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Probing Hotspot Conditions in Spherically Shock Compressed Matter

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November 9, 2015

57th APS Division of Plasma Physics
Savannah, GA, United States
November 16, 2015 through November 20, 2015

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Probing Hotspot Conditions in Spherically Shock Compressed Matter

57th Annual Meeting of the APS Division of Plasma Physics

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November 16, 2015

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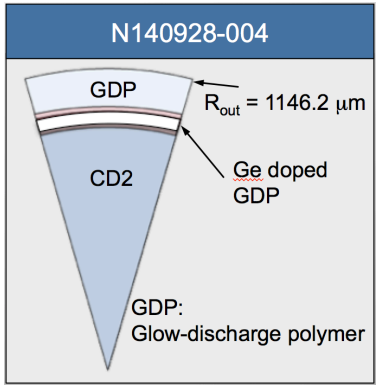
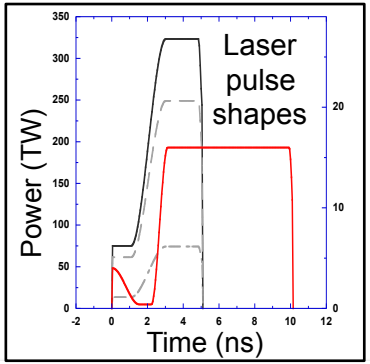
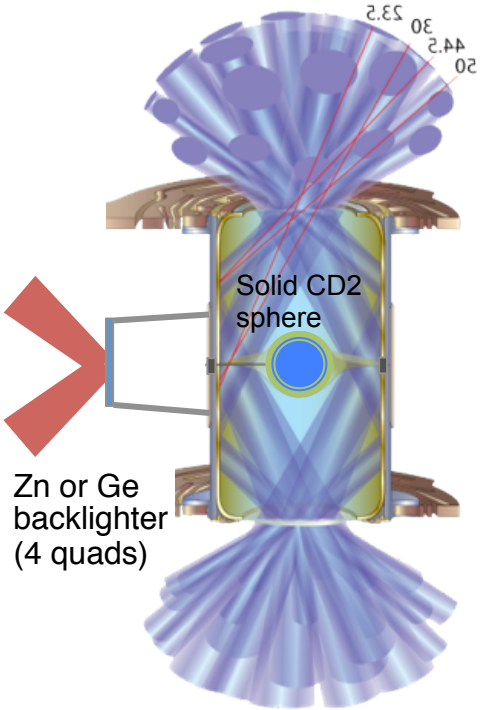
We use spherically converging shock waves to reach high pressures >10 Tpa (100Mbar)







