100-joule laser as a probe of Thomson scattering and a pump for interdisciplinary research in the Compact Helical Device

Kentaro Sakai

Plasma Quantum Process Unit

National Institute for Fusion Science

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超高温プラズマの「ミクロ集団現象」と核融合科学

[1] KS+ PPCF (2026), [2] KS+ JINST (2026)

Summary

- Conceptual design of Thomson scattering system for non-Maxwellian
- Energetic laser + multichannel spectrometer enable us to measure the spectral shapes
  - Even with high T_e and low n_e
  - Monte Carlo simulations reveal a high S/N ratio
- Inverse problem analysis demonstrates non-Maxwellian can be identified

大学共同利用機関法人 自然科学研究機構
核融合科学研究所
National Institute for Fusion Science

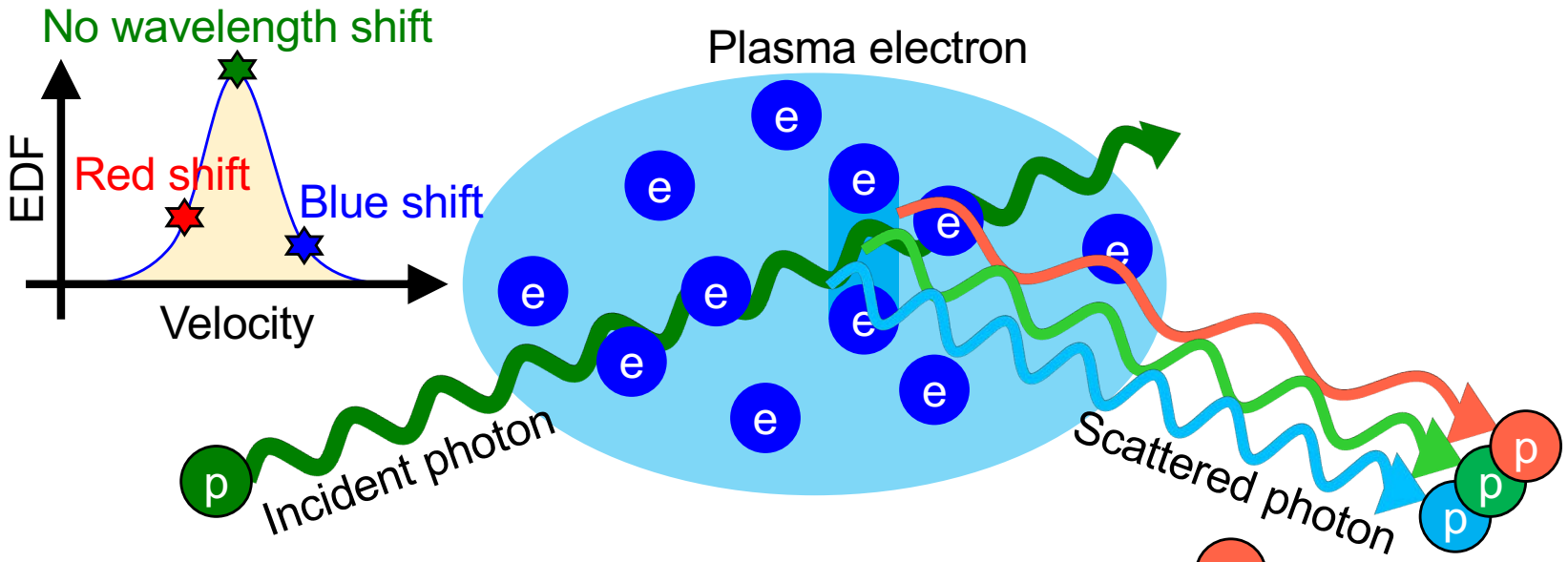
北海道大学
HOKKAIDO UNIVERSITY

超高温プラズマの「ミクロ集団現象」と核融合科学

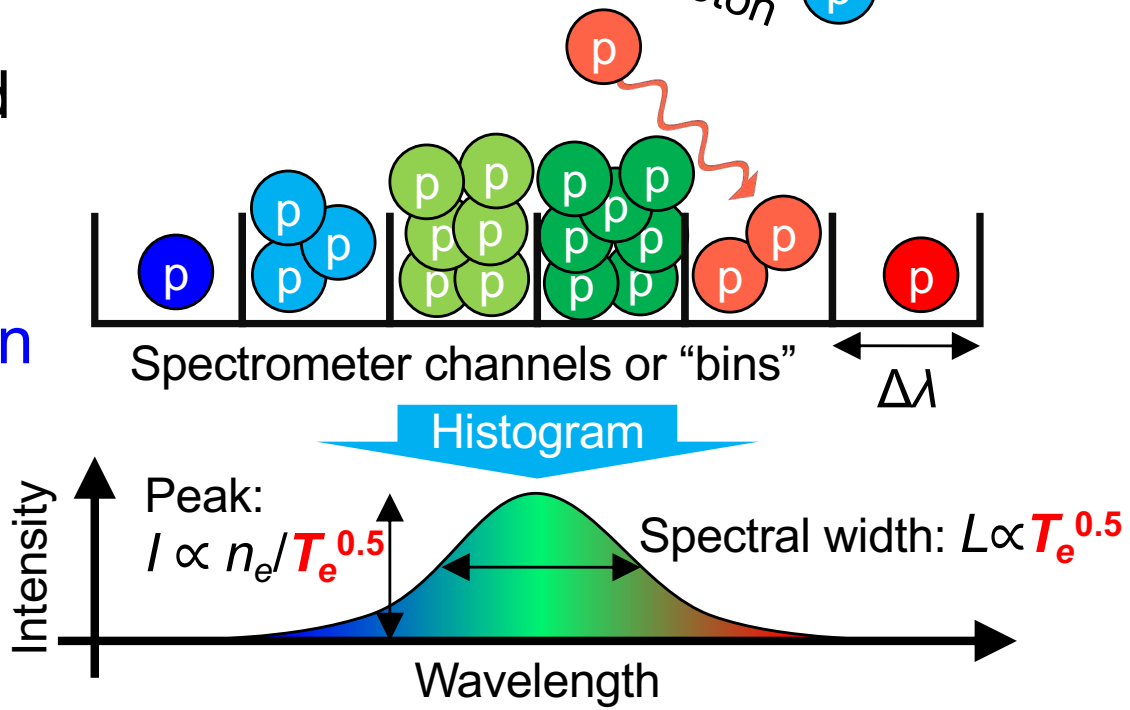
MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

KS+ PPCF (2026); arXiv:2511.06330
KS+ JINST (2026); arXiv:2508.20627

Thomson scattering



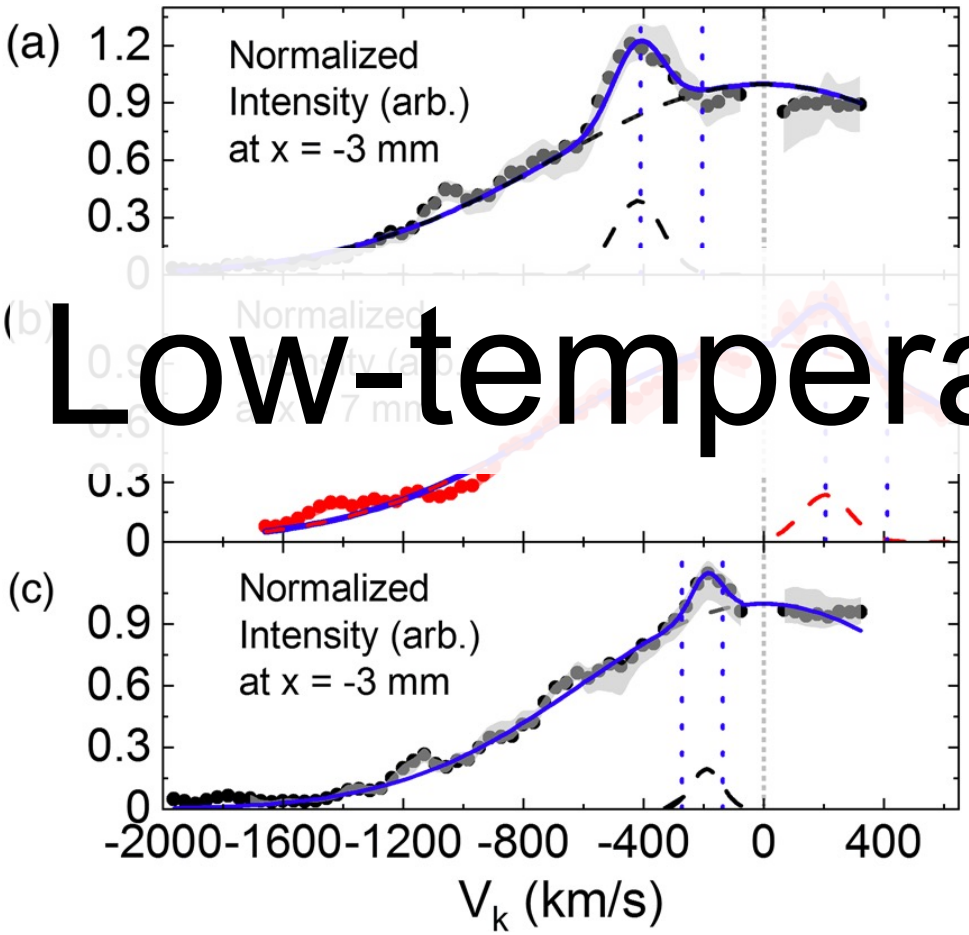
- Light scattering by charged particles
- Doppler spectroscopy of electron – shape of electron distribution function (EDF)
- Histogram of scattered photons relates to EDF



