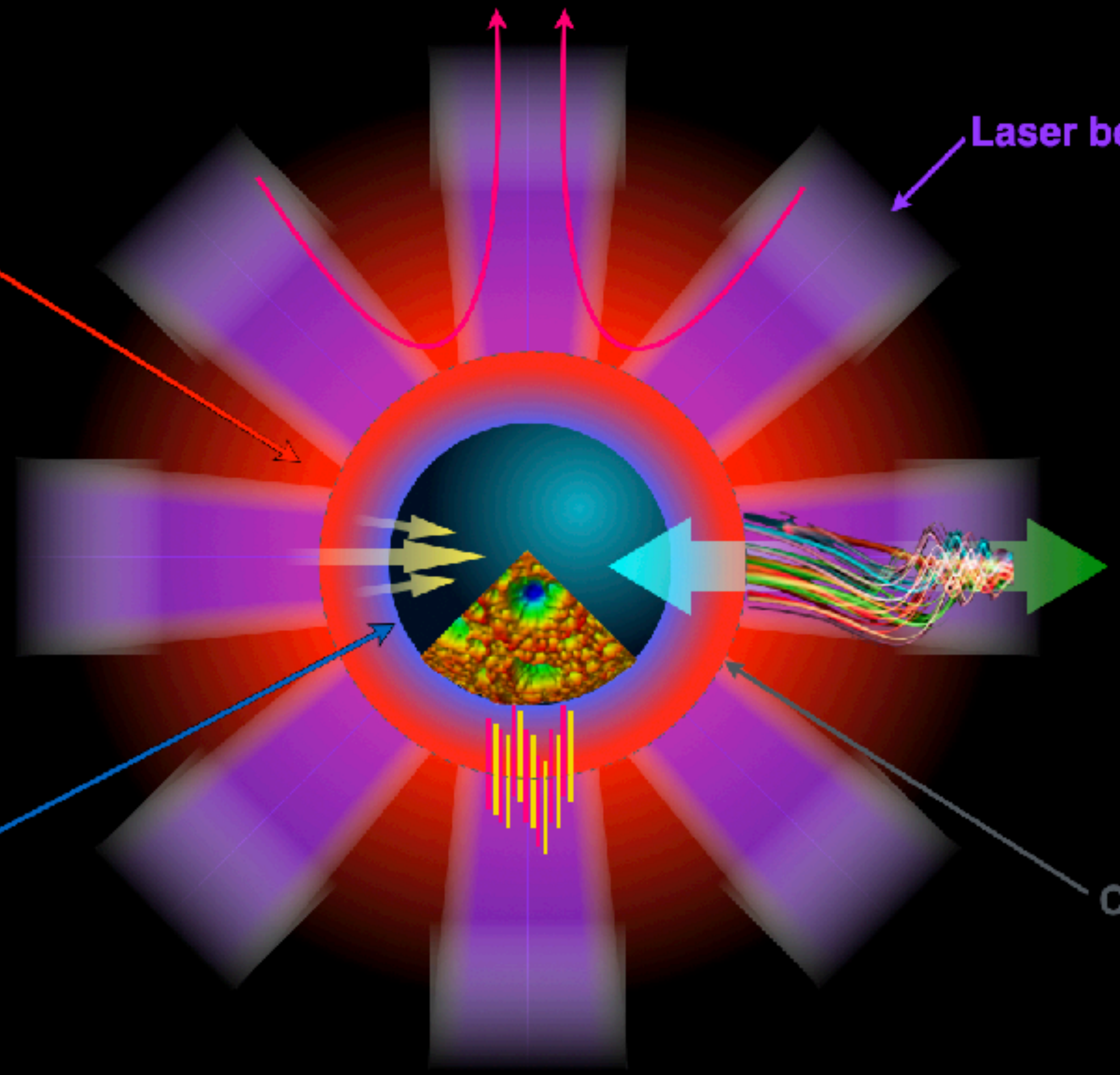
Laser Inertial Fusion Energy: Challenges & Solutions

Cross Beam Energy Transfer depletes the incident laser-beam's power, changing its spatiotemporal distribution, & potentially impacting implosion sphericity



Non-local, kinetic, heat conduction determines energy coupling, dictates the ablation plasma density profile, and can pre-heat the fusion fuel

Laser-plasma instabilities excite waves which reflect laser light and accelerate electrons to high energy, potentially pre-heating the fusion fuel

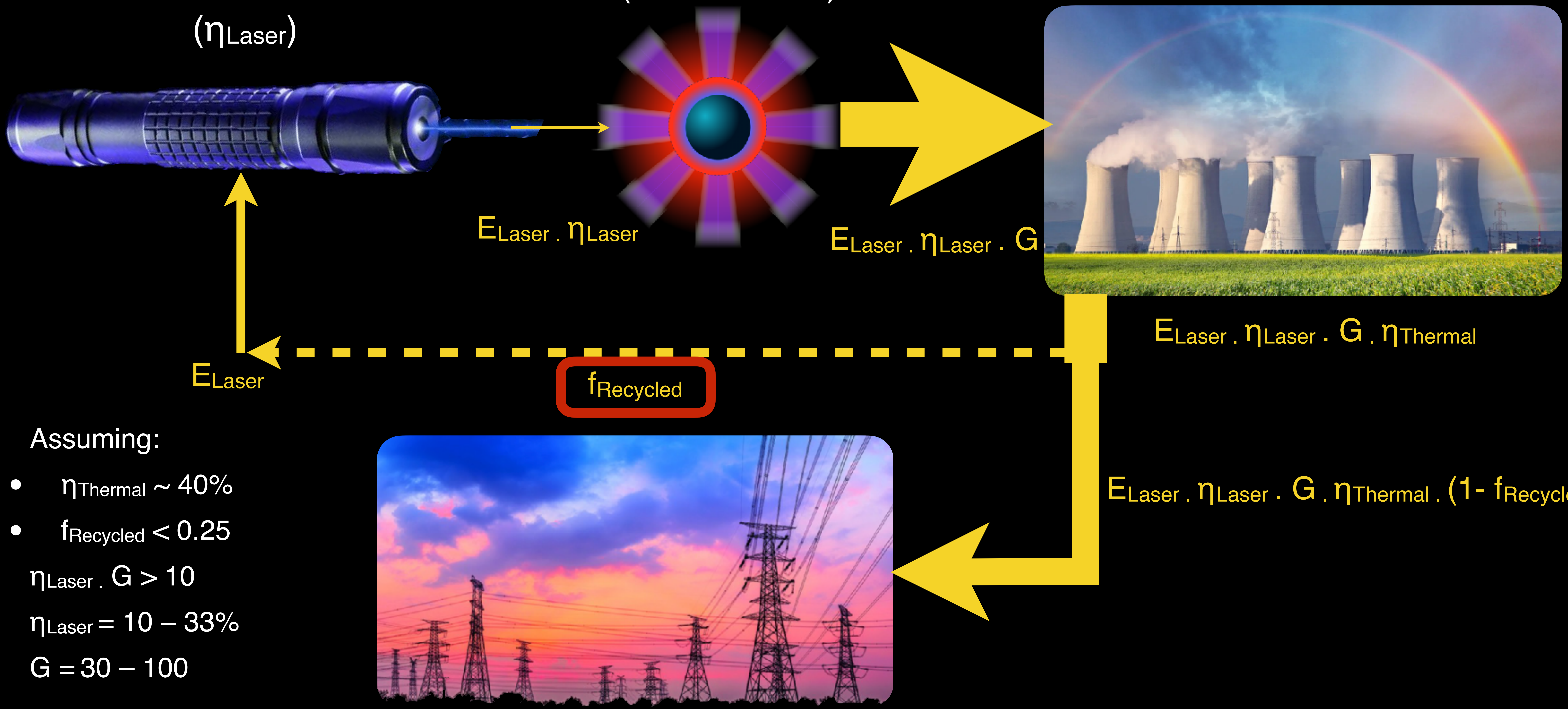
Laser intensity inhomogeneities imprint perturbations early in the implosion before the critical surface detaches, increasing hydrodynamic instability-growth

R.H.H. Scott[1], D. Barlow[1], A. Nutter[2], K. Glize[1], N. Woolsey[2], T. Goffrey[3], T. Arber[3], A. Solodov[4], M. Rosenberg[4],
[1] Central Laser Facility, STFC Rutherford Appleton Laboratory, UK. 2 York Plasma Institute, University of York, UK.
[3] Department of Physics, University of Warwick, UK. [4] Laboratory for Laser Energetics, University of Rochester, USA.

19th December 2023

robbie.scott@stfc.ac.uk

Laser (Inertial) Fusion Energy: Basic Energetics



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

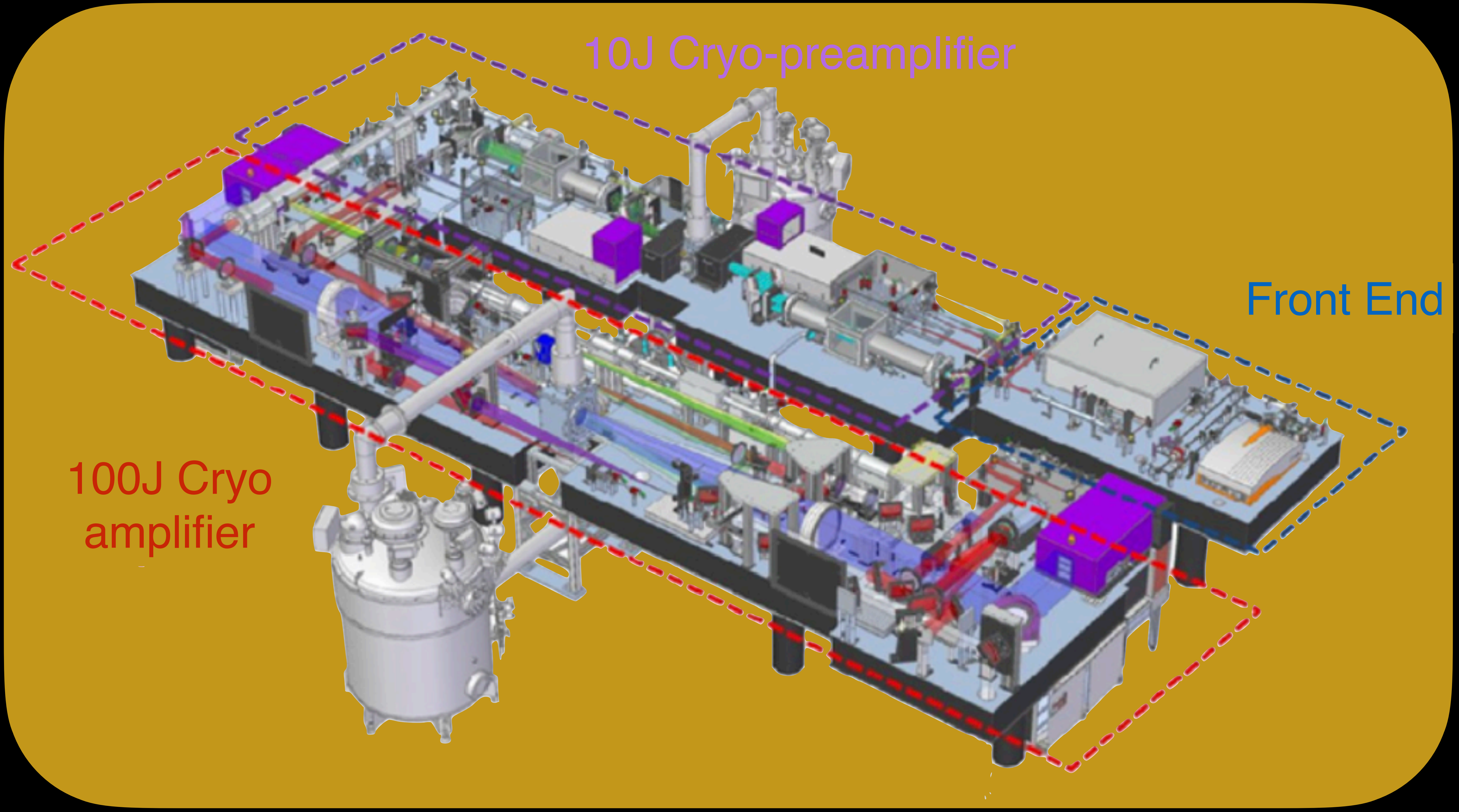
robbie.scott@stfc.ac.uk

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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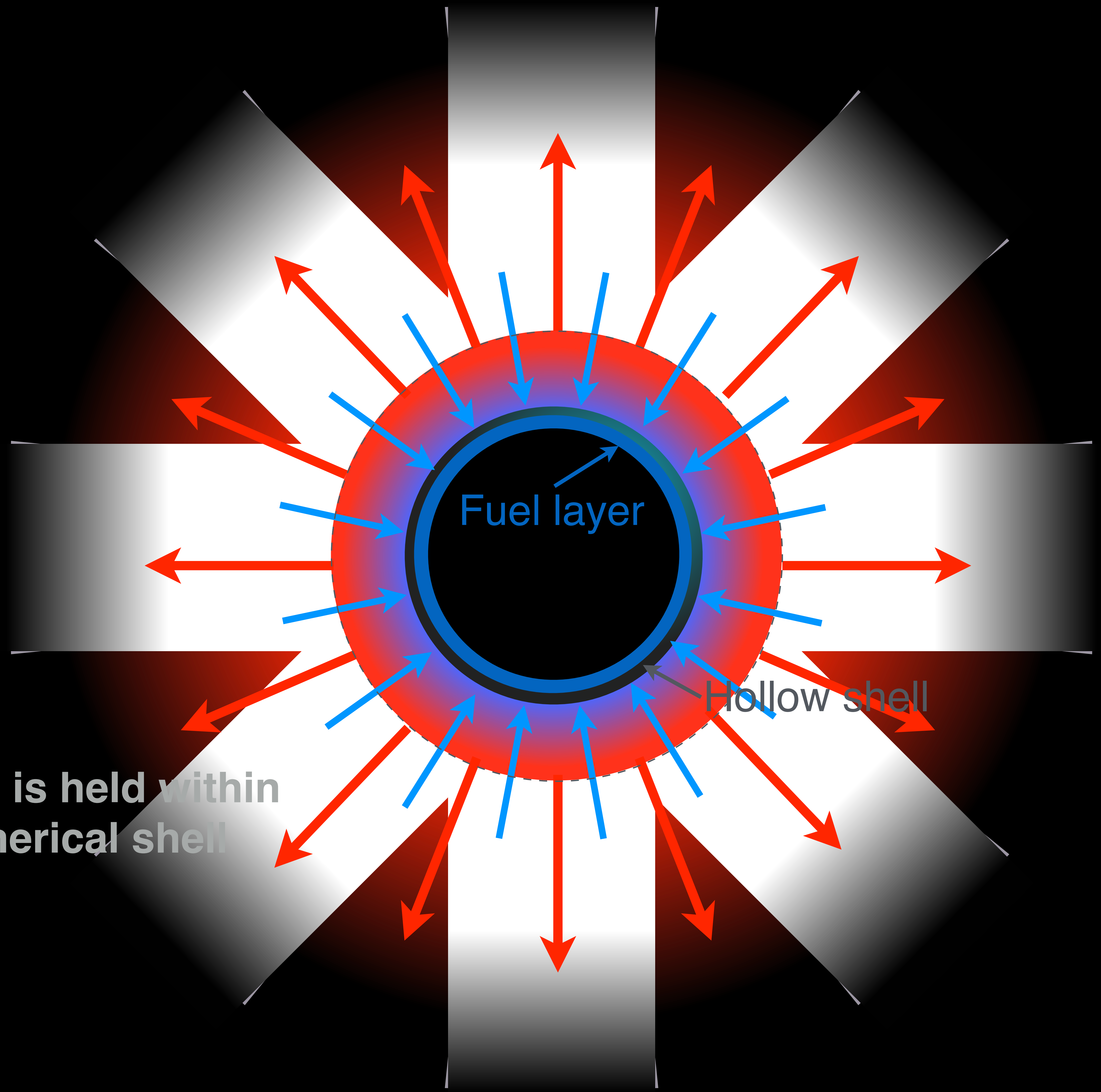
Laser (inertial) Fusion



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

robbie.scott@stfc.ac.uk

Laser (inertial) Fusion

Hotspot temperature

Bremsstrahlung emission power loss

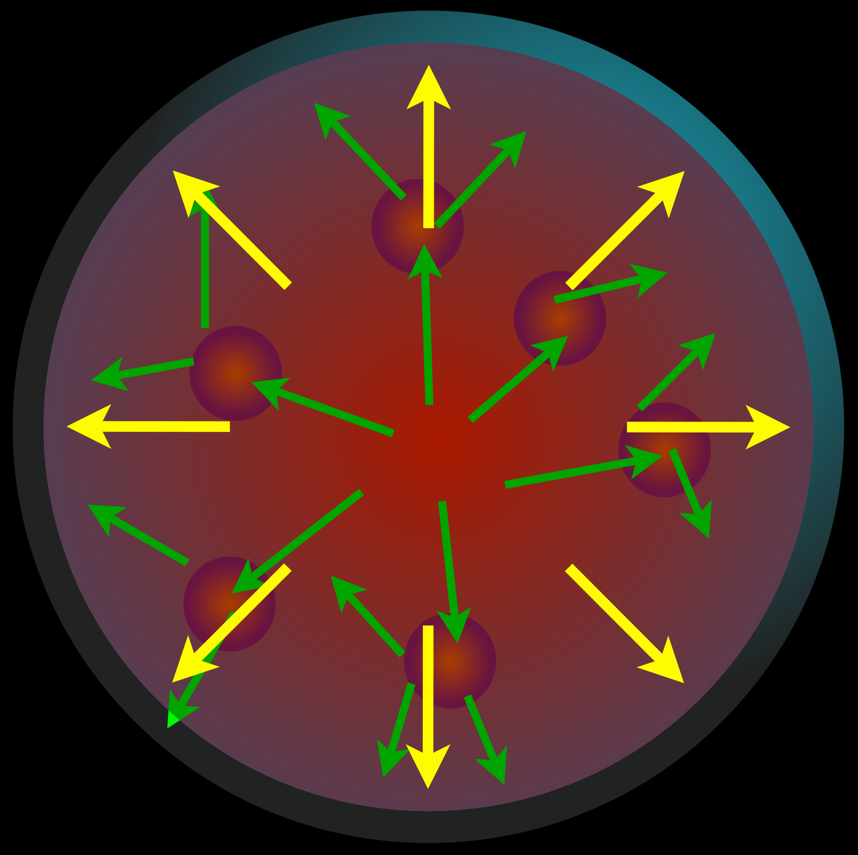
Compressive power gain, then loss

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

Specific heat capacity of DT

Alpha particle redeposition power gain

Electron thermal conductivity power loss



more heating

Deceleration converts shell's kinetic energy into more pressure,

Fusion reactions [illegible] create more alpha particles

The alpha particles [illegible] with their own kinetic energy.

[illegible] heating [illegible] fusion reactions,

robbie.scott@stfc.ac.uk

Ignition & High-Gain

- Ignition Criteria:
  - Hotspot ion temperature > 5 keV
  - Hotspot areal density (ρR_{HS}) > 0.3 g/cm^2

- Inertial fusion fuel fraction burnt:
  - $f_{burnt} = \rho R_{fuel} / (6 + \rho R_{fuel})$*

- Fusion yield is proportional to:
  - $Y = f_{burnt} . M_{fuel}$
  - $Y \propto \rho R_{fuel} . M_{fuel}$

- Gain $\propto \rho R_{fuel} . M_{fuel} / E_{in}$

- High-gain requires:
  - Minimising input energy (E_{in})
  - Maximising compression (ρR_{fuel})
  - Maximising fuel mass (M_{fuel})

*Fraley et al., 1974.

