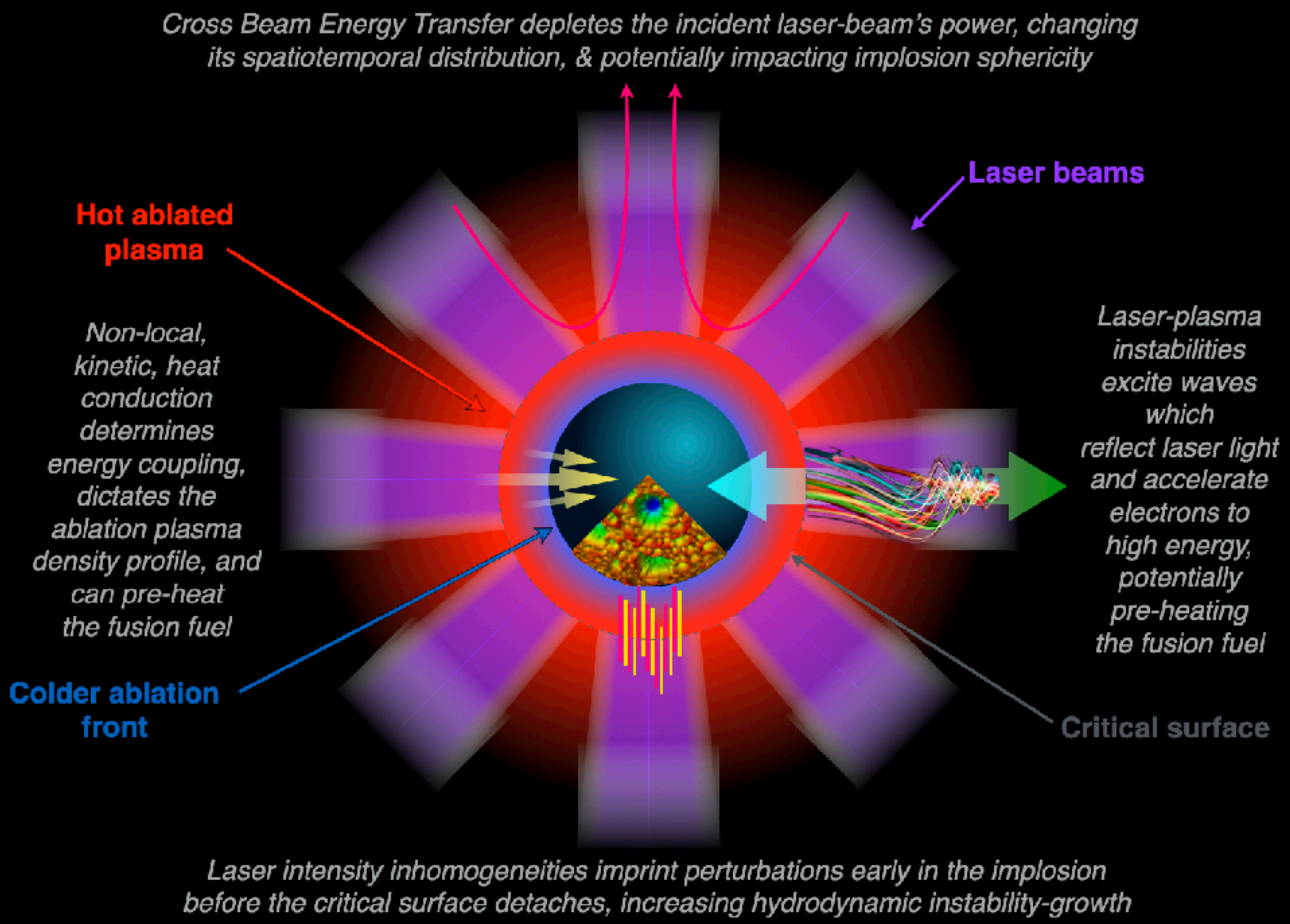
# (Laser) Inertial Fusion Energy

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17th January 2024

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# Main Ways to Do Fusion: Stars, Magnets and Inertia

**Fusion fuel has to be heated to 100 million degrees**

**The highest melting-point materials melt at ~3000 degrees**

**How can we hold the fuel in place?**

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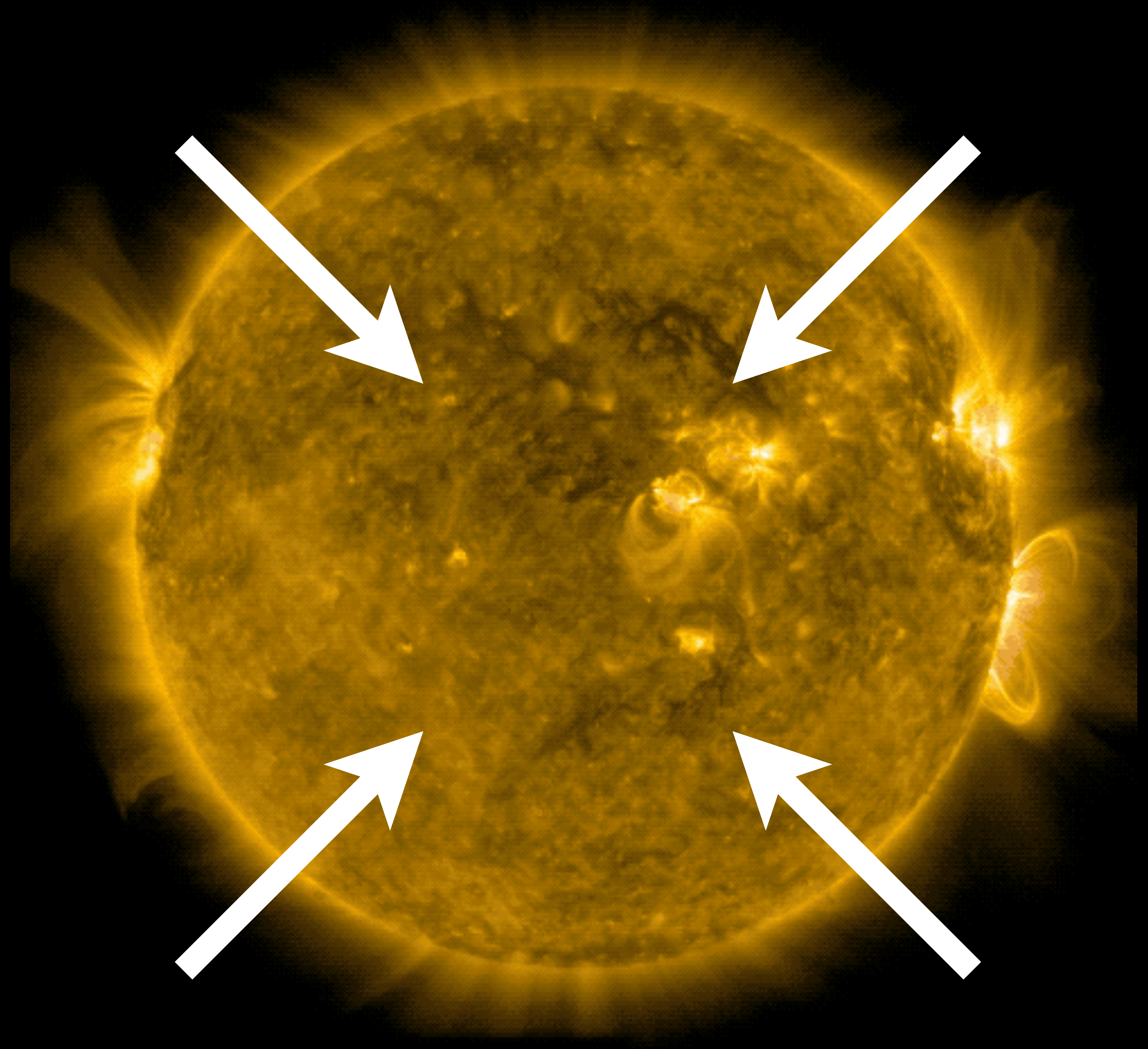
# Main Ways to Do Fusion: **Stars**, Magnets and Inertia