Froula+ (2011)

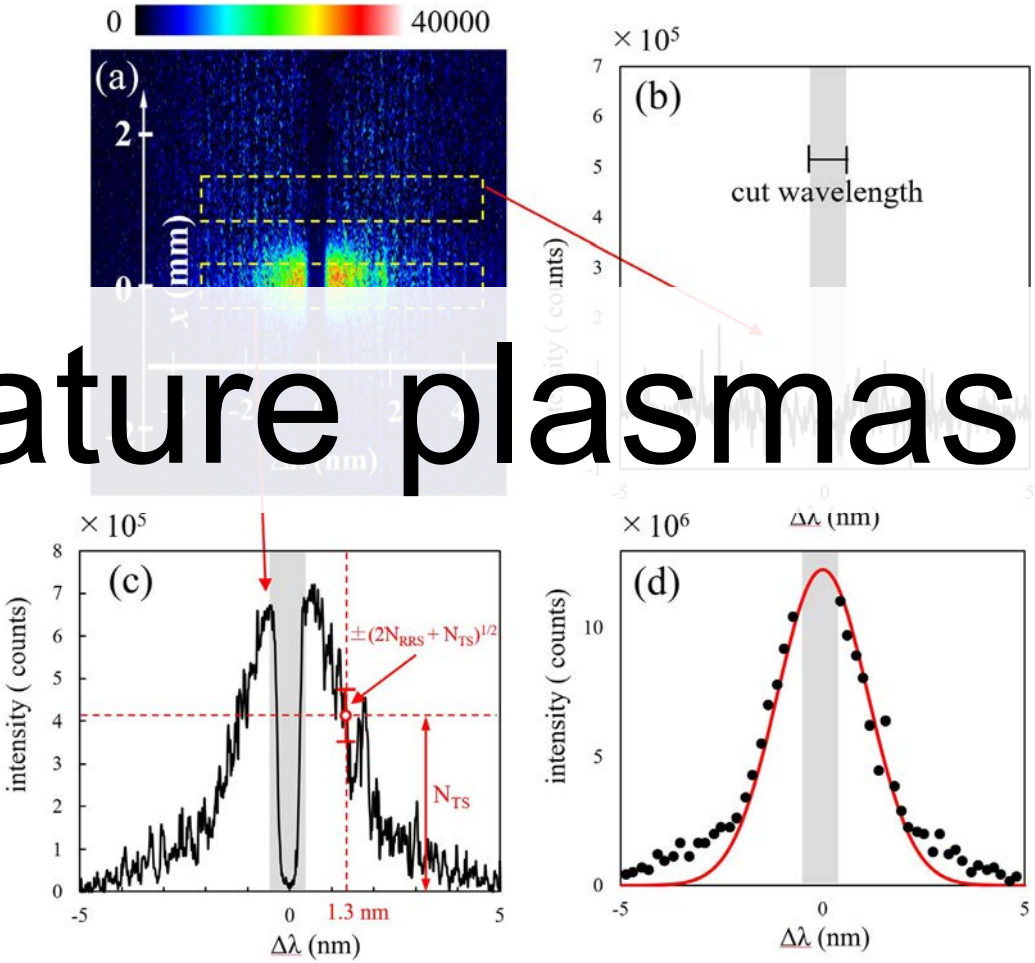
Detection of non-Maxwellian with Thomson scattering

Electron beam due to reconnection



Shi+ PRL (2022)

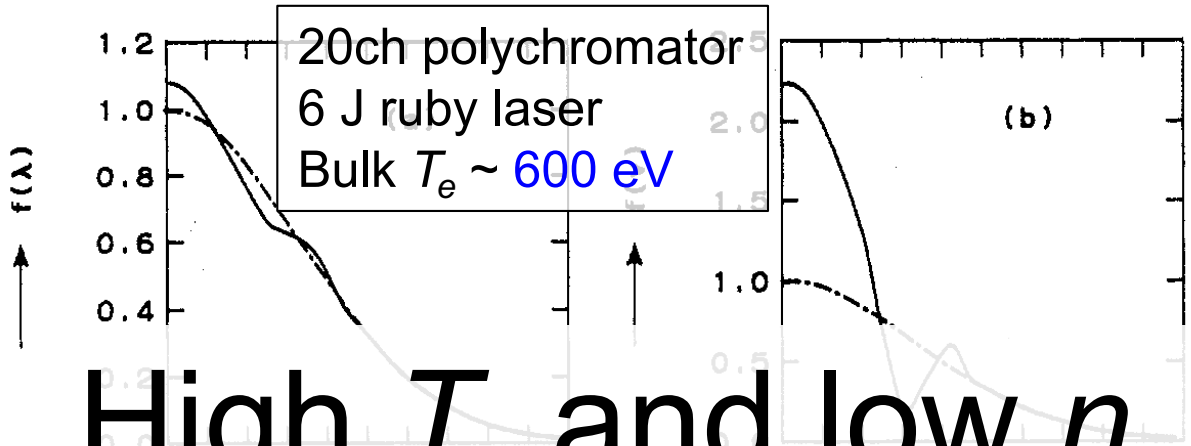
High-energy tail in streamer discharge

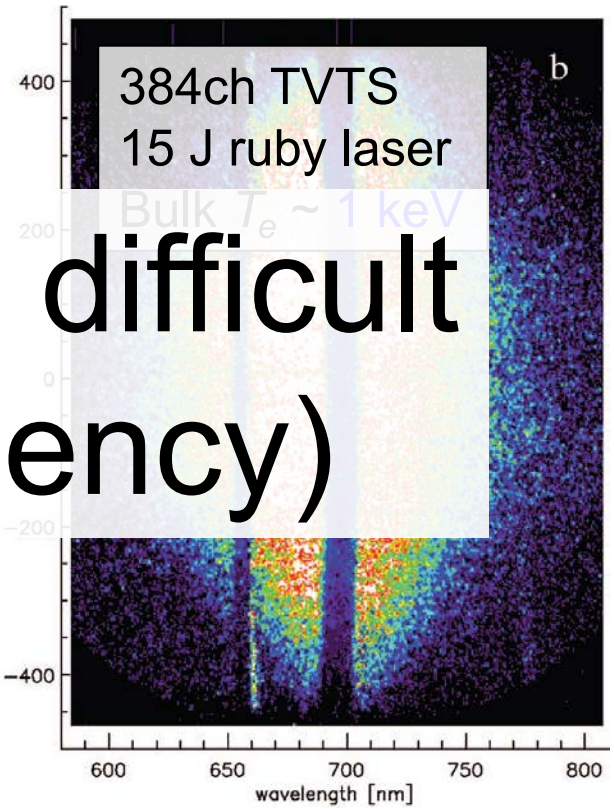


Tomita+ J. Phys. D: Appl. Phys. (2020)

