EUROfusion

Integration of the recombination continuum and Balmer line emission spectroscopy for detachment studies on the JET-ILW divertor

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Motivation

- More detailed picture of the role of atomic physics in detachment requires precise measurements of plasma parameters
- Towards integration of grating and filtered imaging spectroscopy $\Rightarrow$ detachment physics is 2D!
- Codes benchmarking $\Rightarrow$ detachment modelling sensitive to small changes in atomic/molecular physics assumptions

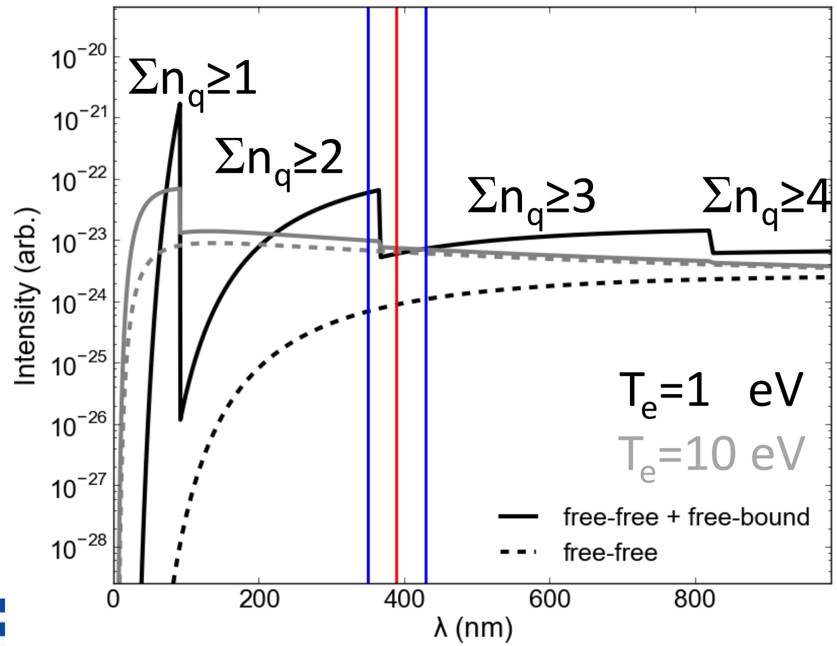
Continuum emission T_e dependence

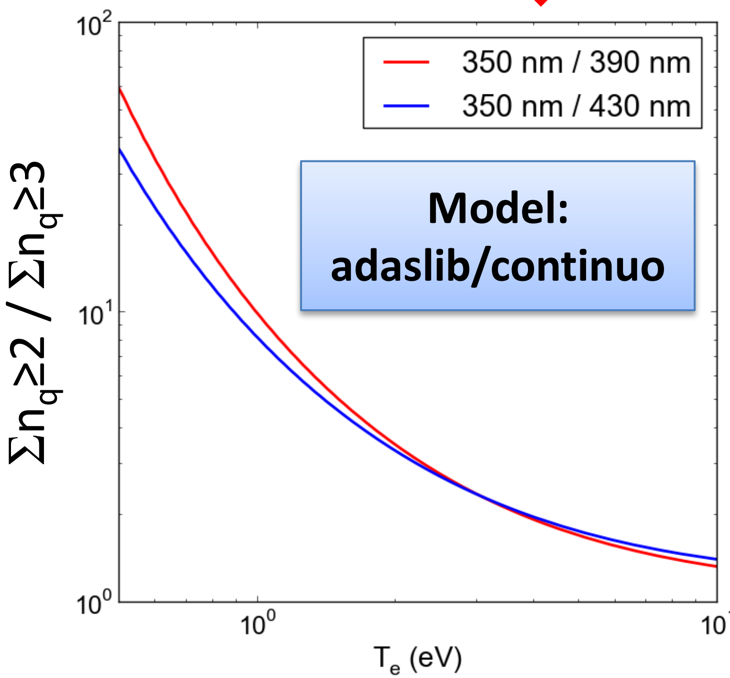
⇒ Continuum diagnostic technique demonstrated on Alcator C-Mod [Lumma, Terry, Lipschultz *Phys. Plasmas* **4** (7) 1997]

$$\epsilon_\lambda^{ff} \propto \lambda^{-2} N_e^2 Z_{eff} T_e^{-1/2}$$

$$\epsilon_\lambda^{fb} \propto \lambda^{-2} N_i N_e T_e^{-3/2} \times \sum_{n_q \geq n_{qmin}} \frac{1}{n_q^3} \exp\left(\frac{E_R}{n_q^2 T_e}\right)$$

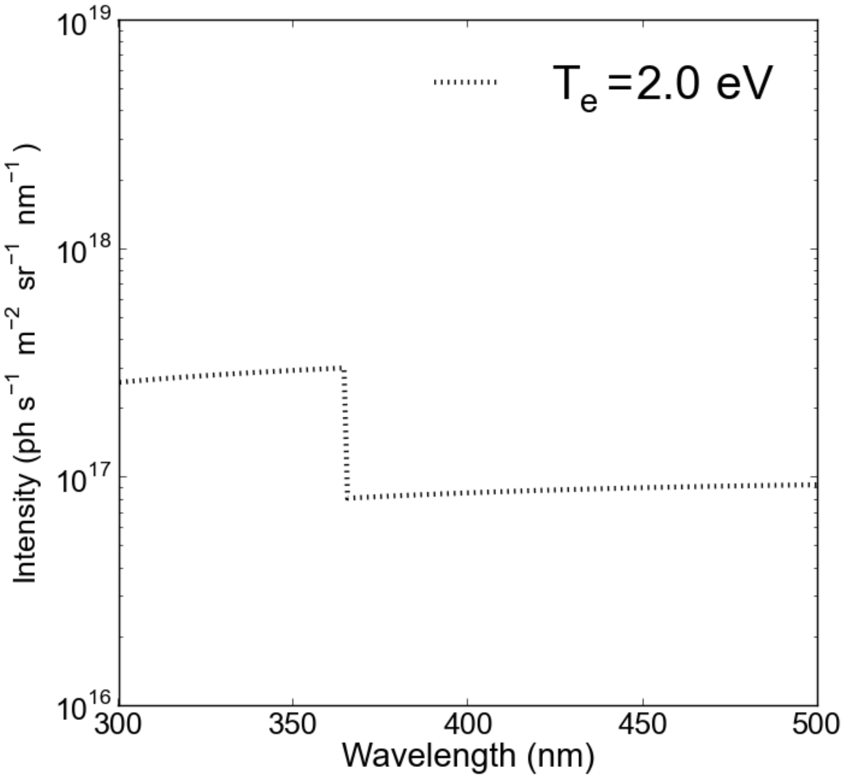
Driving term for $\Sigma n_q \geq 2$ / $\Sigma n_q \geq 3$ ratio





Continuum emission: Line integration effects

- Consider 2-shell emission with $\mathbf{T_{e,1}=2.0\ eV}$ and $\mathbf{T_{e,2}=0.5\ eV}$ (constant $\mathbf{N_e}$)