**In stars gravity holds the hot fuel in-place**

**Unfortunately stars are  impractical to build on earth!**

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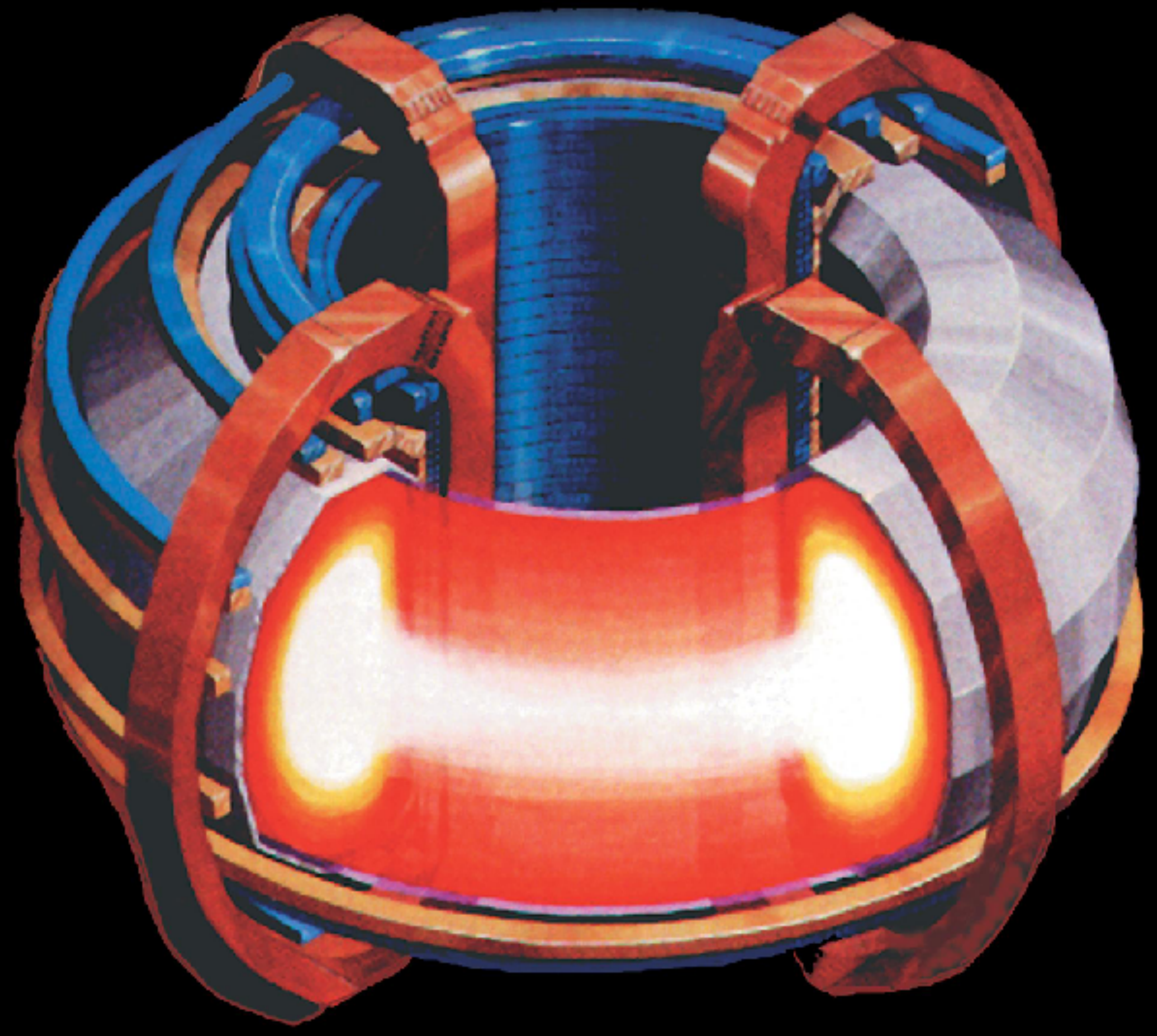
# Main Ways to Do Fusion: Stars, **Magnets** and Inertia

- Magnetic Confinement Fusion:
  - Fuel is so hot it turns into a plasma
  - Magnets hold the plasma in-place



