Energy – Report of the Fusion Energy Sciences Basic Research Needs Workshop – draft Jan. 17, 2023

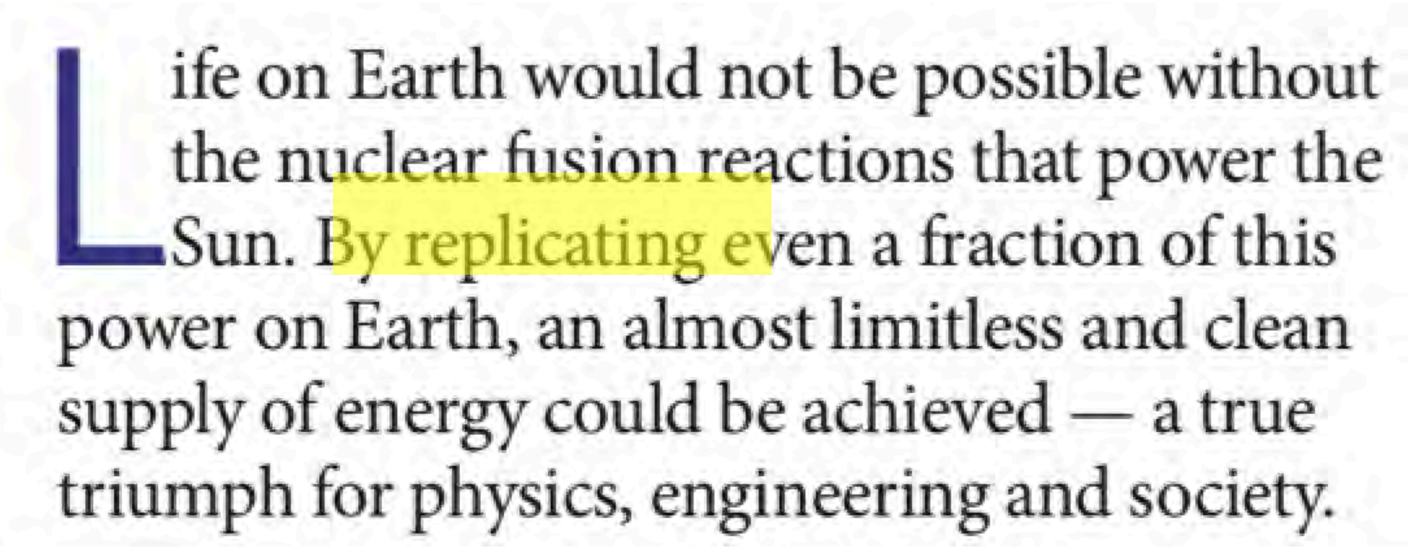
Summary

Laser-driven inertial fusion

- Principles
- Main issues
- Ignition experiments
- Alternative schemes (Fast- and Shock-ignition)
- Towards inertial fusion energy
- Perspective and conclusions

Thanks to:
Angelo Schiavi for continuous collaboration
Colleagues and collaborators cited in the presentation

Partially funded by Sapienza projects and Eurofusion Enabling Research Projects ENR-IFE19.CEA-01 and CfP-FSD-AWP21-ENR-01



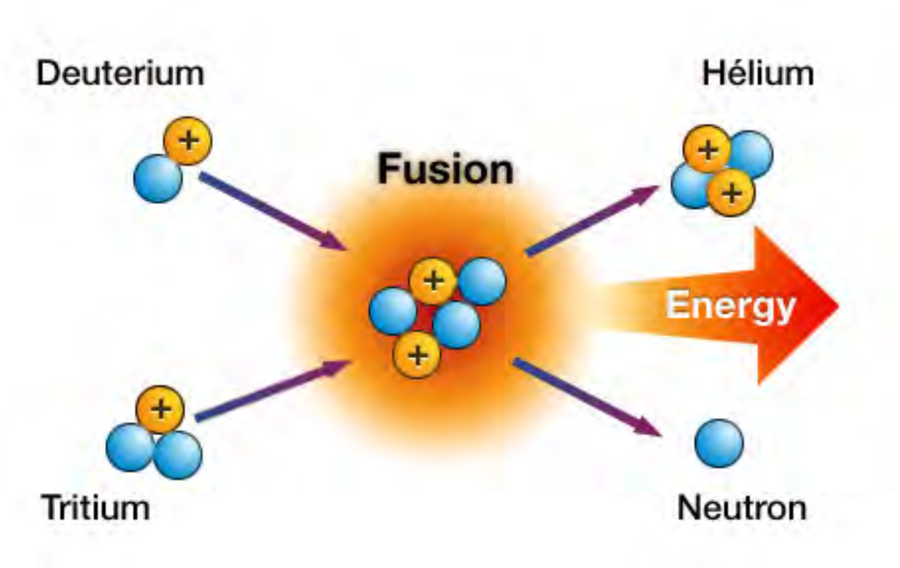
Life on Earth would not be possible without the nuclear fusion reactions that power the Sun. By replicating even a fraction of this power on Earth, an almost limitless and clean supply of energy could be achieved — a true triumph for physics, engineering and society.

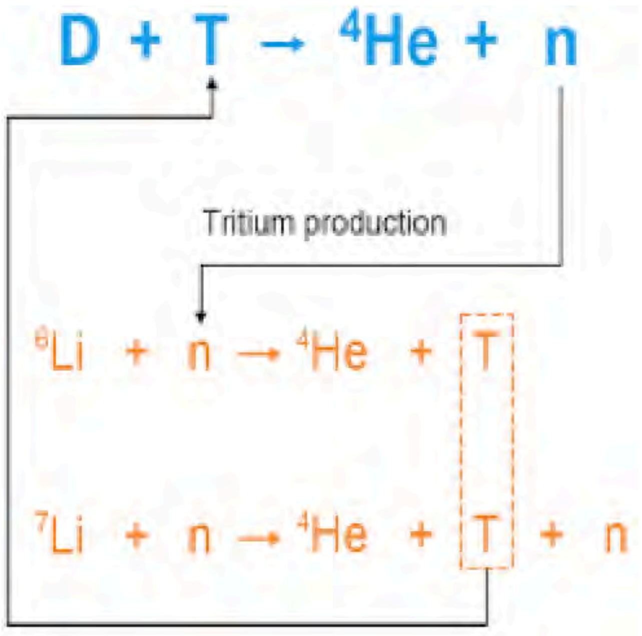
B. Verbeck and A. Taroni, *Nature Phys*. **12**, May 2016

Actually, achieving fusion on Earth is not just "replicating" the Sun

	Sun	**Laboratory/Reactor**
fuel	hydrogen	deuterium-tritium
temperature	$\leq 1.5 \times 10^7$ K	$\geq 10 \times 10^7$ K
confinement	gravitational	magnetic (MCF) inertial (ICF) combined (MagLIF)
	opaque	transparent
pressure	**250 Gbar**	**400 – 500 Gbar in ICF**

Deuterium – Tritium reaction, and Tritium breeding





$D + T \rightarrow {}^{4}He + n$

Tritium production

${}^{6}Li + n \rightarrow {}^{4}He + T$

${}^{7}Li + n \rightarrow {}^{4}He + T + n$

Released energy (Q):

17.6 MeV/reaction

= 340 GJ/g

= 8.1 tep/g

Deuterium and lithium raw materials for DT fusion energy

(D + T --> α + n + 17.6 MeV)

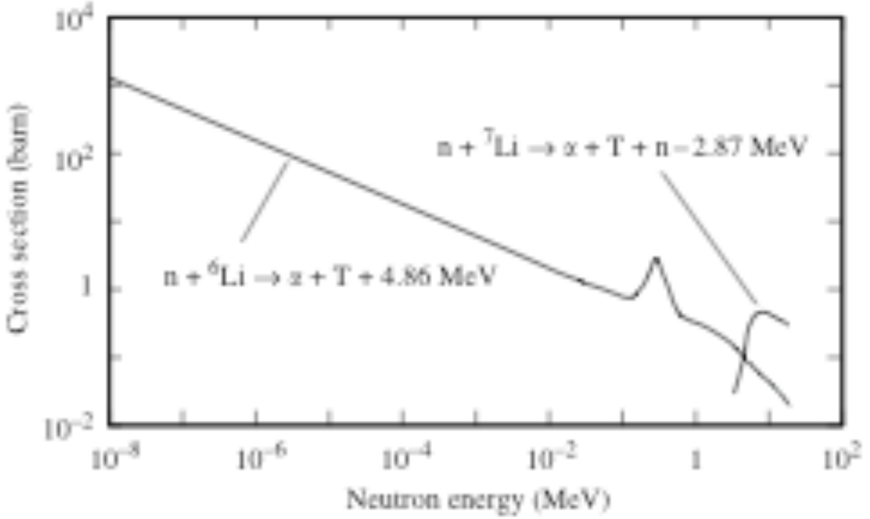
- Deuterium from water: 37 g of D per 1000 kg of water;
  cost: 4000 $/kg

- Tritium bred from Lithium by DT fusion neutrons;

  Lithium reserves: 12 Mt in the earth crust; 10^{11} t in the oceans
  (present production 106 kt/year)

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + \alpha + 4.86\ \mathrm{MeV},$$

$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + \alpha + \mathrm{n} - 2.87\ \mathrm{MeV}.$$

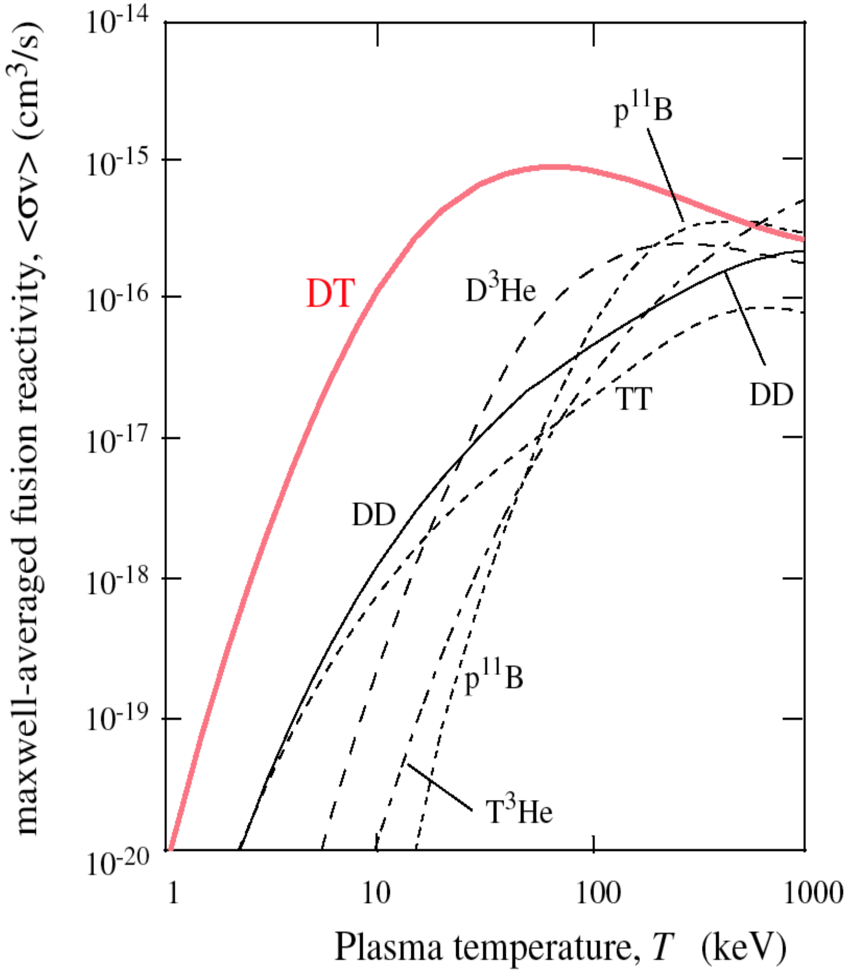


However, controlled fusion requires the achievement of extreme conditions

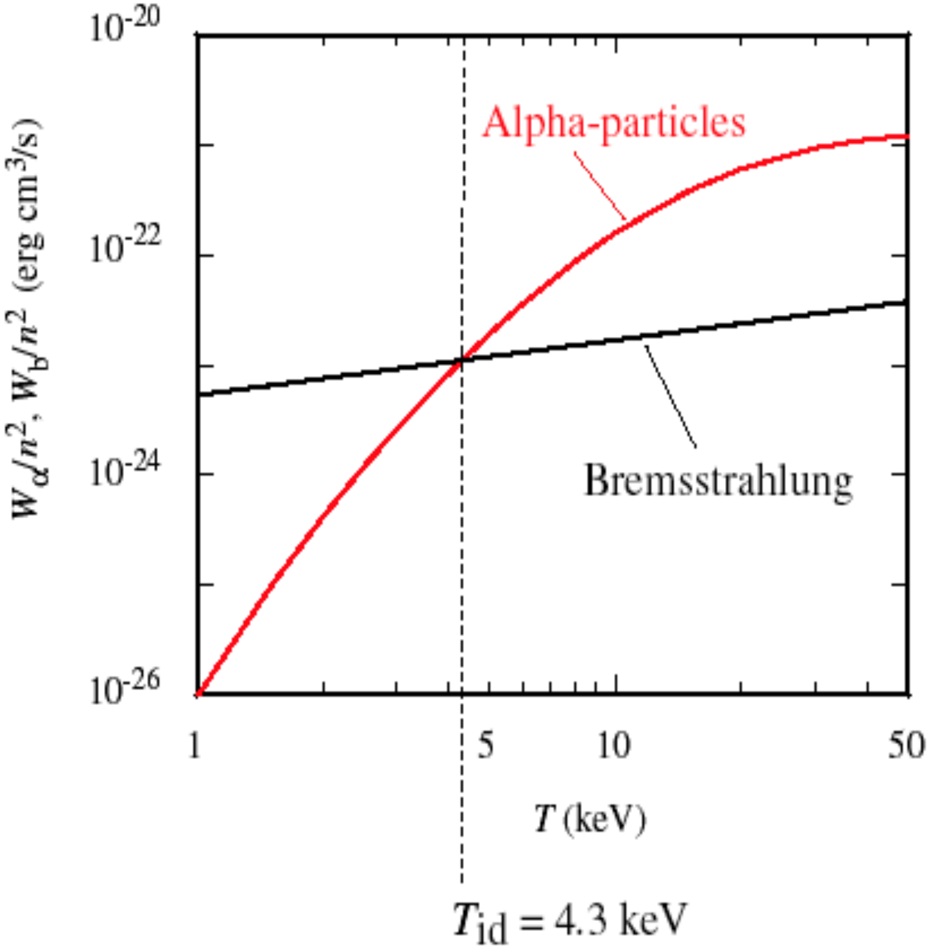
- thermonuclear reactions (no beam-target, no beam-beam)
- temperature $T \geq 5 \times 10^7$ K ==> plasma
- *confinement*:
  the reacting plasma must be kept at suitable density and temperature, and its energy/mass must be confined for a sufficiently long time τ, so that
  - in a steady reactor the released power exceeds the power spent to keep the plasma reacting
  - in a pulsed reactor the released energy per pulse exceeds the energy spent to bring the fuel to burning conditions

Even for deuterium-tritium the temperature must exceed 5 keV

D + T => α + n + 17.6 MeV
has by far the largest reactivity



at 4.2 keV fusion alpha particle power exceeds bremsstrahlung power



Inertial confinement fusion (ICF)

- **Fusion reactions**
  - **from a target containing a few mg of DT fuel**
  - **compressed to very high density (ρ > 1000 times solid density)**
  - **and heated to very high temperature**

- No external confinement => **fuel *confined by its own inertia***

  (mass) confinement time $\tau = R/c_s$,

  c_s: sound speed;
  R: linear dimension of the compressed fuel

- Explosive, **pulsed process**
  - Energy has to be provided cyclically by a suitable **driver**
  - The mass of the **fuel must be limited to about 10 mg**, in order to contain the explosion
    (1 mg of DT releases 340 MJ, equivalent to 85 kg of TNT)
    [Q_{DT} = 17.6 MeV/reaction = 340 MJ/mg = 3.4 x 10^{14} J/kg]

The essential physical ingredients of ICF:
Compression
Hot spot ignition

(homogeneous sphere of DT, radius R, density ρ)

- COMPRESSION:

  burn fraction $> 30\% \Longrightarrow \rho R > 3$ g/cm^2

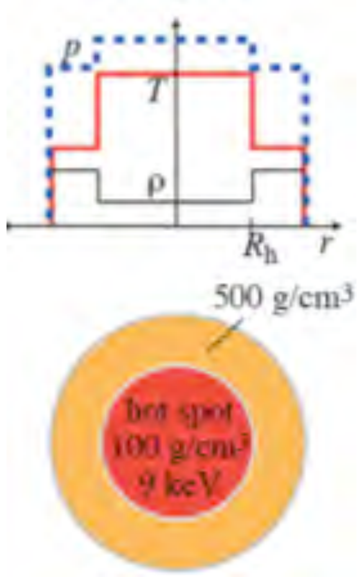
  mass $m_{DT} = (4\pi/3)\rho R^3 <$ few mg ==>

$$\boxed{\rho > \frac{300}{\sqrt{m_{DT}(\mathrm{mg})}}\ \mathrm{g/cm^3}}$$

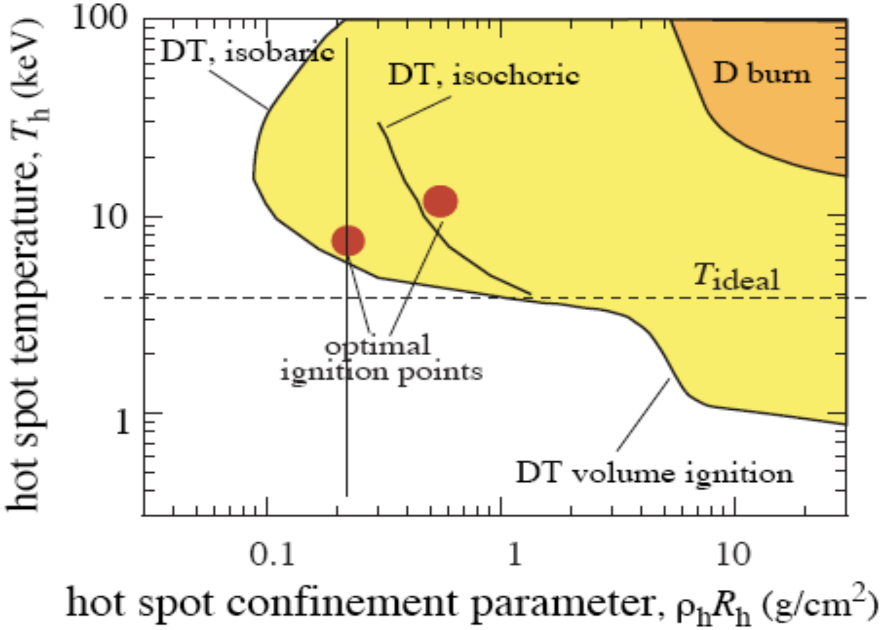
- HOT SPOT IGNITION
  - do not heat the whole fuel to 5 keV; it would cost too much!
  - heat to 5 – 10 keV the smallest amount of fuel capable of self-heating and triggering a burn wave