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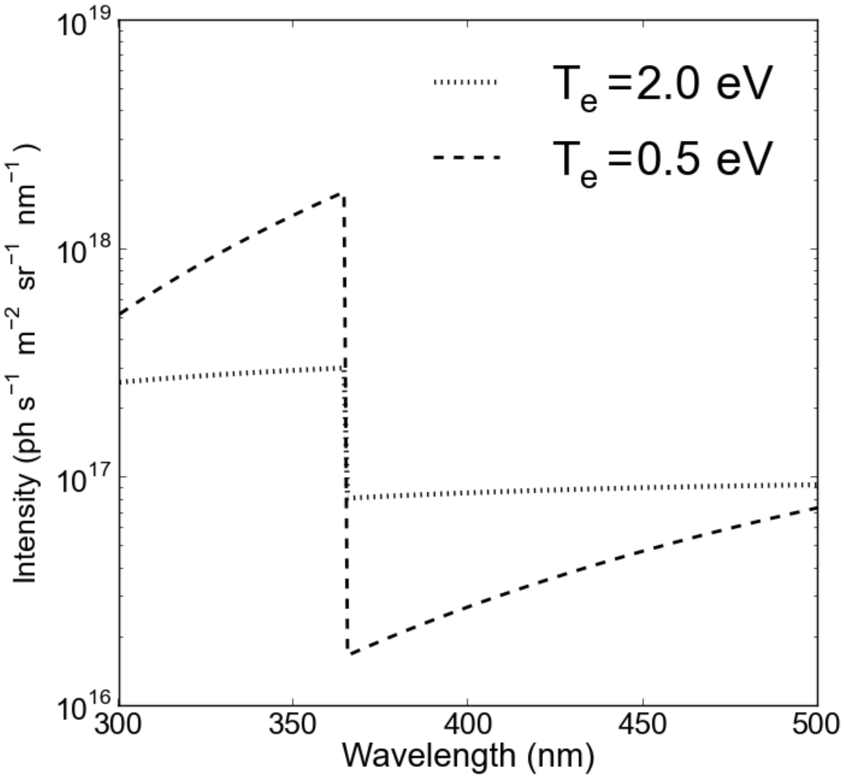
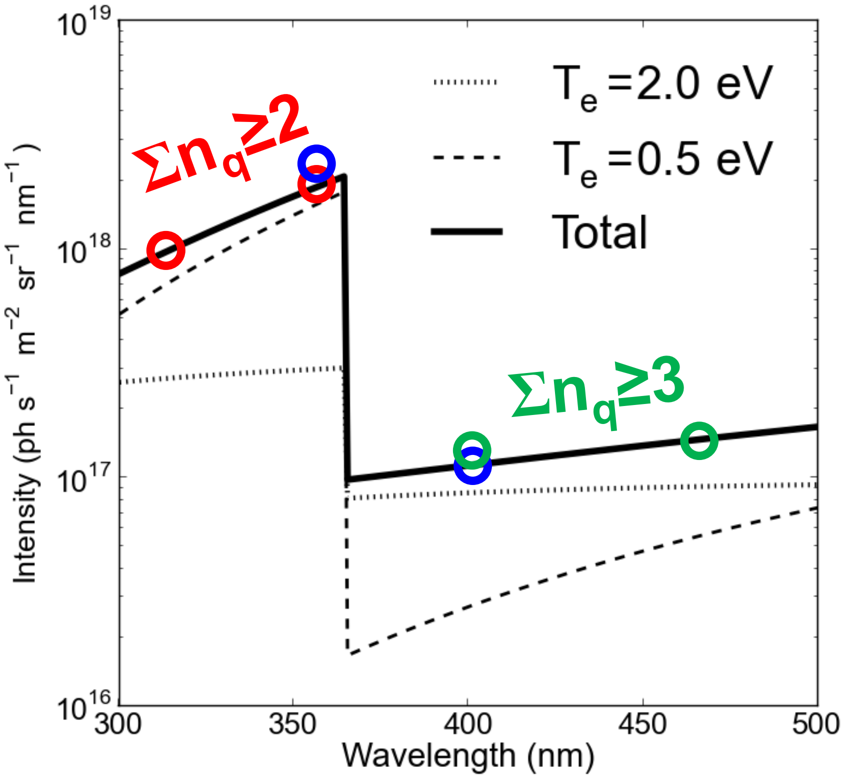


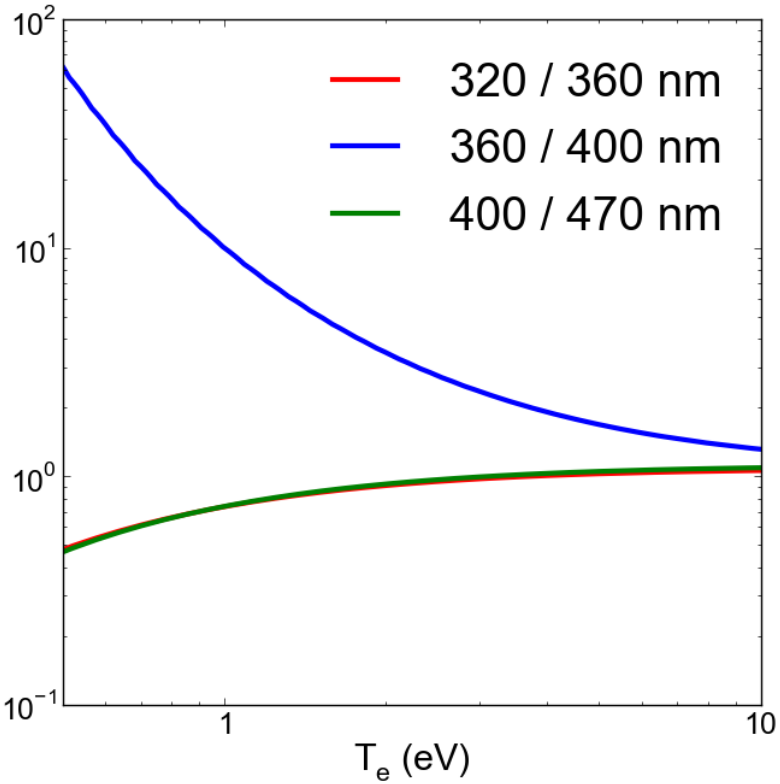
Continuum emission: Line integration effects

- Consider 2-shell emission with $\mathbf{T_{e,1}}$**=2.0 eV** and $\mathbf{T_{e,2}}$**=0.5 eV** (constant $\mathbf{N_e}$)
- Line-of-sight integrated $\mathbf{T_e}$ total emission:
  - $\mathbf{T_e}$ **= 0.59 eV**
  - $\mathbf{T_e}$ **= 0.78 eV**
  - $\mathbf{T_e}$ **= 1.04 eV**

$\varepsilon^{fb}(\lambda < 365$ nm) weighted towards lowest T_e

$\varepsilon^{fb}(\lambda > 365$ nm) weighted towards higher T_e





Relevant JET-ILW diagnostics

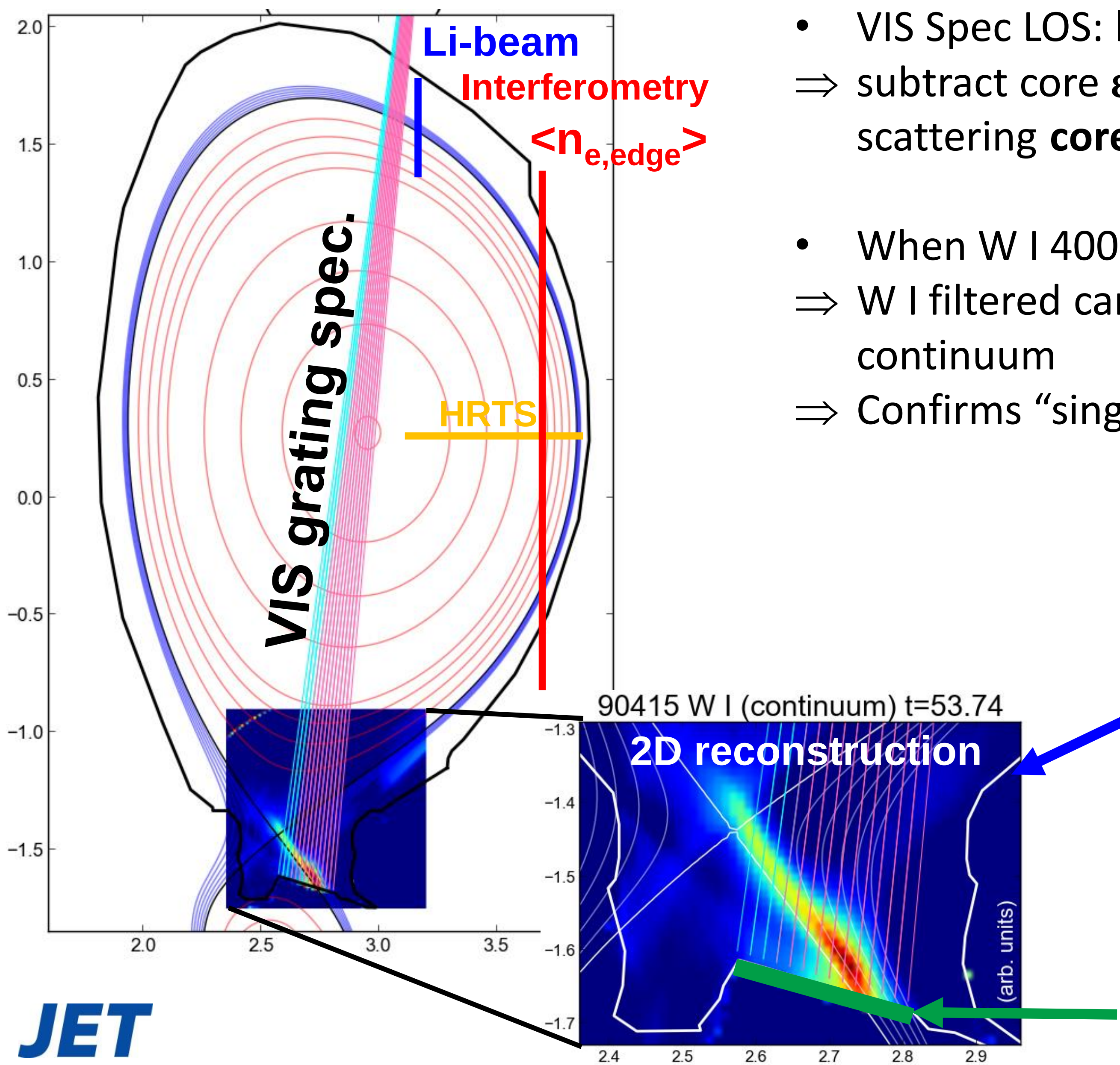
- VIS Spec LOS: long path length

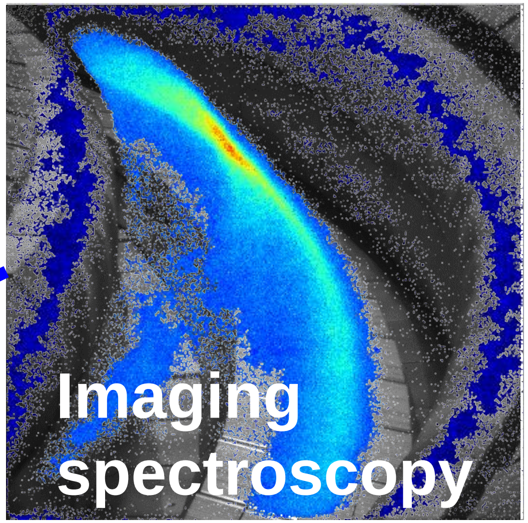
⇒ subtract core $\varepsilon^{ff} + \varepsilon^{fb}$ using Thomson scattering **core T_e, N_e** profiles

