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64th Annual Meeting of the APS Division of Plasma Physics, Spokane, October 2022

A Bayesian approach to inferring neutron spectra from projectile fusion

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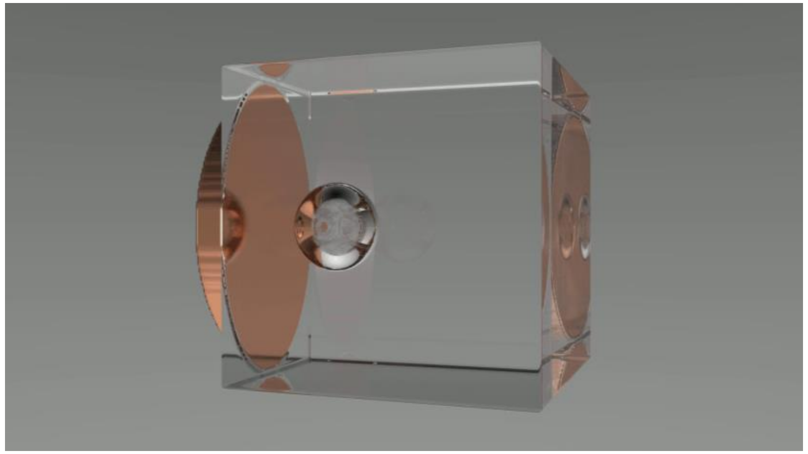
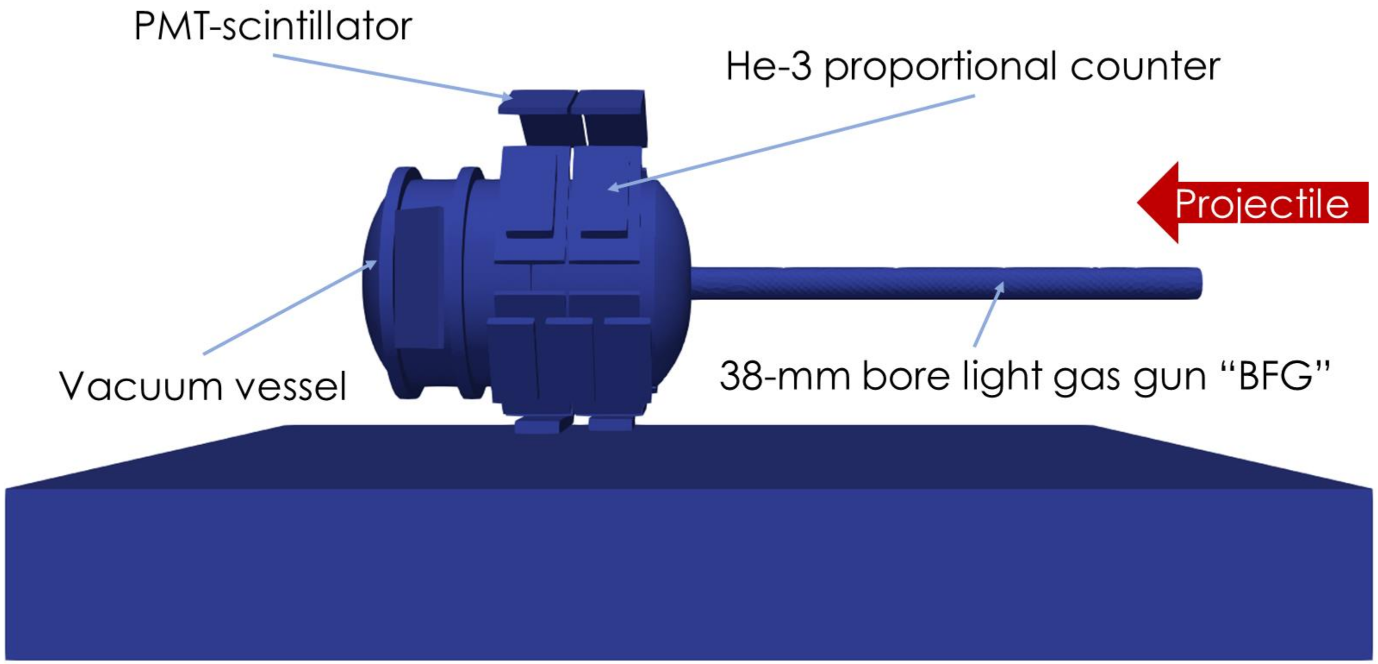
Motivation