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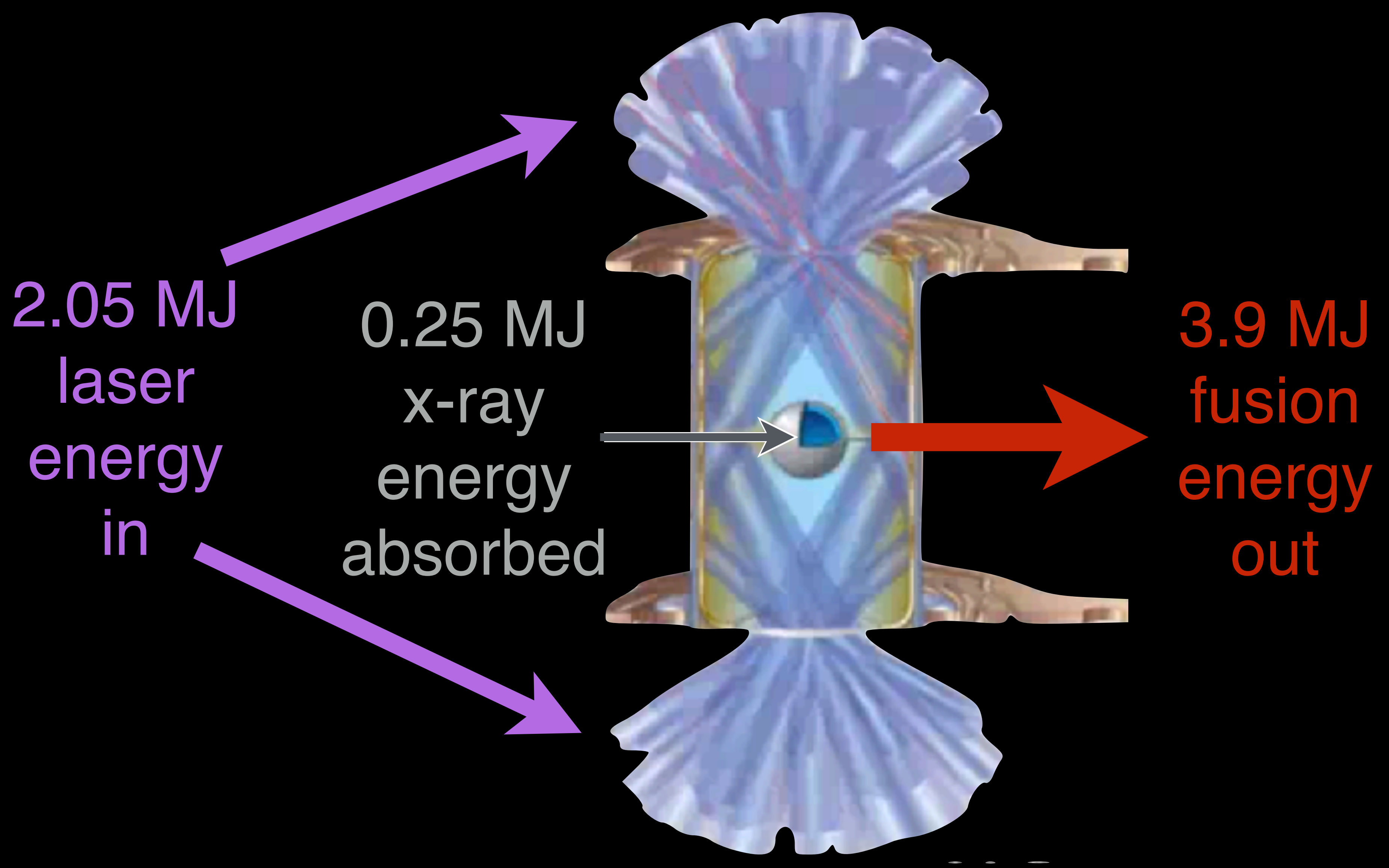
High Gain 1: Reducing Energy Input by Increasing Coupling

NIF ‘indirect’ drive

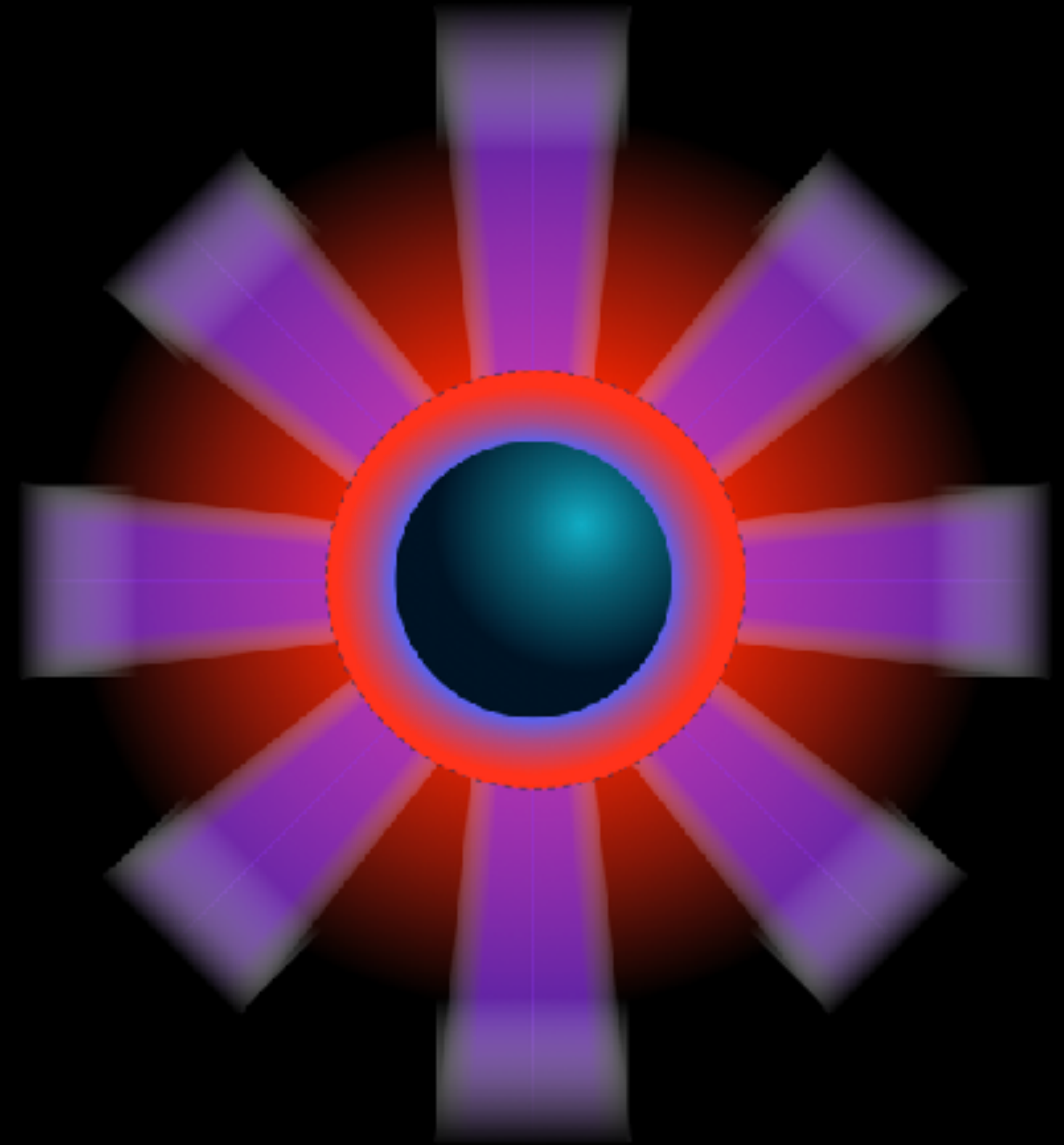


2.05 MJ laser energy in

0.25 MJ x-ray energy absorbed

3.9 MJ fusion energy out

Direct 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

- ✅ 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

robbie.scott@stfc.ac.uk

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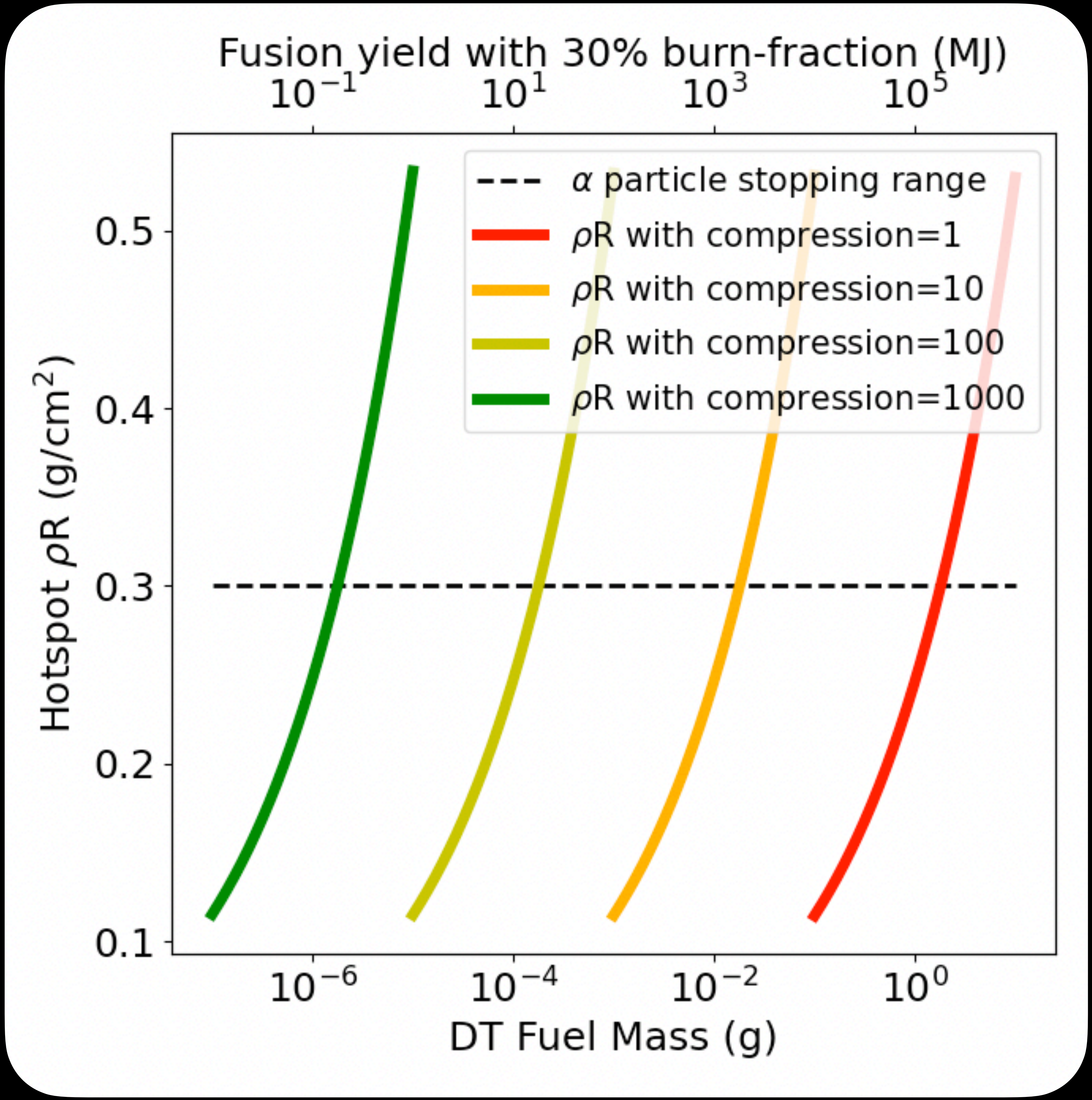
  - Maximising compression
  - Maximising fuel mass

robbie.scott@stfc.ac.uk

High Gain 2: Maximising Compression

- But why is compression so important in ICF?
- Idea:
  - $\rho_{DT} = 0.25$g/cc when solid
  - Ignition requirement: $\rho R_{HS} > 0.3$ g/cm^2
  - => $R_{HS} = 1.2$cm
  - Can't we just heat a 1.2cm radius of solid density DT to 5 keV?
  - No!
    - Fusion yield would be unmanageable
    - Input energy requirement is huge (5000 MJ)

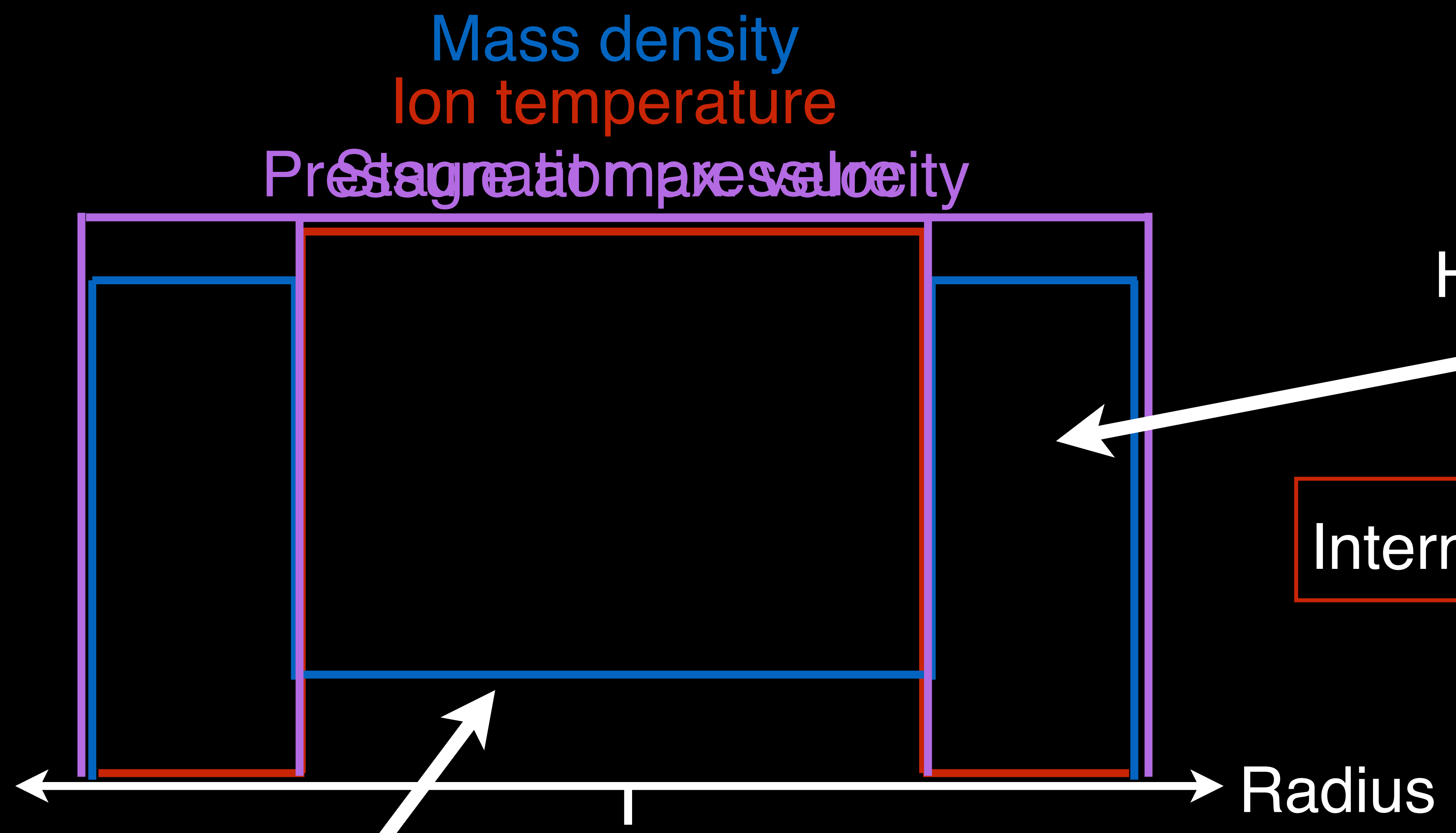


Maximising Compression: Central Hotspot Ignition±

Ablation:
Imparts kinetic energy to shell

→

Stagnation:
Converts kinetic energy to internal energy



High density, cold shell maximises fuel mass while minimising compression energy

Internal energy ~ 3/2 pressure x volume

Lower density hotspot minimises energy required to achieve ignition ion temperature (5keV)

±Nuckols, Nature, 1972

robbie.scott@stfc.ac.uk

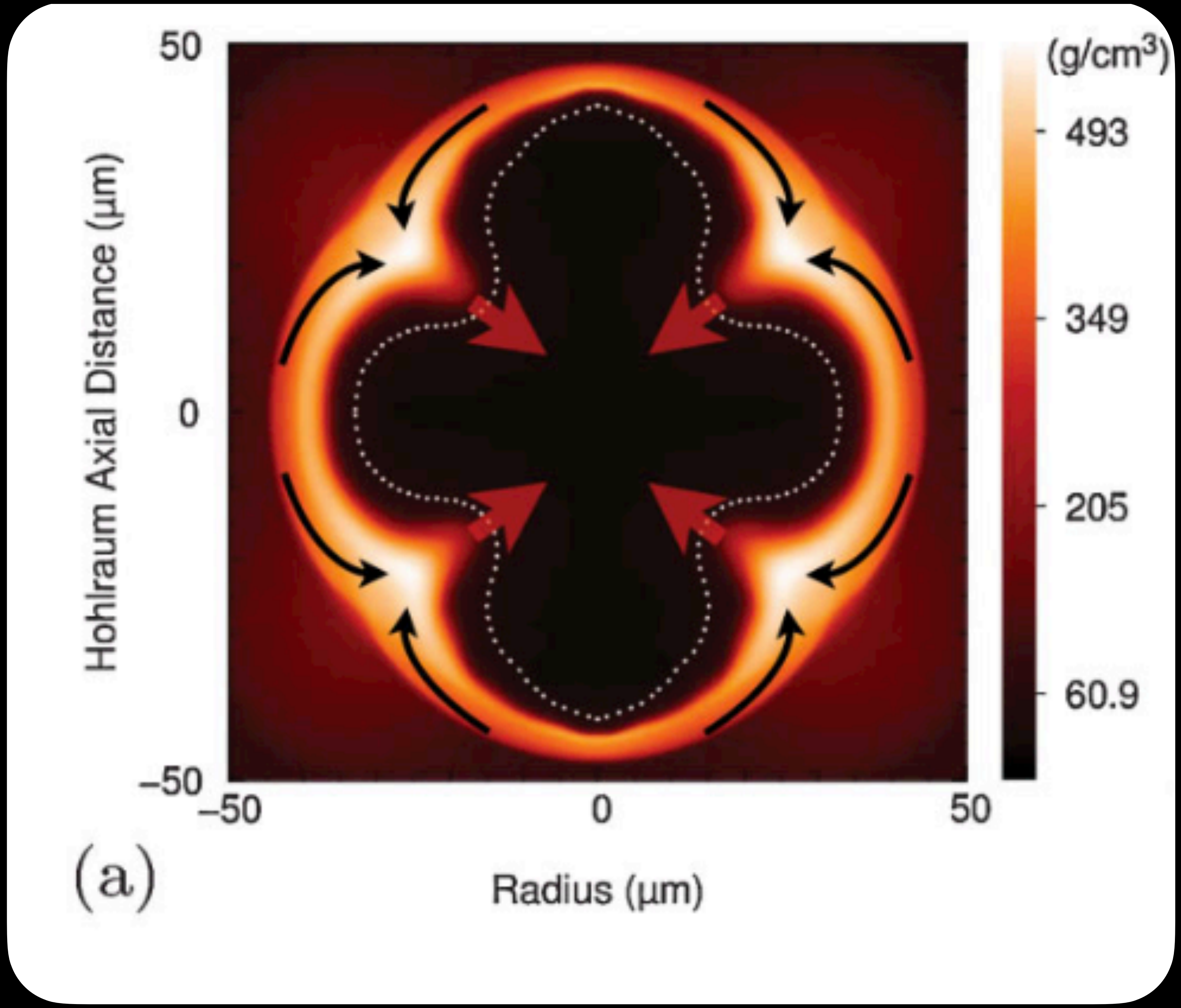
Compression: Low Mode Asymmetries & Residual Kinetic Energy[*]

