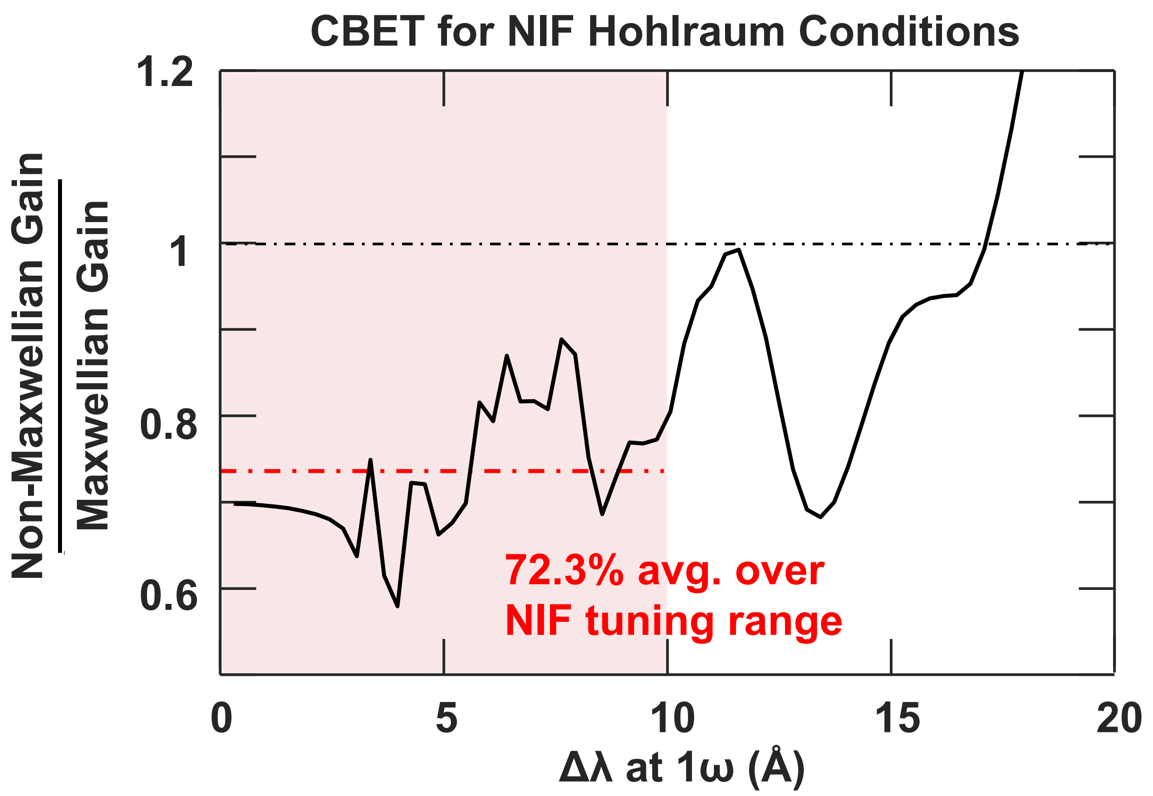
Impact of non-Maxwellian electron distribution functions on crossed-beam energy transfer



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Summary

Dedicated crossed-beam energy transfer experiments are providing key insights that should improve the design of integrated implosions

- Two-beam pump-probe experiments at the Jupiter Laser Facility observed good agreement with traditional CBET modeling at plasma wave amplitudes beyond the range relevant to ICF (calling the usual saturation clamp into question)*
- But multi-beam experiments at LLE (with more ICF relevant conditions) have shown that non-Maxwellian electron distribution functions (EDF's) driven by laser heating can strongly impact CBET; extrapolating to NIF conditions gives a ~30% reduction in gain (appears broadly consistent with the reduction imposed by the clamp)**
  - A non-Maxwellian inline CBET model should improve the predictive capability of integrated ICF implosions†
- Other processes affected by non-Maxwellian EDF's may be sensitive to the tails, which will be measured with angularly resolved Thomson scattering‡

* P. Michel et al., PRL 113, 205001 (2014);
D. Turnbull et al., PRL 116, 205001 (2016);
D. Turnbull et al., PRL 118, 015001 (2017);
D. Turnbull et al., PPCF 60, 054017 (2018).
** D. Turnbull et al, accepted to Nat. Phys. (2019).
† Under development by D. Strozzi & P. Michel
‡ See talk by A. Milder in Session GO6, Tues AM

Collaborators

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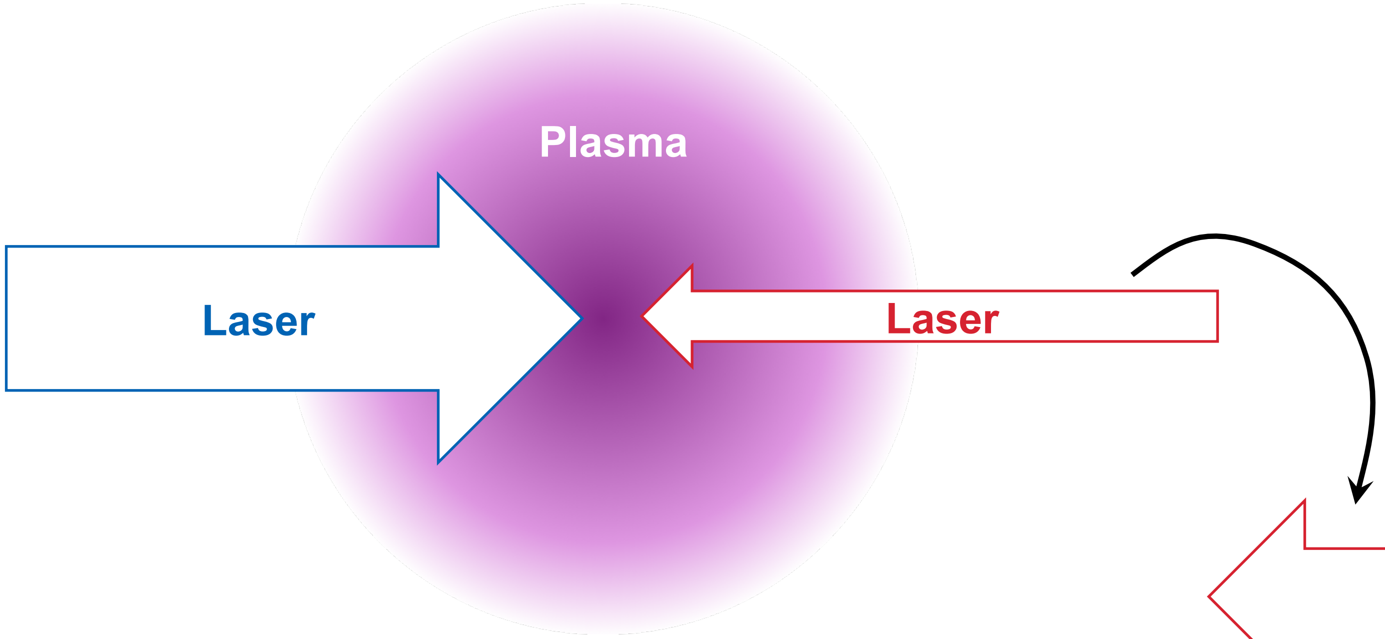
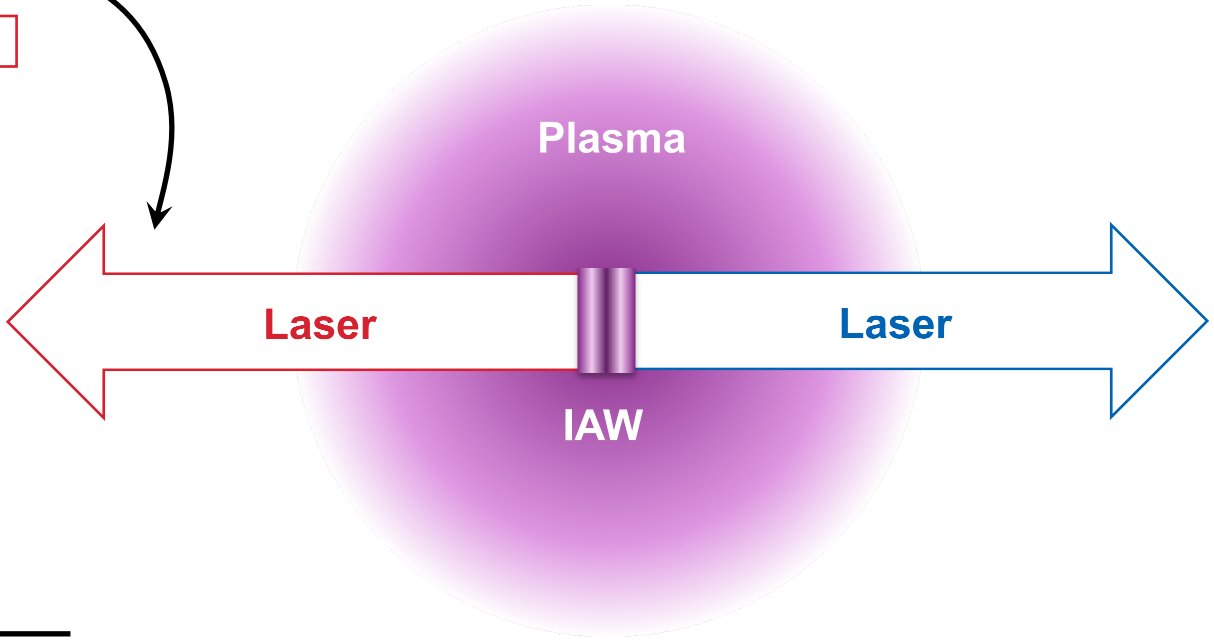
Lawrence Livermore National Laboratory

Outline

- Importance of CBET in ICF / current state of understanding
- Review of experiments at JLF
- Review of experiments at LLE
- Angularly resolved Thomson scattering

CBET is simply seeded stimulated Brillouin scattering (SBS)—the decay of an incident photon into a scattered photon and an ion acoustic wave (IAW) phonon



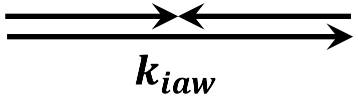


conservation of energy

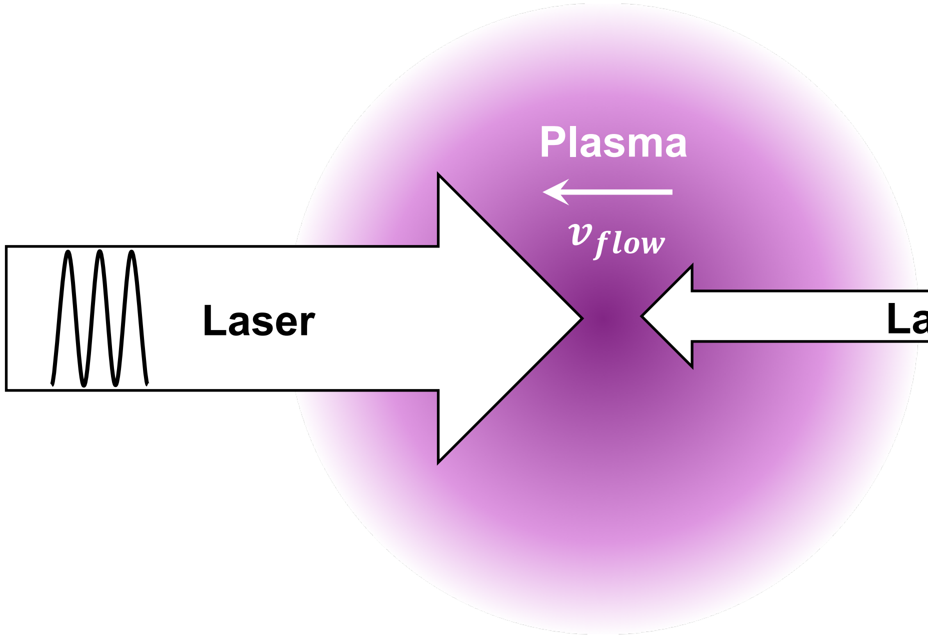
$$\omega_{incident} = \omega_{scattered} + \omega_{iaw}$$

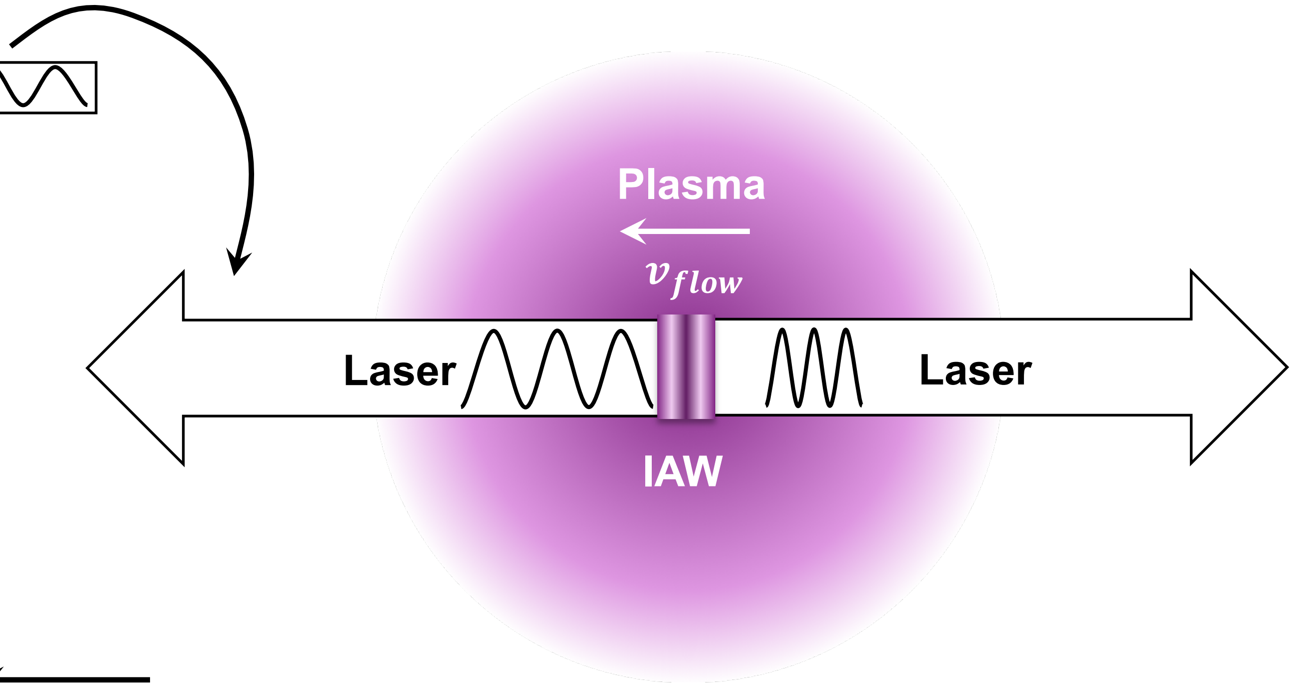
conservation of momentum

$$k_{incident} = k_{scattered} + k_{iaw}$$



Flows enable coupling between frequency-degenerate lasers, which makes CBET difficult to avoid in ICF environments





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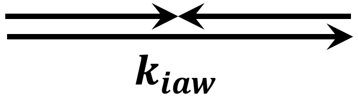
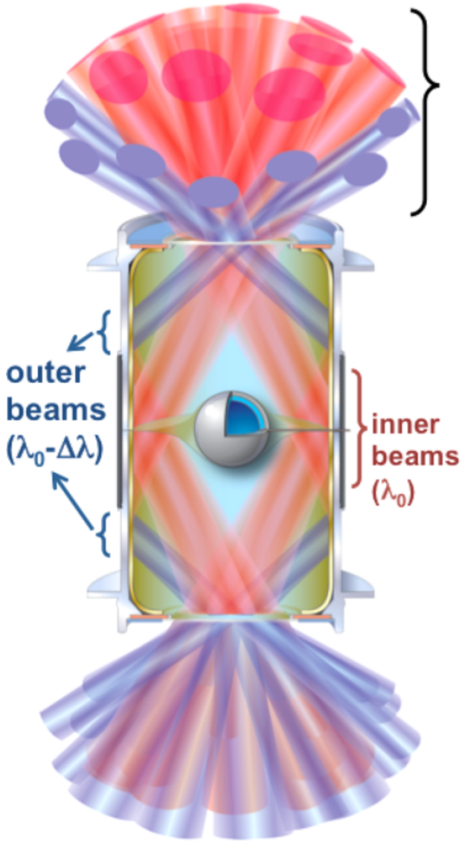
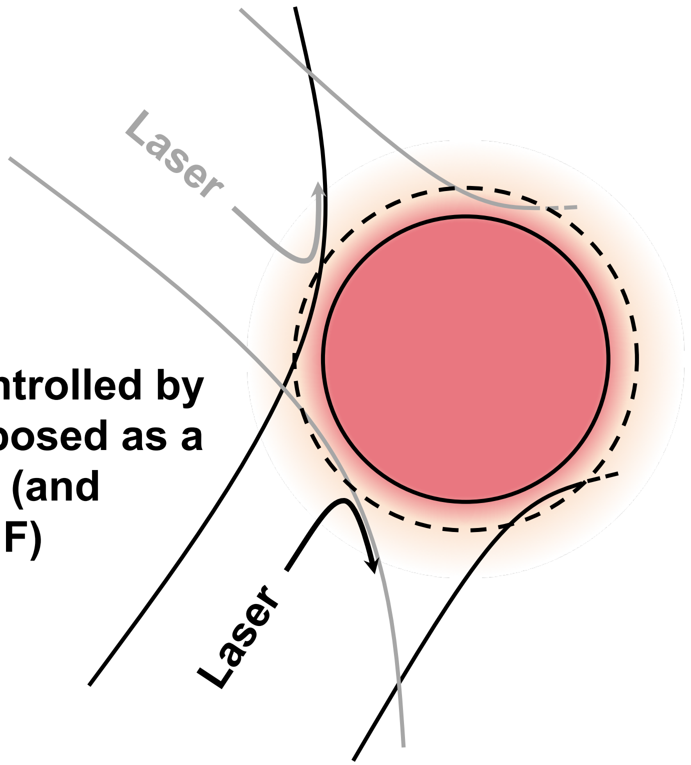