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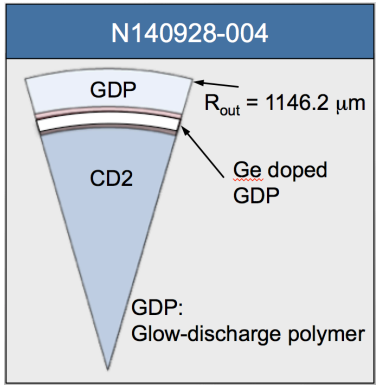
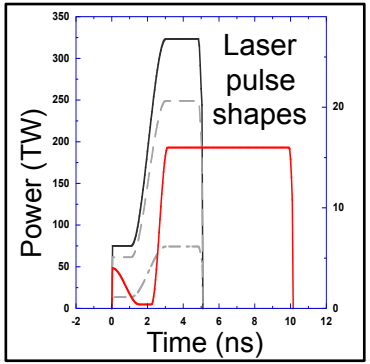
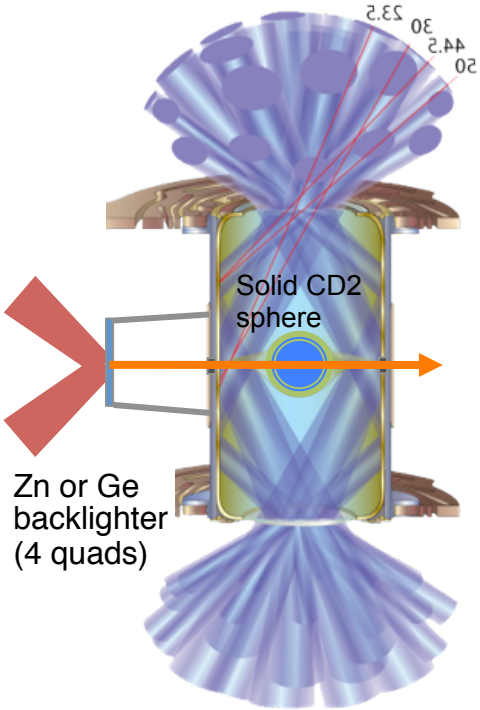
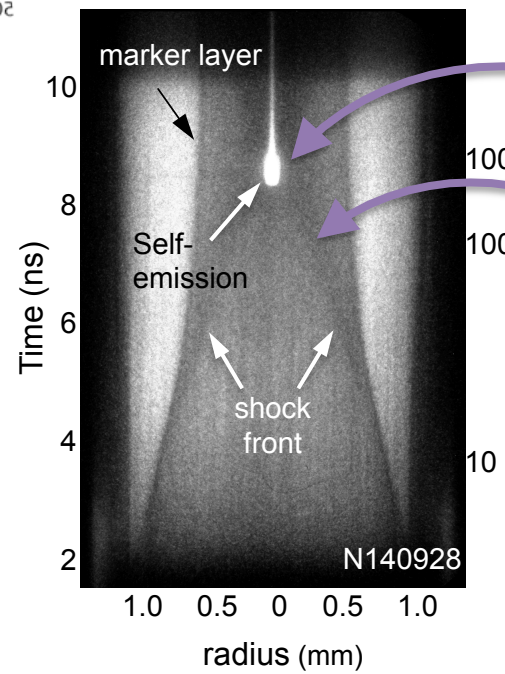
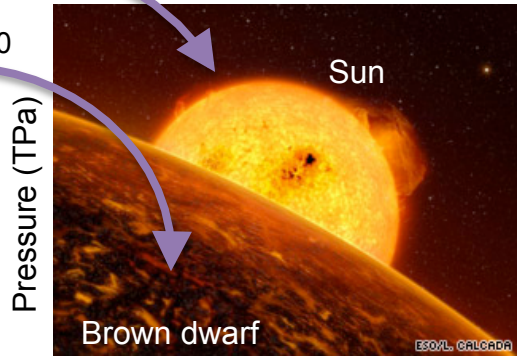






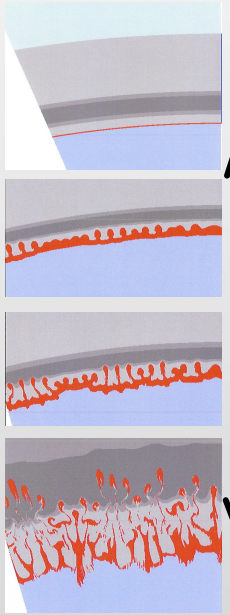
Streaked Radiography





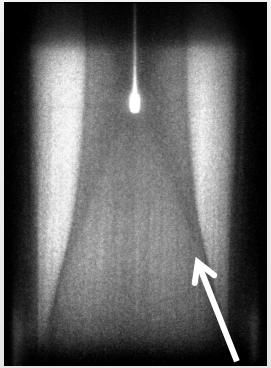
Shocked Solid Spheres are Hydrodynamically Stable, Unlike Imploding Capsules