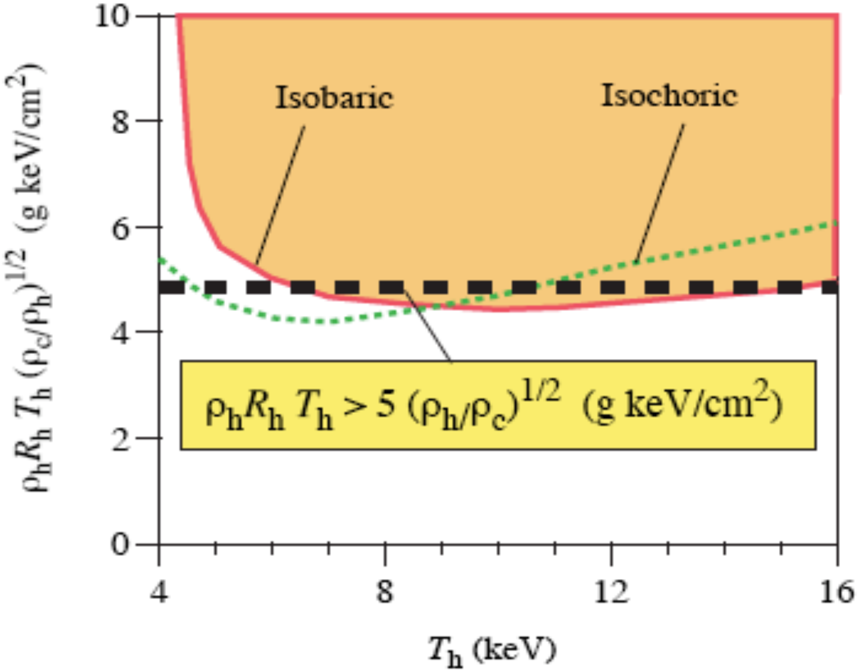
Hot spot ignition condition: Lawson-like ρ*R vs T* and ρ*RT* criteria

fuel at ignition



$T_h > 7$ keV; $\rho_h R_h > 0.25$ g/cm^2



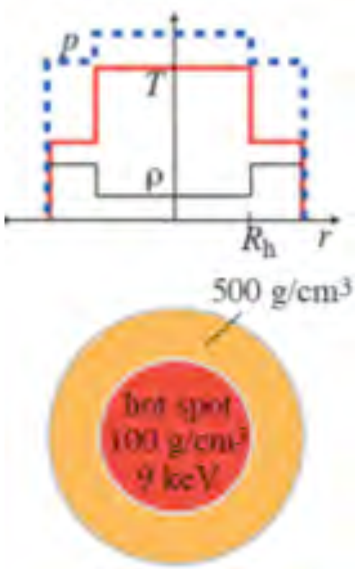


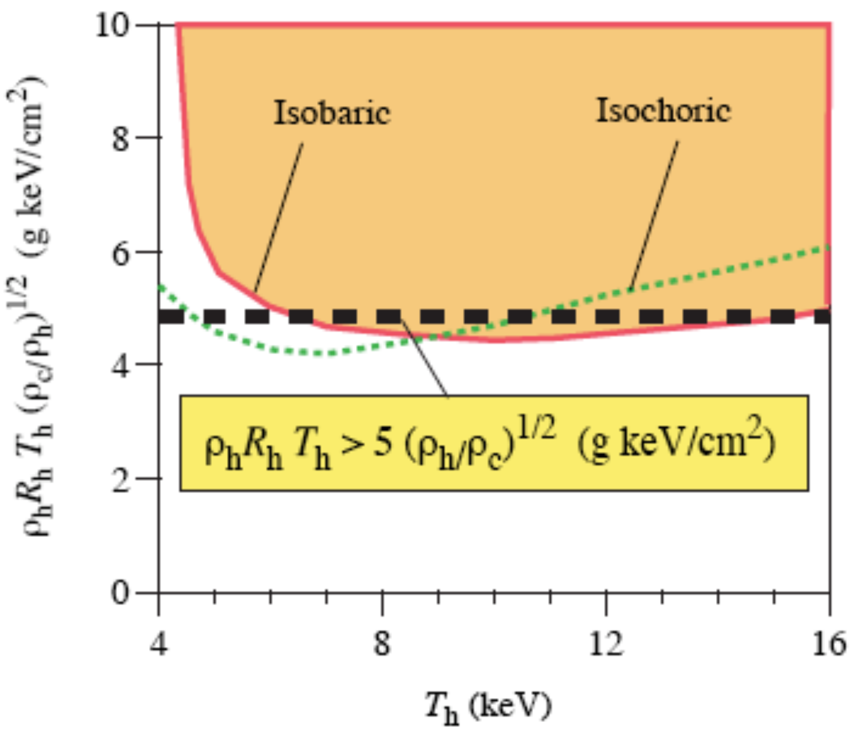
$\rho_h R_h T_h > 5 (\rho_h/\rho_c)^{1/2}$ (g keV/cm^2)

Ignition:
once the hot spot is generated, competition between heating (α-particles) and cooling (electrons, bremsstrahlung, mechanical work)

The ignition condition is
essentially a condition on the hot spot pressure

fuel at ignition





pressure for ignition:

[assuming $\rho_c/\rho_h = 5 - 7$]

$$p\ (\text{Gbar}) > \frac{500}{\left(\dfrac{R_h}{30\ \mu\text{m}}\right)}$$

S. Atzeni *et al.*, NJP (2013);
J. Lindl *et al.*, NF (2014)
P. Patel, PoP (2020)

300–500 Gbar required ≈ pressure at the centre of the Sun

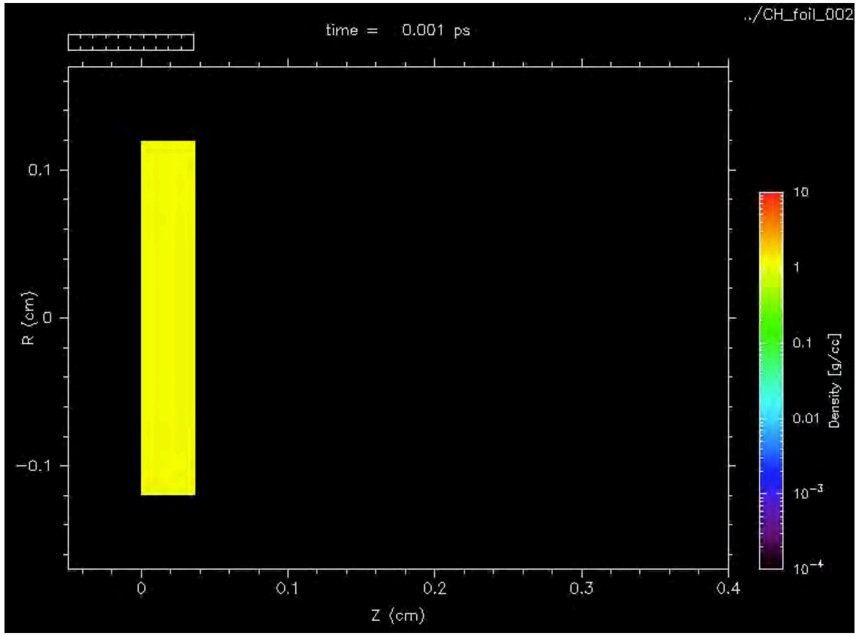
How to generate 500 Gbar?

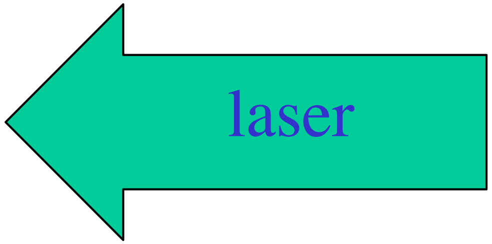
- Laser-driven or X-ray driven ablation (100 Mbar),
  => rocket

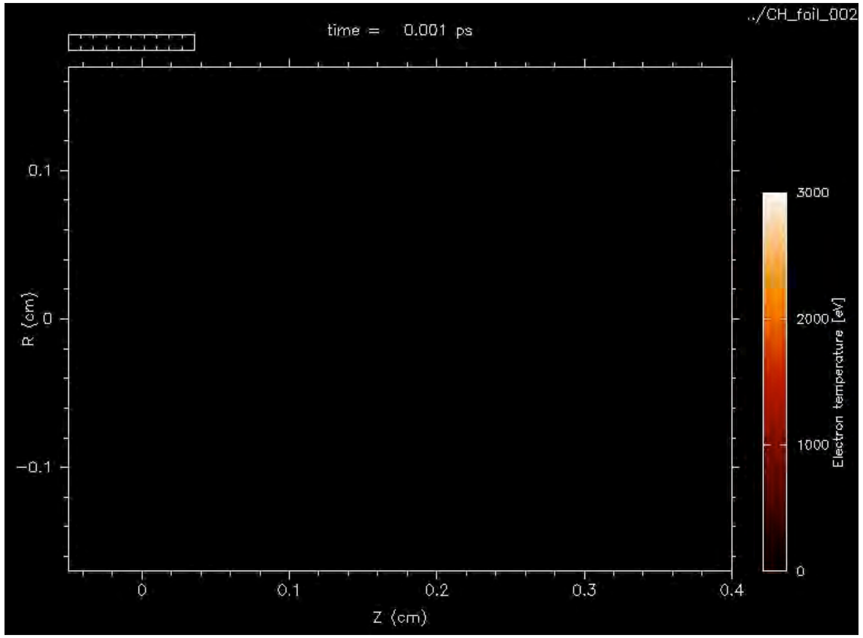
- spherical rocket

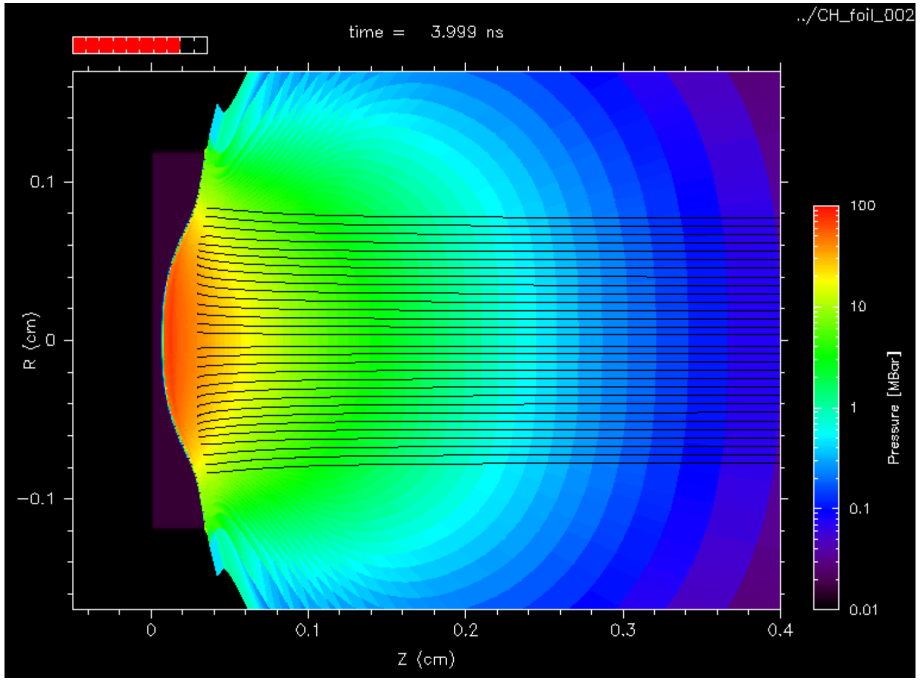
- multiplication x few 1000’s by geometrical convergence

Laser pulse on a solid: : pressure up to 100 Mbar

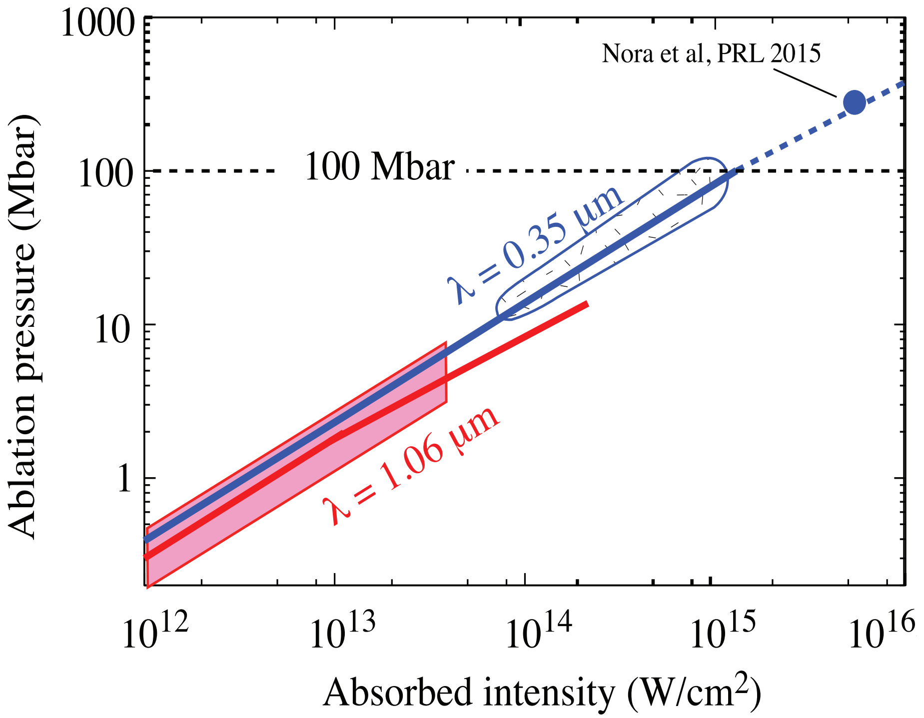


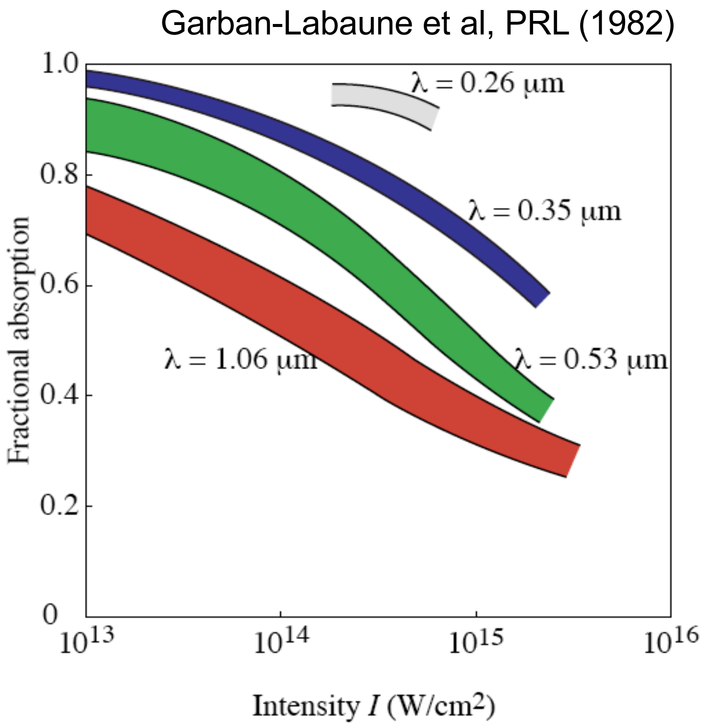






Laser drive can generate pressure of 100 Mbar

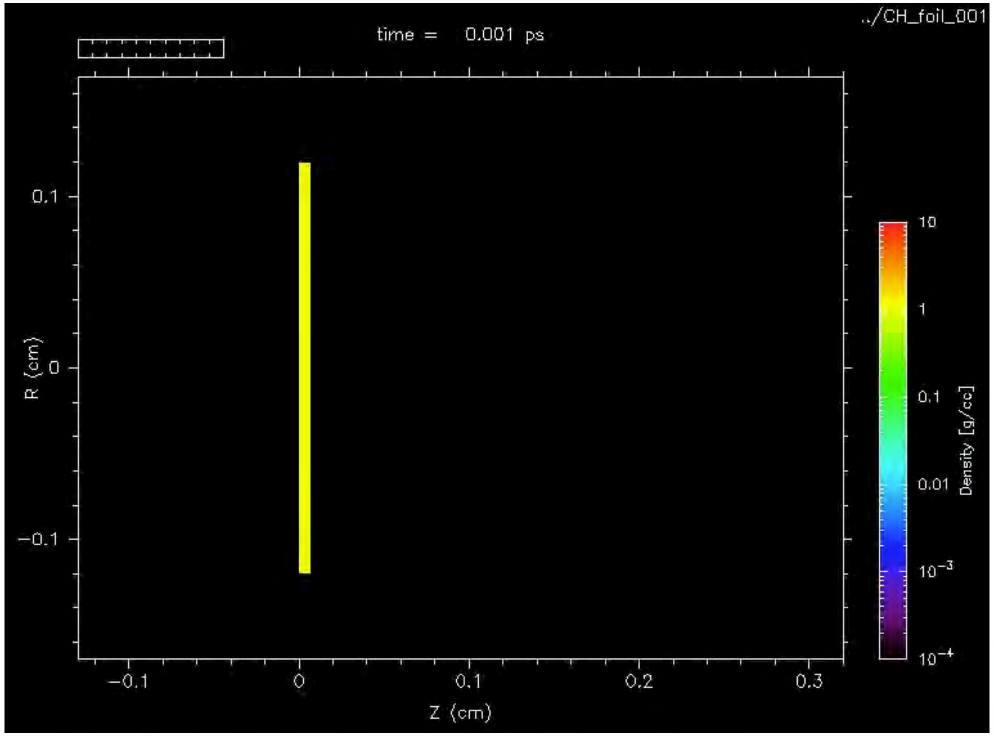


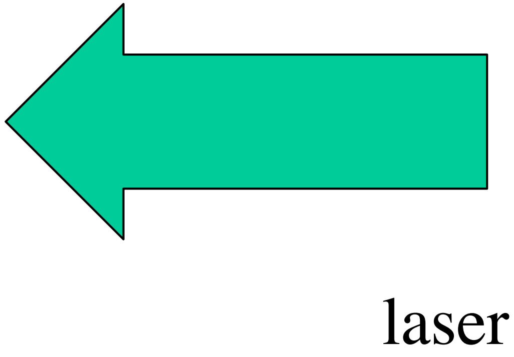


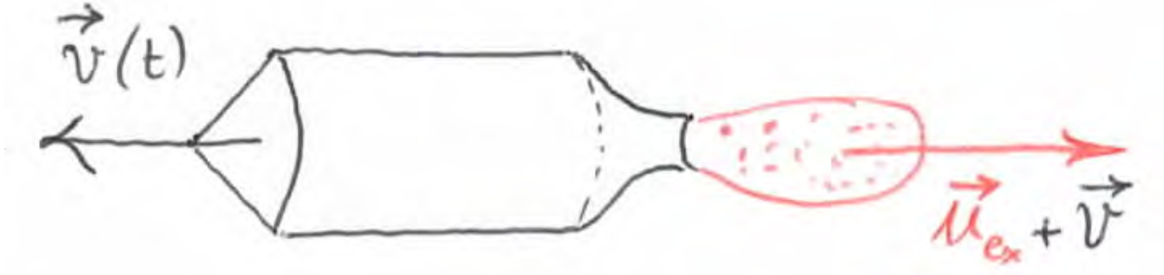
uv light required for efficient absorption

> 100 Mbar also obtained with thermal X-rays (with T = 300 eV)
[see e.g. Lindl, Phys. Plasmas (1995)]

Laser-driven rocket







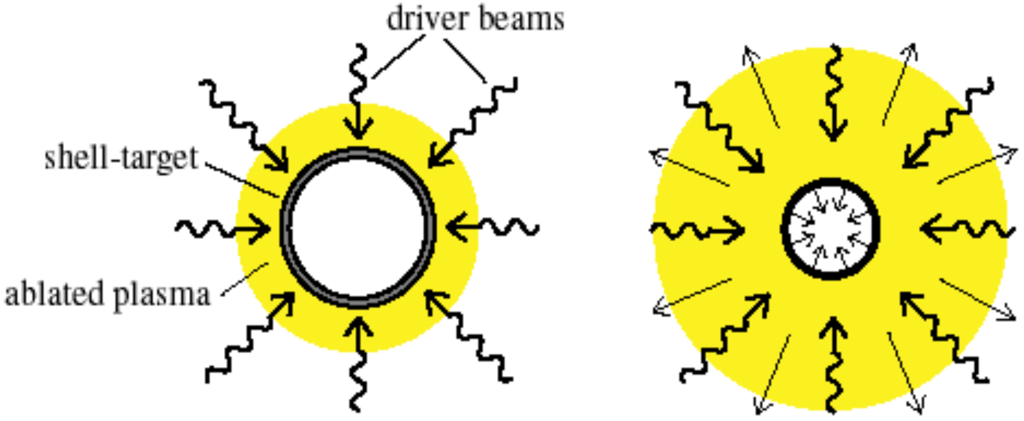
$$\mathbf{v}(t) = -\mathbf{u}_{ex} \ln \frac{m_0}{m(t)}$$