Ablation:
Imparts kinetic energy to shell

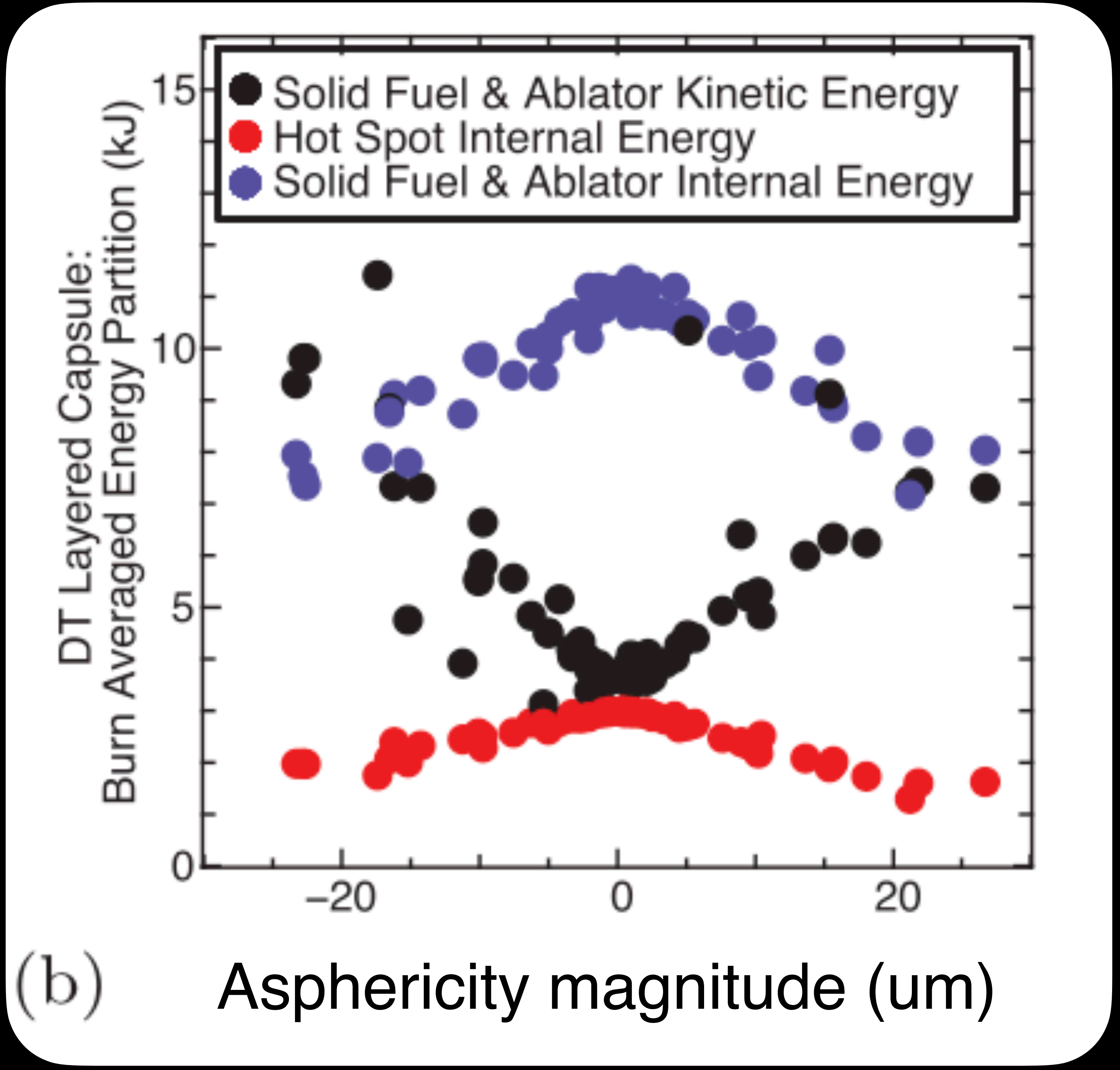
→

Stagnation:
Converts kinetic energy to internal energy

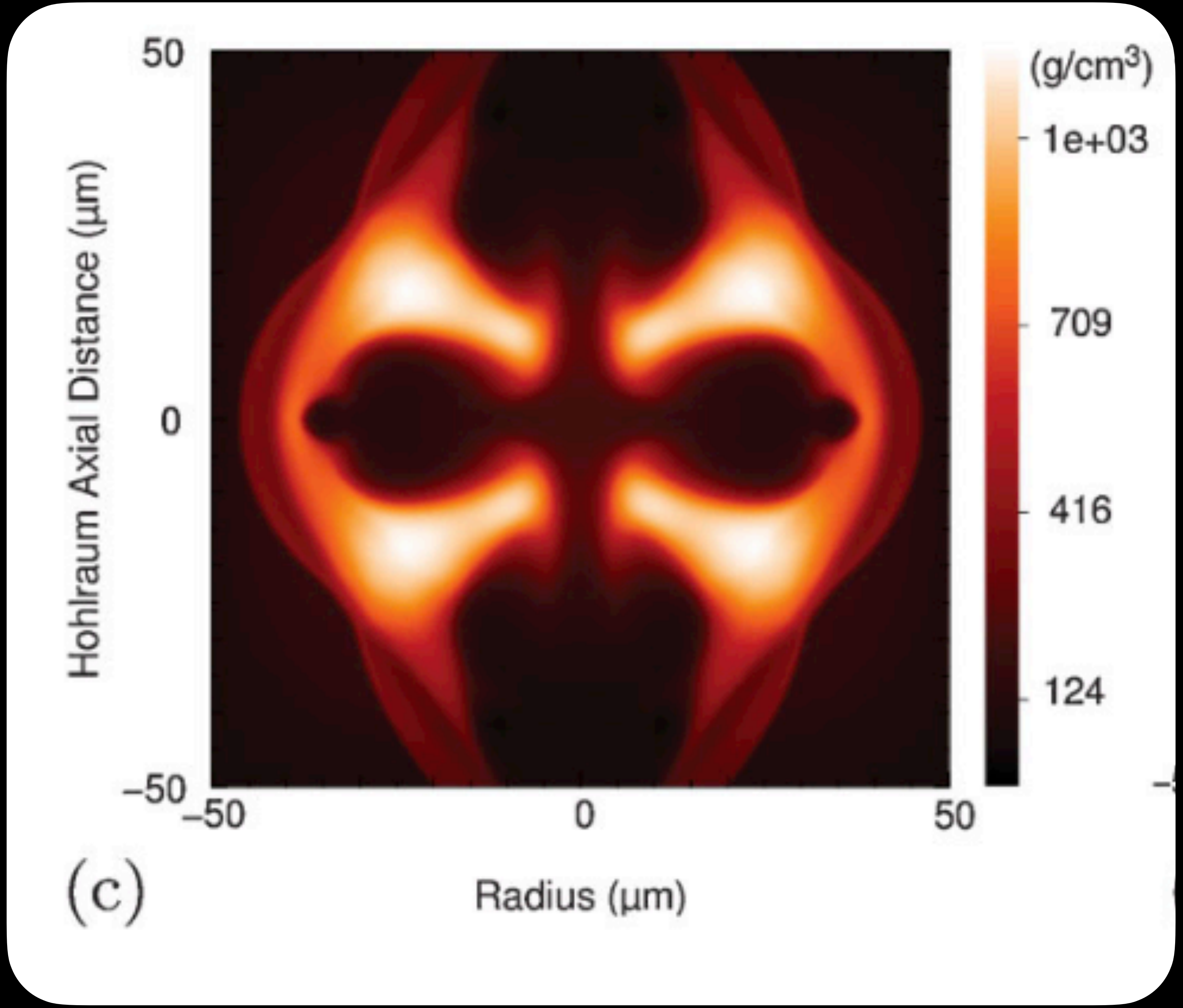
How efficiently?



Density profile at bang time when low-mode asymmetries are present



Increasing low-mode asymmetry amplitude increases residual kinetic energy in the shell



Density profile after bang time; the shell does not fully stagnate

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[*] Scott et al., PRL, 2013. Kritcher et al, PoP, 2014.

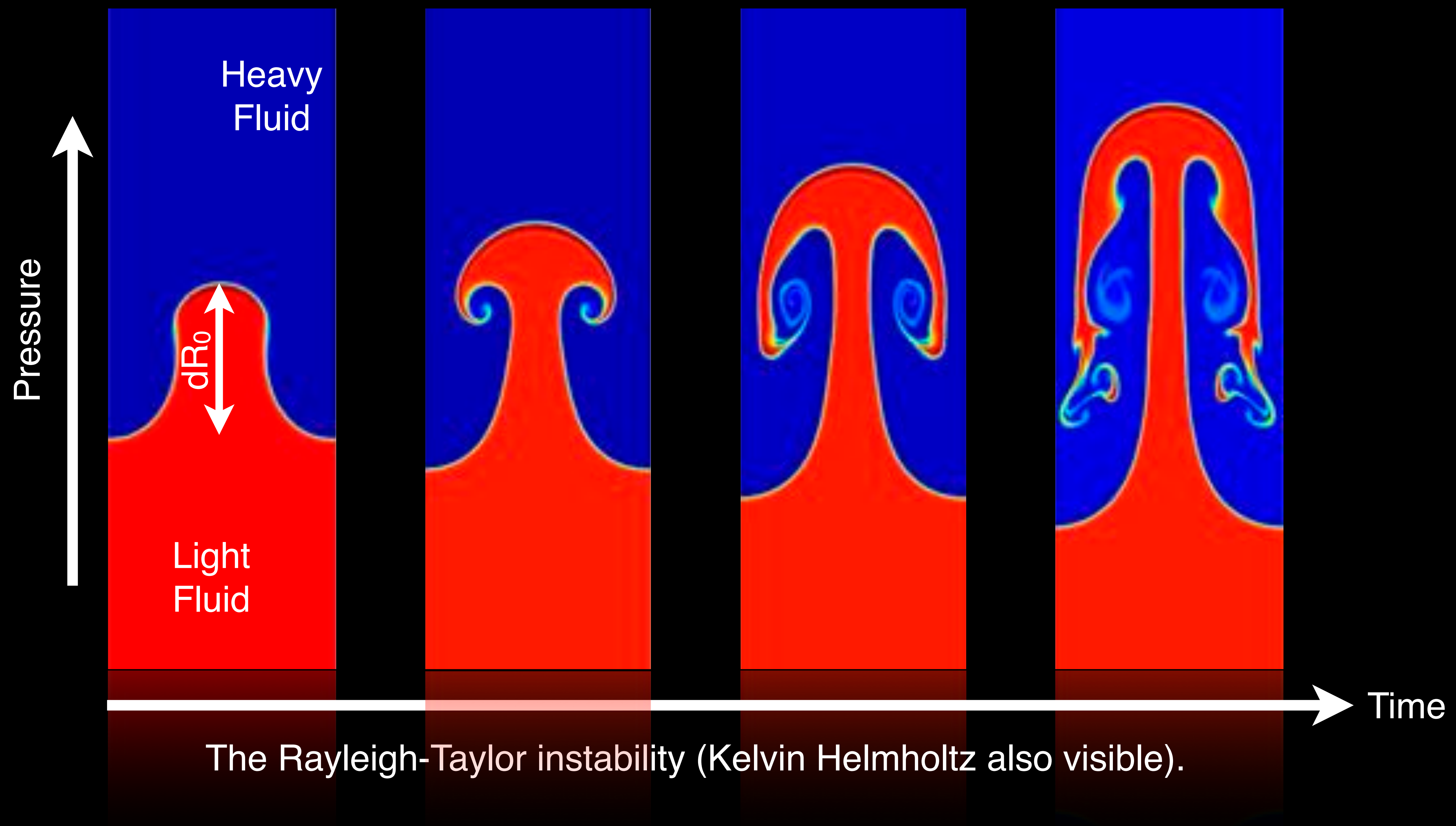
robbie.scott@stfc.ac.uk

Maximising Compression: The Rayleigh-Taylor Instability

Internal energy ~ 3/2 pressure x volume

- High-compression requires:
  - Compressible fuel
  - Compressibility ∝ 1 / Adiabat
  - Adiabat = Fuel pressure / Fermi pressure

- Lower adiabat => less internal energy => less KE
- But lower-adiabat enhances Rayleigh-Taylor (RT) growth
  - $dR(k,t) = dR_0(k)\exp(\gamma_{RT}(k)\, t)$
  - dR_0 = initial perturbation amplitude, t = time
  - $\gamma_{RT,Ablative}(k) = C_1(ak / (1 + kL_{min})^{1/2} - C_2ku_a$*
  - C_1 & C_2 constants
  - a = acceleration
  - k = perturbation wavenumber
  - L_{min} = density scale length at ablation front
  - u_a = ablative stabilisation rate



The Rayleigh-Taylor instability (Kelvin Helmholtz also visible).

*Takabe et al., Physics of Fluids, 1986.

robbie.scott@stfc.ac.uk

Maximising Compression: The Rayleigh-Taylor Instability

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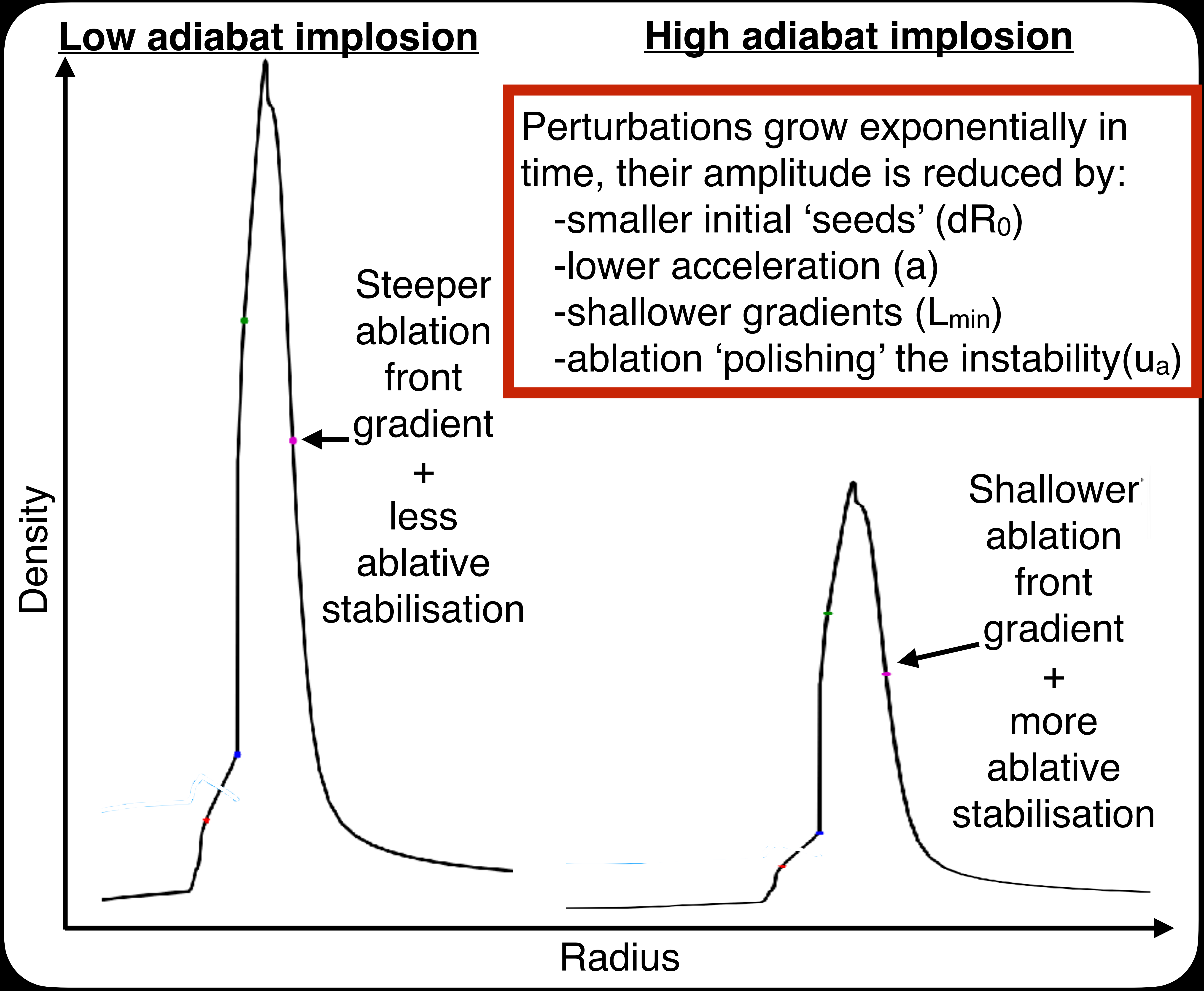
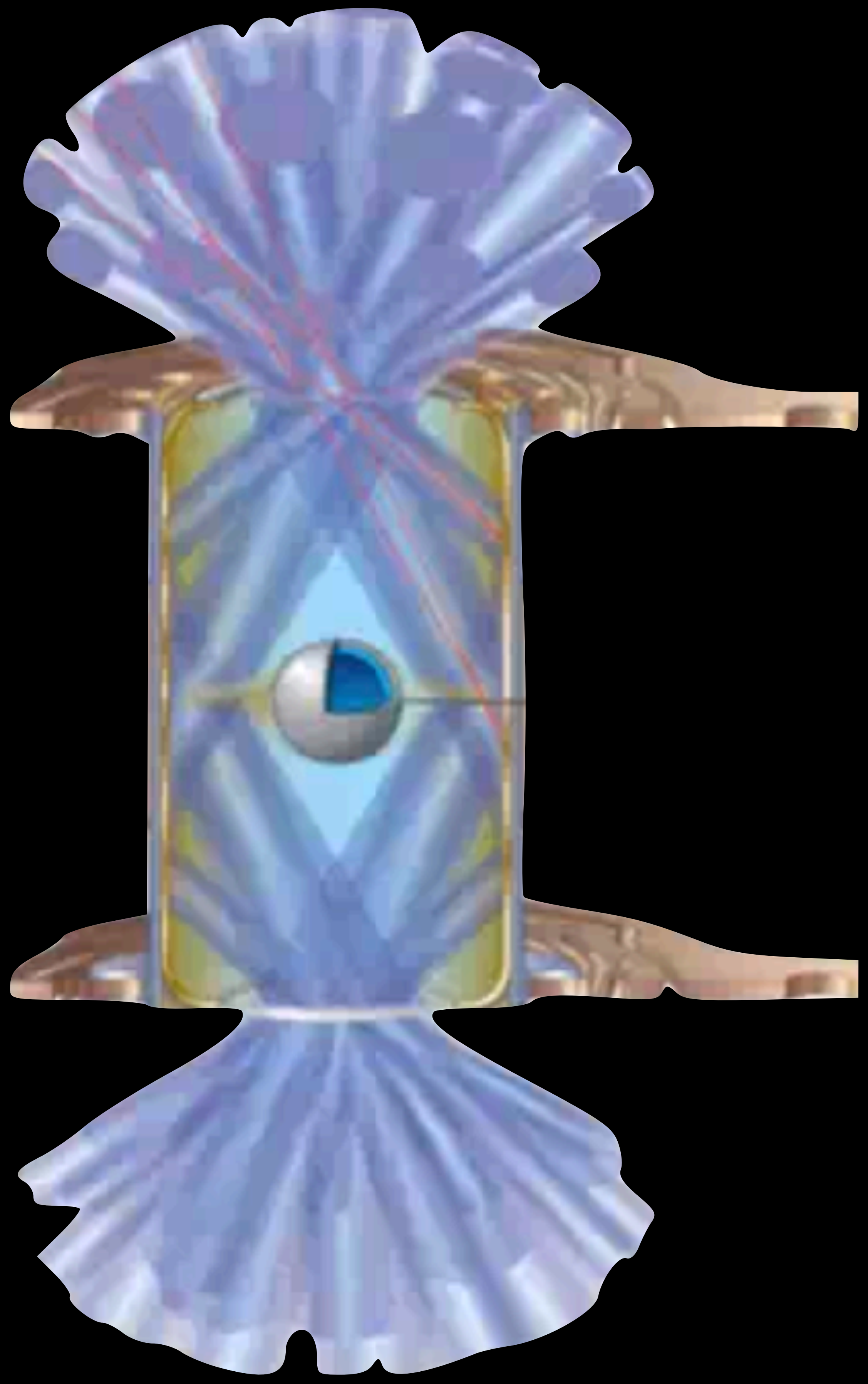


Perturbations grow exponentially in time, their amplitude is reduced by:
- -smaller initial 'seeds' (dR_0)
- -lower acceleration (a)
- -shallower gradients (L_{min})
- -ablation 'polishing' the instability(u_a)

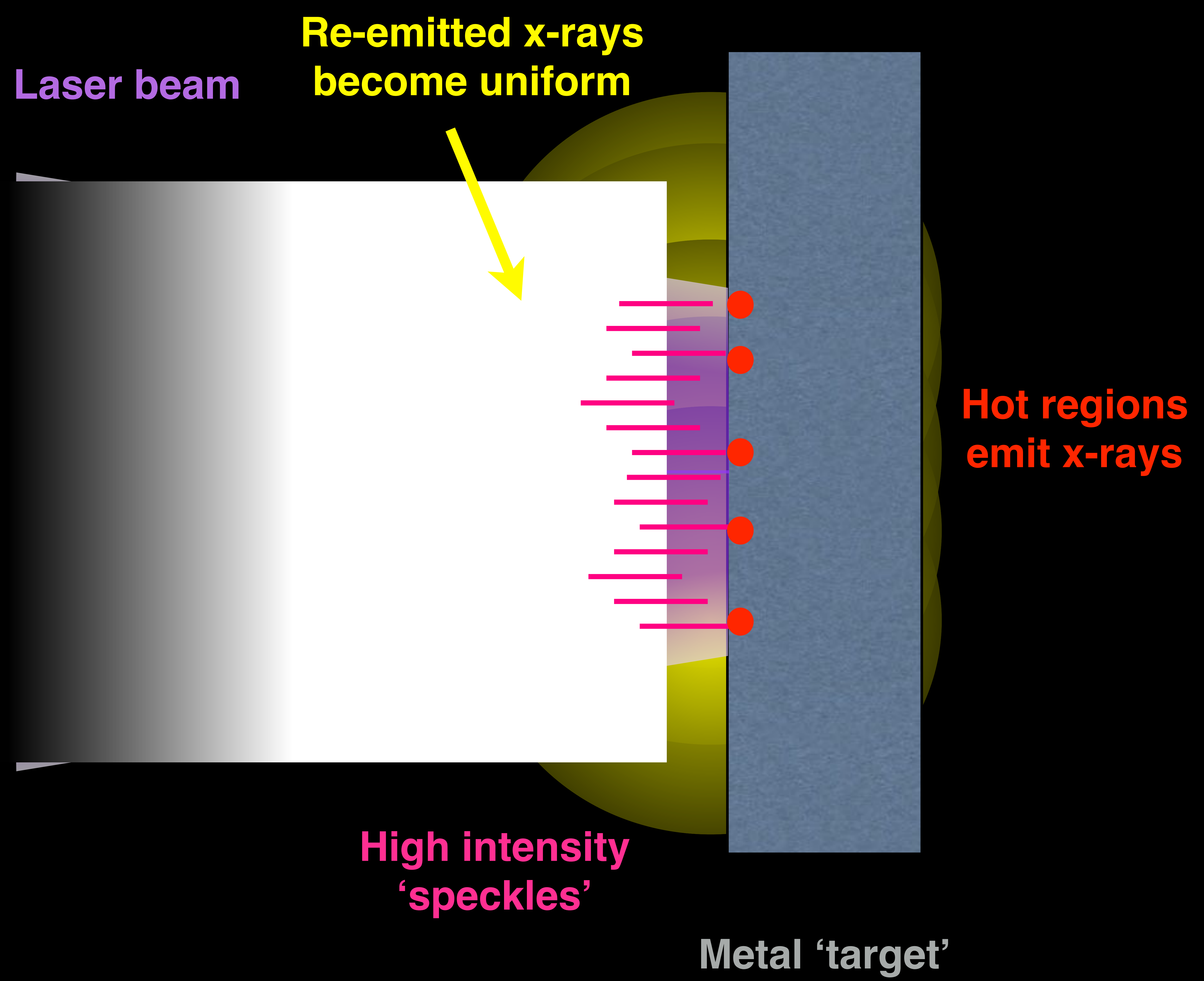
*Takabe et al., Physics of Fluids, 1986.