- When W I 400.9 nm line not present

⇒ W I filtered camera measures continuum

⇒ Confirms “single shell” emission





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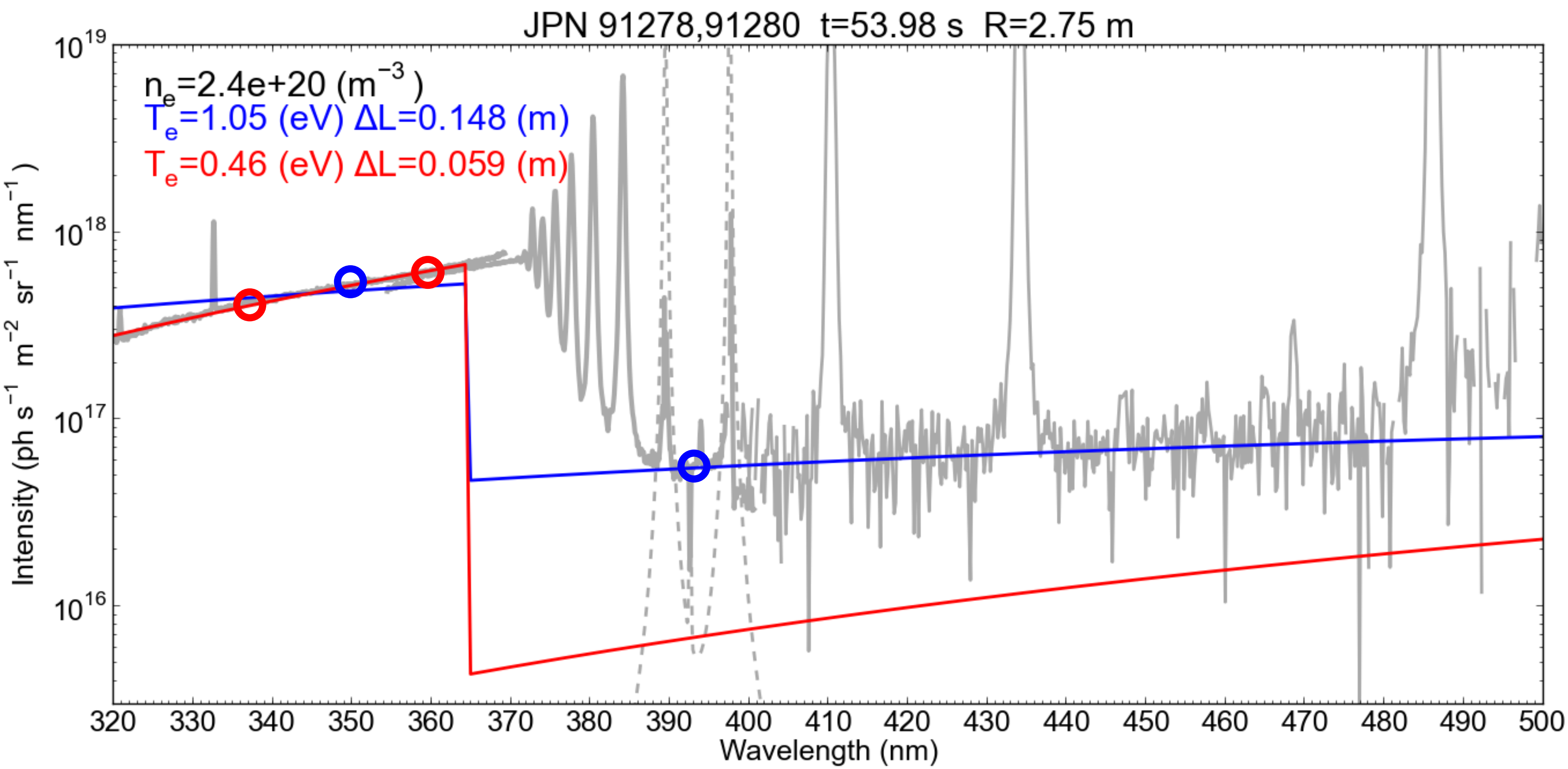
Composite continuum spectrum and fits



- **$T_e \Rightarrow \varepsilon^{fb}$ edge ratio vs. $T_e \Rightarrow \varepsilon^{fb}$ < 365 nm**
- Constrain fit using line-averaged $\mathbf{N_e}$ from Stark broadening
- **λ > 400 nm** need higher signal/noise measurements for more precise **$T_e \Rightarrow \varepsilon^{fb}$ > 365 nm**

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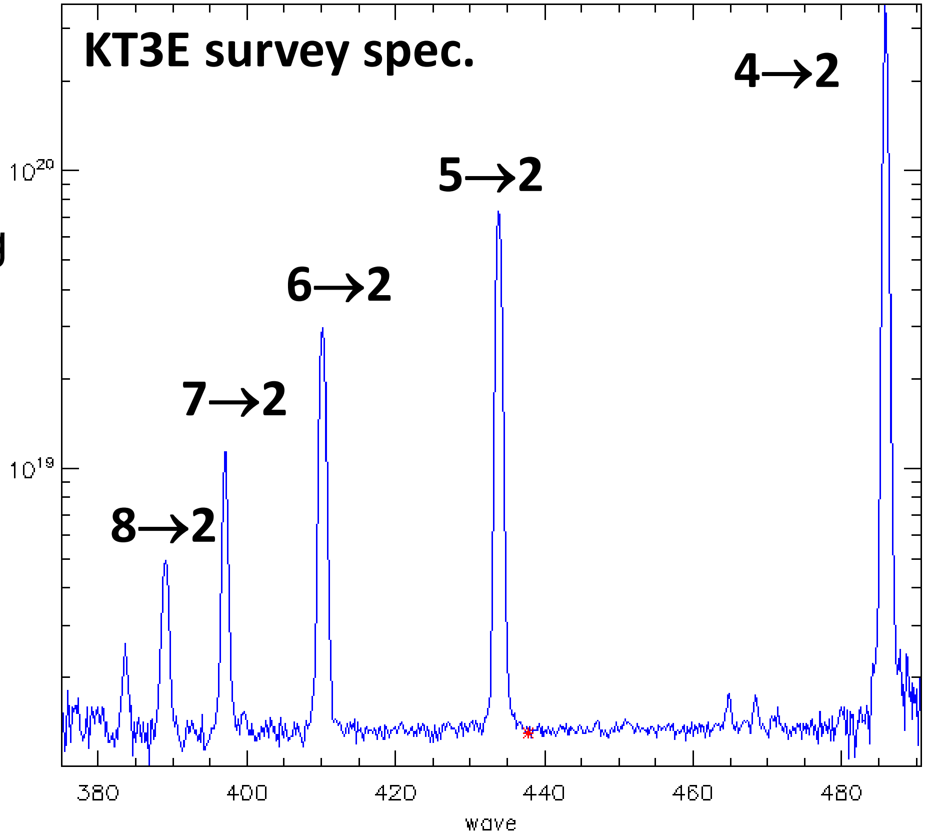
Inferring T_e from H Balmer lines

$$I_{i\to j} = \frac{1}{4\pi}\int_{LOS} \epsilon_{i\to j} dl = \frac{1}{4\pi}\bar{\epsilon}_{i\to j}\Delta L$$

