‘Multicolor’ Soft X-ray Detector Sensitivities and Optimization

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ABSTRACT

'Multicolor' Soft X-ray (SXR) arrays have been used recently on the National Spherical Torus Experiment (NSTX) to provide fast (<1ms) measurements of electron temperature (T_e) perturbations. This system consists of three banks of detectors tangentially viewing the same plasma volume through a set of beryllium filters. By comparing the ratios of SXR intensity and emissivity, temperature information can be extracted from the signals which are functions of T_e, n_e, and impurity concentration. The present system relies on clean plasmas restricted to small concentrations of low-Z impurities for calculation of $T_e(r,t)$. Using the CHIANTI spectral code, one can add impurity line emission using measurements and estimates to expand the capabilities of the fast T_e measurement. The sensitivity of the calculation to impurities is a function of T_e and filter transmission. It will be shown that by optimizing the combination of filters, 'multicolor' SXR measurements can provide fast, robust T_e profile measurements while demonstrating both sensitivity and immunity to impurities.

Optimization of ‘multicolor’ filters can maximize sensitivity to changes in electron temperature while minimizing sensitivity to uncertainties in impurity concentrations.

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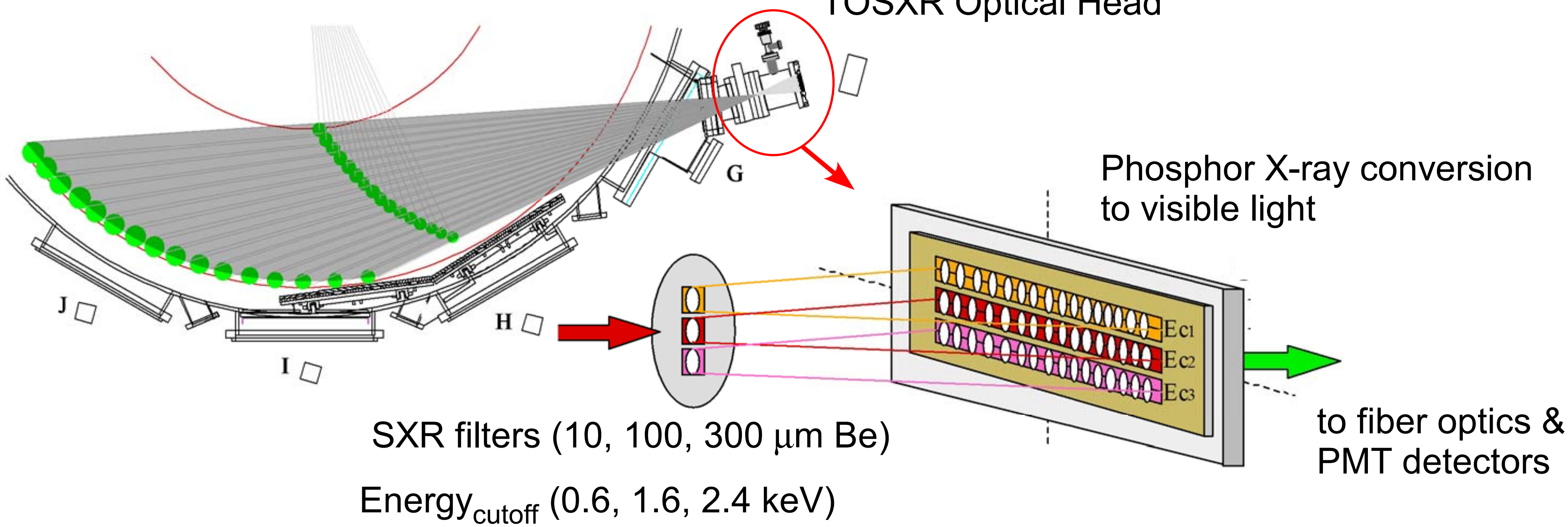
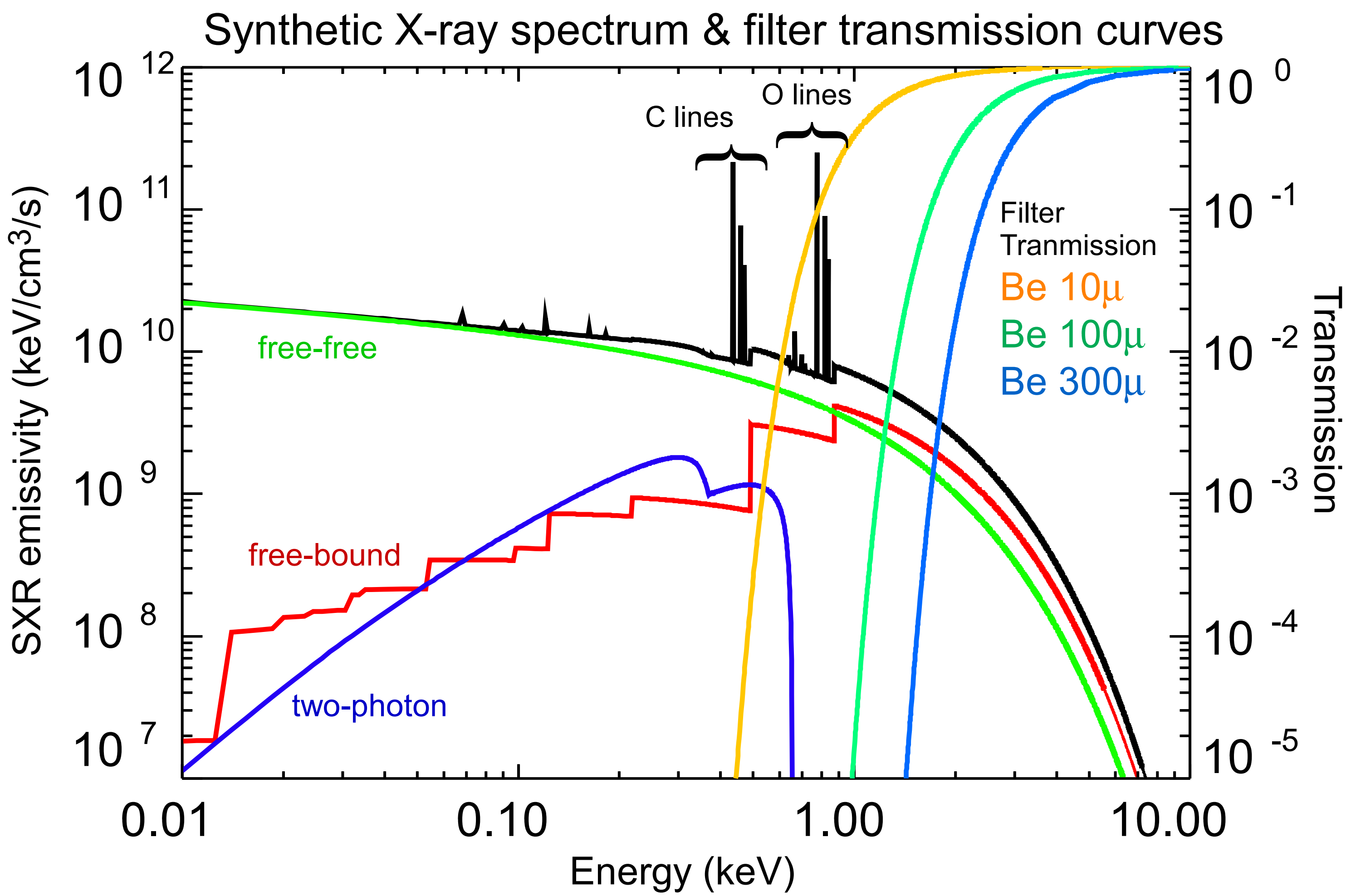
Multi-color SXR System Provides Fast $T_e(r,t)$ on NSTX