CBET is an important effect in both indirect- and direct-drive ICF



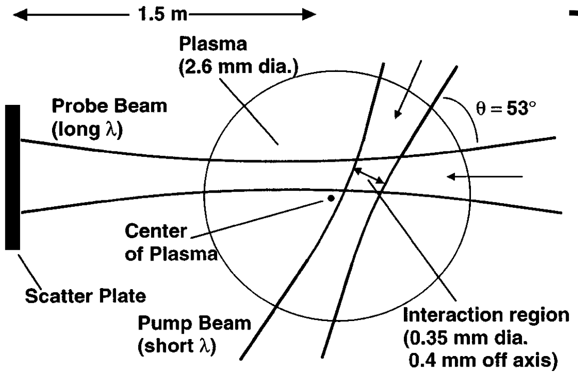
CBET primarily controlled by wavelength detuning Δλ (historically) , but flow is also important

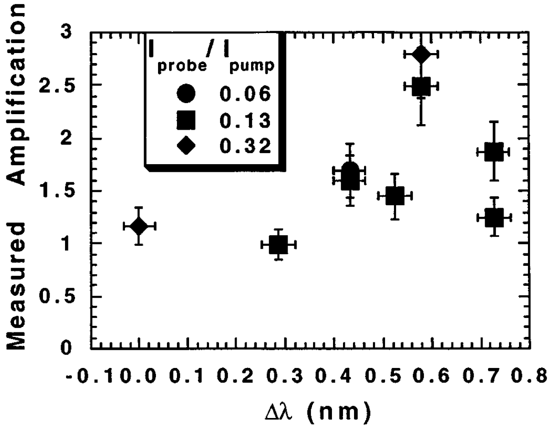
CBET primarily controlled by flow, but Δλ is proposed as a mitigation strategy (and demonstrated at NIF)



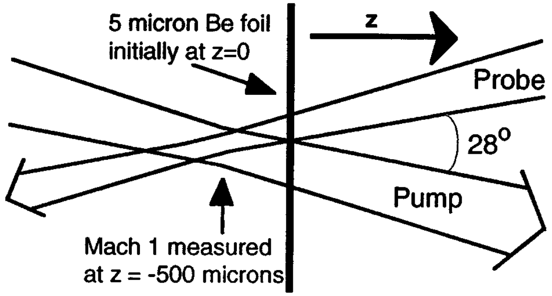
An improved understanding of CBET will impact the design of integrated ICF implosions

Early experiments observed CBET but proved difficult to calculate accurately

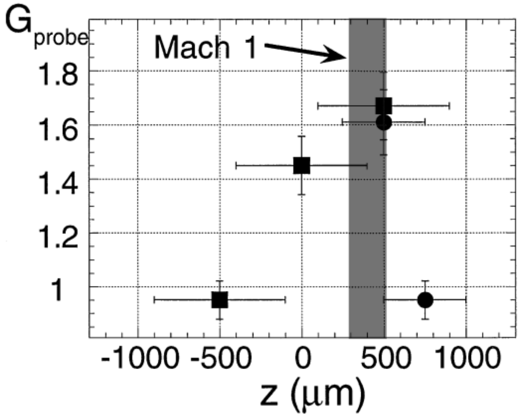




Gas bag expts. on Nova using Δλ had anomalous peak location, gain "20x below" theory*



Exploding foil expts. were difficult to simulate & observed modest transfer << predicted pump depletion**



Provided proof-of-principle, but not quantitative agreement

* Kirkwood *et al.*, PRL 76, 2065 (1996).
** Wharton *et al.*, PRL 81, 2248 (1998).

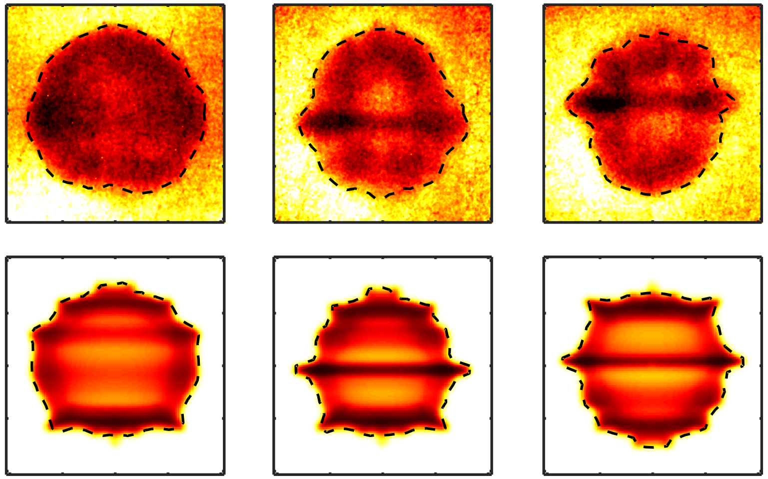
Inclusion of a CBET model has been instrumental in simulating recent DD-ICF implosions*, but ad hoc multipliers are still typically required**

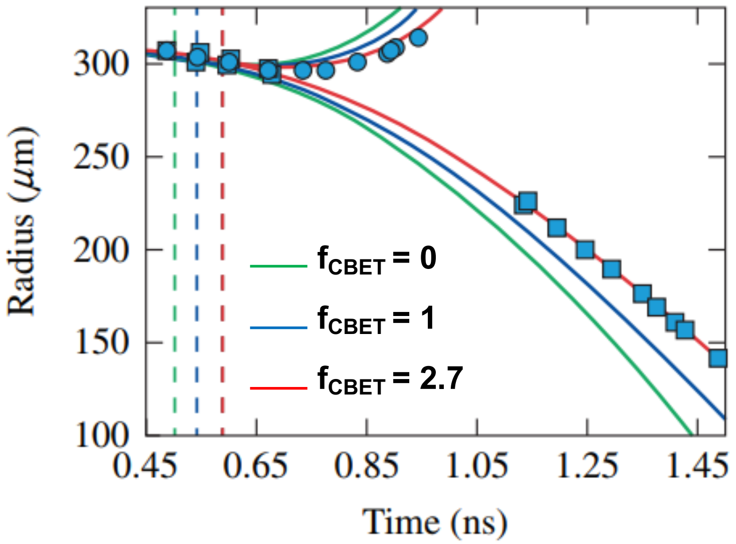
NIF Results*

$\Delta\lambda = 0$ Å $\Delta\lambda = \pm 2.3$ Å

Experiment

Simulation



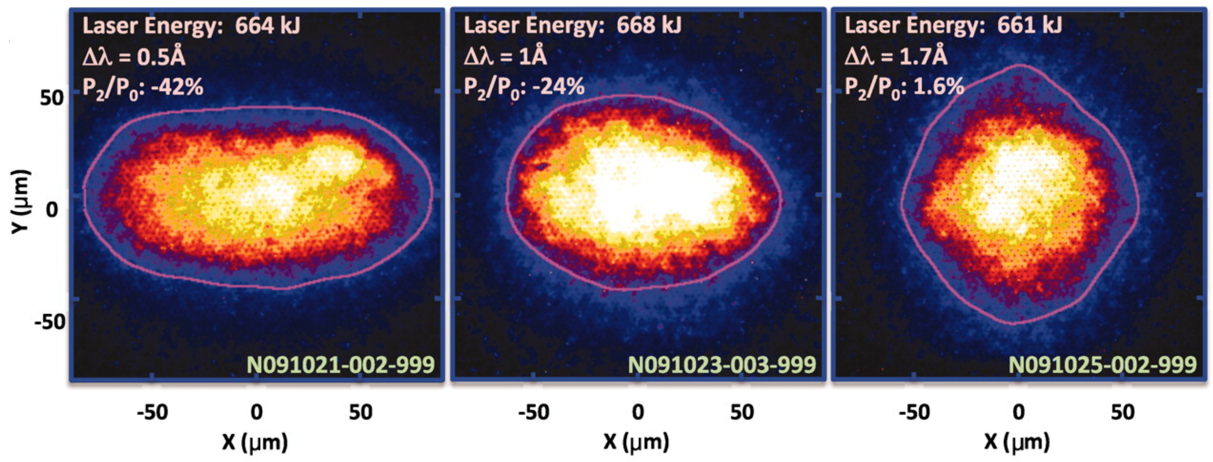


**

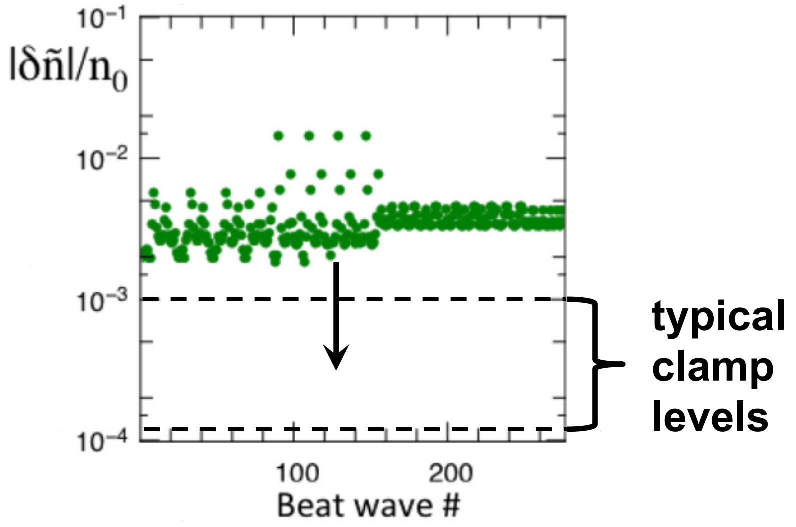
The persistence of multipliers limits confidence in our ability to simulate CBET

* Marozas *et al*., PRL 120, 085001 (2018).
** Davis *et al*., PoP 23, 056306 (2016).

Similarly, CBET was integral to the success of early NIF ID-ICF experiments*, but ad hoc clamps were later added to account for apparent saturation**



Expected IAW amplitudes for each quad pairing



Inability to calculate CBET has been one factor pushing the ID-ICF program away from high-gas-fill hohlraums; demonstrating improved understanding could restore a larger operable design space

* Glenzer *et al*., Science 327, 1228 (2010).
** Michel *et al*., PRL 109, 195004 (2012);
Michel *et al*, PoP 20, 056308 (2013);
Kritcher *et al*., PRE 98, 053206 (2018).

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- Review of experiments at LLE
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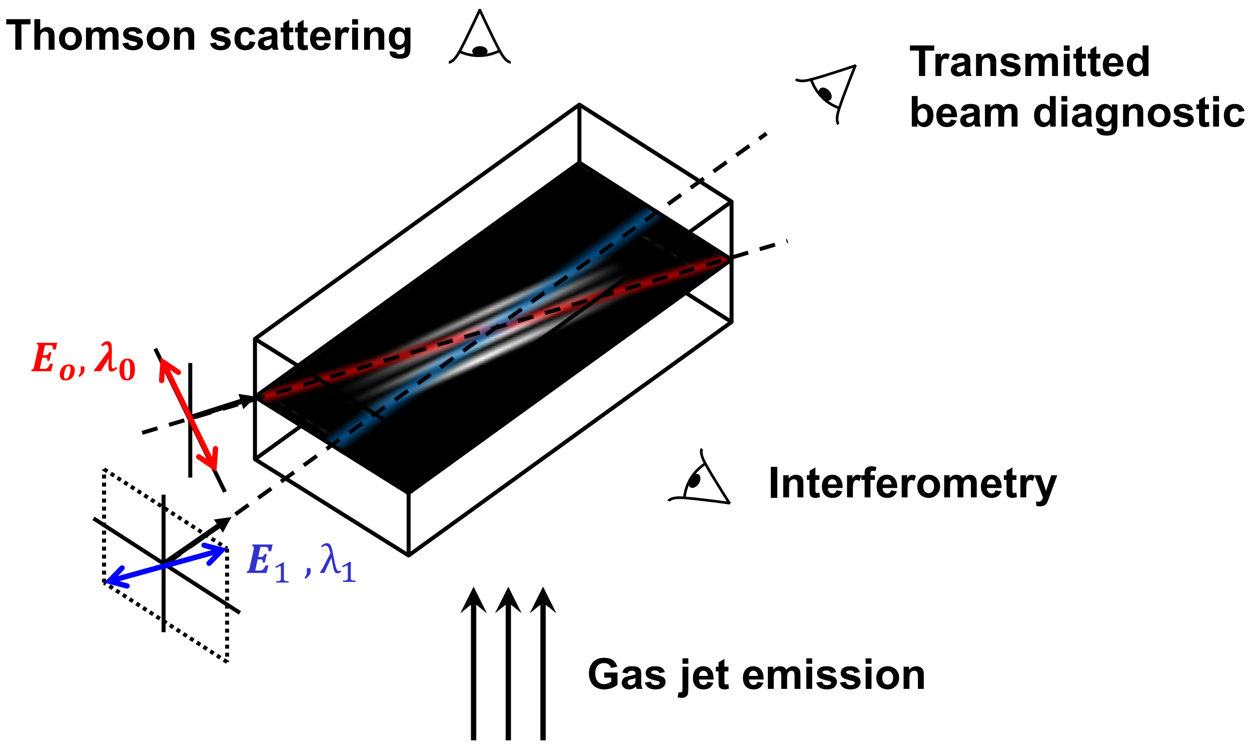
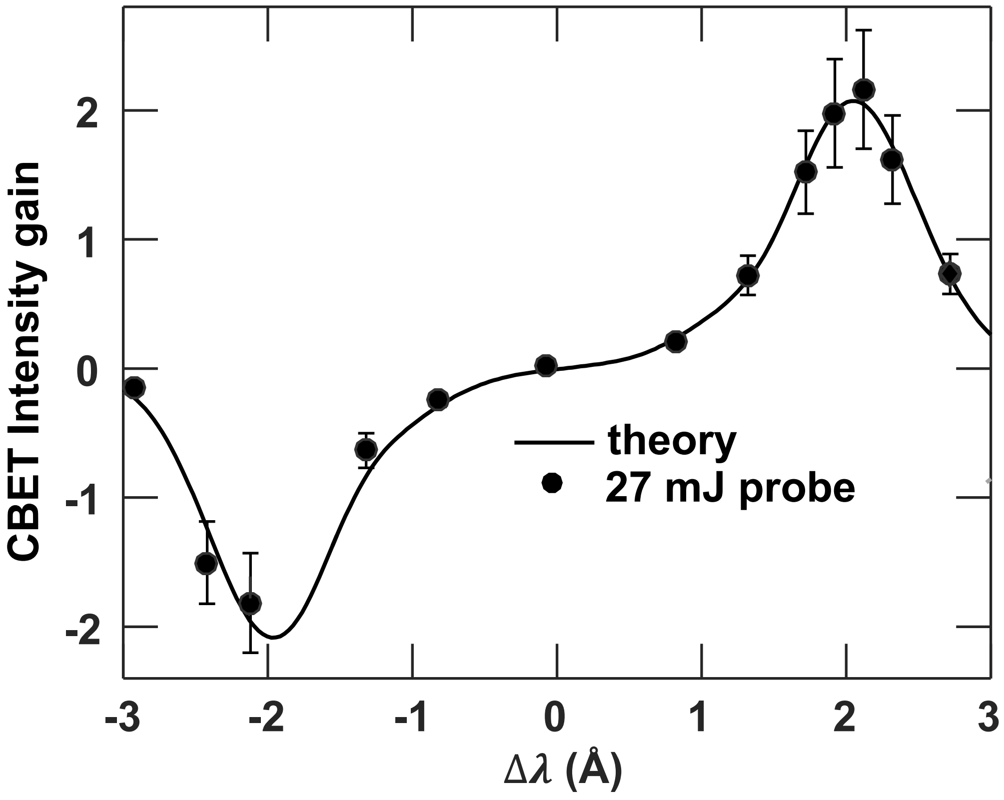
A CBET platform was first developed at LLNL's Jupiter Laser Facility to test and improve models



Using wavelength detuning and uniform, well-characterized plasmas isolates CBET physics from hydrodynamic uncertainty

The observed CBET was in reasonably good agreement with the linear theory used in ID-ICF calculations for small IAW amplitudes

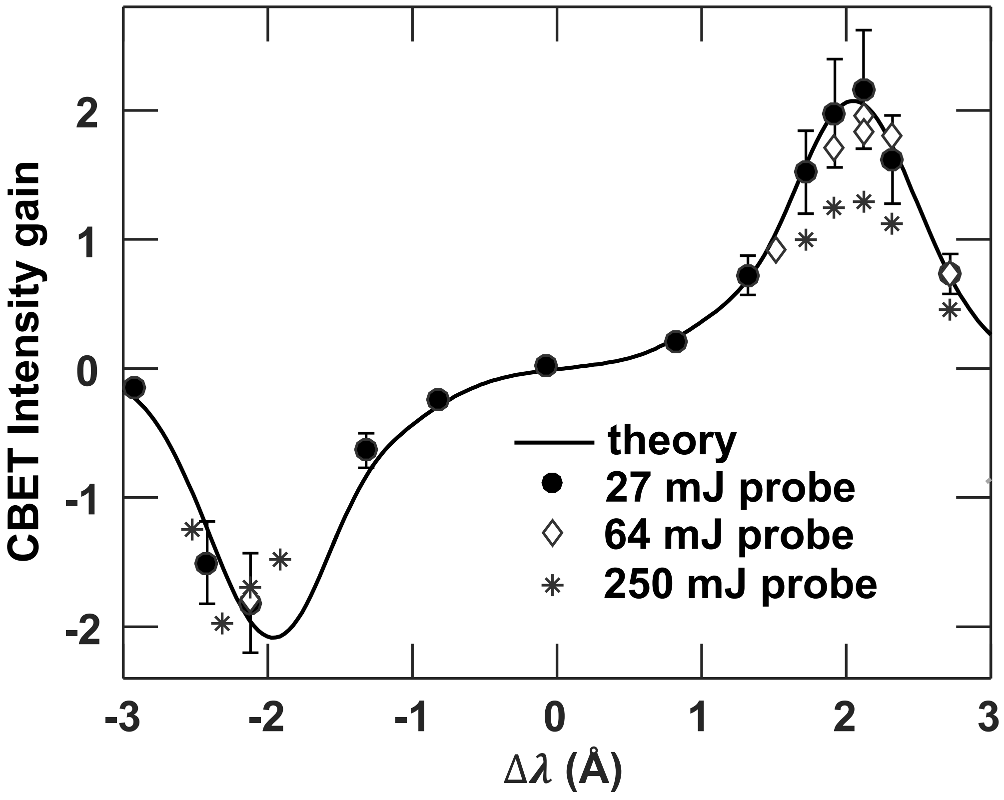


Parameter	Theory input	Measured	HYDRA
n_e/n_c	0.0104	0.011	0.01
T_e (eV)	220	224	231
T_i/T_e	0.115	--	0.09
I_{pump} (W cm^{-2})	3.2e13	3.6e13	3.6e13
Ion comp.	30%C, 70%H	--	20%C, 80%H

This represented a significant improvement over previous CBET experiments in terms of quantitative agreement

* D. Turnbull *et al.*, PRL 118, 015001 (2017).