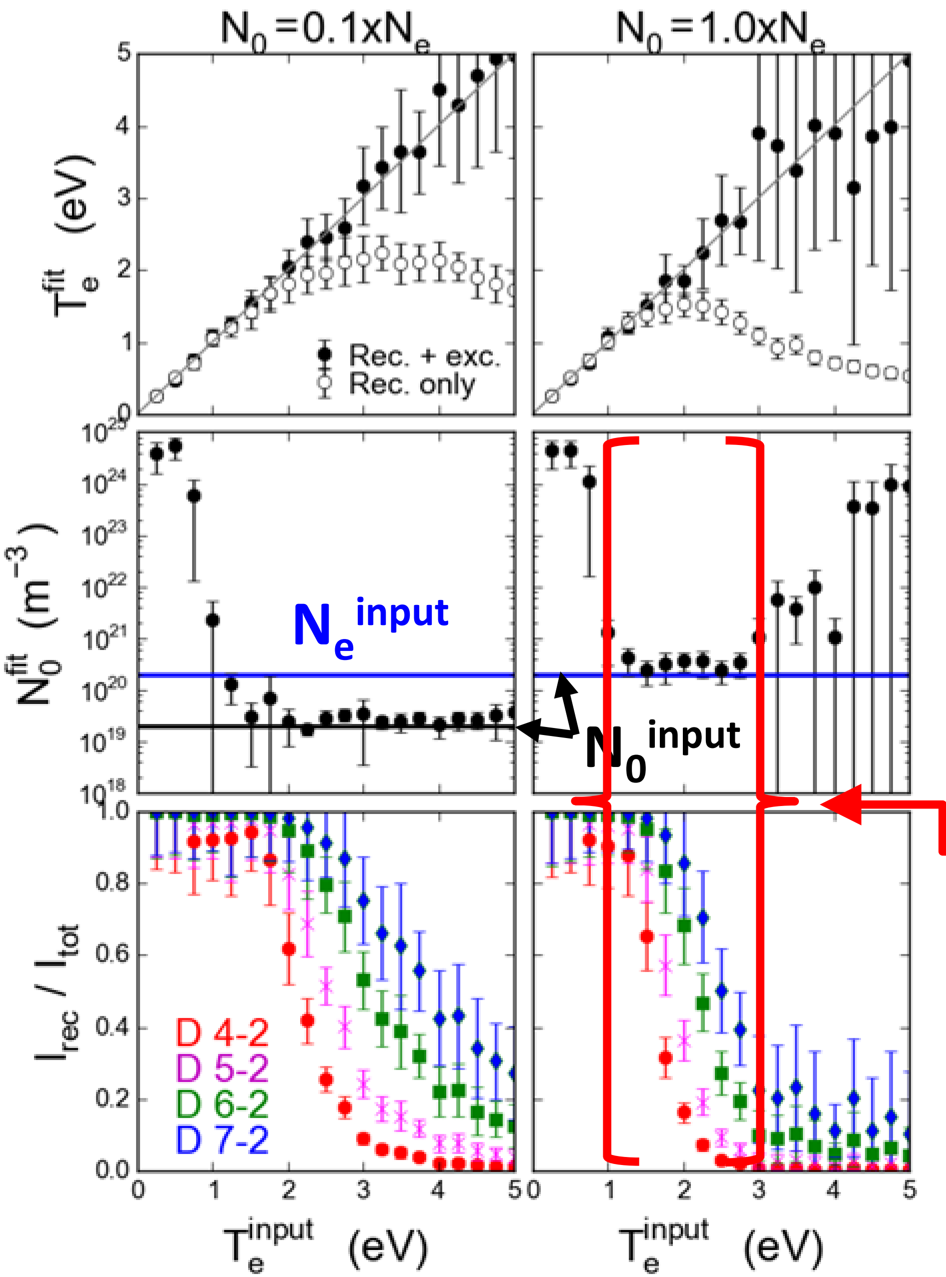
Atomic data set:
ADAS ADF15
pec12#h_pju#h0.dat

$$I_{i\to j} = \frac{\Delta L}{4\pi}\left[\mathrm{PEC}(T_e, N_e)^{(exc)}_{i\to j} N_e N_0 + \mathrm{PEC}(T_e, N_e)^{(rec)}_{i\to j} N_e N_i\right]$$

- **Knowns (if $N_e \approx N_i$), Unknowns**
- Which lines to choose?
  - High-n: possible continuum merging
  - Low-n, other possible populating mechanisms?
    - *e.g.*, MAR reaction chain populates n=3 [Post *et al.*, *Contr. Plasma Phys.* **34** 1994]
  - Use mid-n lines for fitting



Synthetic fits: Absolute line intensities



- **If ΔL estimate available (assume ±50% uncertainty):**

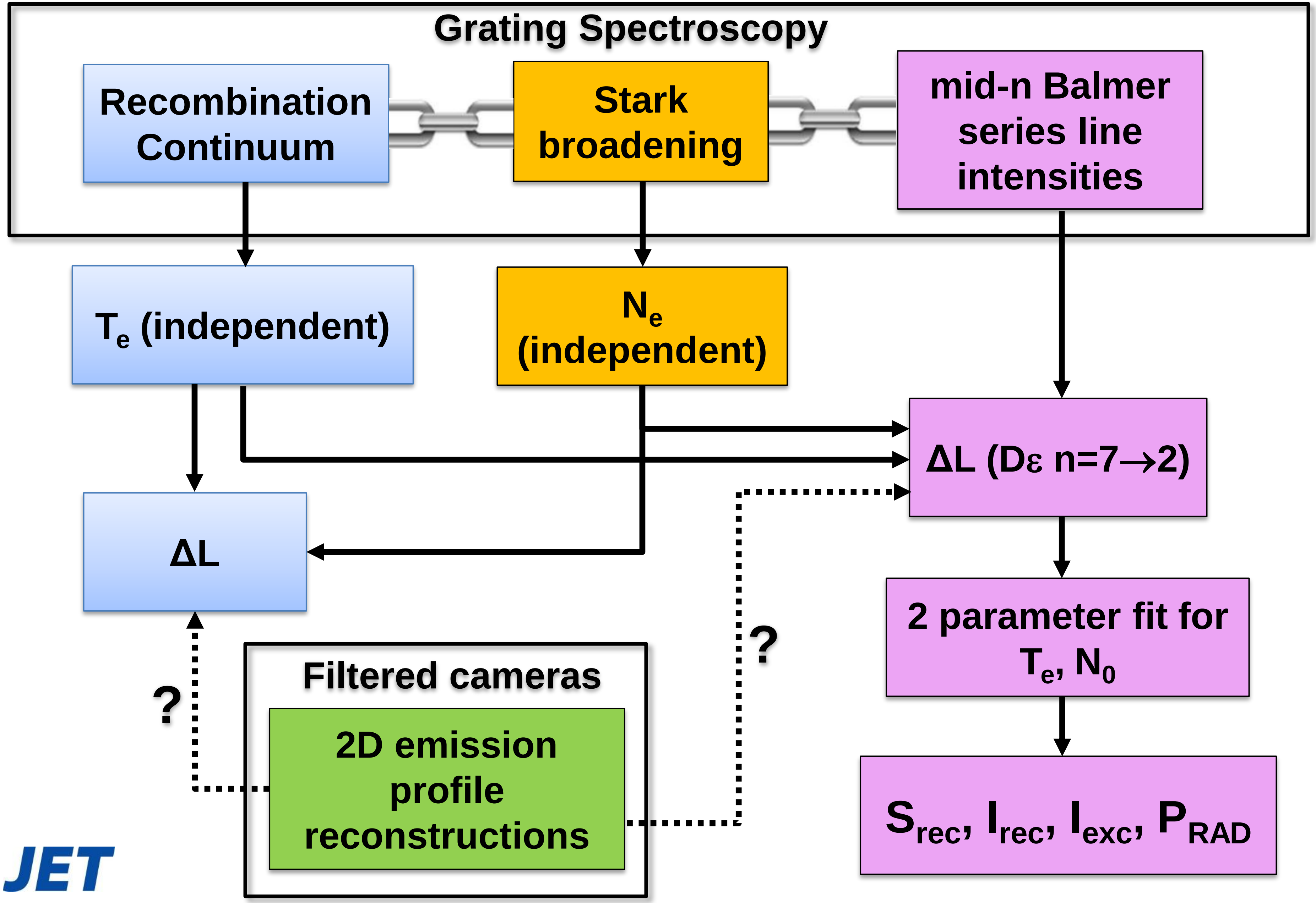
⇒ 2 parameter fit for $\mathbf{N_0}$, $\mathbf{T_e}$

- Good $\mathbf{T_e}$ recovery

- Good $\mathbf{N_0}$ recovery

⇒ Bracketed by $\mathbf{T_e}$ range in which both excitation and recombination are relevant