Multicolor Tangential Optical Soft X-ray Array



- “Multicolor” filters simultaneously samples same plasma volume
- Provides fast $T_e(R)$ via spectral fitting and normalization to Thomson profiles

Filters Provide Coarse Sub-sampling of SXR Spectrum



Plasma parameters

n_e = 1e13 cm^{-3}

T_e = 1keV

C = 2%

O = 0.5%

- CHIANTI X-ray spectral code computes line and continuum spectra
- Ratios of signals with different filters affected by T_e and impurities

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Approximation: Filter Ratios Sensitive to ΔT_e

- Assume plasma emission dominated by continuum radiation:

$$\frac{dP_x}{dh\nu} \sim \frac{1}{\sqrt{T_e(\mathrm{keV})}} \gamma(T_e, Z) Z_{eff} n_e^2 \exp\left(-\frac{h\nu}{T_e}\right)$$

- Ratio of measured SXR power depends on T_e and cutoff energy, E_c

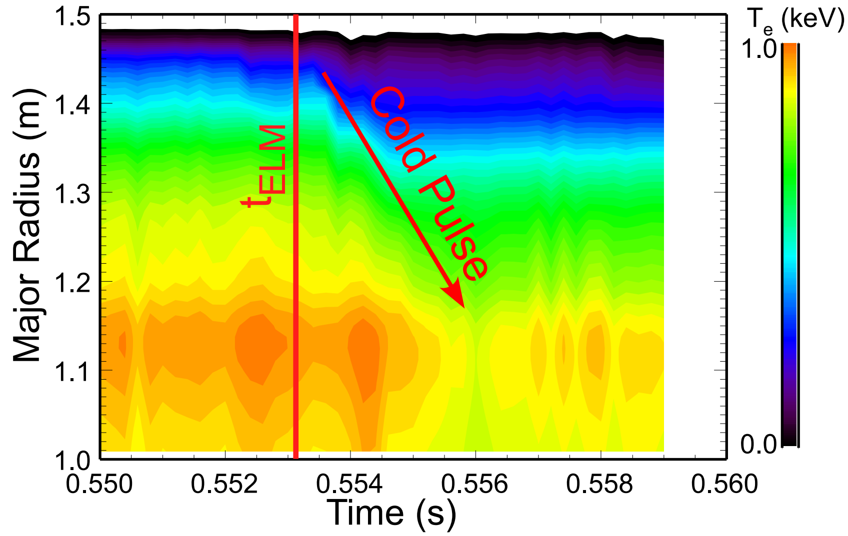
$$\mathrm{Ratio} \equiv R = \frac{P_1}{P_2} = \exp\left(\frac{-\Delta E_c}{T_e}\right)$$

- Normalize ratio to Multi-point Thomson Scattering (MPTS), use SXR ratios to propagate ΔT_e in time

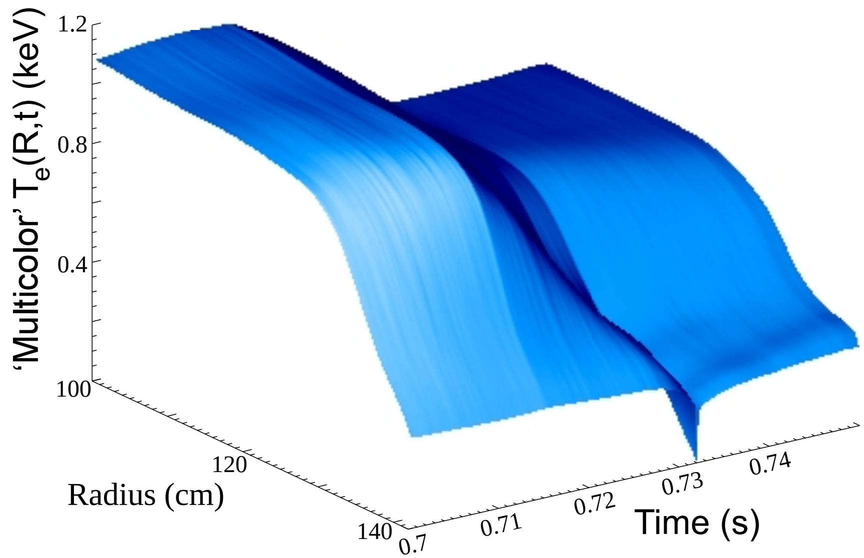
SXR System Observes Fast T_e Changes on NSTX

- 'Giant' ELMs induce cold pulse propagation from edge to core in ~few ms
- Fast $T_e(R,t)$ from SXR system provides measure of high perturbed χ_e

Calculated fast $T_e(R)$ during ELM cold pulse



- Internal reconnection event causes fast redistribution of T_e
- Crash and peaking of T_e profile confirmed by MPTS system



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Linearization of X-ray Emission Equation for Response and Sensitivity Calculations

- Isolate and identify SXR contributions using linearized emission:

$$\varepsilon\left(n_e,T_e,f\right)=n_e^2\sum_{Z_i}c_i\int_{E_\nu}\mathcal{S}\left(n_e,T_e,Z_i\right)\mathcal{T}\left(f\right)dE_\nu=n_e^2\sum_{Z_i}c_i\mathcal{N}_i\left(n_e,T_e,f\right)$$

measured SXR emission — impurity concentration — integrated filtered CHIANTI spectrum — normalized impurity emission function

