Prompt gamma-ray measurements in ICF experiments

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ICF Gamma Ray Physics

a LANL-led collaboration across multiple institutions

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National Security Technologies LLC — Vision • Service • Partnership

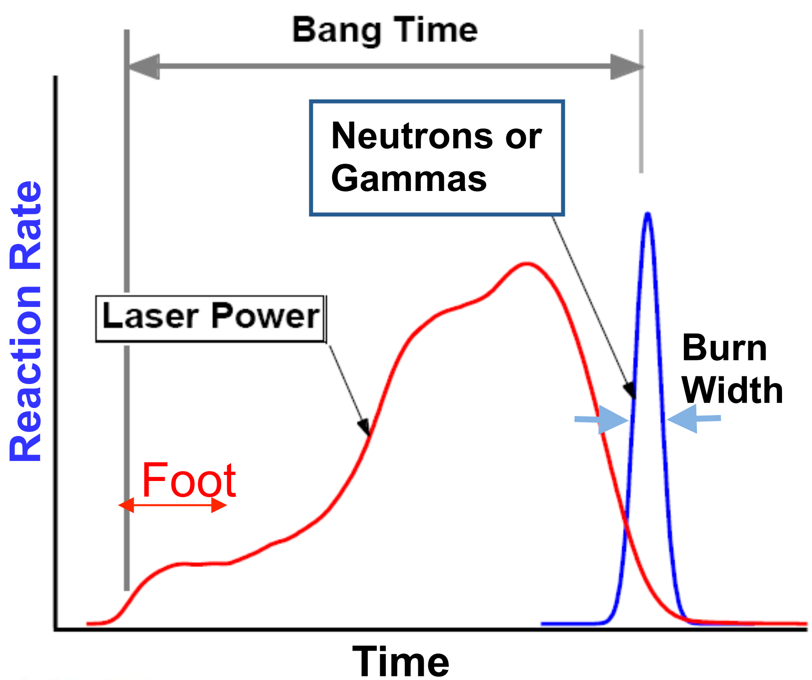
Outline

- Intro to Gas Cherenkov Detectors (GCD)
- Gamma Reaction History
- Future Gamma Diagnostics

Gamma-rays provide the most un-perturbed nuclear signature of ICF performance

Doppler Broadened (T_i) no escape (hopefully)

$$D + T \rightarrow {}^5He^* \begin{cases} \xrightarrow{\sim 1} n\,(14.1\ MeV) + \alpha\,(3.5\ MeV) \\ \xrightarrow{\sim 4e-5} {}^5He + \gamma\,(16.75 MeV) \rightarrow n + \alpha \end{cases}$$

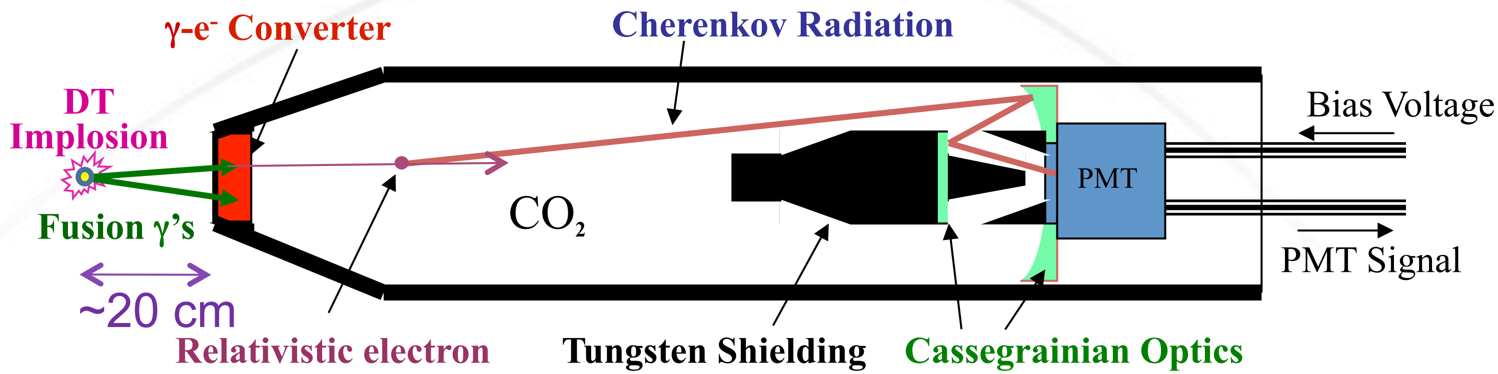


- **Bang Time** - used to establish laser energy coupling to target (shell velocity)

$$ITF = I_0 S^3 \left(\frac{v}{v_0}\right)^8 \left(\frac{\alpha}{\alpha_0}\right)^{-4} \left(1 - 1.2\frac{\Delta R^{K-wtd}_{hotspot}}{R_{hotspot}}\right)^{4+\varepsilon} \left(\frac{M_{clean}}{M_{DT}}\right)^{0.5}$$

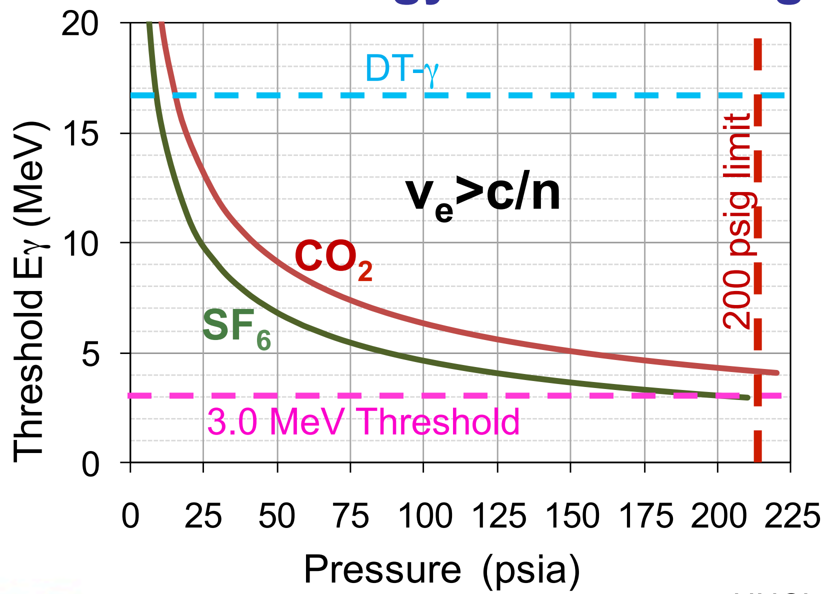
- **Burn Width & other RH features** - used for failure mode correlation

Gas Cherenkov Detectors (GCD) convert MeV gammas to UV/Visible for easy detection

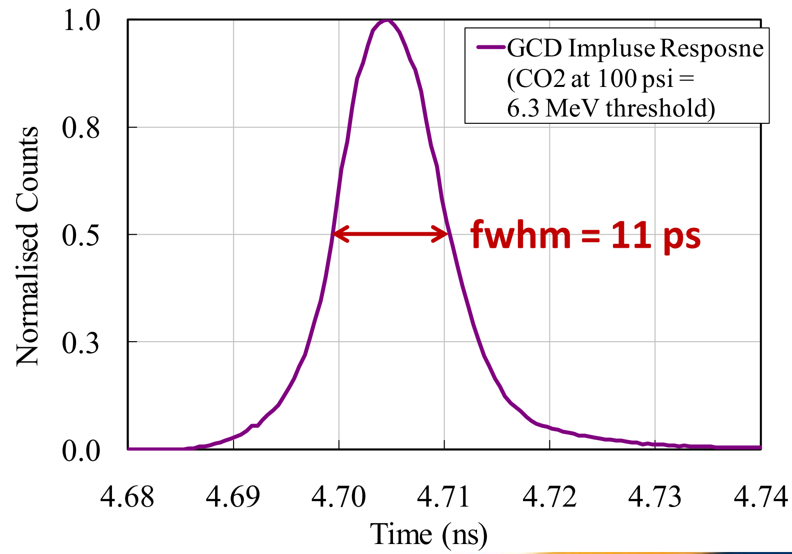


GCD-1

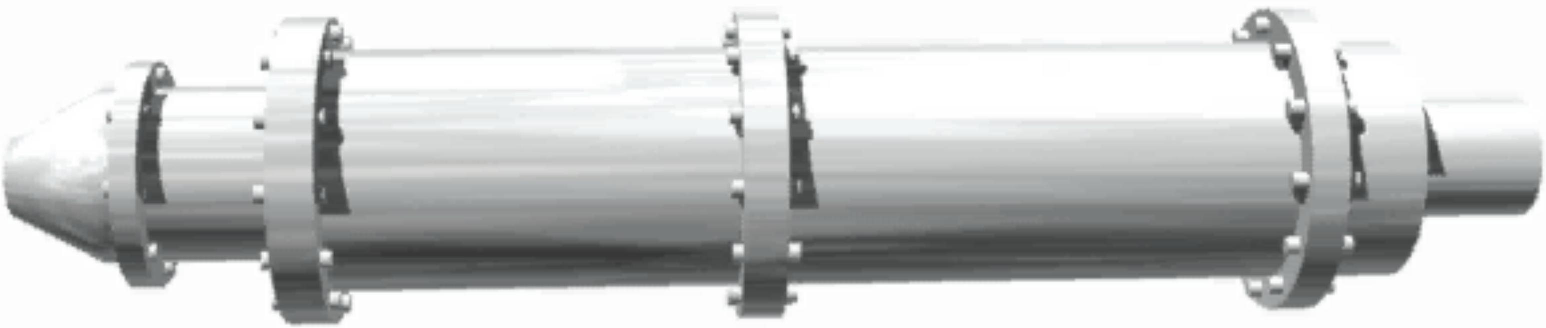
Variable Energy Thresholding



Fast Time Response

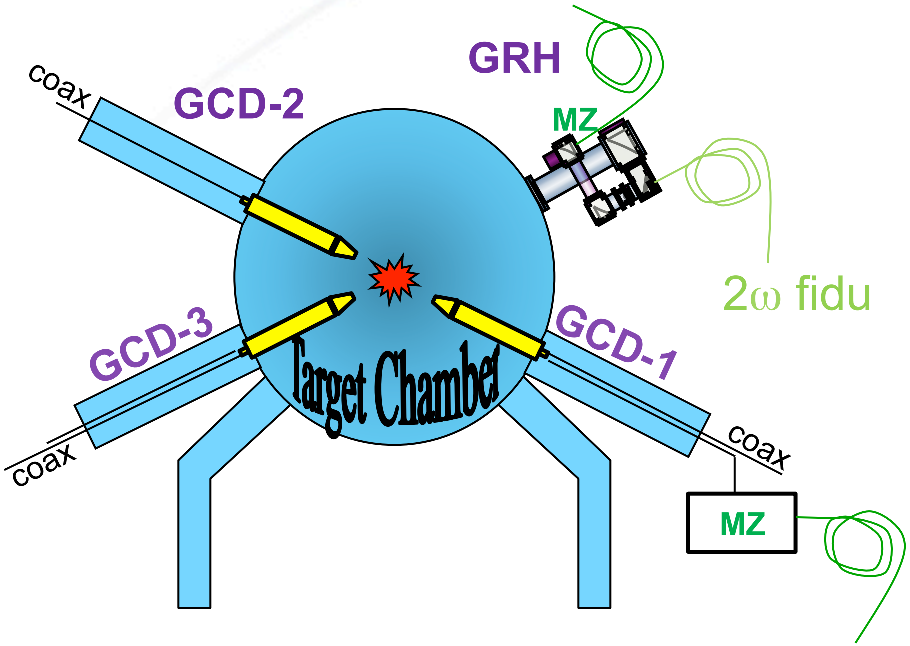


GCD Animation



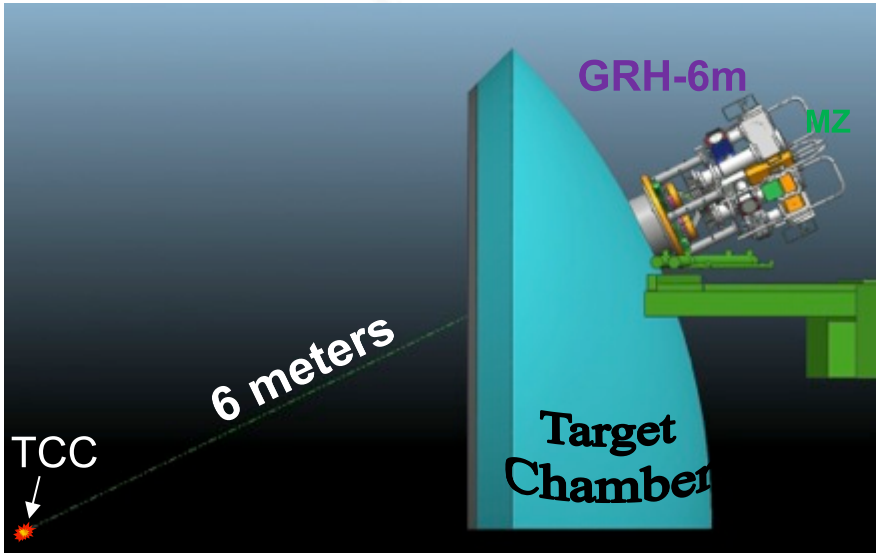
Gamma Ray Diagnostic capability at OMEGA & NIF