400 km/s “easily” achievable; efficiency is quite low (5–15%)

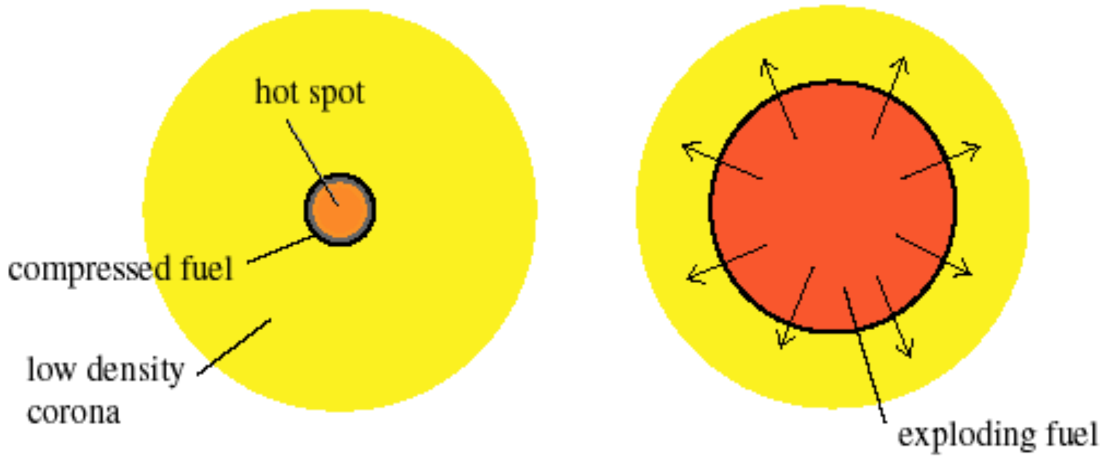
ICF by a laser-driven imploding spherical rocket:

Imploding fuel kinetic energy converted into internal energy and concentrated in the centre of the fuel

(a) irradiation **(b) implosion driven by ablation**



(c) central ignition **(d) burn and explosion**



implosion velocity for ignition:

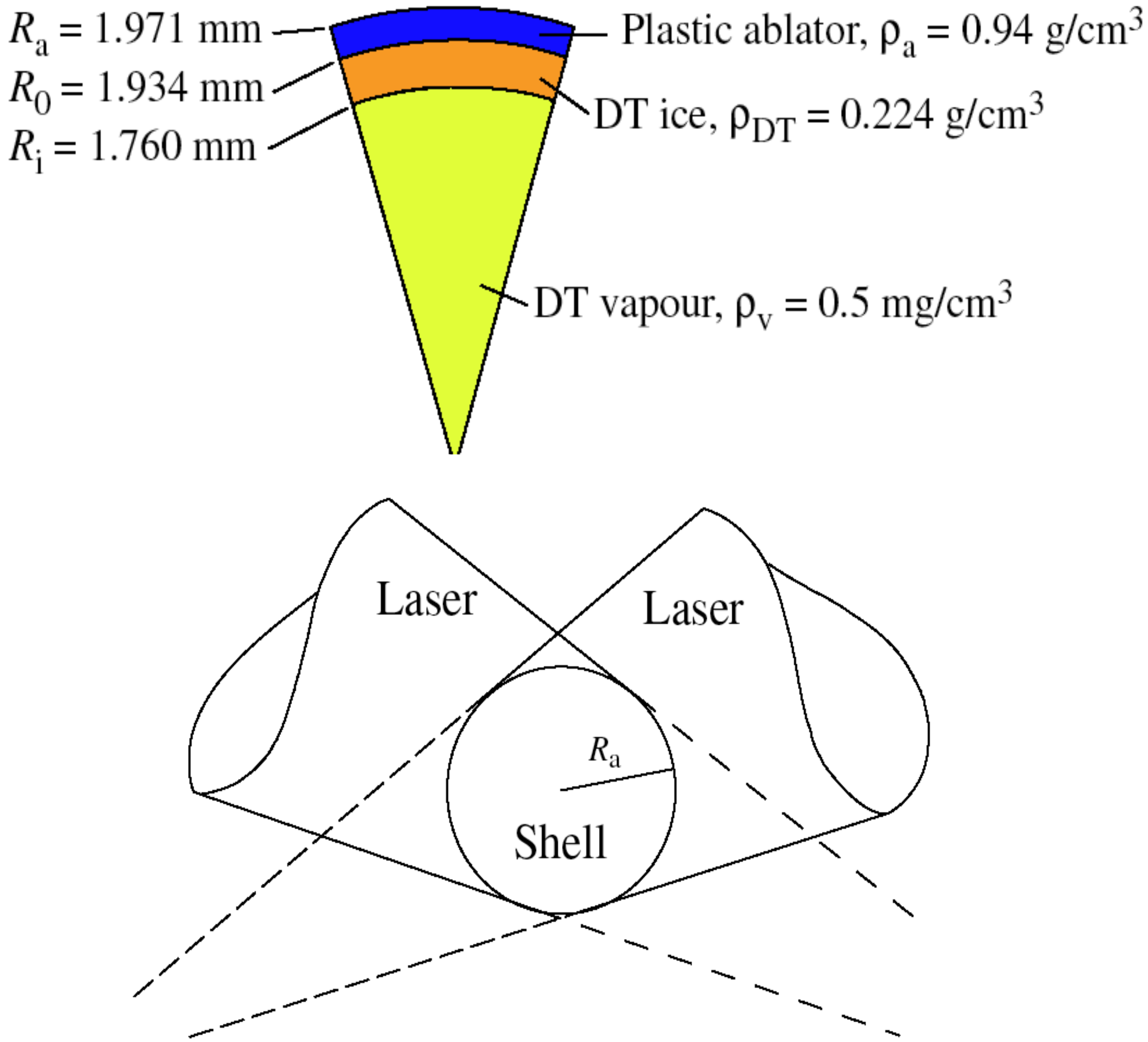
$u_{\mathrm{imp}} > 300 - 400$ km/s

depending of the fuel mass:

$u_{\mathrm{imp}} \propto m^{-1/8}$

(see, e.g., S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion, Oxford University Press, 2004)

Target (in the simplest scheme): hollow shell, irradiated by a large number of overlapping beams



Target (hollow shell)

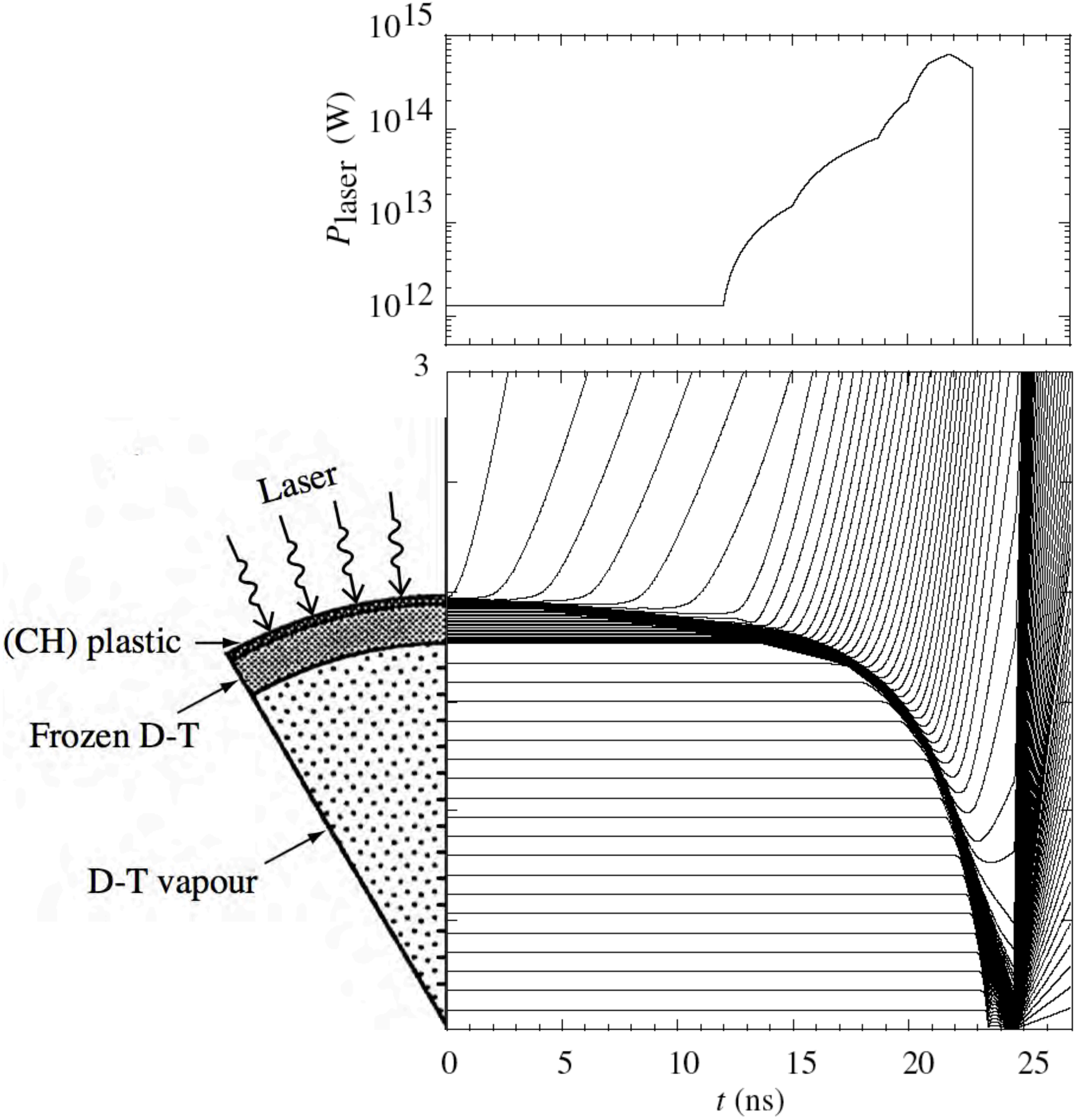
- Fuel mass: few mg
- Radius: 1 – 3 mm
- Fuel radius / thickness = 10

Laser driver pulse

- Energy: 1 – 5 MJ
- Duration: 10 – 20 ns
- Peak power: 300 – 500 TW
- Peak intensity: 10^{15} W/cm^2
- Wavelength: (1/4) – (1/3) μm

Compressed fuel

- Density: 200 – 1000 g/cm^3
- Low average entropy, but hot-spot with T = 10 keV



Laser power vs time
(notice the log scale)

1-D
“Flow chart”

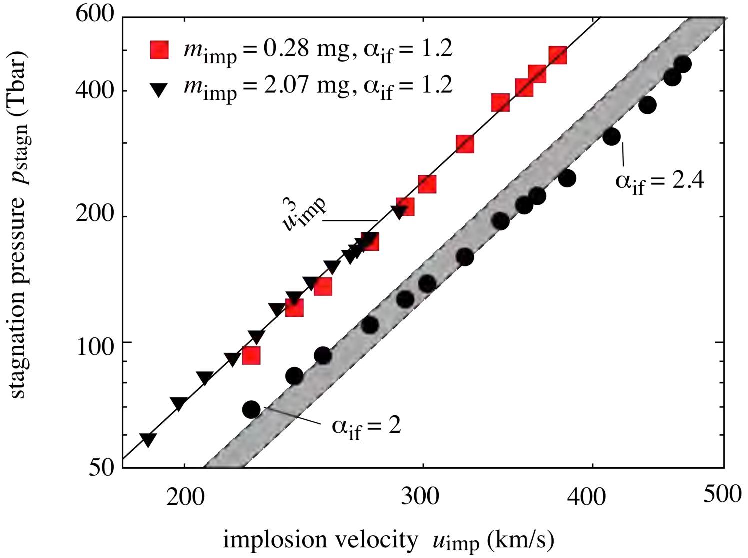
=

Diagramma orario

Central ignition relies on large implosion velocity

Hot Pressure at stagnation is a strong function of the implosion velocity

$$(p \sim u_{\mathrm{imp}}^{3}\, \alpha_{\mathrm{if}}^{-0.9})$$



==>

High implosion velocity required for standard ignition:

$u_{\mathrm{imp}} > 300 – 400$ km/s

depending of the fuel mass and on the compressed fuel in-flight isentrope:

$$u_{\mathrm{imp}} \propto m^{-0.15} \quad \alpha_{\mathrm{if}}^{2/9}$$

==>

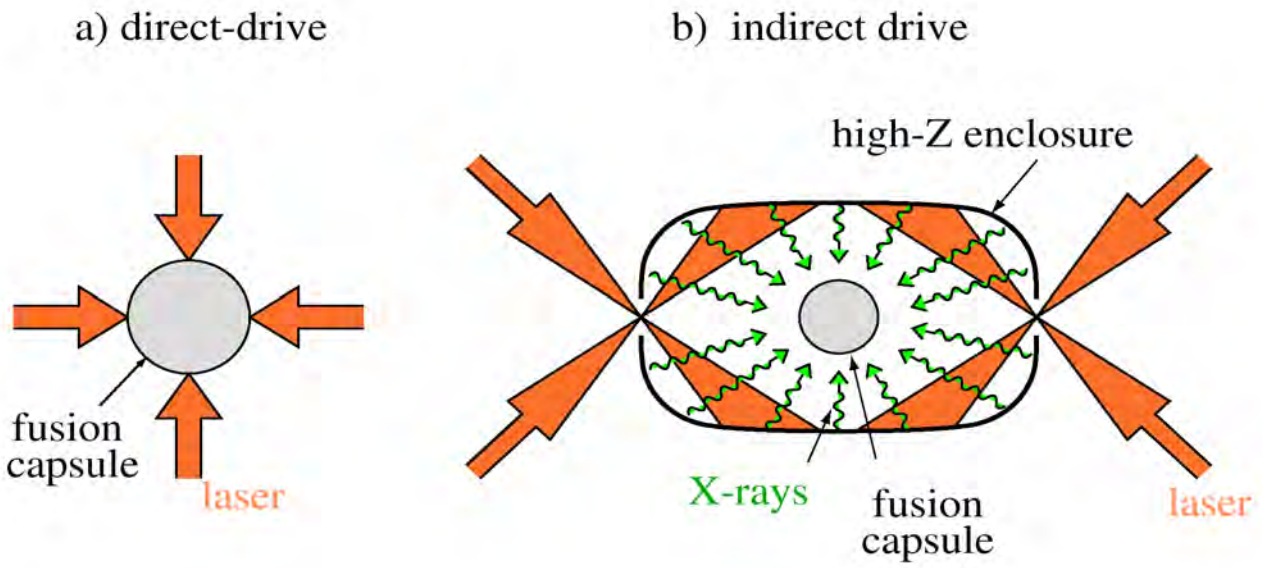
required laser energy decreases strongly with increasing implosion velocity

$$E \propto u_{\mathrm{imp}}^{-6}\, \alpha_{\mathrm{if}}^{1.8}\, p_{\mathrm{abl}}^{-0.8}$$

Herrmann, Tabak, Lindl, *NF* **41**, 99 (2001); Atzeni & Meyer-ter-Vehn, *Nuclear Fusion* (2001);
Kemp, MtVm SA, *Phys. Rev. Lett.* (2001)

direct drive and indirect drive

In indirect drive, the fuel containing capsule is irradiated by thermal X-rays (200-300 eV), generated and confined in a cavity (hohlraum).



Indirect-drive

pros: reduced RTI growth

short-scale irradiation uniformity

Cons: lower efficiency (≈5 times smaller than in direct-drive)

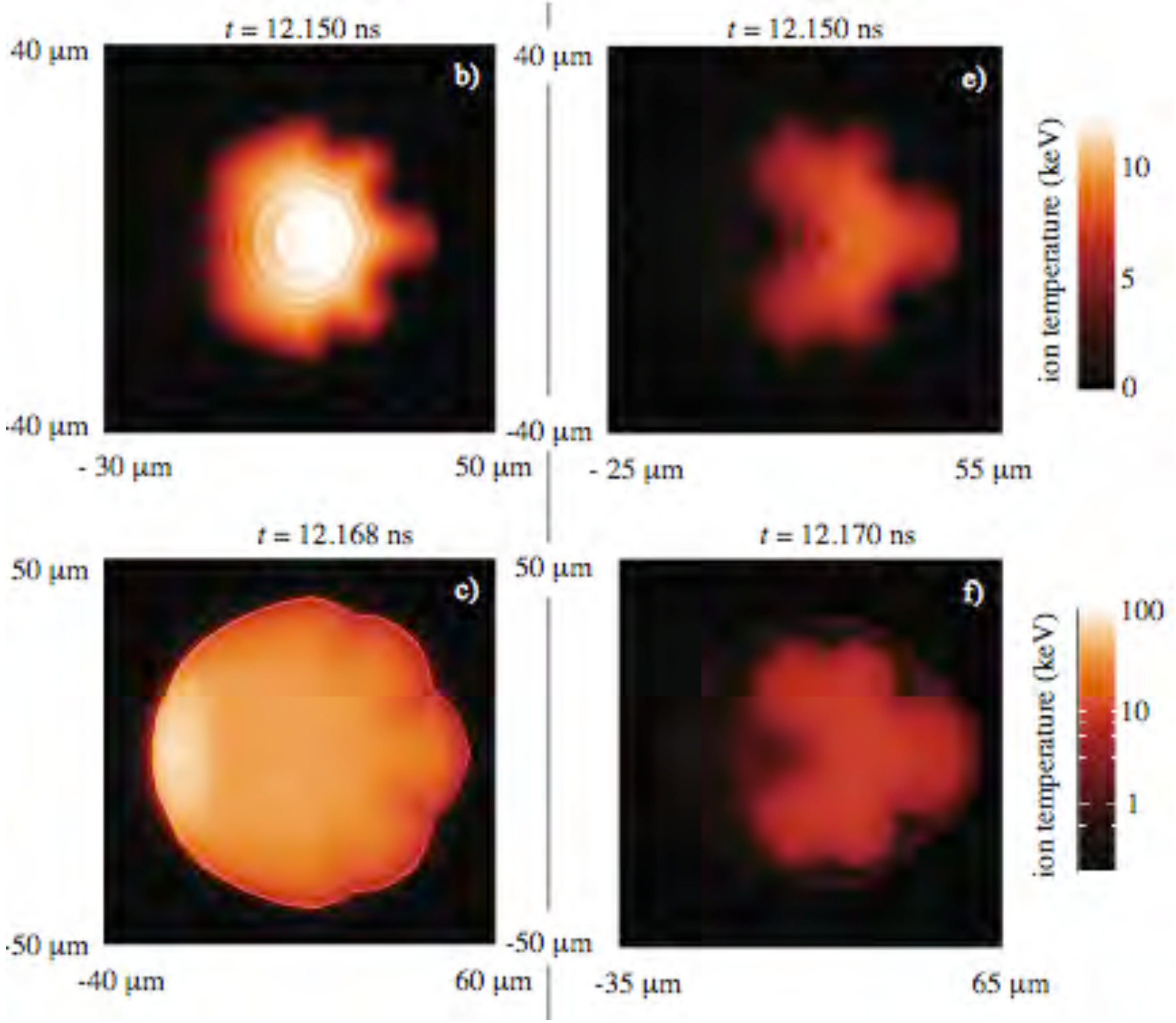
Laboratory Inertial Confinement Fusion (ICF) essentials