- Change in measured emission expressed as linear change in n_e, T_e, c_i

$$\Delta\varepsilon=\Delta n_e\frac{\partial\varepsilon}{\partial n_e}+\Delta T_e\frac{\partial\varepsilon}{\partial T_e}+\sum_{Z_i}\Delta c_i\frac{\partial\varepsilon}{\partial c_i}$$

$$\frac{\Delta\varepsilon}{\varepsilon}=\frac{2\Delta n_e}{n_e}+\Delta T_e\frac{\varepsilon'}{\varepsilon}+\sum_{Z_i}\Delta c_i\frac{\mathcal{N}_i}{\varepsilon}$$

- Filtered relative difference identifies sensitivity to ΔT_e, Δc_i

$$\left(\frac{\Delta\varepsilon_{f_1}}{\varepsilon_{f_1}}-\frac{\Delta\varepsilon_{f_2}}{\varepsilon_{f_2}}\right)=\Delta T_e\left(\frac{\varepsilon'_{f_1}}{\varepsilon_{f_1}}-\frac{\varepsilon'_{f_2}}{\varepsilon_{f_2}}\right)+\sum_{Z_i}\Delta c_i\left(\frac{\mathcal{N}_{i,f_1}}{\varepsilon_{f_1}}-\frac{\mathcal{N}_{i,f_2}}{\varepsilon_{f_2}}\right)$$

T_e sensitivity factor for f_1,f_2 — c_i sensitivity factor for f_1,f_2

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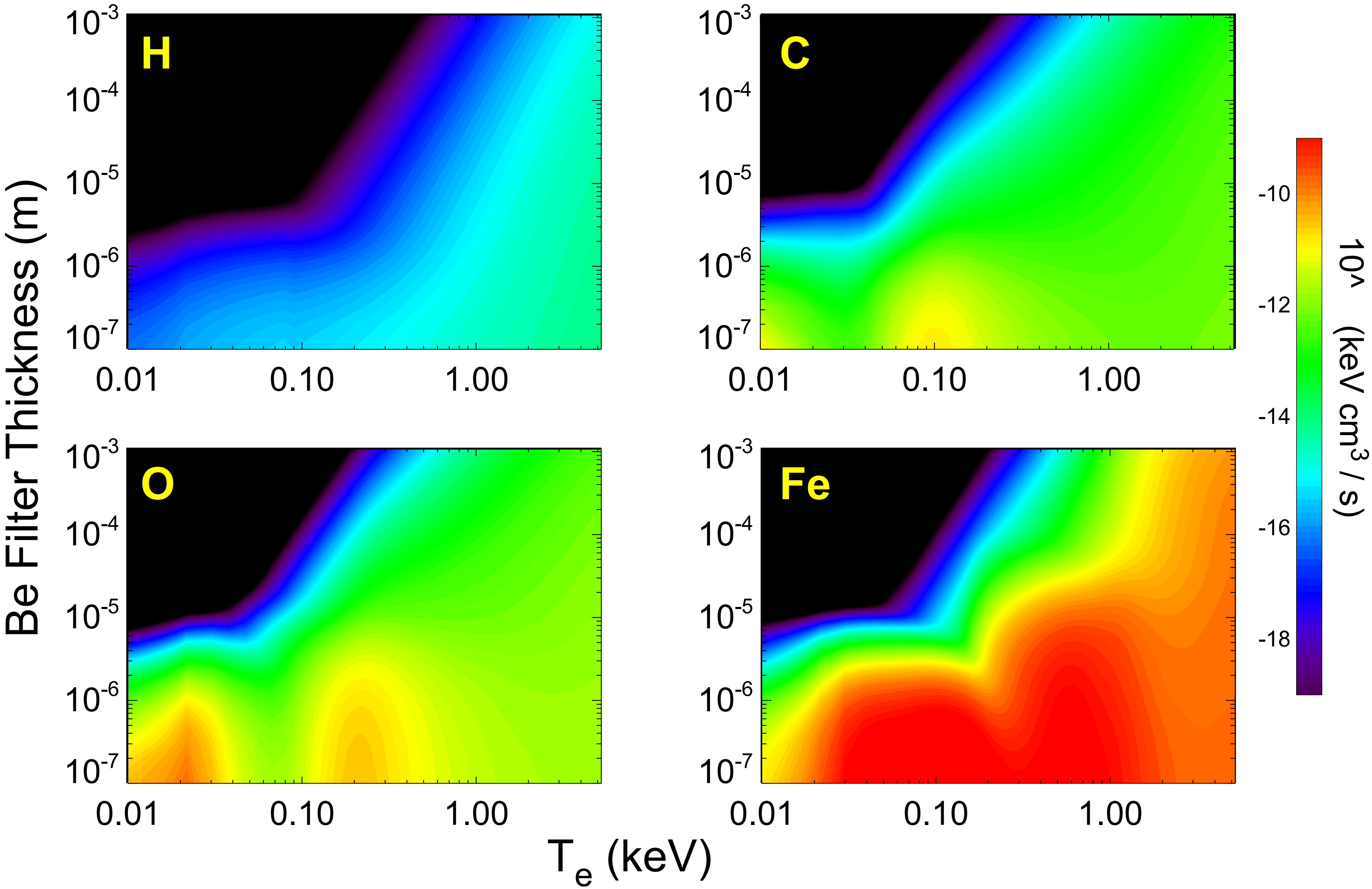
Pre-calculated Normalized Emission Functions, $\mathcal{N}$



3D Lookup Table Uses Tricubic Splines for Accurate Interpolated Response and Gradients