OMEGA-60



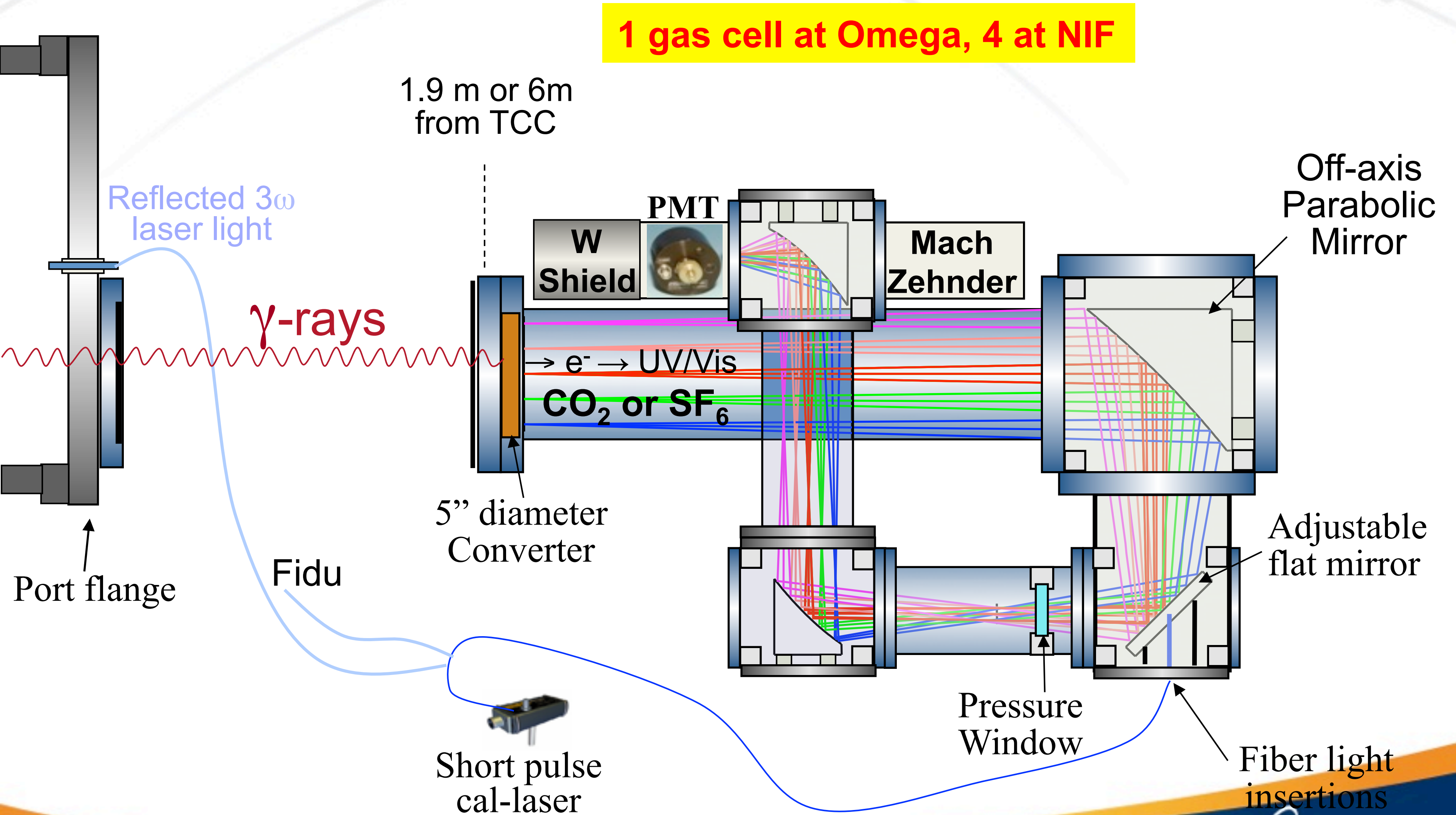
- 3 GCDs (20cm), 1 GRH (187cm)
  - ➢ Coax (40ft) & Mach Zehnders
  - ➢ Only GRH absolutely timed

NIF

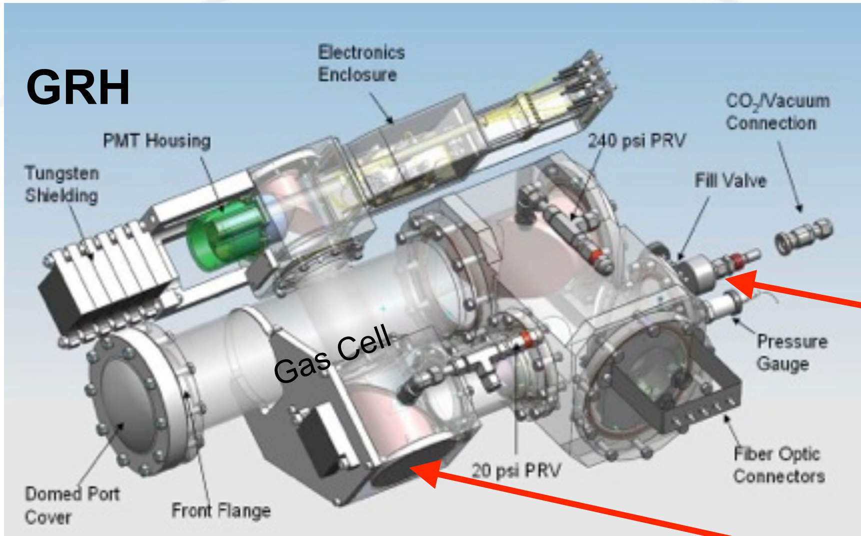


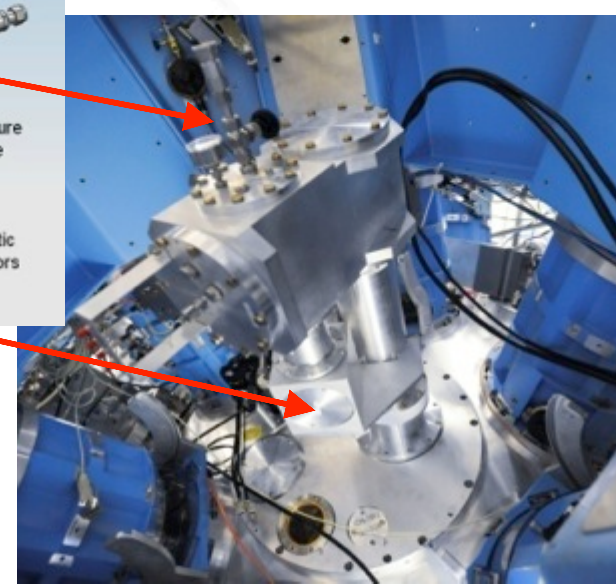
- 4 GRHs (607 cm)
  - ➢ Mach Zehnders only (160 ft)
  - ➢ All absolutely timed

Gamma Reaction History (GRH) is optimized to operate outside target chamber.

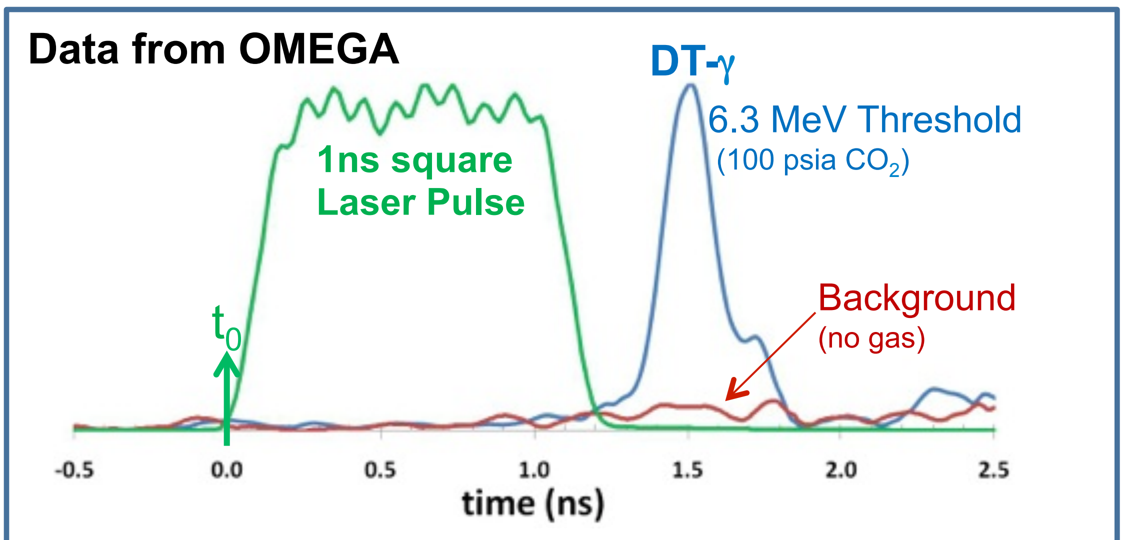


Single-channel GRH prototype performance demonstrated at OMEGA (U. of Rochester) in 2009



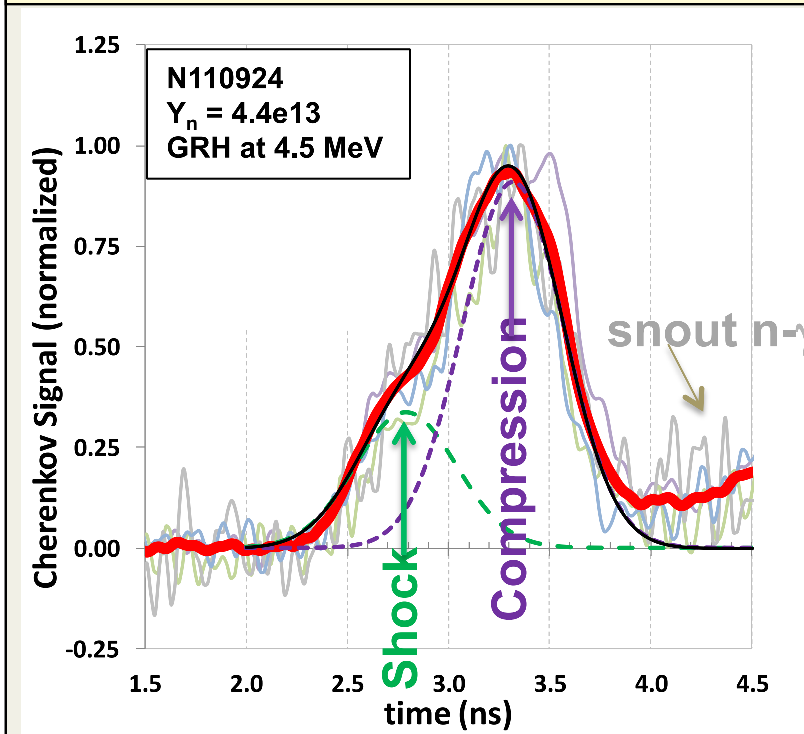


Installed on OMEGA



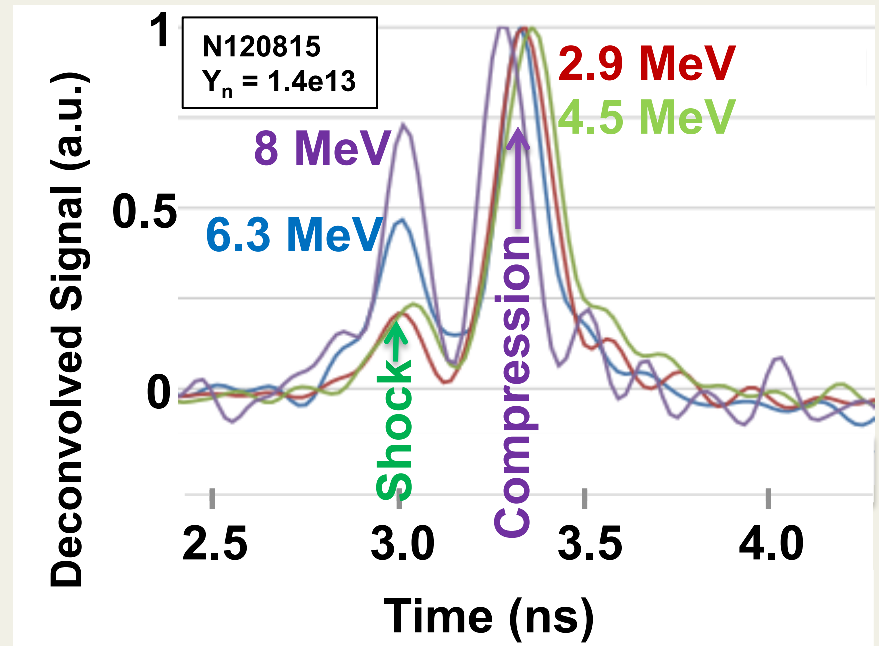
NIF has produced Interesting Direct-Drive Reaction Histories