**Tokamaks are like a bent bottle, with the two (leaky) ends joined together**

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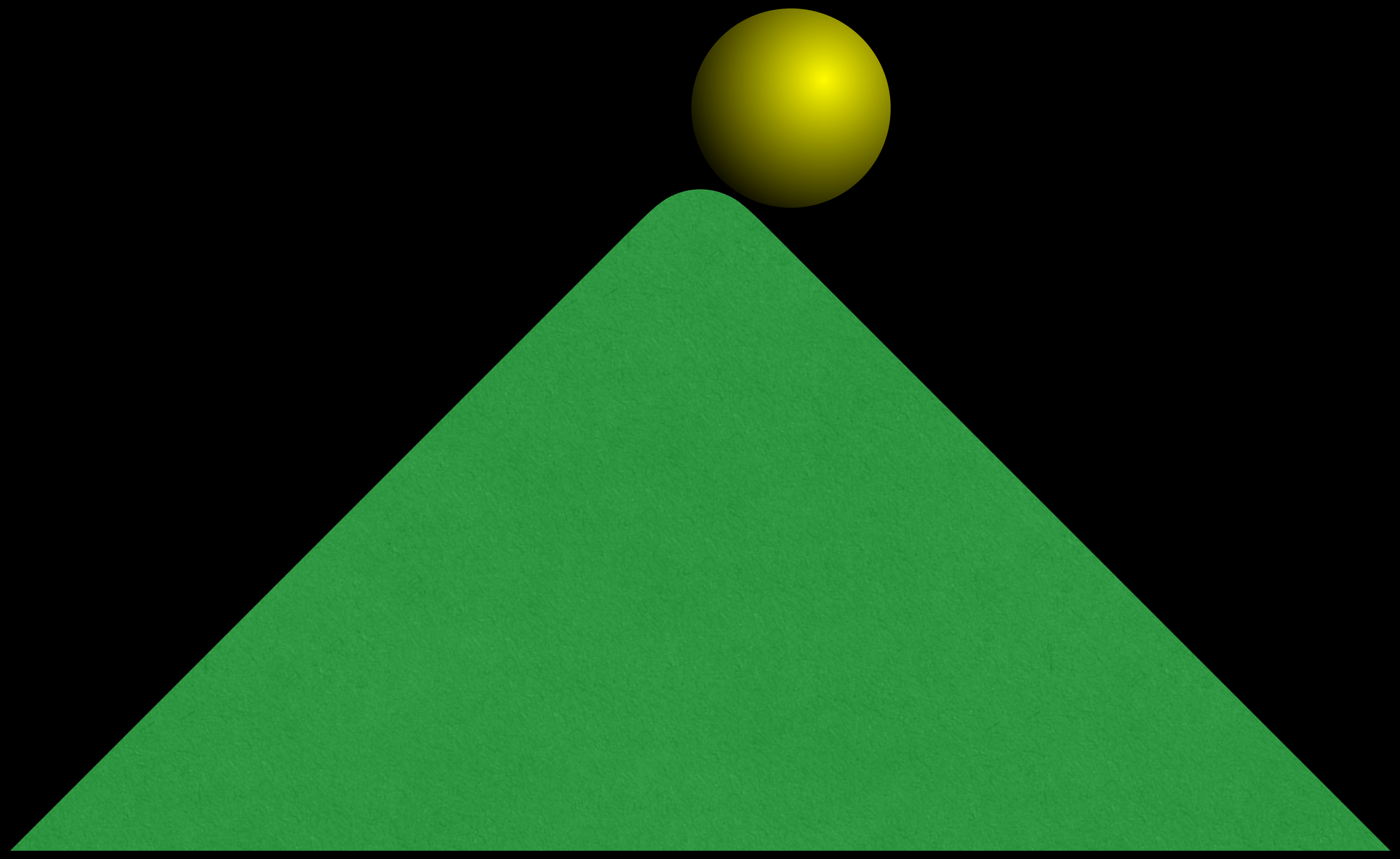
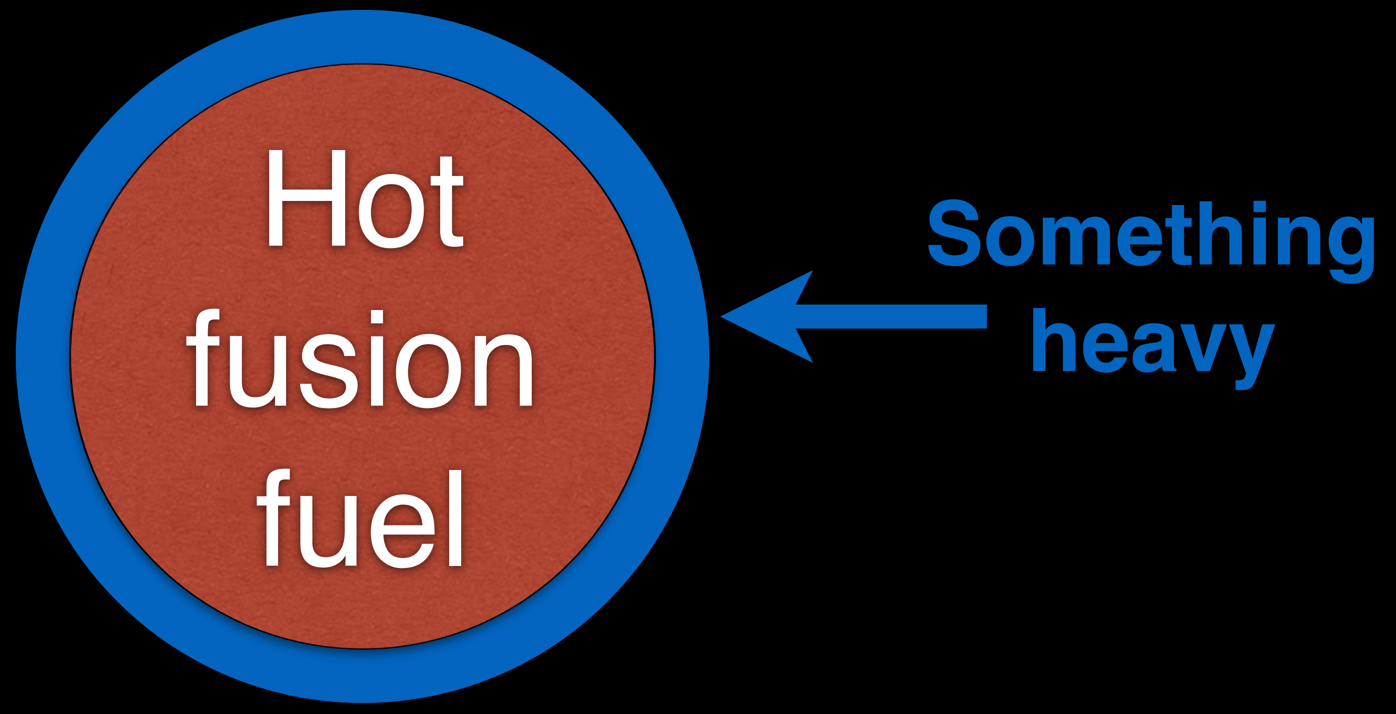
# Main Ways to Do Fusion: Stars, Magnets and **Inertia**

- Inertial Confinement Fusion:
  - Inertia holds things in place for a while … but eventually they accelerate
  - Can inertia be used to hold the hot fusion fuel in place for long enough for the atoms to fuse?






**Inertial Confinement Fusion: the basis of Laser Fusion**

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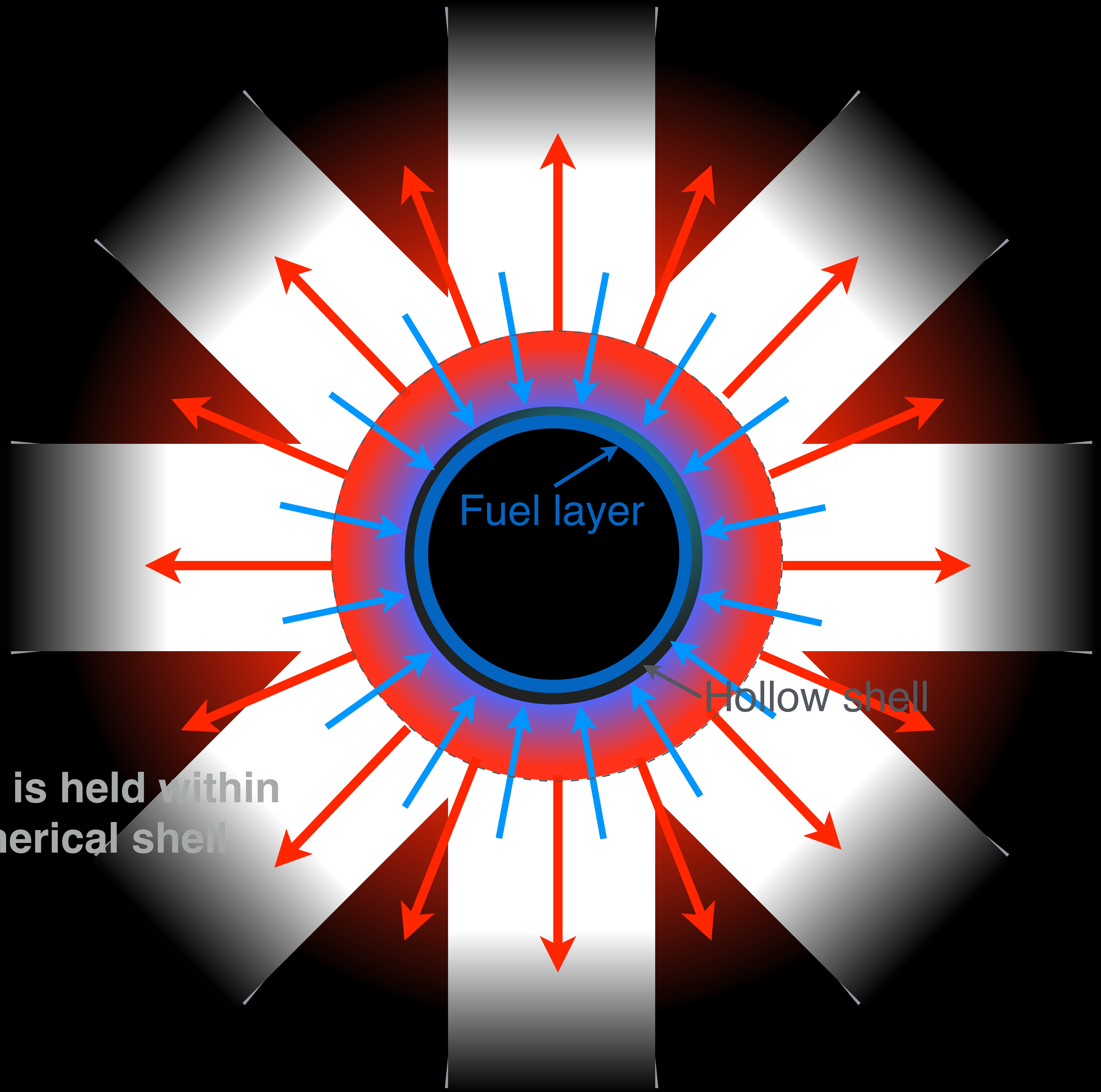
# (Laser) Inertial Fusion