- First Light Fusion (FLF) has achieved the first example of **projectile-driven nuclear fusion** (Burdiak, Skidmore et al. 2022, for recent results see poster by Zoran Pesic)
- Several shots yielded particle detections with time-of-flight (TOF) measurements consistent with $D(d, n)^3He$ fusion neutrons
- To support FLF progress towards net energy gain, we have developed a **novel and robust Bayesian method** to infer plasma conditions (neutron yield, temperature, bulk velocity) in the low-to-mid yield regime

For further information, including papers:
https://firstlightfusion.com/science-hub

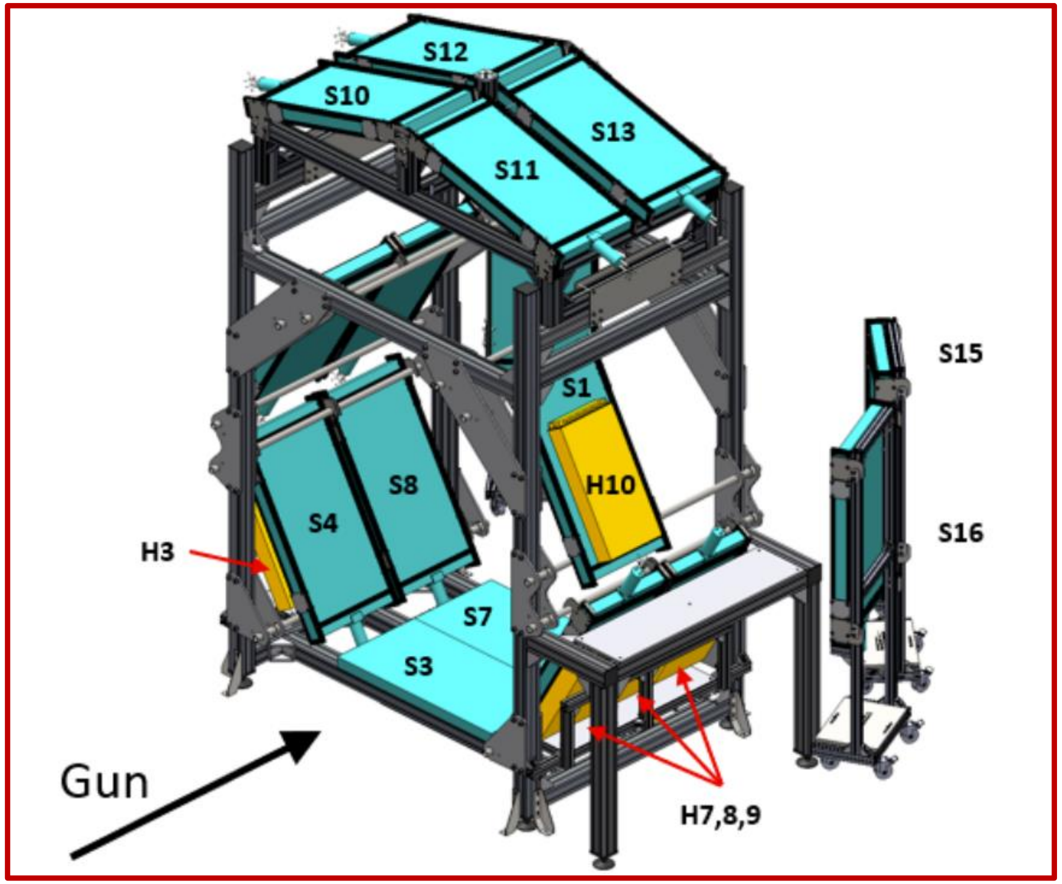


Experimental set up



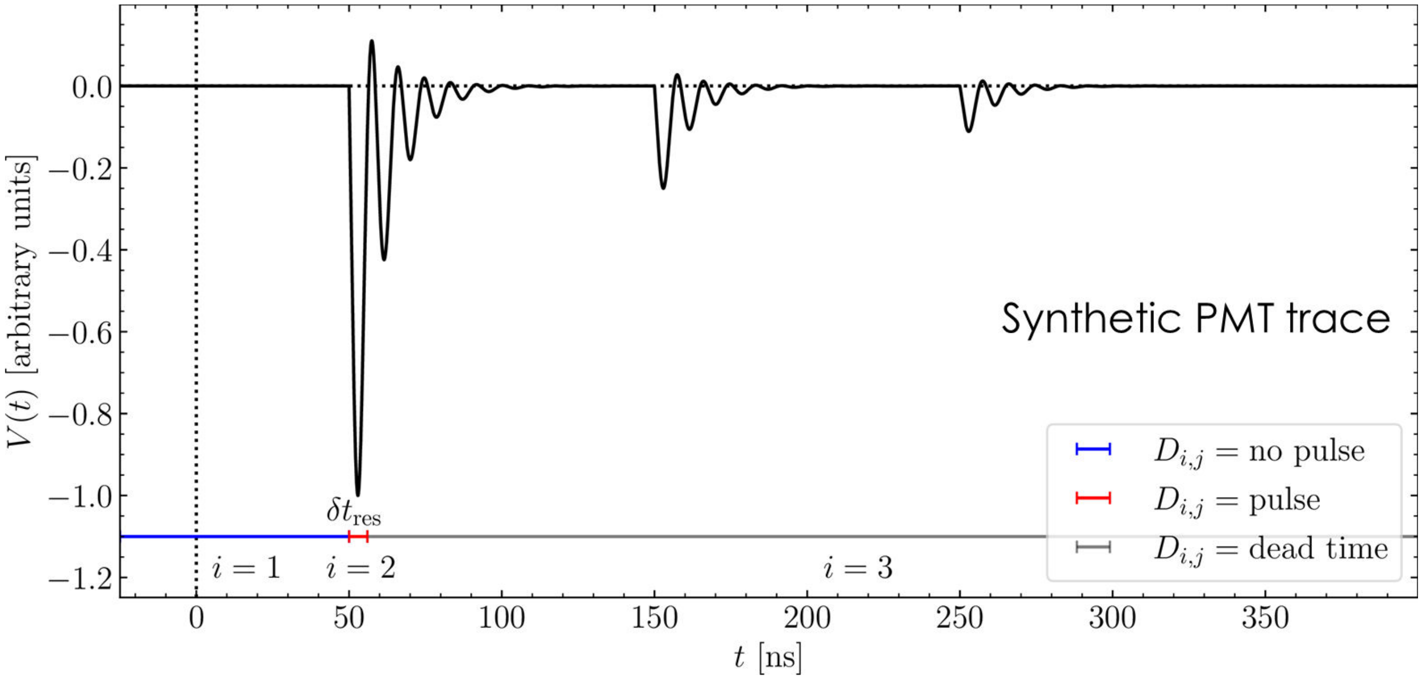
CAD model using PARAMAK
(Shimwell et al. 2021)

Detector array



Inferring model parameters from the data

- Bayes theorem is used to infer parameters from the data
- We construct **Poisson-based** likelihood functions for each detector j over I distinct time windows
- μ_i is the model **expected number** of particles in a time window i



Detector likelihood function

$$P(D_j|\boldsymbol{\theta}, M) = \prod_i^I P(D_{i,j}|\boldsymbol{\theta}, M), \quad \text{where} \quad P(D_{i,j}|\boldsymbol{\theta}, M) = \begin{cases} e^{-\mu_i} & \text{if } D_{i,j} = \text{no pulse}, \\ 1 - e^{-\mu_i} & \text{if } D_{i,j} = \text{pulse}, \\ 1 & \text{if } D_{i,j} = \text{dead time} \end{cases}$$