CH-coated Glass Capsule



- Ablatively-driven implosion with shock & compression yields having burnwidths ~600 ps

Xe-doped Exploding Pusher



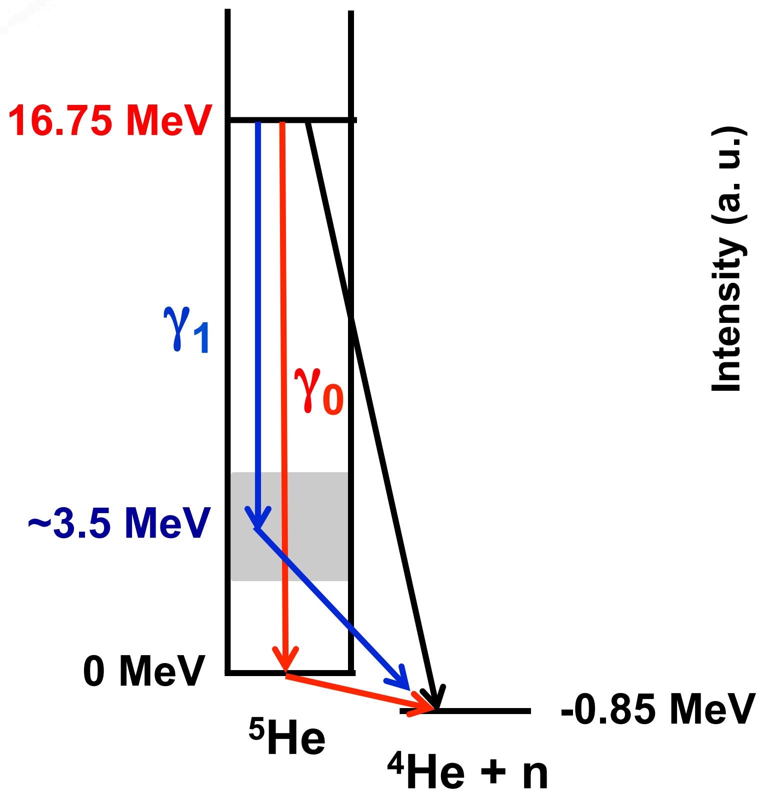
- Comparable shock & compression yield
- Low-threshold signals (2.9 & 4.5 MeV) more dominant at Compression due to higher shell ρR

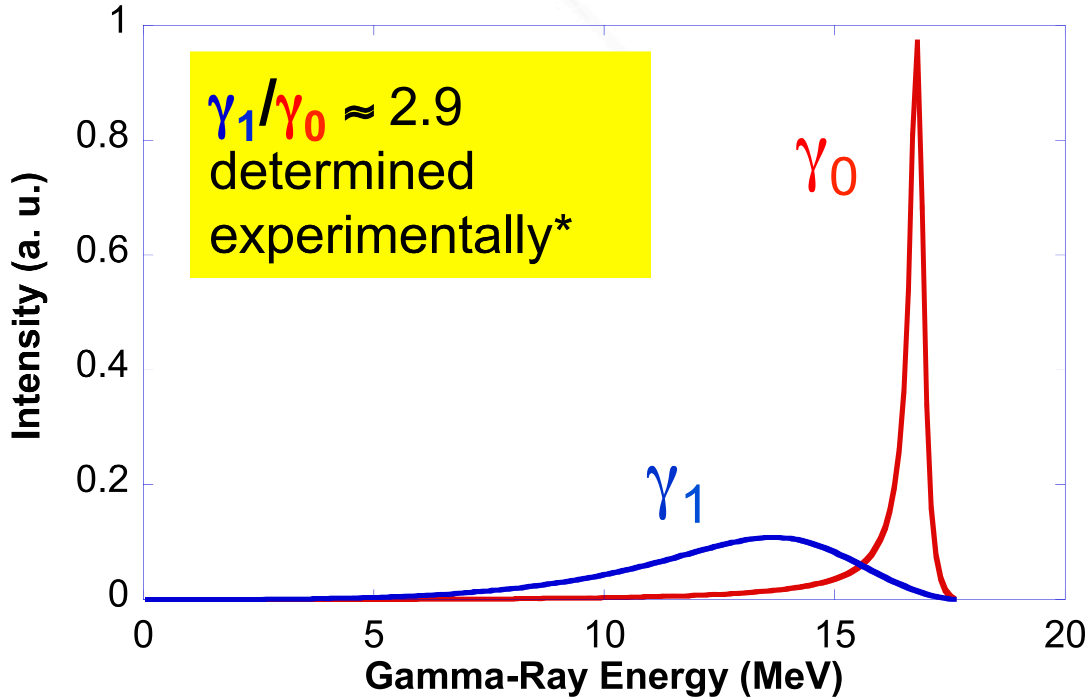
DT γ-ray Spectrum consists of 2 prominent lines

$D + T \rightarrow {}^5He^* \rightarrow {}^4He\ (3.5\ MeV) + n\ (14.1\ MeV)$

$\rightarrow {}^5He + \gamma_0\ (16.75\ MeV)$

$\rightarrow {}^5He^* + \gamma_1\ (\sim 13.5\ MeV)$





* Courtesy C.J. Horsfield (AWE), assuming lines shapes offered by R-Matrix analysis (G. Hale, LANL)

GCD & GRH have provided great HED & Burn Physics results at OMEGA

Accomplished:

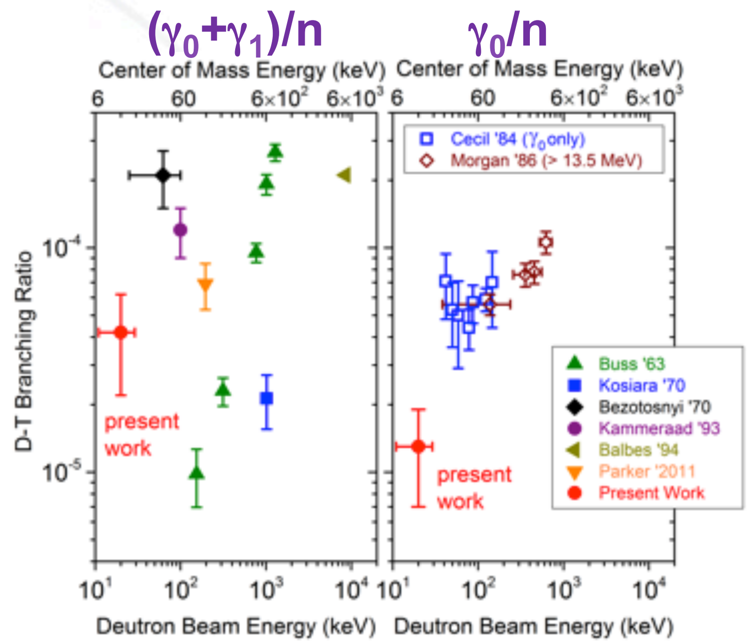
- *DT Branching Ratio = (4.2±2)e-5 γ/n*
- *Characterization of other fusion gammas (D^3He, HT, T_2, T_3He, $^3He^3He$, HD,…)*
- *(n,n') gammas from pucks of various materials → ablator areal density of CH & SiO2 implosions*

In Progress:

- *Kinetic Plasma Effects*
  - *Fuel Ion Segregation*
  - *Knudsen Reactivity Reduction*
  - *Transport validation (mass, momentum, energy)*
- *Charged-Particle Stopping Power*
- *Charged-Particle induced gammas for Mix diagnosis*

PHYSICS OF PLASMAS 19, 056313 (2012)

D-T gamma-to-neutron branching ratio determined from inertial confinement fusion plasmas[a)]



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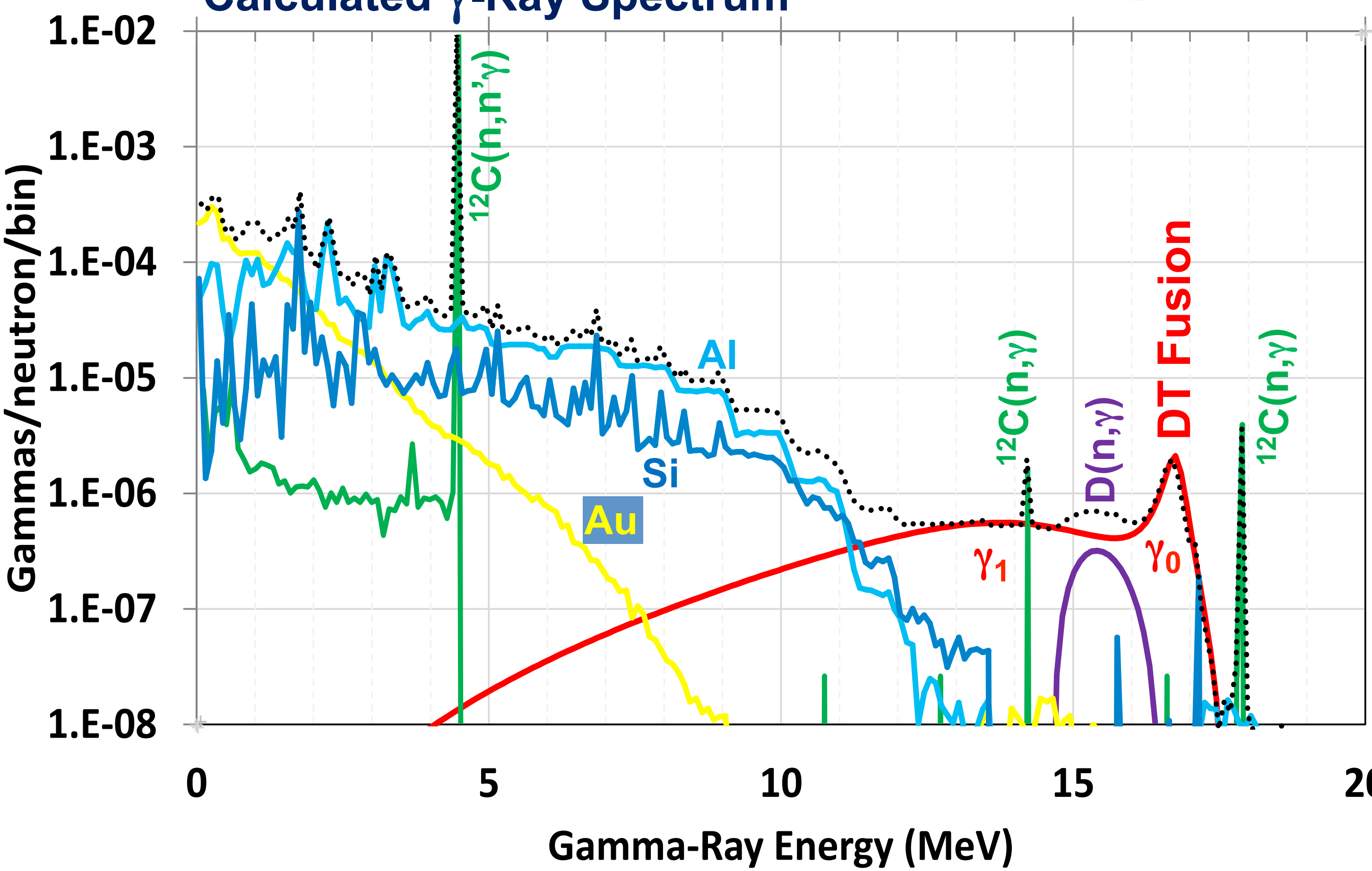
The Prompt γ-Ray Energy Spectrum from Indirect-Drive, Cryo-Layered Implosions is full of information!

Calculated γ-Ray Spectrum



- **TOTAL Y_{DT}** (→TDSF)
  - $Y_{DT} = B_{\gamma/n}\ Y_{DT\gamma}$
  - $TDSF=1-(Y_{n(13\text{-}15)}/Y_{DT})$
- **Ablator ρR**
  - 12C(n,n'γ)
  - 12C(n,γ)?
- **Cold fuel ρR**
  - D(n,γ)

Goals

- **Hohl/TMP**
- **Mix?**
  - $^{9}Be(\alpha,n)^{12}C^*$
  - $^{13}C(d,n)^{14}N^*$
- **Other**
  - Pucks
  - Dopants
  - Surprises!