**Huge inward pressure is caused by the ablation**




**The fusion fuel is held within a hollow spherical shell**

**Laser beams or laser-generated x-rays illuminate a hollow spherical shell containing the fusion fuel**

**Hot, ablated plasma expands very rapidly outwards**

**The fuel shell implodes, compressing and heating the fusion fuel to conditions exceeding those in the centre of the Sun**

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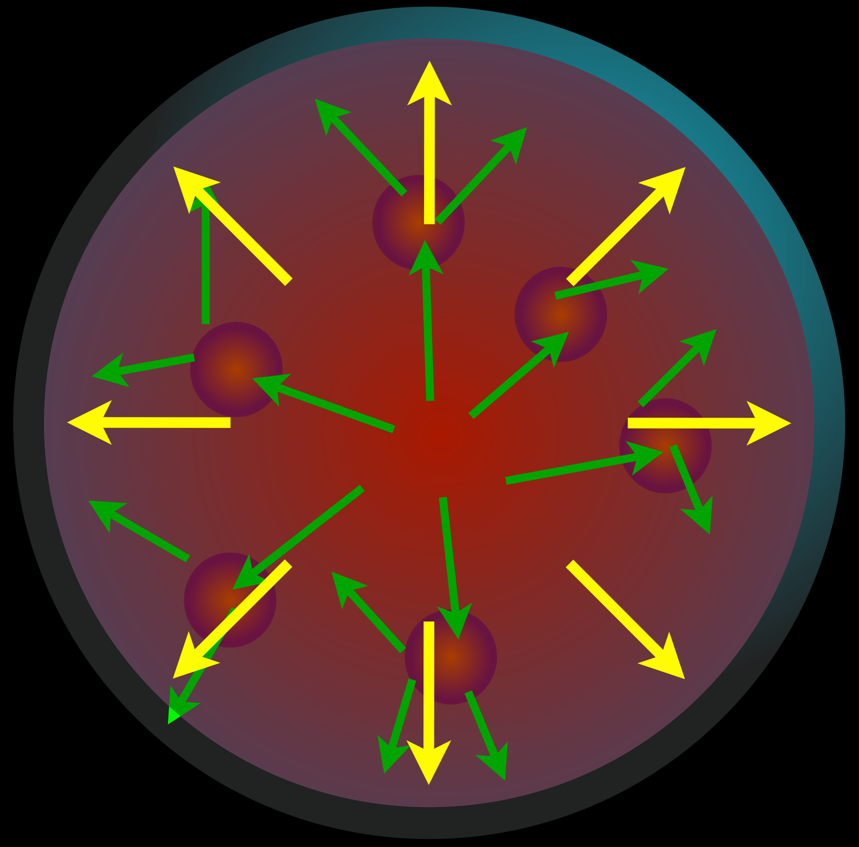
# (Laser) Inertial Fusion

$$c_{\mathrm{DT}} \frac{dT_{\mathrm{th}}}{dt} = f_\alpha Q_\alpha - f_B Q_{\mathrm{B,DT}} - Q_{\mathrm{e}} - \frac{1}{m} p \frac{dV}{dt}$$

- Hotspot temperature
- Bremsstrahlung emission power loss
- Compressive power gain, then loss
- Specific heat capacity of DT
- Alpha particle redeposition power gain
- Electron thermal conductivity power loss



**more heating**

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# The National Ignition Facility (NIF)

- Biggest laser in the world
- Size of 3 football pitches
- 192 laser beams
- Each laser pulse:
  - Energy:
    - 2.1 MJ
    - 1 Mars bar!
  - Duration:
    - 10 billionths of a second
  - Power:
    - 500,000,000,000,000 W
    - 1 million times global electrical power usage!