Combining detector likelihood functions

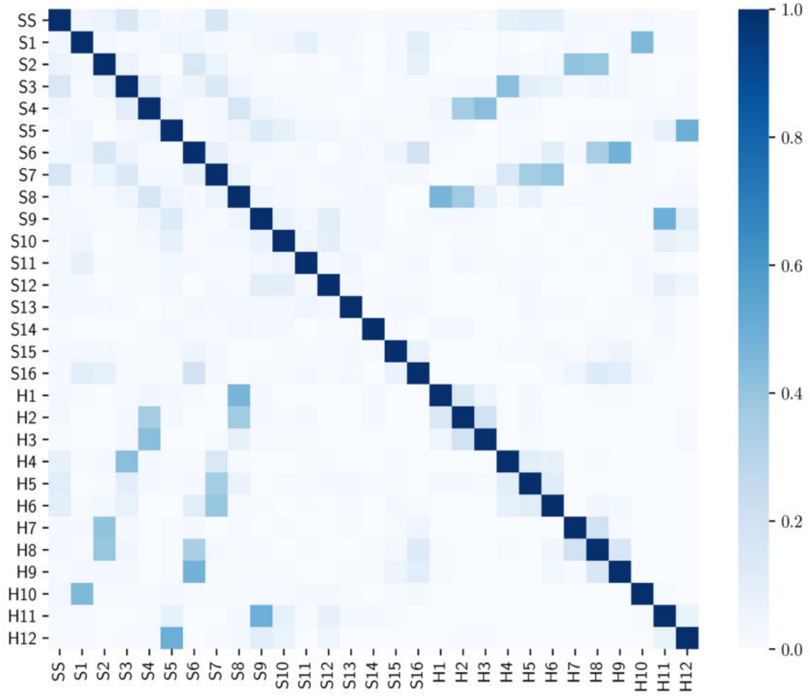
- We form a **joint likelihood function** for the detector array by using a Gaussian copula density function c that accounts for **correlated behaviour** between detector pairs:
- We use **neutronics modelling** with OPENMC to determine the **expected fraction** of neutrons that are common to detector pairs

Joint likelihood function