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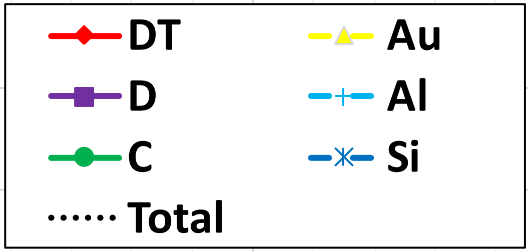
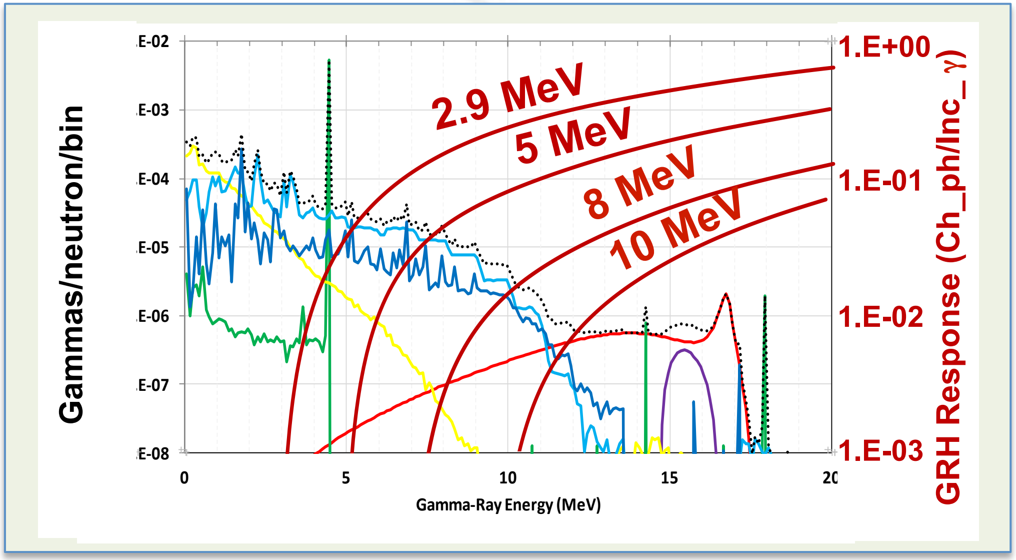
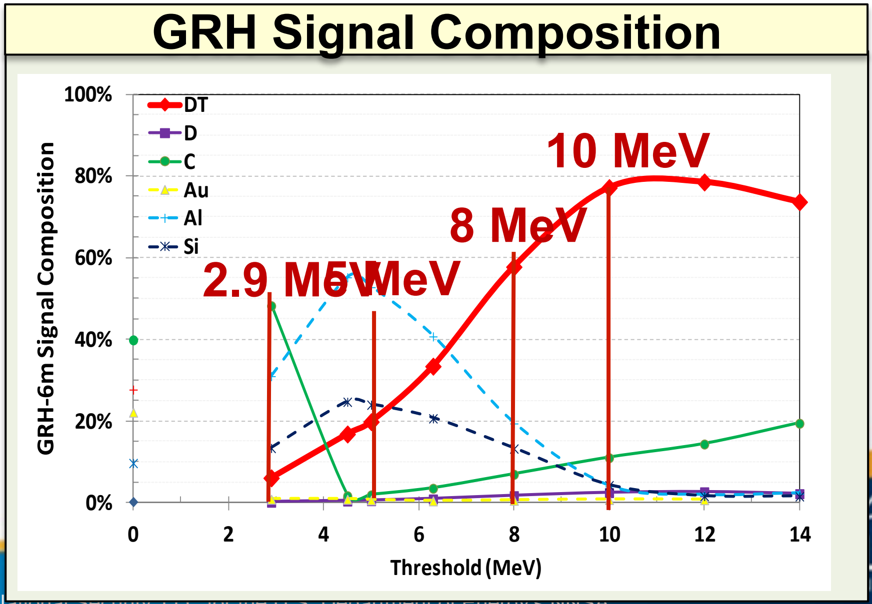
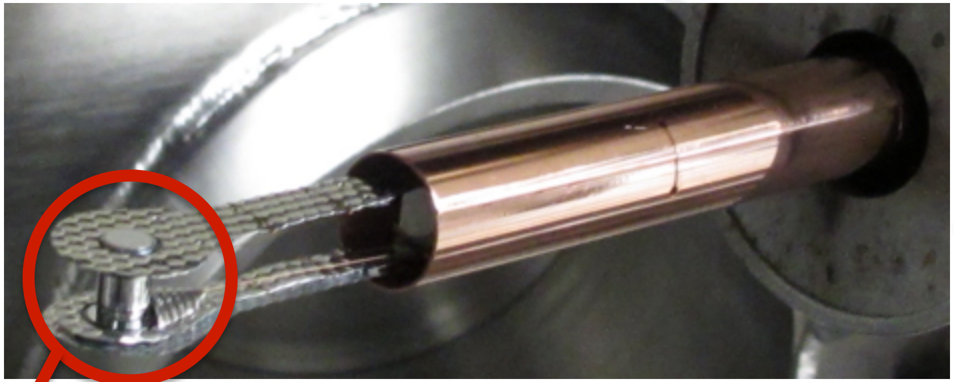
GRH isolates DT fusion and $^{12}C(n,n')$ γ-rays



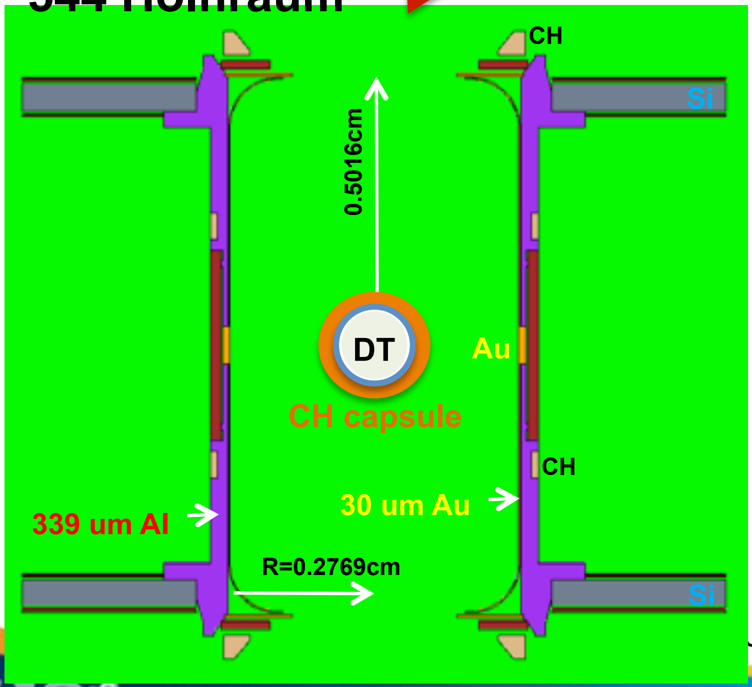


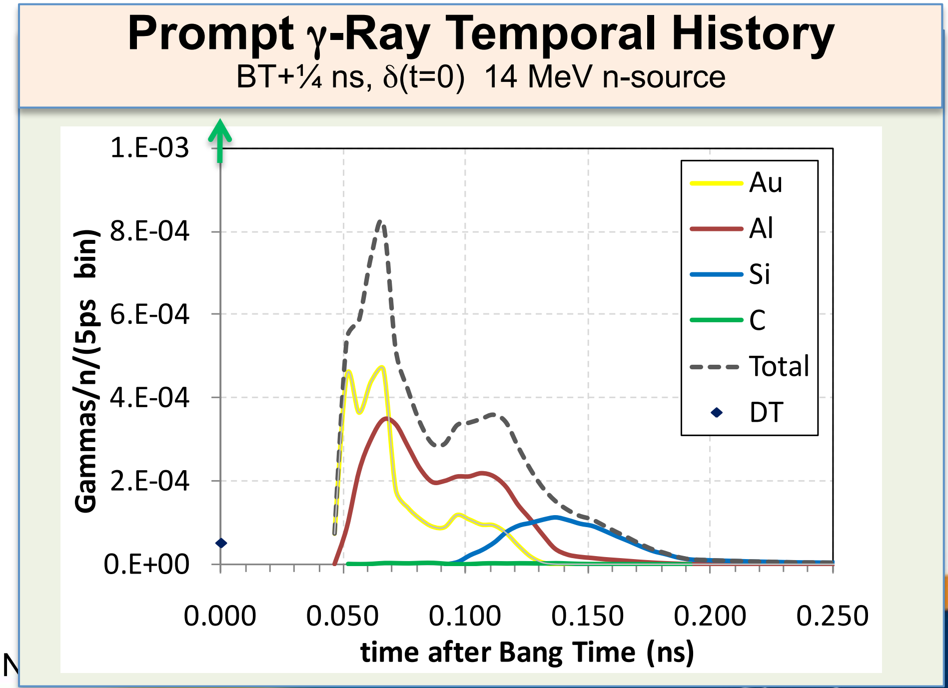


14 MeV neutron-induced γ-Rays from CH Capsule & Hohlraum assembly are simulated in MCNP

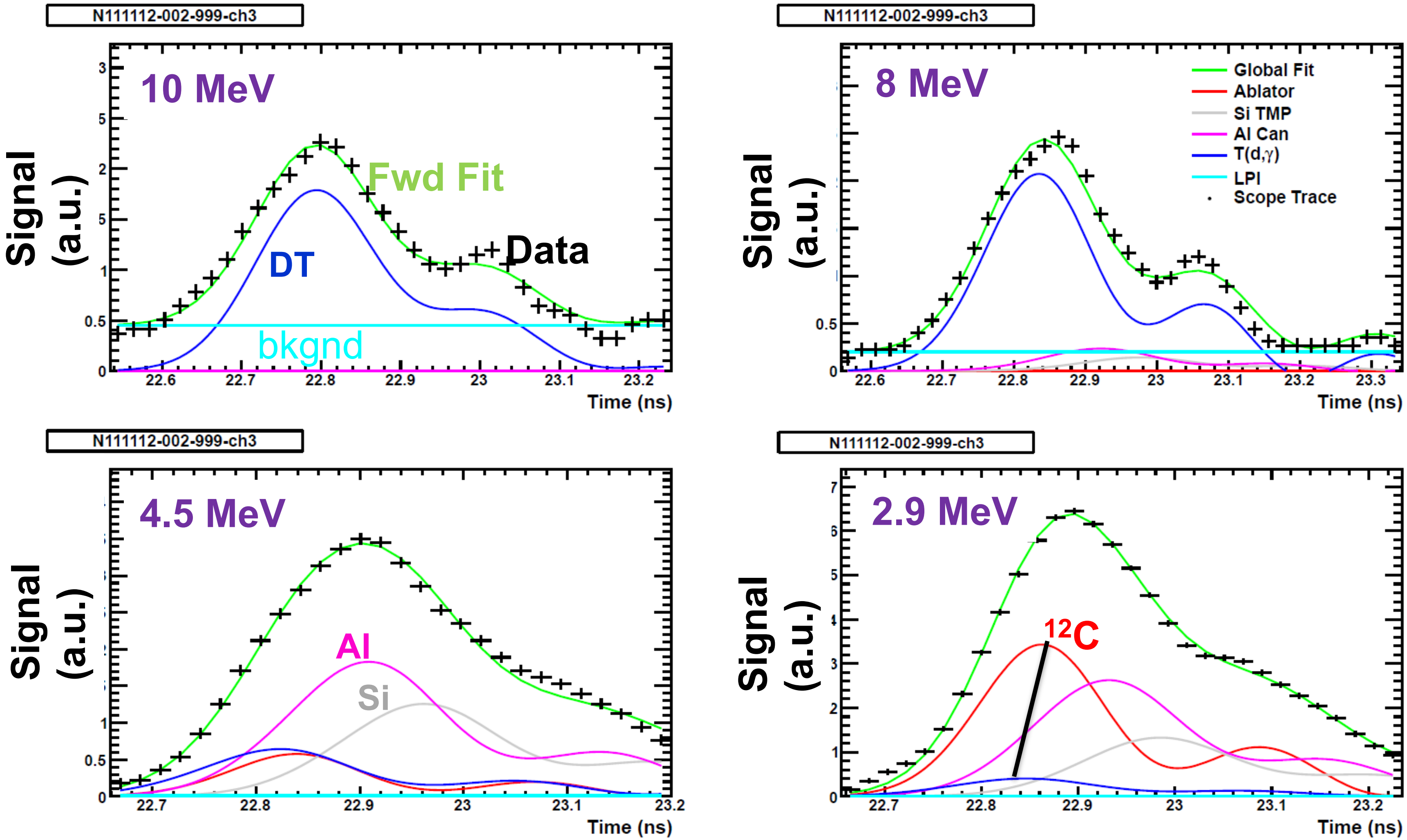


544 Holhraum





Gaussian forward fit decomposition into spectral components provides Total DT & $^{12}C(n,n'\gamma)$ yields and absolute timing (BT, BW, $t_{C\gamma}$)