Parameter estimates from combined analysis



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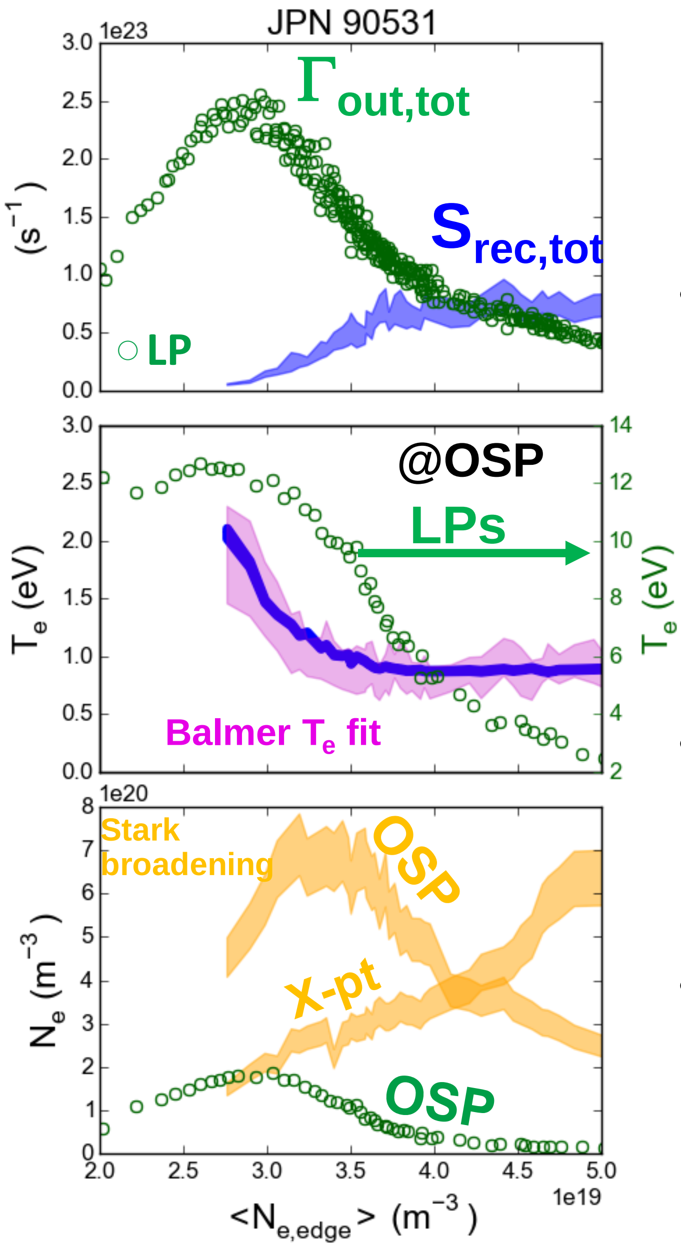
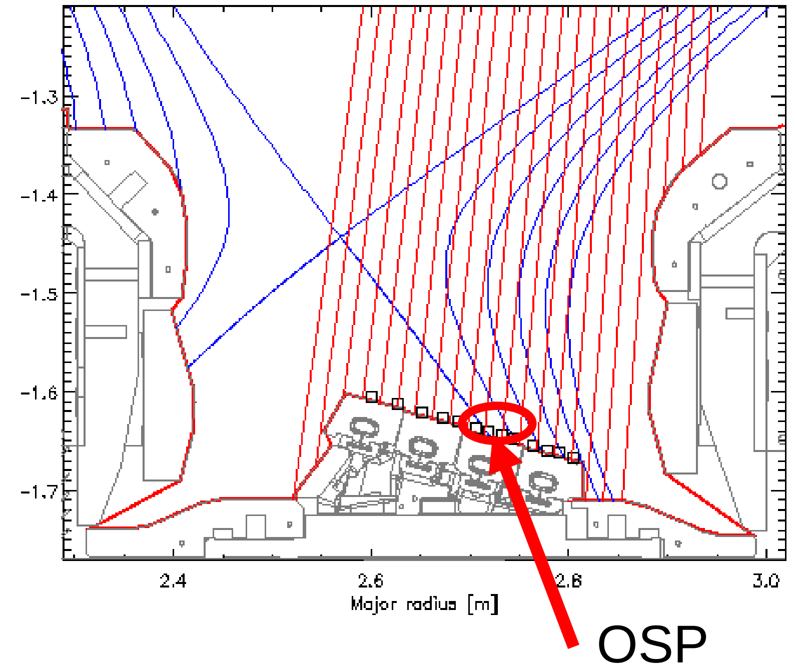


- Low $S_{rec,tot}$

  ⇒ not a significant ion sink except at highest $\langle N_{e,edge} \rangle$



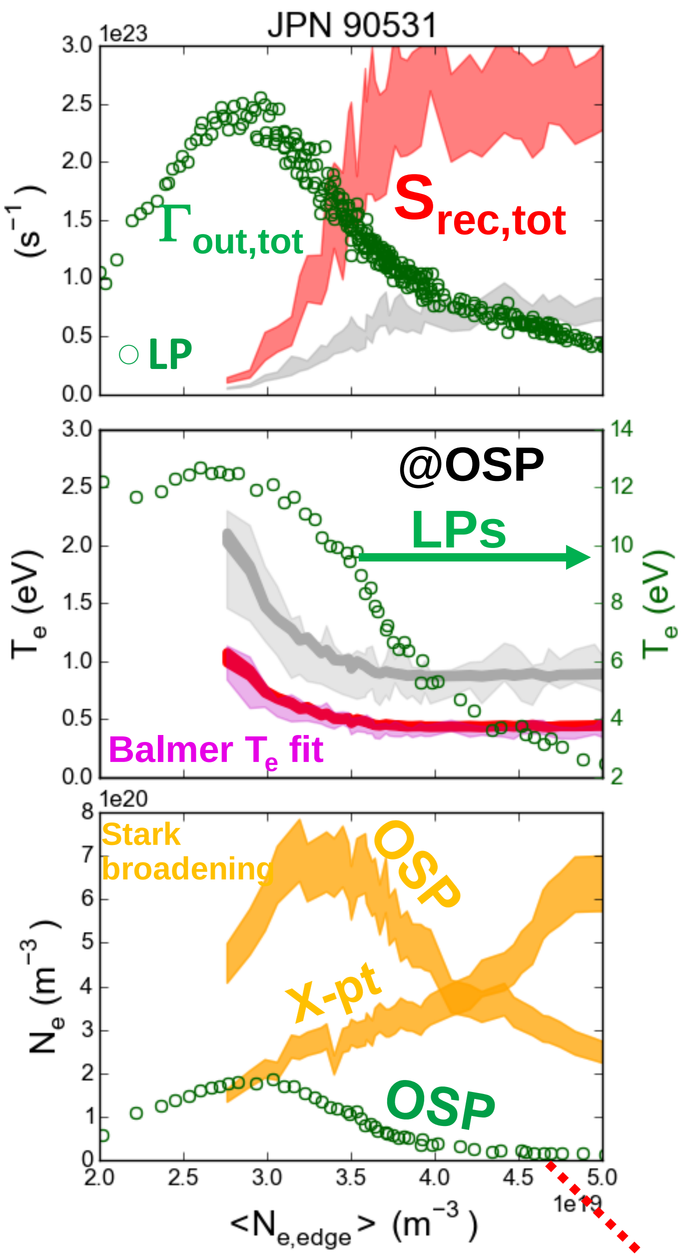
- T_e, N_e: LP vs spectroscopy

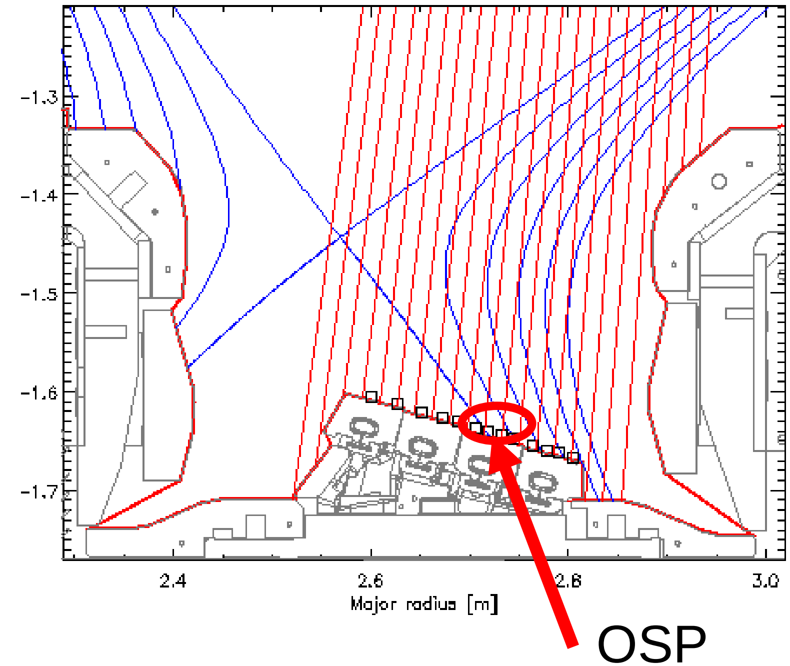
  ⇒ poor agreement

- Good agreement in T_e from recomb. and Balmer fit (ΔL link)

  ⇒ consistency between the two emission processes

Parameter estimates ($T_e \Rightarrow \varepsilon^{fb} < 365$ nm): L-mode density ramp