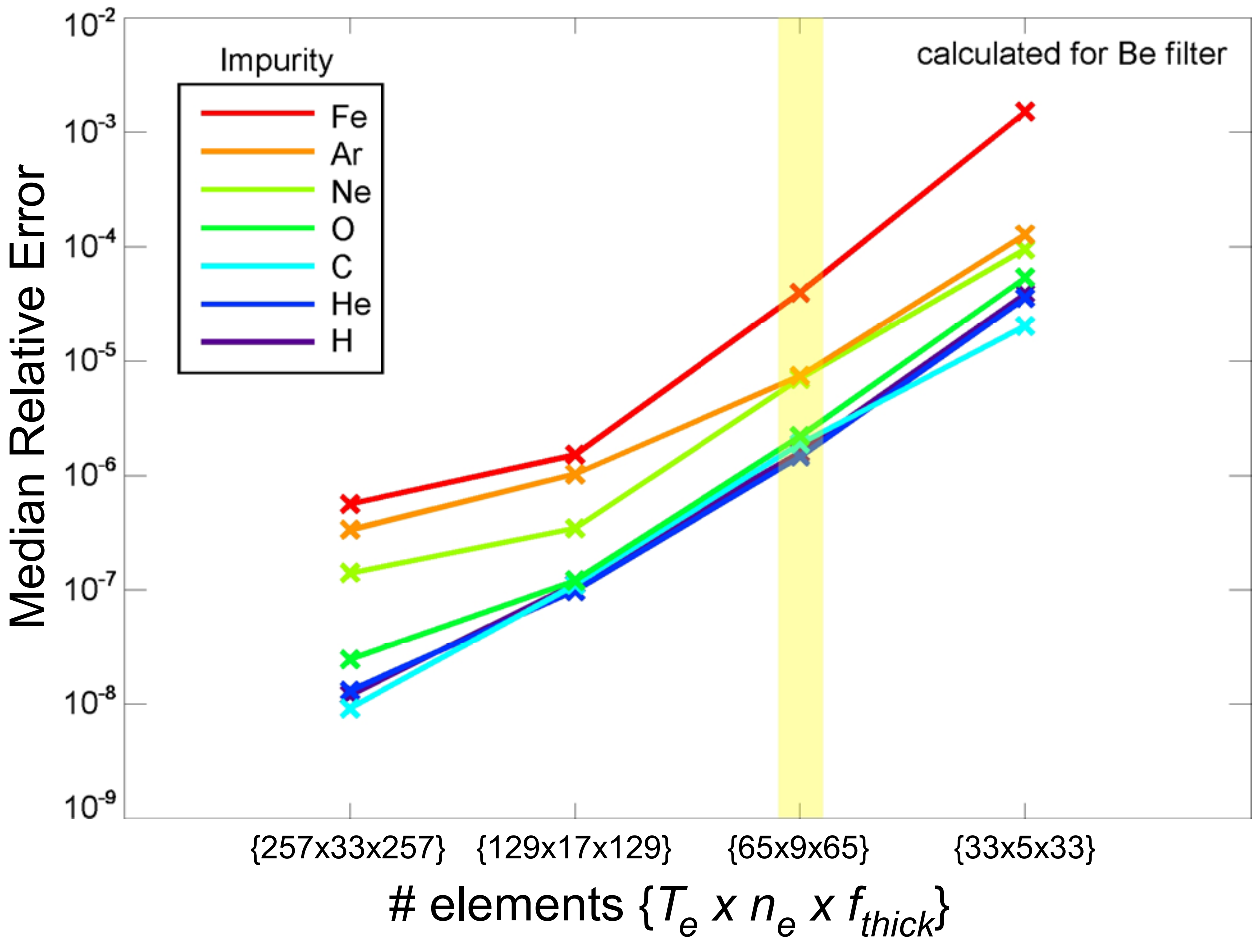


table size chosen to balance memory footprint vs. interpolation accuracy

T_e x n_e x f_{thick}	*Table Memory Footprint*
33x5x33	6MB
65x9x65	37M
129x17x129	260M
257x33x257	1900M

$$err = \frac{|calc\_emis - interp\_emis|}{calc\_emis}$$

- Tables precalculated for typical plasma impurities
- Tricubic splines use PSPLINE library, provides:

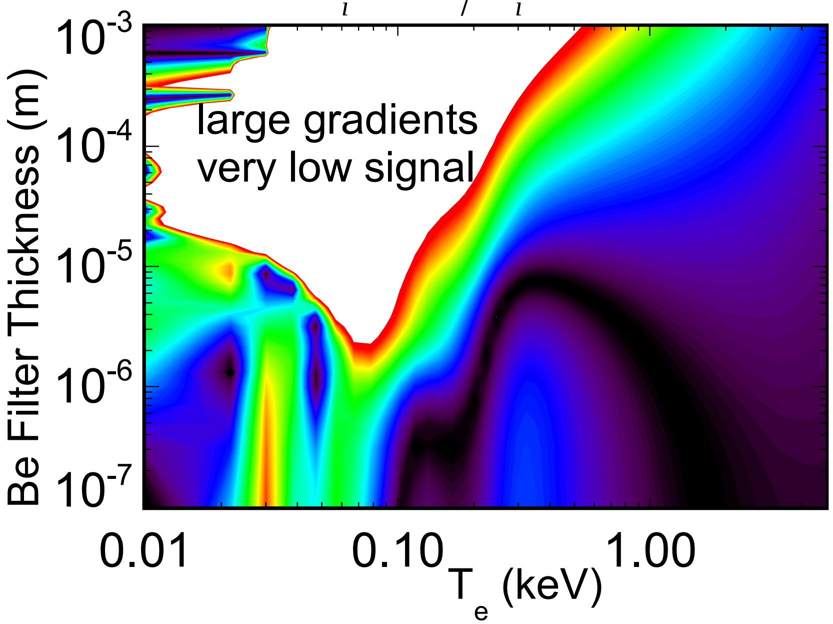
$$\mathcal{N}, \frac{\partial \mathcal{N}}{\partial T_e}, \frac{\partial \mathcal{N}}{\partial f_{thick}}, \frac{\partial^2 \mathcal{N}}{\partial f_{thick} \partial T_e}, \frac{\partial^2 \mathcal{N}}{\partial c_i \partial T_e}$$

T_e Sensitivity Maximizes Gradient Difference Weighted by Normalized SNR

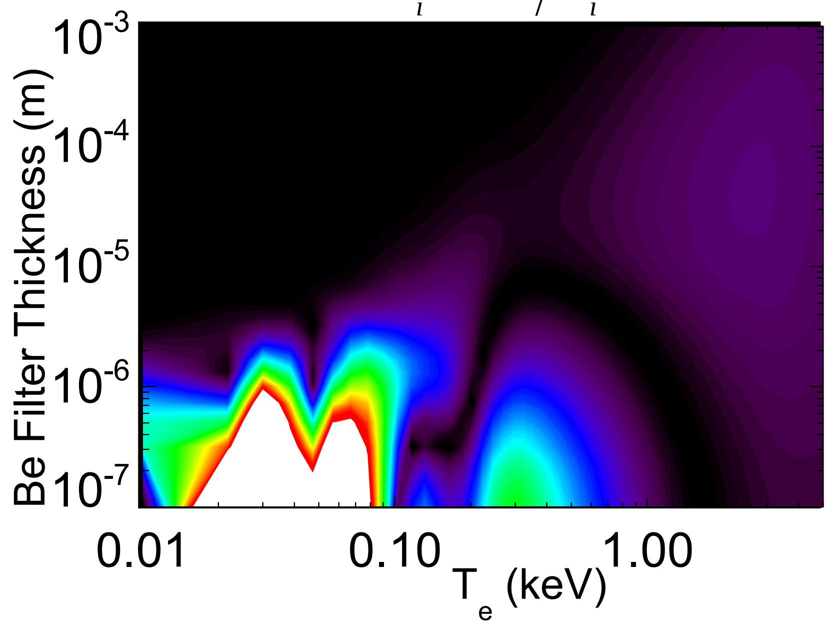
$$\left(\frac{\Delta\varepsilon_{f_1}}{\varepsilon_{f_1}}-\frac{\Delta\varepsilon_{f_2}}{\varepsilon_{f_2}}\right)=\Delta T_e\left(\frac{\varepsilon'_{f_1}}{\varepsilon_{f_1}}-\frac{\varepsilon'_{f_2}}{\varepsilon_{f_2}}\right)+\sum_{Z_i}\Delta c_i\left(\frac{\mathcal{N}_{i,f_1}}{\varepsilon_{f_1}}-\frac{\mathcal{N}_{i,f_2}}{\varepsilon_{f_2}}\right)$$