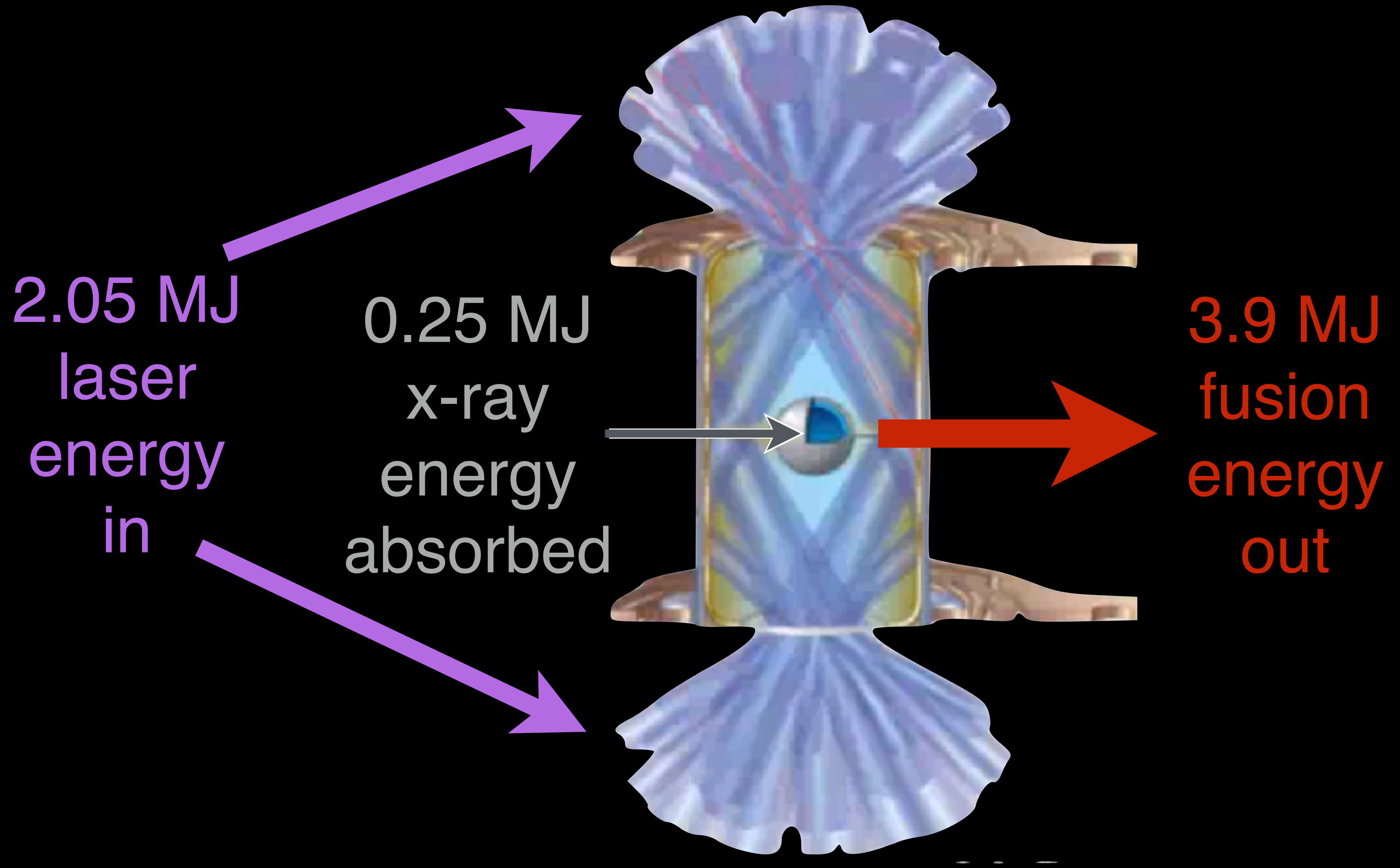
NIF's 10m diameter target chamber

Illustration of Laser Fusion on NIF

NIF from the outside

# High Gain 1: Reducing Energy Input by Increasing Coupling

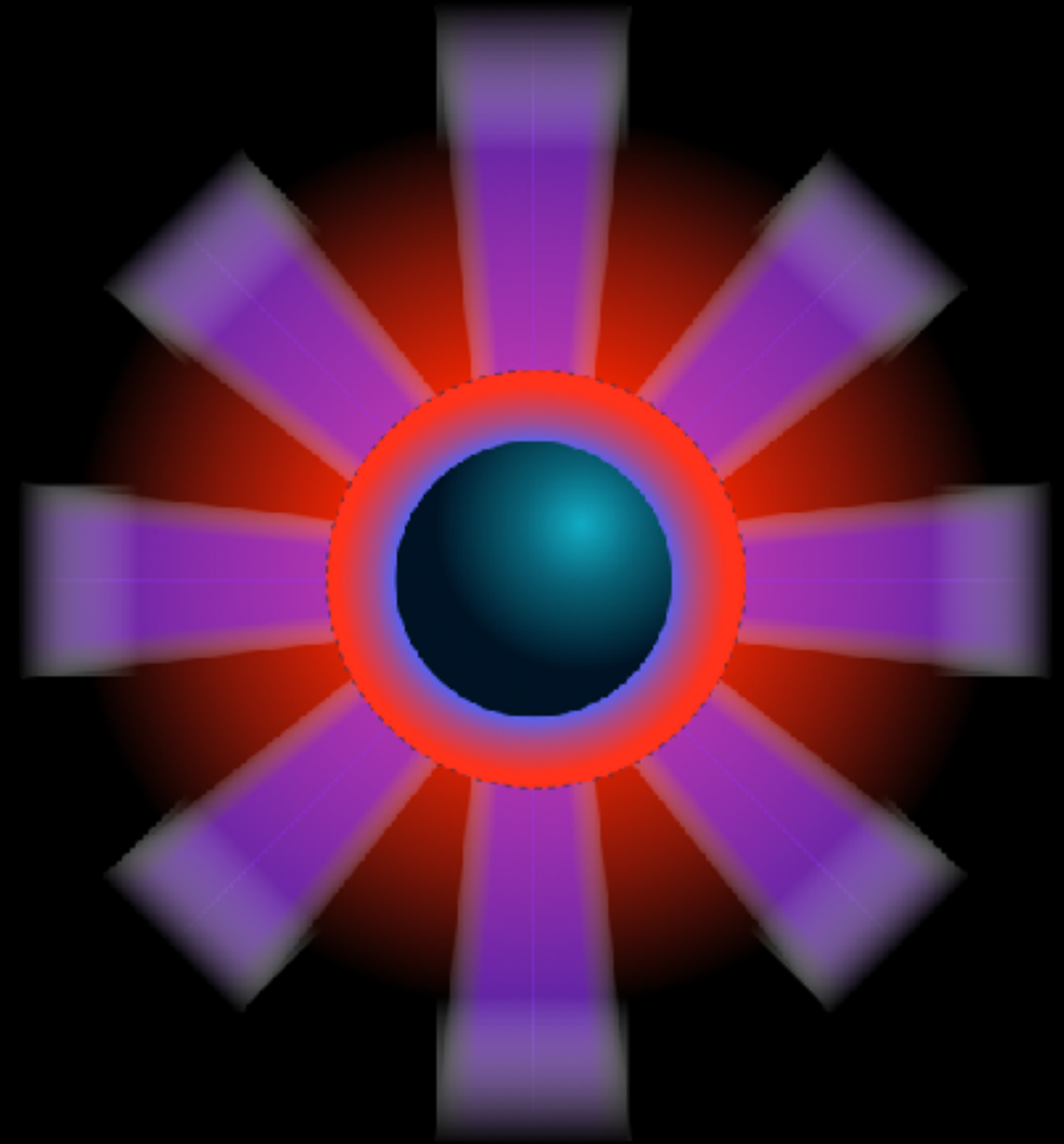
NIF ‘indirect’ drive




- ✅ 1st demonstration of fusion energy gain
  - Fusion Gain = 1.9
  - Implosion gain = 15.6!
  - Proven the physics works
- ❌ Inefficient
- ❌ Complex, expensive targets
- ❌ Material activation

} Make fusion energy challenging

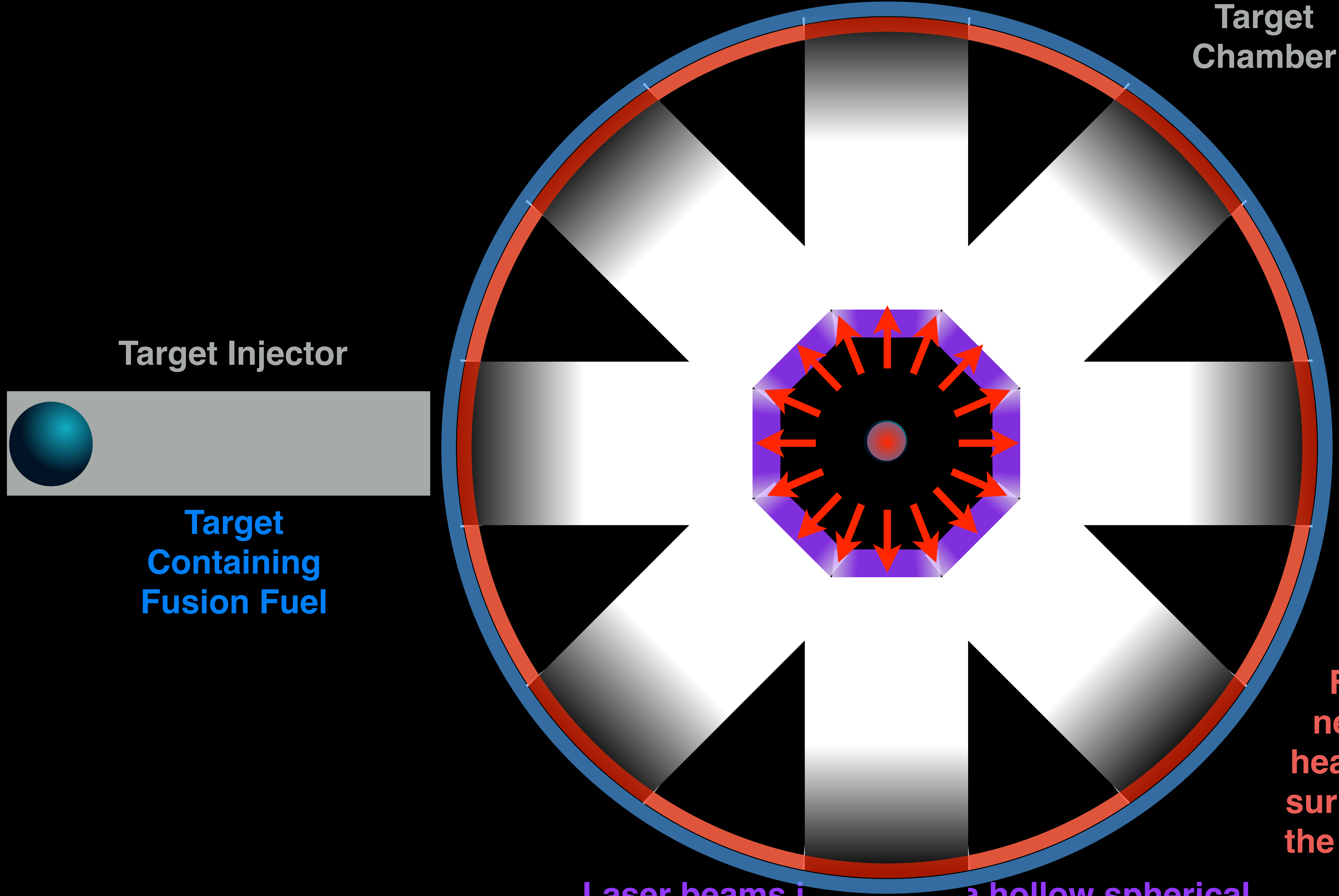
Direct Drive



- ✅ Same proven ignition physics
- ✅ ~ 6 x higher efficiency
  - ✅ Lower energy laser
    - ✅ Higher fusion energy-gain
    - ✅ Cheaper laser
- ✅ Simpler, cheaper, targets
- ❌ Some physics uncertainties remain