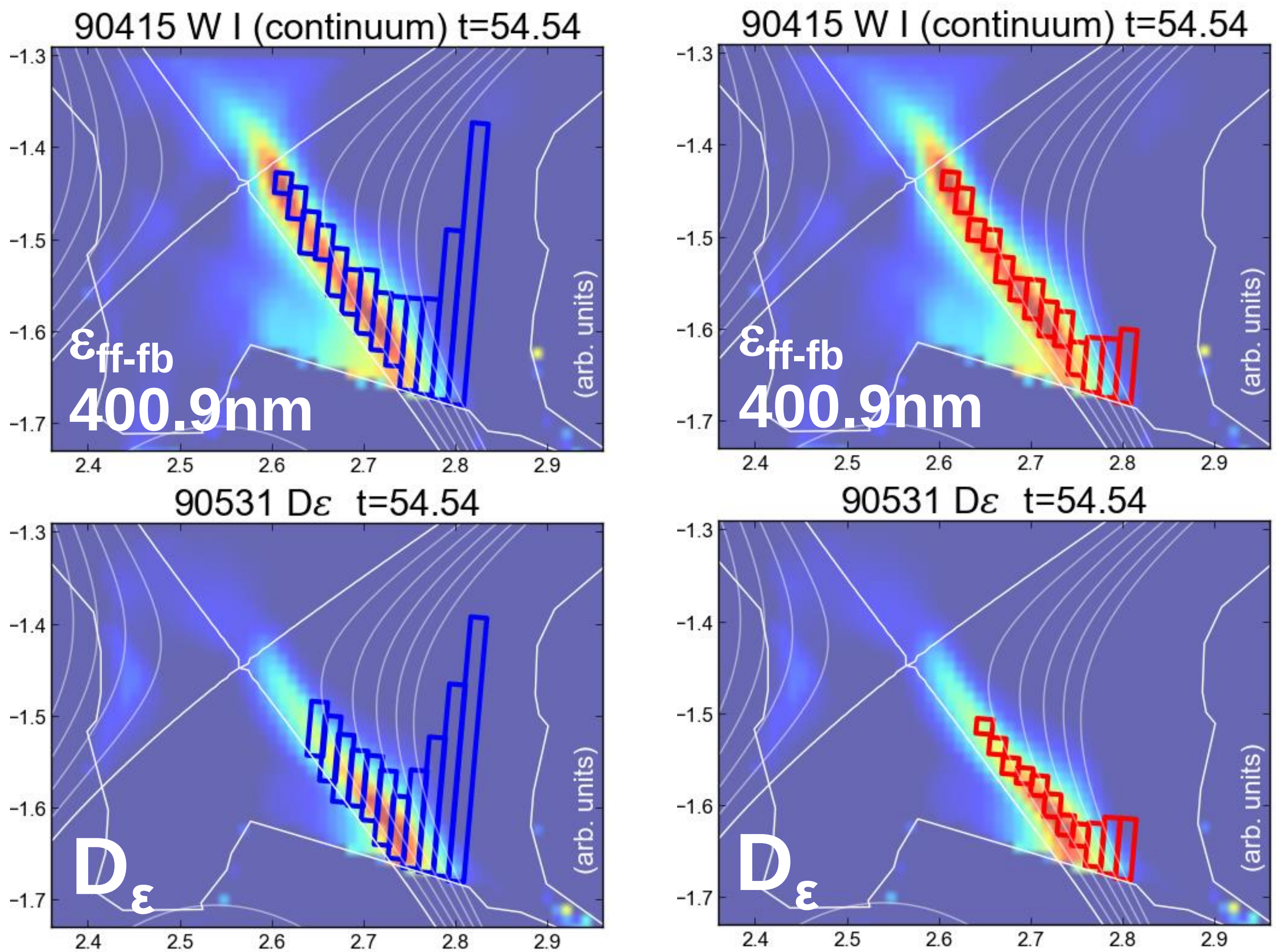
- $S_{rec,tot} \approx 4 \times S_{rec,tot}$

  ⇒ significant ion sink!

- Balmer Te fit "follows" continuum Te

  ⇒ Underscores importance of line integration profile effects

ΔL estimates: $T_e \Rightarrow \varepsilon^{fb}$ edge ratio vs. $T_e \Rightarrow \varepsilon^{fb} < 365$ nm



ΔL estimate from recombination continuum

ΔL estimate from **Dε (7→2)** line (recombination dominated)

- Qualitatively consistent with 2D emission profiles
  ⇒ which ΔL estimate is more representative of total emission?
- More information on n_e, T_e profiles along spectral LOS needed!
  ⇒ Inverse problem