CAPSULE

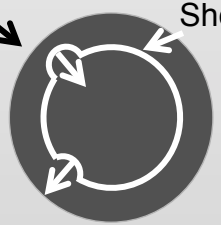


Capsule implosions are prone to Hydrodynamic instabilities at each interface

SOLID SPHERE

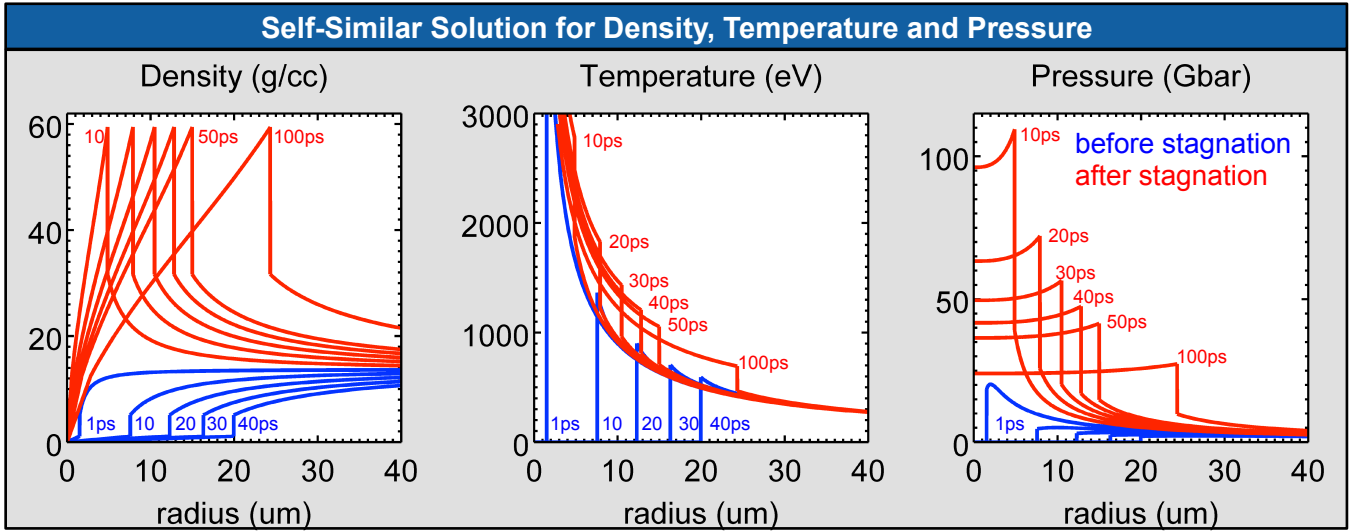


Converging shockwaves are self-symmetrizing



- The shock wave keeps ‘forgetting’ about past conditions: it is undergoing a damped oscillation
- We have a self-similar system

What happens in the center?



see also Guderley, 1942 and
Atzeni & Meyer-Ter-Vehn: The Physics of Inertial Fusion

⇒ Convergence and reflected shock enhance ρ, T and P

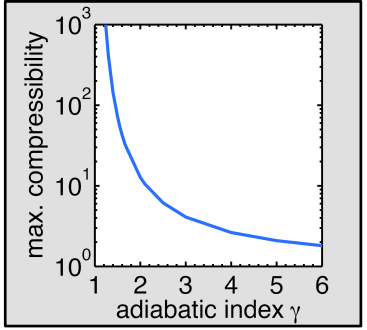
Where does this break down in a real implosion?

What will limit the size and burn duration of the observable hotspot?

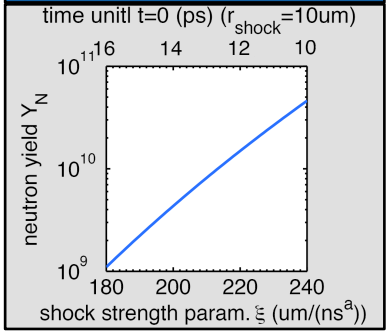
Self similar solution for imploding shock wave has 2 “knobs” that constrain the physics

- γ: adiabatic index
- ξ: shock strength parameter, $\xi = \dfrac{r/r_0}{|t/t_0|^a}$