Increasing the incident probe energy led to deviation from linear theory



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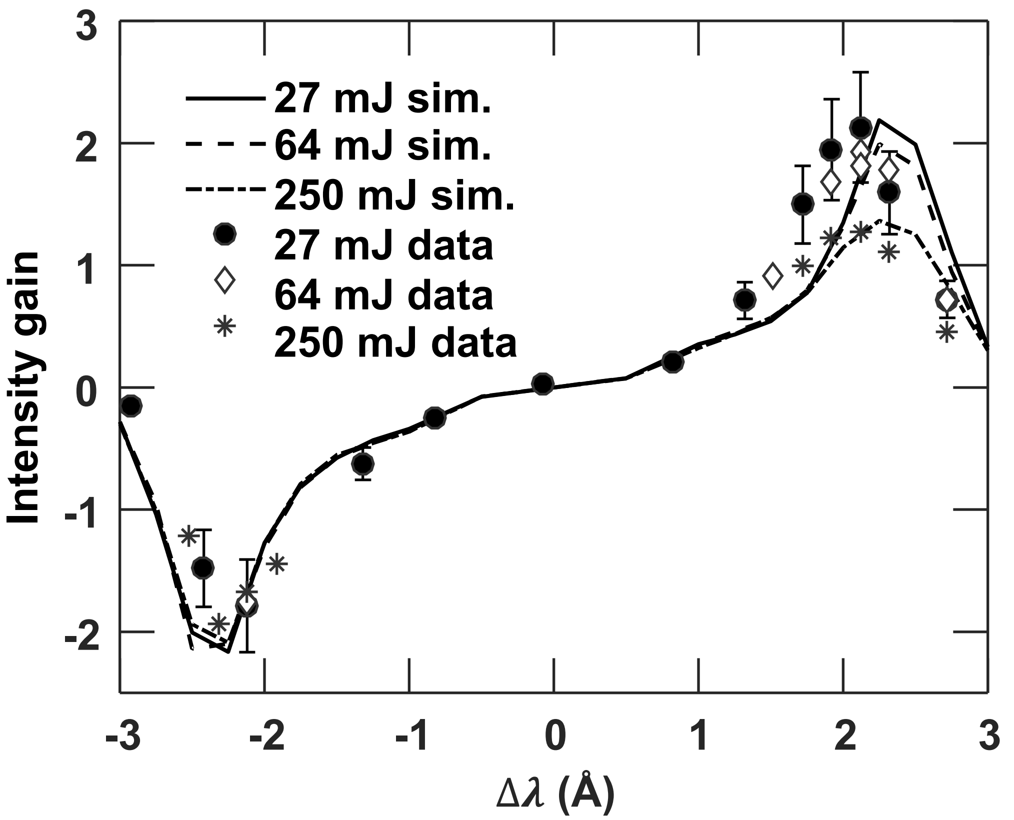
* D. Turnbull *et al.*, PPCF 60, 054017 (2018).

VAMPIRE* simulations reproduce a large amount of data fairly well with a single clamp at the $\delta n/n = 1.5\%$ level**



This level is larger than typical IAW amplitudes in ICF experiments, suggesting saturation should not be expected (though clamps have been implemented at >10x lower levels)

* A. Colaitis *et al.*, PoP 25, 033114 (2018).
** D. Turnbull *et al.*, PPCF 60, 054017 (2018).

Despite best CBET validation to date, knowledge gaps and questions remain

- Experiments observed an anomalous peak location (same w/ Kirkwood on Nova)
- Lacked certain key measurements (e.g. T_i)
- Density, temperature, wavelength, and intensity all relatively far from ICF relevant
- Limited # of beams and geometries (multi-beam physics is particularly important for ICF)

Motivation for additional experiments persists

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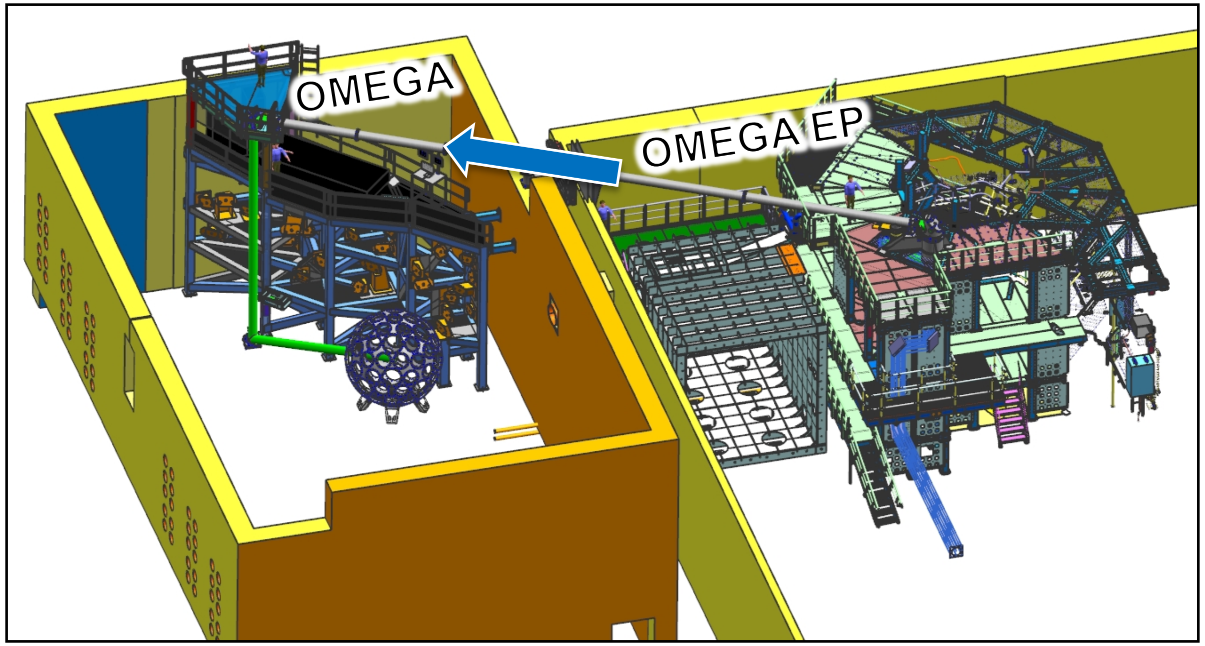
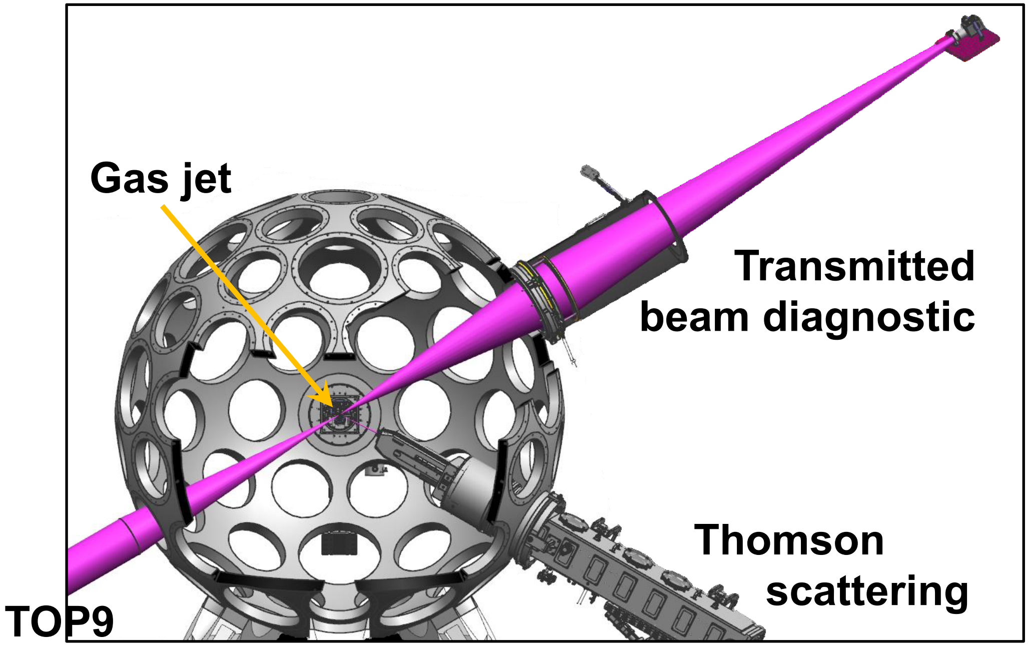
Tunable OMEGA P9 beam (TOP9; 350.2—353.4 nm) was built at LLE to continue CBET studies and develop understanding that can be scaled to ignition plasmas



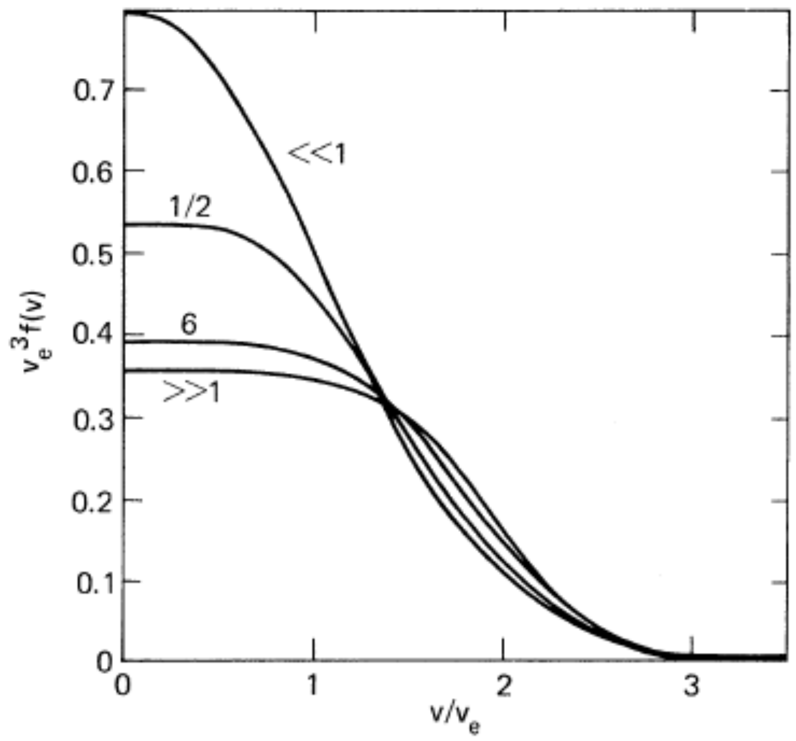


* C. Dorrer *et al.*, Opt. Exp. 25, 26802 (2017).
B. Kruschwitz *et al.*, SPIE Proc. 10898 (2019).

Initial TOP9 experiments studied the effect of non-Maxwellian (super-Gaussian) electron distribution functions (EDF’s) driven by inverse bremsstrahlung heating

- IB absorption preferentially heats low energy electrons, distorting the EDF away from a Maxwellian
- Langdon defined* $\alpha \equiv Zv_{osc}^2/v_{th}^2$
  - $\alpha \ll 1$ → Maxwellian (m=2)
  - $\alpha \gg 1$ → super-Gaussian m=5
- Matte** showed (with Fokker-Planck) that moderate heating produces intermediate super-Gaussian EDF’s 2<m<5 , well-predicted by:

$$m(\alpha) = 2 + 3/(1 + 1.66/\alpha^{0.724})$$

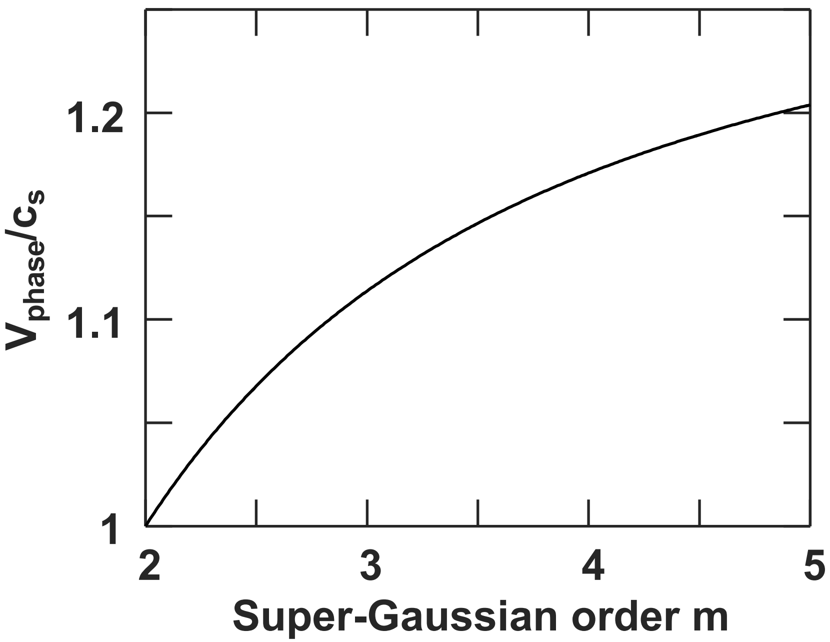


Despite potentially impacting many different processes in ICF plasmas, experimental evidence was scarce

* A B Langdon et al., PRL. 44, 576 (1980).
** J-P Matte et al., PPCF 30, 1665 (1988).