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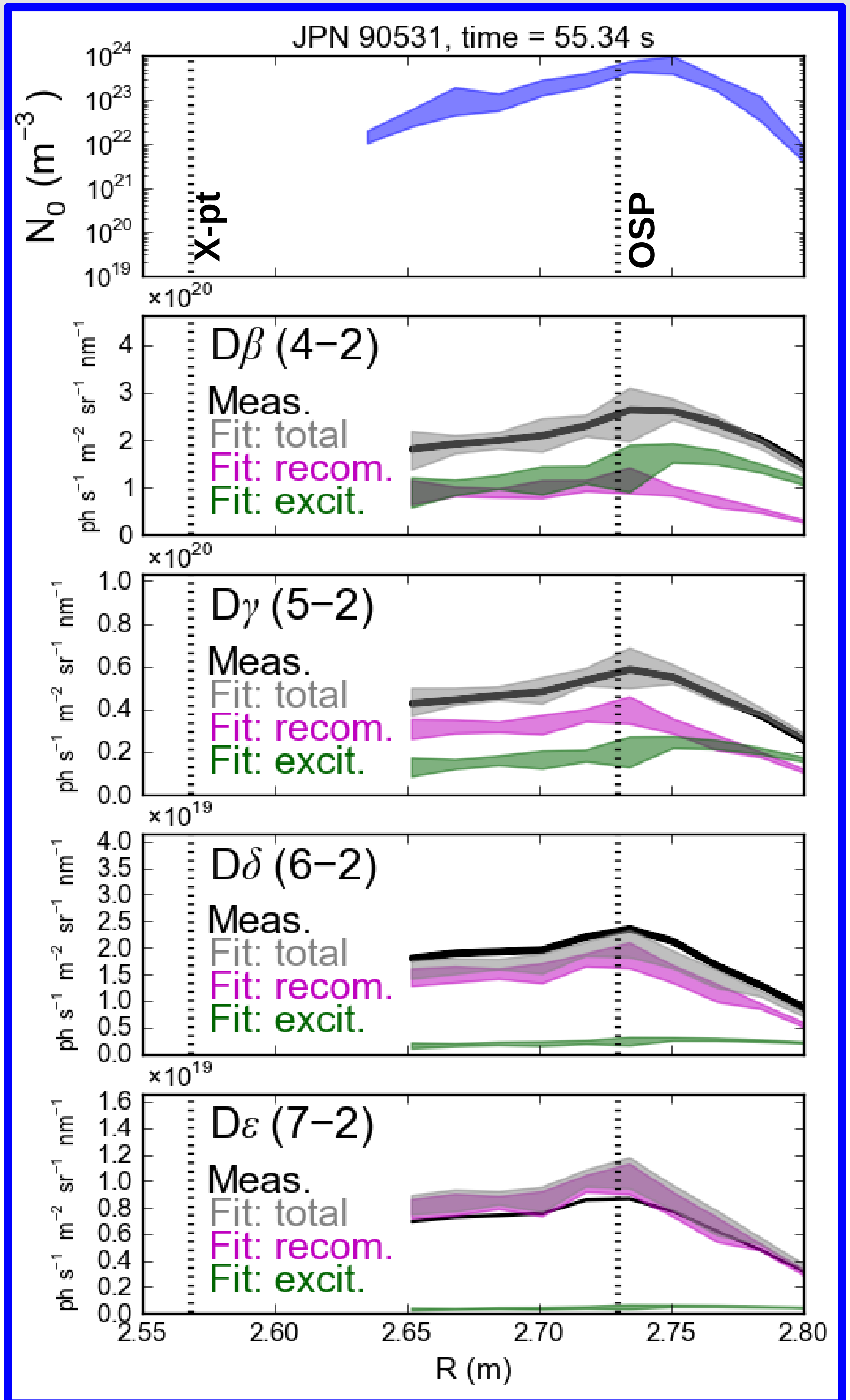
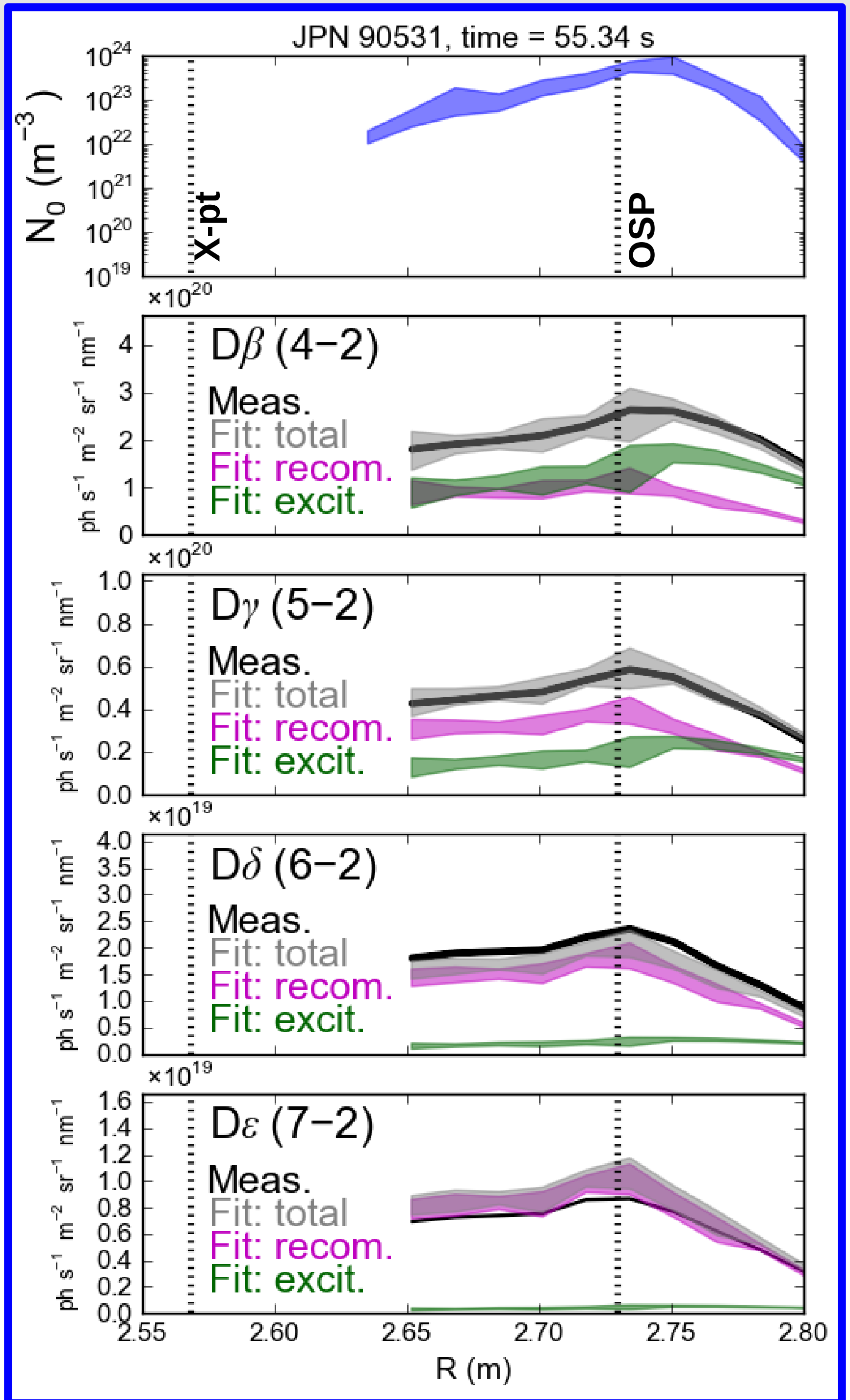
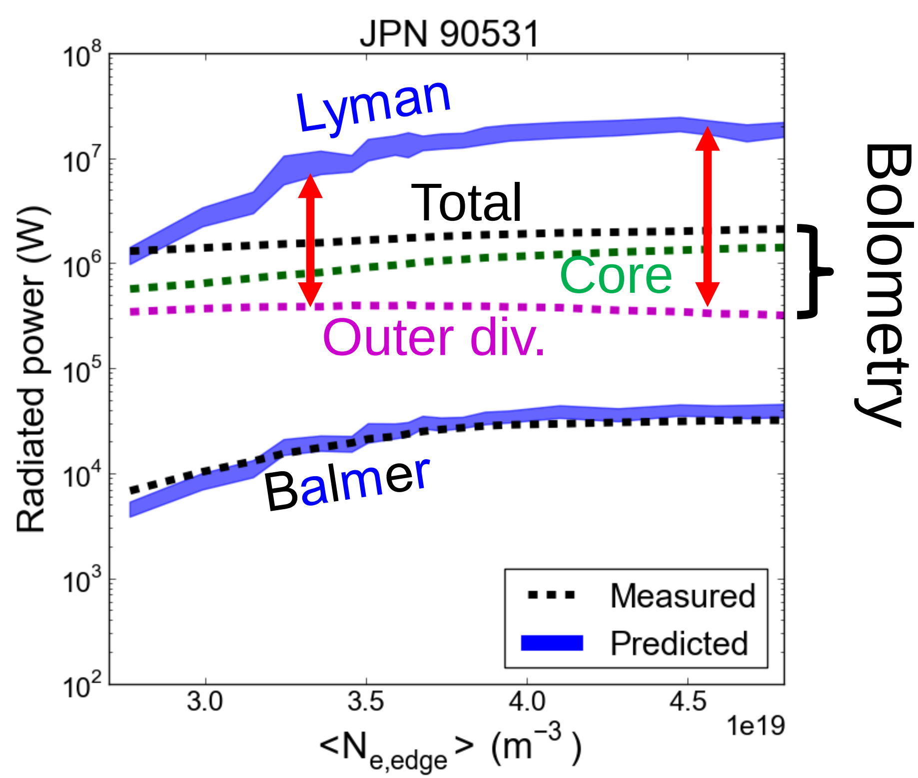
Neutral density and Rec/Exc
($T_e \Rightarrow \varepsilon^{fb}$ edge ratio)



- **Dβ, Dγ Excitation contribution** significant (i.e., can't recover measured line intensities with **recombination** alone)
- Balmer line fit predicts **$10^{22} < N_0 < 10^{24}$ m^{-3}** for **$1.0 < T_e < 1.5$ eV**
- Using **T_e, N_e, N_0** ⇒ extrapolate to Lyman series line intensities and calculate outer divertor **radiated power**

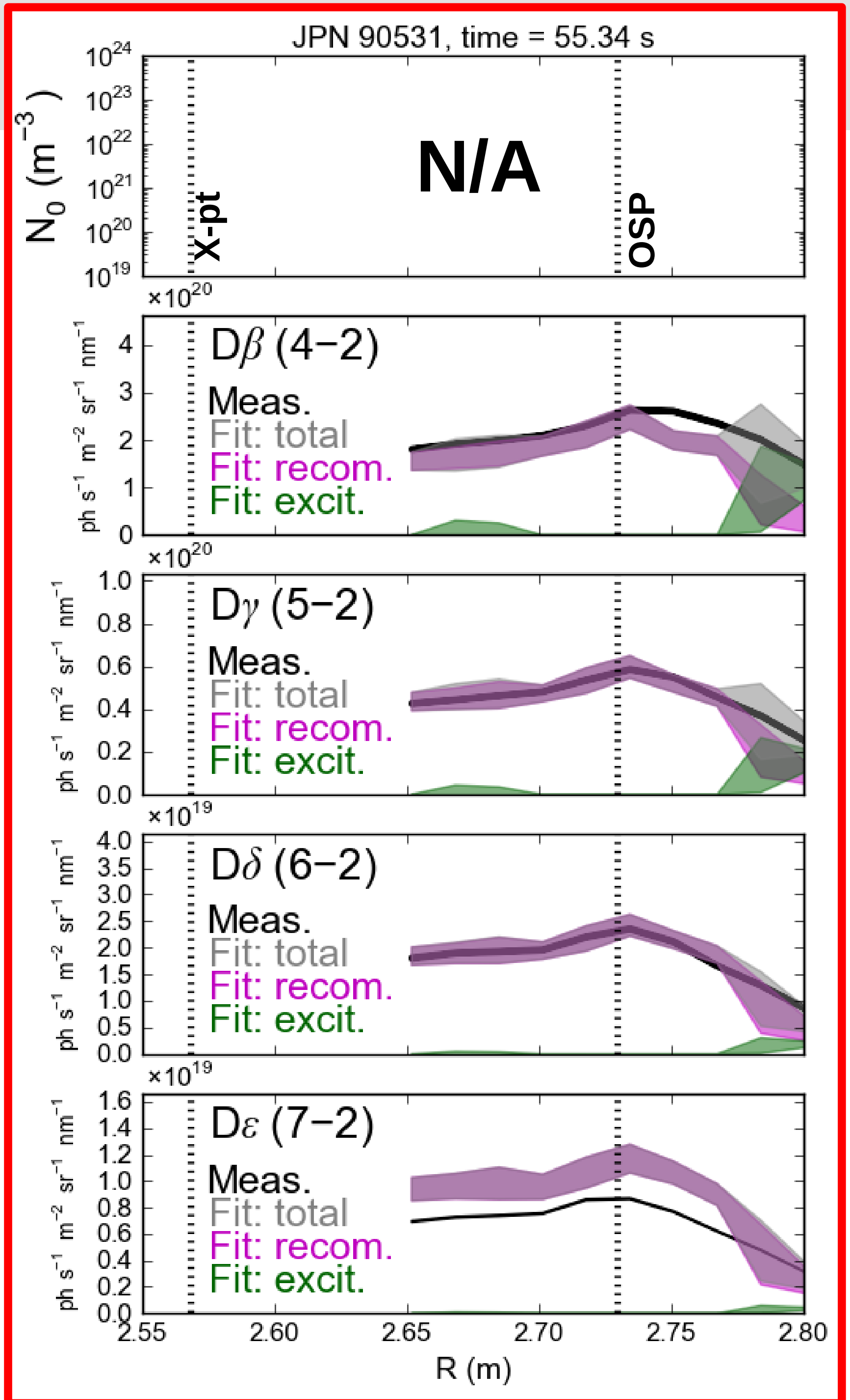
Neutral density and Rec/Exc ($T_e \Rightarrow \varepsilon^{fb}$ edge ratio)