Four basic requirements

- Implosion velocity u_{imp} of 300 – 400 km/s:
  100 Mbar pressure, efficient “rocket acceleration”
  => uv radiation or X-rays, $I = 10^{15}$ W/cm^2
- Low-entropy compression (low “adiabat” $\alpha = p/p_{\text{Fermi-degenerate}}$)
  => **accurate temporal pulse shaping**
- Symmetric implosion => **uniform irradiation**
- **Control of Rayleigh-Taylor instability (RTI):**
  conflicts with previous requirements:
  RTI growth increases with increasing u_{imp} and decreasing α

symmetry: requires uniform illumination, as well as accurate target positioning

small mispositioning can lead to failure



10 µm displacement

Gain = 95% of 1D gain

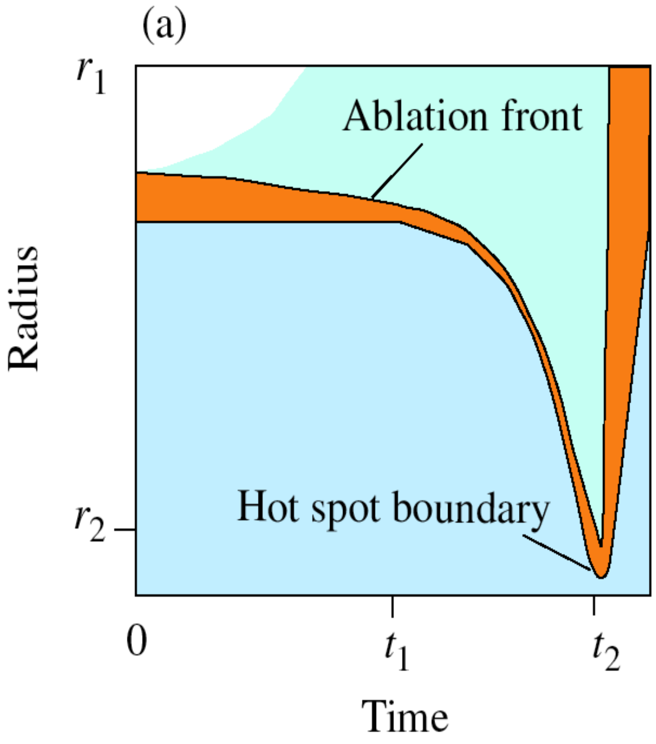
20 µm displacement

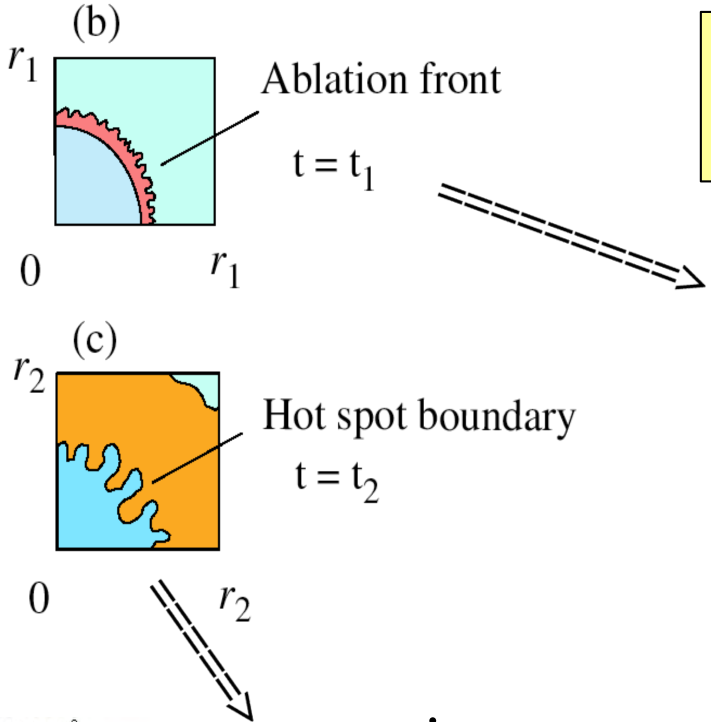
Gain = 1% of 1D gain

S. Atzeni, A. Schiavi, A. Marocchino, *Plasma Phys. Controll. Fusion* 2011

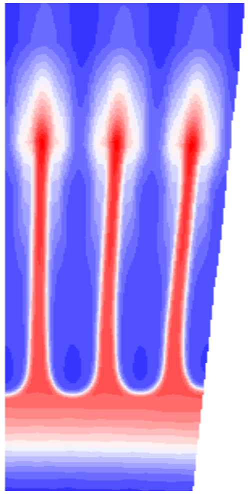
Rayleigh-Taylor instability
unavoidable in inertial fusion

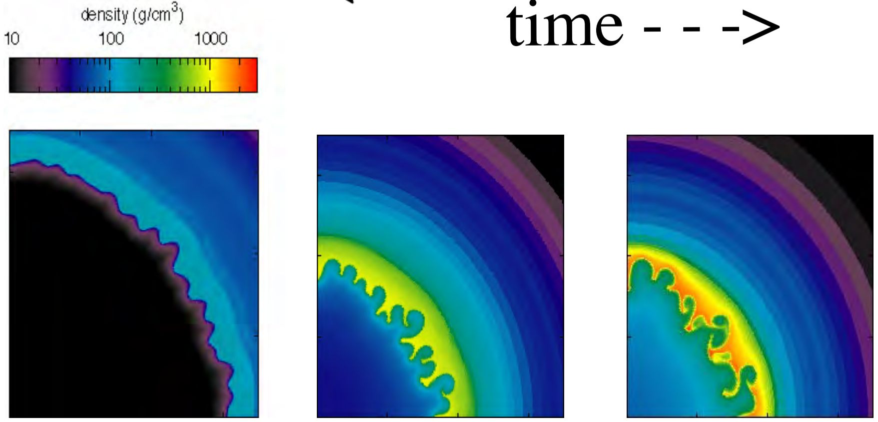
The more dangerous the larger the implosion velocity





Shell corrugation
(breaking?)





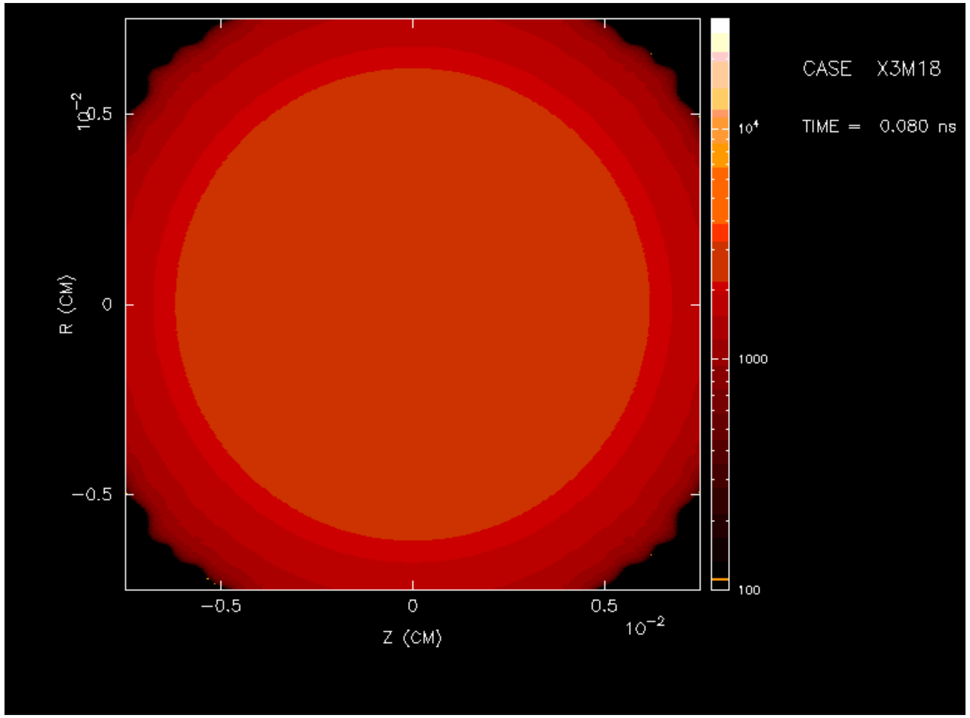
deceleration-phase instability
at the hot spot boundary

hot spot deformation

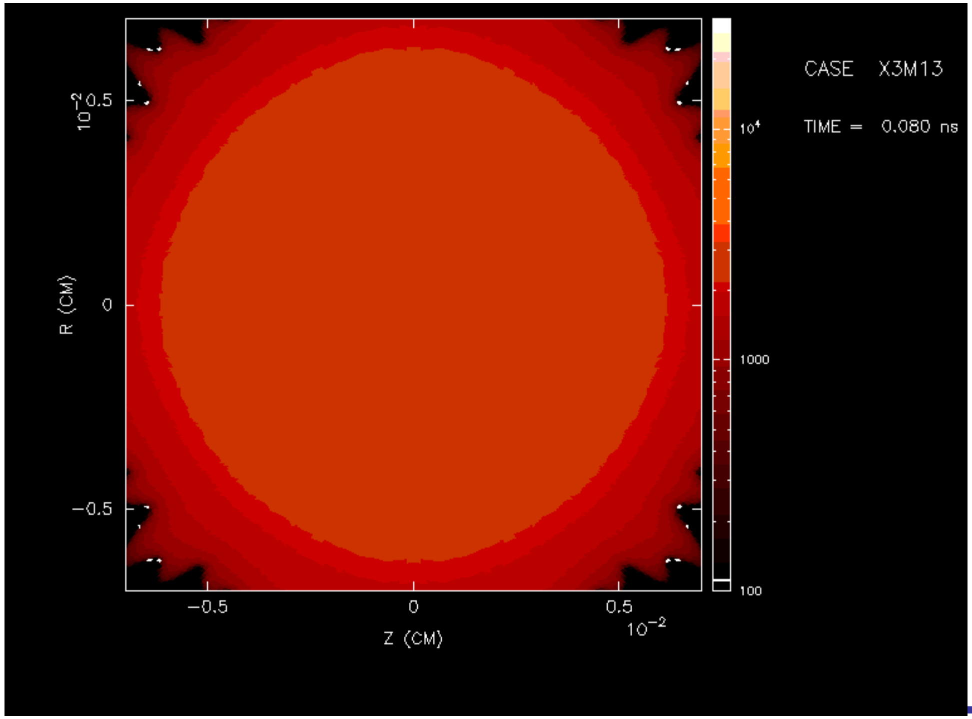
Atzeni & Schiavi, PPCF 2004

RTI hinders hot spot formation

Here simulations assuming initial multimode spectrum on the inner surface of the shell



“moderate” initial amplitude (1.5 μm rms) at the end of the implosion coasting stage:
⇒ deformed hot spot;
⇒ ignition still occurs



“large” initial amplitude (6 μm rms):
⇒ hot spot NOT formed

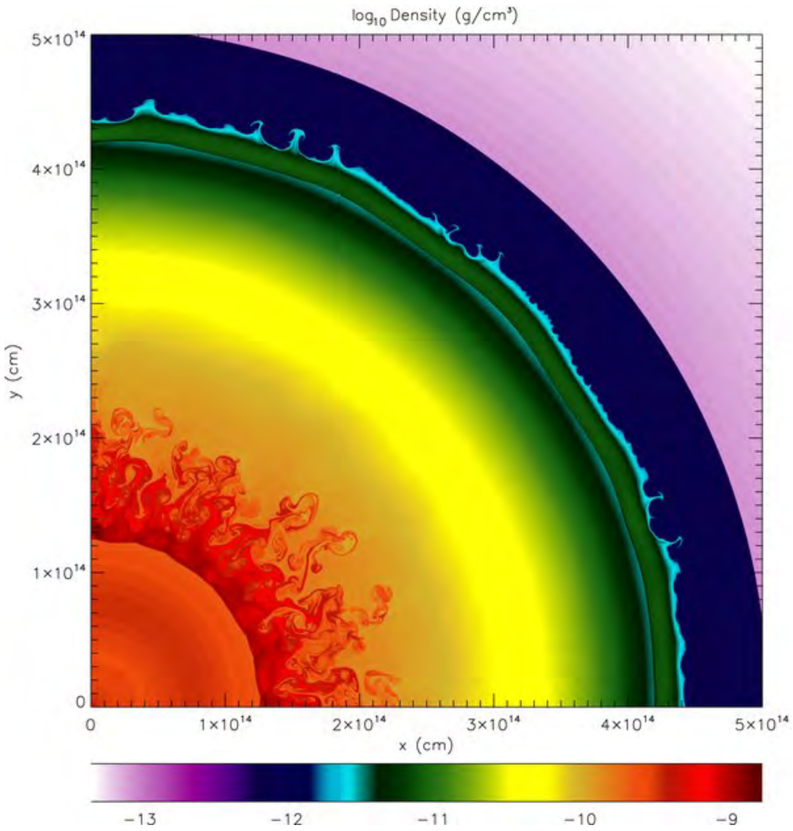
Ion temperature (eV) map evolution

movies by S. Atzeni and A. Schiavi, 2004

Similar processes, with scales differing by 18 orders of magnitude:

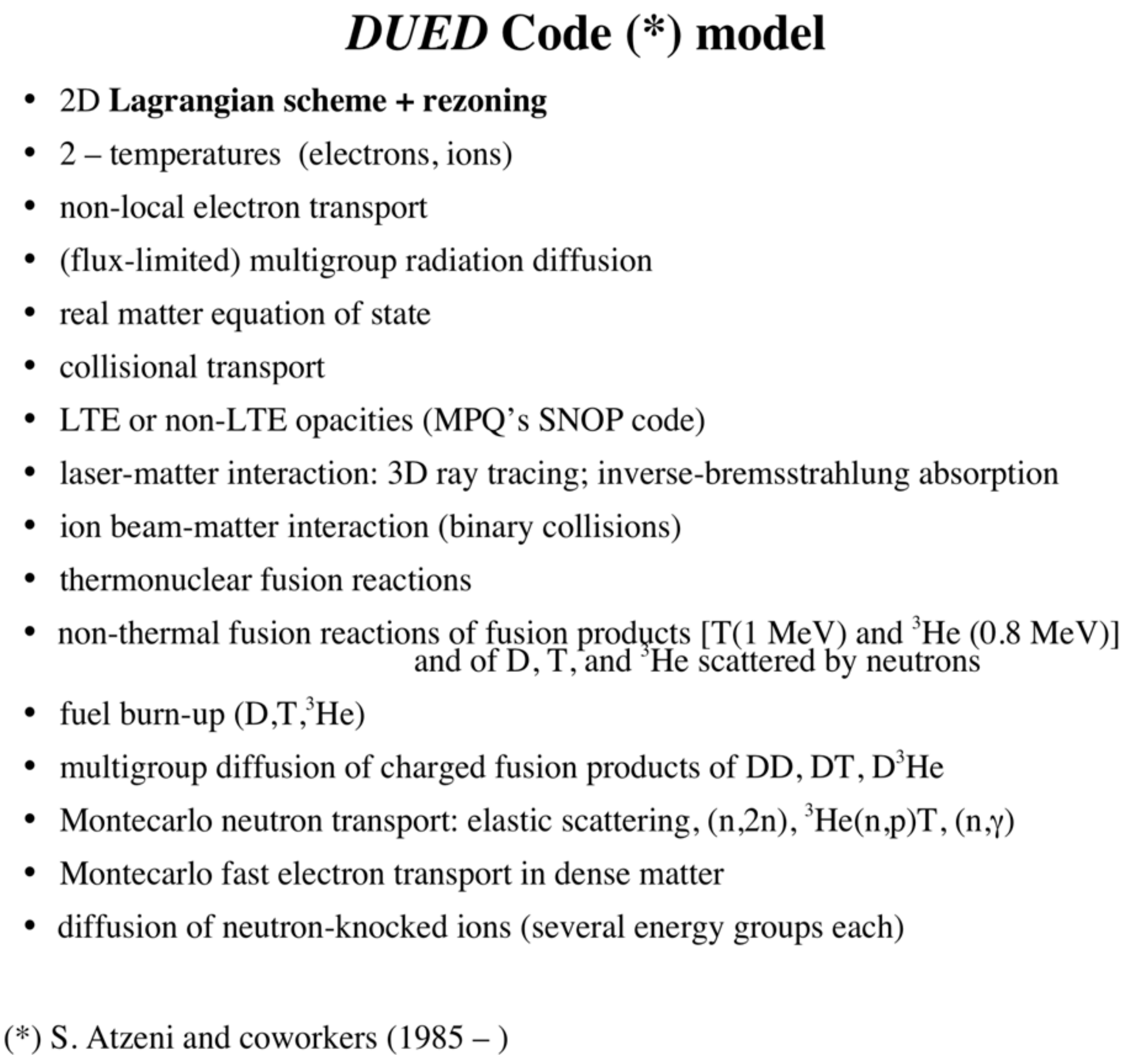
- laser driven inertial fusion capsule (left)
- supernova (right)

S. Haan, *Nucl. Fusion*, **44**, S171 (2004);
shell diameter: 90 micrometers



C. C. Joggerst et al., *Astroph. J.* **693**, 1780 (2009)
frame size: 5*10^9 km

ICF target simulation codes include a lot of physics and must resolve “small” scales



DUED Code (*) model

- 2D **Lagrangian scheme + rezoning**
- 2 – temperatures (electrons, ions)
- non-local electron transport
- (flux-limited) multigroup radiation diffusion
- real matter equation of state
- collisional transport
- LTE or non-LTE opacities (MPQ’s SNOP code)
- laser-matter interaction: 3D ray tracing; inverse-bremsstrahlung absorption
- ion beam-matter interaction (binary collisions)
- thermonuclear fusion reactions
- non-thermal fusion reactions of fusion products [T(1 MeV) and ^{3}He (0.8 MeV)] and of D, T, and ^{3}He scattered by neutrons
- fuel burn-up (D,T,^{3}He)
- multigroup diffusion of charged fusion products of DD, DT, D^{3}He
- Montecarlo neutron transport: elastic scattering, (n,2n), ^{3}He(n,p)T, (n,γ)
- Montecarlo fast electron transport in dense matter
- diffusion of neutron-knocked ions (several energy groups each)

(*) S. Atzeni and coworkers (1985 –)

Testing ignition

≈ 1995: experimental, theoretical, computational data base,
supporting design of ignition experiments (Lindl, PoP 1995)