$t_{C\gamma}$ > BT

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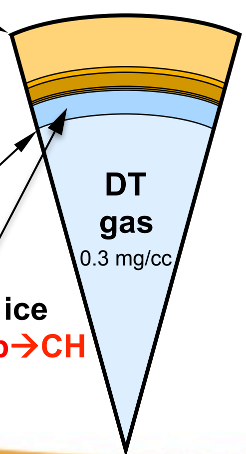
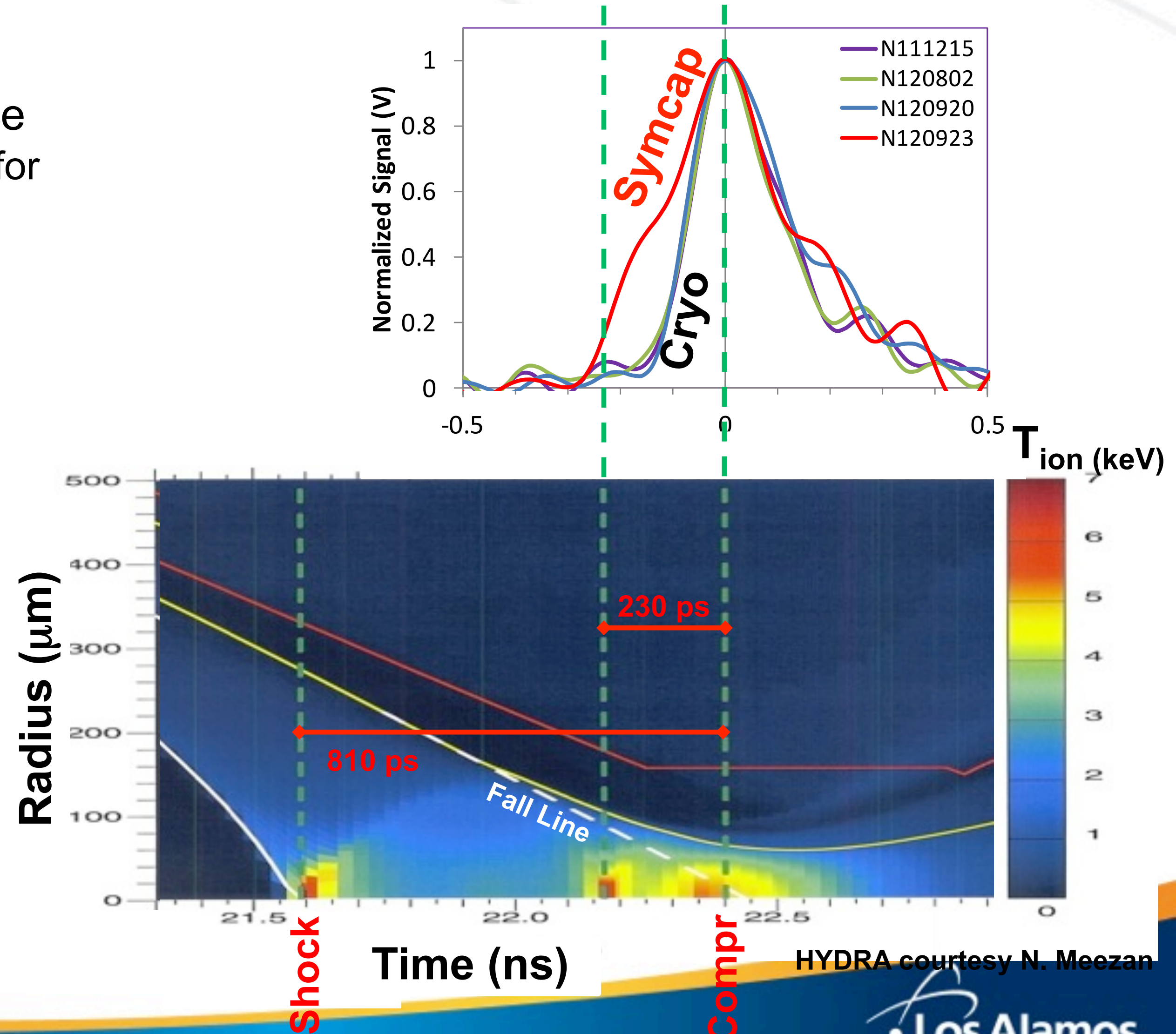
D. Sayre

Indirect Drive: DT Symcap produces discernible "Re-Shock flash", Cryo-layered implosions do not

- Symcap uses surrogate CH layer in place of DT ice
  - provides harder boundary for shock reflection
- Re-Shock flash occurs before Fall Line reaches core
  - Y_{Compr}/ $Y_{Re\text{-}Shock}$ is a measure of mix

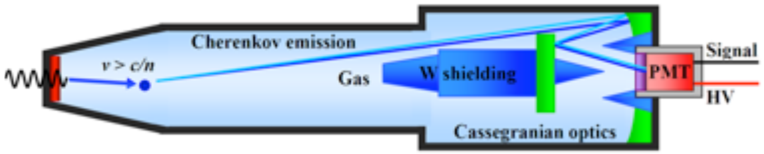




Future gamma diagnostics will add significant capability

- Gas Cherenkov Detectors (temporal detectors):

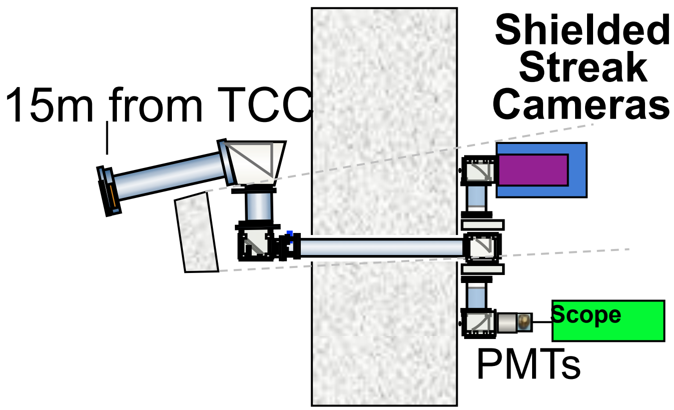
"Super" GCD



400 psia C_2F_6

- Low Threshold, High Sensitivity
  - ~2 MeV threshold
  - 20 cm from TCC (TIM mounted)

GRH-15m



- High Temporal Resolution
  - Streak Camera for ~10ps resolution
  - Camera behind 6' bio shield wall

“Super” GCD (GCD-3 at Ω) provides High-Sensitivity, Low-Threshold capability now at OMEGA and eventually at NIF

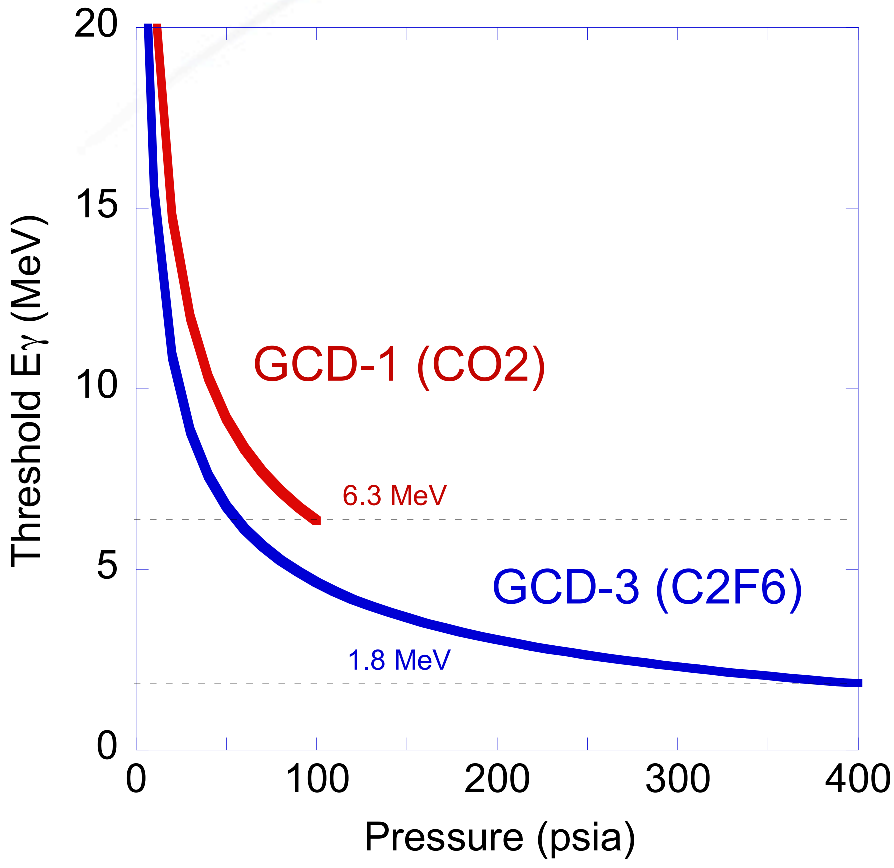
“Super” GCD

- Low Threshold, High Sensitivity
  - ~2 MeV threshold
  - 20 cm from TCC (TIM mounted)

Physics Driven Requirements:

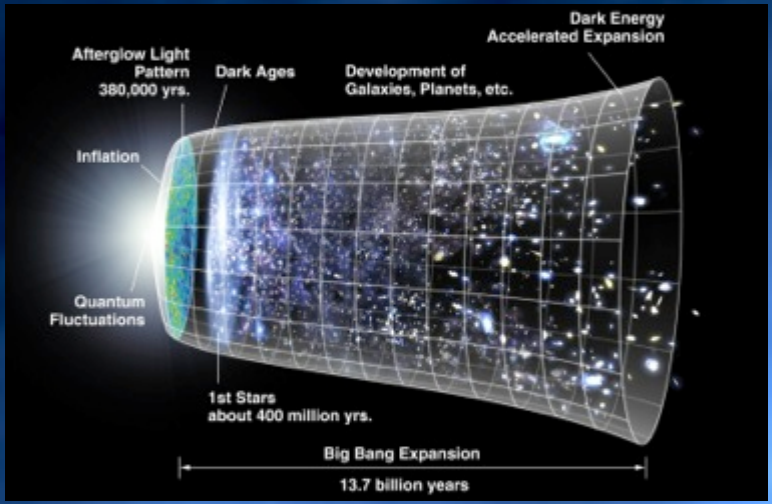
- Low Threshold (≤2 MeV) to reveal new portions of gamma-ray spectrum
  - High pressure (400 psia) → redesigned pressure boundary
  - Fluorinated gases → metal seals to achieve <1e-9 scc/s leak rate to avoid damage to TRS catalyst
- High Sensitivity
  - TIM-based to capture solid angle
  - Modular optics package to optimize SNR
- Absolute Timing & Dry Run capability
  - 2ω fidu injection
- Improved SNR
  - better shielding
  - additional precursor to signal delay

Lower Energy Threshold (~ 2 MeV) opens up new portions of gamma-ray study



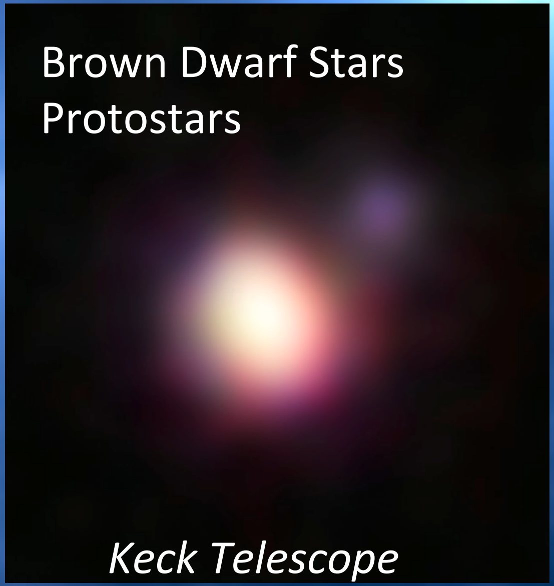
- **New gamma-ray detection (too low E for GCD-1, too dim for GRH):**
  - ^{16}O(n,n'γ) at **6.1 MeV** (SiO_2 ρR)
  - ^{13}C(d_{ko},n)^{14}N* at **5.69 MeV** (CH Mix)
  - ^{9}Be(α,n)^{12}C* at **4.44 MeV** (Be Mix)
  - ^{9}Be(d_{ko},n)^{10}B* **3.4 MeV** (Be Mix)
  - ^{10}B(d_{ko},n)^{11}C* at **~7 MeV** (B_4C or BH Mix)
  - HD-γ at **5.5 MeV** (MIT Zylstra PhD)

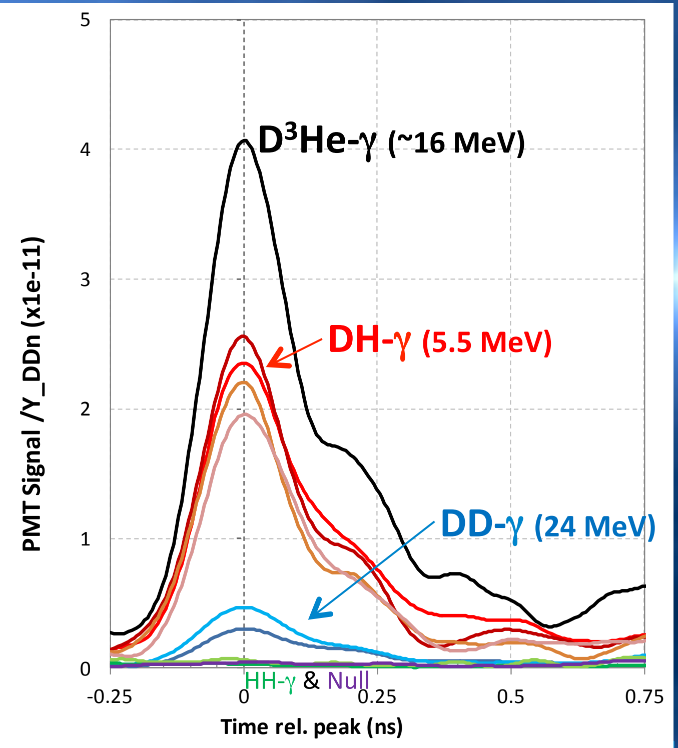
The p+D reaction relevant to BBN, formation of proto stars, and brown dwarfs, is being investigated at OMEGA in July-August