$$P(D_1, D_2, \dots, D_J | \boldsymbol{\theta}, M) = c(u_1, u_2, \dots, u_J) \prod_{j=1}^{J} P(D_j | \boldsymbol{\theta}, M)$$

$$\text{where} \quad c(u_1, u_2, \dots, u_J) = \frac{1}{\sqrt{|\mathbf{R}|}} \exp\left(-\frac{1}{2} \boldsymbol{q}^{\mathrm{T}} . (\mathbf{R} - \mathbf{I}) . \boldsymbol{q}\right)$$

Detector correlation matrix



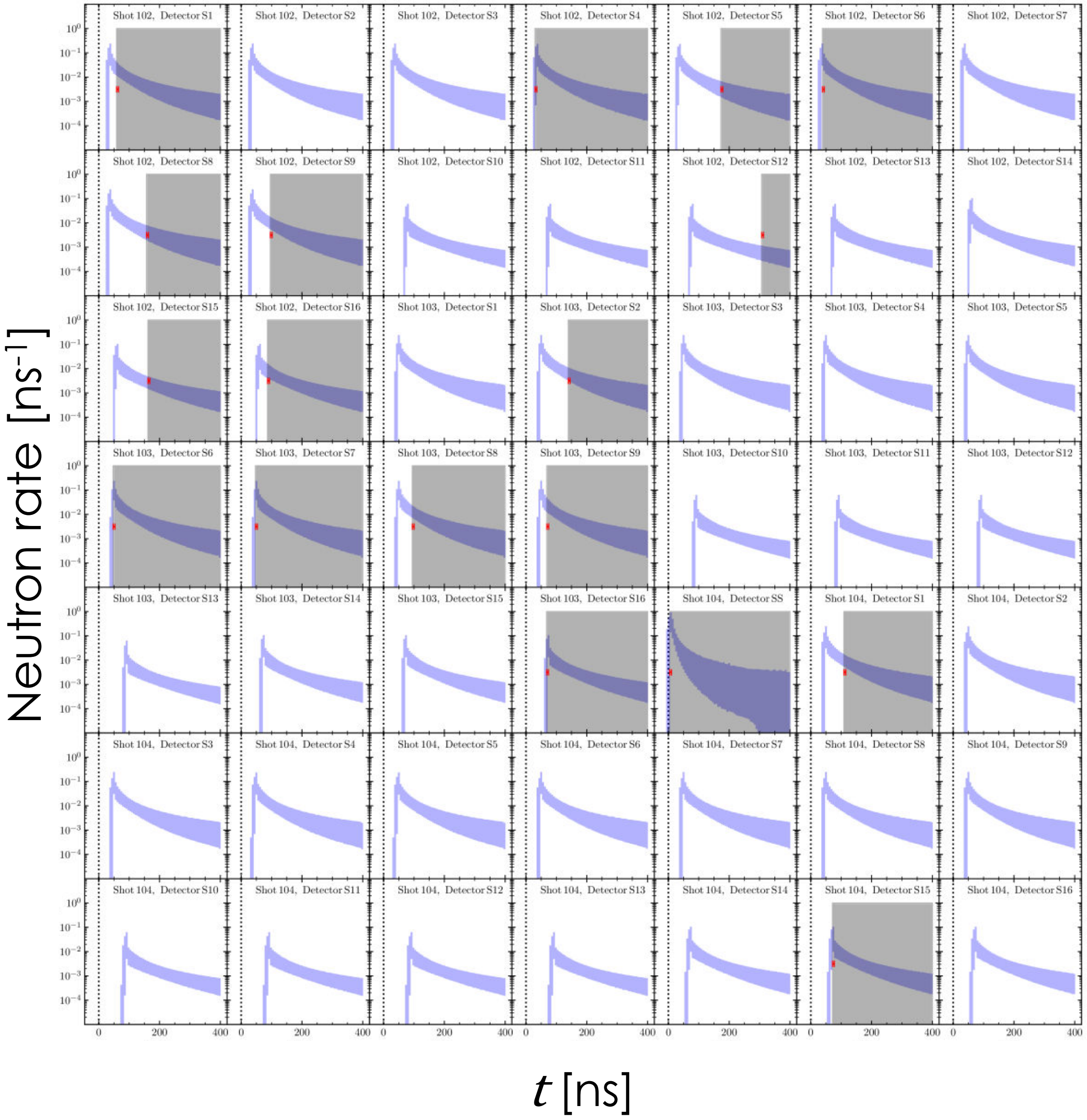
Simple analytical source & transport model