} Help with fusion energy

# Energy Generation using Laser Fusion




- Requirements:
  - Energy efficiency
  - Economic manufacturing:
    - Lasers
    - Targets
  - Rapid shot rate
  - Robust chamber
  - …

Development of these technologies is the major next step required for Laser Fusion Energy

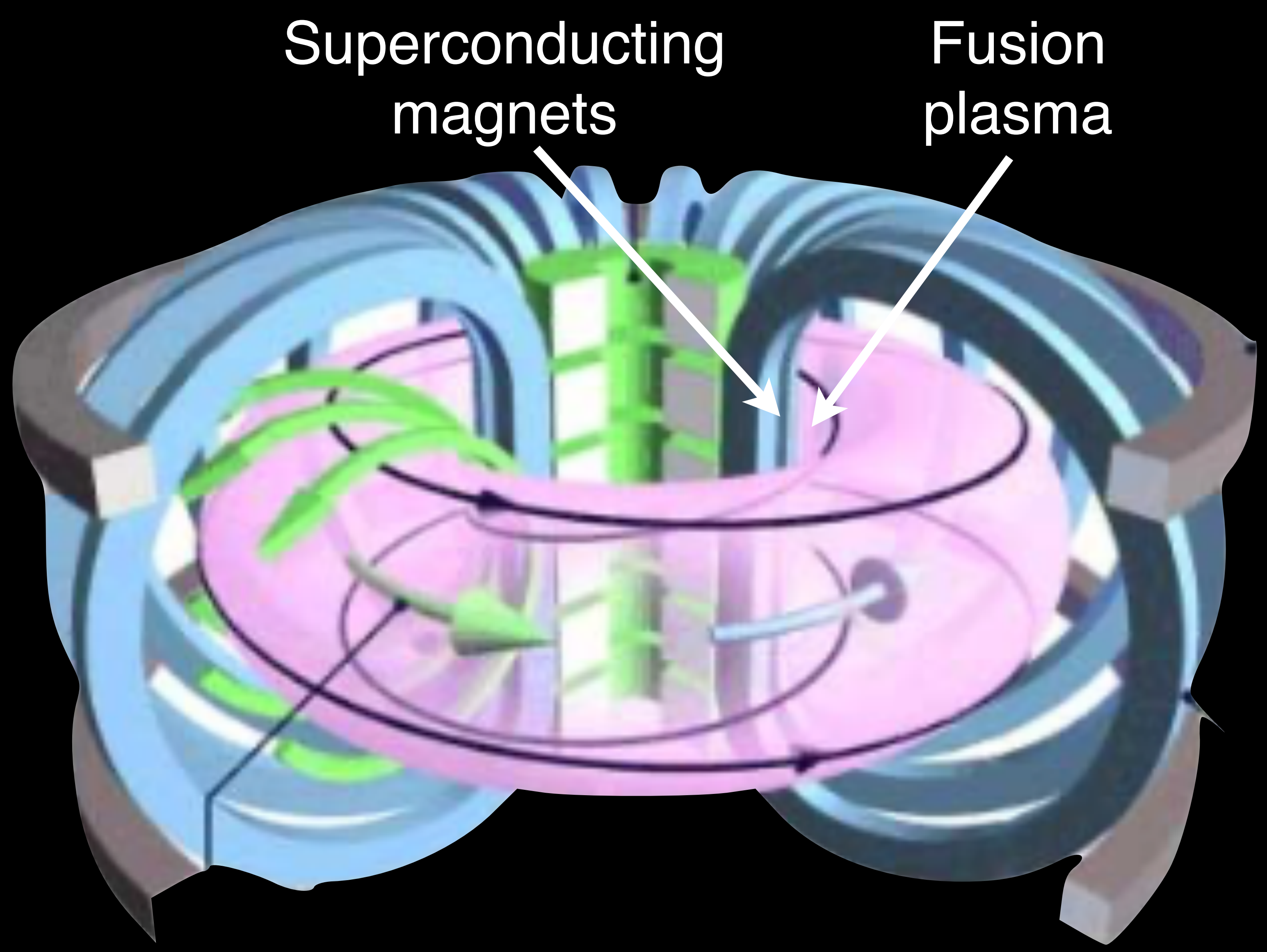
# Potential Advantages of Inertial Fusion Energy

- Inertial drivers enable separation between the plasma and critical infrastructure:
  - Reduced neutron damage
  - Reduced thermal damage
  - Simplified reactor maintenance

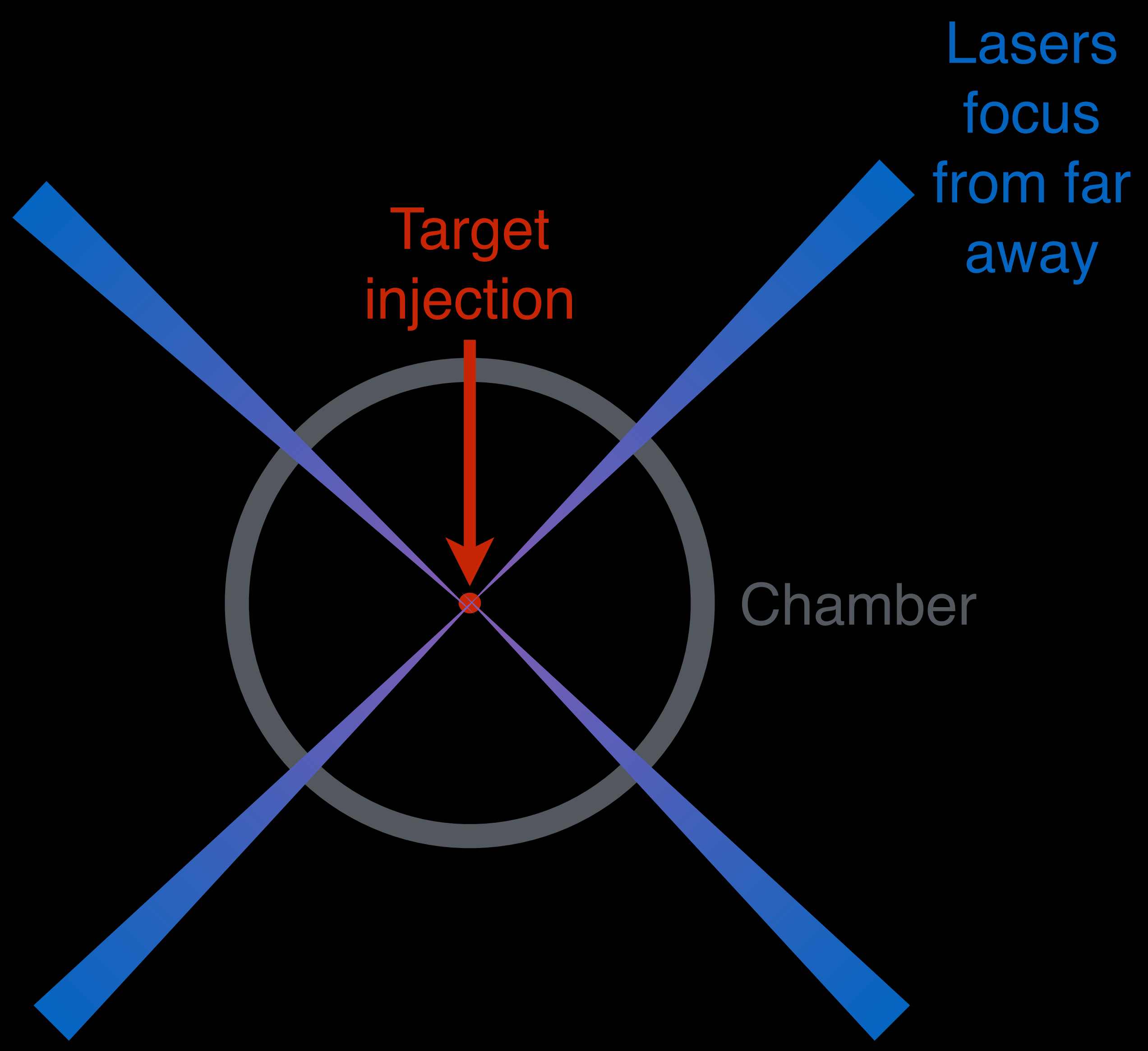
- Modular technology:
  - Driver (e.g. laser)
  - Targets
  - Target injection
  - Chamber