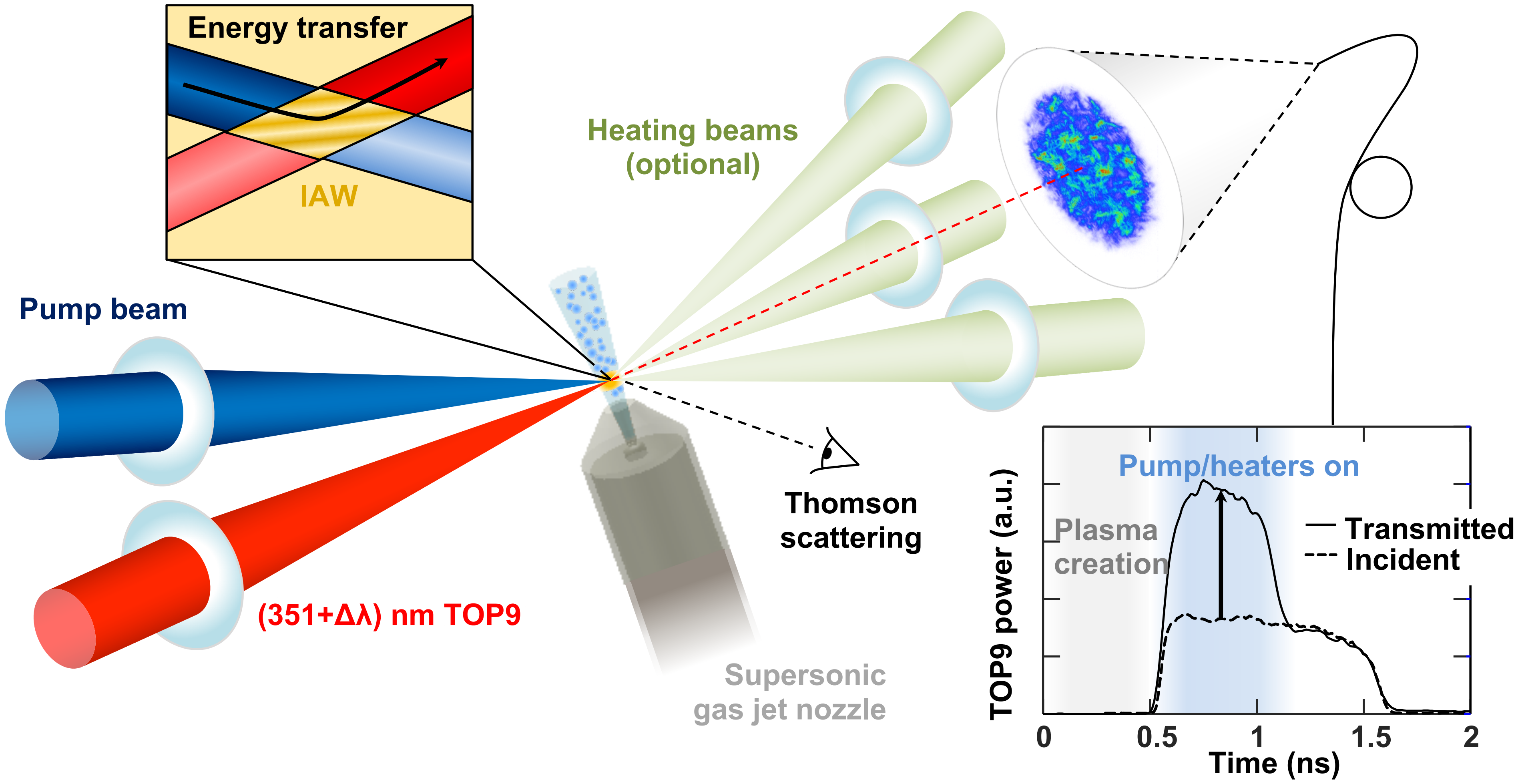
Super-Gaussian EDF's also impact the IAW's that mediate CBET*

- The smaller # of low energy electron available to shield ion oscillations increases the frequency of IAW's, resulting in the modified dispersion relation $\omega = kc_s \left(\frac{3\Gamma^2(3/m)}{\Gamma(1/m)\Gamma(5/m)} \right)^{1/2}$
  - Afeyan conjectured that this might explain resonance peak anomalies in early experiments



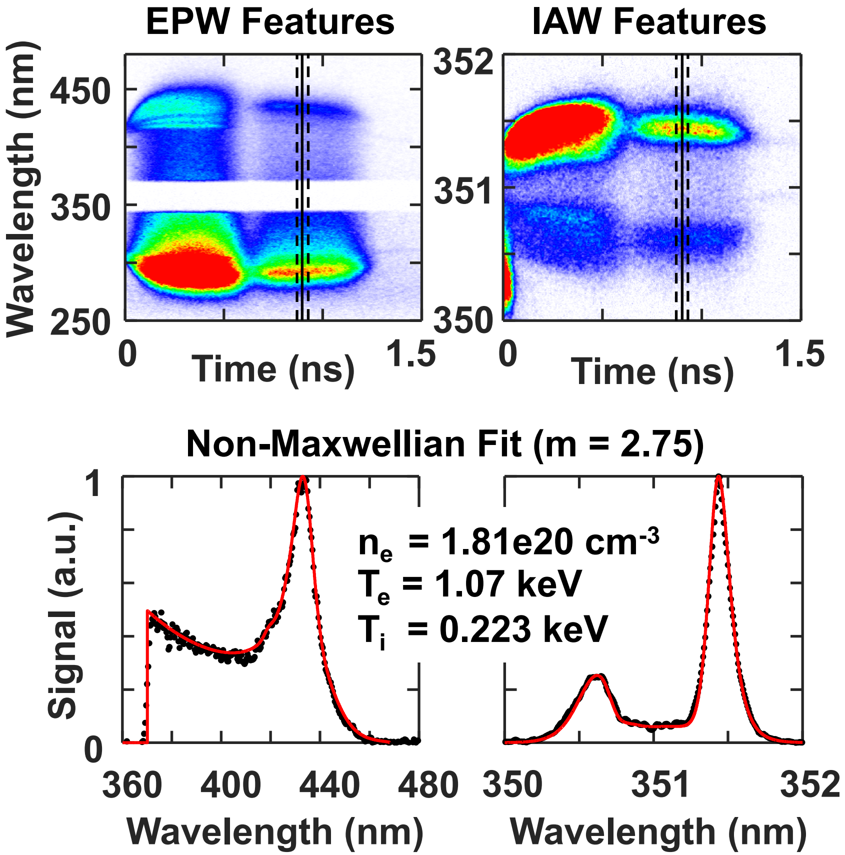
* B. Afeyan et al., PRL 80, 2322 (1998).

Experiments were executed as shown:



* D. Turnbull *et al*, accepted to Nat. Phys. (2019).

Thomson scattering clearly shows the need for a non-Maxwellian distribution function; a Maxwellian assumption would give O(10's%) errors in n_e, T_e, and T_i



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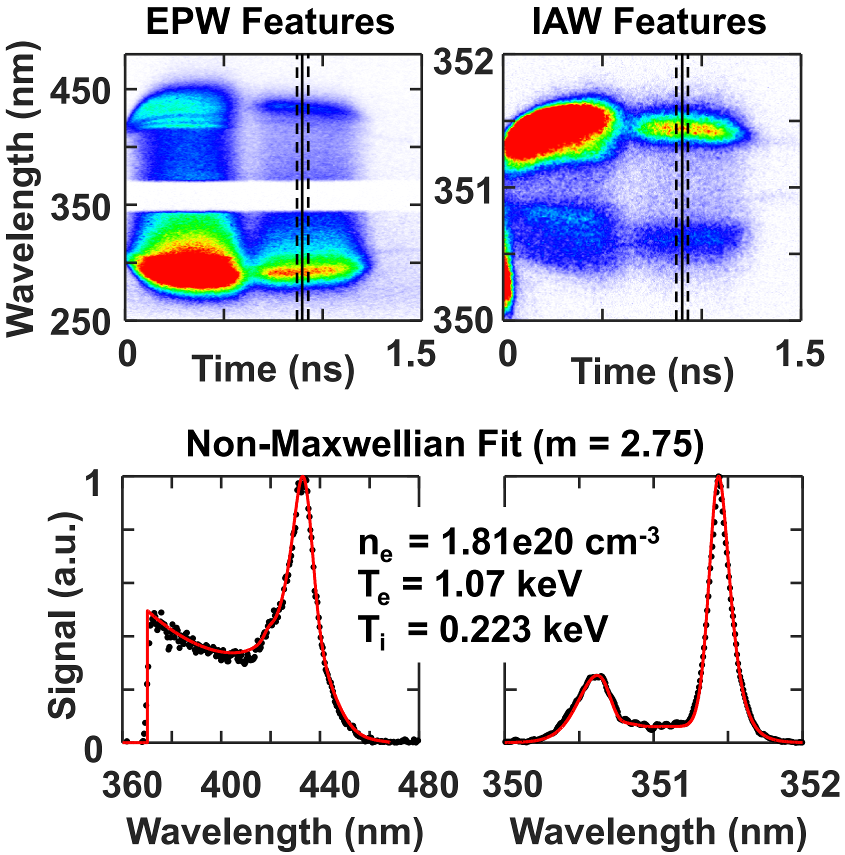

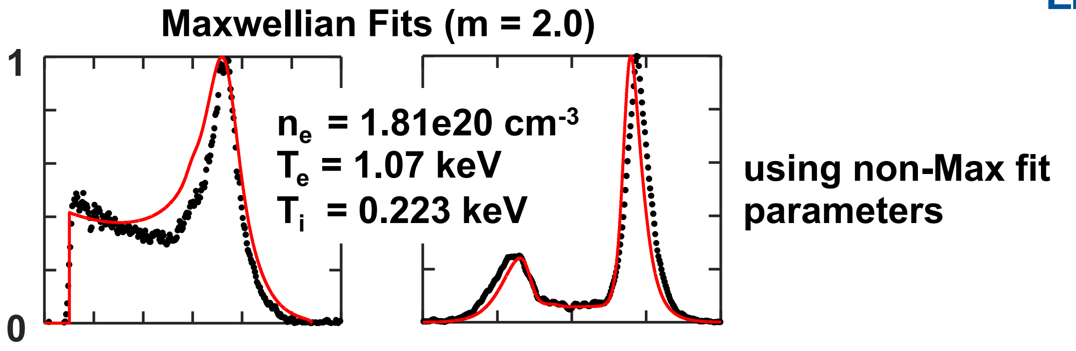

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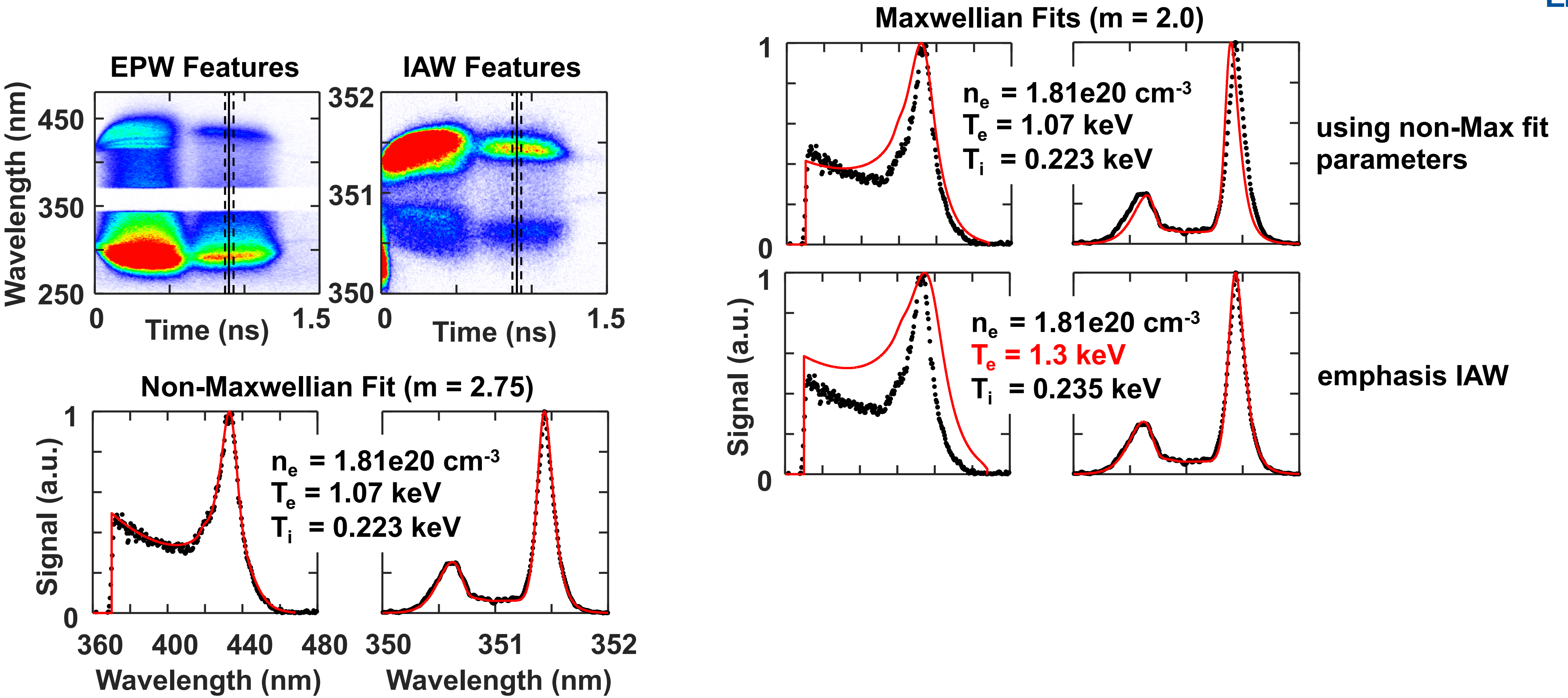

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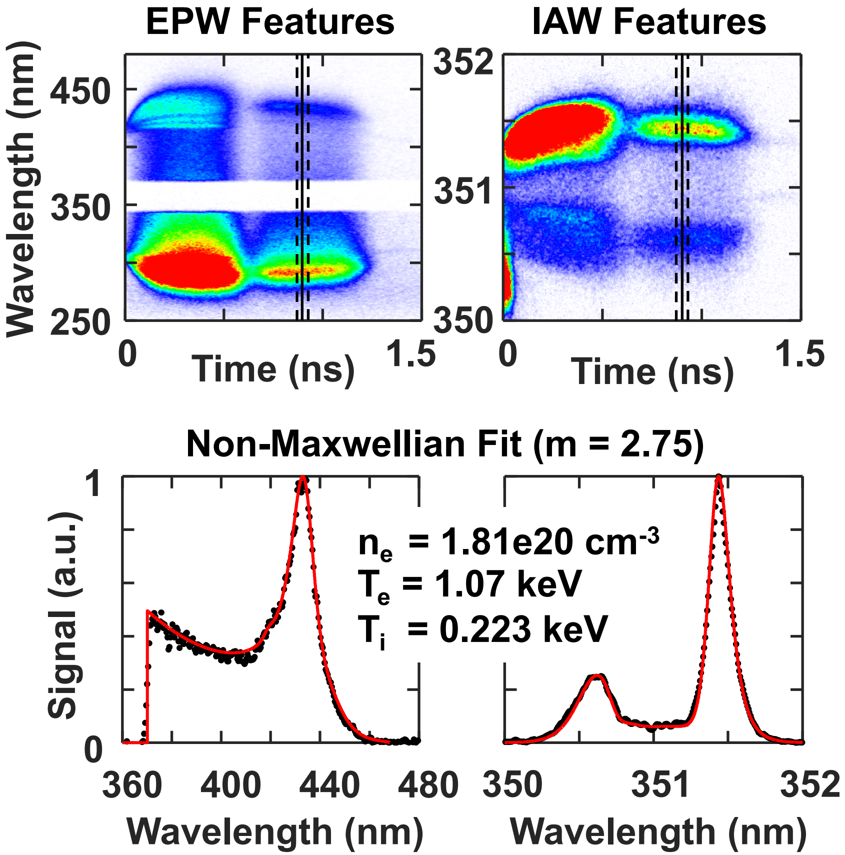