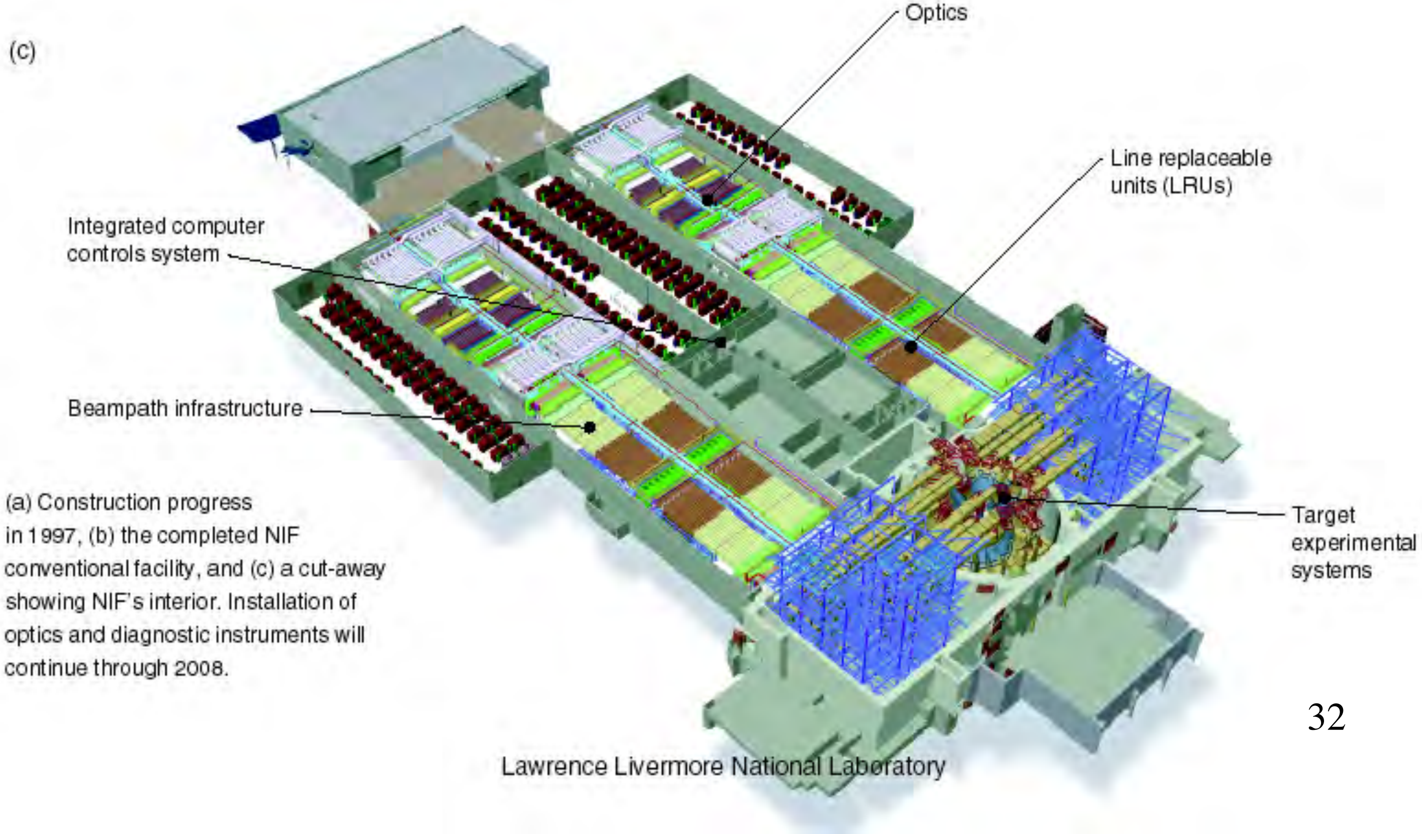
Indirect drive: weaker RTI, low sensitivity to beam non-uniformities

Required laser pulse:
1.8 MJ – 500 TW; vuv (0.35 μm), accurate pulse shaping (**NIF laser**)

fuel mass $m_{DT} = 0.17$ mg
implosion velocity $u = 370$ km/s; adiabat $\alpha = 1.5$

objective: $Y > 15$ MJ (gain $G \geq 10$)
fuel at ignition:
hot spot pressure > 350 Gbar; $\langle \rho R \rangle = 1.5$ g/cm^2;
peak density = 1000 g/cm^3

NIF Laser



(a) Construction progress in 1997, (b) the completed NIF conventional facility, and (c) a cut-away showing NIF's interior. Installation of optics and diagnostic instruments will continue through 2008.

Lawrence Livermore National Laboratory

Laser NIF

- laser a vetro:Nd, con triplicazione di frequenza ($\lambda = 0.35\ \mu$m)
- energia totale per impulso: 1.9 MJ
- potenza di picco: 500 TW
- 192 fasci, focalizzabili con errore < 50 μm
- potenza (di ciascun *bundle* di fasci) programmabile nel tempo (range dinamico 1:100);
- funziona meglio delle specifiche di progetto!
- costruito fra il 1998 e il 2009; opera a piena potenza dal 2011
- costo: 4 G$; finanziato dal Defence Program del DoE (ora dalla NNSA del DoE)

NIF hohlraum
coupling & symmetry

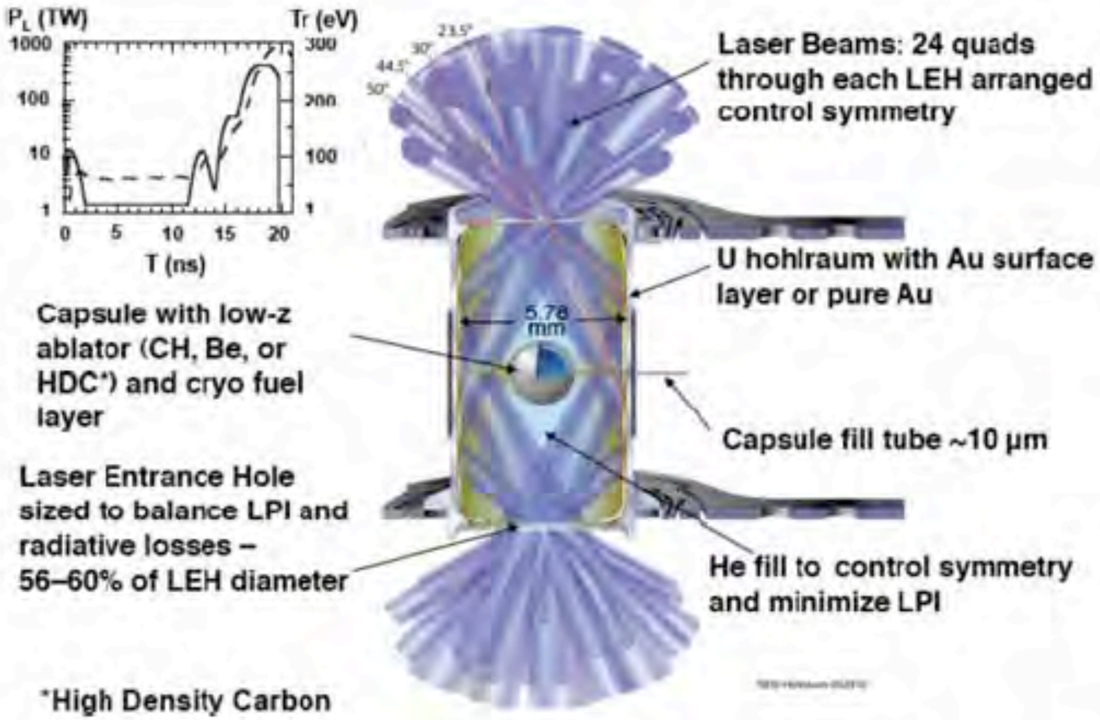


FIG. 2. Schematic of ignition target design, highlighting key features and options for hohlraum and capsule materials. Also indicated is the laser pulse shape showing the laser power in TW and the radiation temperature reached at that power versus time in ns.

symmetry control:
- beam orientation
- beam pointing
- hohlraum aspect ratio
- hohlraum fill

beam coupling: choice of materials

entropy control: cryogenic fuel, pulse shaping

preheat limitation: ablator doping

(courtesy of LLNL)

National ignition campaign, NIC, (2010-12) demonstrated strong compression, but did not achieve ignition

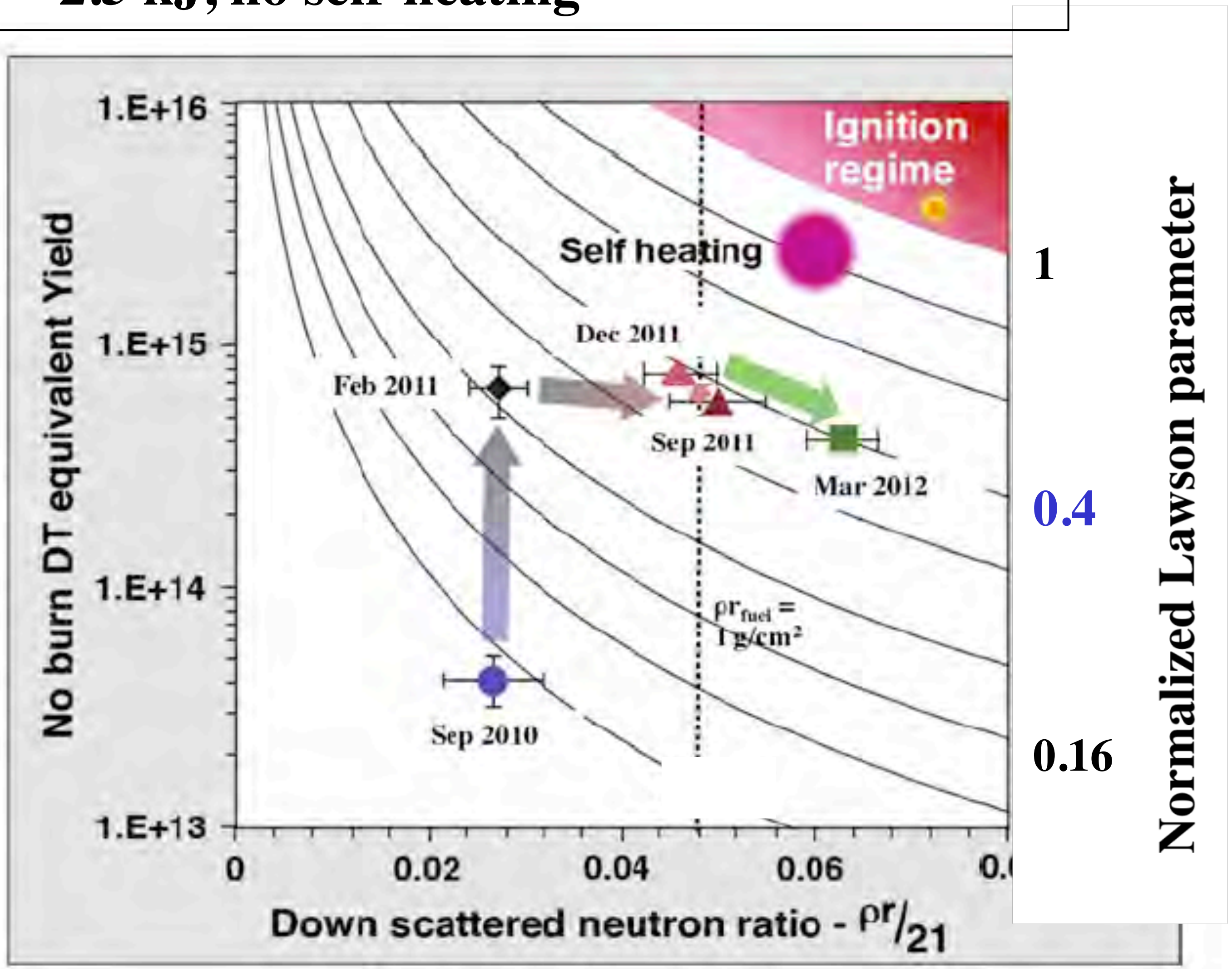
	NIC baseline goal	achieved	best result prior to NIC
Fusion yield	few MJ	few kJ	
Confinement parameter ρ*R*	1.5 g/cm^2	1.3 g/cm^2	0.2 g/cm^2
DT peak density	1000 g/cm^3	800 g/cm^3	200 g/cm^3
peak pressure	350 Gbar	130 Gbar	
implosion velocity with nominal NIC imploding mass	370 km/s	350 km/s	
laser energy	1.5 MJ	1.95 MJ	
peak laser power	450 TW	520 TW	

- implosion velocity smaller than expected
- pressure (much) smaller than expected

Note that NIF laser outperforms design specs

D. Hicks *et al*., *Phys. Plasmas* **19**, 122702 (2012); N. B. Meezan *et al*., *Phys. Plasmas* **20**, 056311 (2013); O. L. Landen *et al*., *Plasma Phys. Controll. Fusion* **54**, 124026 (2012); J. D. Lindl *et al*., *Phys. Plasmas* **21**, 020501 (2014)

2010 – 2011: great initial improvement;
2012: no progres
Maximum yield = 2.5 kJ, no self-heating



D. Hicks *et al*., *Phys. Plasmas* **19**, 122702 (2012); N. B. Meezan *et al*., *Phys. Plasmas* **20**, 056311 (2013); O. L. Landen *et al*., *Plasma Phys. Controll. Fusion* **54**, 124026 (2012); J. D. Lindl *et al*., *Phys. Plasmas* **21**, 020501 (2014)

confinement ⟶

Adapted from Rosen, APS-DPP 2014, LLNL-PRES-662854

NIF baseline ignition experiments (NIC campaign) vs simulations

NIC campaign: **general qualitative agreement**, strong compression**, but**

Ignition is a strongly non linear process (a bifurcation); several simultaneous small discrepancies can have dramatic effects:

- 15% laser light backscattered from the hohlraum (vs few % expected), due to parametric instabilities
- Implosion velocity 10% smaller than expected (for given absorbed energy)
- Low-mode asymmetries, turned out to be time dependent, and poorly controllable
- once the required implosion velocity was approached (by increasing laser power and/or reducing shell thickness) fuel contaminated as a consequence of instabilities

J. D. Lindl *et al*., *Phys*. *Plasmas* **21**, 020501 (2014)

From the 2010-2012 NIC to the 2021-22 MJ shots (I)

2011-2013 debate

Two extreme approaches (*):
- incremental, adjust by try and error
- back to basis: understand each individual aspect, then try again

The actual path,
made possible by **very high resolution diagnostics** and **ad-hoc experiments**

I)
- first, back to basis
  fluid modelling checked, verified that *when hohlraum plasma does not excite LPI's and alters symmetry, and there is not mixing* fluid models are fully predictive (see next vg)

- Issues: LPI, hohlraum plasma filling, effects of small "engineering features" (capsule fill tube; supporting tent)

(*) as emerged at the NIF study group, July 2011

outstanding (and unique) diagnostics essential for understanding the above results

e.g. neutron and X-ray images, with resolution of a few microns and a few ps

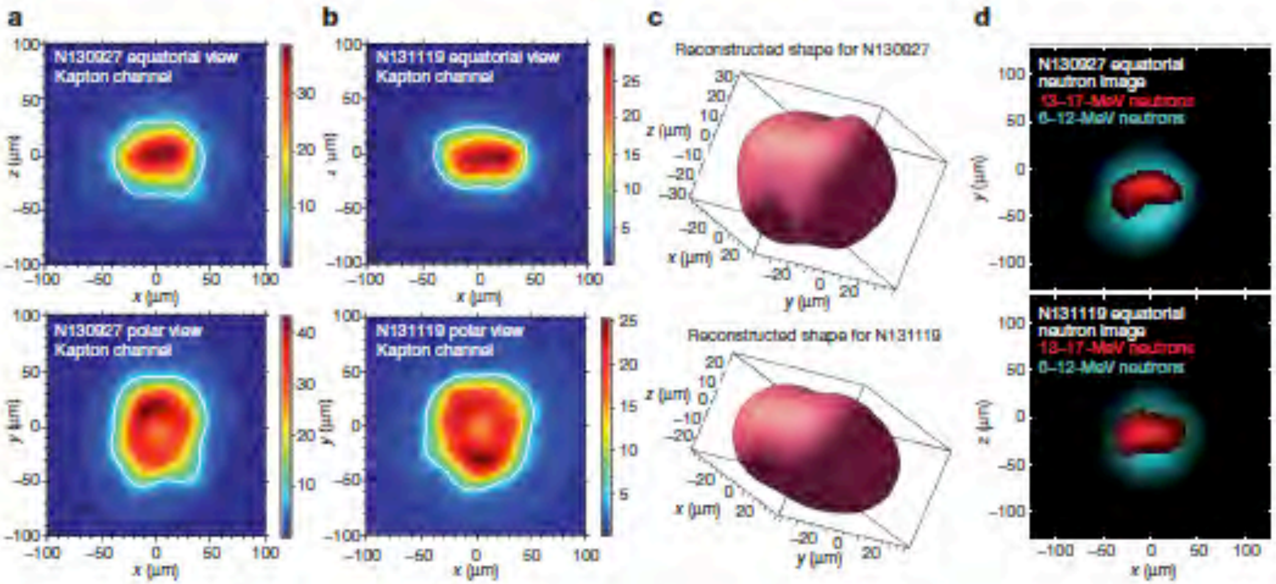


Figure 2 | X-ray and neutron images of the hotspot at bang-time. **a**, Equatorial (side-on) and polar (top-down) views of the hotspot shape for N130927. Kapton is the filter material in the imaging system that allows transmission of X-rays with energies of more than 6 keV. **b**, As in **a**, but for N131119. In these X-ray images, the contour shown in white is taken at the 17%-peak-brightness level (the colour scales show the brightness in arbitrary units) and is used to obtain a description of the shape in Legendre modes (equatorial view) and Fourier modes (polar view). **c**, Three-dimensional reconstructions of the hotspots. **d**, Superposition of direct (13–17 MeV) and down-scattered (6–12 MeV) neutron images from N130927 and N131119. (X-ray image analysis courtesy of N. Izumi, S. Khan, T. Ma and A. Pak of the NIF Shape Working Group; neutron image analysis courtesy of D. Fittinghoff, G. Grim, N. Guler and F. Merrill of the NIF Neutron Imaging System Working Group.)

O. Hurricane *et al*., Nature **506**, 343 (2014)

high resolution radiography,

showing implosion, stagnation, bounce

[D. Hicks *et al*., *Phys*. *Plasmas* **19**, 122702 (2012)]

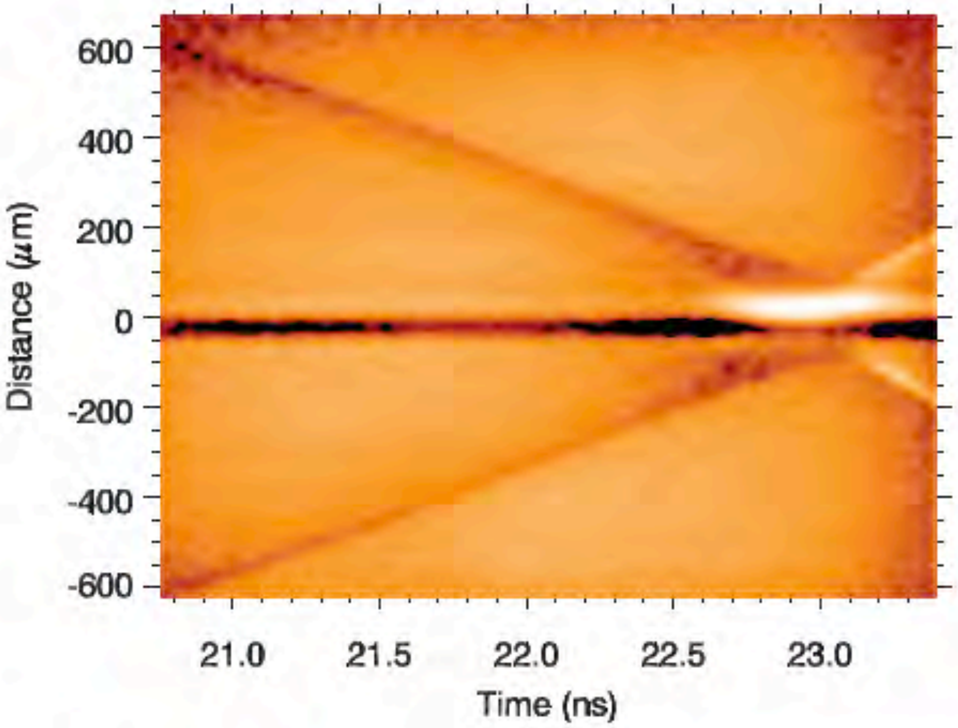
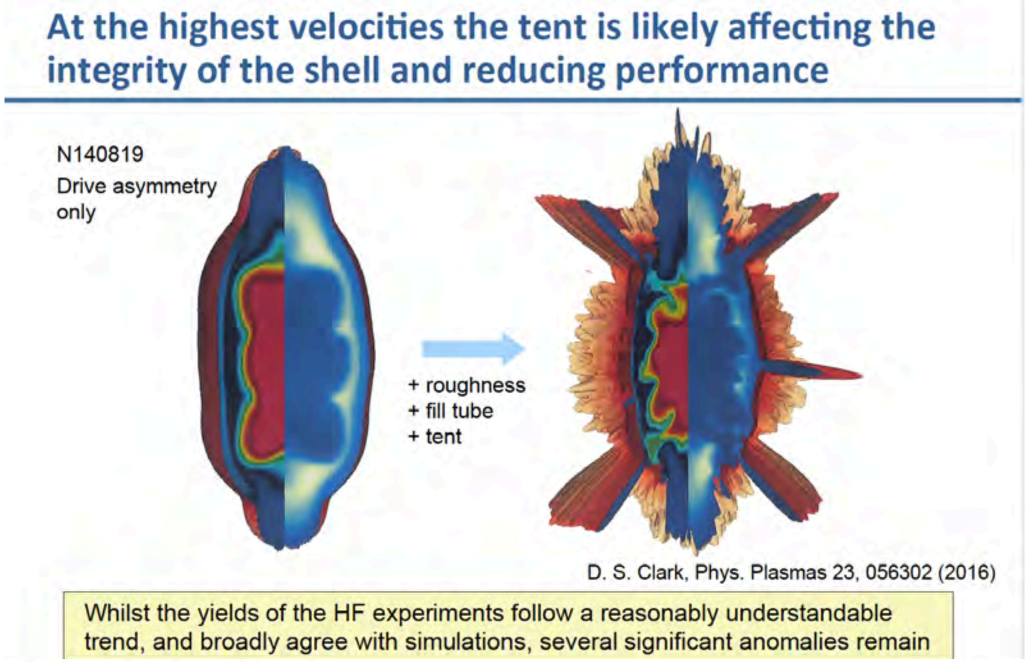


FIG. 15. Streaked radiograph from shot N120408 showing spatial and temporal scales. The central wire provides a background reference. X-ray emission from the stagnating core is visible at ~22.9 ns. At later times, the radiating, outgoing blast wave is apparent.