robbie.scott@stfc.ac.uk

RT Seed Amplitude: Laser Beam Smoothing by Convertion to X-Rays



'Indirect Drive' Laser Fusion



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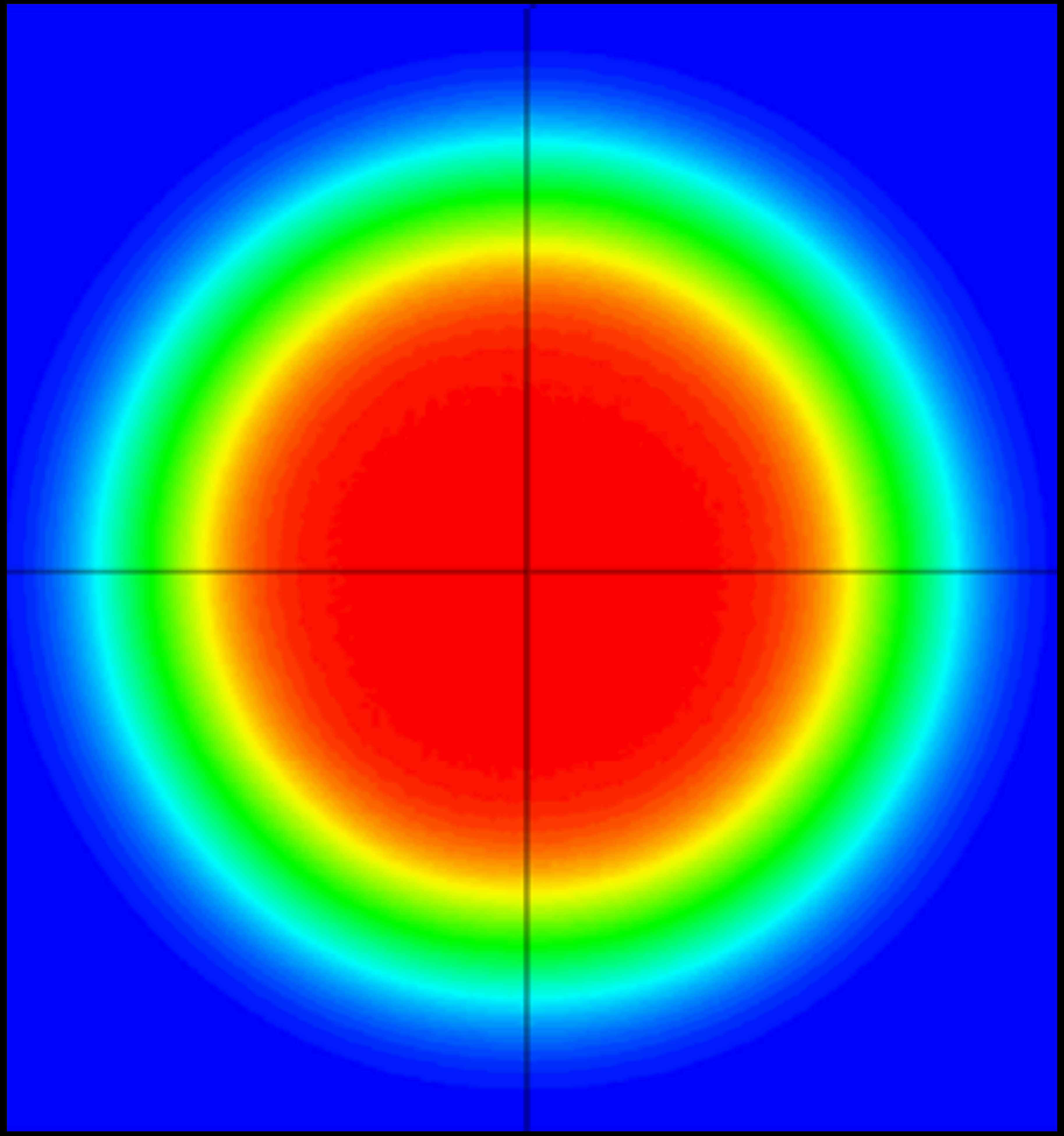
RT Seed Amplitude: Laser Smoothing of Imprint



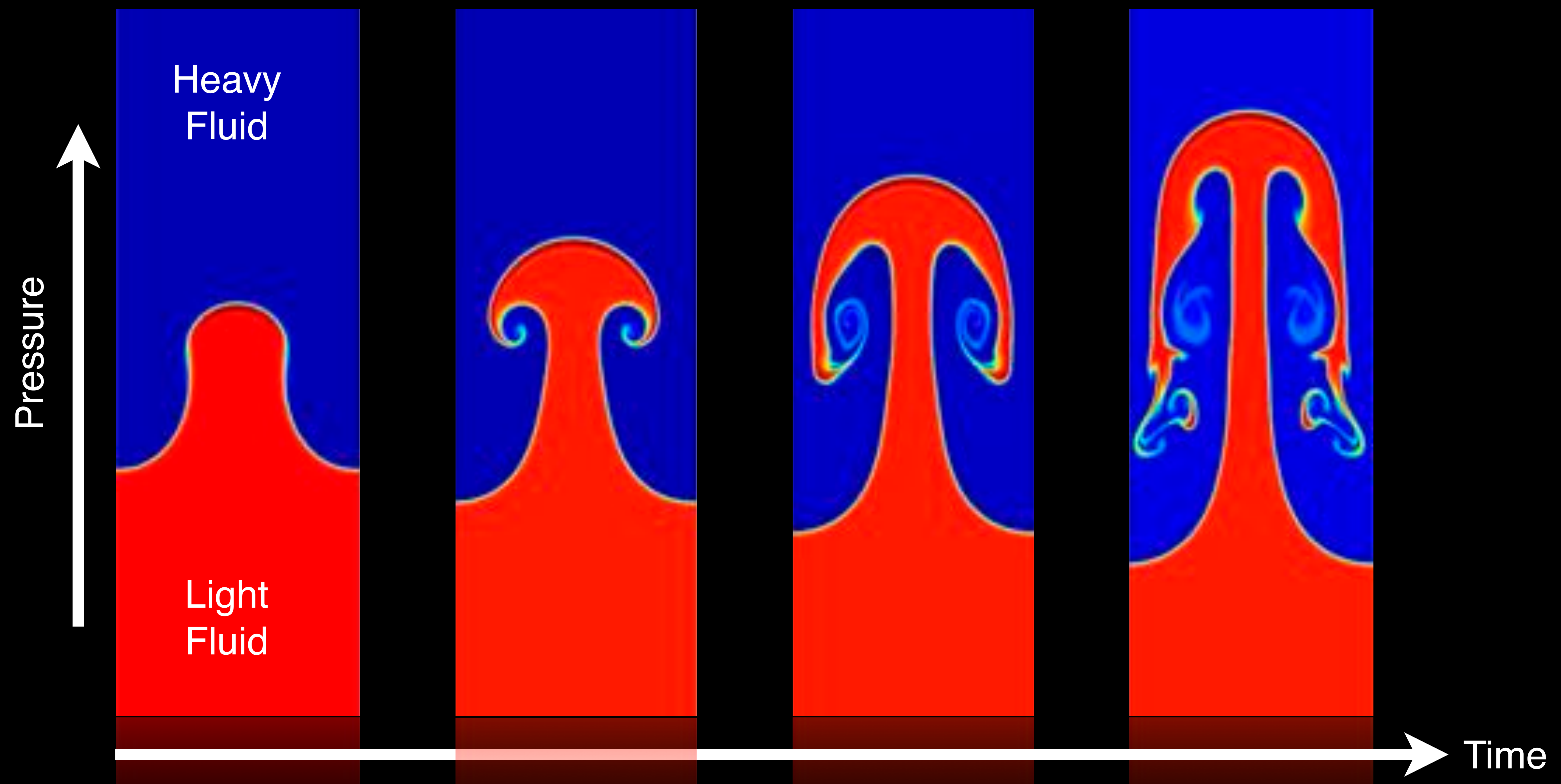
Imprint is likely the most important factor limiting Omega’s Direct Drive performance.
<u>Broader bandwidth lasers</u>
are predicted to reduce or suppress imprint.
Accurate modelling will require advanced techniques such as Vlasov Fokker Planck heat transport.

Phase plates cause diffraction in the far field creating high intensity ‘speckles’.
The associated variations in ablation pressure seed the Rayleigh Taylor instability.

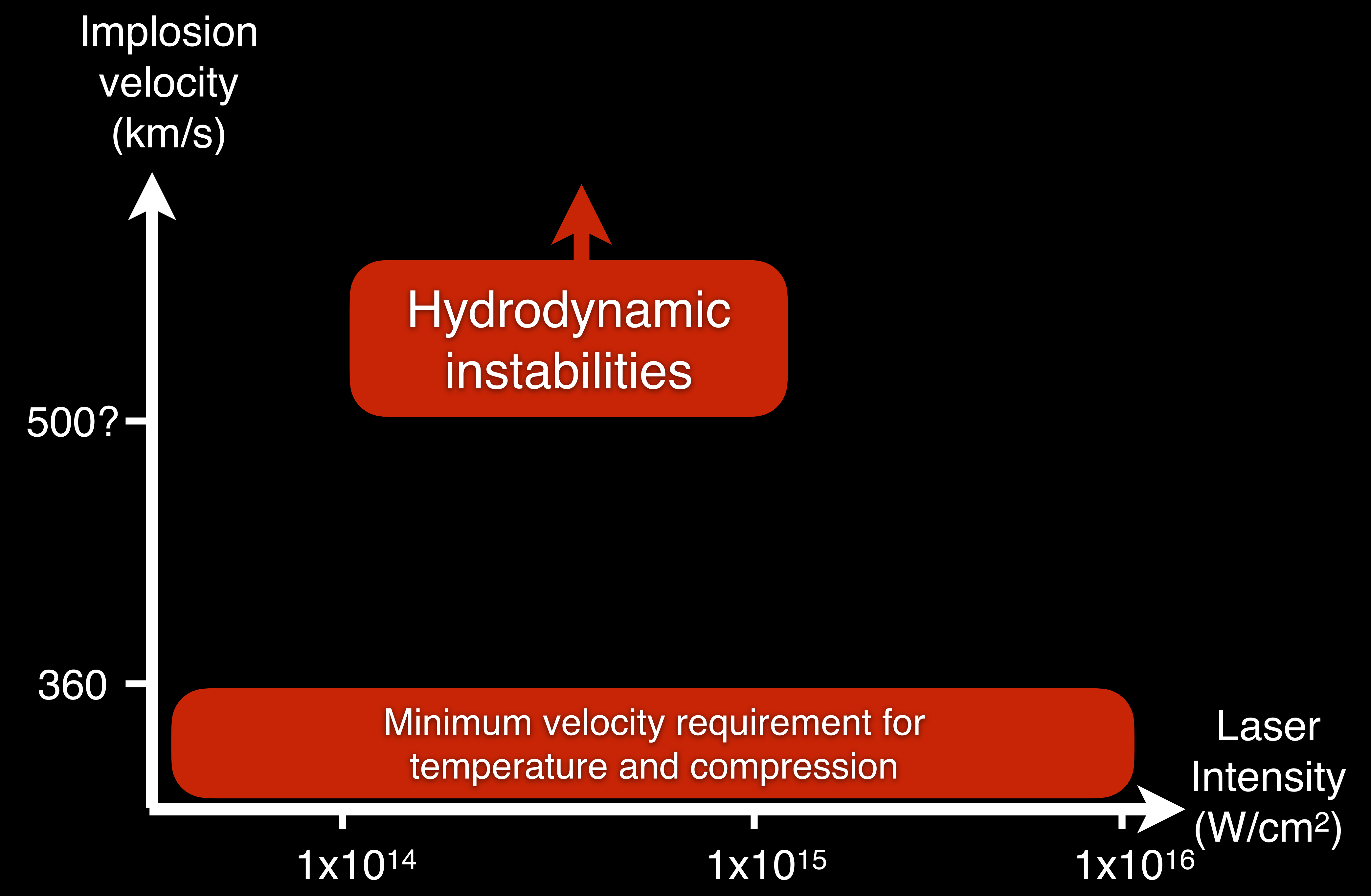
Smoothing by Spectral Dispersion uses spectral variations to rapidly move the speckles,
smoothing the ablation pressure perturbations and hence the RT seeds.

A time-averaged Omega laser beam

Central Hotspot Ignition: the constraining parameter-space



The Rayleigh-Taylor instability (Kelvin Helmholtz also visible).



Simplified representation of Laser Fusion’s parameter space

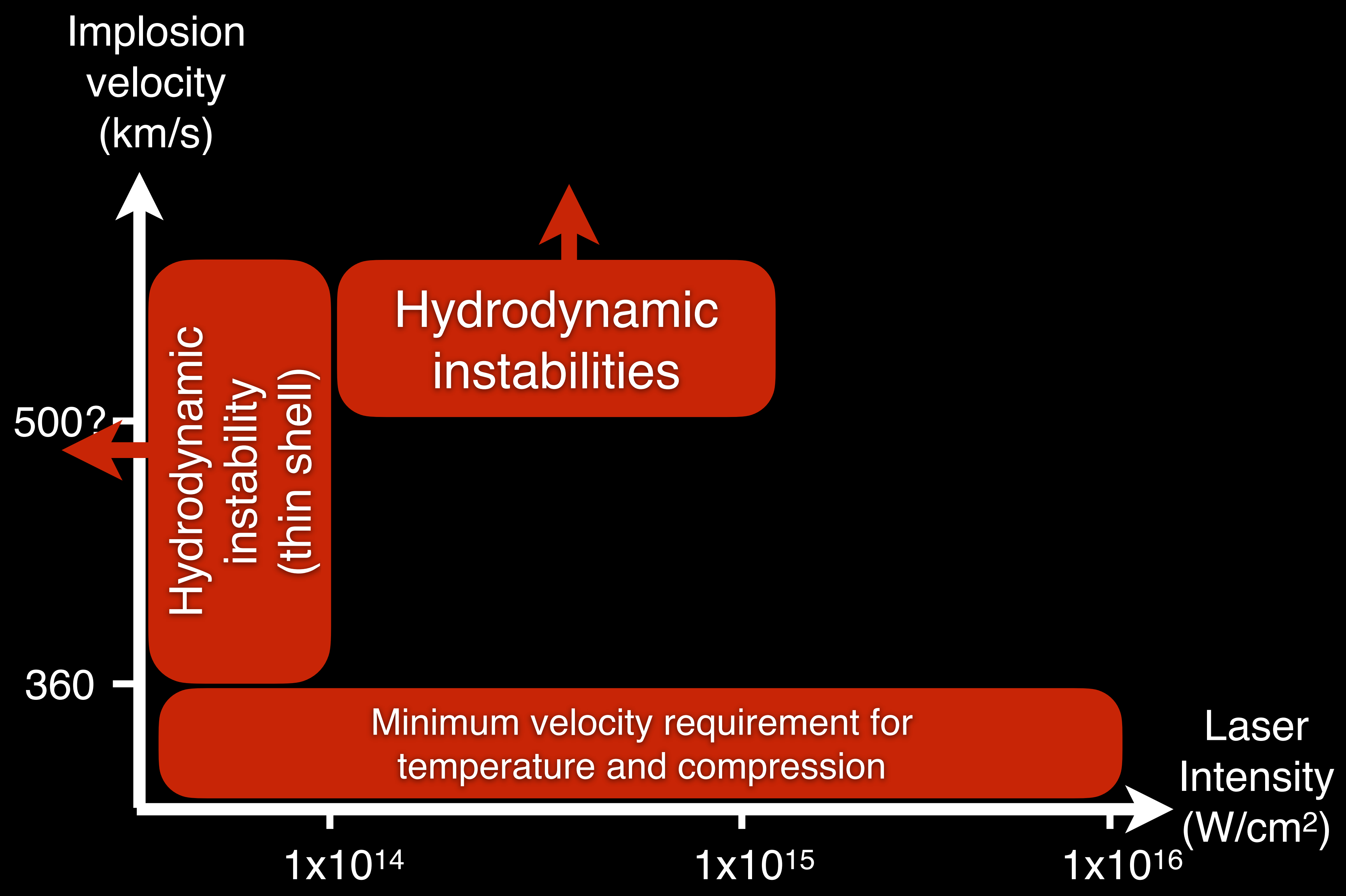
* internal energy $\propto$ pressure x volume

robbie.scott@stfc.ac.uk

Central Hotspot Ignition: the constraining parameter-space

- Energy ~ $I_{Laser} A_{shell} t_{imp}$
- To maintain energy: I_{Laser} ⬇ A_{shell} ⬆
- $M_{shell} = A_{shell} \, . \, \Delta R_{shell}$