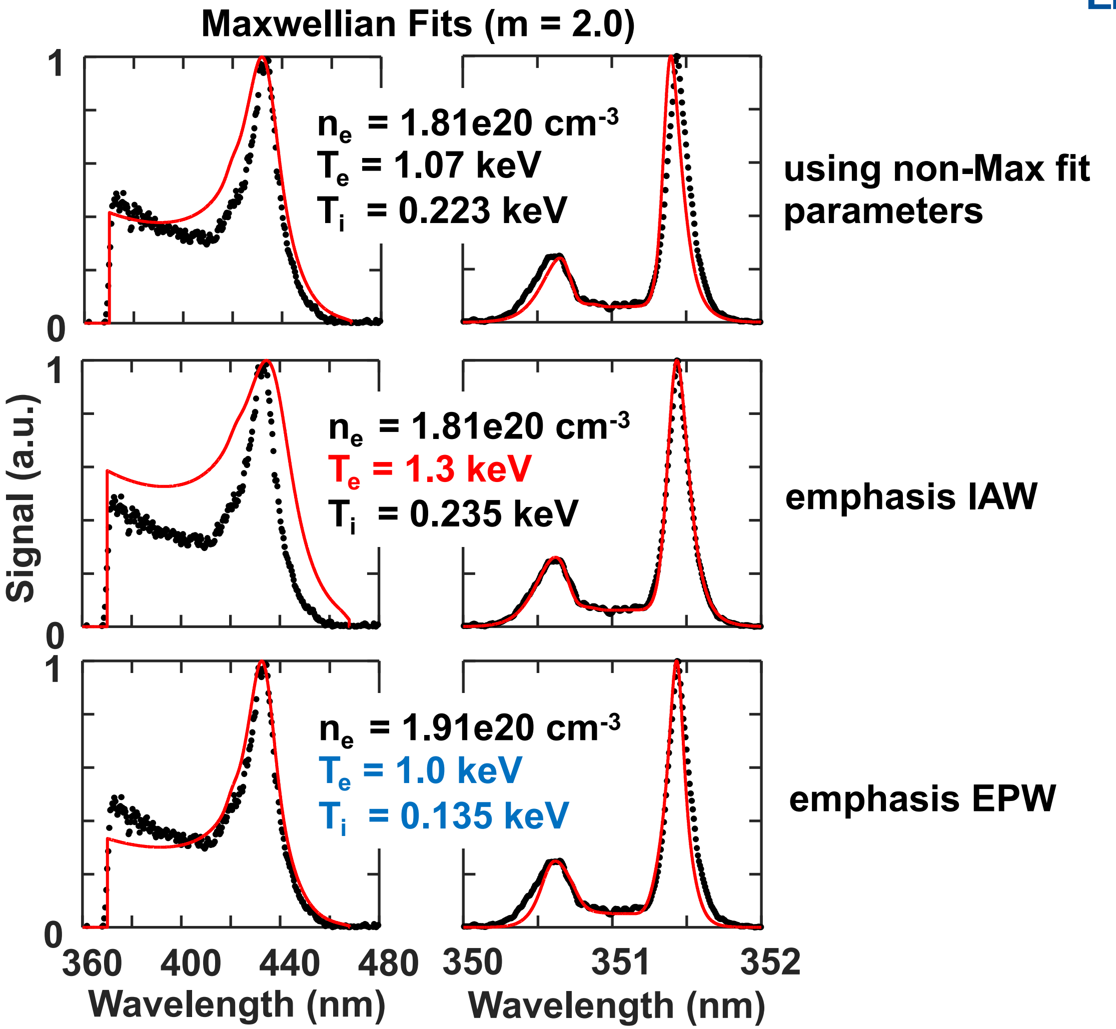

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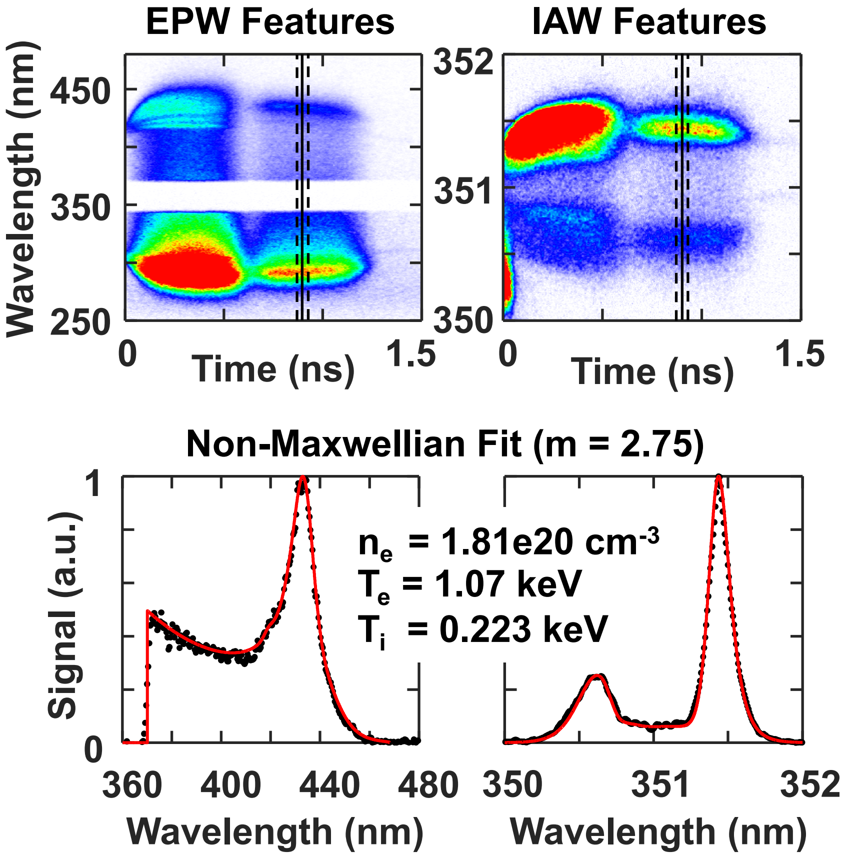
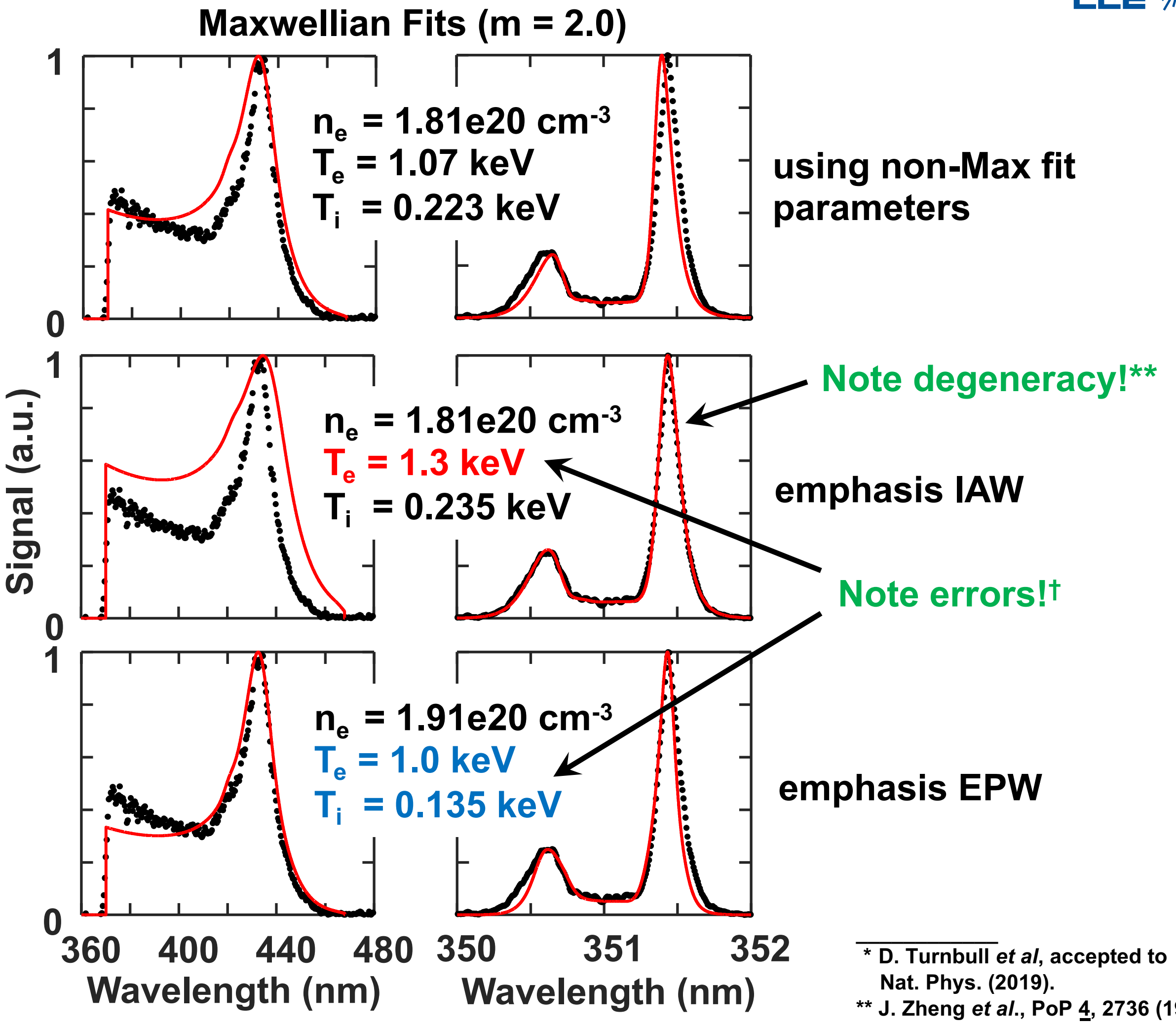


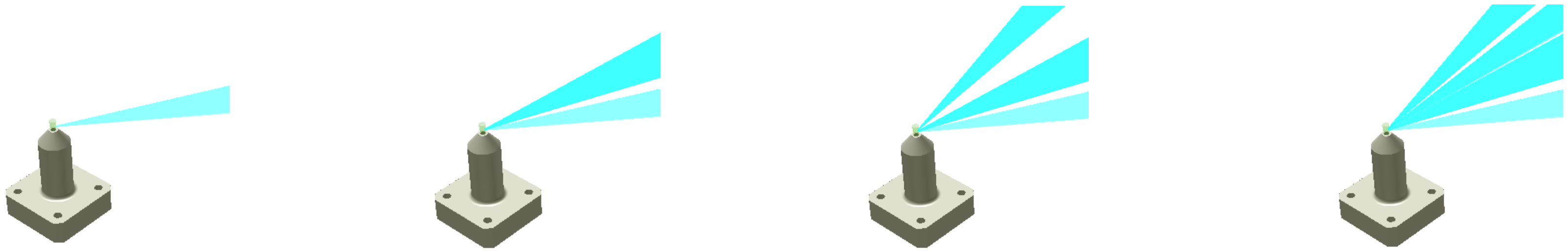


* D. Turnbull *et al*, accepted to Nat. Phys. (2019).
** J. Zheng *et al*., PoP 4, 2736 (1997).
† A. Milder *et al*., PoP 26, 022711 (2019).

Intensity scaling showed a clear increase in the super-Gaussian exponent of the non-Maxwellian EDF* in agreement with existing theory**

	1 beam	2 beams	3 beams	4 beams
I (10^{14} W cm^{-2})	5.1	10.2	15.3	20.4
T_e (keV)	0.84	0.98	1.07	1.1
α	0.17	0.3	0.41	0.53
$m_{observed}$	**2.4**	**2.65**	**2.75**	**2.85**
$m_{calculated}$	**2.43**	**2.6**	**2.72**	**2.83**

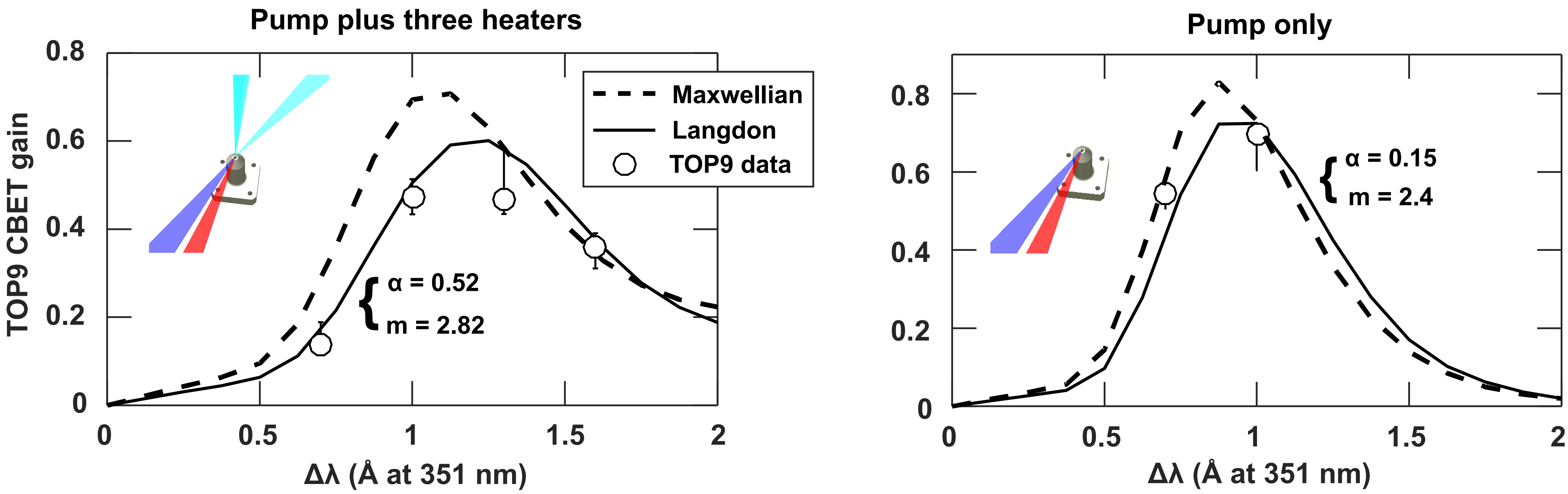
$$\boldsymbol{m(\alpha) = 2 + \frac{3}{1+\frac{1.66}{\alpha^{0.724}}}} \quad **$$



This confirms that the formula can actually be used in simulations to convert intensity to EDF

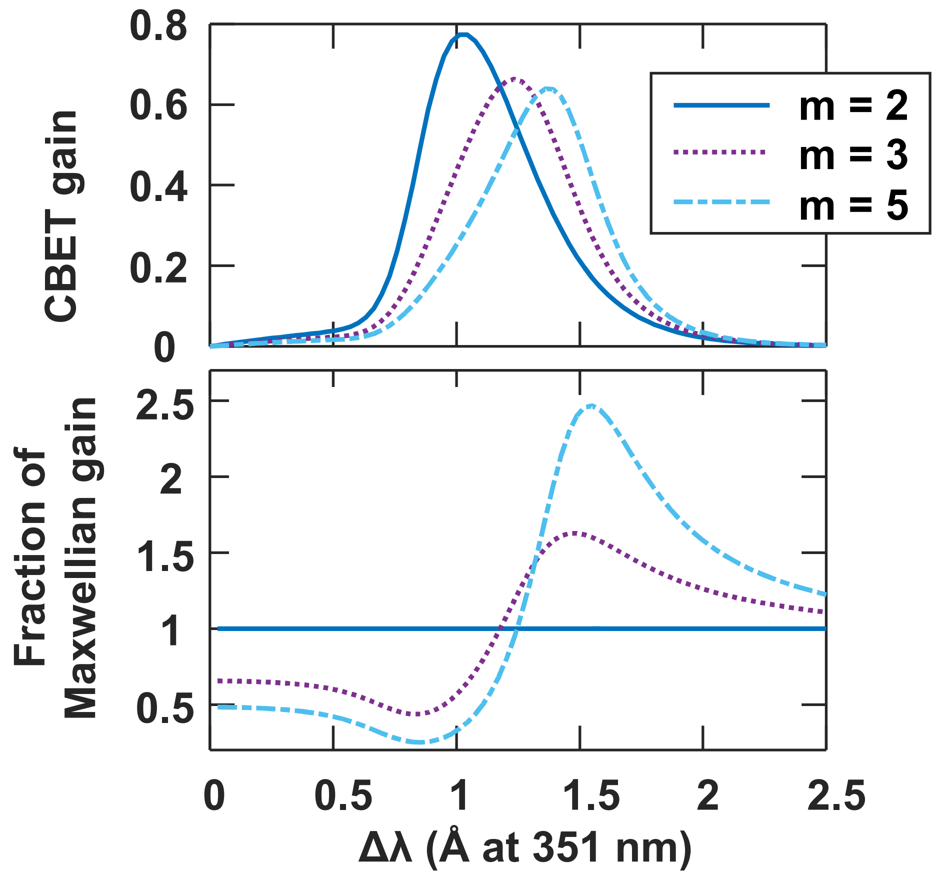
* D. Turnbull *et al*, accepted to Nat. Phys. (2019).
** J-P Matte *et al.*, PPCF 30, 1665 (1988).

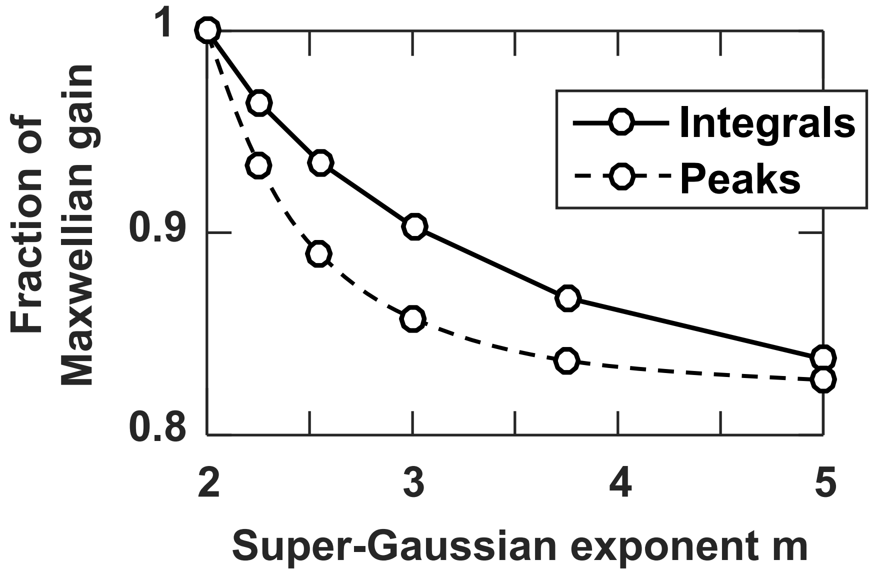
The CBET data confirmed the impact of the non-Maxwellian electrons on IAW's that was evident in the Thomson scattering data



* D. Turnbull *et al*, accepted to Nat. Phys. (2019).

The impact of the super-Gaussian distribution on IAW's is primarily a resonance shift concern in strongly damped plasmas



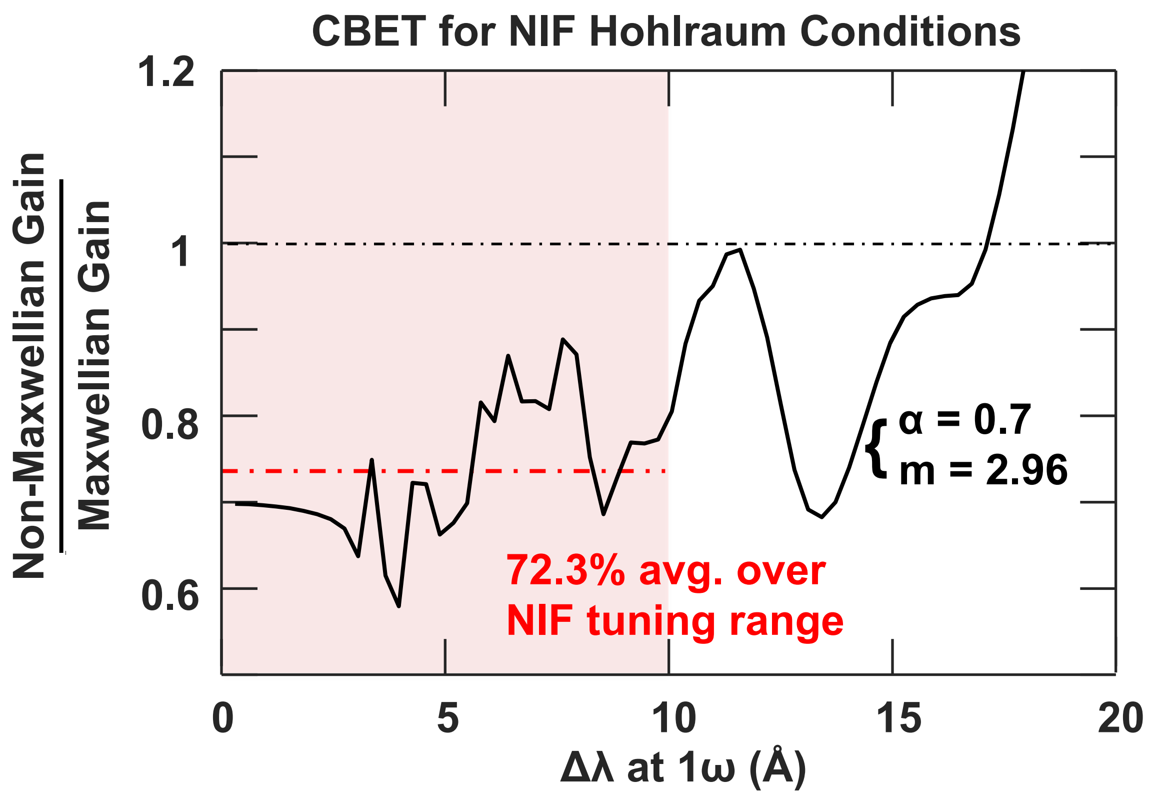


This most strongly affects situations where CBET doesn't integrate over a flow gradient (ID-ICF), but also modifies detuning requirements for CBET mitigation in DD-ICF

* D. Turnbull *et al*, accepted to Nat. Phys. (2019).