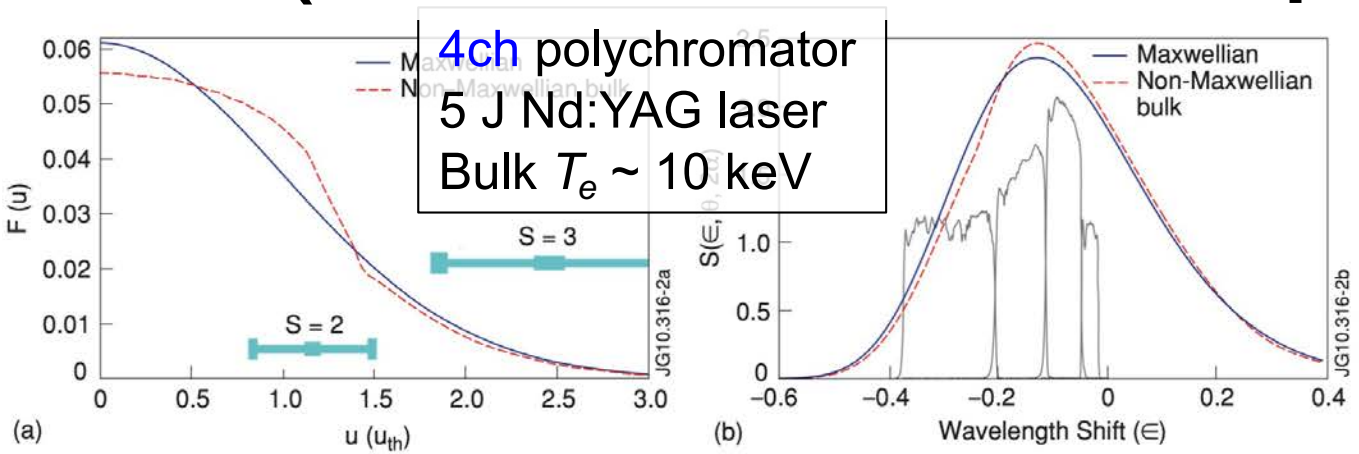
Low-temperature plasmas

Detection of non-Maxwellian with Thomson scattering





High T_e and low n_e is difficult (low collision frequency)



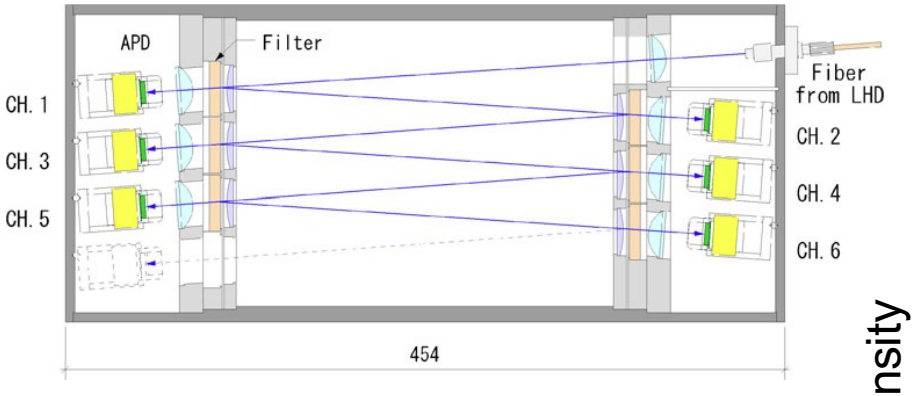
van der Meiden+ RSI (2006)
No clear non-Maxwellian

Beausang+ RSI (2011)
Mostly based on ECE measurements

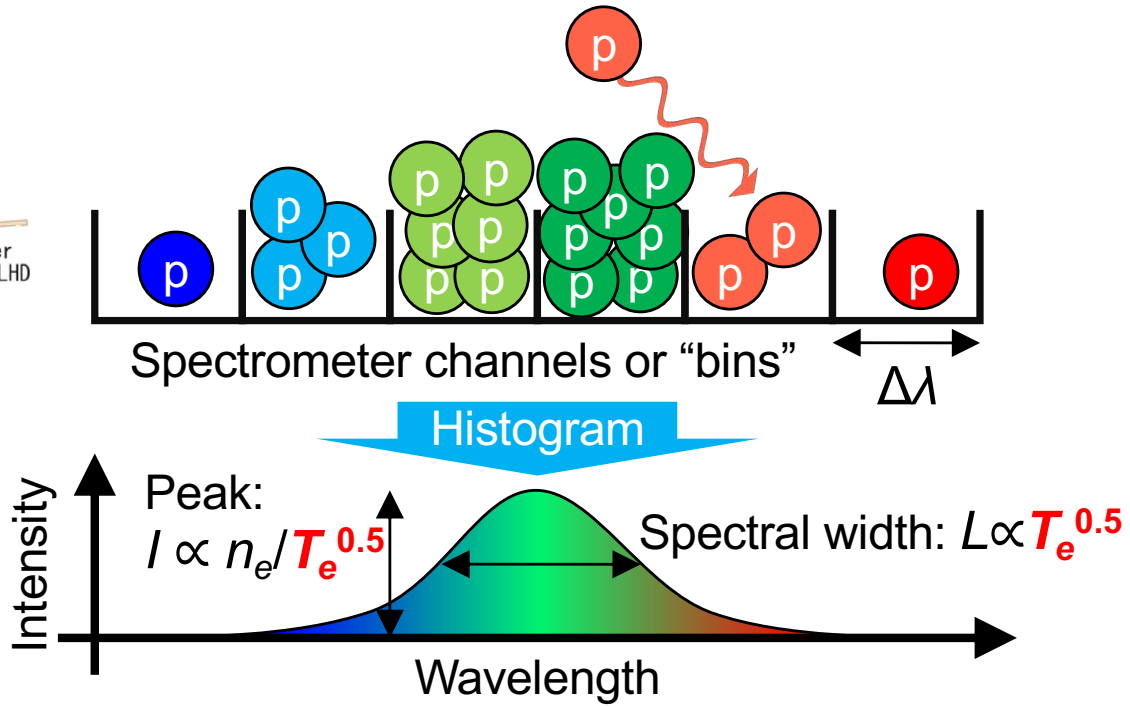
Requirements to observe EDFs

- High wavelength resolution ($\Delta\lambda \ll L$) for EDFs
- Poor S/N with **high T_e**, low E_L, and small $\Delta\lambda$
  - **MCF plasmas!**
  - Conventionally, $\Delta\lambda$ is enlarged to increase S/N ratio

Typical system in MCF plasmas:
filtered polychromator array (~10 ch)
with pulsed YAG laser (~1 J)



Yamada+ J. Fusion Energy (2025)