- We started with a **simple parameterisation** of the incident neutron field at each detector:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}E\,\mathrm{d}\Omega} = \frac{Y_{\mathrm{total}}}{4\pi}\left[\underbrace{(1 - X_{\mathrm{scatt}})\frac{1}{\sigma_E\sqrt{\pi}}\exp\left[-\frac{1}{2}\frac{(E-E_0)^2}{\sigma_E^2}\right]}_{\text{Prompt}} + \underbrace{X_{\mathrm{scatt}}\,S(E)}_{\text{Scattered}}\right]$$

- The normalised **scattered spectrum** S is a **power-law** with index α
- For D(d,n)^{3}He nuclear fusion, $E_0 = 2.45\ \mathrm{MeV}$ and $\sigma_E = 35\sqrt{T_{\mathrm{eff}} / 1\mathrm{keV}}\ \mathrm{keV}$, where T_{eff} is the neutron-weighted plasma ion temperature
- We use the DYNESTY (Speagle 2020) and BILBY (Ashton et al. 2019) packages to sample the **posterior parameter probability densities**

Inferred neutron detector rates from the BFG shot campaign

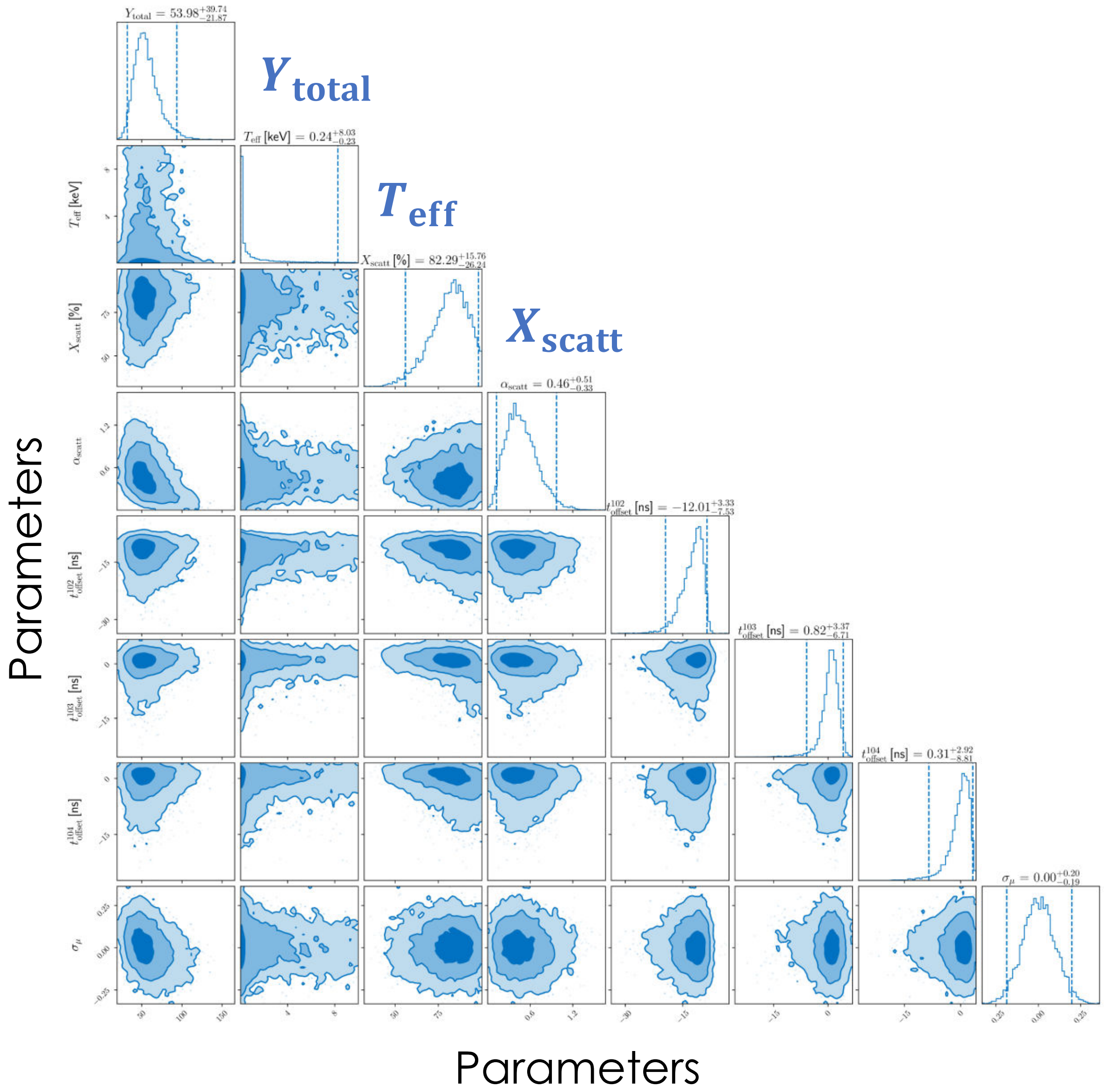


Measured arrival time

Dead time

Inferred neutron detection rate (95% CI)