  } Enables rapid parallel development

- Reduced tritium inventory (1/10th)
- Reduced capital expenditure (potentially)




Magnetic Fusion Tokamak: complex technology is adjacent to the harsh fusion plasma and surrounds it like a Russian doll




Laser fusion: modular components are far way from fusion plasma

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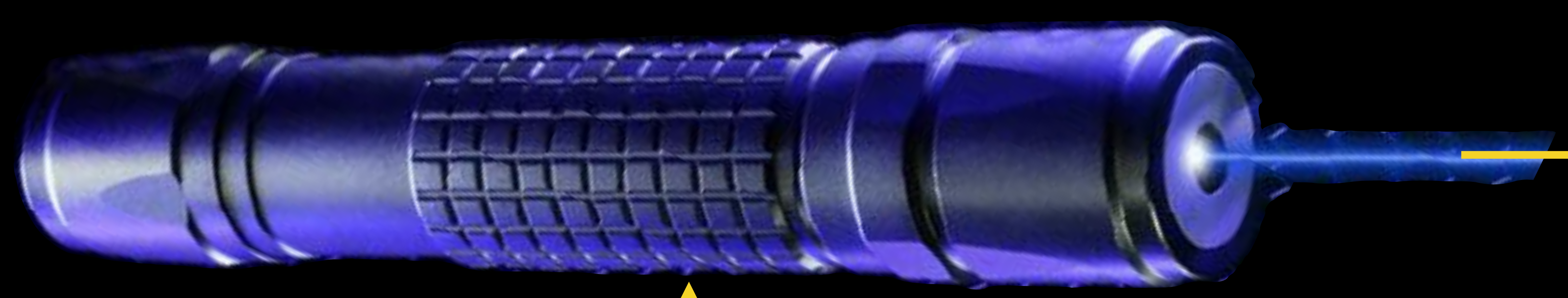
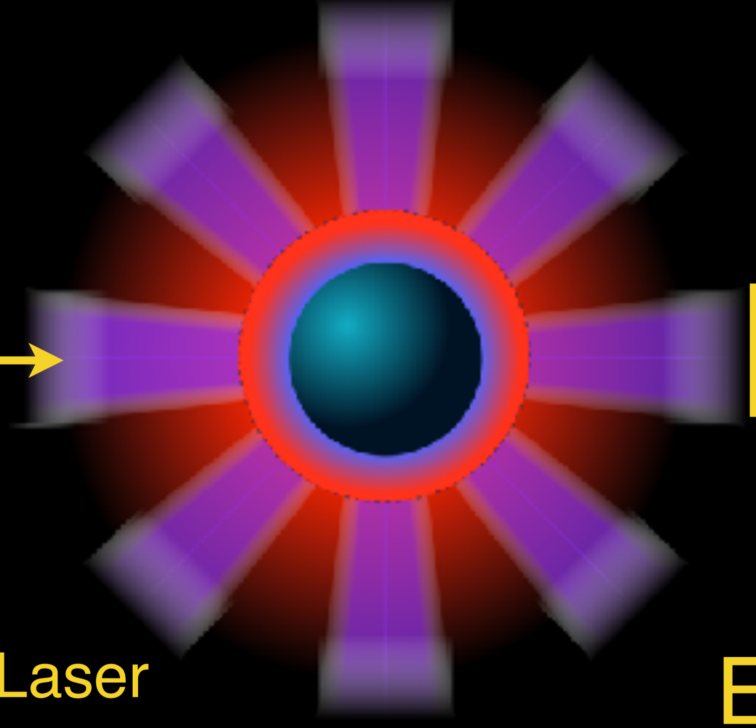
# Laser (Inertial) Fusion Energy: Basic Energetics

Laser driver ($\eta_{Laser}$)



Implosion ($G = E_{out} / E_{in}$)



Energy generation ($\eta_{Thermal}$)

$E_{Laser} \,.\, \eta_{Laser}$

$E_{Laser} \,.\, \eta_{Laser} \,.\, G$

$E_{Laser} \,.\, \eta_{Laser} \,.\, G \,.\, \eta_{Thermal}$

$E_{Laser}$

$f_{Recycled}$

$E_{Laser} \,.\, \eta_{Laser} \,.\, G \,.\, \eta_{Thermal} \,.\, (1- f_{Recycled})$

Usable energy

- Assuming:
  - $\eta_{Thermal} \sim 40\%$
  - $f_{Recycled} < 0.25$
- $\eta_{Laser} \,.\, G > 10$
- $\eta_{Laser} = 10 - 33\%$
- $G = 30 - 100$

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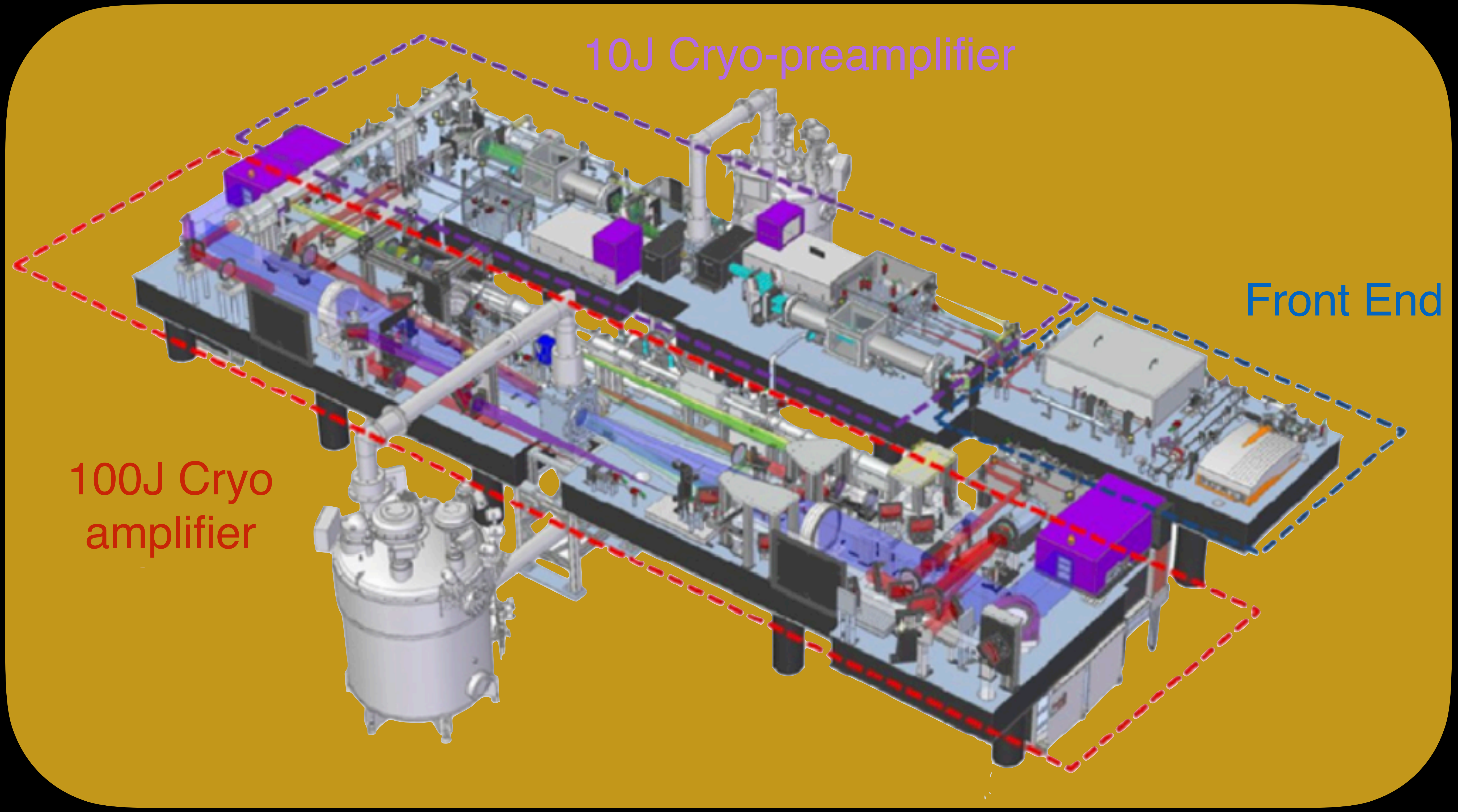
# Energy Efficient Lasers for Fusion