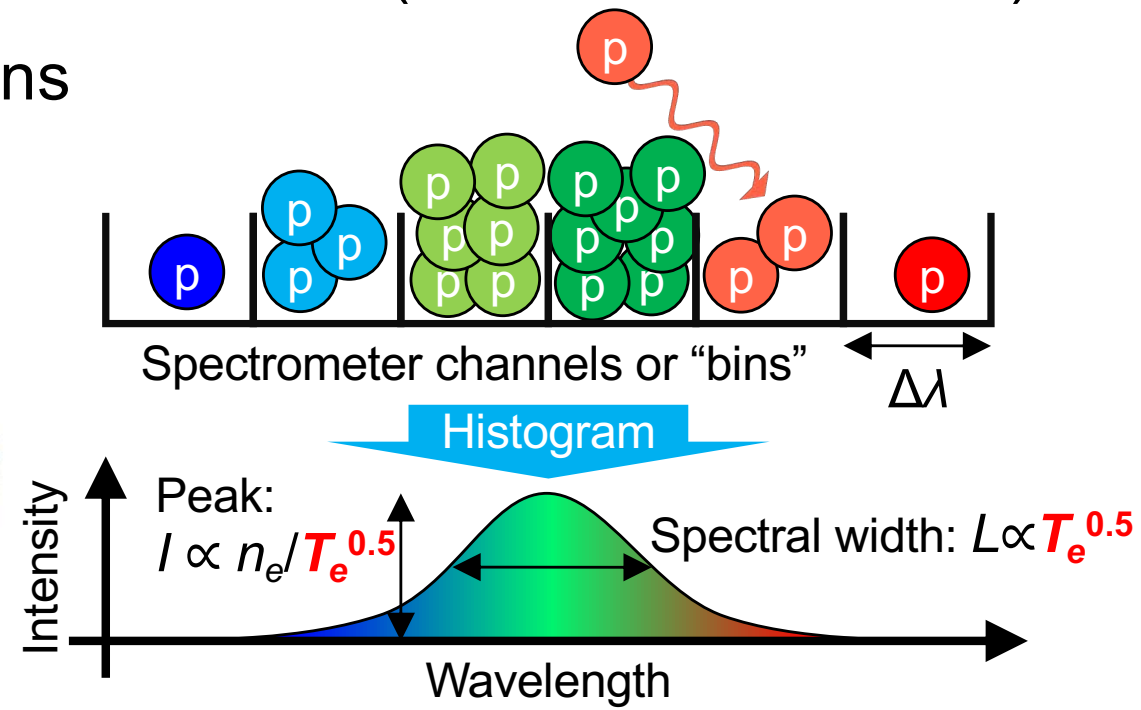
Requirements to observe EDFs

- To overcome this, we propose to use
  - Multichannel spectrometer (10→**1000 ch**)
  - Super-strong probe laser (1→**100 J**)

100 times each from typical system

S/N should be similar
(0th order estimation)

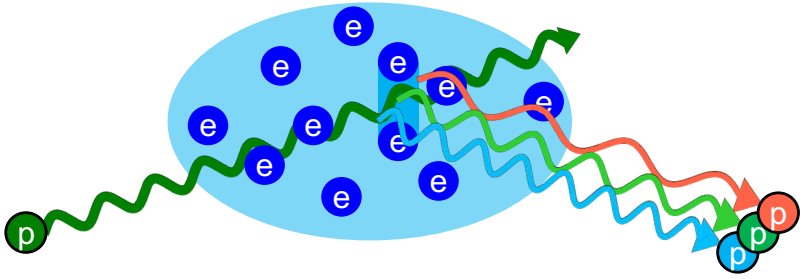
- Elite HE (Amplitude)
  - 100 J @ 1053 nm
  - Pulse duration: 15 ns
  - **2億円以上!!!!!**

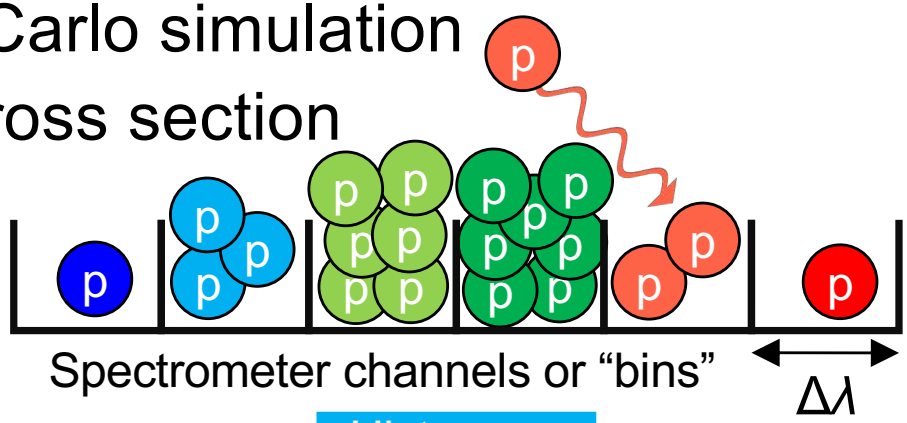


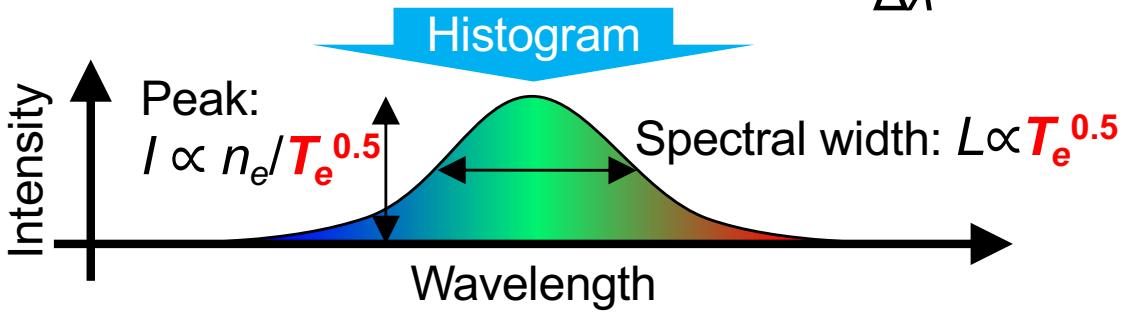
Monte Carlo simulation of TS to evaluate system performance

- Unknown things of the idea;
  - Signal-to-noise ratio
  - How the spectrum looks like with non-Maxwellian
- We developed a simulation method of TS
  - Individual photon scattering as a stochastic process
  - Stochastic ➡ Monte Carlo simulation
  - Based on Thomson cross section

Treat individual interaction between electron and photon







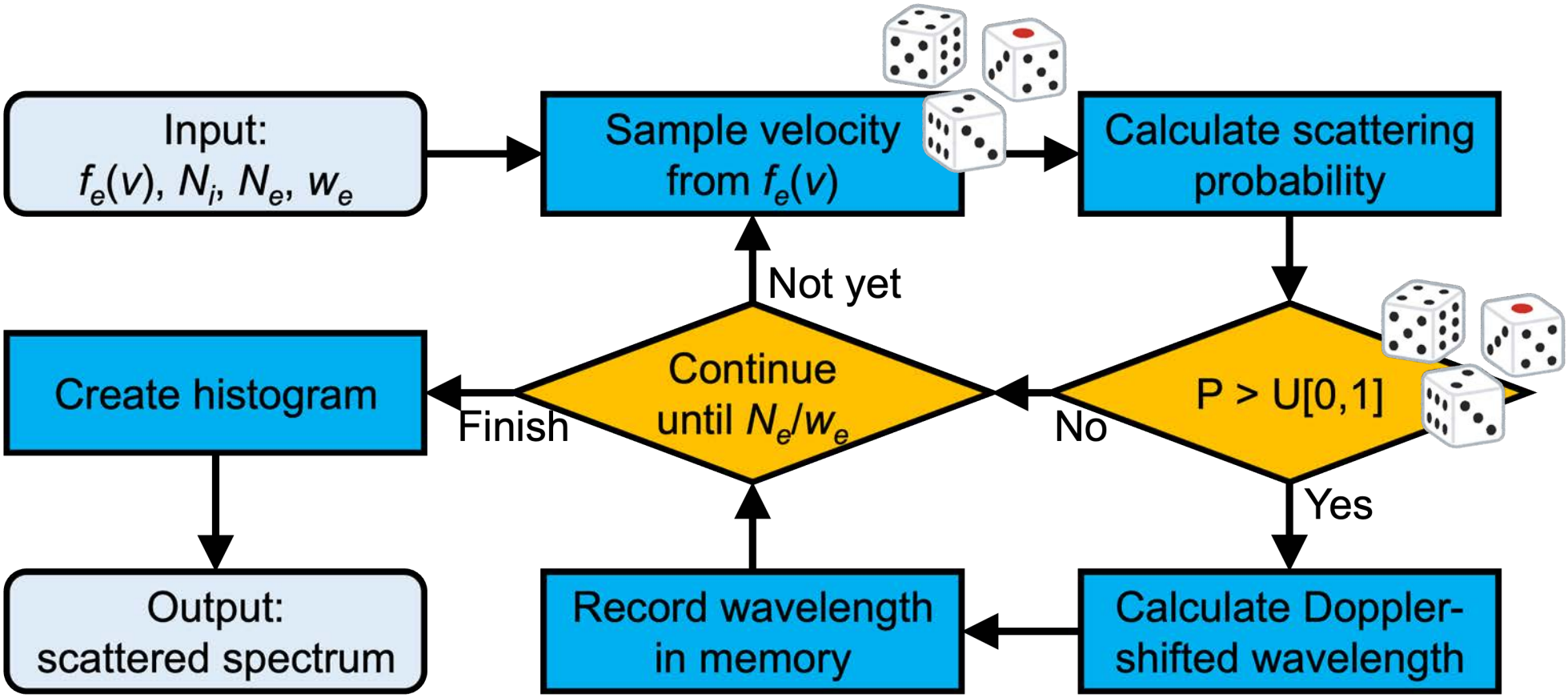
Concept of Monte Carlo sim.