- Identify regions of high gradient
- Emission measurement accuracy depends on SXR signal levels
- Use SNR weighted gradient values for filter optimization at given T_e

$$\sum_i c_i \mathcal{N}' \Big/ \sum_i c_i \mathcal{N}$$



$$SNR(\mathcal{N})\cdot\sum_i c_i \mathcal{N}' \Big/ \sum_i c_i \mathcal{N}$$



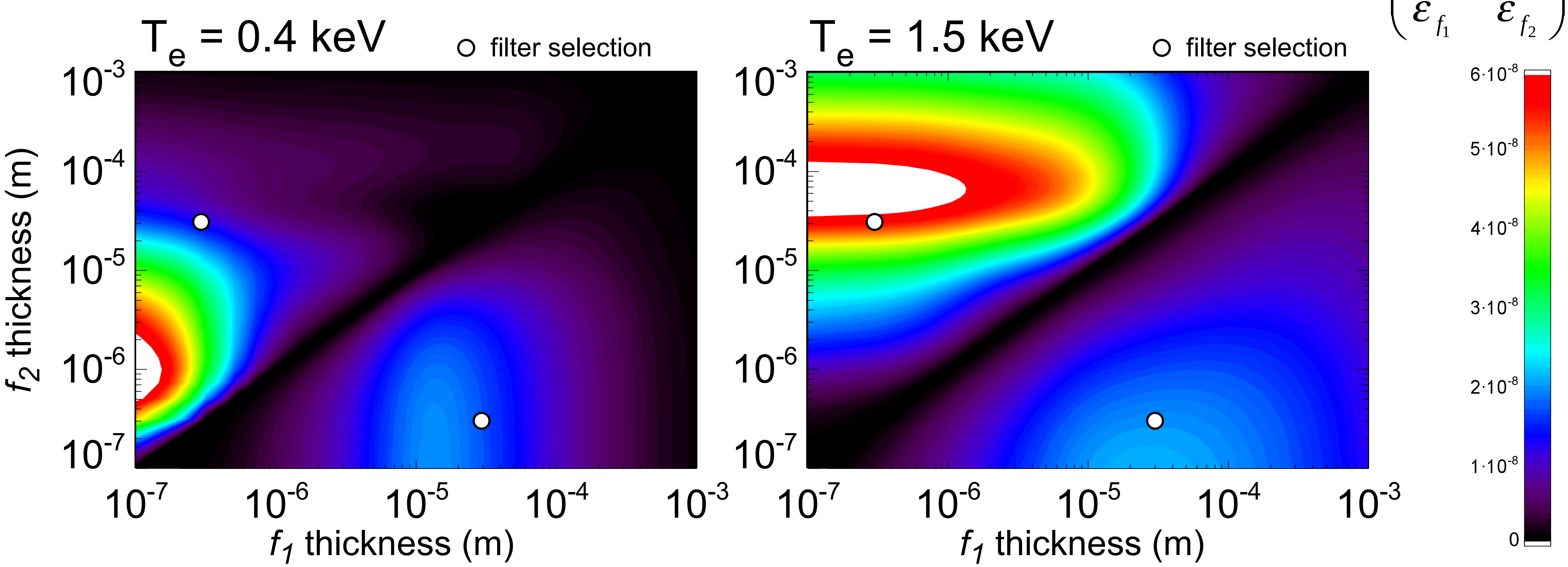
T_e Sensitivity Varies with Plasma Conditions

- Calculate normalized ratio differences at given T_e in 'clean' and 'dirty' plasma conditions
- Select filter combinations to maximize T_e sensitivity

'Dirty' Plasma	'Clean' Plasma
C: 4%	C: 2%
O: 1%	O: 0.5%
Fe: 0.2%	

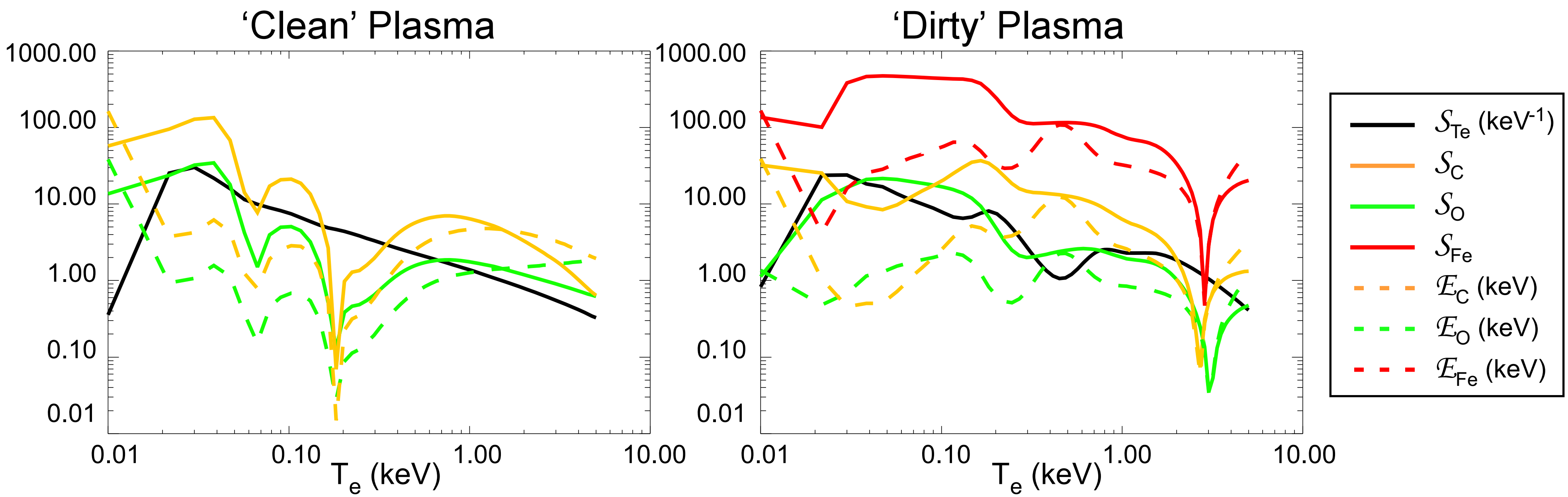
Weighted Normalized Ratio Differences

$$SNR \bullet \left(\frac{\varepsilon'_{f_1}}{\varepsilon_{f_1}} - \frac{\varepsilon'_{f_2}}{\varepsilon_{f_2}} \right)$$



