Max-Planck-Institut für Plasmaphysik

NBI heating scenarios with flexible heating mix

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E3 Retreat 2021, adapted from Talk at 47th EPS Plasma Physics conference, 2020/1, Sitges, Spain

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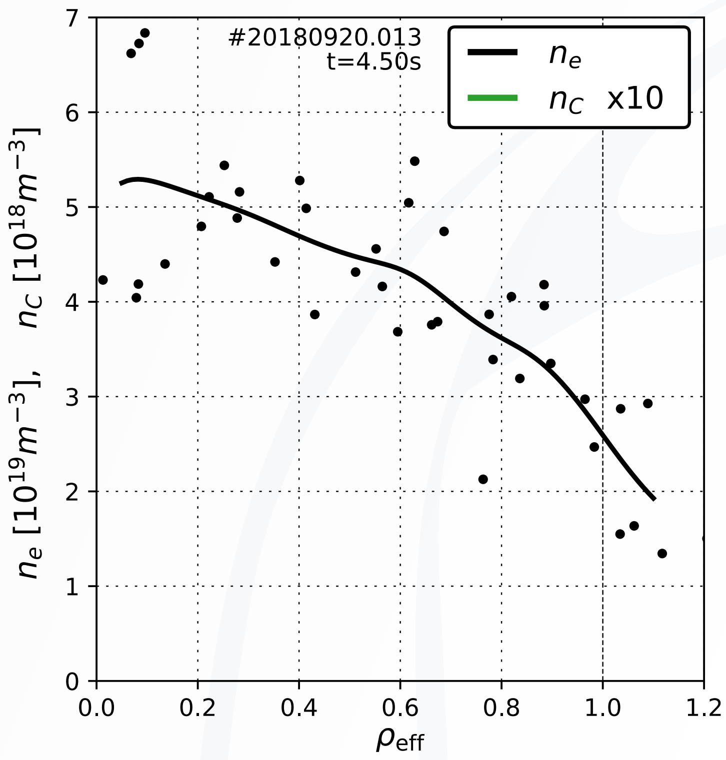
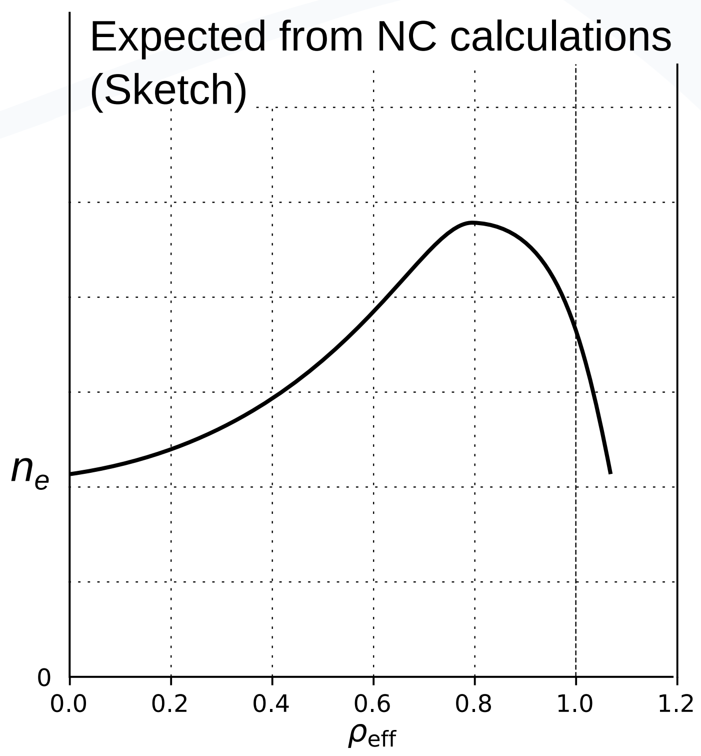
Gas-fuelled ECRH discharges

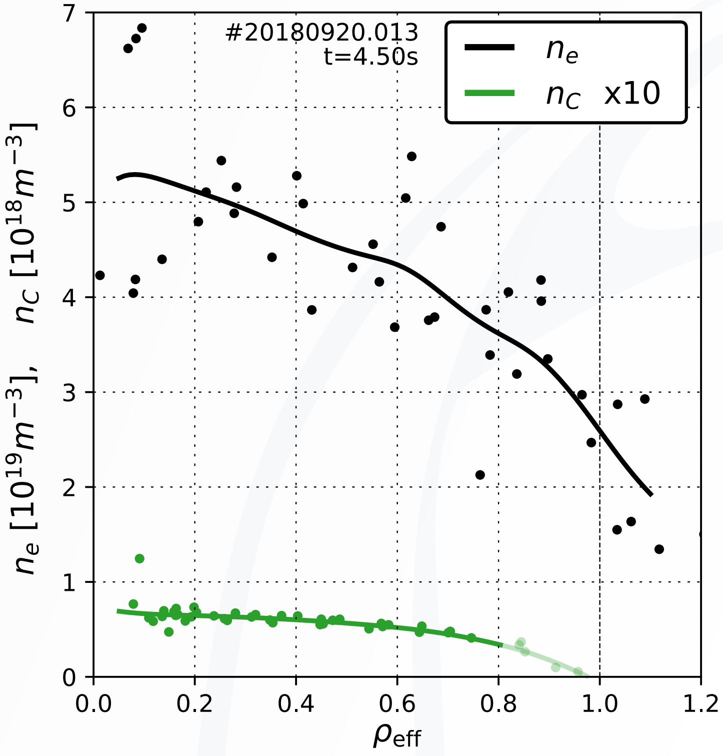
- Flat or slightly peaked density profiles despite outward neoclassical thermo-diffusion:
  An anomalous pinch required to counteract *[C D Beidler et al 2018 PPCF 60 105008]*