$\rho \Rightarrow \gamma$



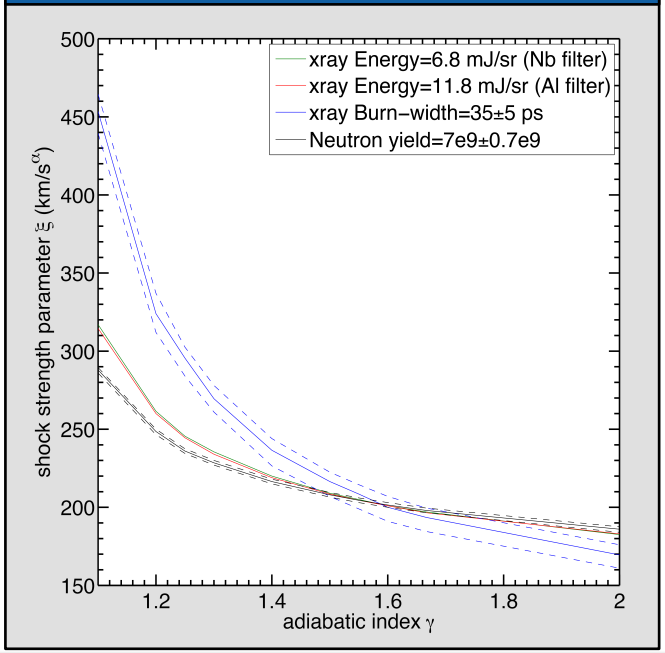
$Y_N \Rightarrow \xi$



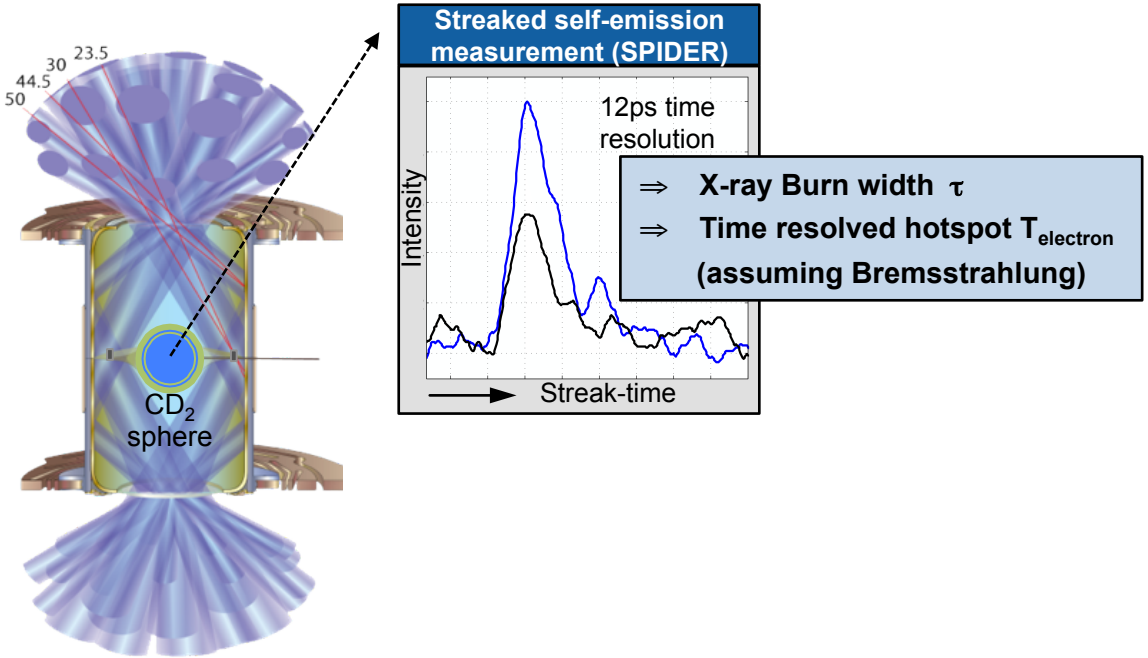
- A small change in γ results in a large change in the final density/ compressibility
- A small change in ξ results in a large change of the Neutron yield

$\Rightarrow$ Measuring the density & Neutron yield strongly constrains γ and ξ, thus the Equation of State

Observables are consistent with self-similar solution

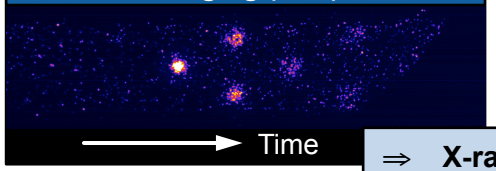


Shocked Solid Spheres are Hydrodynamically Stable, Unlike Imploding Capsules

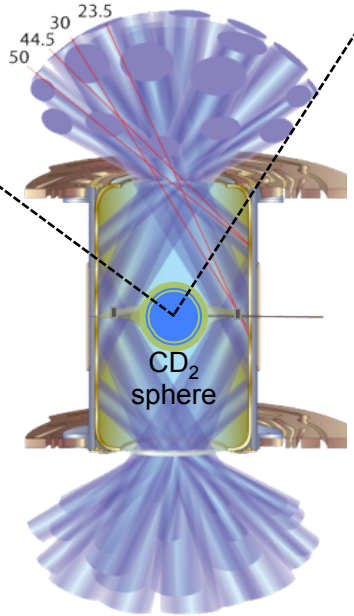


Shocked Solid Spheres are Hydrodynamically Stable, Unlike Imploding Capsules

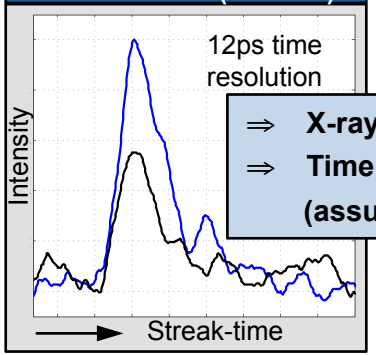
Time-resolved Penumbral Imaging (DIXI)