T_e Error Introduced from Impurity Sensitivities/Uncertainties

Sensitivities from selected filters: $f_{30\mu}/f_{0.3\mu}$ relative difference



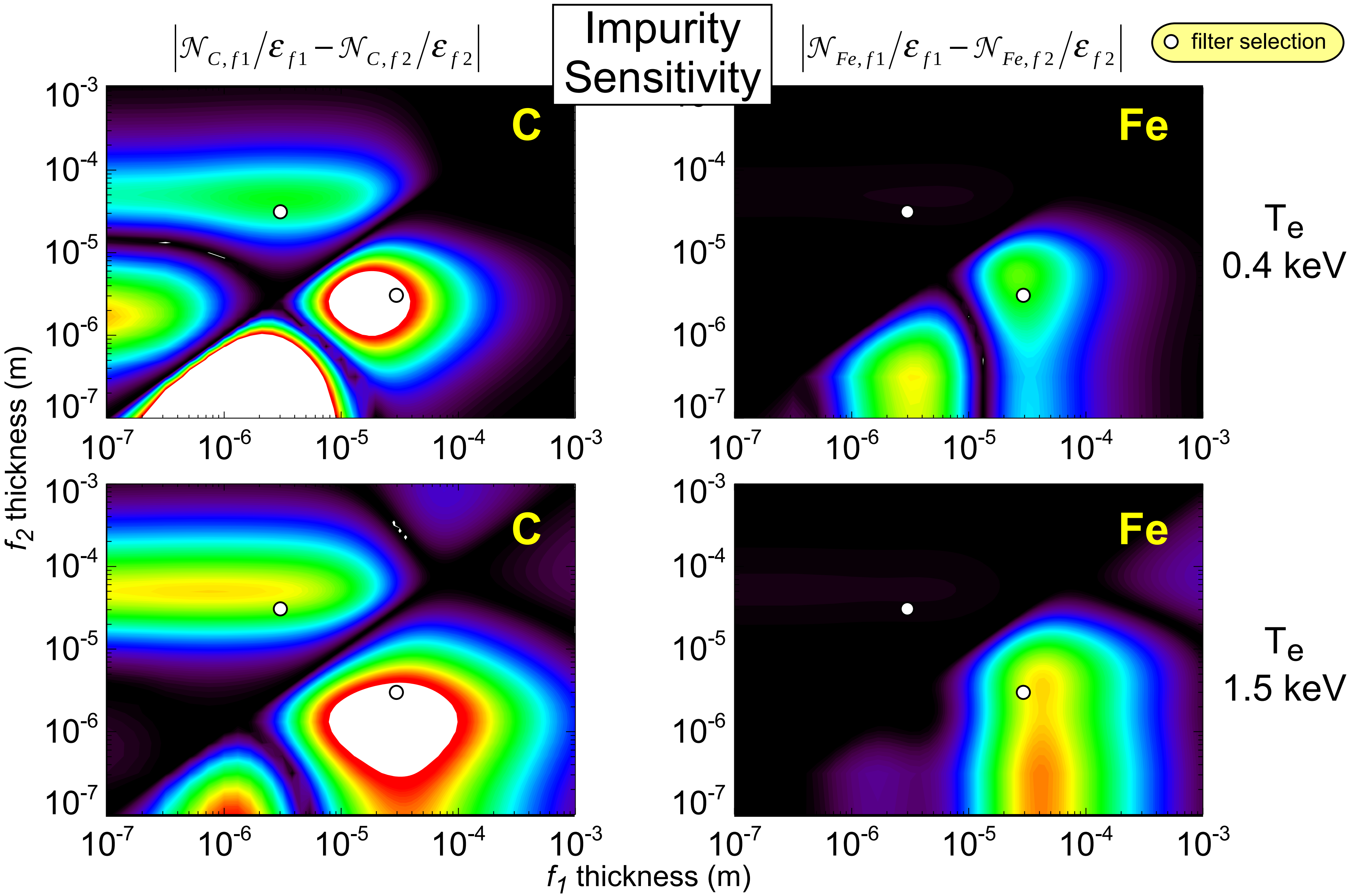
$$\mathcal{R} = \left(\frac{\Delta\varepsilon_{f_1}}{\varepsilon_{f_1}} - \frac{\Delta\varepsilon_{f_2}}{\varepsilon_{f_2}} \right) = \Delta T_e \cdot \mathcal{S}_{Te}$$

T_e error: $\tilde{T}_e = \sum_i \tilde{c}_i \mathcal{E}_i$

unknown changes in impurity concentration affect calculated T_e

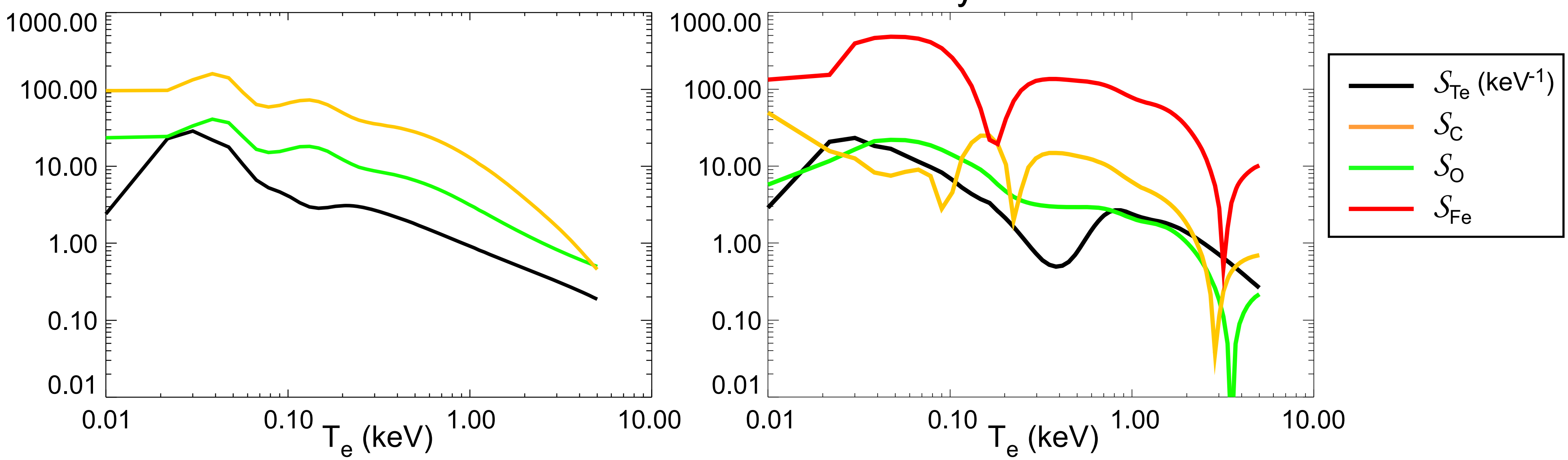
- Ratios shows good T_e sensitivity for 'clean' plasma
  - T_e (0.5keV): ΔTe of 10% $\rightarrow$ ~12% change in $\mathcal{R}$
  - T_e error from Δc_C, and Δc_O: ~7 eV/% and ~25 eV/%