$$N_{e^-} = \sum_{j}^{N_i} \sum_{k}^{N_e} \underbrace{\frac{\Delta\Omega}{S} \frac{d^2\sigma_T^{rel}}{d\omega_s d\Omega} \varepsilon_d}$$

Expected number of photoelectron
~ scattering probability for an electron and a photon

- Calculate the expected number of detected photoelectron (~scattering probability)
- Accept according to the scattering probability
- Repeat for all the electrons (~10^{13}) and photons (10^{20})
- Too huge calculation – macro-particle (like PIC)

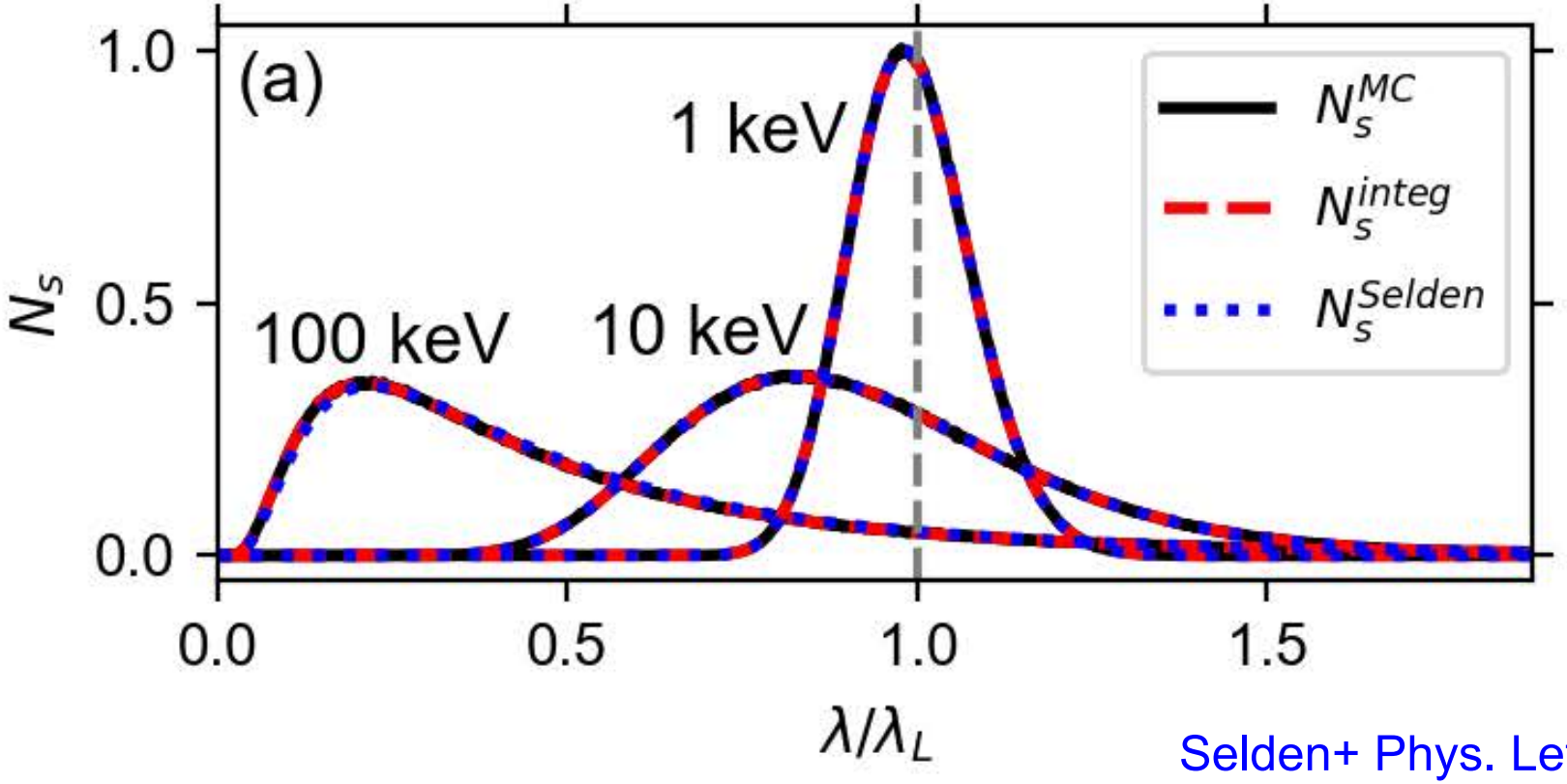
How simulation works



- Continue the loop for all the macro-particles
- The weight of a single macro-particle is adjusted so that $P \lesssim 1$

KS+ JINST (2026)

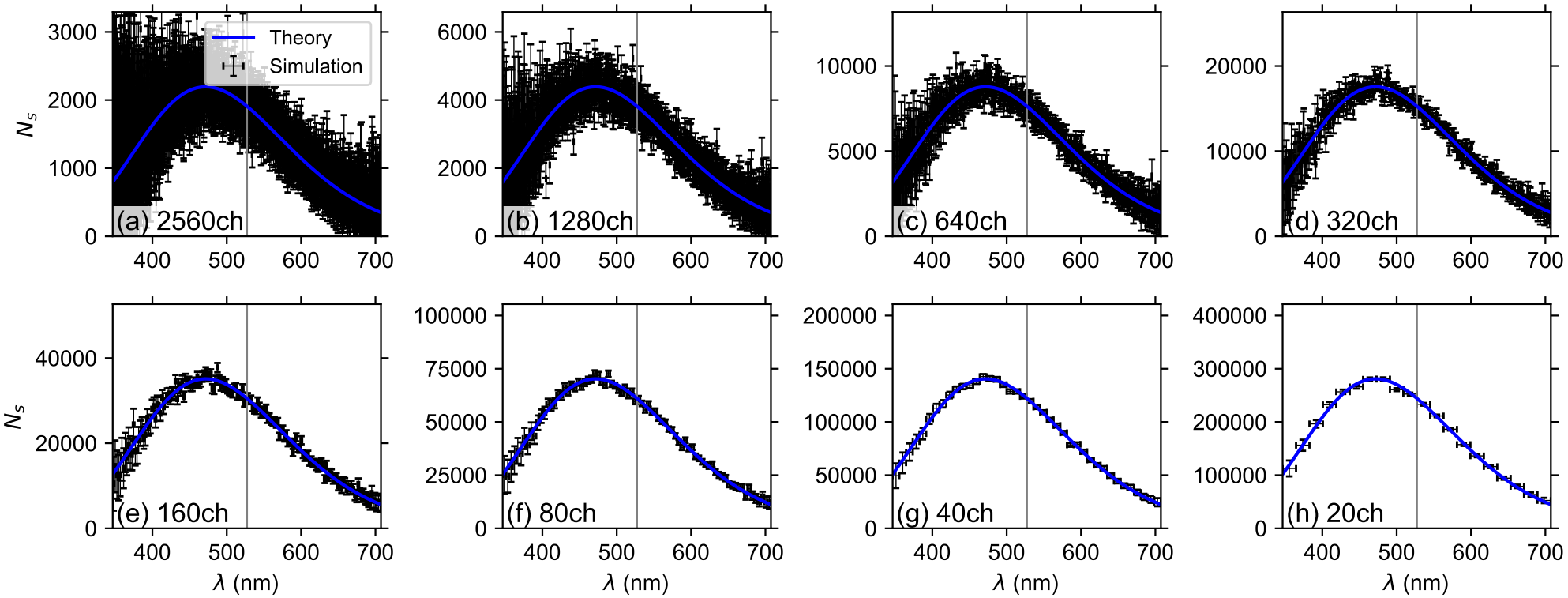
Validation: simulation vs theory



Selden+ Phys. Lett. A (1980)

- Simulated spectra well agree with both numerical and approximate analytical ones
- Better than the analytical model at high T_e