$p + D \rightarrow {}^3He + \gamma$ (5.5 MeV)

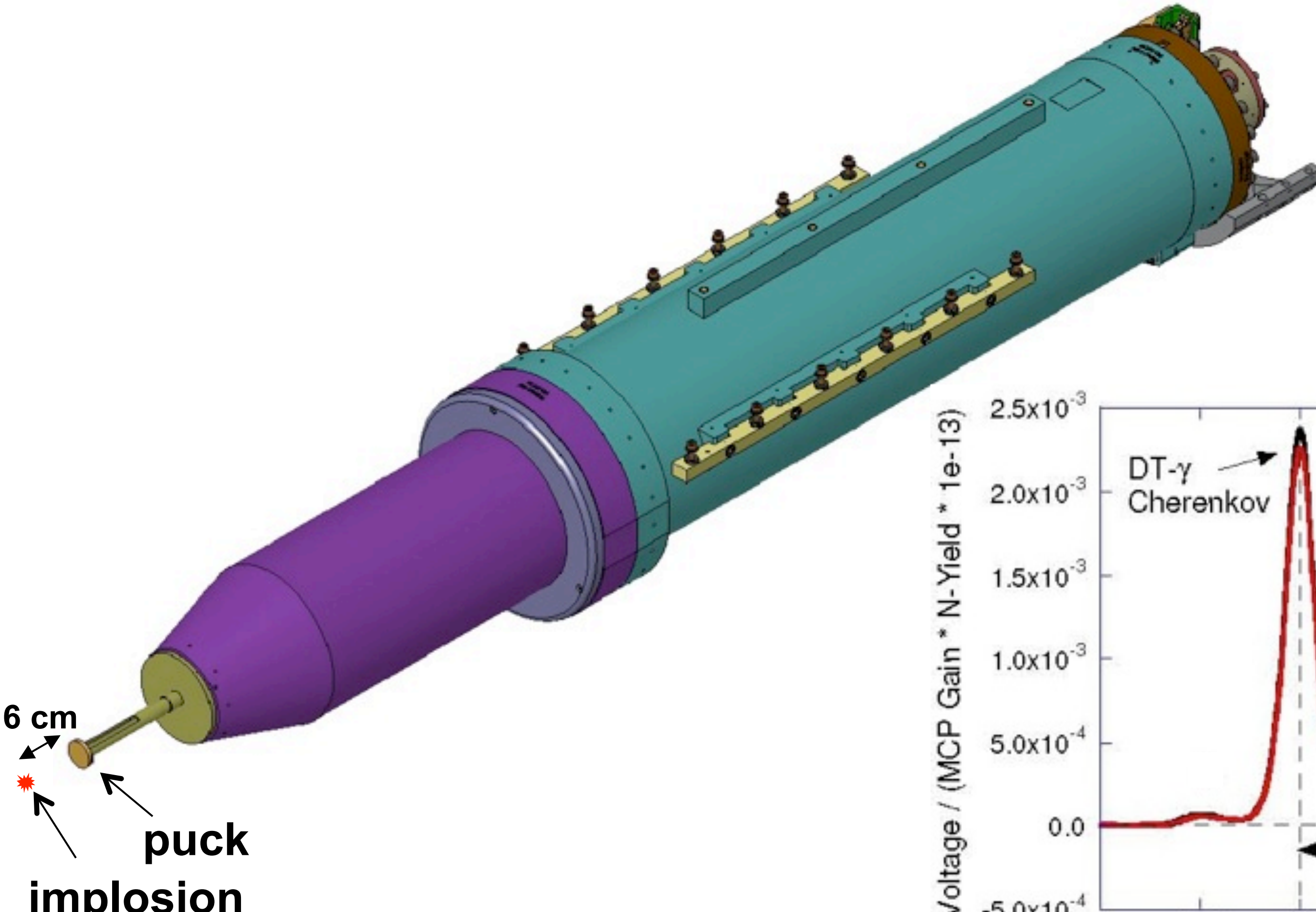
A. Zylstra
(PhD thesis)

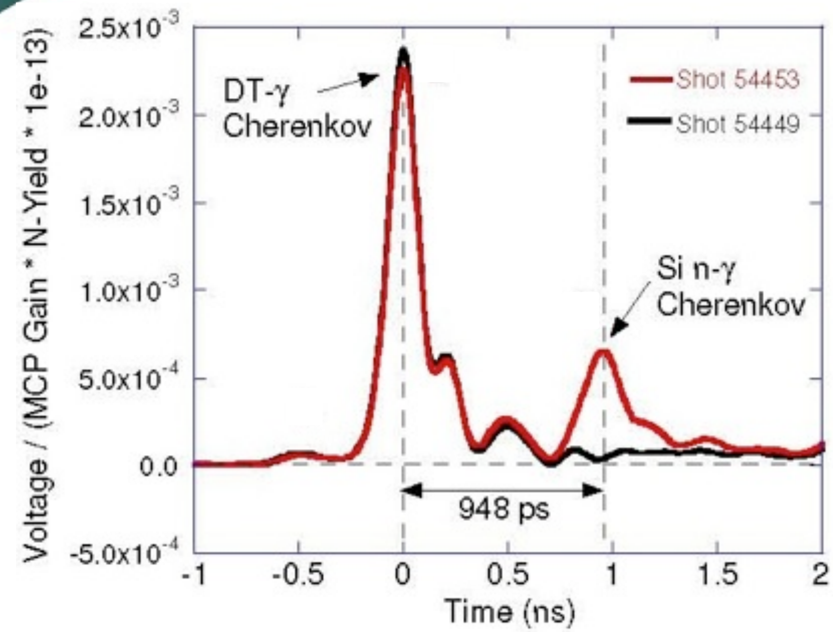




LANL's new GCD-3 uniquely identified HD fusion gammas at 5.5 MeV for the first time (as well as D^3He-γ & D_2-γ)

Integral puck holder allows study of 14 MeV neutron interactions with materials placed near implosion



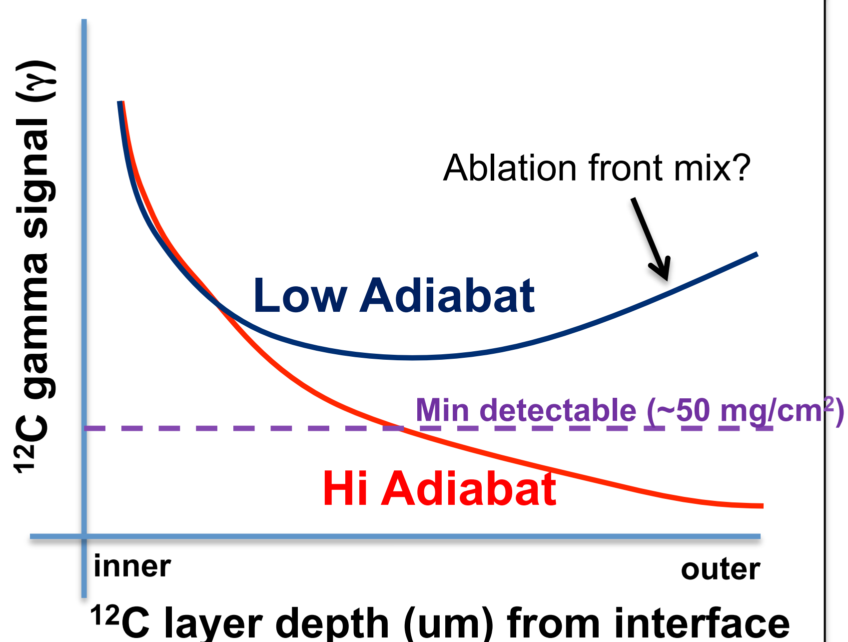


Y. Kim, et. al, JoP, 2010

Gamma Rays may illuminate "Dark Mix"

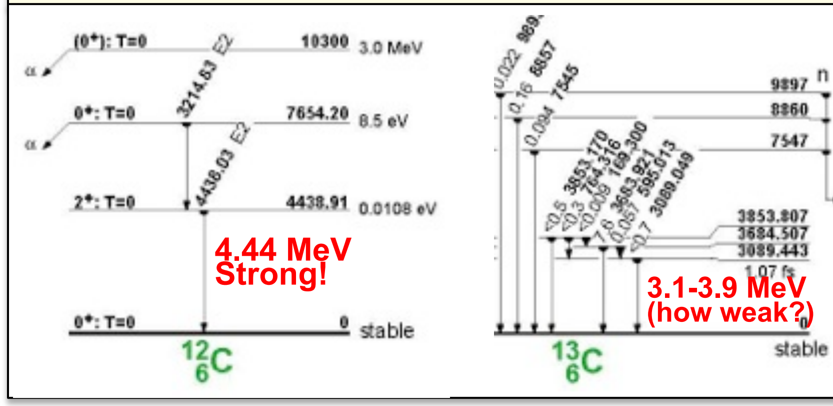
^{12}C vs ^{13}C pucks at OMEGA will determine feasibility

^{12}C layer buried in ^{13}C-based ablator (CH or HDC)

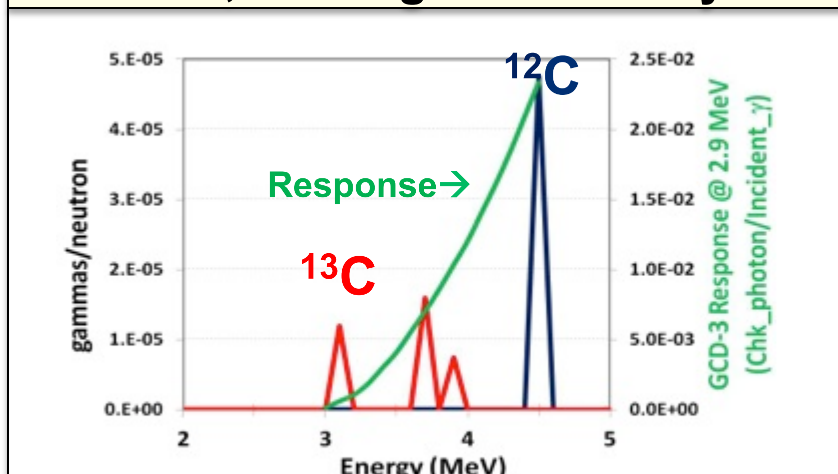


- To determine where carbon ablator mix is coming from and when
- Sensitive to Dark Mix (unlike x-rays & separated reactants)

Carbon Energy Level Diagrams



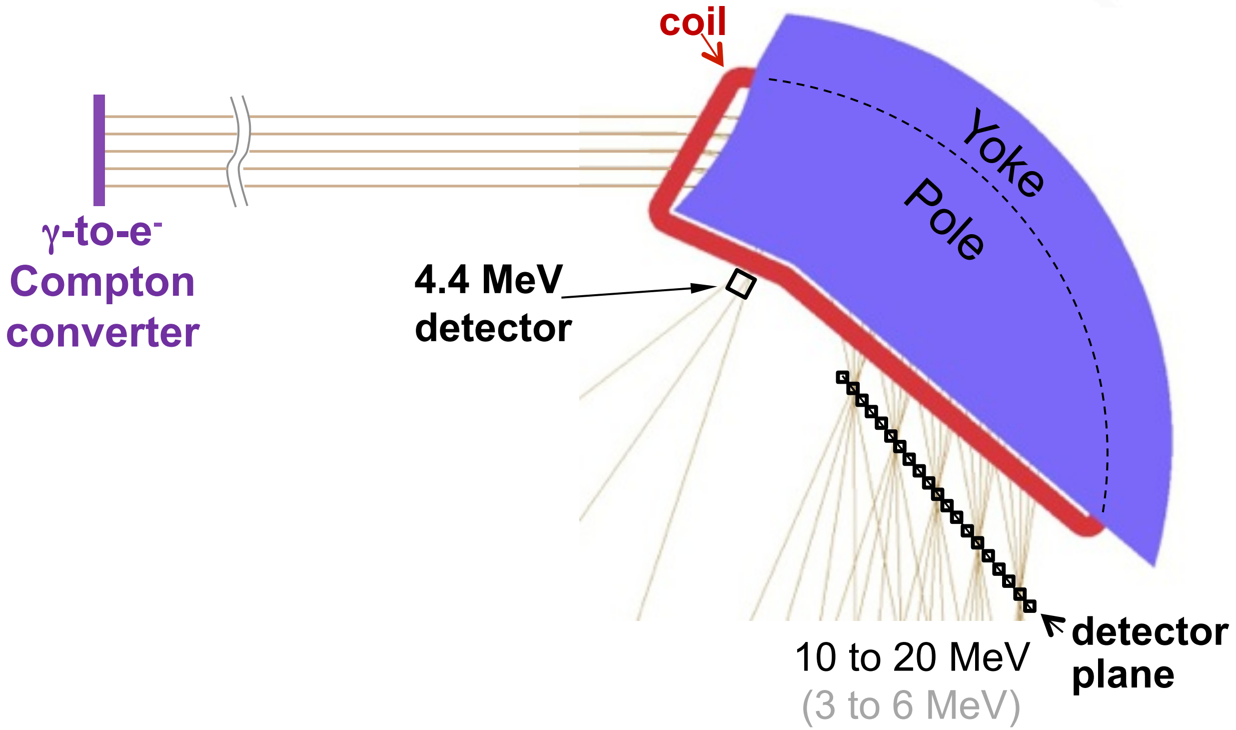
MCNP predicts ~6x less signal for 13C, but large uncertainty