The effect of *engineering features*

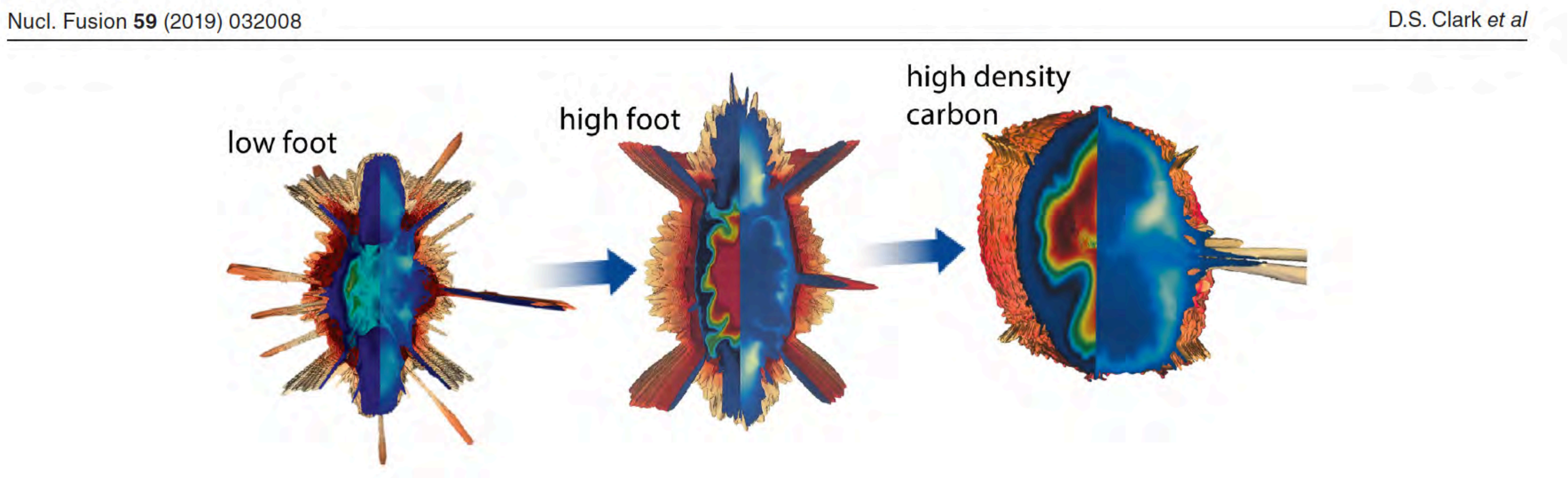


At the highest velocities the tent is likely affecting the integrity of the shell and reducing performance

D. S. Clark, Phys. Plasmas 23, 056302 (2016)

Whilst the yields of the HF experiments follow a reasonably understandable trend, and broadly agree with simulations, several significant anomalies remain

P. Patel, presentation at the "Kinetic Physics in ICF Workshop", Livermore, April 5–7, 2016



Nucl. Fusion **59** (2019) 032008 D.S. Clark *et al*

From the 2010-2012 NIC to the 2021-22 MJ shots(II)

The actual path,

II) a series of changes, aiming at solving each of the above (conflicting) issues

- **increase foot power and shorten laser pulse to reduce plasma formation =>** reduce LPI, reduce time-dependent asymmetry, reduce RTI growth
- **increase efficiency**: change hohlraum shape and material, make hohlraum smaller
- **reduce instability seeds =>** diamond instead of plastic, smaller fill tube, thinner tent, improve capsule surface quality, improve DT ice quality

2013-2014: try to get 1D implosion, Even if at the expense of compression => yield from 2 kJ to 25 kJ

2013-14 (high-foot) experiments

(**Hurricane** et al, Nature 2014):

higher foot power:

- entropy increased to
  - reduce RTI growth
  - make imploding shell thicker

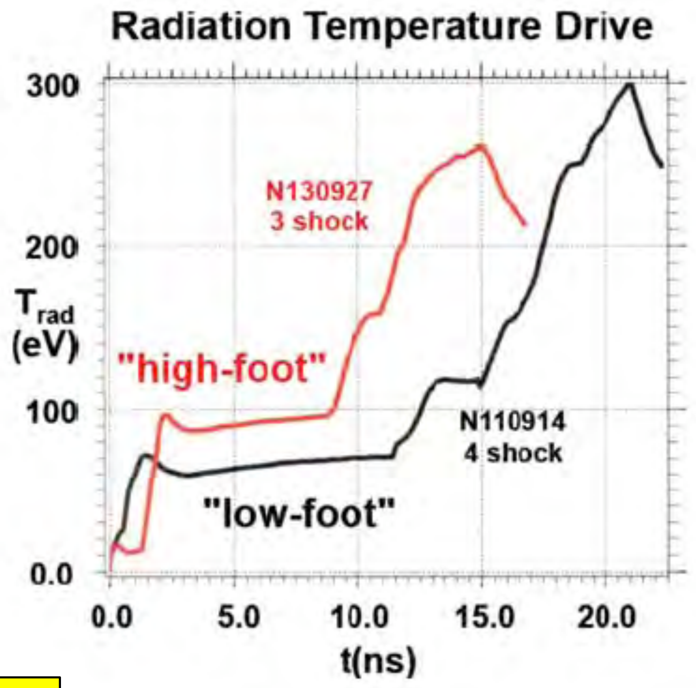
- shorter pulse => less plasma, less LPI's

implosion velocity ≈ 320 km/s; $\alpha \approx 2.5$

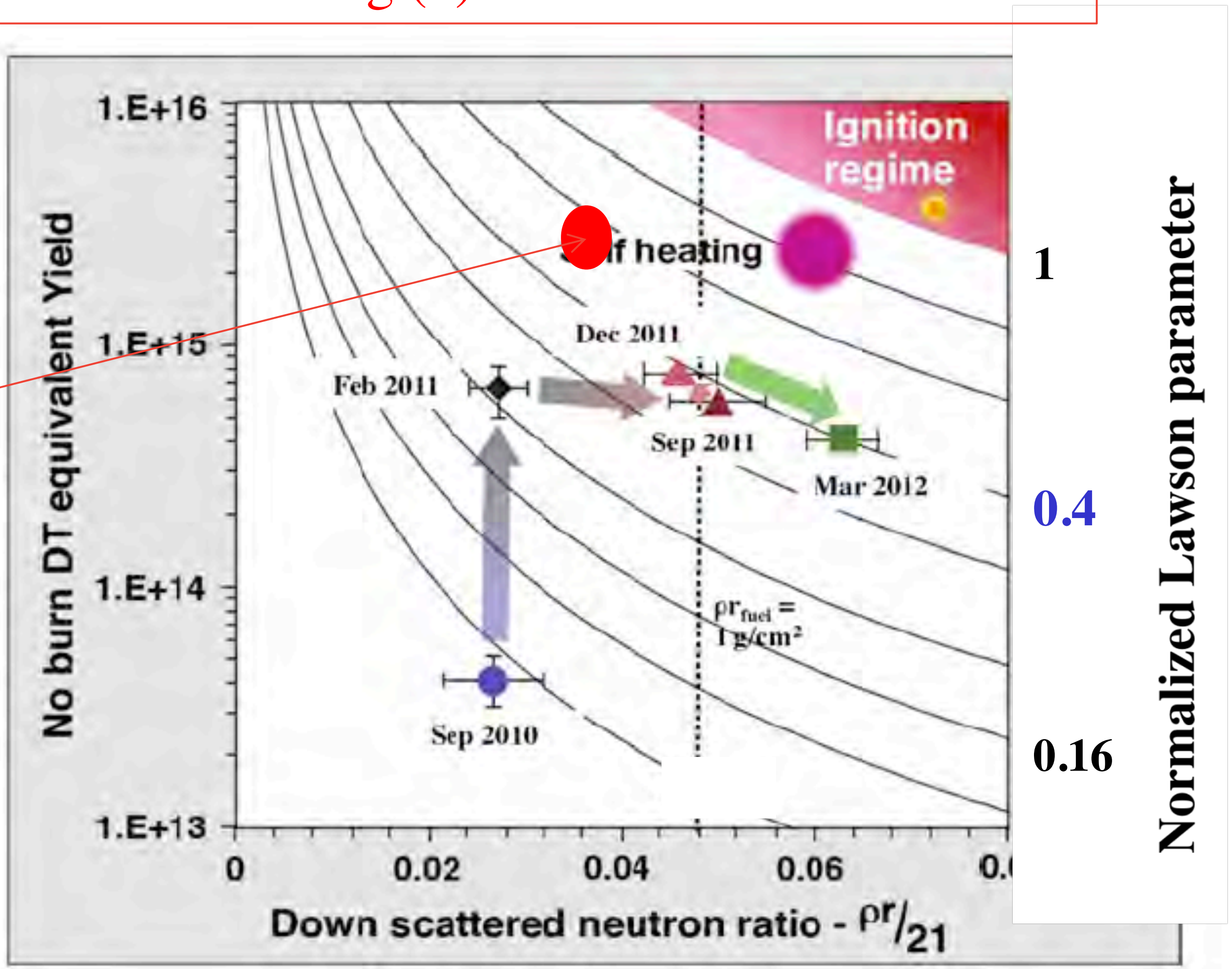
=> fusion yield nearly as predicted by 1D sims

⇒ fuel gain > 1

⇒ yield multiplication by self-heating $M_y = 2$



2013 – 2014: fusion energy exceeding hot spot internal energy
Yield up to 27 kJ
50% of the yield due to self-heating (*)



Nov. 2013 – Spring 2014

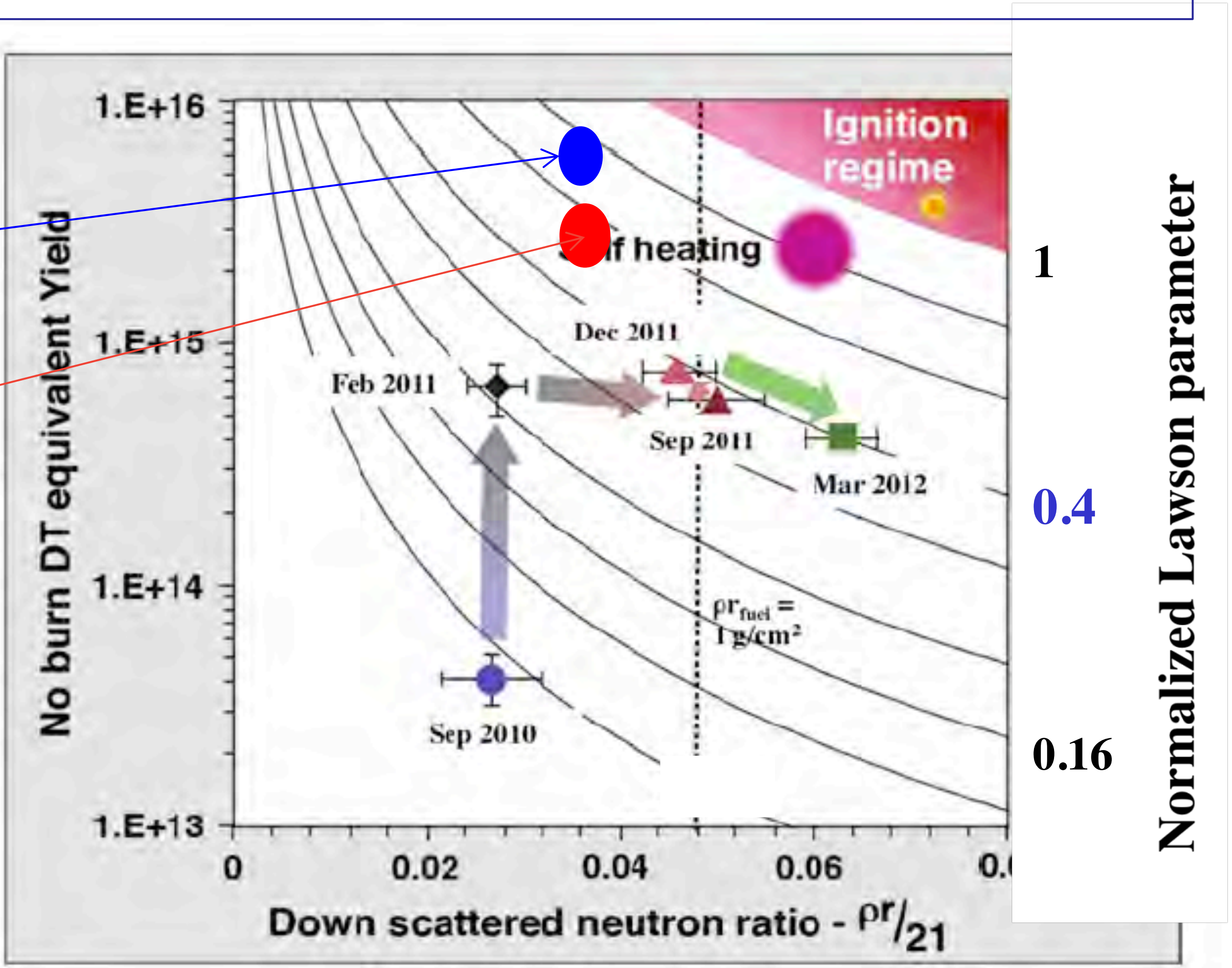
Higher yield, but reduced compression

confinement ⟶

(*) O. Hurricane *et al*., Nature **506**, 343 (2014)
H. S. Park et al. PRL 112, 055001 (2014)

2017–2018: reduce gas fill density, shorter pulse, diamond ablator

- Yield up to 55 kJ (**)
- hot spot pressure: 360 Gbar



2017-2018

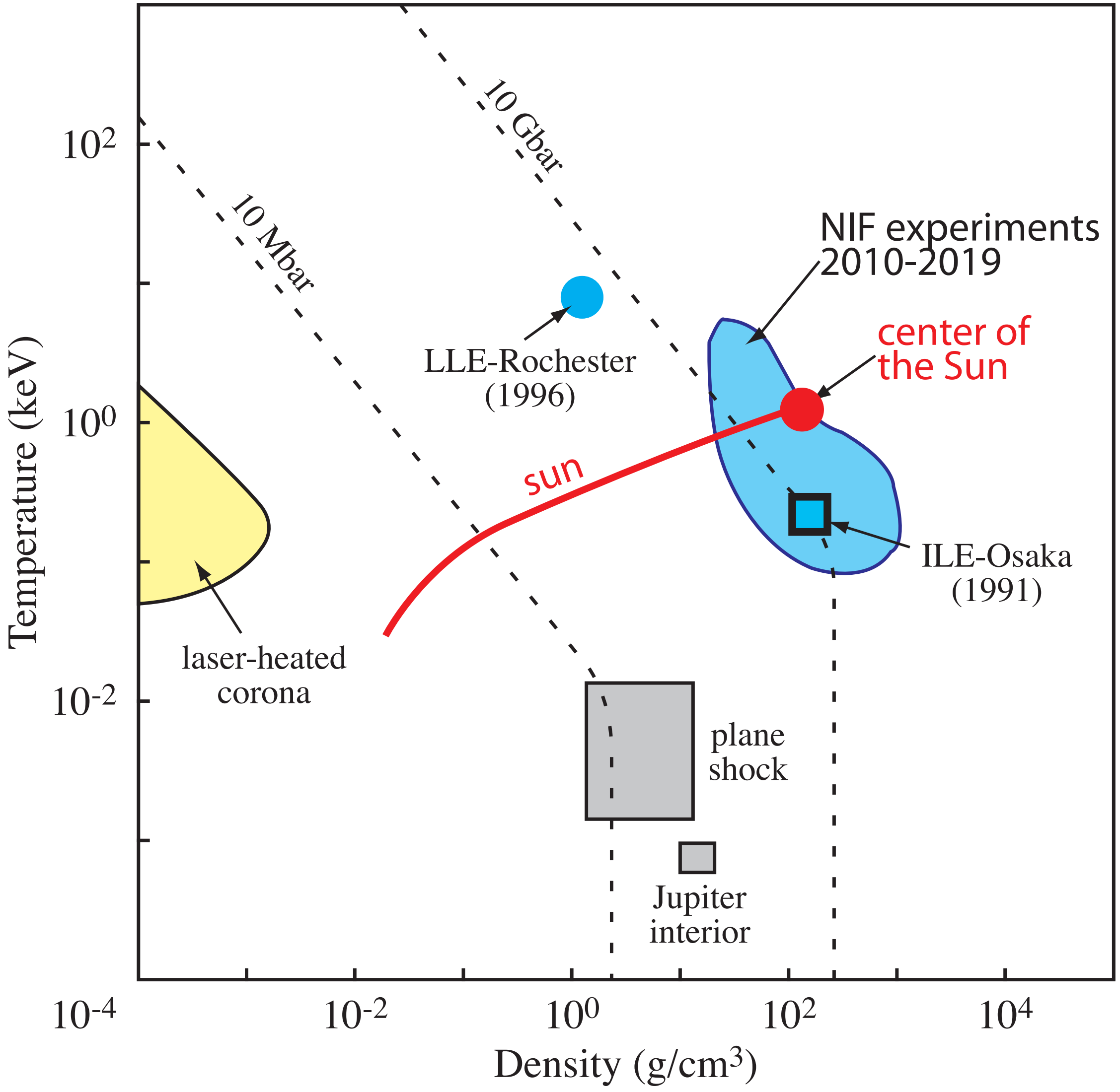
Nov. 2013 –
Spring 2014

Higher yield;
Same compression as
2013-2014 shots

confinement ⟶

(**) S. Le Pape *et al*., PRL **120**, 245003 (2018)

Pressure higher than pressure at the centre of the sun achieved at the NIF (2017-2018)



How far from ignition? (a 2018 slide)

Yield in high foot experiments ~ 60 kJ, while ignition yield $Y > 1$ MJ

Really so far from ignition? Is yield the right metric?