Filter Combination can Maximize Sensitivity to Impurities



Can Optimize Filters for Impurity Measurements

Sensitivities from $f_{30\mu}:f_{3\mu}$ relative difference



		$\mathcal{R}$(0.5keV)	$\mathcal{R}$(1.0keV)	$\mathcal{R}$(0.5keV)	$\mathcal{R}$(1.0keV)
Δc_C	1%	7%	3%	2%	2%
Δc_O	1%	29%	12%	10%	5%
Δc_{Fe}	0.1%			16%	10%
ΔT_e	10%	9%	8%	3%	20%

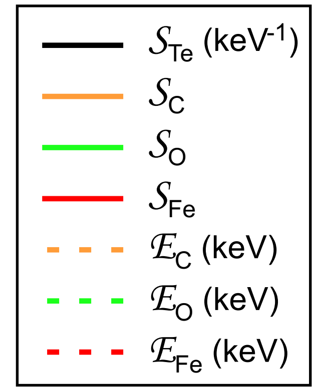
Impurity Sensitivity

$$\mathcal{R}_i = \left(\frac{\Delta\varepsilon_{f_1}}{\varepsilon_{f_1}} - \frac{\Delta\varepsilon_{f_2}}{\varepsilon_{f_2}} \right) = \Delta c_i \cdot \mathcal{S}_i$$

- Can use impurity sensitive differences to reduce error in calculated ΔTe

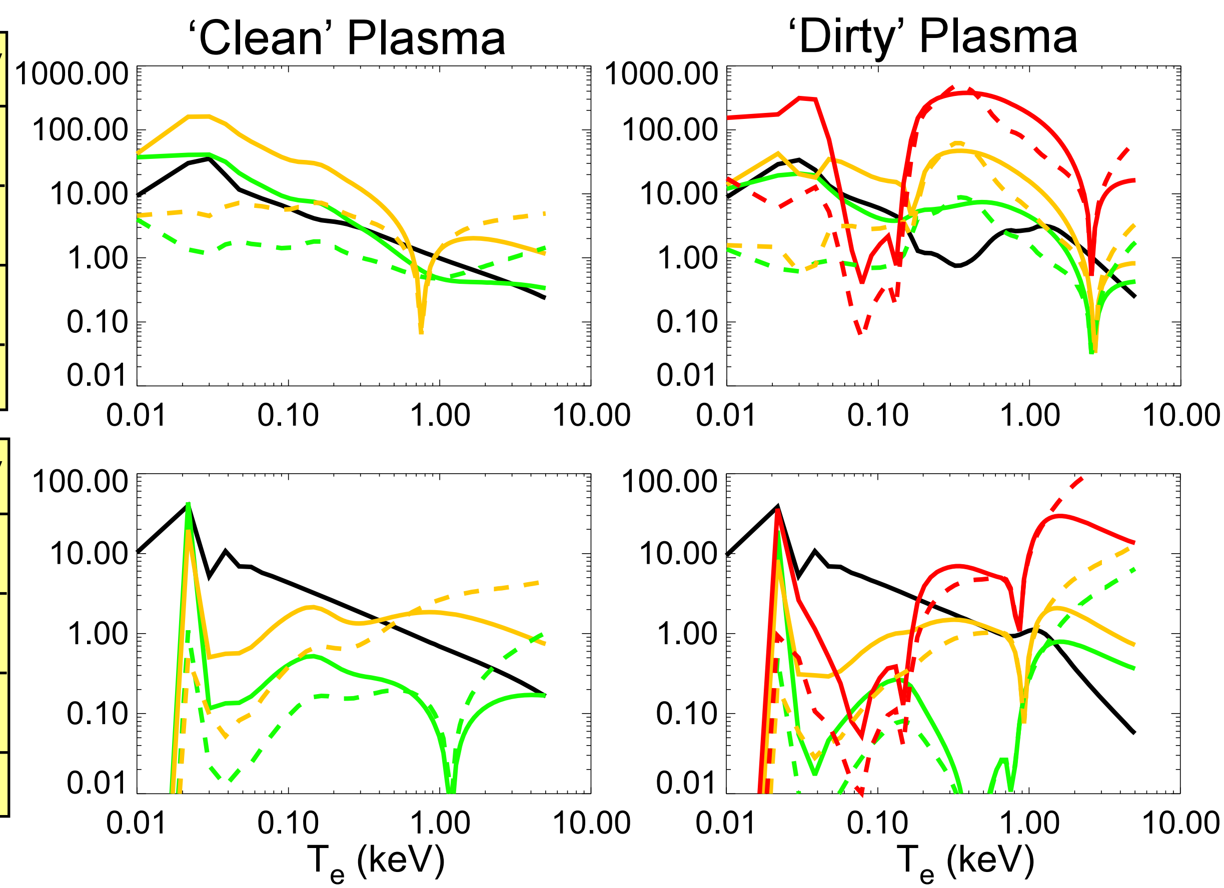
Sensitivity of Present TOSXR System on NSTX

- $f_{100\mu}:f_{10\mu}$ difference: good T_e sensitivity in 'clean' plasmas
  - impurity sensitivity dominates in 'dirty' plasmas
- $f_{300\mu}:f_{100\mu}$ difference: much less sensitive to impurities