Concept by W. Stoeffl

Future gamma diagnostics will add significant capability

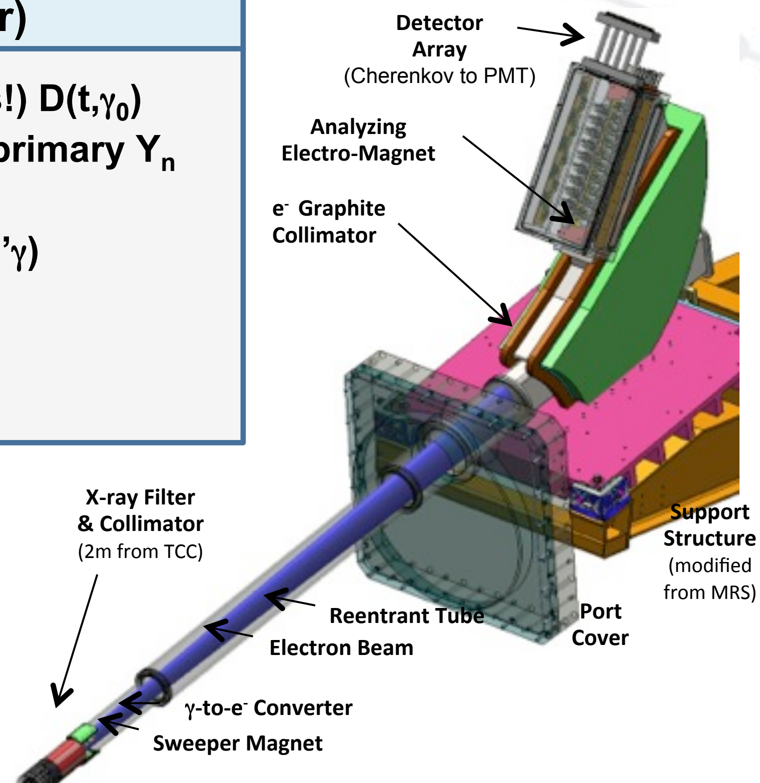
- Spectroscopic detectors:
  - **Gamma-to-Electron Magnetic Spectrometer (GEMS)**

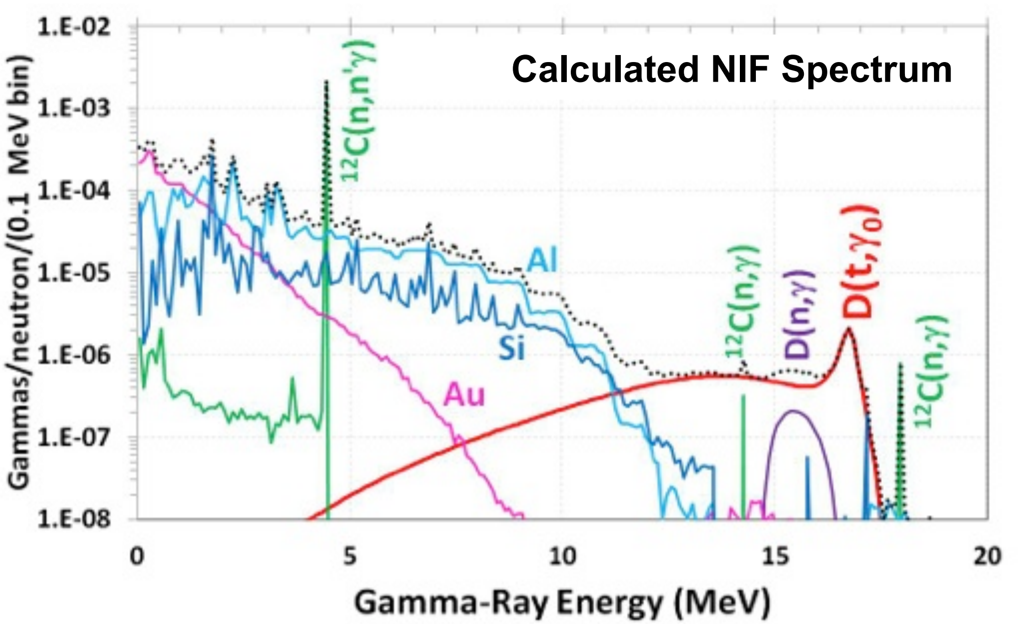


Gamma Spectroscopy will be an enabling technology for NIF

GEMS (Gamma-to-Electron Magnetic Spectrometer)

- Total Yield (no Total Yield measurement currently exists!) $D(t,\gamma_0)$
- Total Down Scatter Fraction (TDSF) when combined w/ primary Y_n
- 4π Global Fuel ρR (Fuel ρR currently line-of-sight) $D(n,\gamma)$
- Ablator ρR (reduced uncertainty relative to GRH) $^{12}C(n,n'\gamma)$
- Mix studies (e.g., $^{9}Be(\alpha,n\gamma)$, $^{13}C(d_{ko},n\gamma)$, $^{11}B(d_{ko},n\gamma)$)
- Neutron Interactions on materials (i.e., pucks)
- Astrophysical studies (e.g., s & r-processes)



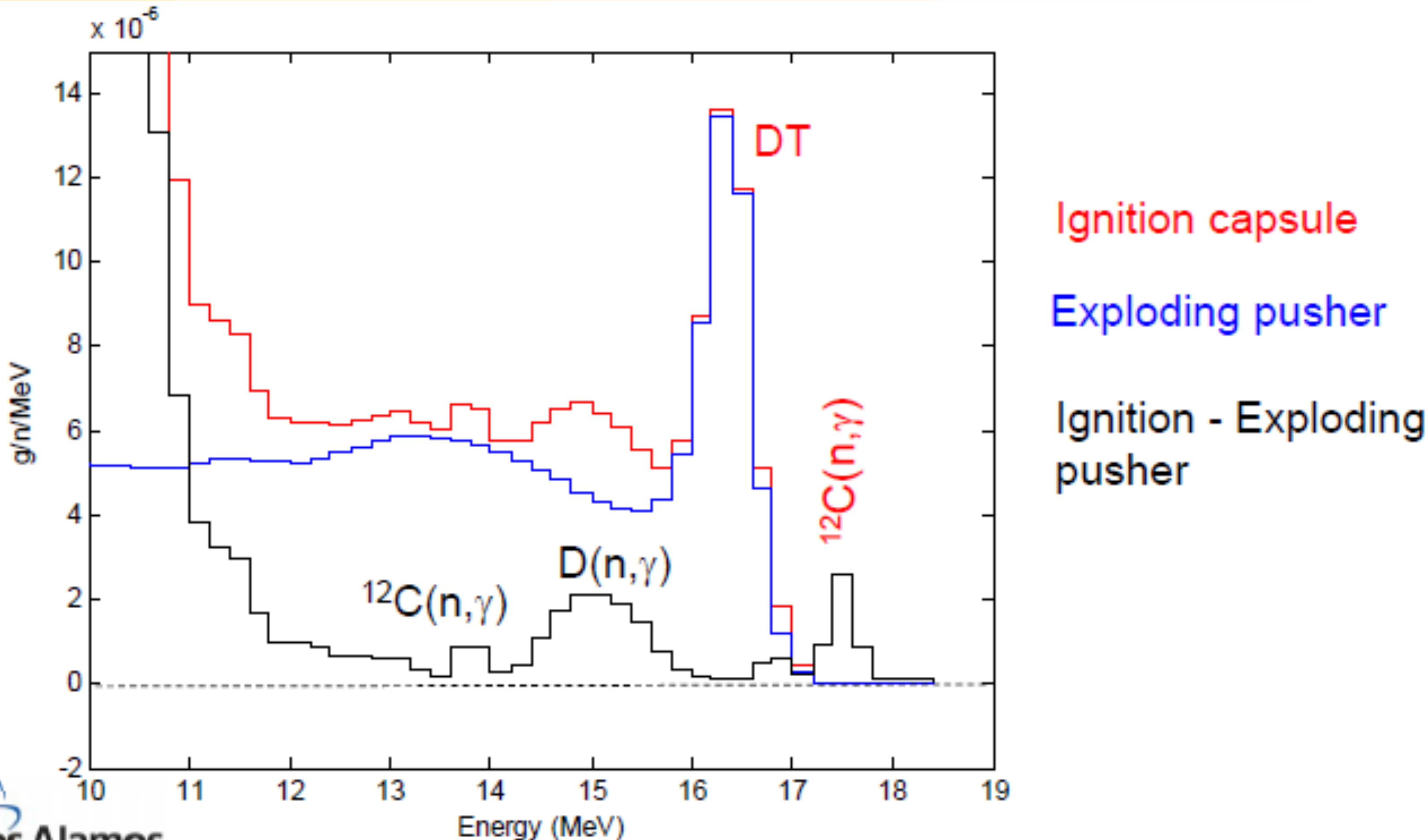


NIF CDR held in July 2013

- Energy Resolution: $\Delta E/E \leq 5\%$
- Energy Range: $E_0 \pm 33\%$ within 2-25 MeV
- Temporal response < 1.5 ns
- Viable at $Y_{DTn} \geq 5e14$

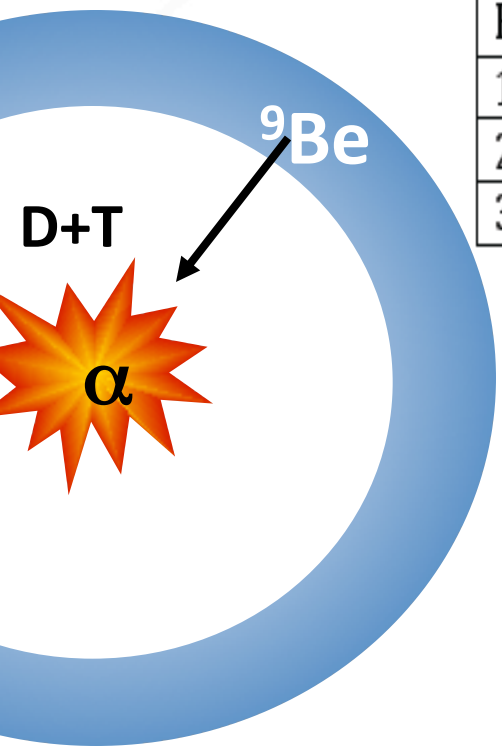
High Resolution Mode (Goal)

Exploding pusher can be used to extract $^{12}C(n,\gamma)$ and $D(n,\gamma)$ from Ignition Capsule



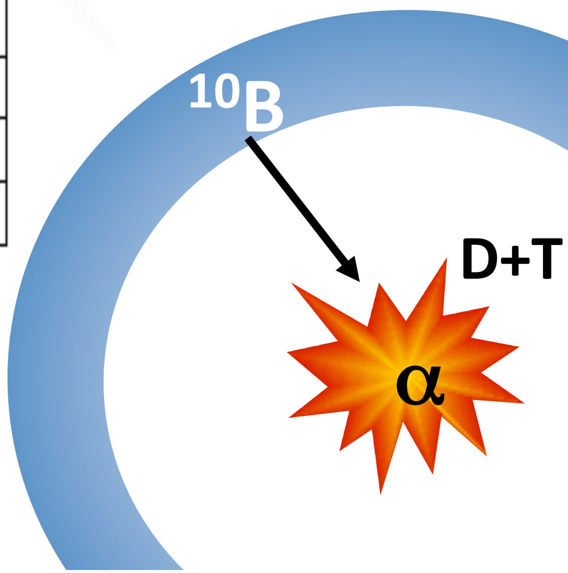
A. Hayes-Sterbenz (LANL)

Hydro-dynamical Mixing of Ablator into Hotspot



$^{9}Be(\alpha, n\gamma)^{12}C$ gamma-rays (4.44 MeV)

HS Radius (μm)	0.1 μg ^{9}Be in HS	1 μg ^{9}Be in HS
10	1.2×10^{-4}	1.2×10^{-3} γ/n
20	3.0×10^{-5}	3.0×10^{-4}
30	1.35×10^{-5}	1.35×10^{-4}