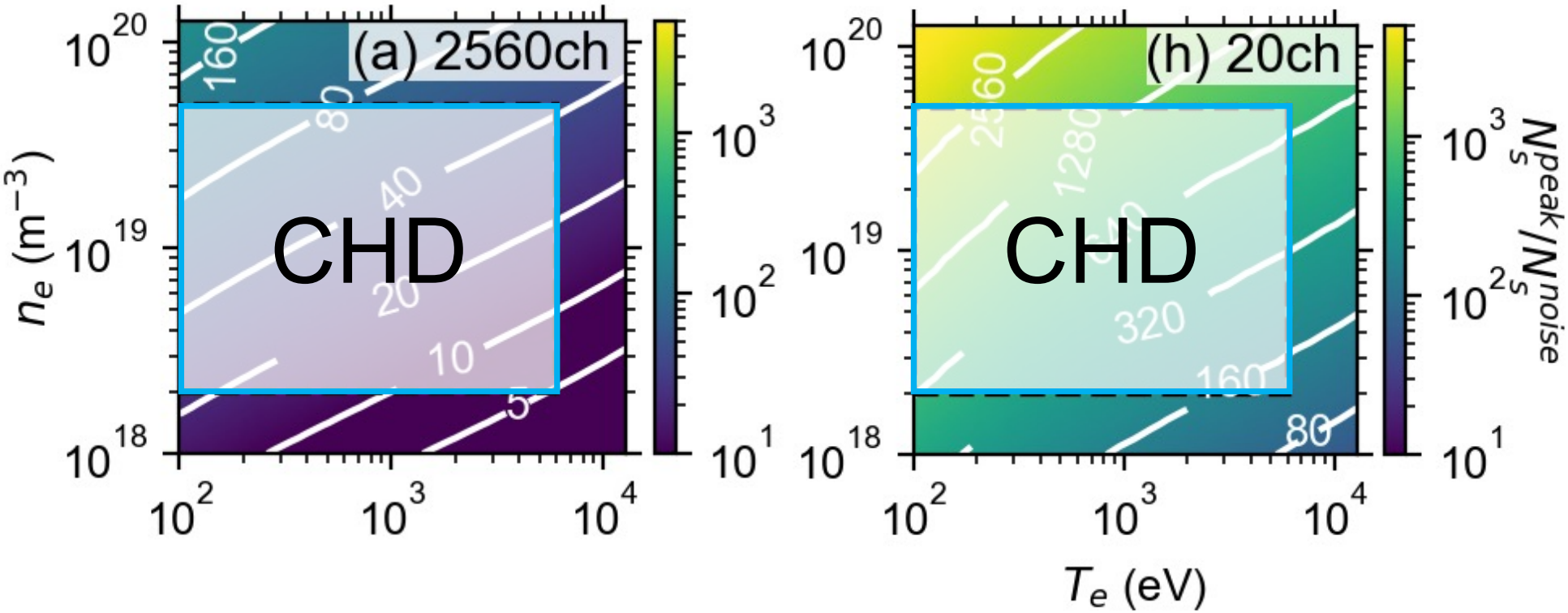
Signal-to-noise ratio



- An example: (T_e, n_e)=(6 keV, 2x10^{18} m^{-3})
- Looks so noisy with full resolution (2560ch)
- Noise level decreases as channel decreases
- Post-process binning is effective for better S/N

KS+ PPCF (2026)