A thinner shell is required to maintain mass



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robbie.scott@stfc.ac.uk

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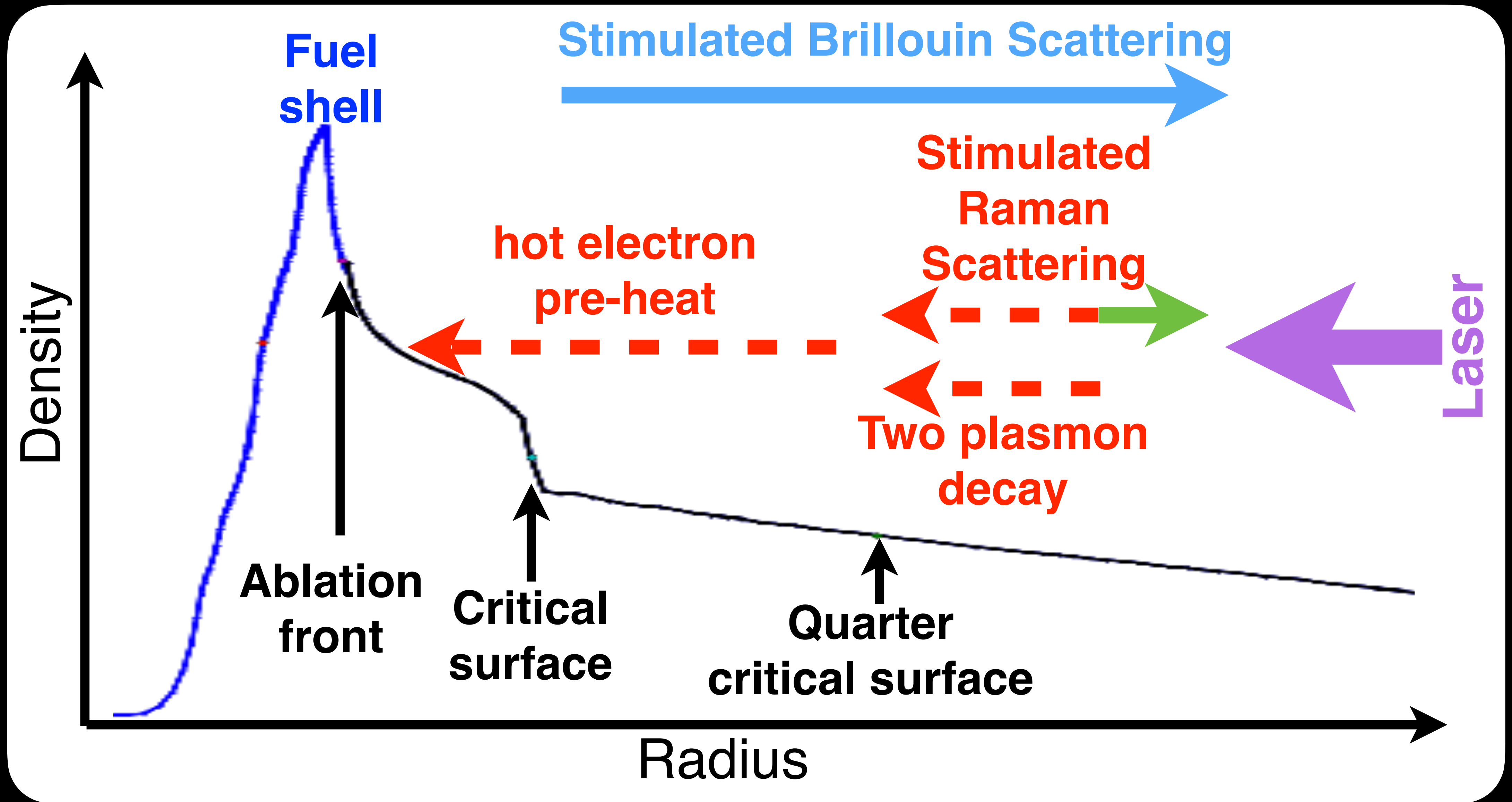
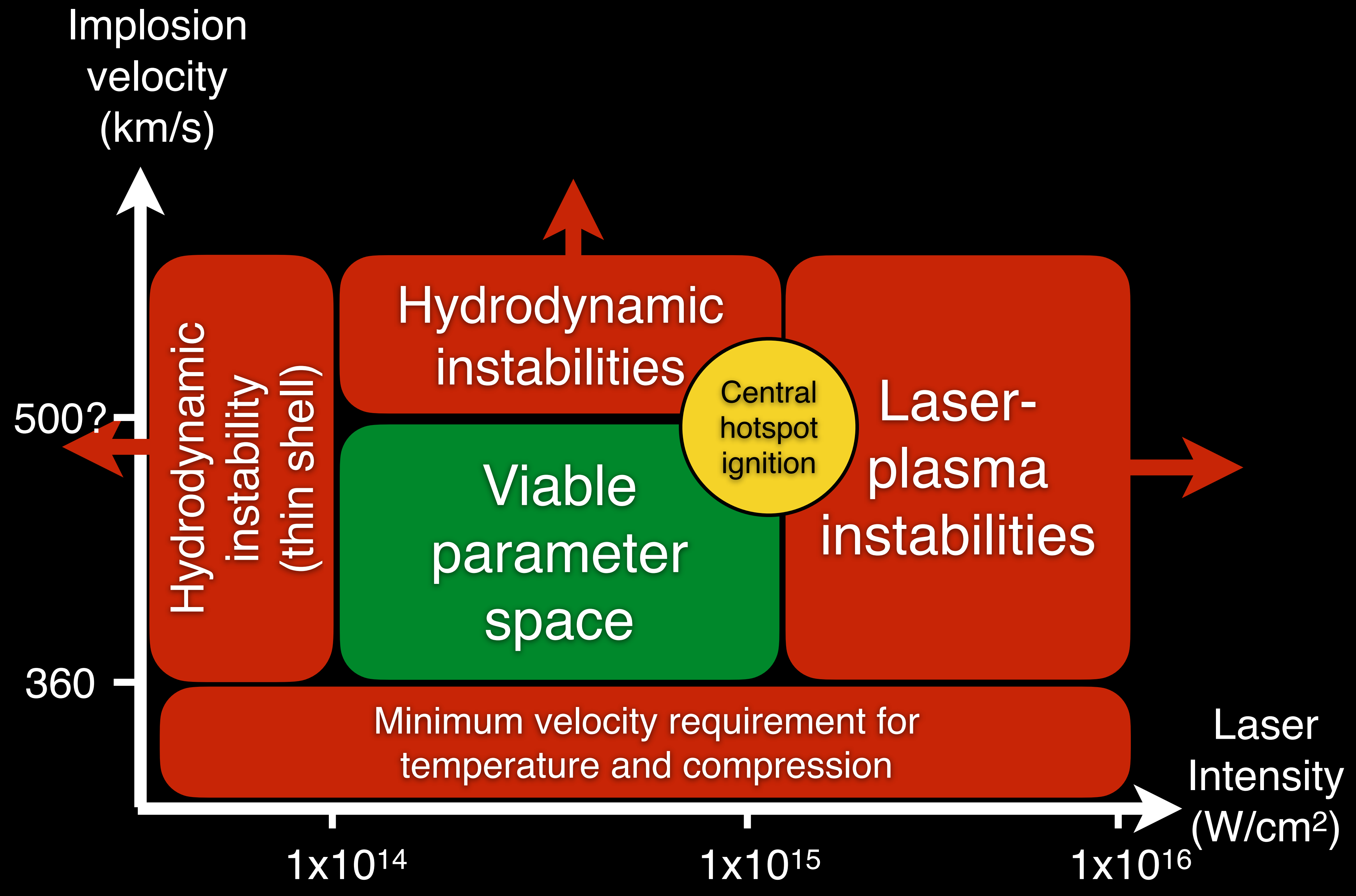


Key laser-plasma instabilities in Laser Fusion



Simplified representation of Laser Fusion's parameter space

- Important parameters:
  - Laser intensity
  - Plasma density scale length

robbie.scott@stfc.ac.uk

Ignition & High-Gain

- Ignition Criteria:
  - Hotspot ion temperature > 5 keV
  - Hotspot areal density (ρR_{HS}) > 0.3 g/cm^2

- Inertial fusion burn fraction:
  - $\phi = \rho R_{fuel} / (6 + \rho R_{fuel})$

- Fusion yield is proportional to:
  - $Y \propto \rho R_{fuel} . M_{fuel}$

- Gain $\propto \rho R_{fuel} . M_{fuel} / E_{in}$

- High-gain requires:
  - Minimising input energy
  - Maximising compression
  - Maximising fuel mass

Increasing compression requires a lower adiabat but this increases RT growth. Is there a solution?

robbie.scott@stfc.ac.uk

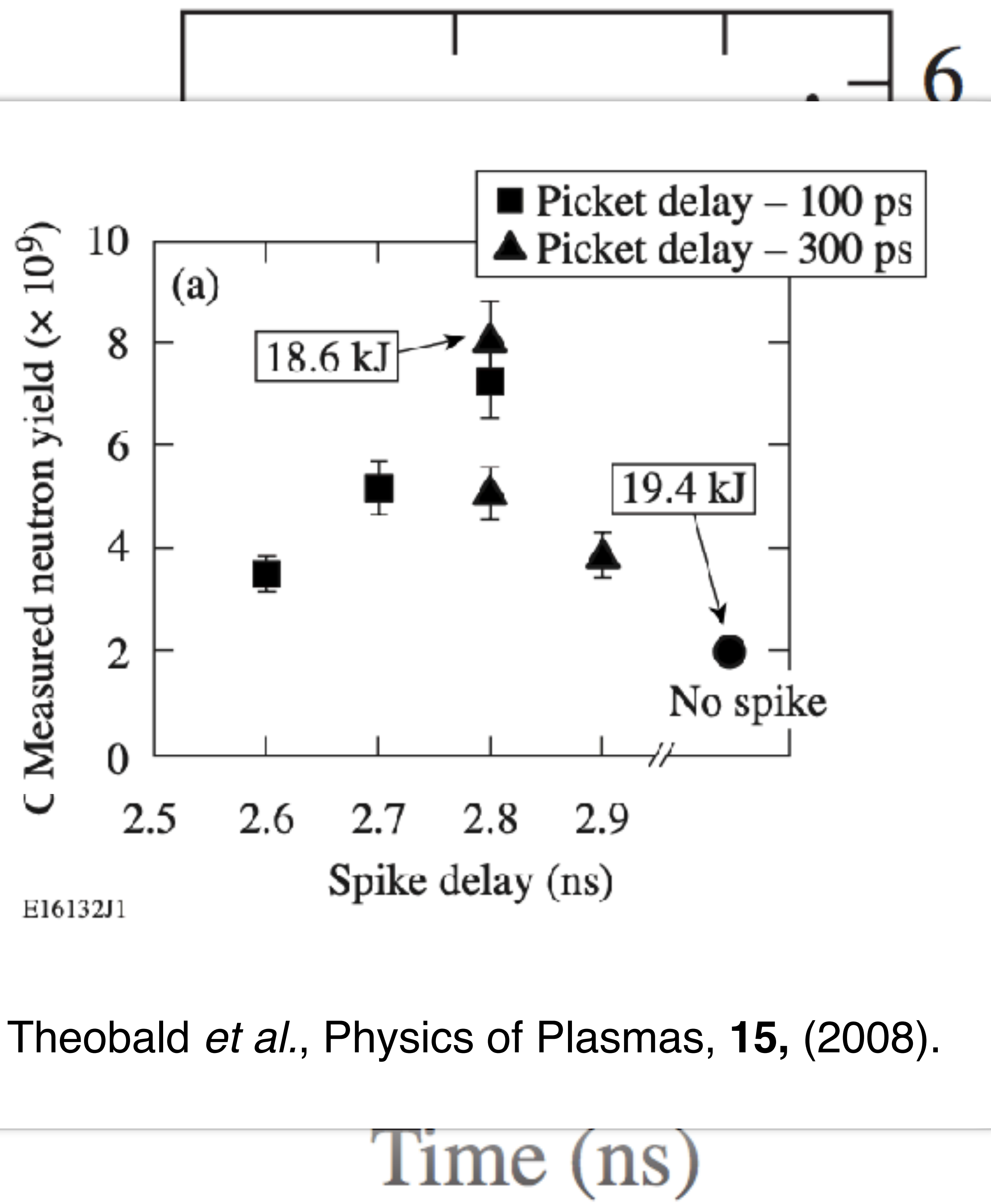
Shock Ignition: Reduced kinetic energy supplemented by a shock

- Central hotspot ignition + a strong shock
- Strong shock transports energy inwards:
  - Increases hotspot pressure
  - Increases areal density

} Less kinetic energy required

- Potential advantages of ignition with <u>reduced implosion velocity</u>:
  - Reduced Rayleigh Taylor growth
  - Higher gain:
    - If kinetic energy is fixed: Increased fuel mass
      - Increased ignition 'margin'
    - If kinetic energy is reduced: Reduced laser energy => cost

- Potential challenges:
  - Laser-plasma instabilities:
    - Reduced laser energy coupling
    - Hot-electron pre-heat of cold fuel => reduced compressibility



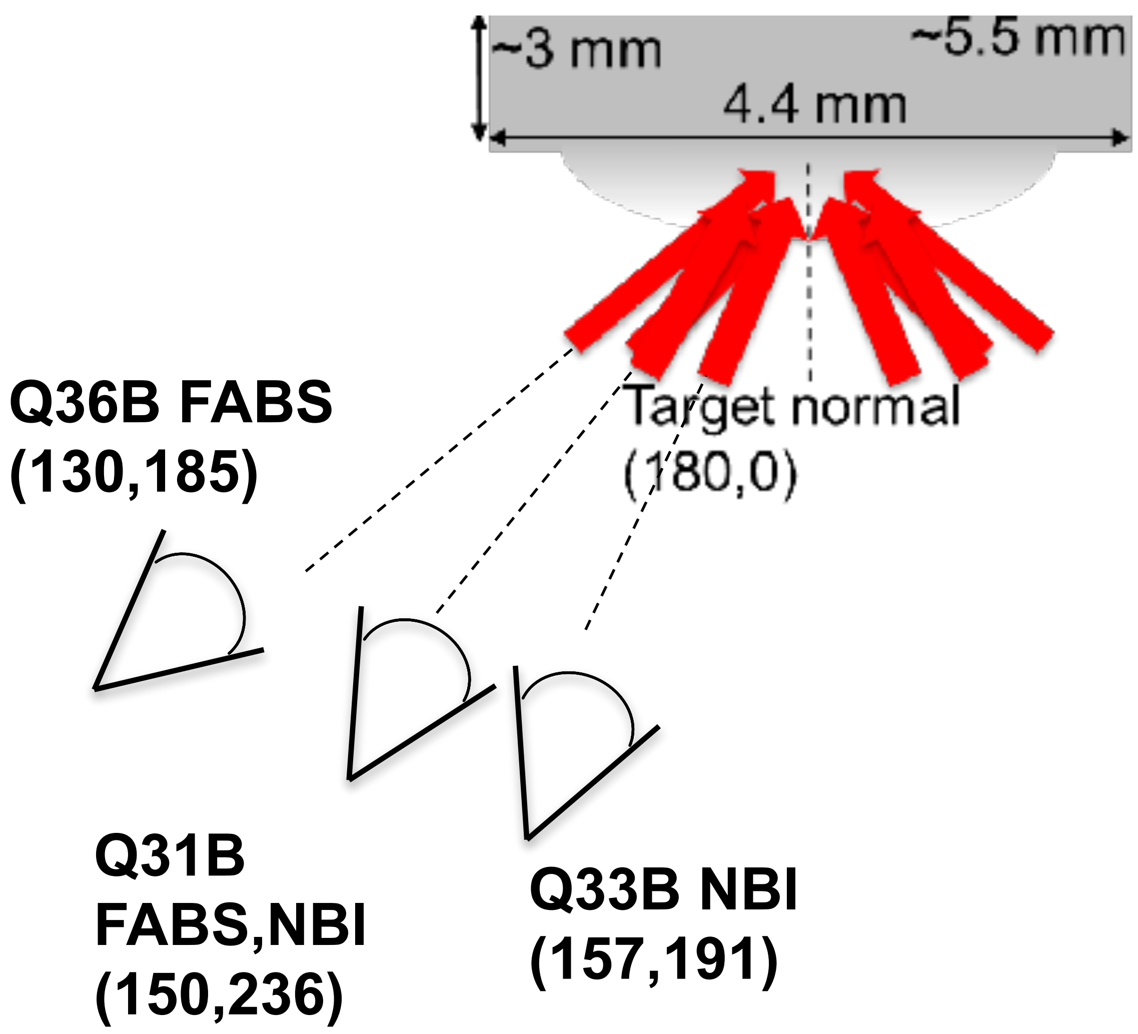
Theobald *et al.*, Physics of Plasmas, **15,** (2008).

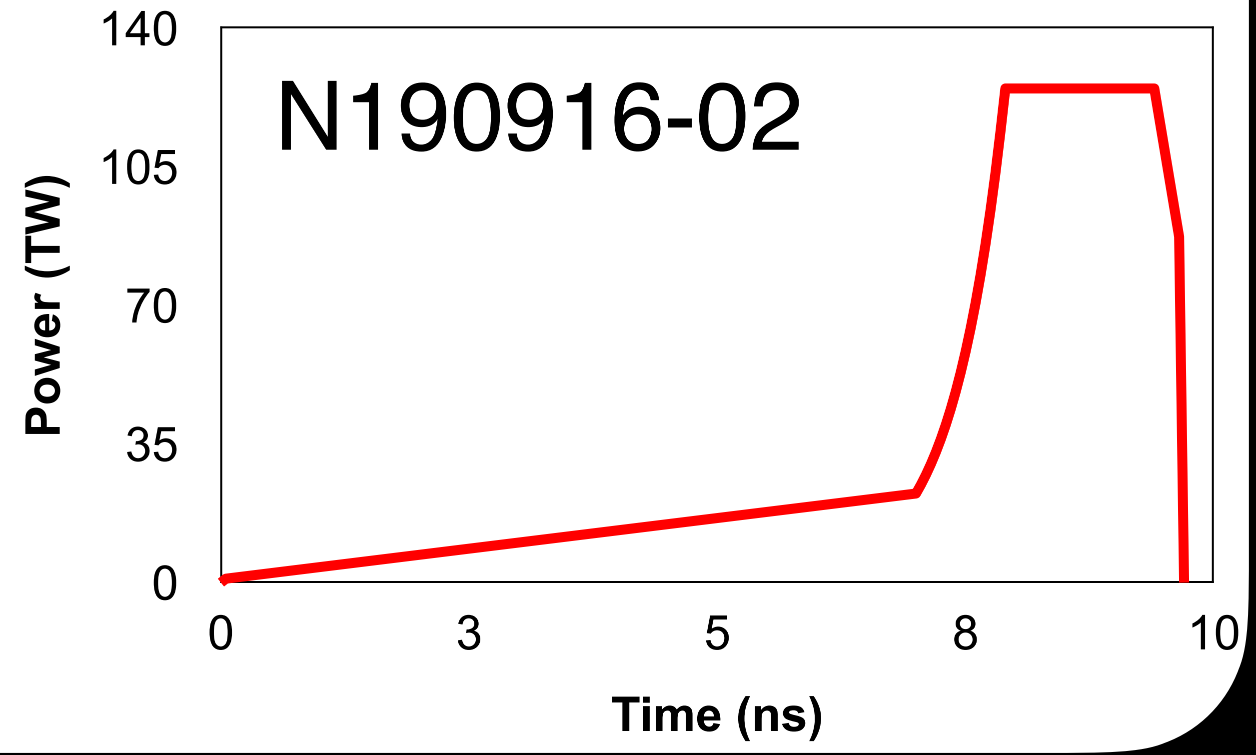
Betti *et al.*, Physical Review Letters, **98,** 155001 (2007).

robbie.scott@stfc.ac.uk

Planar Shock Ignition LPI experiments on NIF

- PI: M. Rosenberg
- Designers: A. Solodov & R. Scott
- Peak intensity: 1×10^{16} W/cm^2
- Normal incidence
- Plasma conditions before rise:
  - Density scalelength ~600um
  - Electron temperature ~4 keV