A calculation for typical NIF conditions suggests that non-Maxwellian EDF's lowers CBET gain by 10s of % over relevant tuning range

$\alpha \equiv Z v_{osc}^2 / v_{th}^2$



Calculations use:

- T_e = 2.8 keV
- T_i = 0.8 keV
- Z = 2, A = 4
- $n_e = 0.03n_c$
- 384 TW FNE
- Beam-by-beam pointing with P.S.

Implementing the non-Maxwellian model will improve prediction of CBET's space- and time-dependence in ID-ICF, and it will reduce (and may eliminate) the need for a saturation clamp

* D. Turnbull *et al*, accepted to Nat. Phys. (2019).

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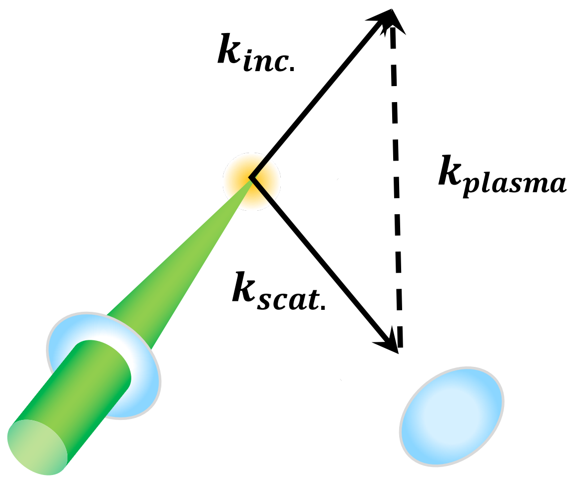
CBET is determined by bulk electrons, but many processes are sensitive to the tails of the EDF

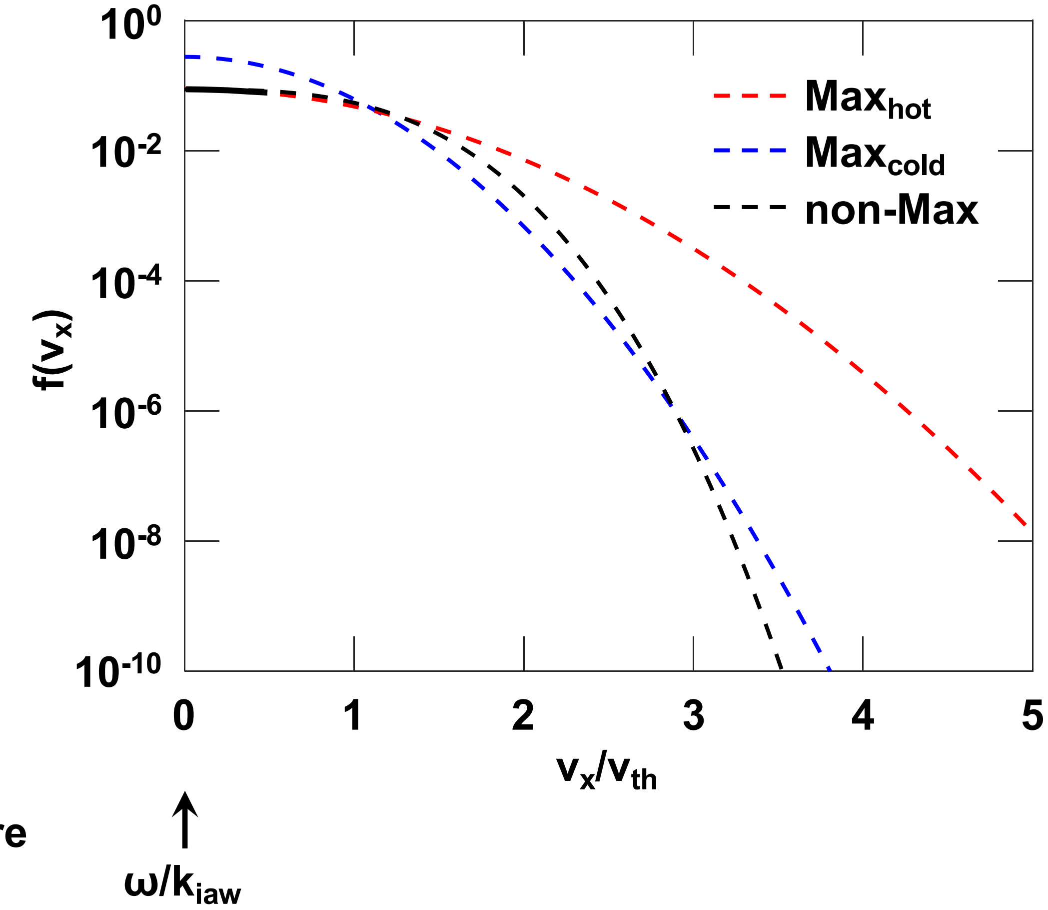
- Subsequent simulation work consistently validated Matte's formula for bulk electrons
- But some have argued that tails are likely more Maxwellian than the pure super-Gaussian distribution for various reasons (e.g., transport*, neglected e-e collisional term**)
- Processes affected by tails of the EDF include x-ray emission†, electron plasma wave instability growth rates‡, heat transport§, etc.

The ability to measure the electron distribution function without assuming its functional form would be extremely useful

* S. Brunner and E. Valeo, PoP 9, 923 (2002).
** E. Fourkal *et al.*, PoP 8, 550 (2001).
† J-P Matte *et al.*, PPCF 30, 1665 (1988).
‡ B. Afeyan *et al.*, PRL 80, 2322 (1998).
§ C. Ridgers *et al.*, PoP 15, 092311 (2008).

Thomson scattering with additional collection angles could help to fill in the electron distribution function





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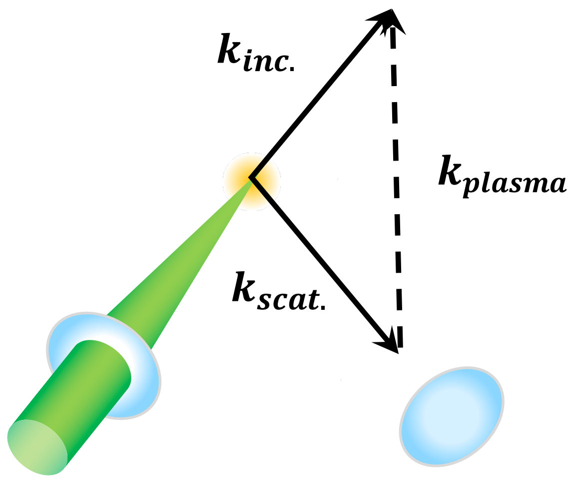
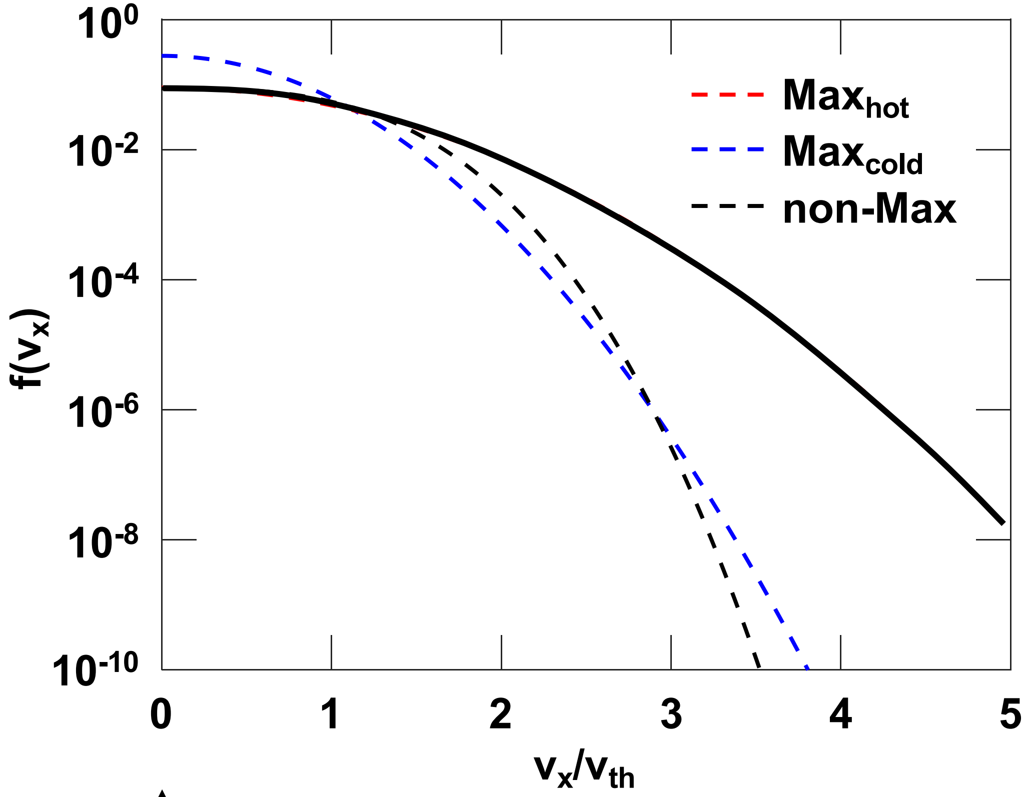
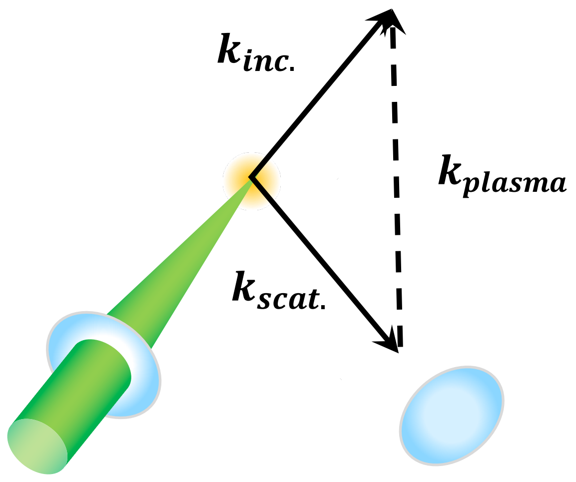


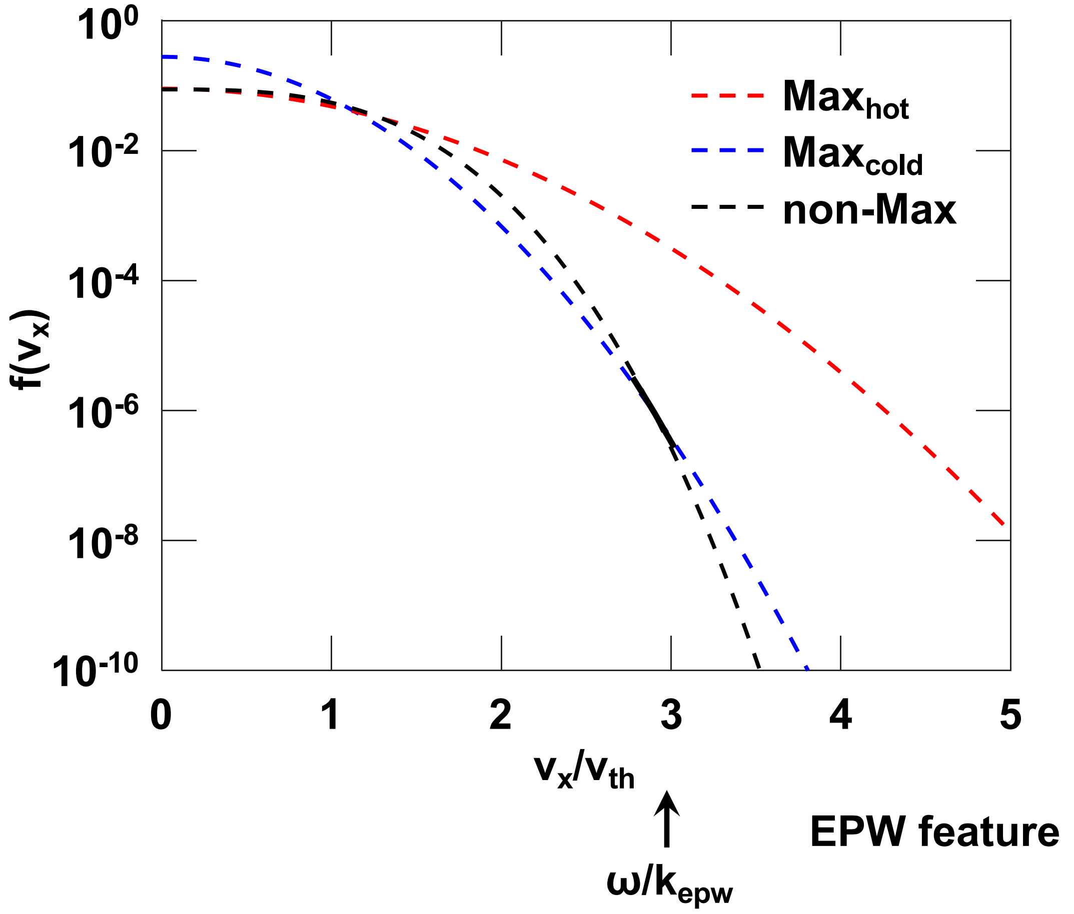


IAW feature
+ Maxwellian

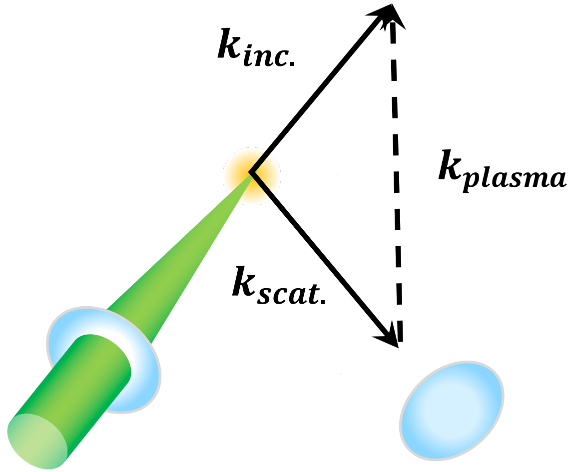
ω/k_{iaw}

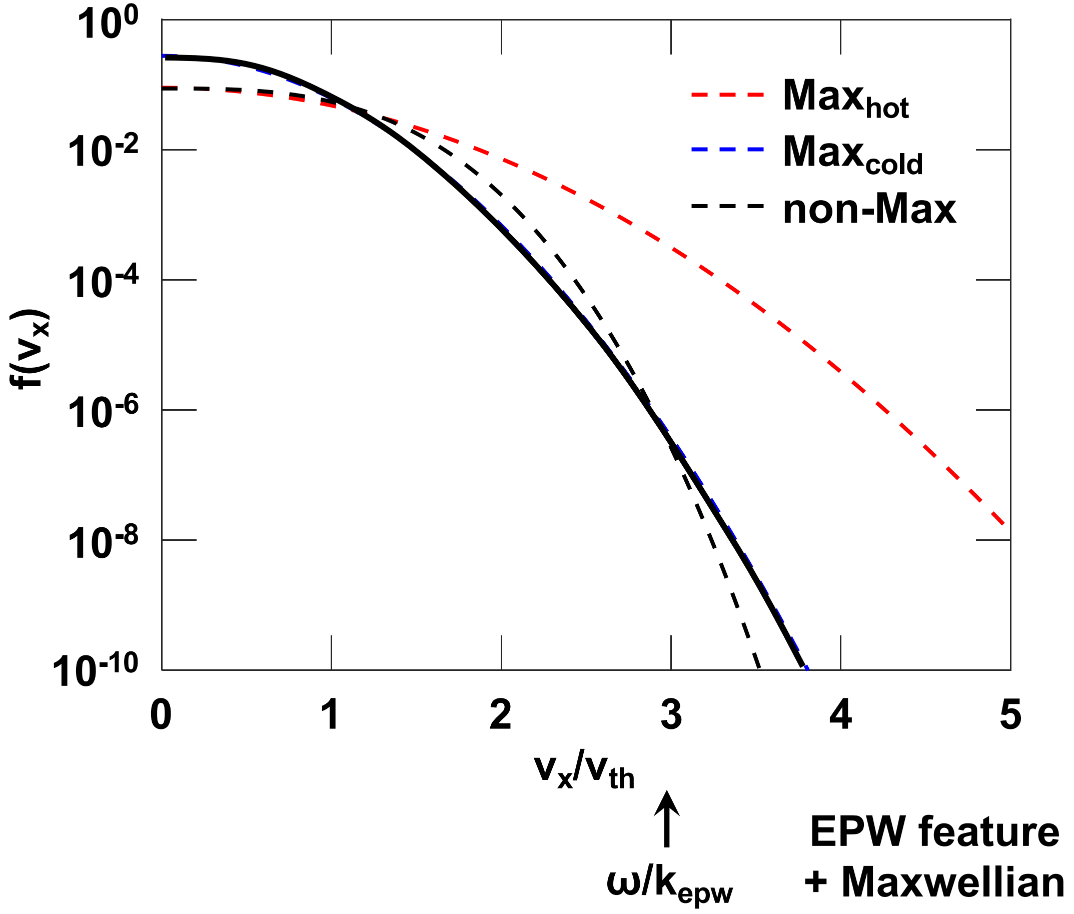
Thomson scattering with additional collection angles could help to fill in the electron distribution function