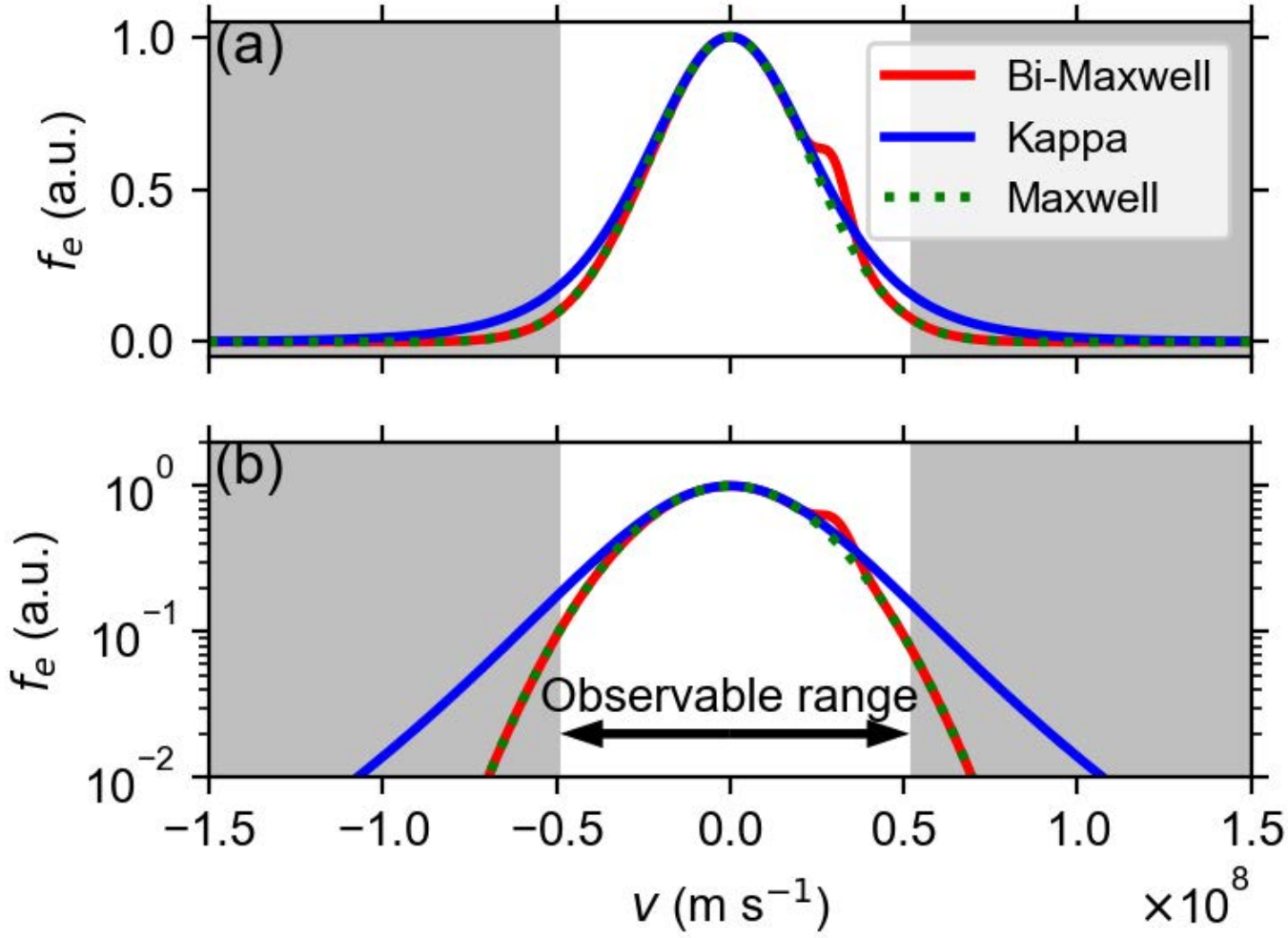
Signal-to-noise ratio



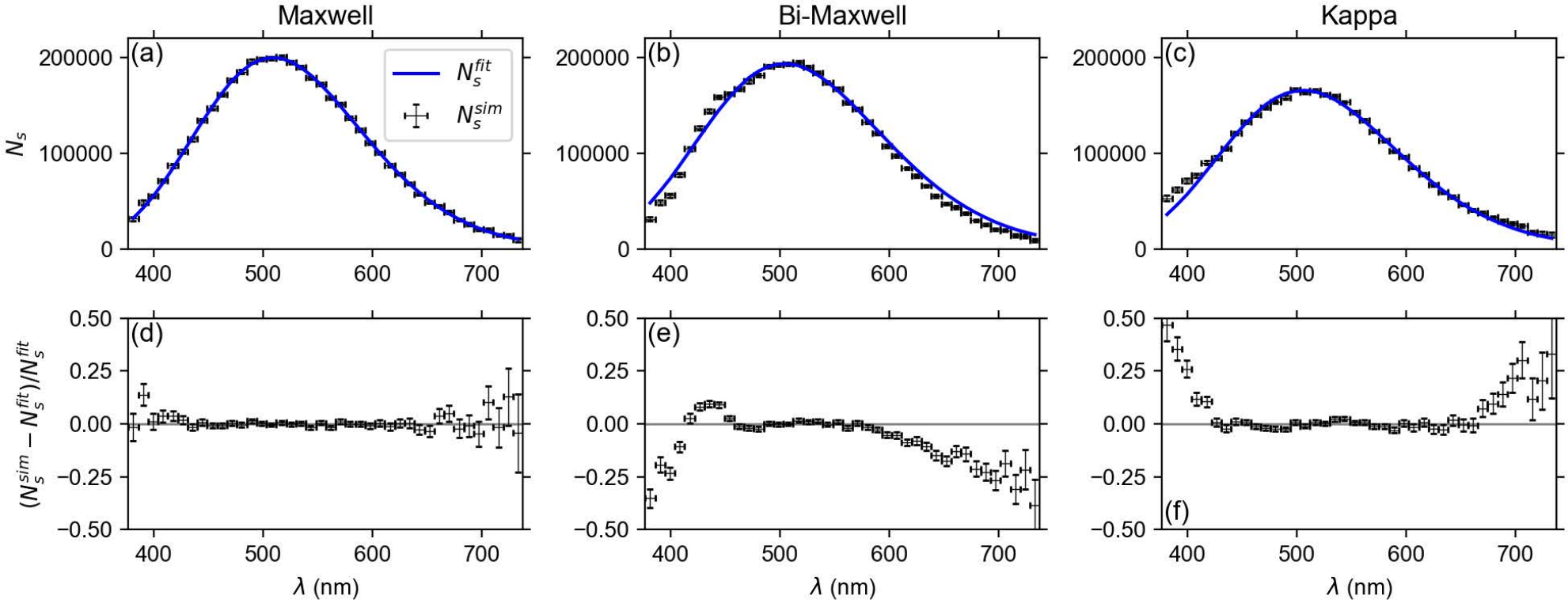
- S/N ratio as a function of T_e and n_e
- Decreases as T_e increases and n_e decreases
- Not so bad even with the highest resolution
- **We expect good S/N ratio for all plasma parameters expected in CHD**

Non-Maxwellian EDFs

- Two examples: kappa and bi-Maxwell
  - Maxwellian with high-energy tail
  - Bump-on-tail like (beam-plasma system)



Non-Maxwellian EDFs

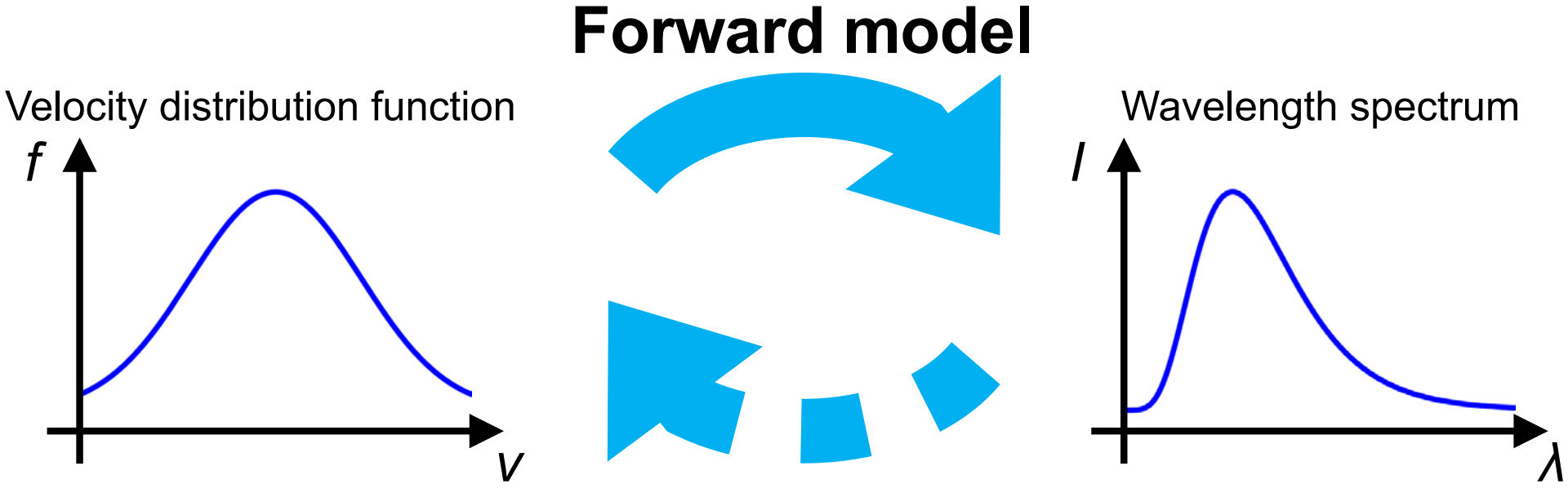


- Maxwell: no clear difference (obvious)
- Bi-Maxwell: bump and less signal at tail
- Kappa: tail is higher than the Maxwellian fit
- **We can find some deviations from Maxwellian because of fine S/N ratio**

Inverse problem analysis

- Forward model: calculate spectrum given EDF
  - Numerical integration or Monte Carlo simulation
- As an inverse problem solver, we use Bayesian inference

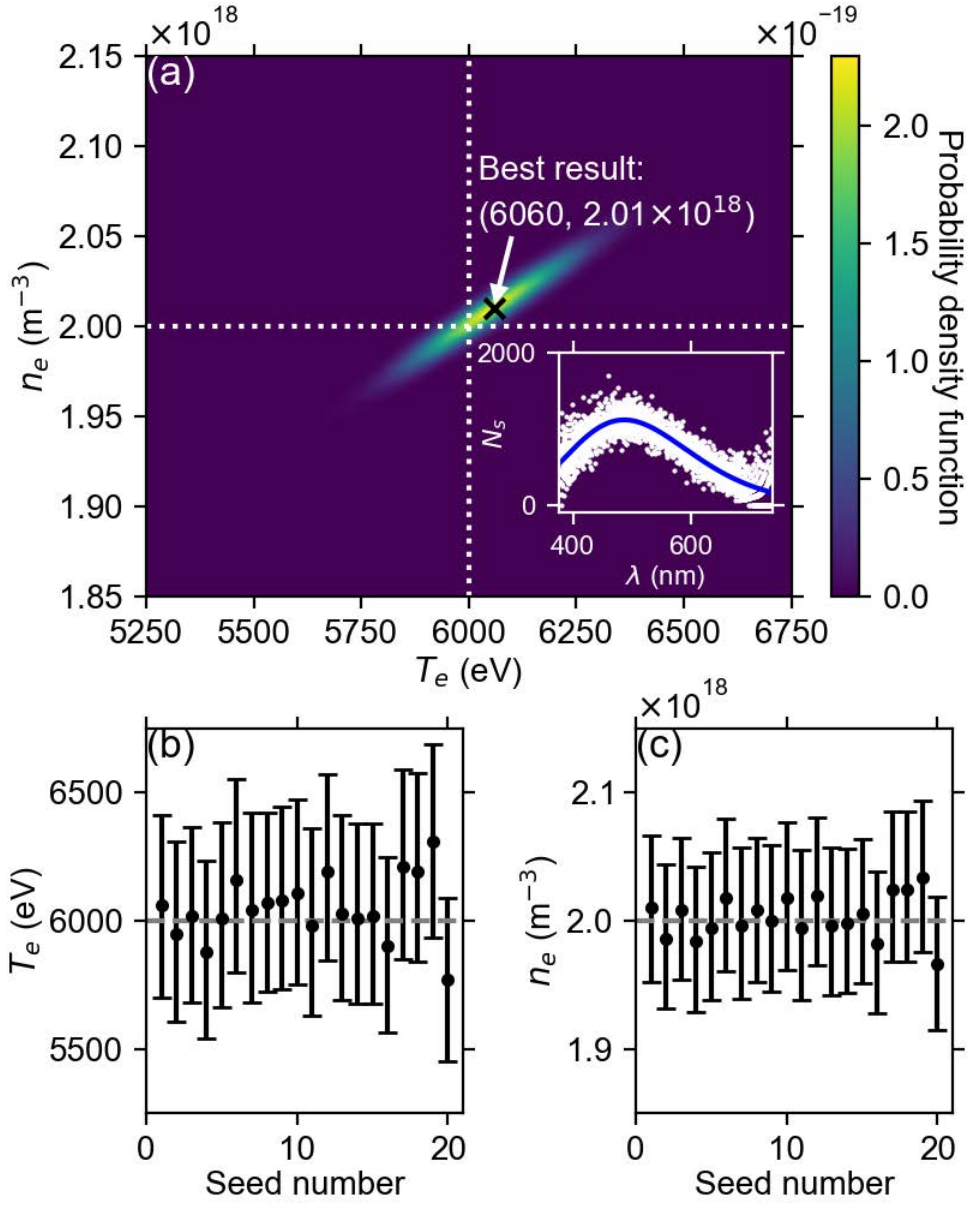
Motoyama+ Comput. Phys. Commun. (2022)