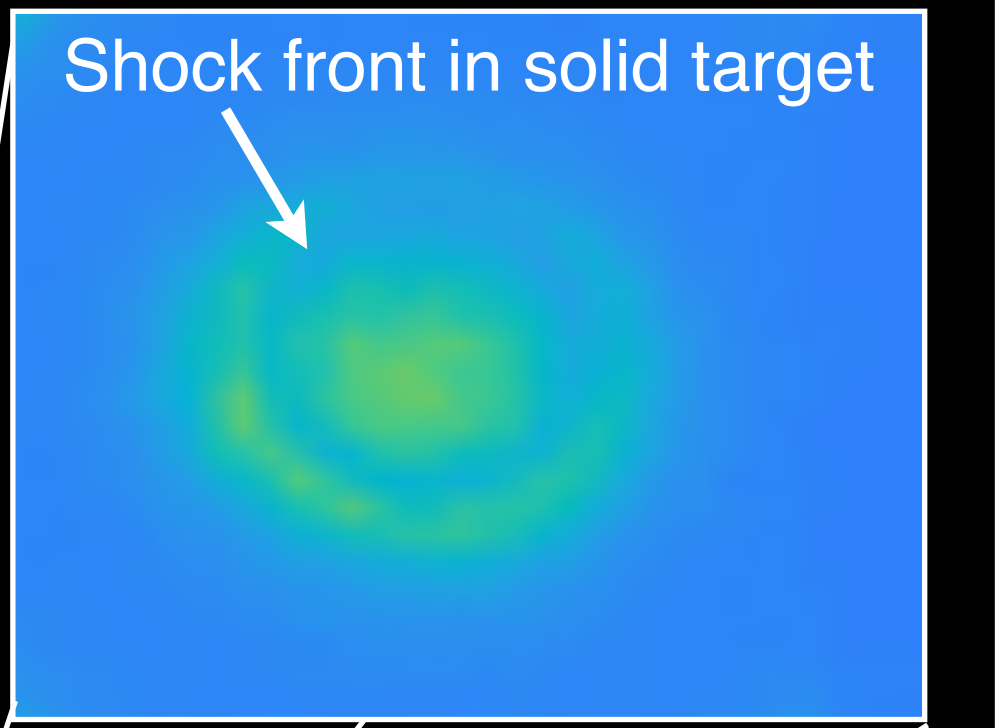


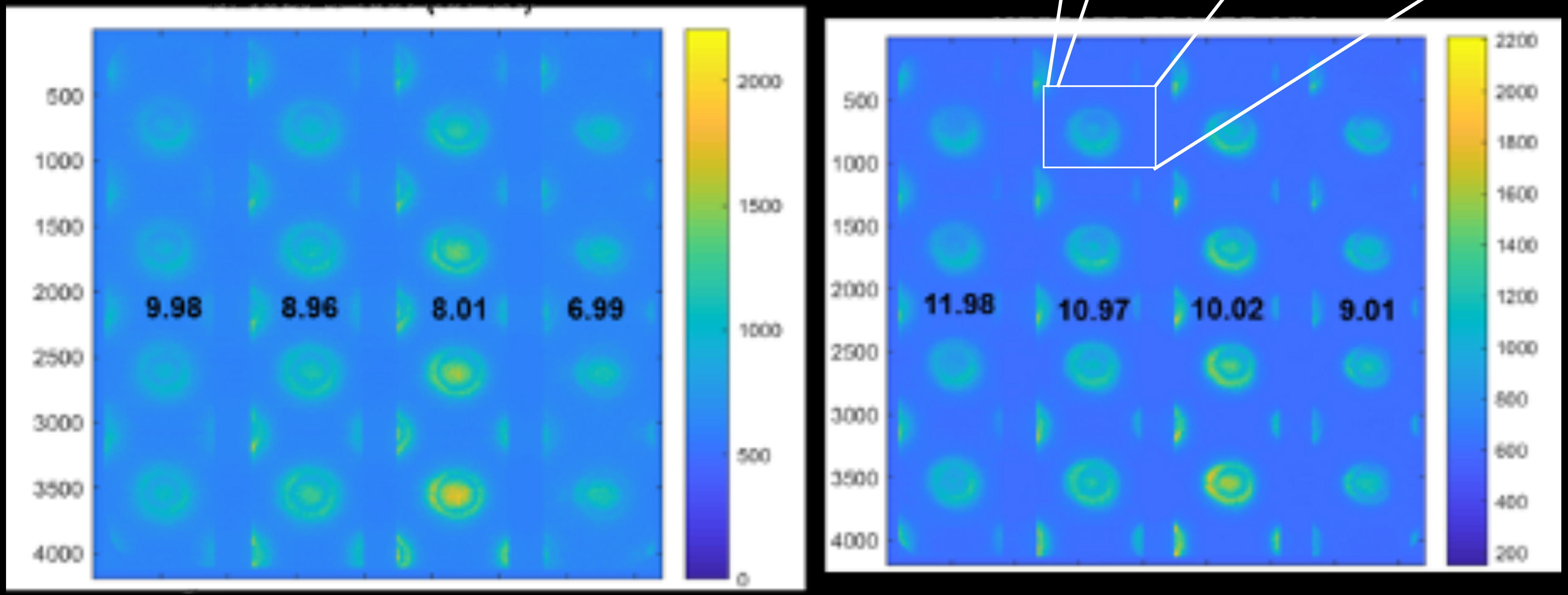


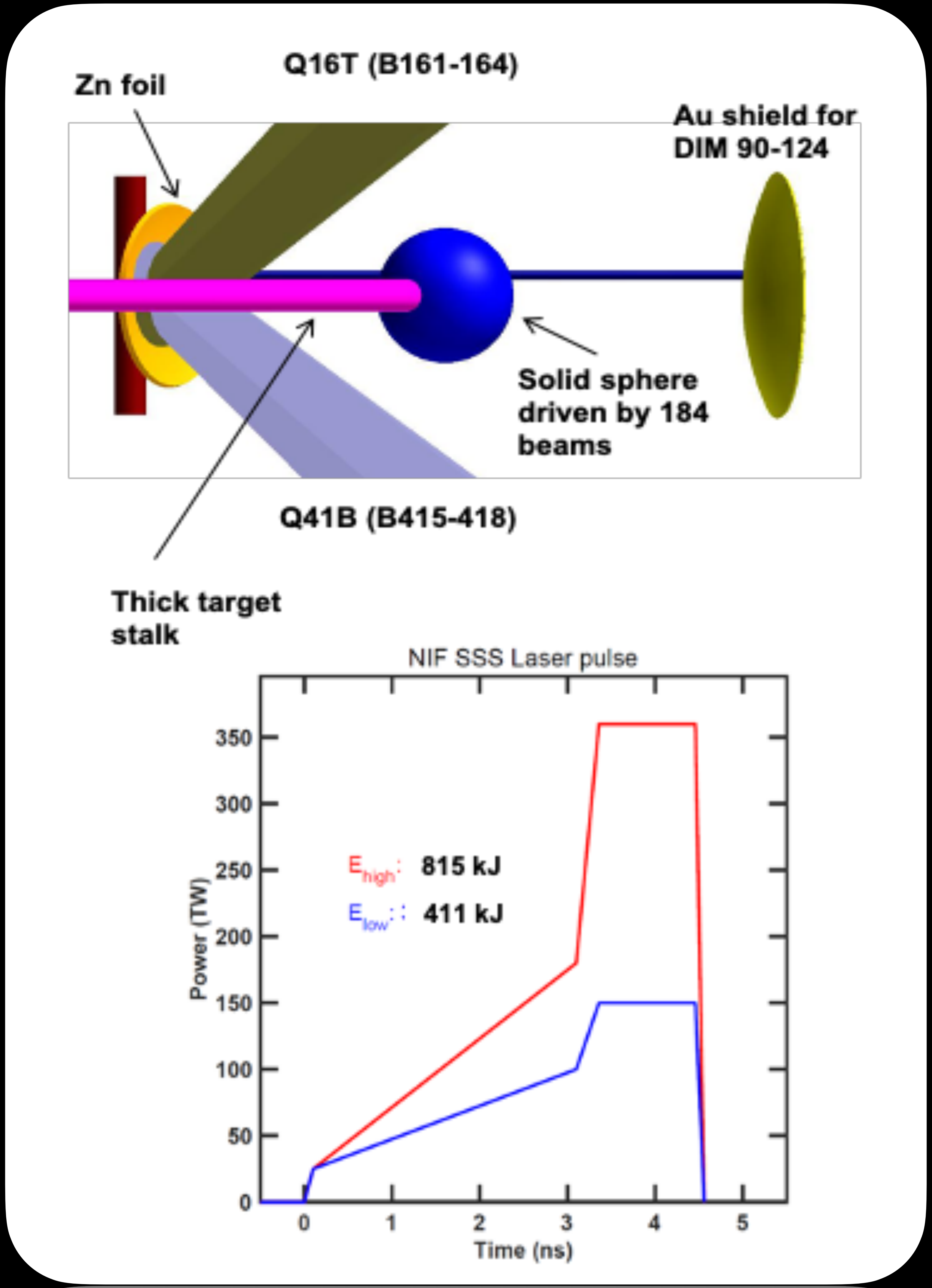
- Dominance of Stimulated Raman Scatter
- Hot-electrons:
  - Temperature = 40-56 keV
  - Fraction of laser energy converted ~12%
- Low Stimulated Brillouin Scatter <0.1%

Spherical Shock Ignition LPI experiments on NIF

- Experiment (Rosenberg, Solodov, Scott, Glize):
  - Solid sphere
  - 184 beams on target
  - 8 beams backlighter
  - Peak intensity 3x10^{15} W/cm^2
- Key observables:
  - Hot-electron Temperature = 56 keV
  - Fraction of laser energy to hot-electrons = 10%
  - Back-lit shock front trajectory
- See RSI 2022: L. Cuervorst



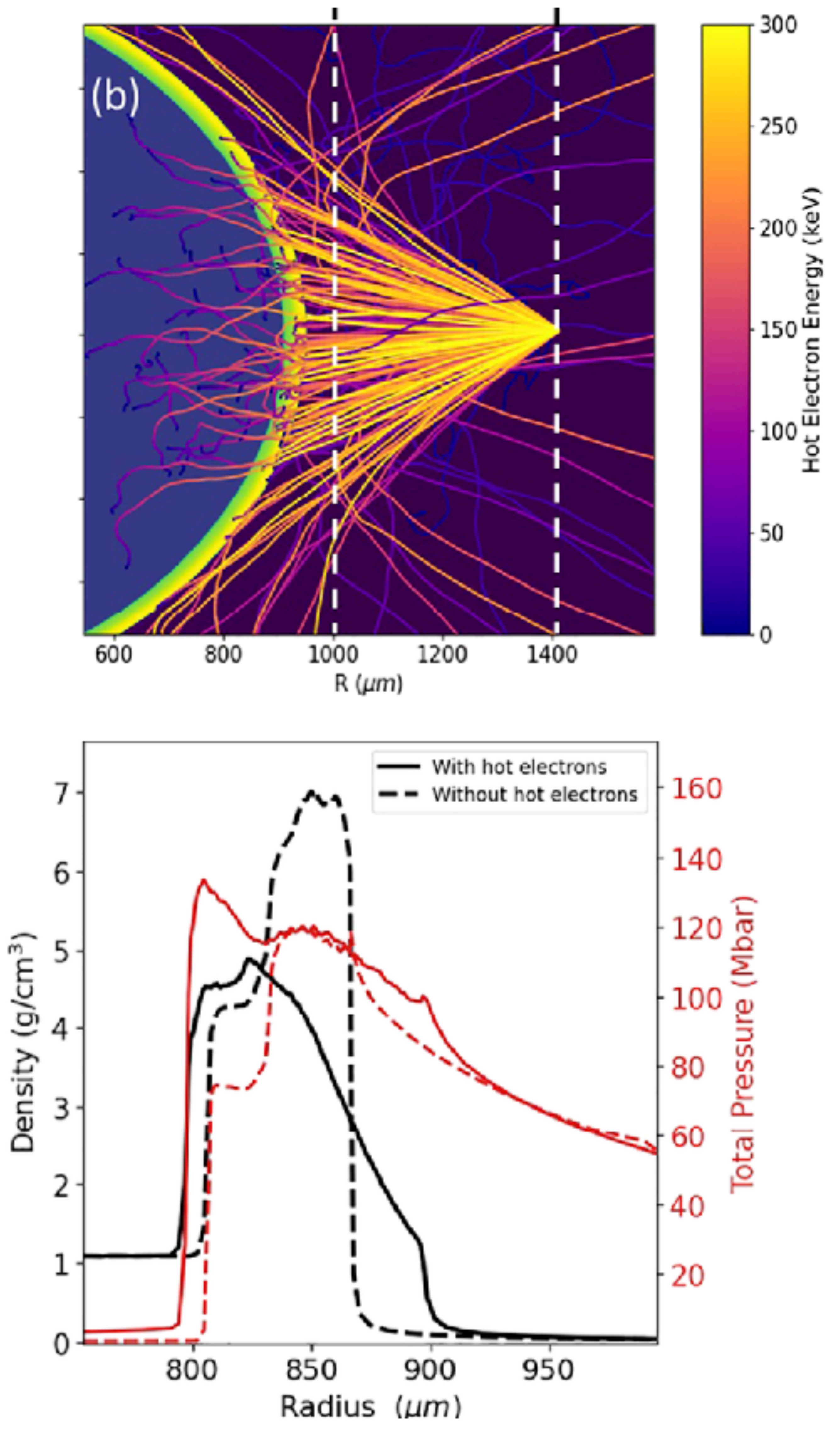




robbie.scott@stfc.ac.uk

Spherical Shock Ignition LPI experiment: implications

- Duncan Barlow (University of York, now CELIA)
- Implosion simulations with in-line Monte Carlo hot-electron transport
- Experimental observables constrain implosion simulation:
  - Shock trajectory:
    - Cross beam energy transfer removing ~40% of laser power
  - Hot-electrons:
    - 55 keV
    - 10 %
    - Effect: A 25-35% reduction in shell areal density
- D. Barlow, Physics of Plasmas, 2022.



Shock Ignition Summary

- **Addition of a strong shock has the potential to be highly beneficial:**
  - Reduced implosion velocity requirement
    - Less RT growth
    - More fuel mass for same kinetic energy: higher gain

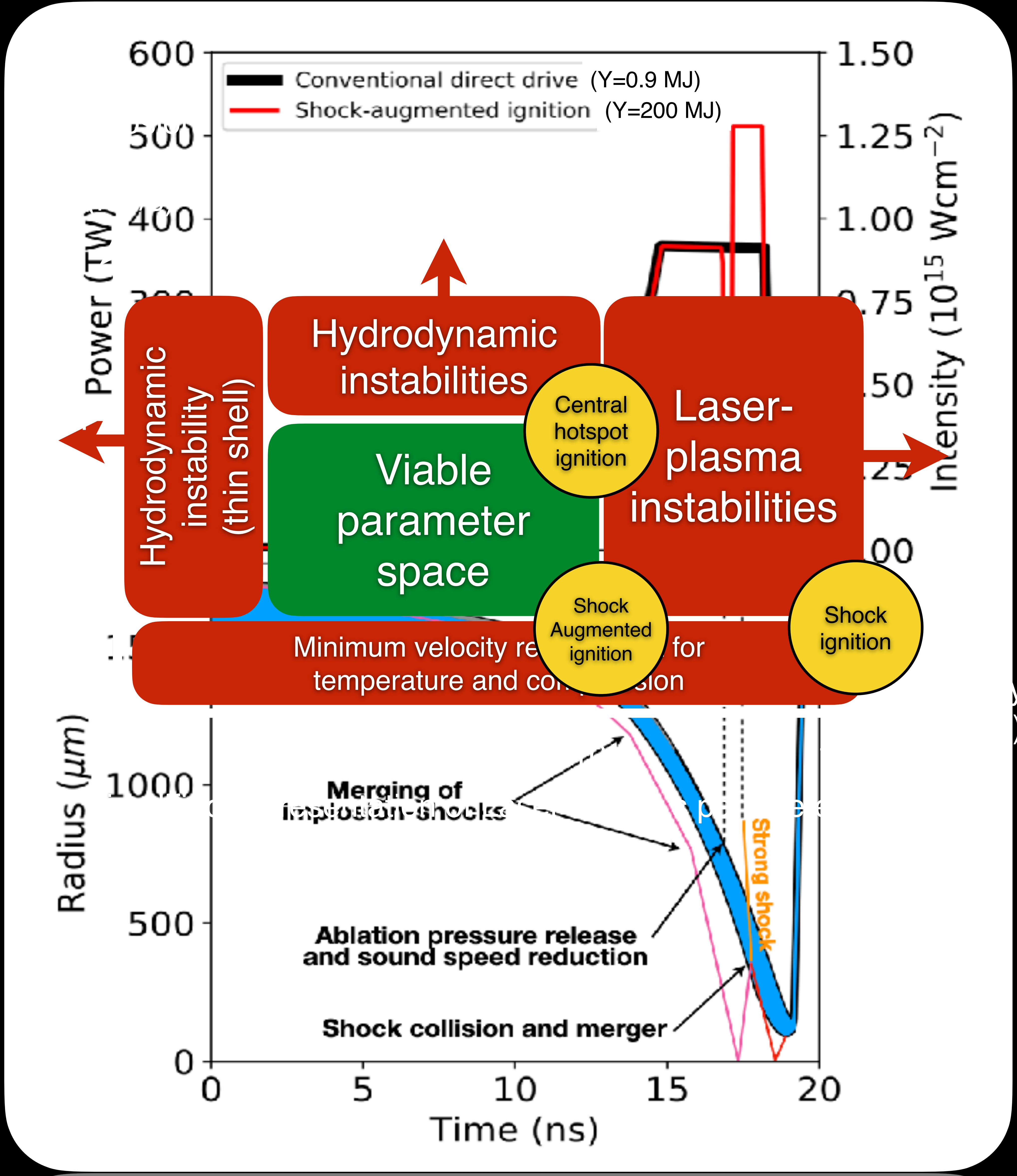
- **Requirement for high intensity creates potential challenges:**
  - Lower laser coupling
  - Fuel pre-heat by hot-electrons
  - Increased laser optics damage for a given aperture

- **Can we get the benefits of the shock without the requirement for high intensity?**

robbie.scott@stfc.ac.uk

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



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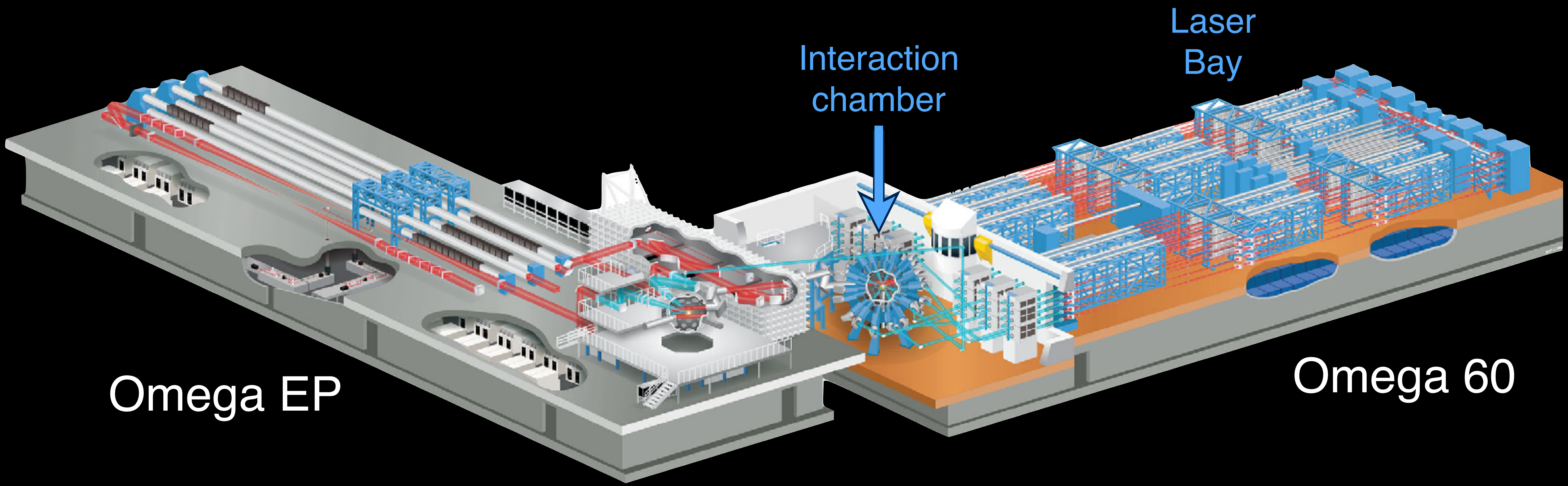
*Scott et al., *Physical Review Letters* (2022)

The Omega Laser Facility

- 60 beams on target
- Spherical direct drive configuration
- Energy ~30 kJ of 351nm light



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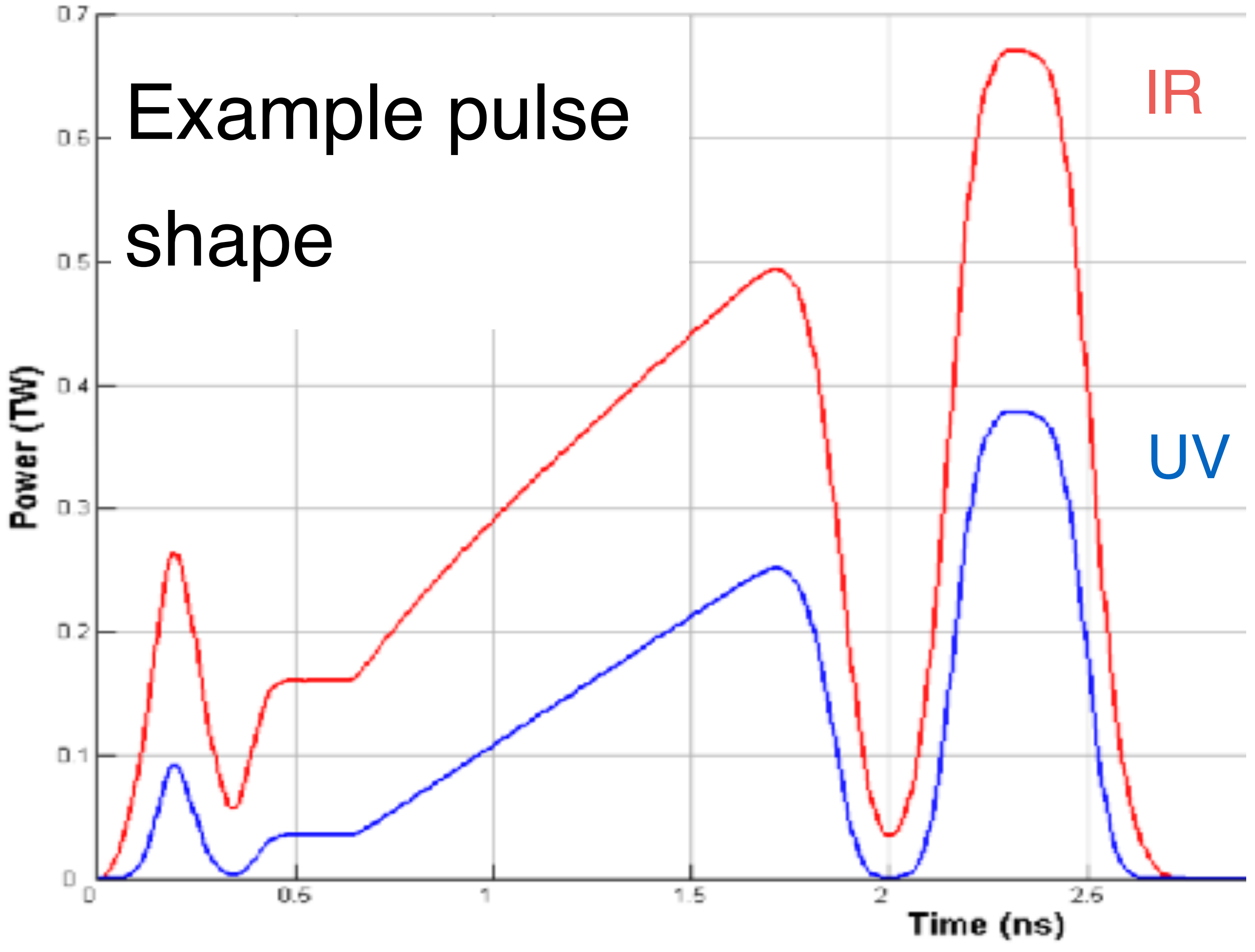
Shock-Augmented Ignition: Omega Experiment Setup