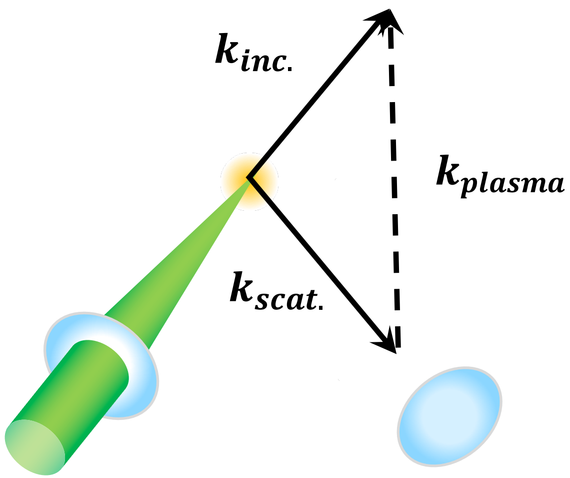
Thomson scattering with additional collection angles could help to fill in the electron distribution function

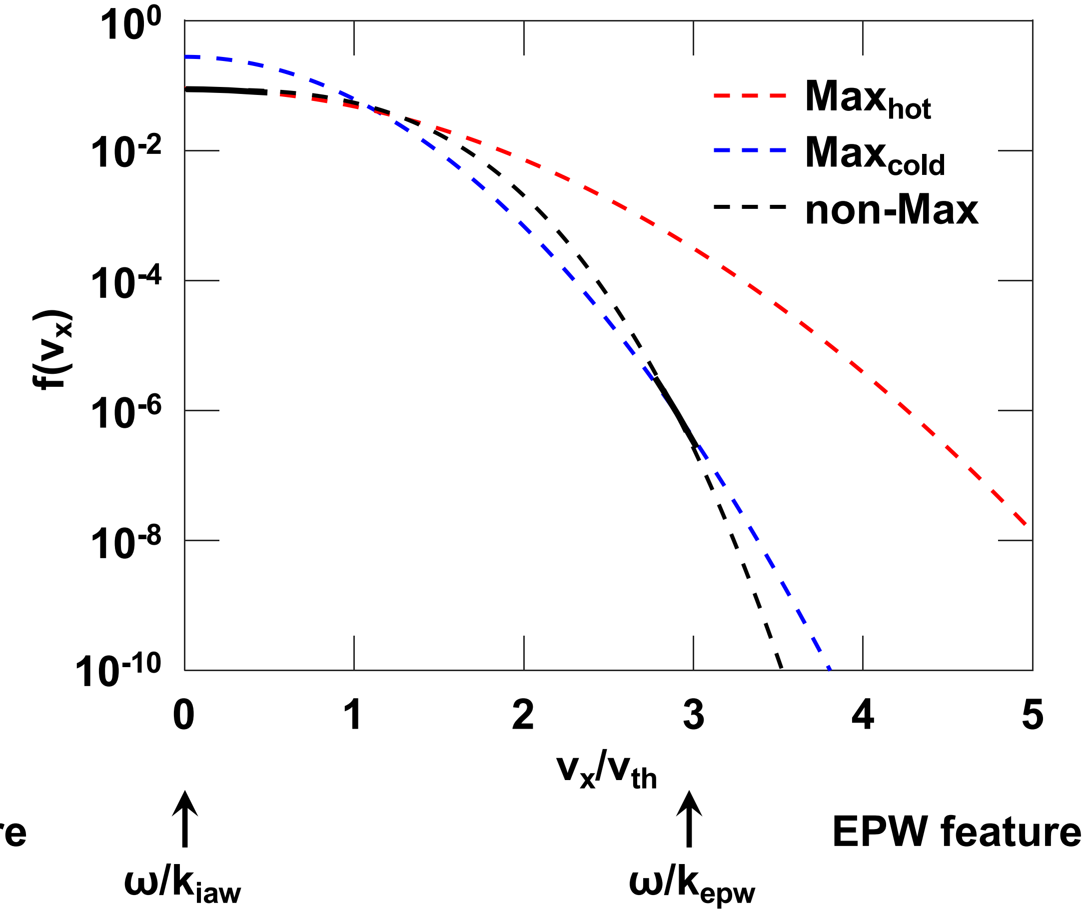




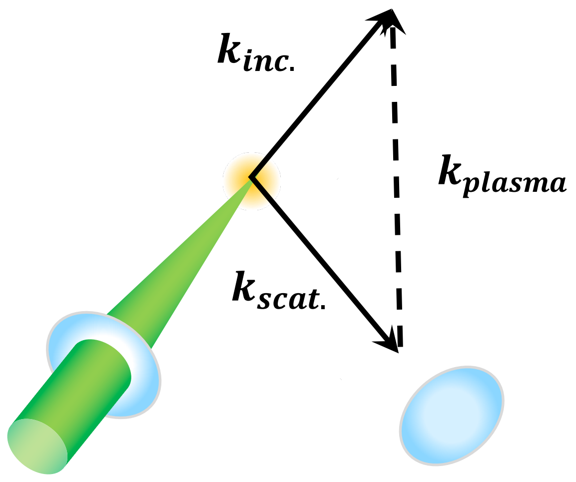
EPW feature
+ Maxwellian

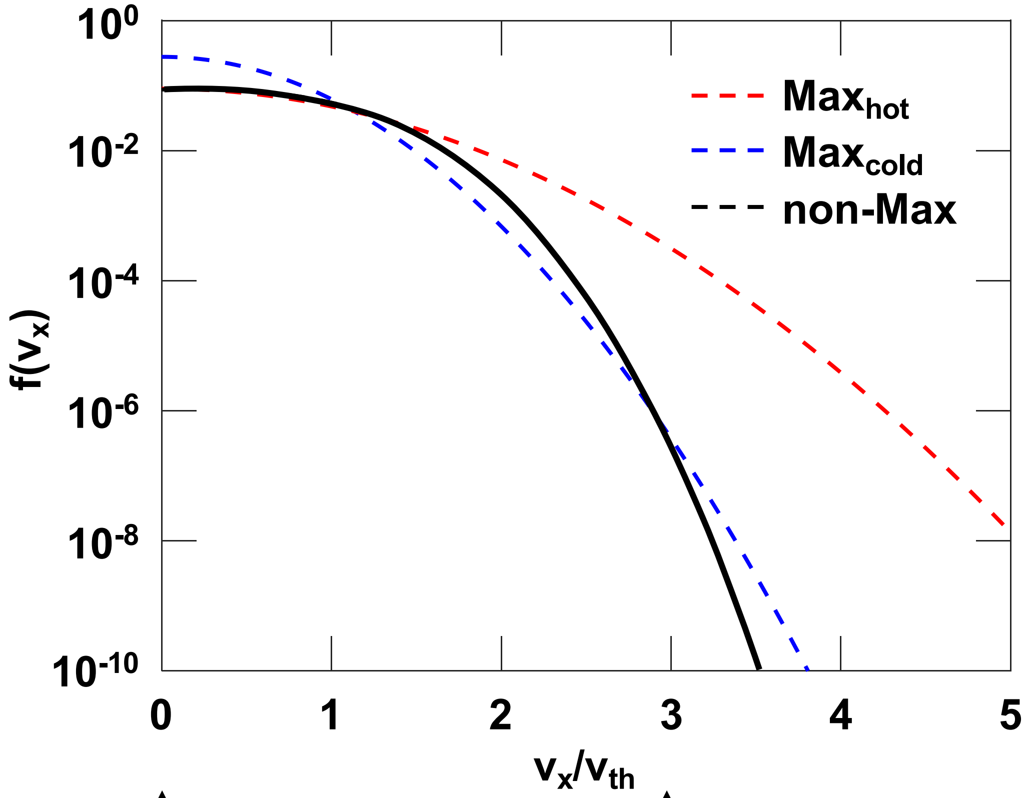
Thomson scattering with additional collection angles could help to fill in the electron distribution function





Thomson scattering with additional collection angles could help to fill in the electron distribution function

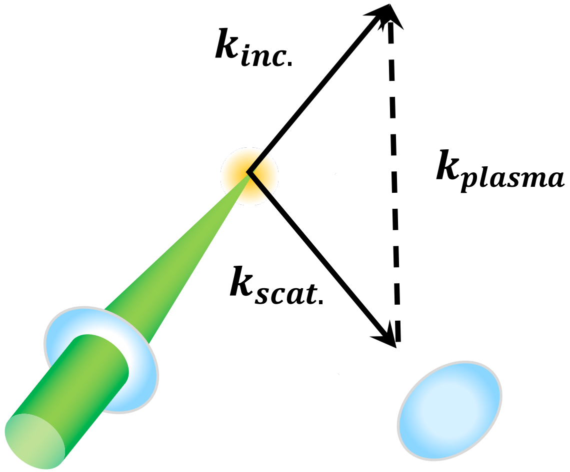


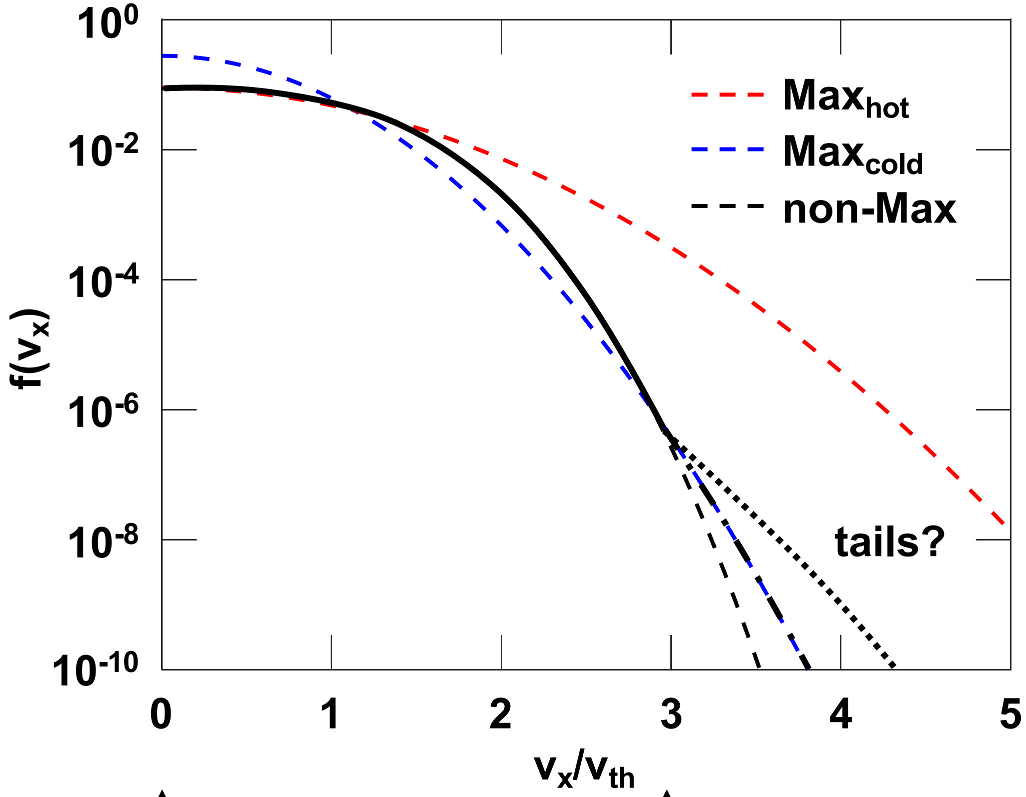


IAW feature
+ super-Gaussian ω/k_{iaw}

ω/k_{epw} EPW feature
+ super-Gaussian

Thomson scattering with additional collection angles could help to fill in the electron distribution function

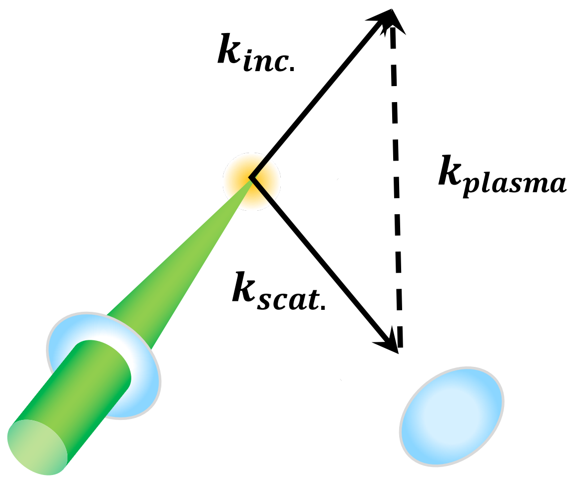


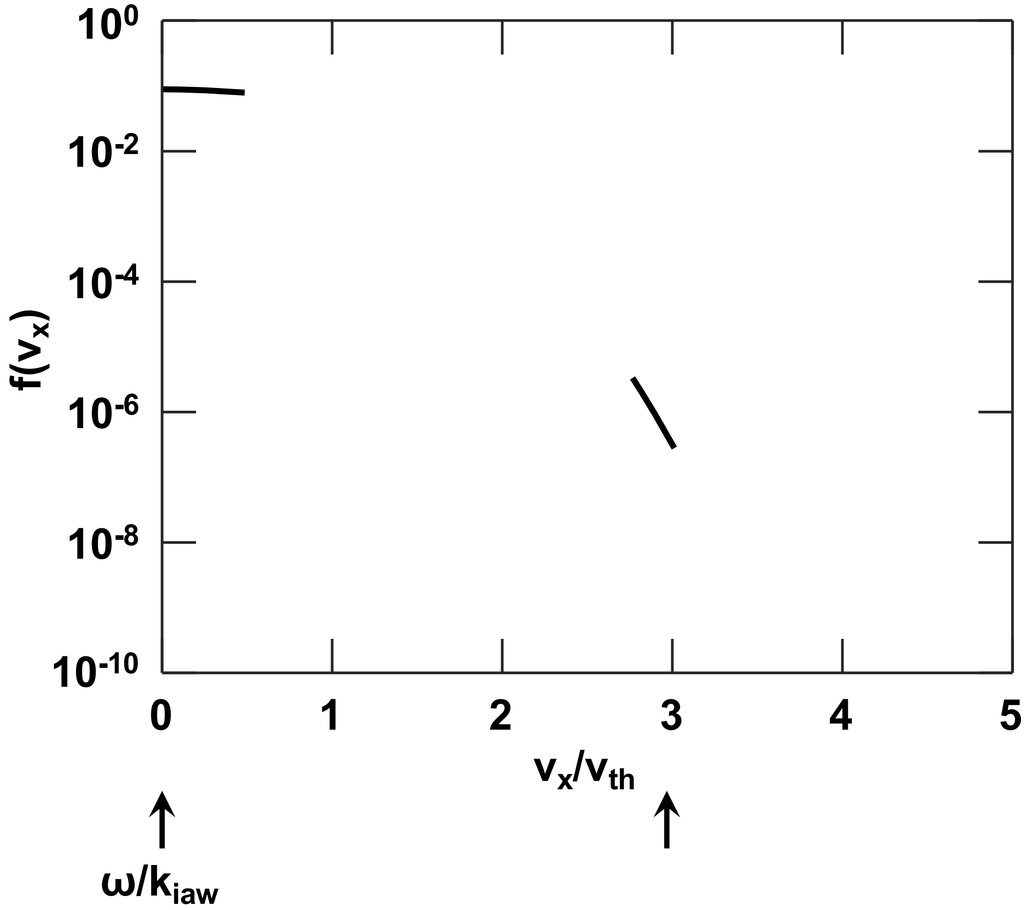


IAW feature + super-Gaussian ω/k_{iaw}

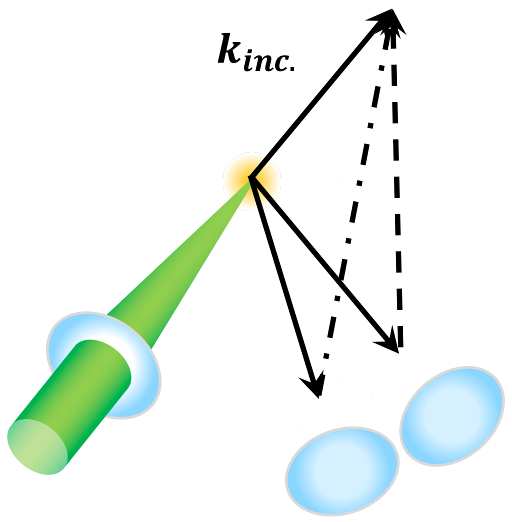
ω/k_{epw} EPW feature + super-Gaussian

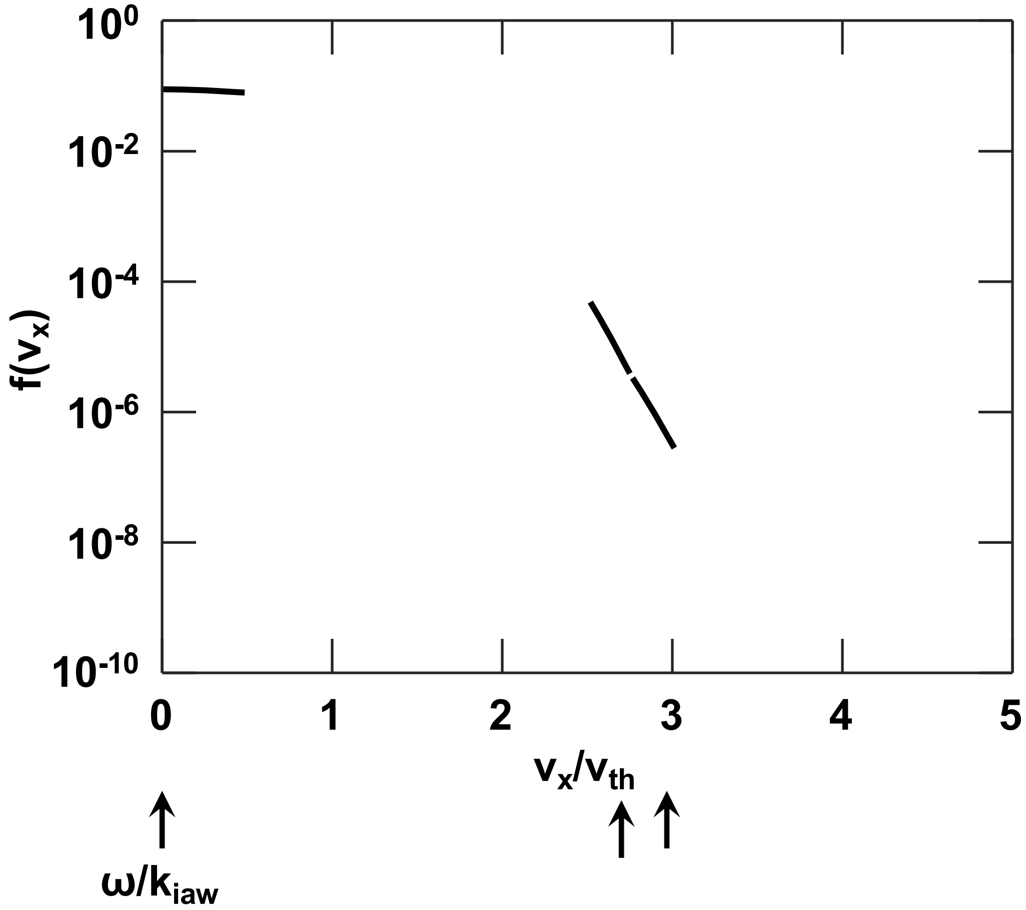
Thomson scattering with additional collection angles could help to fill in the electron distribution function