⇒ **X-ray Burn width τ**



Streaked self-emission measurement (SPIDER)



⇒ **X-ray Burn width τ**

⇒ **Time resolved hotspot $T_{electron}$ (assuming Bremsstrahlung)**

Shocked Solid Spheres are Hydrodynamically Stable, Unlike Imploding Capsules

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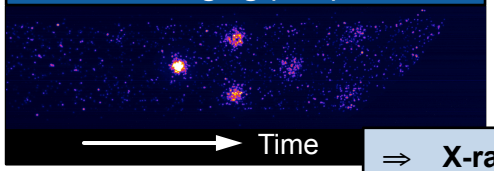
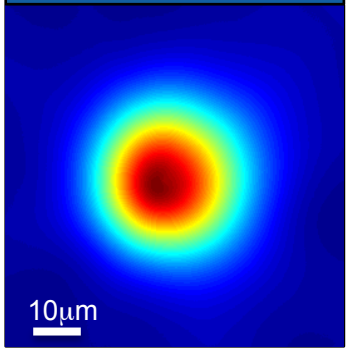


⇒ **X-ray Burn width τ**

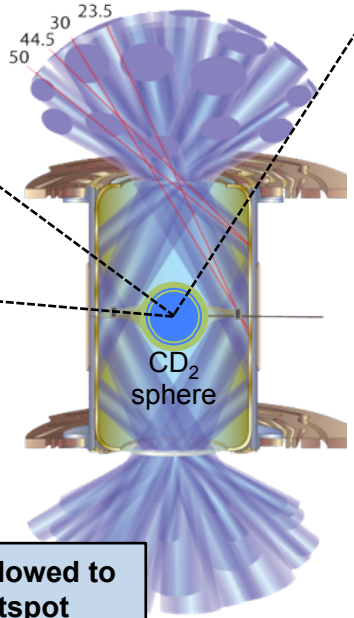
Reconstructed time integrated Penumbral Image



⇒ **Hotspot shape & volume V**

Bachmann *et al.*, RSI 85, 11D614, 2014

⇒ **Penumbral Imaging allowed to image the smallest hotspot (10μm (1/e) radius) with the highest resolution (1.5μm) on the NIF to date**



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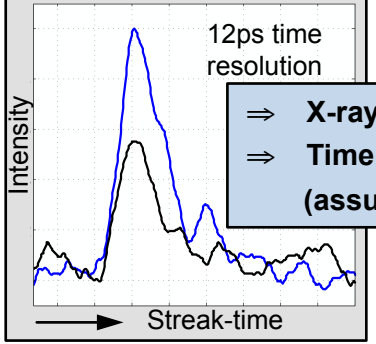

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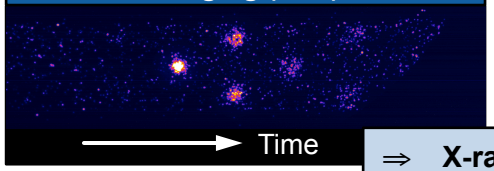
Shocked Solid Spheres are Hydrodynamically Stable, Unlike Imploding Capsules – ADD RESULTS tau, R, T, YN

Time-resolved Penumbral Imaging (DIXI)



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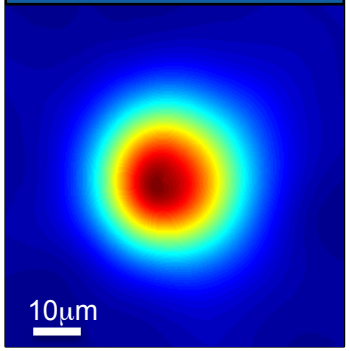

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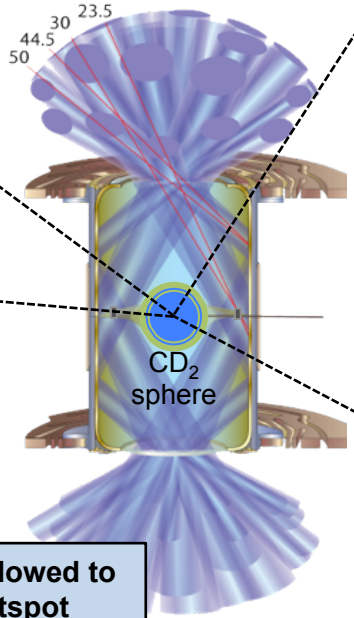