A better metric(*): generalized Lawson parameter $\chi = (p\tau)/(p\tau)_{\mathrm{ignition}}$ [τ: confinement t]

- Yield multiplication by self-heating M_y is a unique function of χ: $M_y = M_y(\chi)$
- In terms of measurable quantities: $\chi = \mathrm{const}\,(\rho R)^{0.61}(Y/m_{DT})^{0.24}$

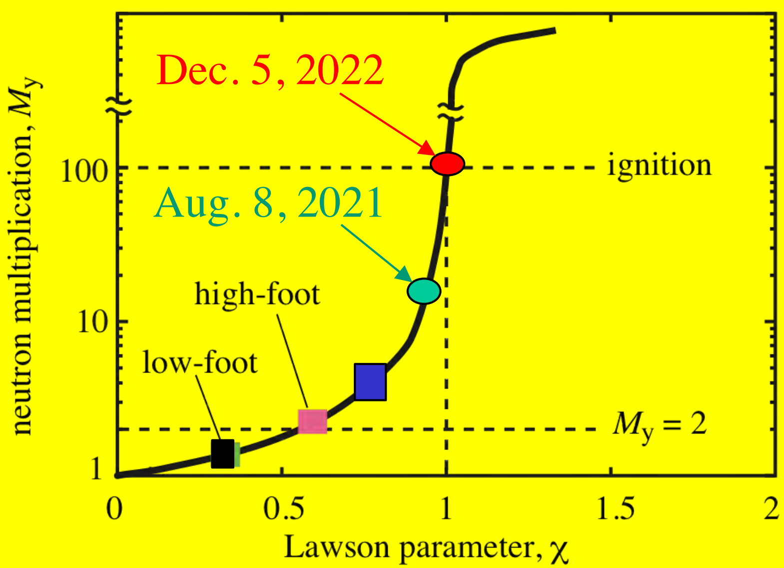
Low foot experiments: $\chi \le 0.3$ ($M_y \le 1.3$)

First High foot experiments: $\chi = 0.6$ ($M_y = 2$)

2018: $\chi = 0.65$ ($M_y = 3$)

For ignition: $\chi \ge 1$ ($M_y > 100$):
progress by a factor ≈ 1.7 needed

SA, EPL **109**, 45001 (2015), adapted



(*) R. Betti et al., Phys. Plasmas 17, 058102 (2010)

How far from ignition?
How to increase Lawson parameter? (a 2018 slide)

What in terms of driver/target hydro parameters?

$\chi \approx \mathrm{ITF}^{0.4}$, with ITF the LLNL ignition threshold factor

[Spears *et al*, PoP 2012, Lindl *et al*., PoP 2014]

$\chi = \chi_{1D}$ x (corrections for deviations from1D)

$\chi_{1D} \approx \eta^{0.4} E^{0.4} u^{2.4} \alpha^{-0.6}$

In the high foot expt. (corrections ...) ≅ 1

=> χ_{1D} must grow by 1.7; all laser energy already used;

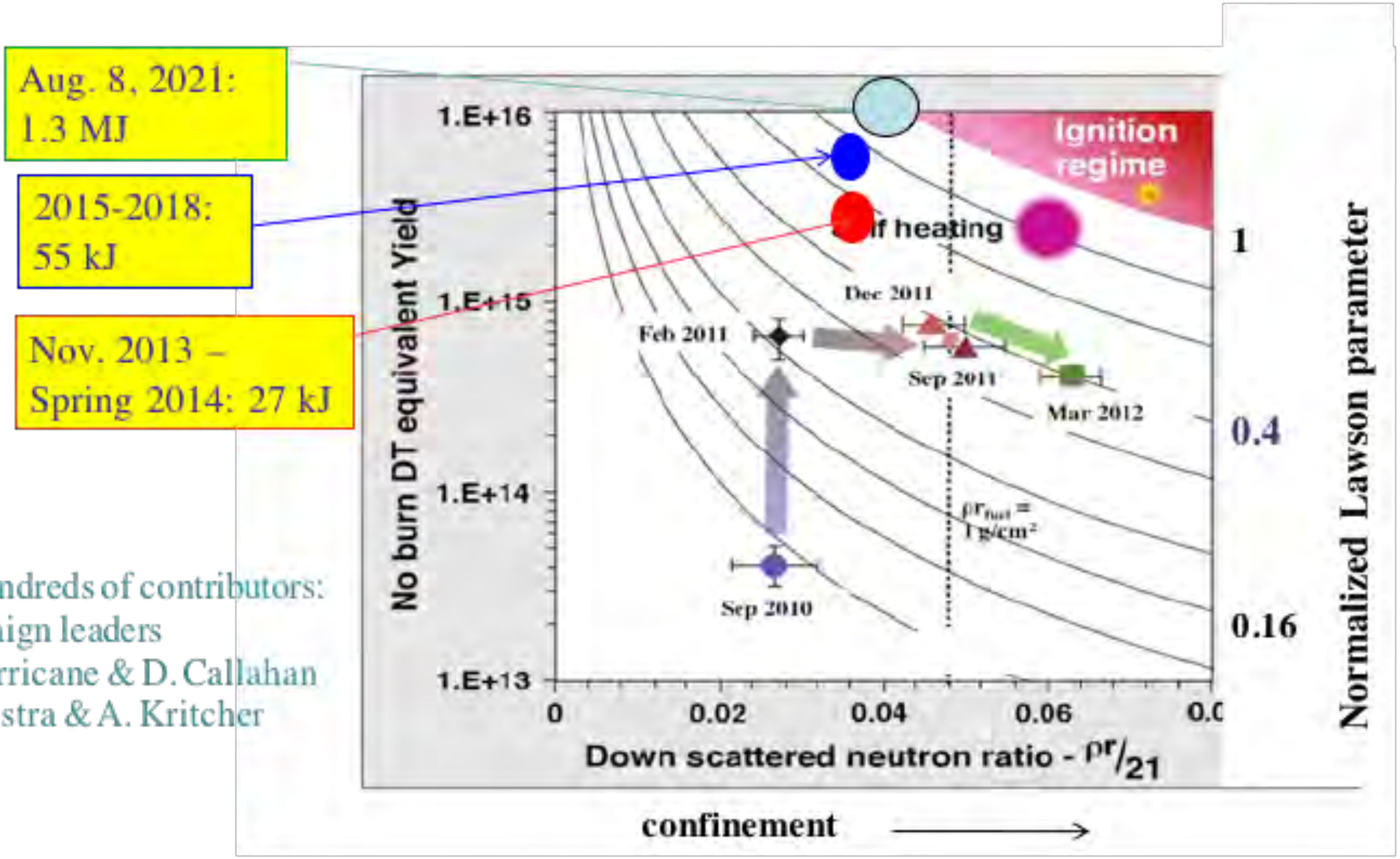
⇒ increase η

⇒ increase u

⇒ decrease α,
without degrading symmetry and stability

This is the rationale informing the strategy leading from the 2011 results to the ignition shot of Dec. 2022

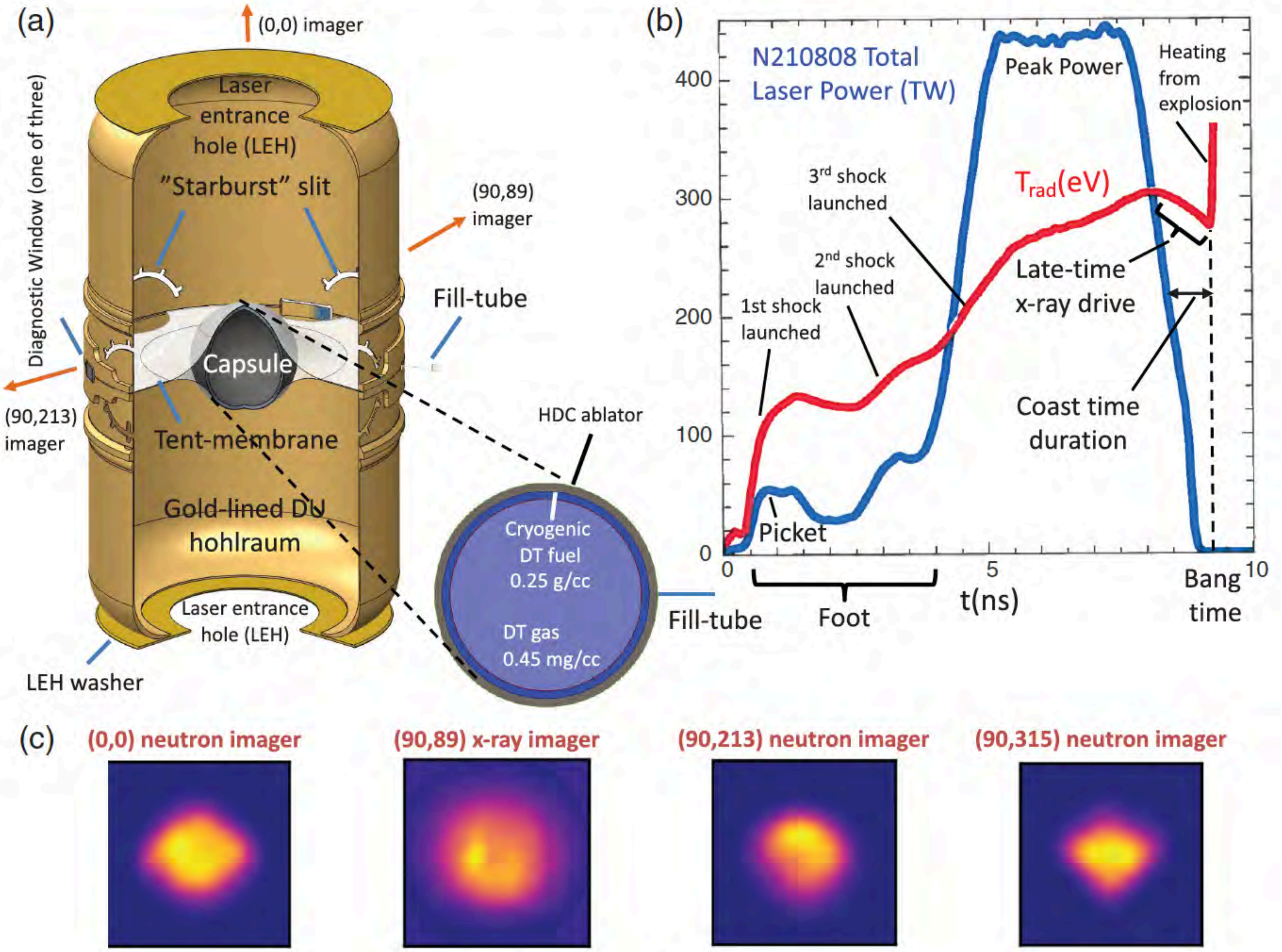
August 8, 2021: 1.3 MJ. Burn multiplication by self-heating > 20 (*,)**
hot spot p: 550 Gbar, hot spot T > 10 keV



(*) hundreds of contributors:
campaign leaders
O. Hurricane & D. Callahan
A. Zylstra & A. Kritcher

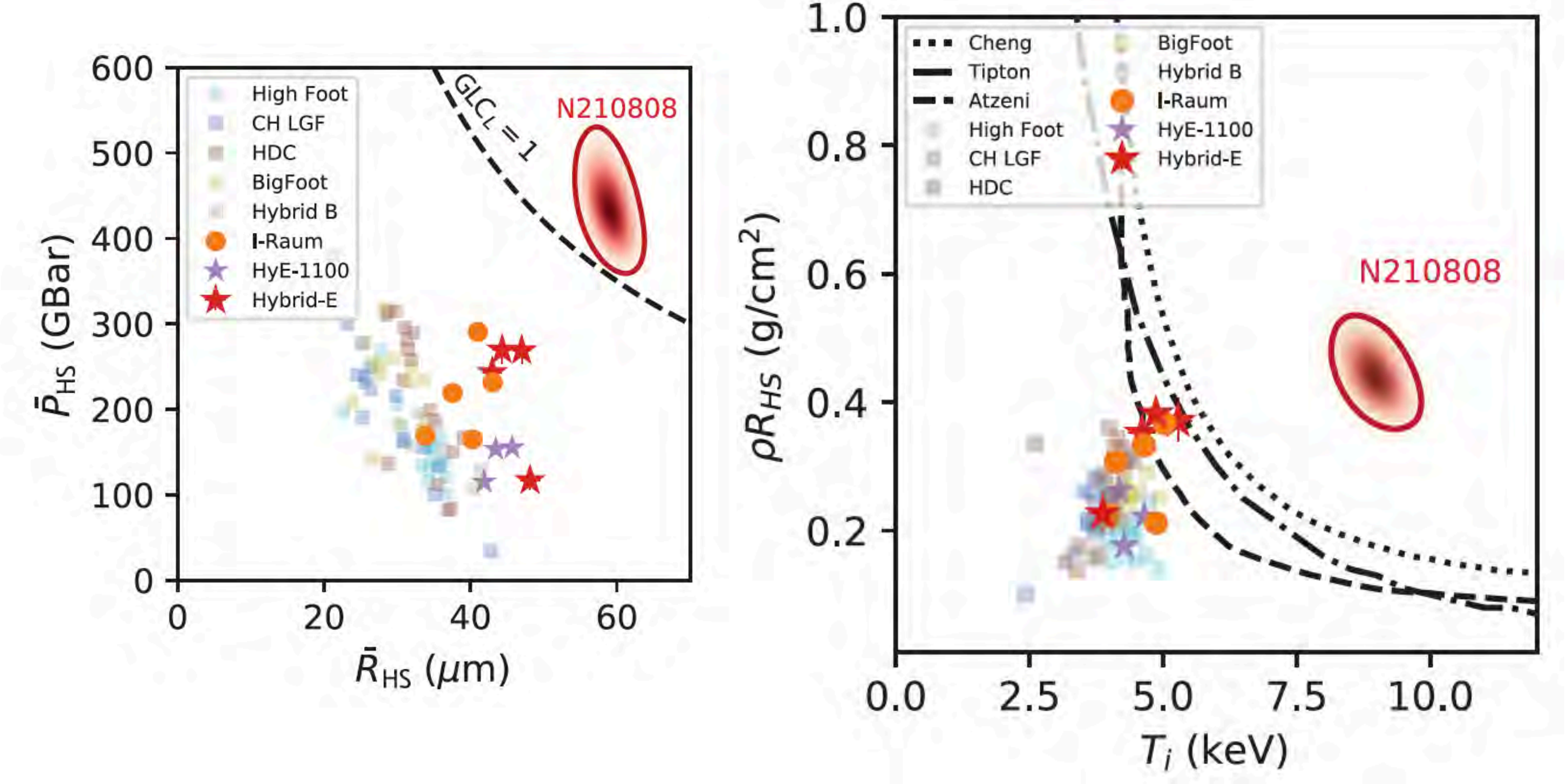
(**) H. Abu Shwareb et al., *Phys. Rev. Lett.* **129**, 075001 (2022); A. L. Kritcher et al., *Phys. Rev.* **106**. 025201 (2022); A. B. Zylstra et al., *Phys. Rev. E* **106**. 025202 (2022)

PHYSICAL REVIEW LETTERS **129,** 075001 (2022)



H. Abu Shwareb et al., *Phys*. *Rev*. *Lett*. **129**, 075001 (2022)

PHYSICAL REVIEW LETTERS **129,** 075001 (2022)



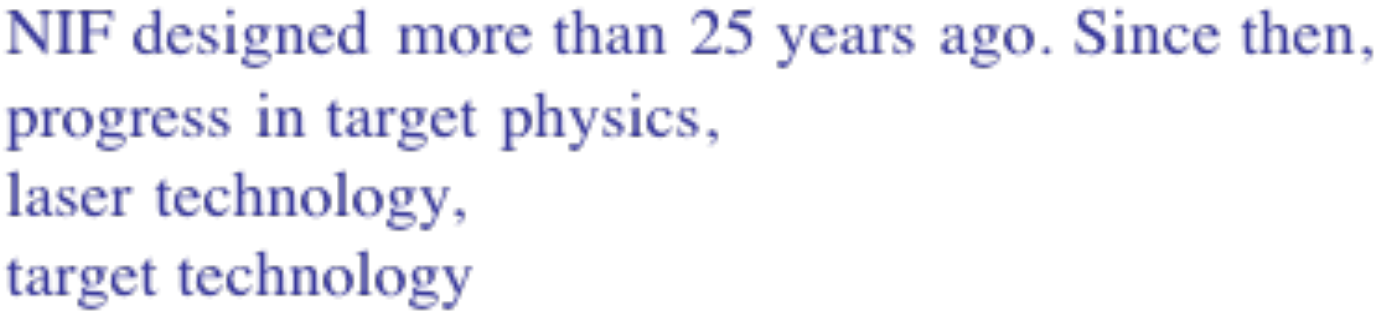
H. Abu Shwareb et al., *Phys*. *Rev*. *Lett*. **129**, 075001 (2022)

NIF 20221205 shot: 3.1 MJ yield, Gain = 1.5

Relevant to Inertial Fusion Energy?

- Yield increase x 5 possible with NIF and similar targets
- Coupling efficiency x 5 possible with direct-drive => 5 times larger fuel mass for the same laser energy => Yield x 15–20
- Gain increase x 2.0 with shock ignition (or fast ignition) [*]

==> $G = 1.5 \times 5 \times 15 \times 2.0 = 210$



NIF designed more than 25 years ago. Since then,
progress in target physics,
laser technology,
target technology

[*] or very efficient d.d. schemes, as proposed by Goncharov, and by Bodner (white papers presented at IFE workshop, Feb. 22–24, 2022)

Are there alternatives to NIF-like schemes? Ignition at smaller laser energy ? Simpler targets?

NIF designed 25 years ago; since then

- laser progress:
  - smooth beams
  - ultraintense lasers
  - pulse shaping
- new ignition schemes (fast ignition, shock ignition)
- improved understanding of RTI

==> • Direct-drive

and/or

• Alternate approaches to ignition (*)

(*) reviews in a *Nuclear Fusion Special issue* (2014)

Direct-drive:
more efficient than indirect-drive

- can be tested on the NIF (polar direct-drive or, better, reconfigure NIF)
- however, still serious issues with RTI @ high implosion velocity

- substantial progress in the past two decades,
  [see reviews by Craxton et al., PoP (2015) and by Betti and Hurricane (Nature Phys. 2016)]

Very recent progress due to use of statistical modeling
[Gopalaswamy, Betti, et al, Nature, 565, 581 (2019)]

Much simpler spherical targets? [Goncharov et al, PRL (2020)]

Instability risks grow with increasing implosion velocity

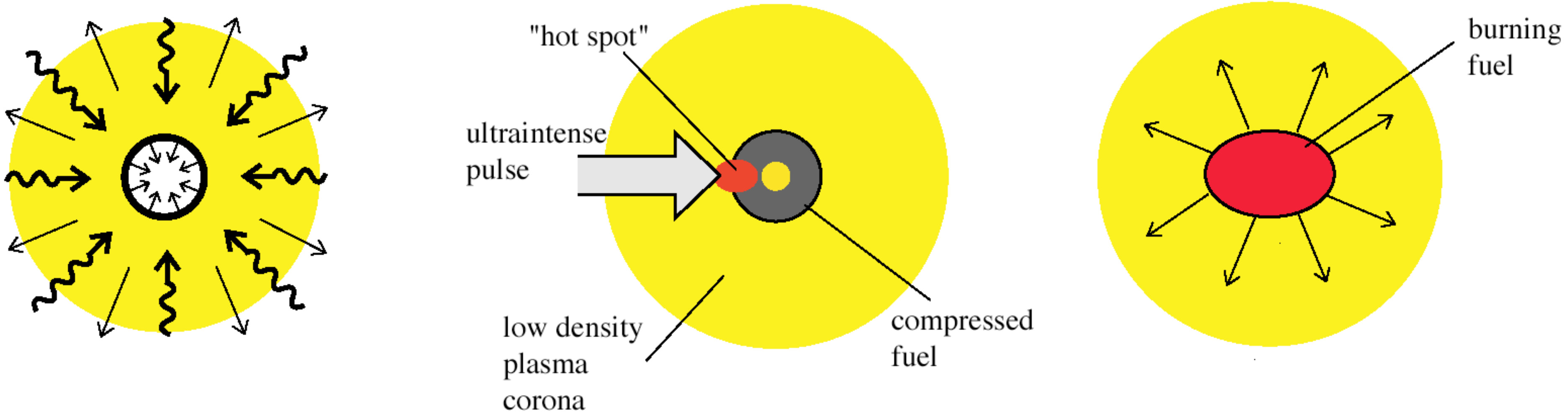
Can ignition be achieved
with “reduced” implosion velocity?

i.e. how can additional means increase
an “insufficient” hot spot pressure?