Inferred model parameters from the BFG shot campaign

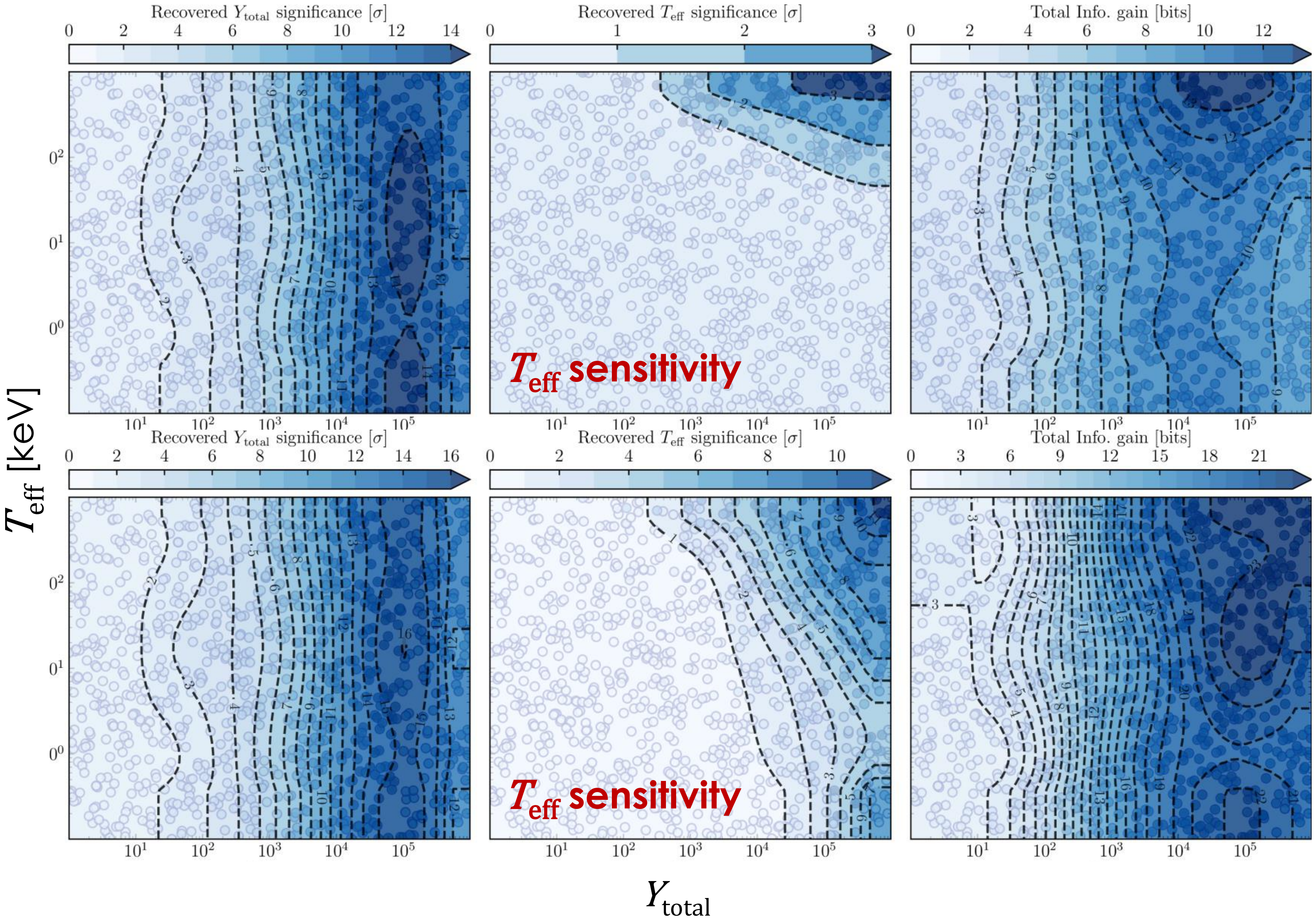


- The **total yield** is $Y_{\text{total}} = 54^{+40}_{-22}$(95% CI), which is consistent with the results of Burdiak et al (2022).
- The **scattered fraction** is $X_{\text{scatt}} = 82^{+16}_{-26}\%$ which is consistent with expectations from neutronics modelling
- The **temperature** is $T_{\text{eff}} = 0.2^{+8.0}_{-0.2}\text{keV}$ (c.f. 240eV from simulations)

Information gain vs yield and temperature

Current detector resolution (δt = 6ns, d =1m)

Improved detector resolution (δt x10 or d x 10 & Y_{total} x 100)



Summary & Future work

- FLF has recently achieved nuclear fusion using a **projectile drive**
- We have developed a **novel and robust Bayesian approach** to infer plasma conditions using neutron time-of-flight data in the low-to-mid yield regime
- We account for **pulse ambiguity** and **correlated behaviour** between detectors
- Results so far do not constrain the neutron-weighted temperature, but improvements in **detector resolution** and **yield increase** will enable us to do so
- We will use neutronics with OPENMC for more accurate time-of-flight and detector response modelling
- A more complete phenomenological model that includes bulk fluid velocity will enable experimental investigation into **source anisotropy** using this method

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Thank you for your attention
Please get in touch

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Upcoming presentations from First Light Fusion:

- Luis SC Bendixsen: FLF facilities and collaboration efforts with academia (PM09.00013)
- Emilio Escauriza: Ablation with a radiative shock driven by gas gun (TO05.00013)
- Francisco Suzuki-Vidal: Rotating plasmas on the OMEGA laser (TO05.00015)

Presentations earlier in the conference:

- Zoran Pesic: Neutron emission from light-gas gun projectile driven targets (BP11.00132)
- Rosie Barker: Experimental measurement of planarity of a 1 TPa shock (TP11.00075)
- Joshua Read: Pressure measurement of an amplified shock using VISAR (TP11.00076)

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