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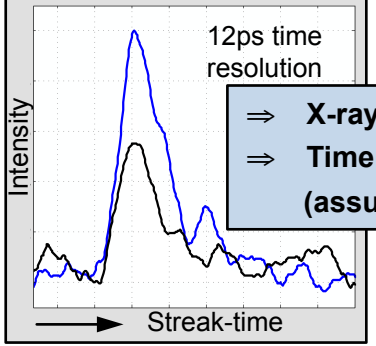

⇒ **X-ray Burn width τ**

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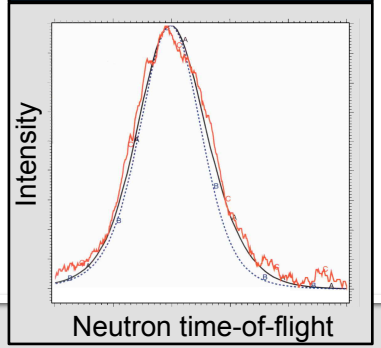
Doppler-broadened Neutron time-of-flight signal



⇒ **DD-Yield Y_N**

⇒ **T_{ion} (from Doppler Broadening)**

Calculation of the Hotspot Density

Y_N = 1.5 e9 (25% of total, from nTOF)
R(17%) = 13.2 μm (from Penumbral Imaging)
t=30ps (x-ray burn width)
T_{mean} = 1.6 keV (from self-emission meas.)

Y_N = 7e9 (total, from nTOF)
R(17%) = 40 μm (from Guderley model)
t = 47 ps (Neutron burn width – from Guderley)
T_{mean}= 1.0 keV (from nTOF)

$$Y_{n,DD} = \int_0^{\infty} \int_{V_{hs}} \frac{n_D^2}{2} \langle \sigma v \rangle_{DD} \, dV dt$$

⇒ $n_{CD2,m}$ = 43 g/cc

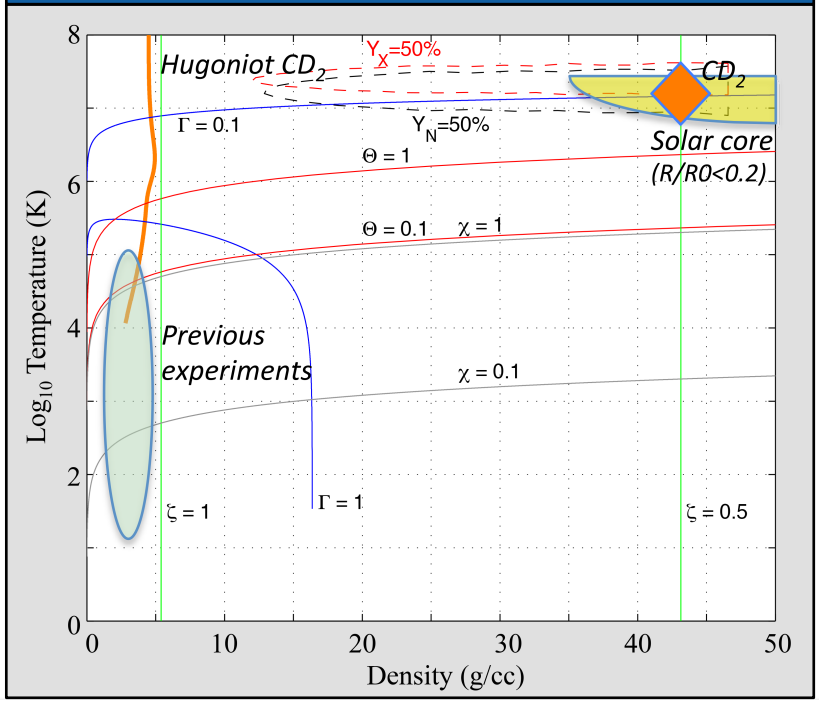
⇒ $n_{CD2,m}$ = 45 g/cc

- **Small change in γ results in large change of density**
- **Small change in shock strength results in large change of Neutron yield**

⇒ **Measuring density & neutron yield strongly constrains the Equation of State**