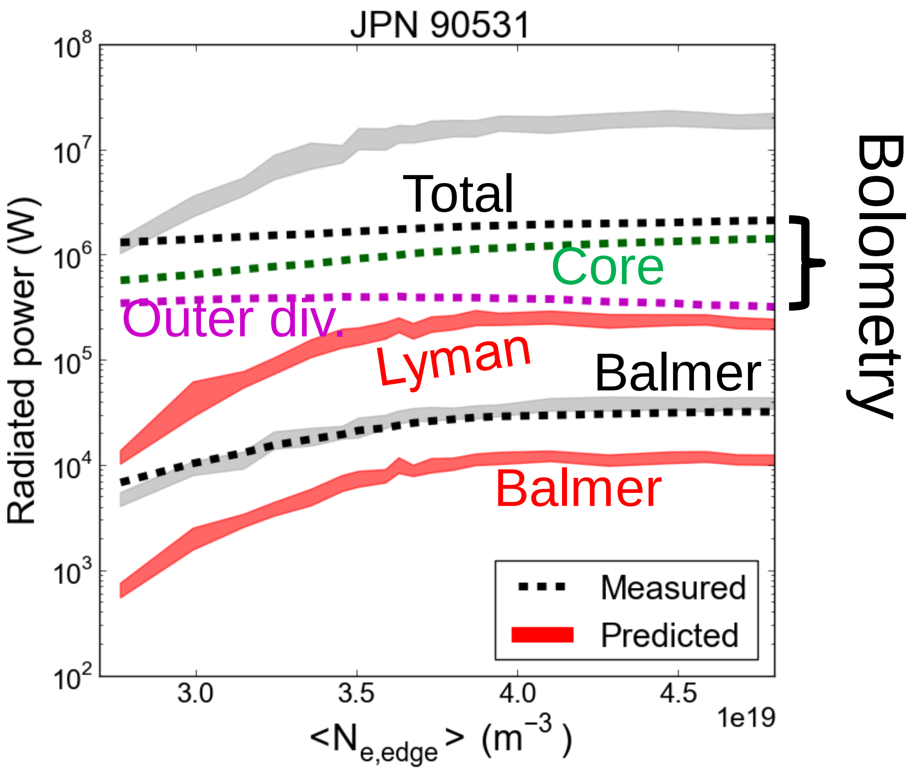




- Good agreement between predicted/measured Balmer series radiated power (i.e. good match to **Dα**)
- **Lyman series predicted power x10¹-10² too high!**

Neutral density and Rec/Exc
($T_e \Rightarrow \varepsilon^{fb} < 365$ nm)



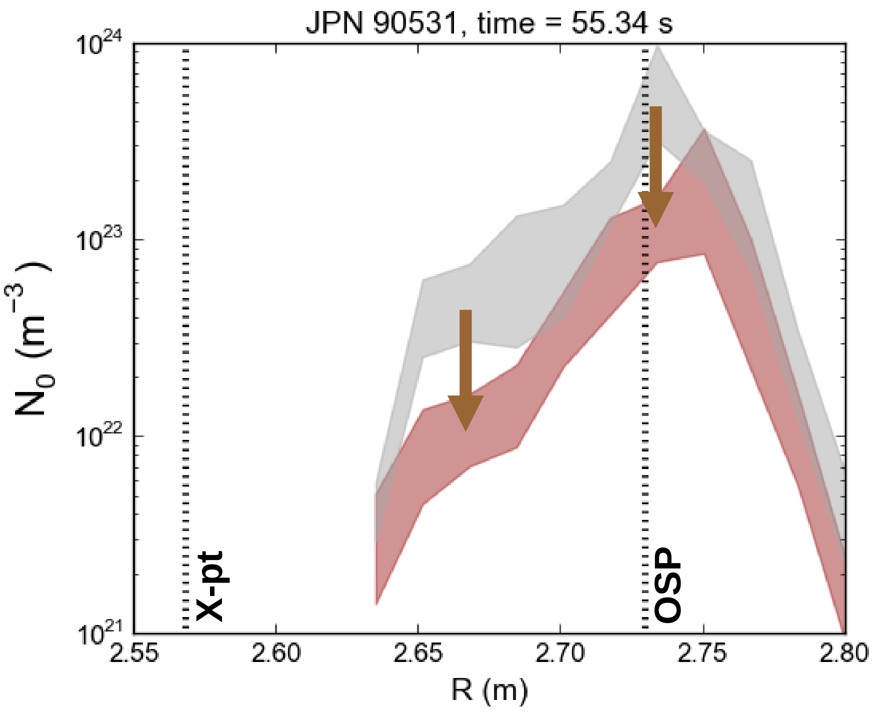


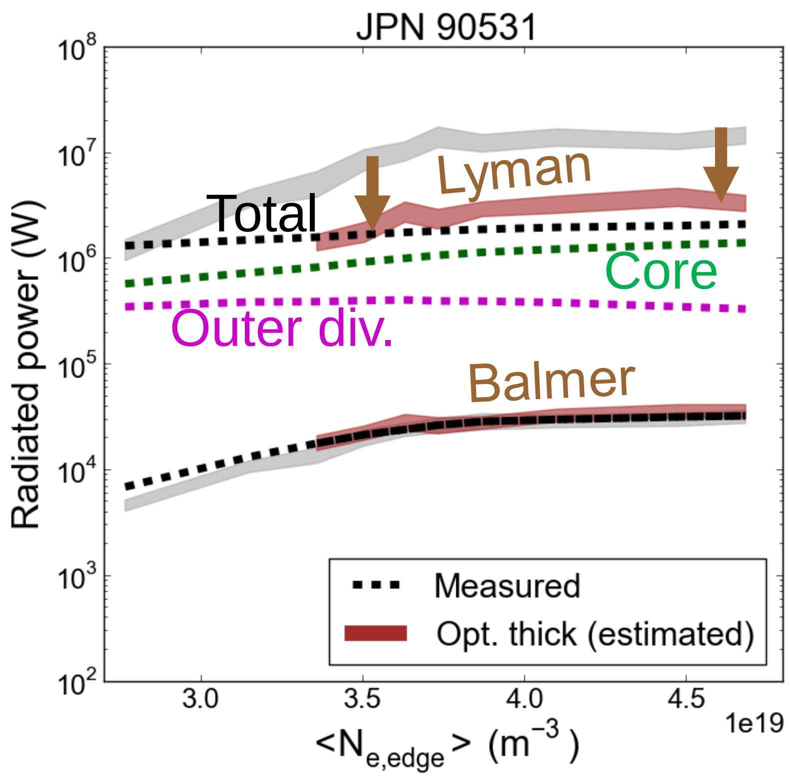
- **$0.4 < T_e < 0.75$ eV** too low for $\mathbf{N_0}$ estimate $\Rightarrow$ predicted power using recombination component only
- **$N_0 \sim 10^{28}$ required for agreement with measured Dα power !?!**

ADF15 PEC coeffficients with estimated opacity correction

- Recent H L-mode experiments suggest opacity could be significant:

  ⇒ Estimated escape factors: $g_{Ly\text{-}\alpha} \approx 0.1$ $g_{Ly\text{-}\beta} \approx 0.55$





- **N_0** and **$P_{RAD\text{-}Ly}$** ×3-4 decrease, but not enough to reconcile bolometry measurements
- Ly-β , Ba-α radial profiles needed for better escape factor estimates

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Summary

- Integrated analysis combines two different (but intimately tied) emission processes ⇒ recombination continuum and Balmer lines
- Interpretation of continuum emission ⇒ low and high **T_e** estimates
- **Key question: which T_e is more representative of total emission?**

  ⇒ **Implications on detachment physics**: volume recombination, neutral density, populations and radiated power!

  ⇒ **Line-integration effects**: fundamental barrier to line-averaged analysis?

Next Steps:

- More precise characterisation of opacity ⇒ provide insight on self-consistency of spectroscopic analysis
- Apply to modelled plasmas with *a priori* knowledge of parameter profiles along line-of-sight