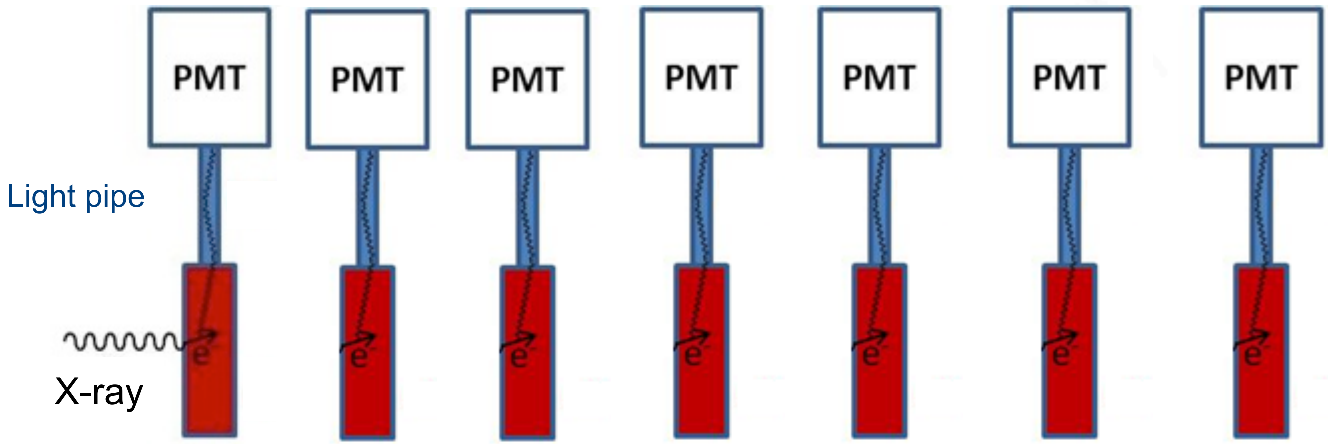


$^{10}B(\alpha, p)^{13}C$ gamma-rays (3.68, 3.86 MeV)

HS Radius (μm)	0.1 μg ^{10}B in HS	1 μg ^{10}B in HS
25	1.34×10^{-5}	1.34×10^{-4}

Compare w/ 1.2×10^{-3} γ/n at 100 mg/cm^{2} ^{12}C

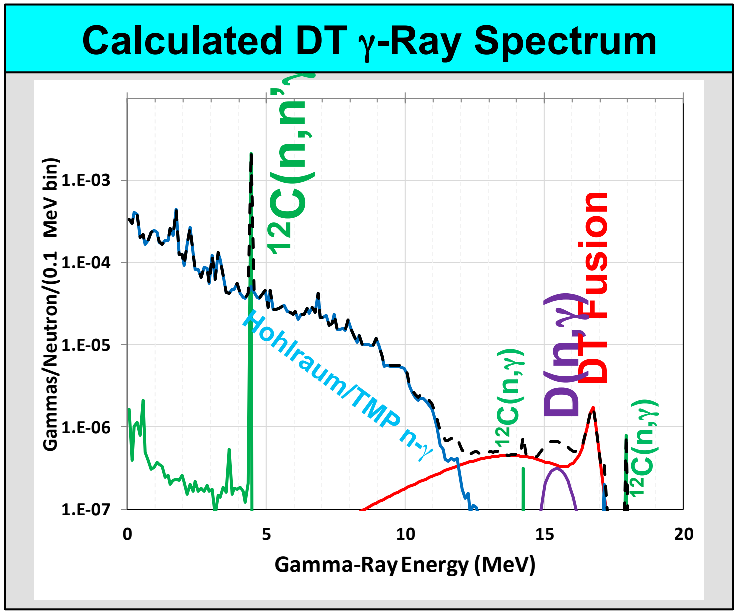
Aerogel Cherenkov Detector (ACD) proposed for low-energy (0.2-2.5 MeV), course spectroscopy

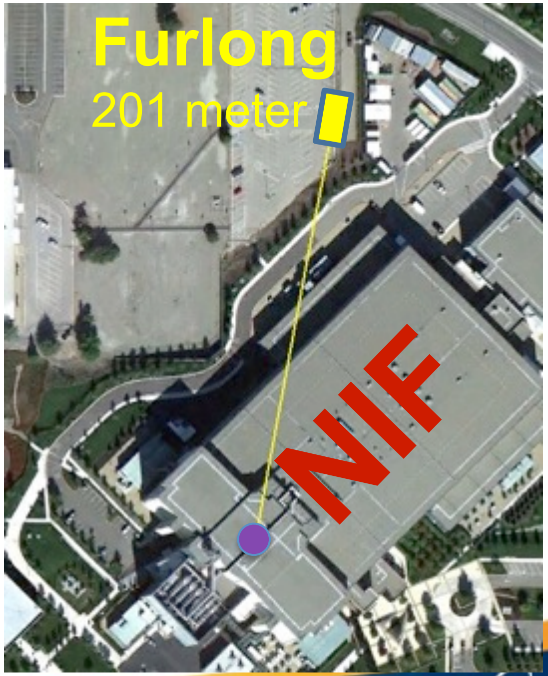


Radiator:	Aerogel-1	Aerogel-2	Aerogel-3	Aerogel-4	Aerogel-5	water	quartz
Refractive index, n:	1.015	1.03	1.05	1.07	1.12	1.33	1.5
Threshold Energy (MeV):	2.47	1.62	1.16	0.93	0.62	0.26	0.17

Options for Future Gamma Diagnostics (cont.)

- Spectroscopic detectors:
  - **Curved Crystal Gamma Spec** (W.Stoeffl)
    - useful for <1.5 MeV
  - **"Furlong"** (W.Stoeffl)
    - Single-hit, pixelated scintillator detector array
    - ~200m from TCC

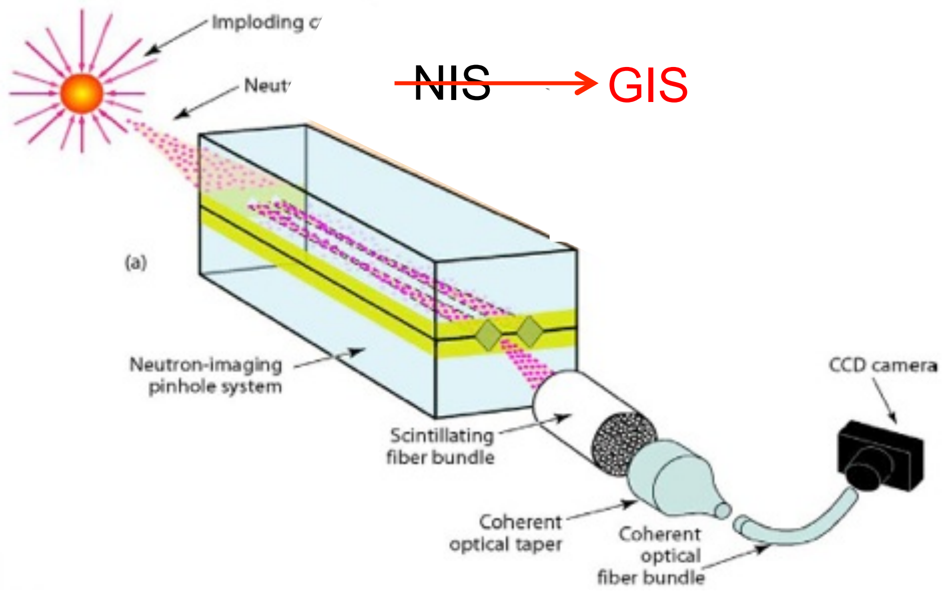




UNCLASSIFIED

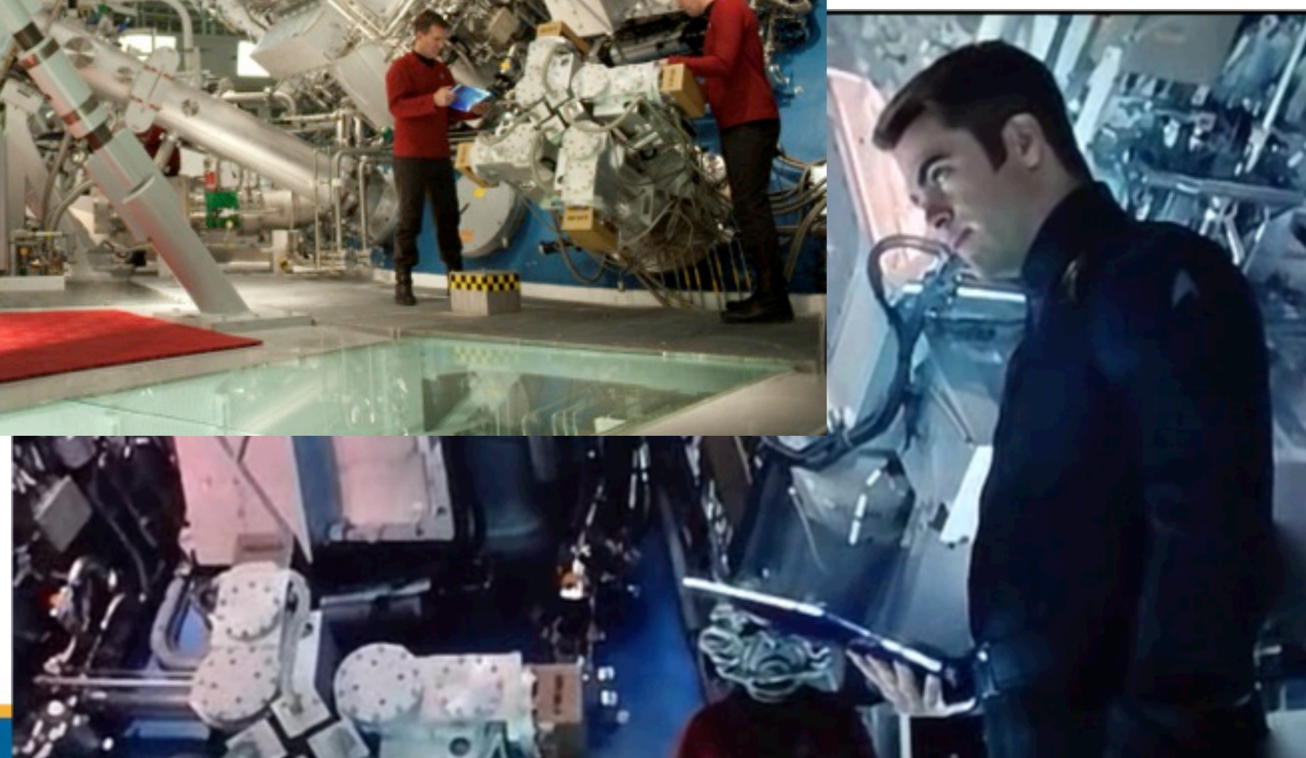
Gamma Imaging System (GIS)

Imaging of $^{12}C(n,n')\gamma$ would reveal ablator mass distribution at bang time



γ-Ray Imaging of Ablator (^{12}C-γ)
(G. Grim, D. Lemieux (U.Ariz))

GRH boldly goes…



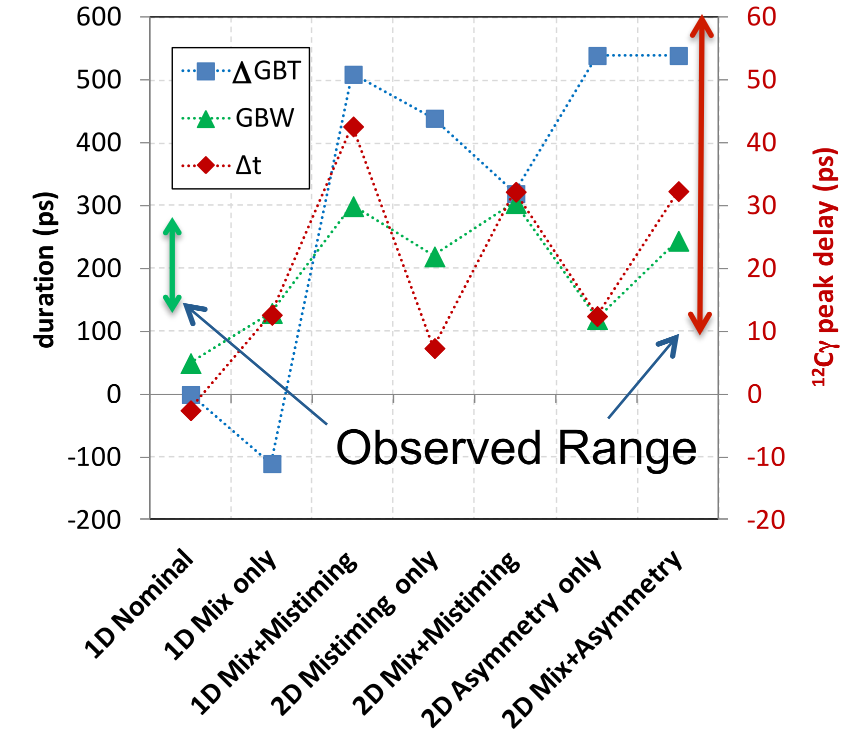
courtesy Scott Chambliss, Paramount Pictures and Bad Robot Productions

- Backups

GRH continues to inform quest for Ignition at NIF

- ~500ps late BT indicative of reduced coupling → Drive Multipliers (~85%)
  - Scatter of nBT relative to GBT indicative of core velocity
- Wide GBW indicative of failure modes during NIC
- Large & late $^{12}C\gamma$ peak indicative of improper stagnation
- Future: ^{12}C layers in ^{13}C capsules for Dark Mix studies

Simulation



GBW & $^{12}C\gamma$ delay (Δt) are strong indicators of ignition failures

NIF Yield Ranges for Gamma Diagnostics