= = > fast ignition

shock ignition

Fast ignition



(a) and (b) symmetric irradiation and implosion

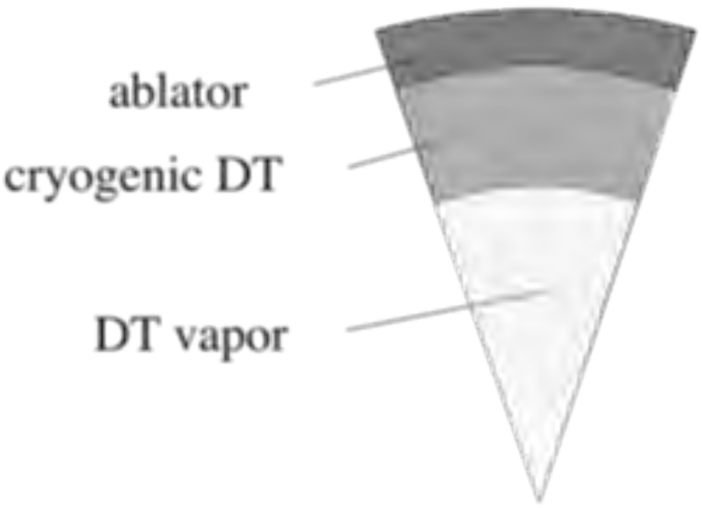
(c) hot spot generation by an ultraintense pulse

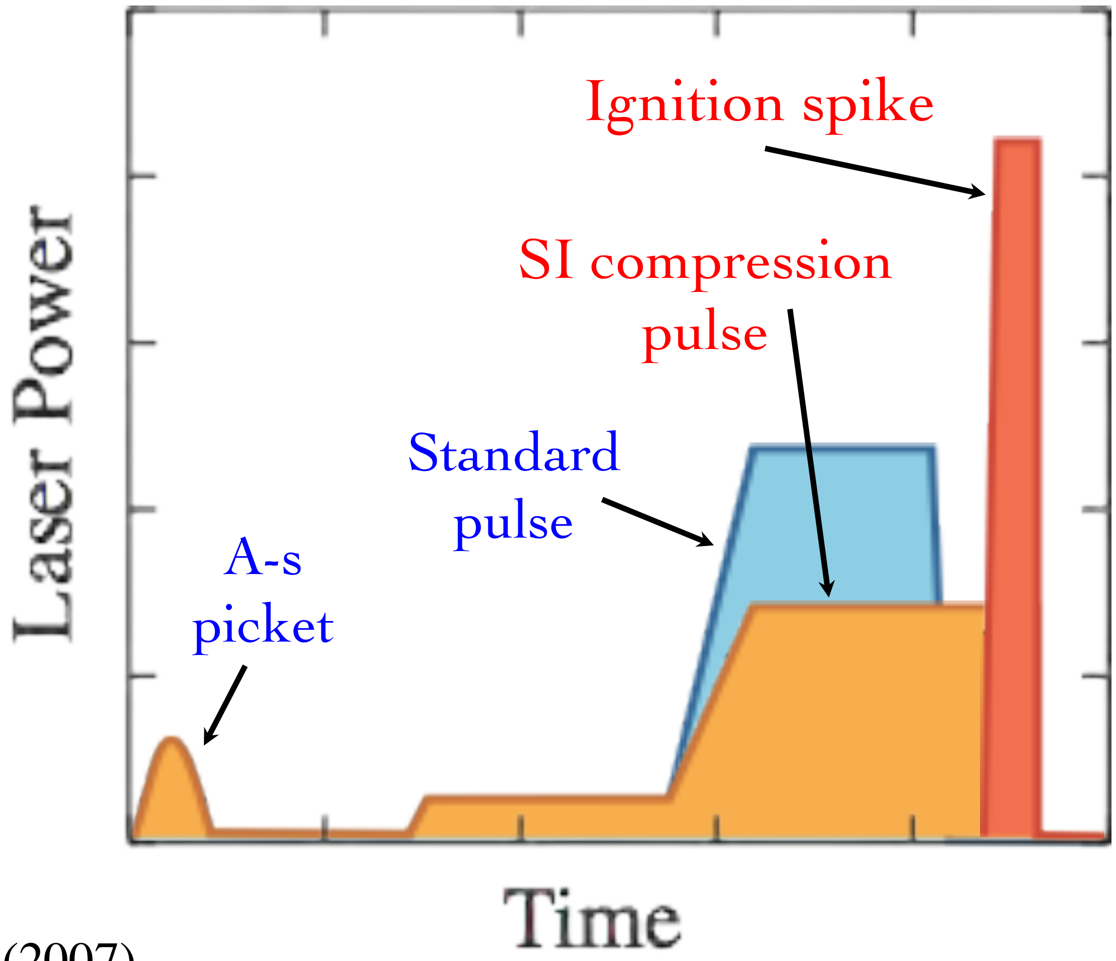
(d) burn

To ignite a DT fuel precompressed to density of 300 g/cm^3 : deliver 20 kJ in 20 ps on a 40 micron diameter spot

- Scheme: M. Tabak et al., Phys. Plasmas 1, 1626 (1994).
- Ignition requirements: S. Atzeni, Phys. Plasmas 6, 3316 (1999); S. Atzeni and M. Tabak, Plasma Phys. Controll. Fusion 47, B769 (2005)

Shock ignition
vs
conventional direct-drive central ignition

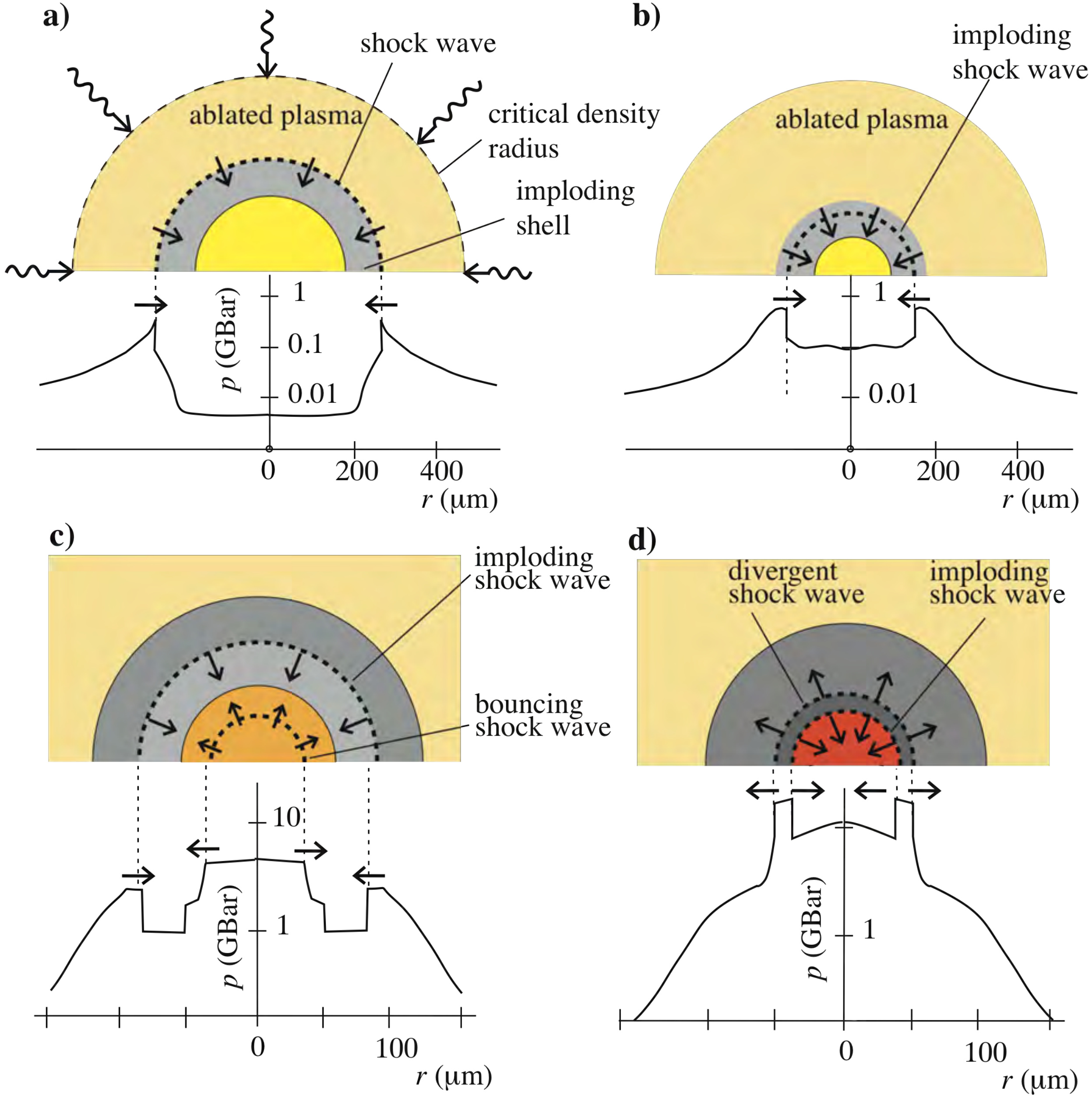




Concept: R. Betti *et al*, PRL 98, 155001 (2007)
Review: S. Atzeni *et al*., *Nucl. Fusion* **54**, 054008 (2014)

stagnation pressure can be amplified by a properly tuned shock: Shock ignition

- a) pulse generates imploding shock
- b) imploding shock amplified as it converges
- c) imploding shock pregresses, while shock bounces from center
- d) the two shocks collide, and launch new shocks; the imploding shock heats the hot spot

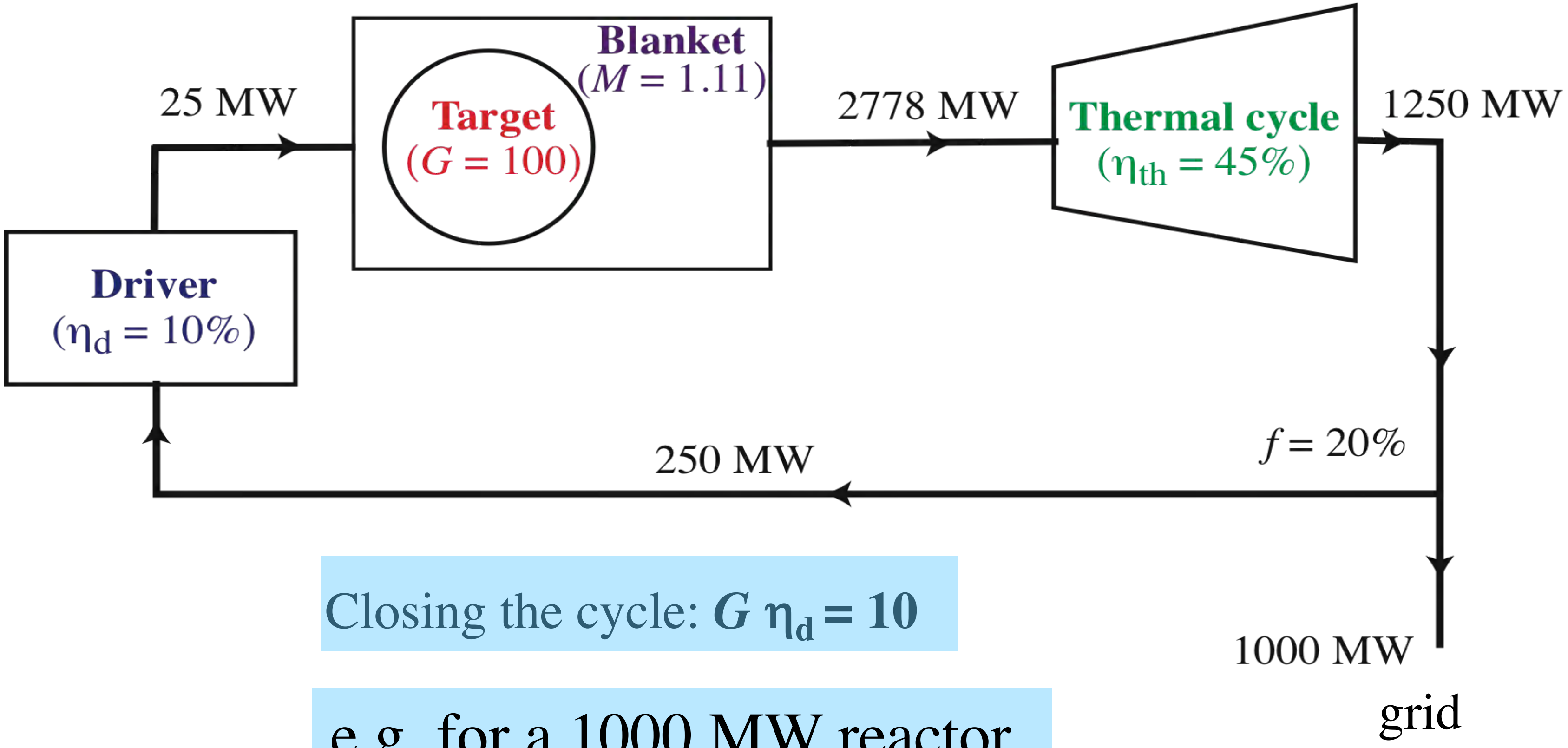


SA, 2011

Inertial fusion energy:

energy production by ICF

Inertial fusion energy reactor cycle



Closing the cycle: $\boldsymbol{G\,\eta_d = 10}$

e.g. for a 1000 MW reactor

$\boldsymbol{G = 100;}$

$\boldsymbol{\eta_d = 10\%}$

$\boldsymbol{E_d = 2.5\ \mathrm{MJ}}$

$\boldsymbol{\nu_{\mathrm{driver}} = 10\ \mathrm{Hz}}$

Substantial progress required in

- target physics
- driver technology
- target technology

	For IFE	NIF	Required progress
Target gain	**100**	1.5	70
Driver efficiency	**10%**	0.7%	15
Driver rep. rate	**few Hz**	1/day	10^5–10^6

cost of target < 30% Cost Of Energy =>

$$\textbf{cost of target} < \textbf{40 cent} \times \left(\frac{Y_{\mathrm{fus}}}{250\ \mathrm{MJ}}\right)\left(\frac{COE}{5\ \mathrm{cent/kWh}}\right)\left(\frac{n_{\mathrm{th}}}{40\%}\right)$$

Enormous progress required
Potential solutions do exist

More efficient targets proposed; can be(partially) tested on the NIF

NIF is a 25 year old concept
10% efficient, Hz operating “small” lasers now exist. Must be scaled up.
Costs must be reduced (possible, with mass production)

Current targets are hand-made and complex. Simpler targets are conceivable.
Mass production is expected to decrease costs by many orders of magnitude
(cfr. semiconductors: 1947 first transistor vs billions of transistors on a chip)

Other areas requiring R&D

- Target injection and tracking
- Reaction chamber vacuum management
- Tritium breeding
- ...

Lasers for fusion and ultra-intense laser applications to non-fusion physics

---

A few examples

- Laboratory astrophysics
  (magnetic turbul. [1], collisional and collisionless shocks [2], RTI in SNR)
- Thermonuclear reaction rates (e.g. He^3-He^3) [3]
- Materials at extreme pressures (e.g. super-ionic fluids [4])
- ultra-intense magnetic fields
- Particle acceleration (ions, electrons, positrons) [5]
- Femtosecond chemistry
- X-ray lasers

[1] G. Gregori et al, *Nature 481, 480 (*2012)
[2] C. Li et al., *Phys Rev Lett* 123, 055002 (2019)
[3] A. Zylstra et al., *Phys Rev Lett* 119, 222701 (2017)
[4] M. Millot et. al, *Nature Phys. 14, 297 (*2018)
[5] M. Borghesi et al, Rev. Mod. Phys. 85, 751 (2013); E. Esarey et al, Rev. Mod. Phys. 81, 1229 (2009)

New initiatives in Europe?

CrossMark

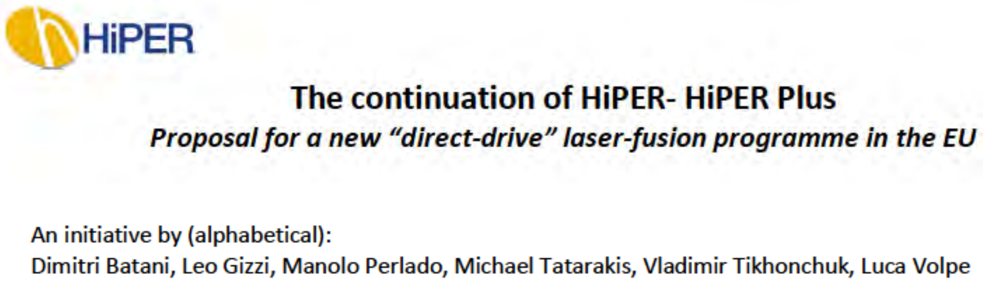
High Power Laser Science and Engineering, (2021), Vol. 9, e52, 4 pages.
doi: 10.1017/hpl.2021.41

HIGH POWER LASER
SCIENCE AND ENGINEERING

PERSPECTIVE

An evaluation of sustainability and societal impact of high-power laser and fusion technologies: a case for a new European research infrastructure

S. Atzeni[1], D. Batani[2], C. N. Danson[3,4], L. A. Gizzi[5], M. Perlado[6], M. Tatarakis[7,8], V. Tikhonchuk[2,9], and L. Volpe[10,11]



HiPER

The continuation of HiPER- HiPER Plus

Proposal for a new "direct-drive" laser-fusion programme in the EU

An initiative by (alphabetical):
Dimitri Batani, Leo Gizzi, Manolo Perlado, Michael Tatarakis, Vladimir Tikhonchuk, Luca Volpe

Concluding remarks

- progress in physics understanding and modelling
- crucial role of diagnostics (often, laser-based: backlighters, proton imaging, ...)
- a number of ingenious schemes proposed
- synergy with other laser-driven physics

Ignition on the NIF achieved using indirect-drive,
Large gain? Alternative schemes to be tested

Path to reactor (very) long, yet possible

- Artsimovich (leader of USSR Tokamak programme) in1973: “Fusion will be ready when society needs it”. I partially agree. In addition to funding, I believe that substantial advances in physics and technology are needed (for both ICF and MCF).

Fusion as a trans-generational enterprise: How to make it rewarding in the medium term?

From scientific feasibility to the reactor: decades, billions of Euro

Scientists and engineers as gothic cathedral builders (*),
without religious motivation.

Some other reward is then necessary:
- knowledge for scientists
- techn. developments with applications in other fields, for engineers
- return on investment in the medium term for industry and investors

Research on ICF can fulfill such demanding conditions

A lot of demanding and possibly fascinating work
for the next generation of scientists ad engineers

(*) cfr. R. Khatchadourian, “A star in a bottle”, The New Yorker, March 3, 2014

Thank you for your attention