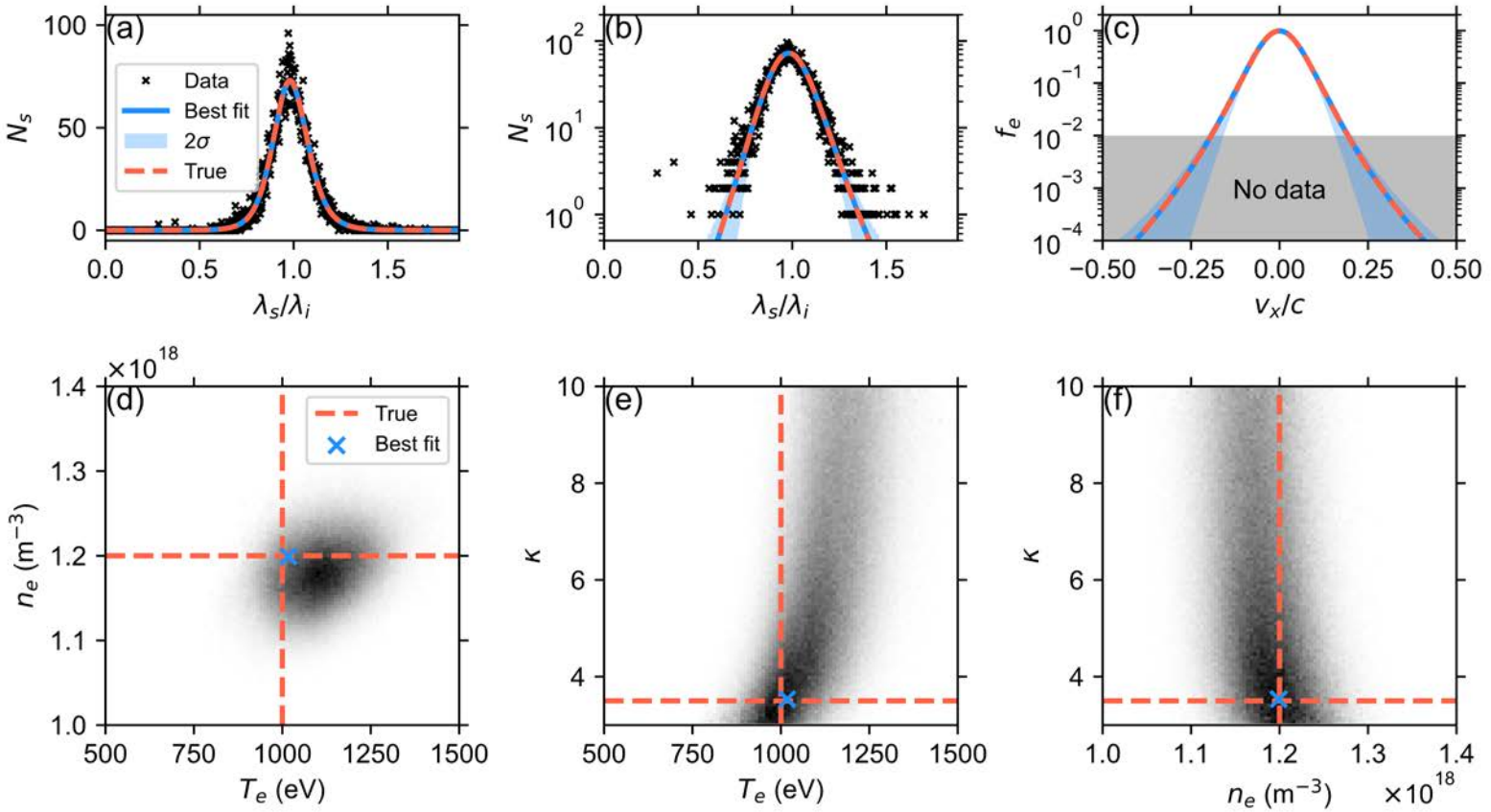
- No solution in general
- Massive in multi-dimension

Inverse problem analysis with Maxwellian EDFs

- Can we estimate T_e & n_e?
- We use the noisiest parameter expected in CHD
  - (T_e, n_e)=(6 keV, 2x10^{18} m^{-3})
- 20 simulated data
- True value is within the error bar
  - Also within the probability density function
- **Proof of high S/N ratio**



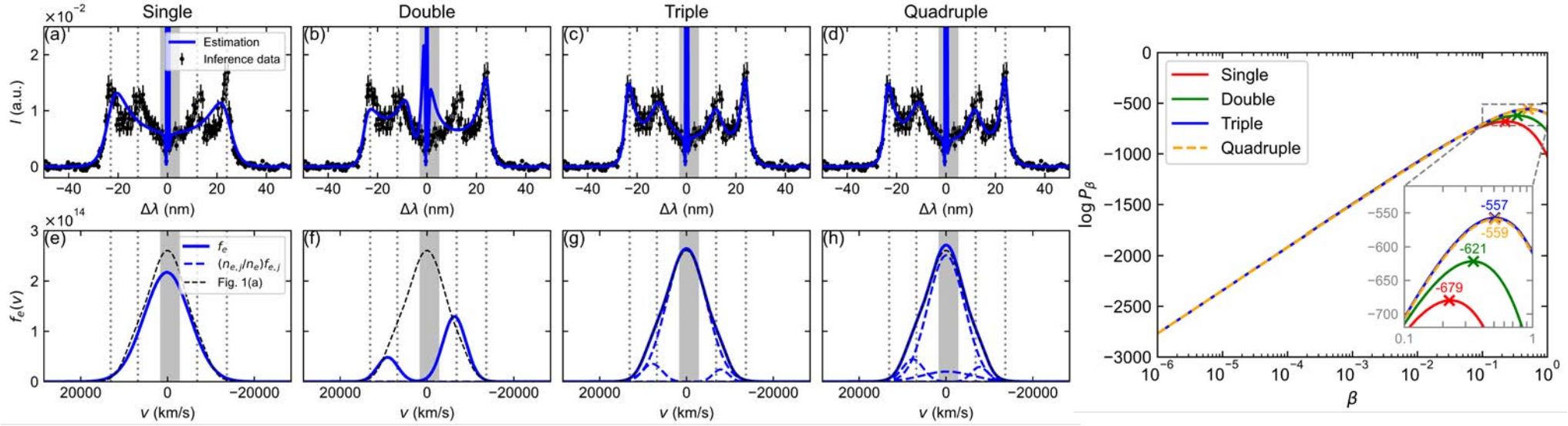
Inverse problem analysis with non-Maxwellian EDFs



- Synthetic spectrum with Kappa EDF
- True EDF is within the error bar of estimation
- Posterior shows kappa index is less sensitive

Discussion:
How can we distinguish EDFs?

- Electron phase-space tomography
  - Multi-pass for anisotropy — Kobayashi+ PoP (2023)
- Combination with fast Thomson scattering
  - Increase temporal resolution — Funaba+ Sci. Rep. (2022)
- Data science to remove preconceptions
  - Model evidence — Motoyama+ Comput. Phys. Commun. (2022)



Bayesian inference of collective Thomson scattering: KS+ submitted

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