We Constrain the Equation of State of CD_2 at Unprecedented Conditions

Phase Diagram of CD_2



$\Gamma = \frac{\text{coulomb energy}}{\text{kinetic energy}}$

$\chi = \frac{\text{Interatomic spacing}}{\text{DeBroglie Wavelength}}$

$\zeta = \frac{\text{Interatomic spacing}}{\text{Bohr radius}}$

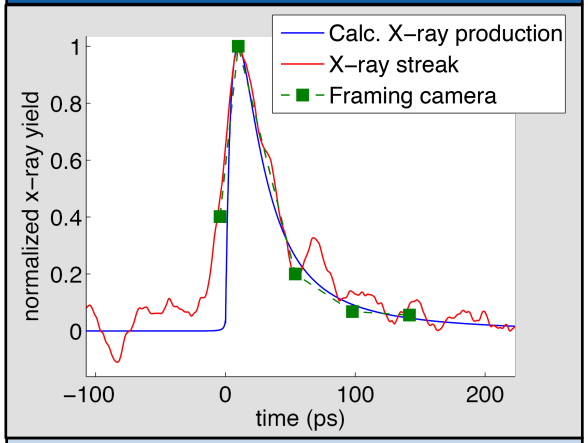
$\theta = \frac{\text{Thermal Energy}}{\text{Fermi Energy}}$

Y_N=50%: Contour containing 50% of the measured neutron yield (from self-similar solution)

Y_X=50%: Contour containing 50% of the measured x-ray yield (from self-similar solution)

Can we Estimate the Pressure?

Comparison of measured and expected (self-similar model) self-emission



⇒ **Hotspot burn is limited by Hydrodynamic time scale**

X-ray burn width: 30-40 ps
X-ray emission radius: 13 μm
⇒ Characteristic velocity (close to sound speed): *13μm/35ps=370km/s*
⇒ Compare Ion sound velocity:

$$c_{s,ion} = \sqrt{\gamma Z k_B T / m_{ion}} = 345 km/s$$

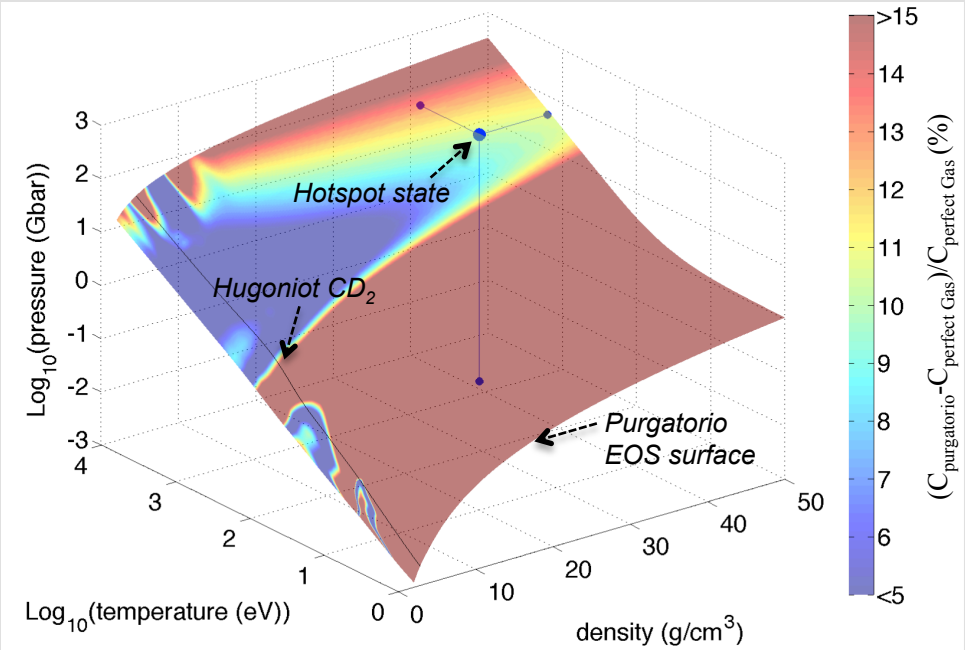
⇒ e-i equilibration time constant: 200 fs

$$c_s = \sqrt{\frac{K}{\rho}} \cong \sqrt{\frac{\gamma P}{\rho}}$$

⇒ **P~3.4…3.9 PPa (34 to 39 Gbar)**

Hotspot State Variables Agree Well with Purgatorio EOS

Purgatorio EOS surface (CD_2) and hotspot state



For the first time, nuclear reactions have been used to constrain the Equation of State of matter at solar core conditions

C: maximum compressibility in a self-similar implosion

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