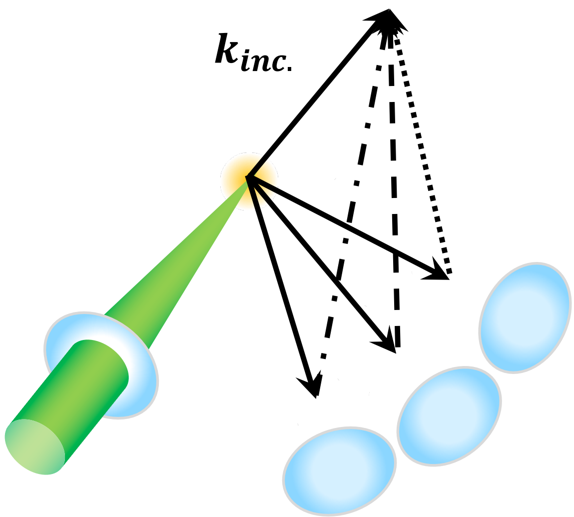


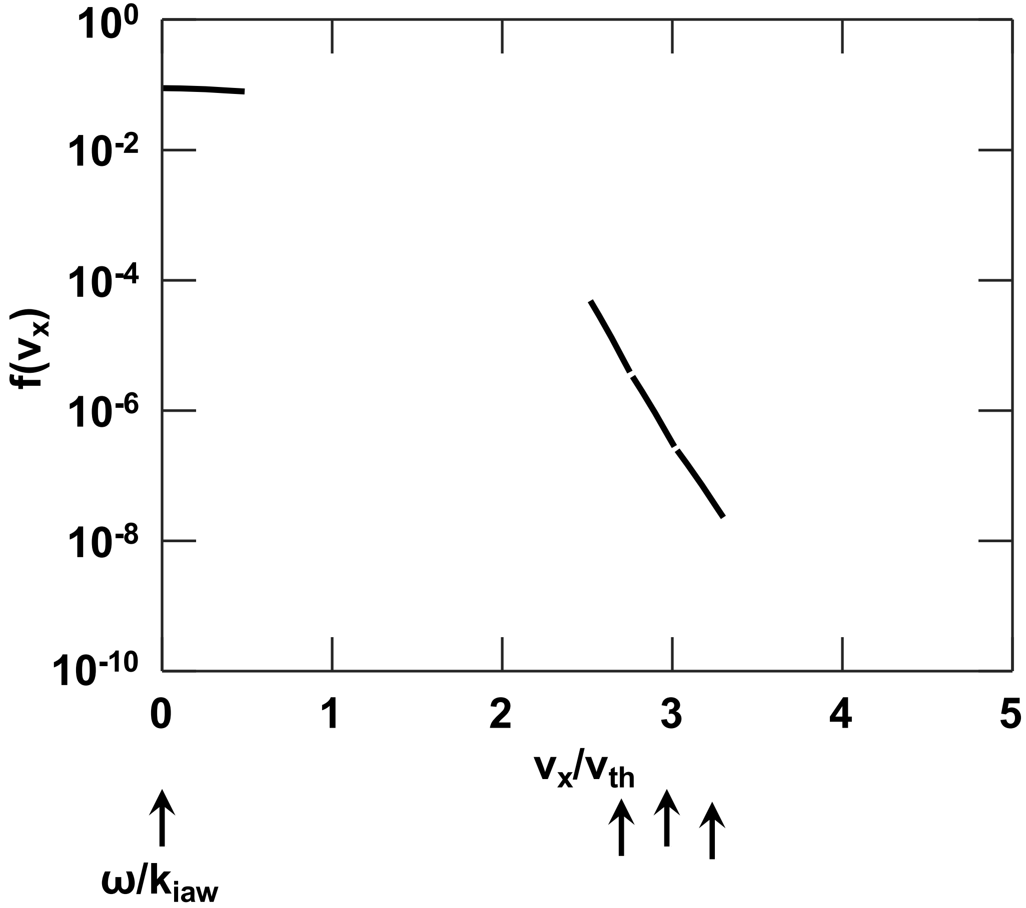
Thomson scattering with additional collection angles could help to fill in the electron distribution function



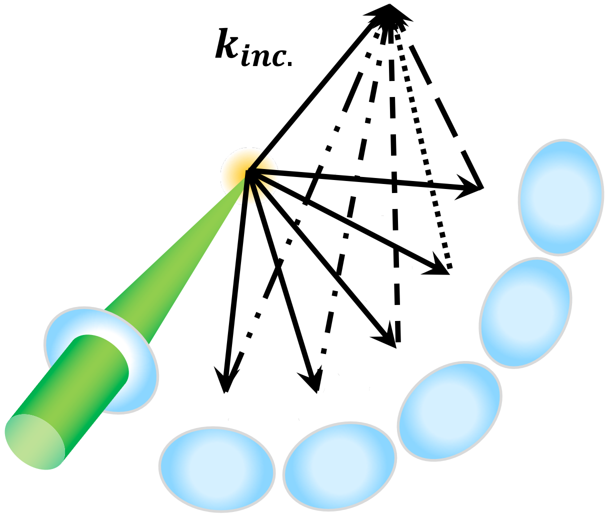


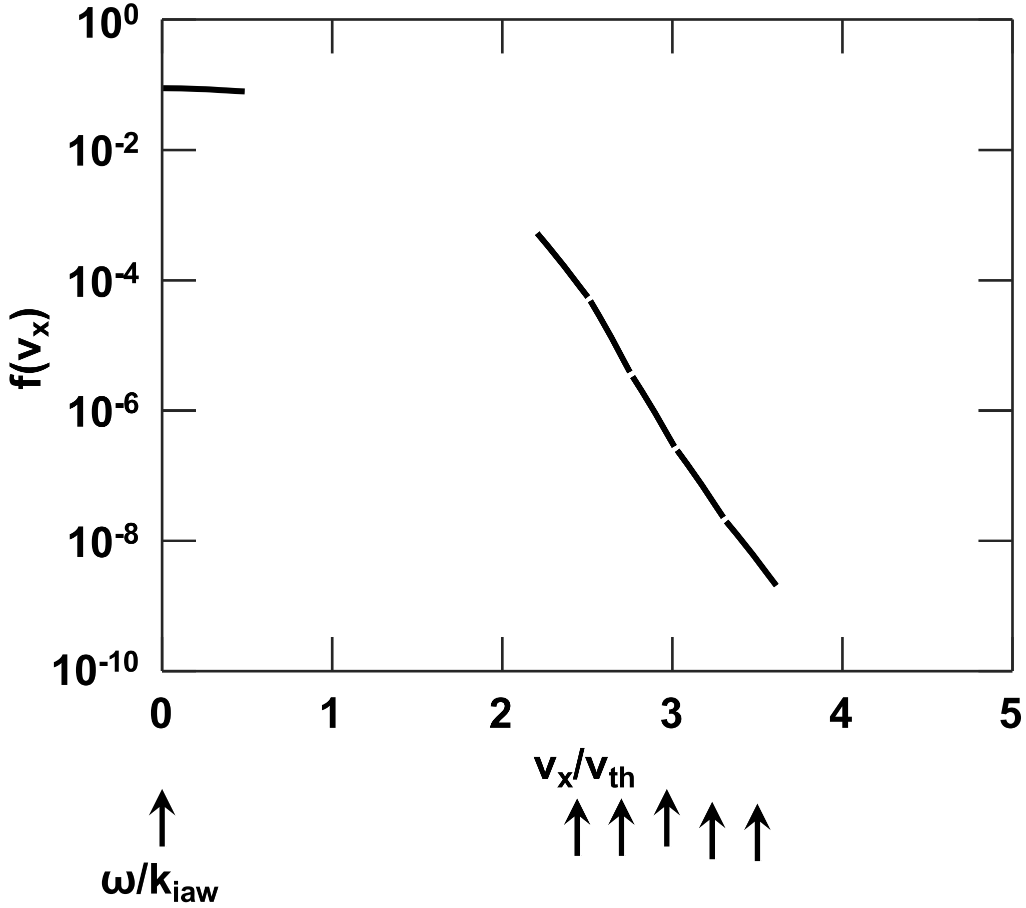
Thomson scattering with additional collection angles could help to fill in the electron distribution function



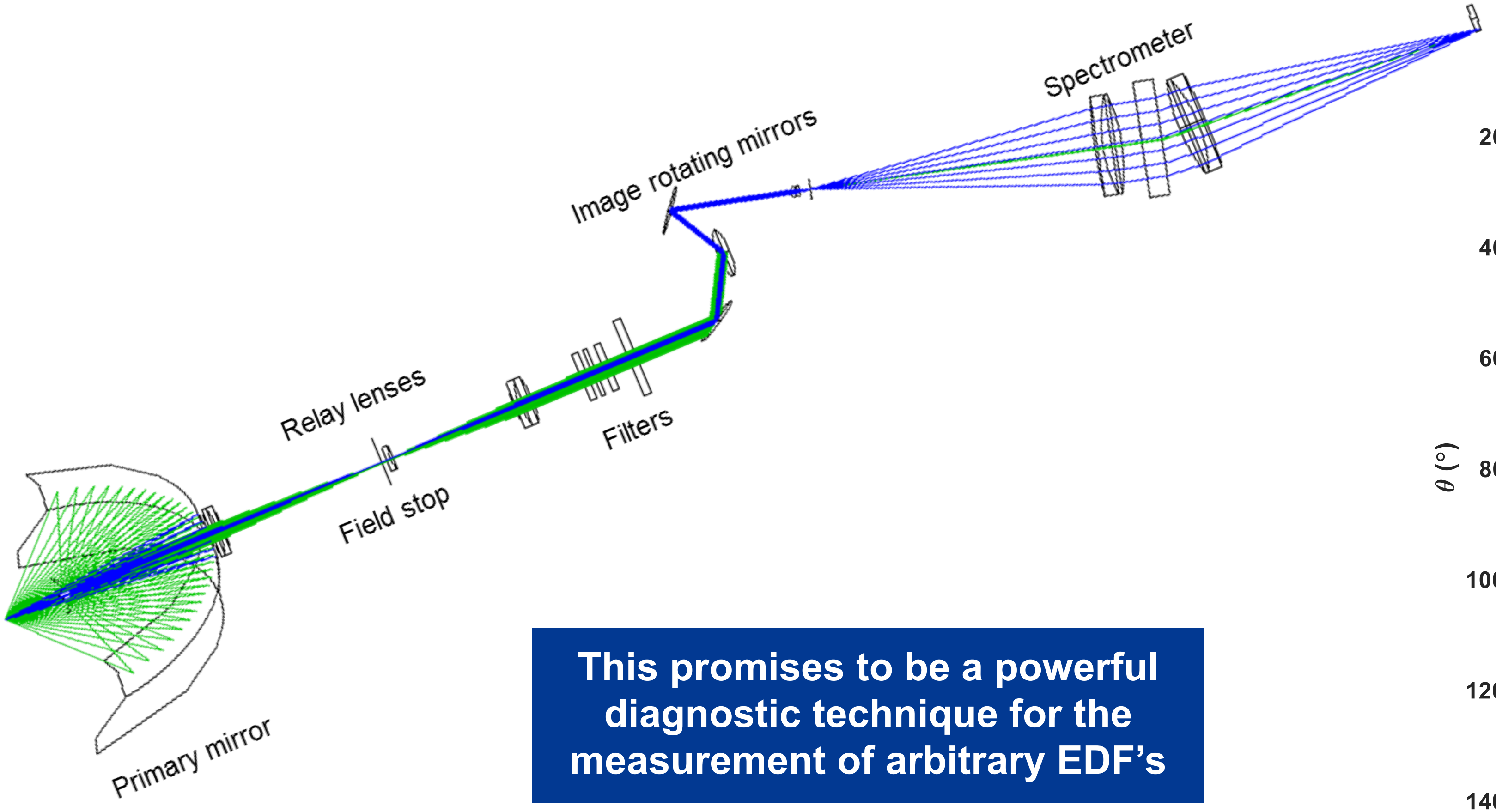


Thomson scattering with additional collection angles could help to fill in the electron distribution function

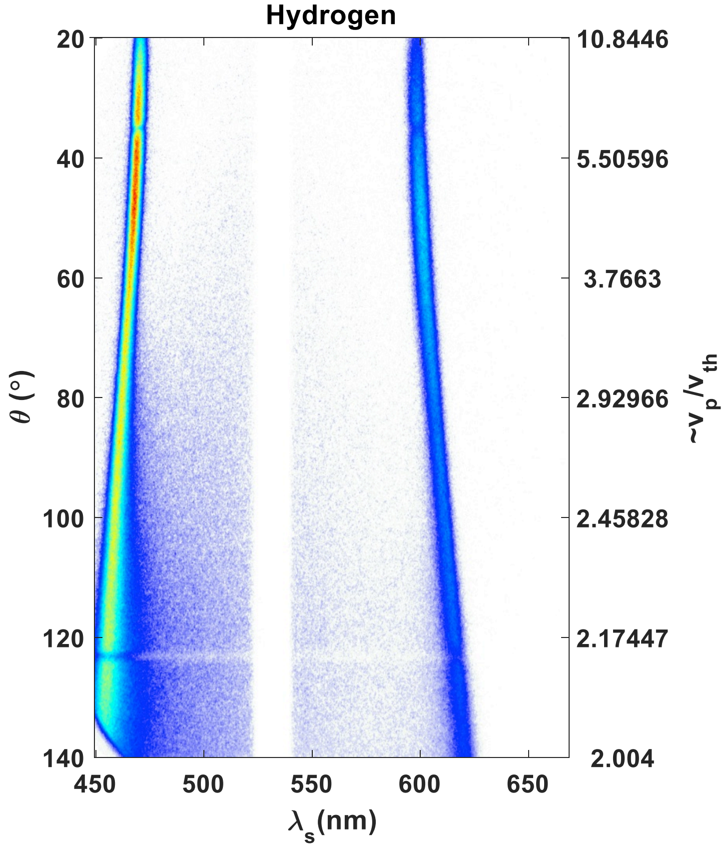




The angularly resolved Thomson scattering instrument allows for continuous collection over ~120° in scattering angle (A. Milder Ph.D. project under D. Froula)



This promises to be a powerful diagnostic technique for the measurement of arbitrary EDF's



† See talk by A. Milder in Session GO6, Tues AM

Summary/Conclusions

Dedicated crossed-beam energy transfer experiments are providing key insights that should improve the design of integrated implosions

- Two-beam pump-probe experiments at the Jupiter Laser Facility observed good agreement with traditional CBET modeling at plasma wave amplitudes beyond the range relevant to ICF (calling the usual saturation clamp into question)*
- But multi-beam experiments at LLE (with more ICF relevant conditions) have shown that non-Maxwellian electron distribution functions (EDF's) driven by laser heating can strongly impact CBET; extrapolating to NIF conditions gives a ~30% reduction in gain (appears broadly consistent with the reduction imposed by the clamp)**
  - A non-Maxwellian inline CBET model should improve the predictive capability of integrated ICF implosions†
- Other processes affected by non-Maxwellian EDF's may be sensitive to the tails, which will be measured with angularly resolved Thomson scattering‡

A closer look at the potential impacts of non-Maxwellian EDF's should be undertaken by the ICF community

* P. Michel et al., PRL 113, 205001 (2014);
D. Turnbull et al., PRL 116, 205001 (2016);
D. Turnbull et al., PRL 118, 015001 (2017);
D. Turnbull et al., PPCF 60, 054017 (2018).
** D. Turnbull et al, accepted to Nat. Phys. (2019).
† Under development by D. Strozzi & P. Michel
‡ See talk by A. Milder in Session GO6, Tues AM