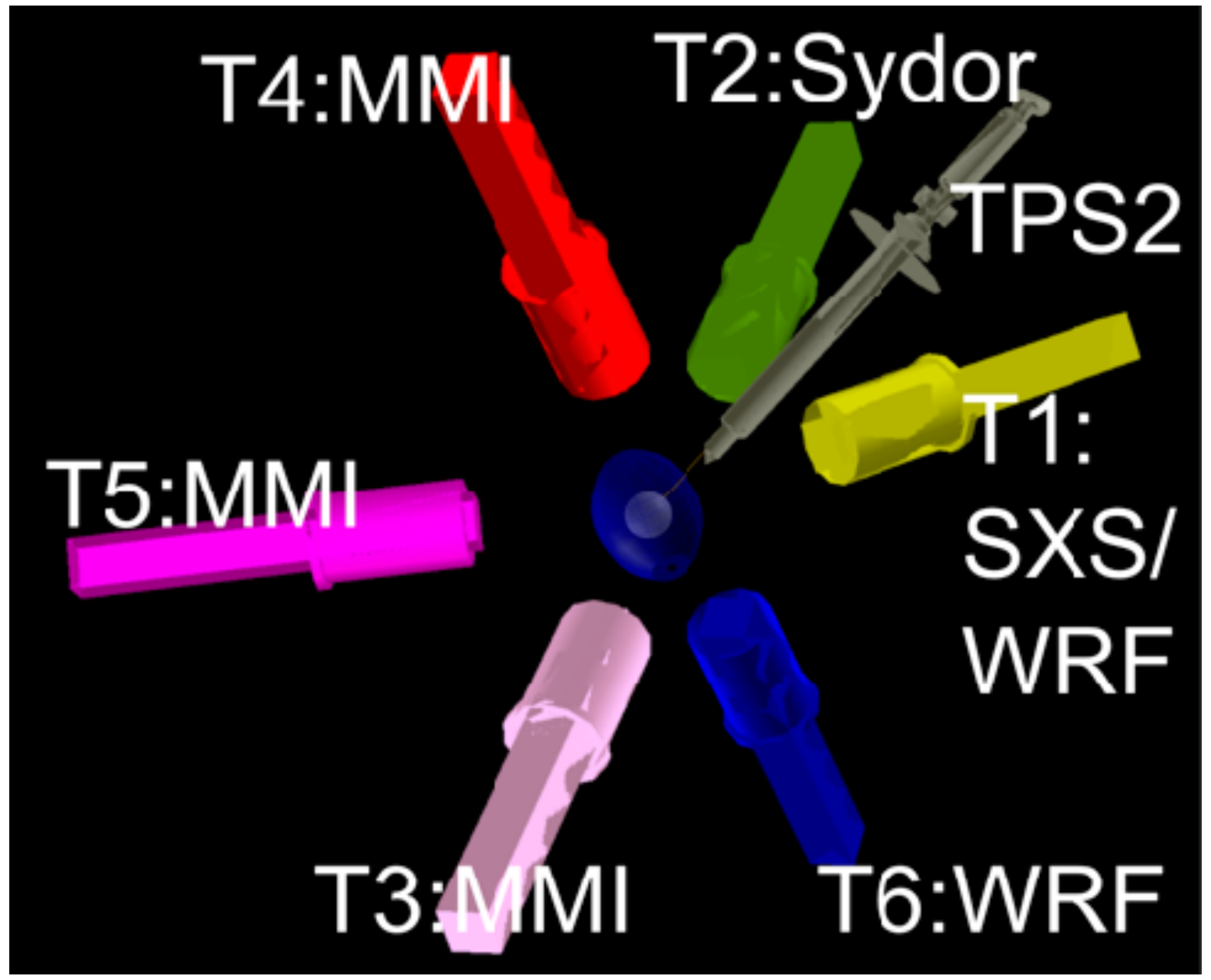
Laser:
- 5 pulse-shapes: vary shock-timing
- 23 kJ UV on target


Example pulse shape

Targets
- ~860 um OD
- 27 um CH wall
- 20 atm DD gas fill

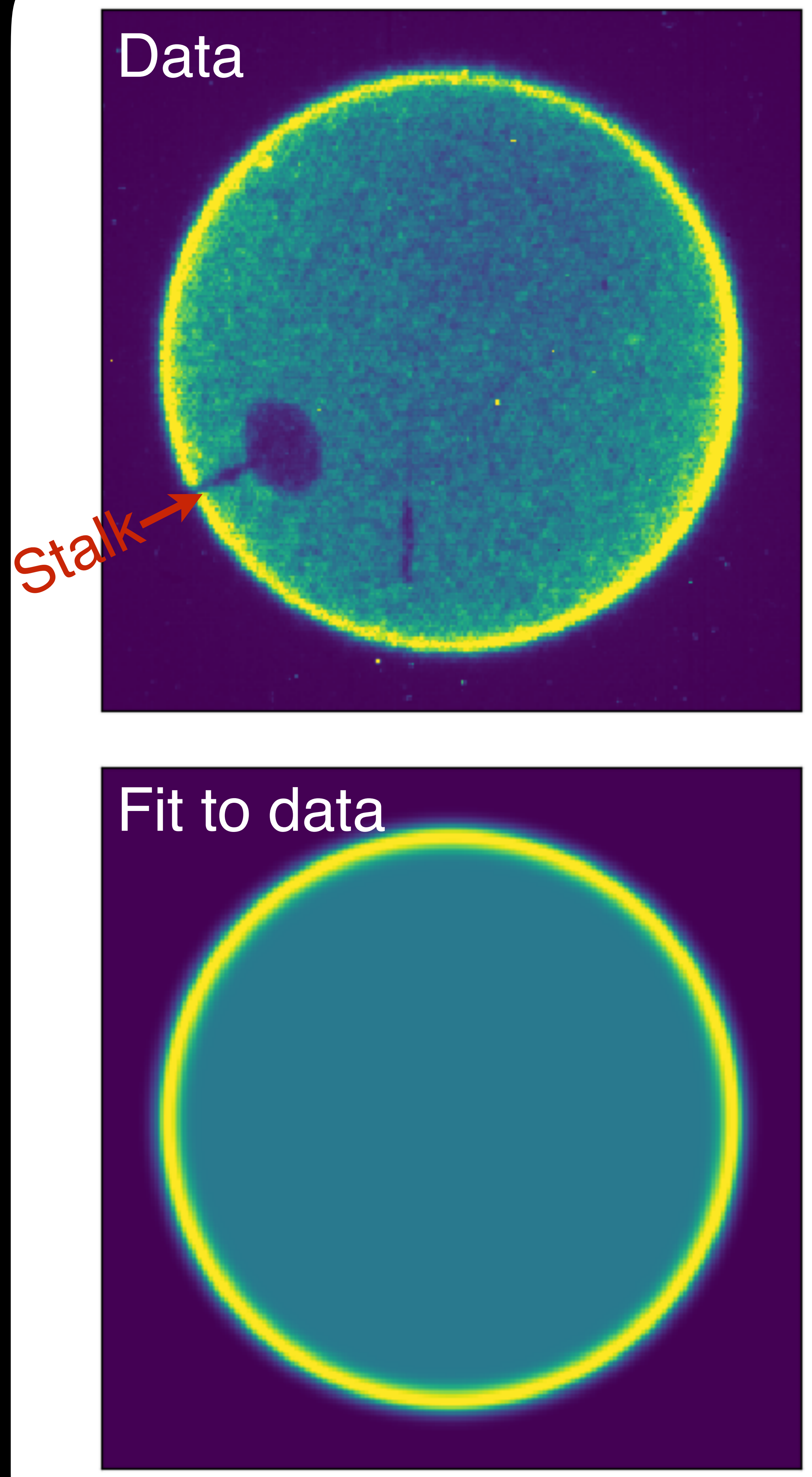

~20um support stalk

- ‘TIM’ diagnostics:
  - 6D hotspot tomography (MMI)
  - Ablation-front imaging (Sydor)
  - Areal density (WRF)
  - Streaked Ar spectra (SXS)
- 19 fixed diagnostics:
  - LPI back-scatter (FABS)
  - Time-resolved hot-spot imaging

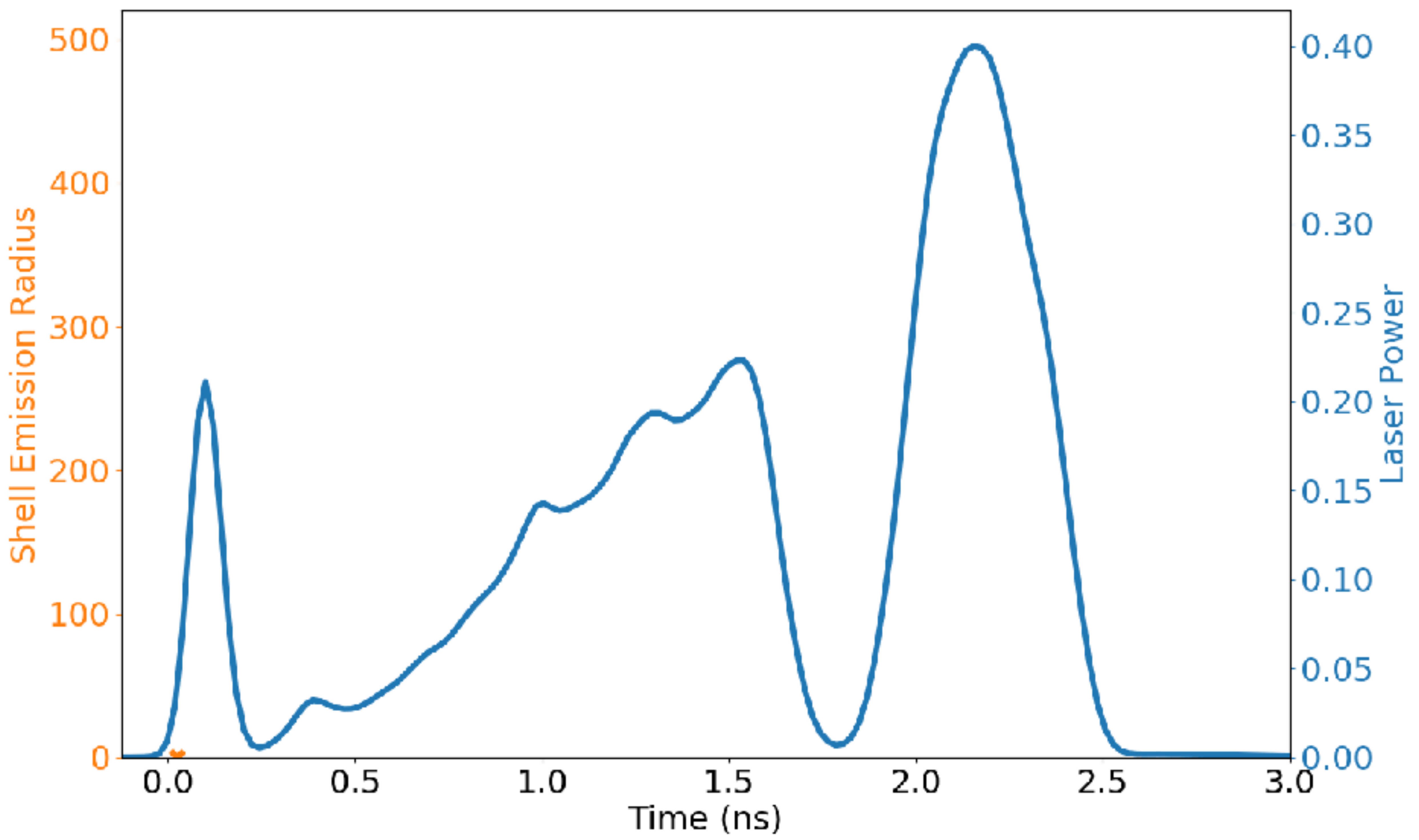


robbie.scott@stfc.ac.uk

Shock Augmented Ignition: Implosion trajectory



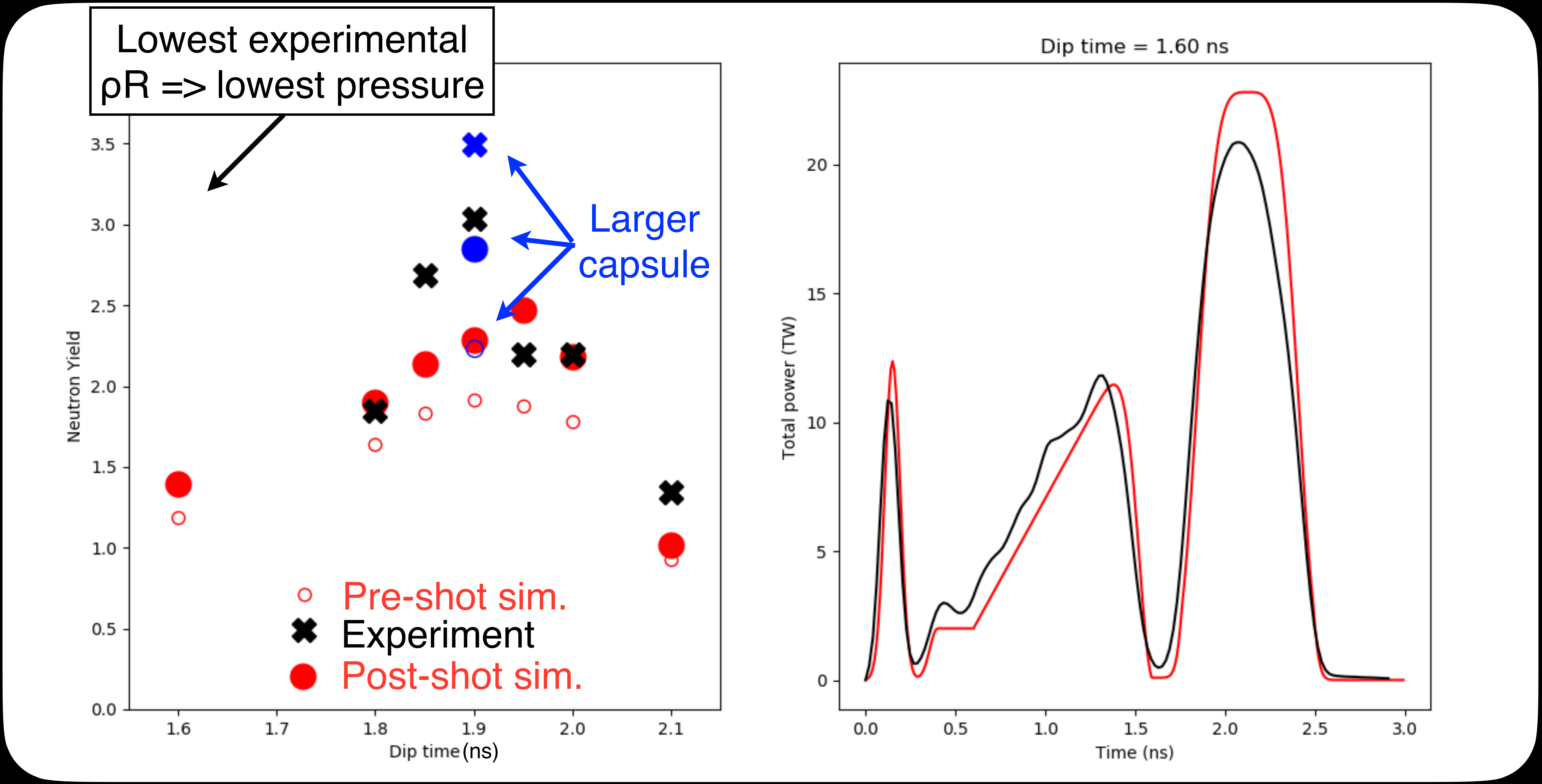
- Gated diagnostic images emission from the ablation front
- Analysis: Matt Khan, University of York



robbie.scott@stfc.ac.uk

Shock-Augmented Ignition Results: Omega Direct Drive

- Clear peak in yield when varying shock timing
- Anomalous result with very early dip