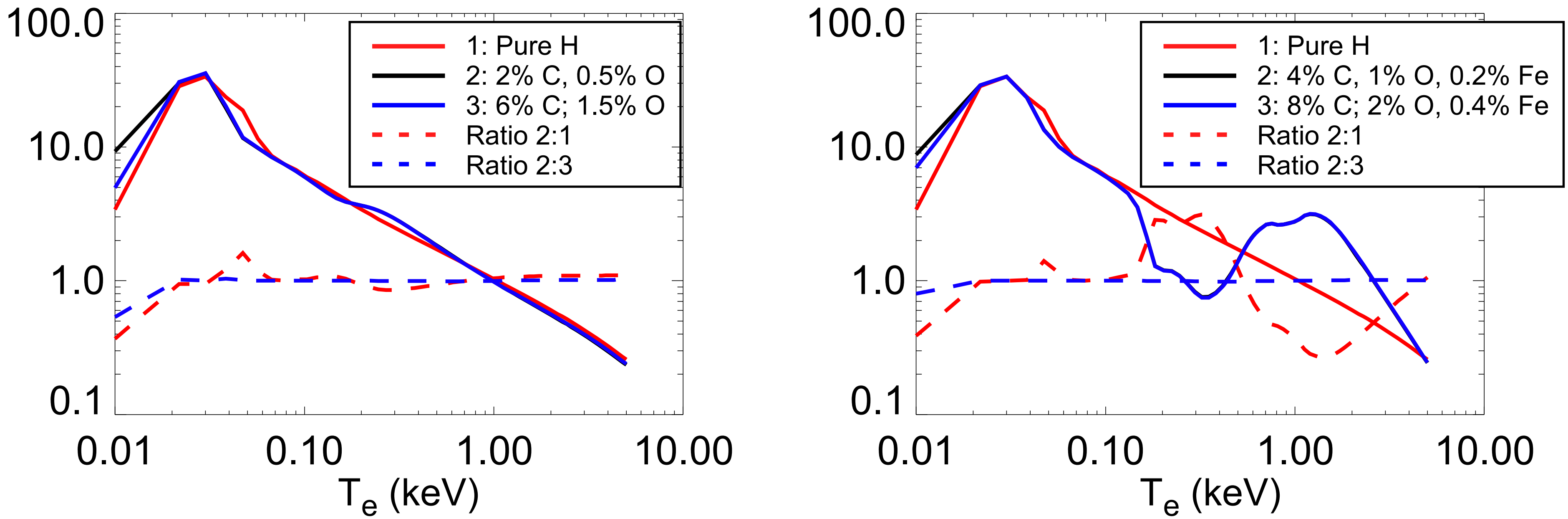
		'Clean'		'Dirty'	
$f_{100\mu}:f_{10\mu}$		0.5keV	1.0keV	0.5keV	1.0keV
Δc_C	1%	1%	.5%	6%	3%
Δc_O	1%	4%	1%	30%	15%
Δc_{Fe}	0.1%			35%	20%
ΔT_e	10%	10%	12%	6%	30%

$f_{300\mu}:f_{100\mu}$		0.5keV	1.0keV	0.5keV	1.0keV
Δc_C	1%	.2%	.05%	.02%	.2%
Δc_O	1%	2%	2%	1%	.2%
Δc_{Fe}	0.1%			5%	10%
ΔT_e	10%	7%	8%	5%	10%



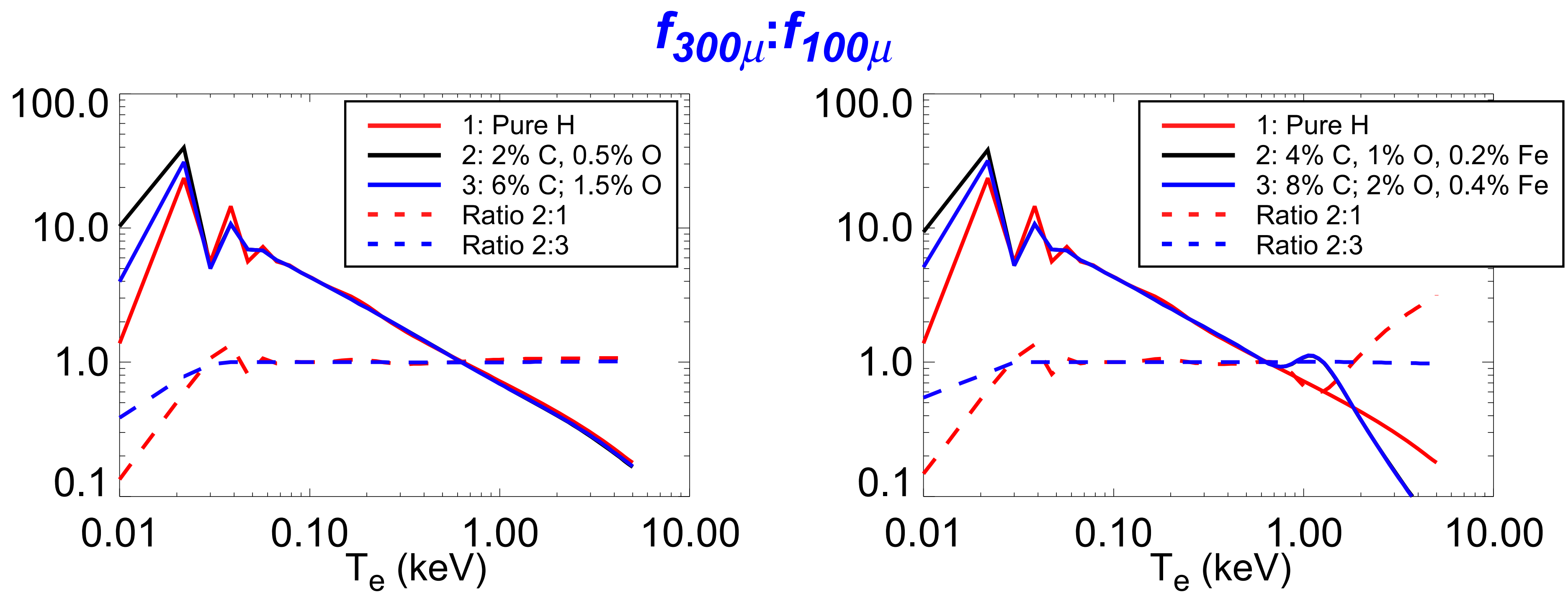
Differences Insensitive to Steady-State Impurity Ucertainties

$f_{100\mu}:f_{10\mu}$



- Factor ~x2 uncertainty in steady state impurity concentrations negligible effect on calculated temperature sensitivity
- High-Z impurities require detection, rough quantification

Thick Filters Provide Reduced Impurity Sensitivity



- Difference of thicker filters immune to low-Z steady state uncertainties
- High-Z uncertainties cause ΔT_e error for T_e > 1keV

Future Work

- Incorporate 3D response tables into SXR fitting calculations
- Develop filter optimization algorithms to maximize T_e sensitivity/minimize errors from impurity uncertainties
- Specify requirements for low/high-Z impurity measurements

Conclusions

- 'Multicolor' SXR system demonstrates fast T_e (R,t) measurements
- Sensitivity lookup tables provide fast calculation, optimization of filters for T_e and impurity sensitivity
- TOSXR filters insensitive to steady-state impurity uncertainties
- Filter optimization can reduce sensitivity to uncertainties in Δc_i

Reprints