- NIF lasers are only **0.6% efficient**
  - 166 times more electricity input to the lasers than laser energy output!
  - Not feasible for power production
- Central Laser Facility:
  - DiPOLE* laser **10% efficient**
  - **30x** efficiency improvement
- Next steps:
  - Cheaper
  - Higher energy
  - Increased bandwidth (more later)




CLF's 100J, 10Hz, Diode-pumped 'DiPOLE' laser

*M. Divoky et al., "150 J DPSSL operating at 1.5 kW level," Opt. Lett., 46, 2021.

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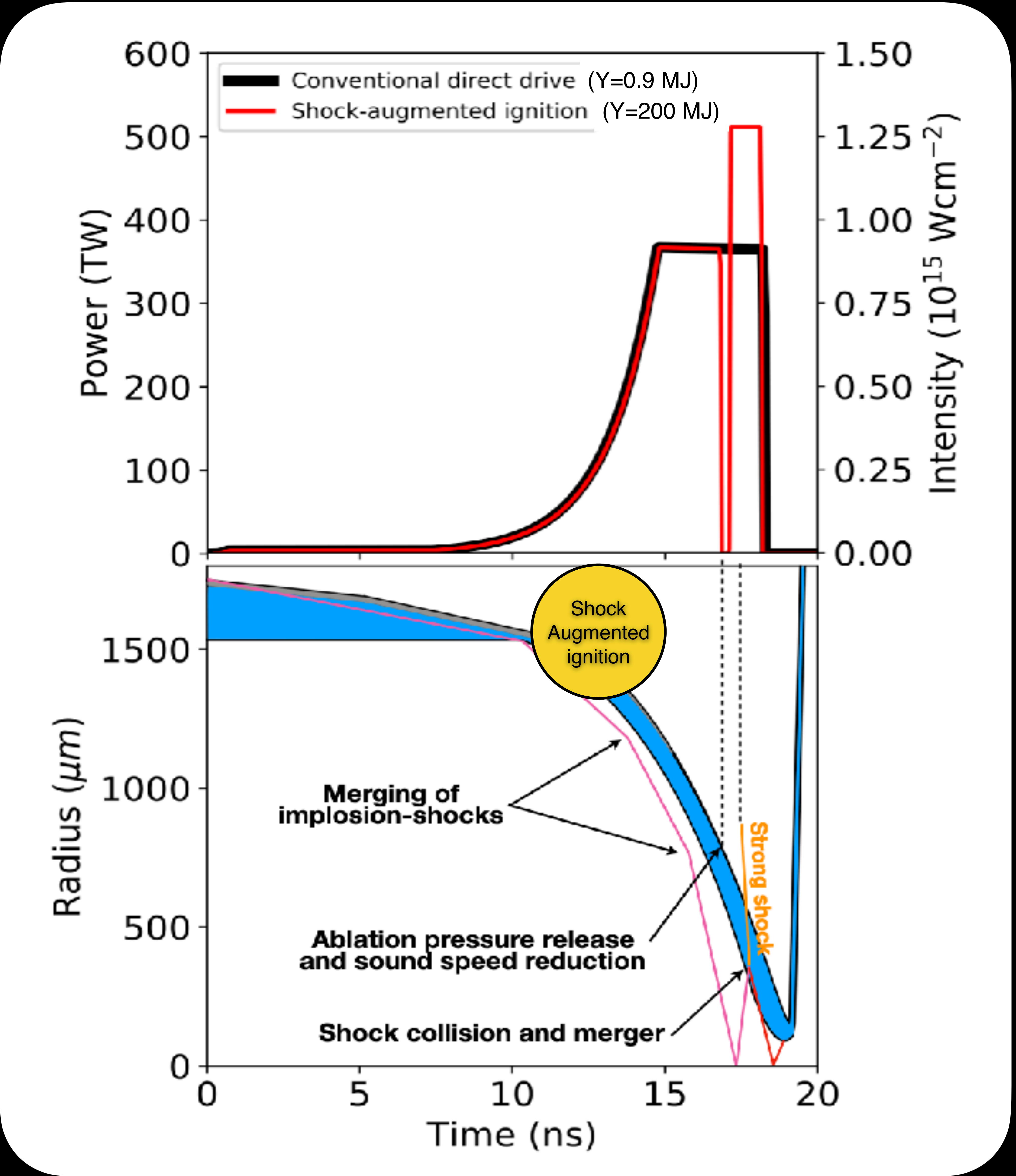
# A Shock-Augmented Approach to Laser Fusion*

- Concept:
  - Generate a very strong shock without very high power or intensity
  - Realise benefits of shock-ignition *and* central hotspot
  - Mitigate main challenges
- Method:
  - Dip in power: pre-conditions ablation plasma
  - Rise in power: launches strong shock
- Advantages (according to simulations):
  - Enhanced implosion stability vs central hotspot ignition
  - Reduced laser-plasma instabilities vs Shock Ignition
  - Increased gain vs central hotspot ignition
  - See experiments tomorrow




*Scott et al., *Physical Review Letters* (2022)

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# UK Inertial Fusion Consortium

- UK Inertial Fusion Consortium
  - Enabling collaboration: 11 UK institutions
  - Creating a common voice: ~ 90 members
  - Developing Strategy: UK Inertial Fusion Roadmap
  - Facilitating dialogue:
    - UK government: UPLiFT proposal
    - Internationally: US IFE initiative, DoE, HiPER+, Taranis
- www.inertial-fusion.co.uk

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# UK Programme: Laser Inertial Fusion Technology for Energy

**HiGAIN Facility Design**

**Technologies:** lasers, targets, injection, engagement, chamber, diagnostics

**Physics:** Direct Drive Shock Augmented Ignition, laser energy, beam number & geometry, beam smoothing, laser bandwidth, target design…

**“the technological transition from energy-gain on NIF to commercially viable Laser Fusion energy”**

## UPLiFT

**Target Manufacturing**
- Mass-manufacturing
- High quality
- Economic
- Cryogenics

**Target Injection & Engagement**
- Acceleration & accuracy
- Thermal Loading
- Tracking & beam steering

**Chamber**
- Target survivability
- Neutron damage
- Debris clearing

**Laser Drivers**
- Energy-efficiency (>10%)
- Repetition rate (10 Hz)
- Bandwidth (~1%)
- Cheap (£/J)

**Physics, Simulations & Diagnosis**
- Direct Drive
- Shock Augmented Ignition
- Laser imprint
- Laser-plasma physics

# Summary

- Laser Fusion works!
- NIF is a fantastic machine, but it was built for **science**, not **energy**
- Known science and technologies can **rapidly advance** Laser Fusion energy:
  - **Laser efficiency** & smoothing methods
  - **Advanced targets**
  - **Direct Drive** Laser Fusion
  - Advanced ignition methods such as **Shock-Augmented Ignition**

  } **UPLiFT**
- Laser Fusion is a highly credible approach to fusion energy & an exciting field to work in
- PhDs at Universities of: **York, Imperial, Oxford, Warwick, Strathclyde, Queens Belfast**

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