Lowest experimental ρR => lowest pressure

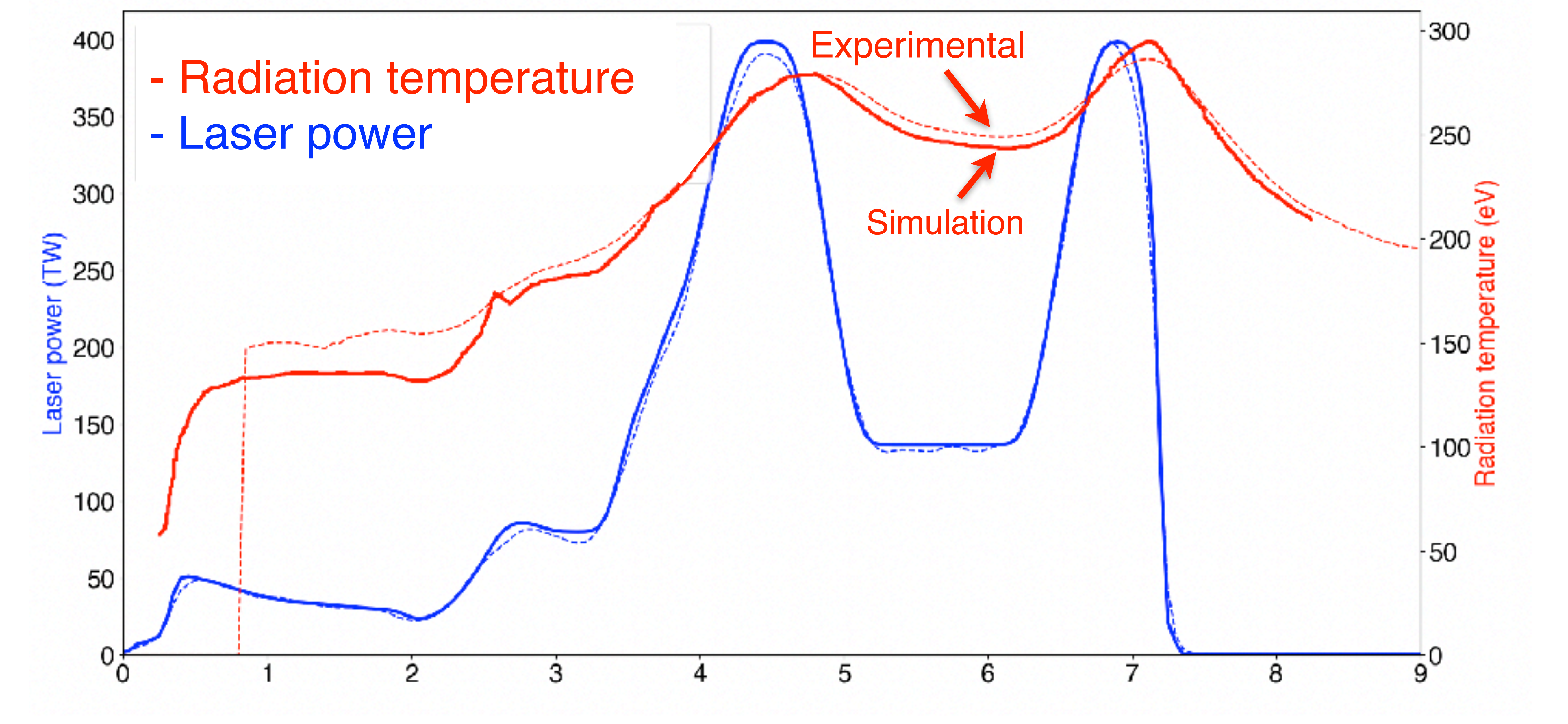
Larger capsule

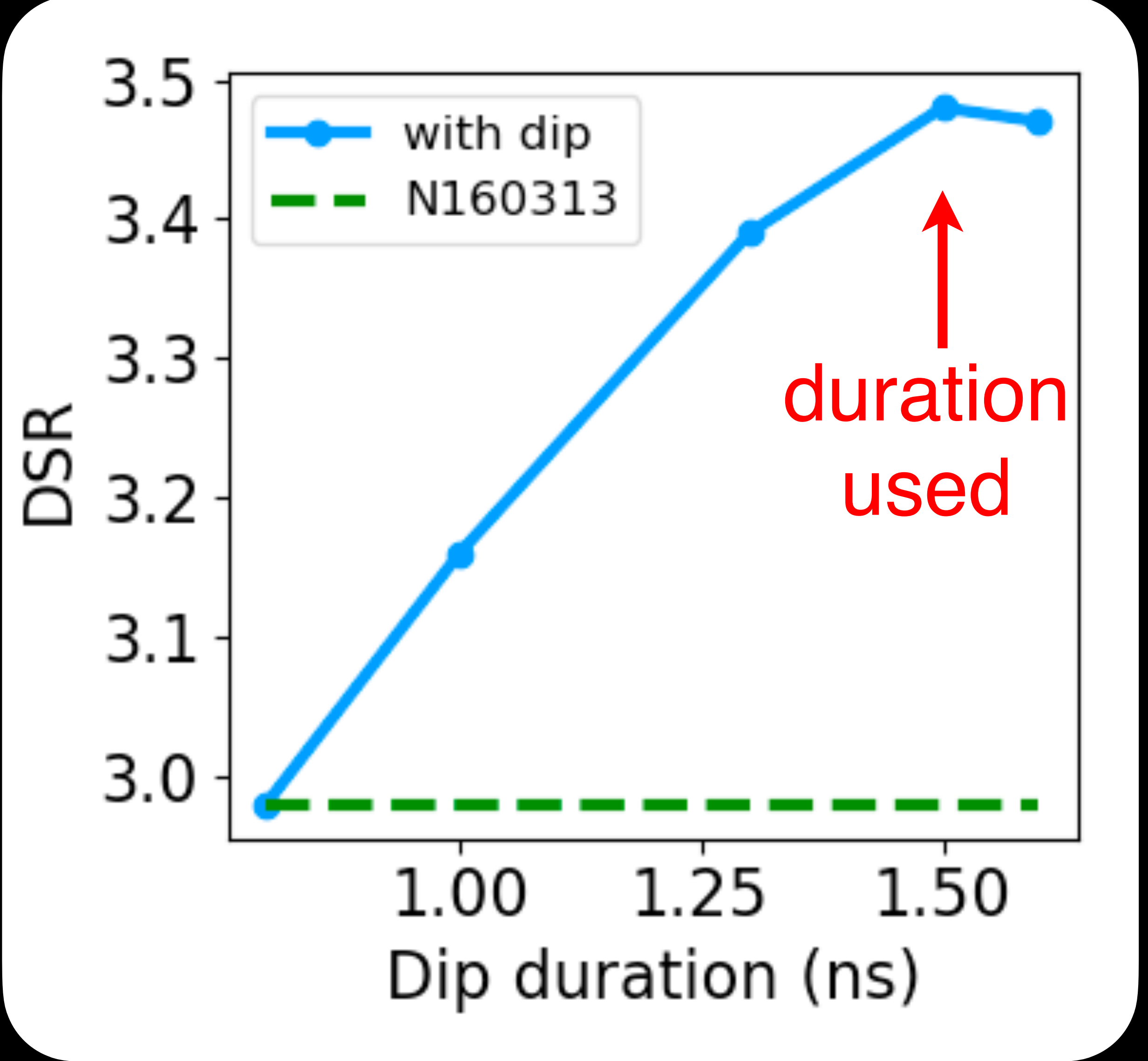
robbie.scott@stfc.ac.uk

NIF Shock Augmented Ignition Campaign

- 3 shots
- ~1.3 MJ laser energy per shot
- Cryogenic ice layer (74% Tritium, 24% Hydrogen, 2% Deuterium): reduced yield enables accurate ρR measurement
- Dip duration selected to maximise ρR

Laser worked excellently & experimental x-ray flux closely matched simulations





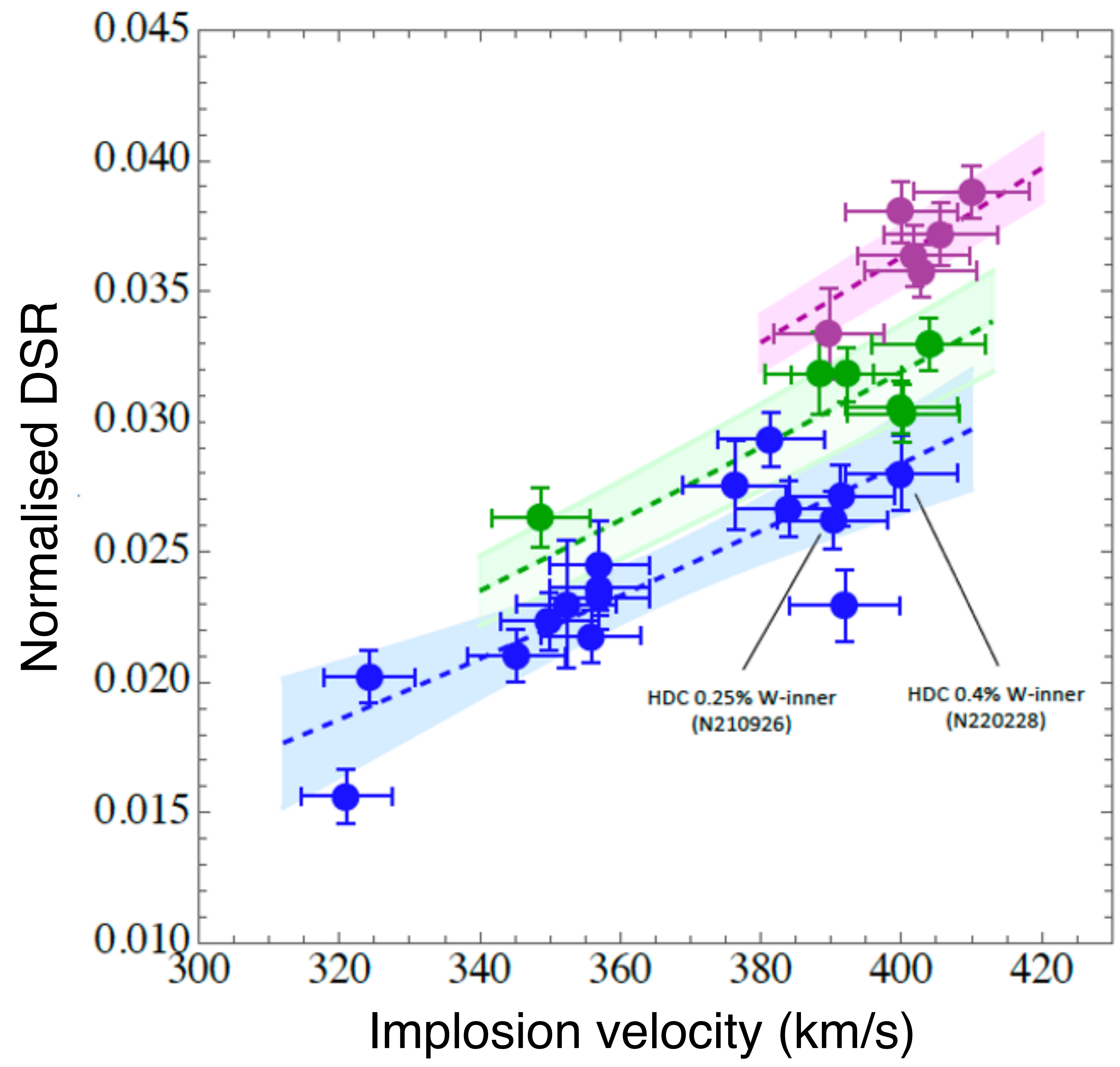
Hydra: Predicted variation in ρR with dip-duration.
ρR = 19.3*DSR

robbie.scott@stfc.ac.uk

Shock Augmented Ignition on NIF

- DSR (i.e. ρR) correlated with implosion velocity
- ~1.7x higher ρR than velocity-equivalent implosions

- SAI near-term potential (from 2D simulations):
    - Laser energy 2.2MJ (today's maximum)
    - YOC ~ 70%
    - Gain ~ 10



Tomassini et al, PRL 2023

robbie.scott@stfc.ac.uk

Ignition & High-Gain

- Ignition Criteria:
  - Hotspot ion temperature > 5 keV
  - Hotspot areal density (ρR_{HS}) > 0.3 g/cm^2

- Inertial fusion burn fraction:
  - $\phi = \rho R_{fuel} / (6 + \rho R_{fuel})$

- Fusion yield is proportional to:
  - $Y \propto \rho R_{fuel} . M_{fuel}$

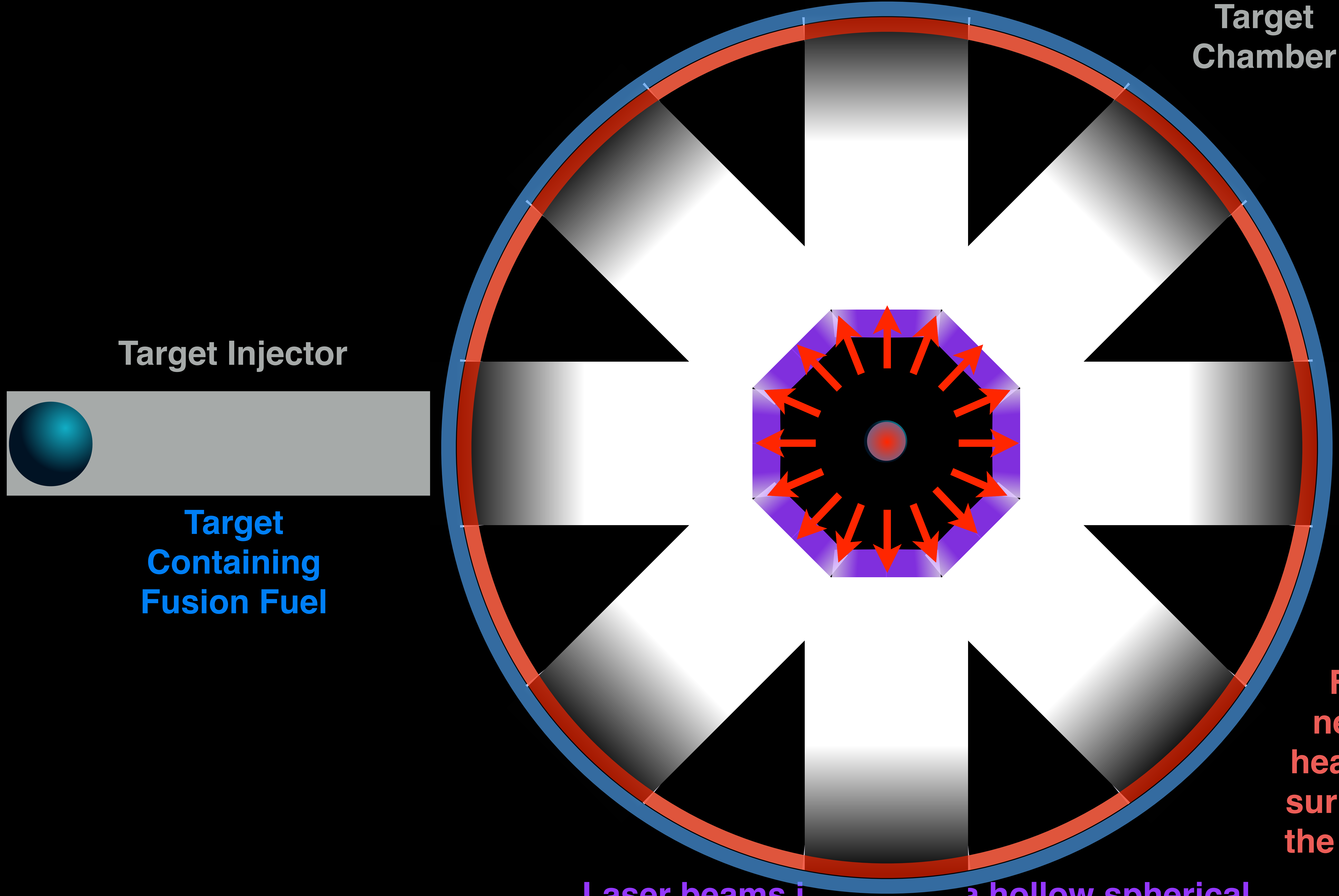
- Gain $\propto \rho R_{fuel} . M_{fuel} / E_{in}$

- High-gain requires:
  - Minimising input energy
  - Maximising compression
  - Maximising fuel mass

A combination of Direct Drive and shock-ignited methods improve all high-gain metrics and based on available evidence are the best candidates for Laser Fusion Energy generation

robbie.scott@stfc.ac.uk

Energy Generation using Laser Fusion



Target Chamber

Hot chamber boils water turning a steam turbine

Target Injector

Target Containing Fusion Fuel

Fusion neutrons heat lithium surrounding the chamber

Laser beams illuminate a hollow spherical shell containing the fusion fuel

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

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

robbie.scott@stfc.ac.uk

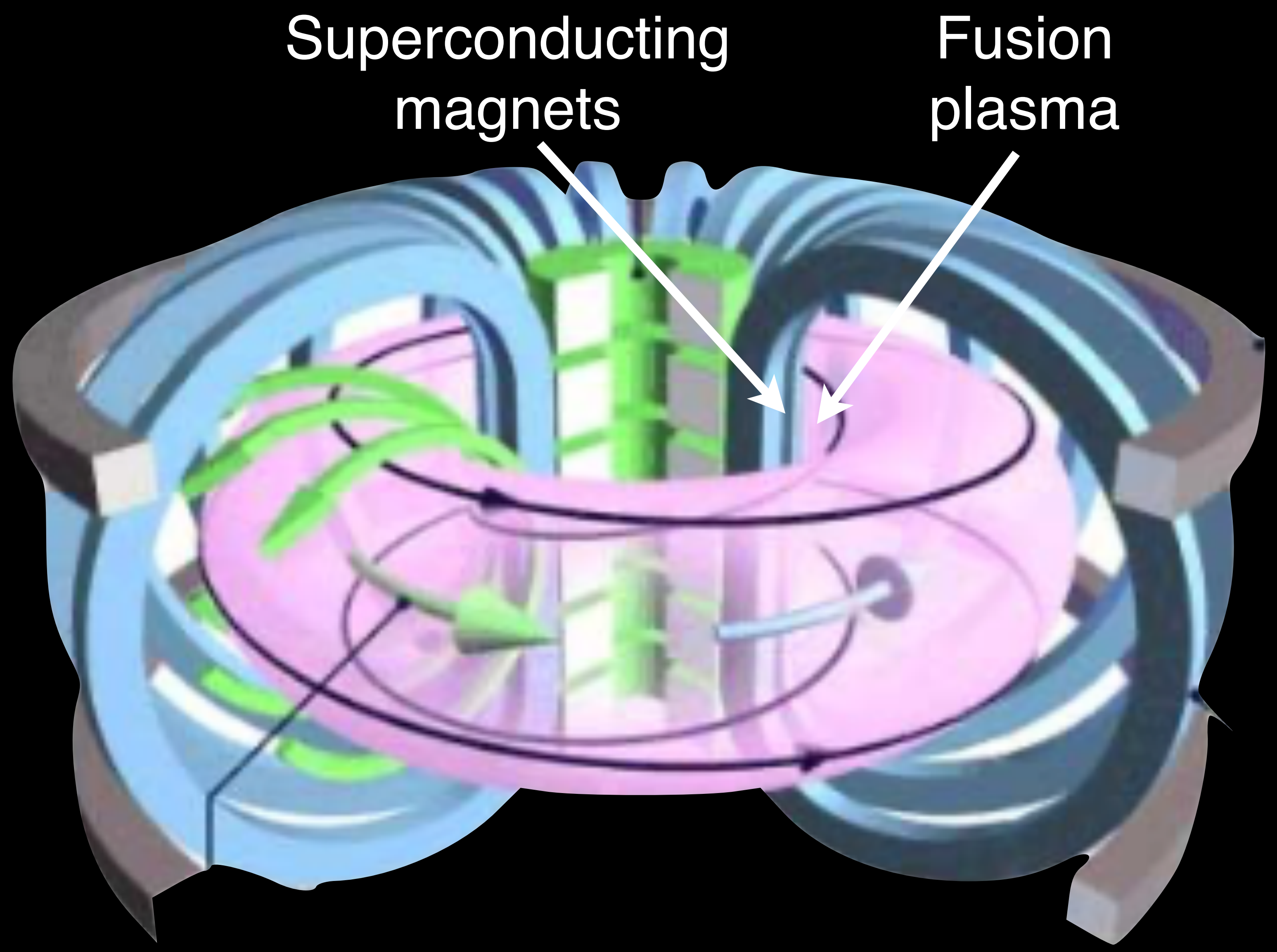
Potential Advantages of Inertial Fusion Energy

- 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

robbie.scott@stfc.ac.uk

UPLIFT

UK Inertial Fusion Consortium

CLF central laser facility

CLF central laser facility

UNIVERSITY OF OXFORD

Imperial College London

UNIVERSITY of York

WARWICK
THE UNIVERSITY OF WARWICK

scitech PRECISION

AWE

University of Strathclyde Glasgow

QUEEN'S UNIVERSITY BELFAST

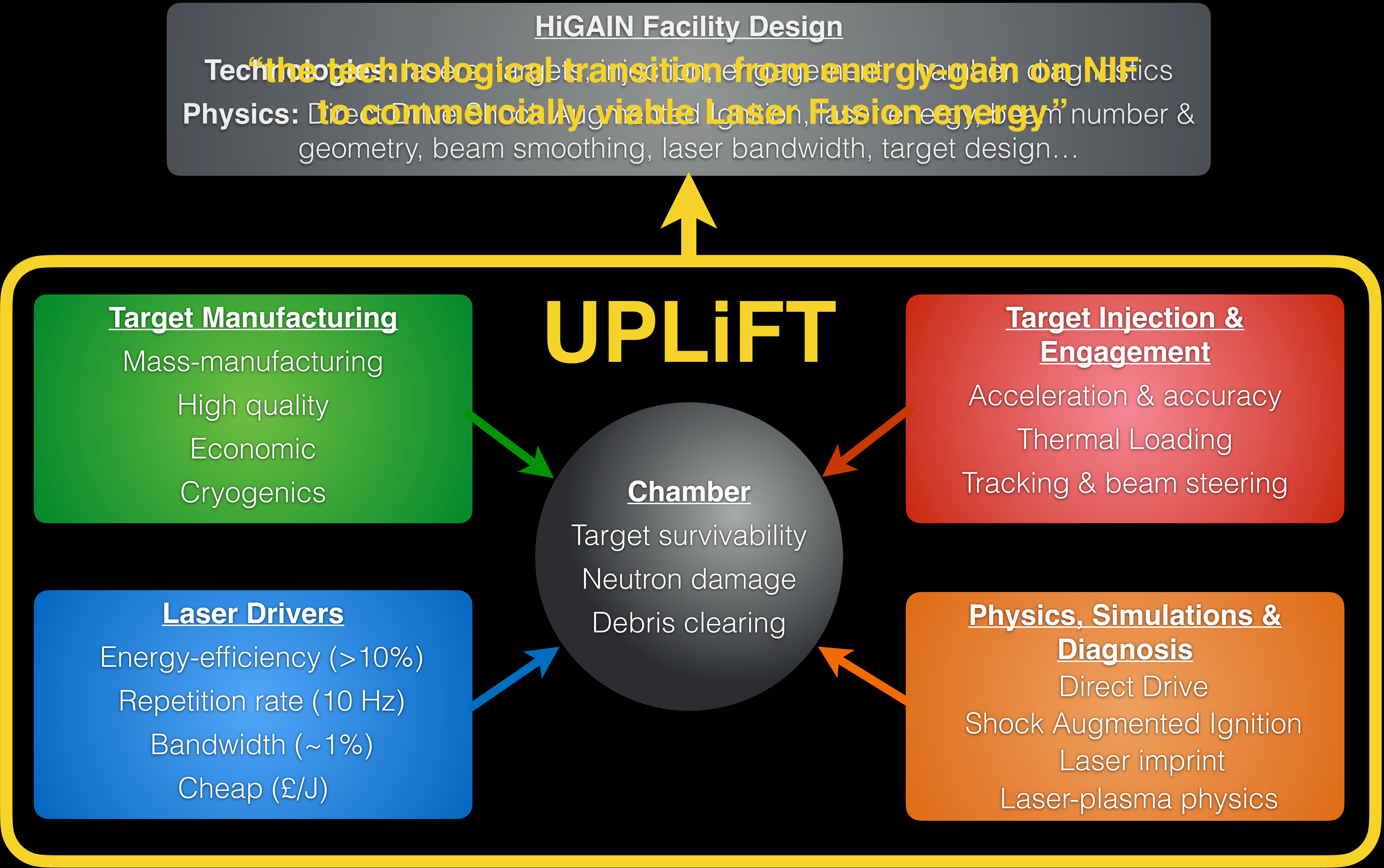
first light

Lancaster University

- 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

robbie.scott@stfc.ac.uk

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
- If UPLiFT is funded, do apply for jobs!

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