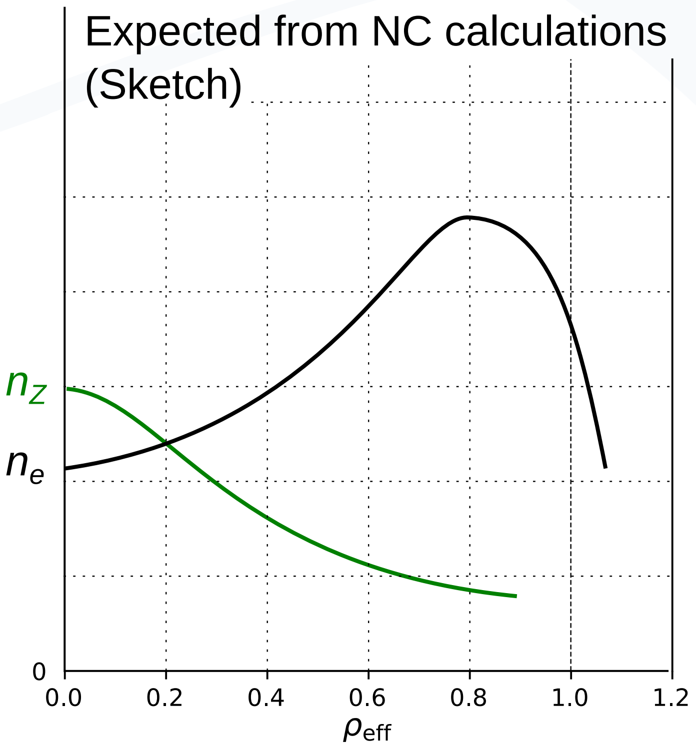




Gas-fuelled ECRH discharges

- Flat or slightly peaked density profiles despite outward neoclassical thermo-diffusion:
  An anomalous pinch required to counteract *[C D Beidler et al 2018 PPCF 60 105008]*
- Flat impurity profiles despite neoclassical pinch:
  High turbulent impurity diffusion shown by LBO injection experiments *[B. Geiger et al 2019 Nucl. Fus. 59 046009]*





Density gradient turbulence suppression

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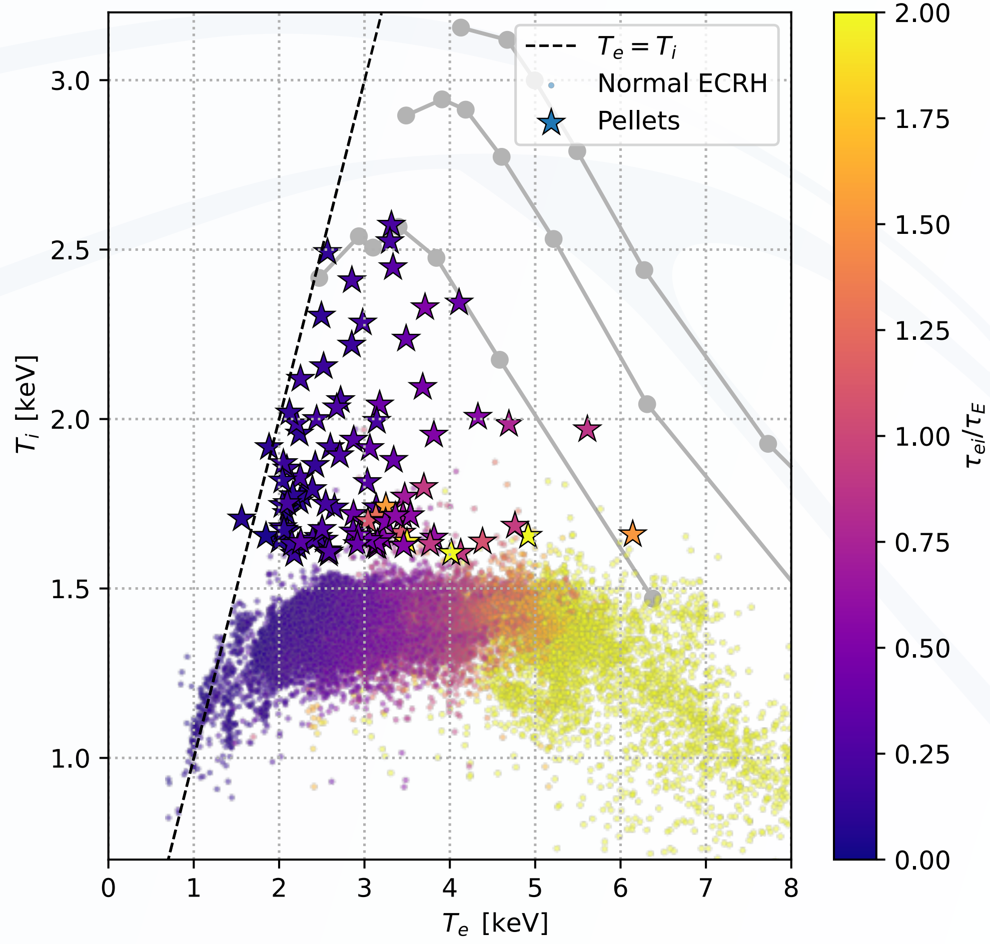

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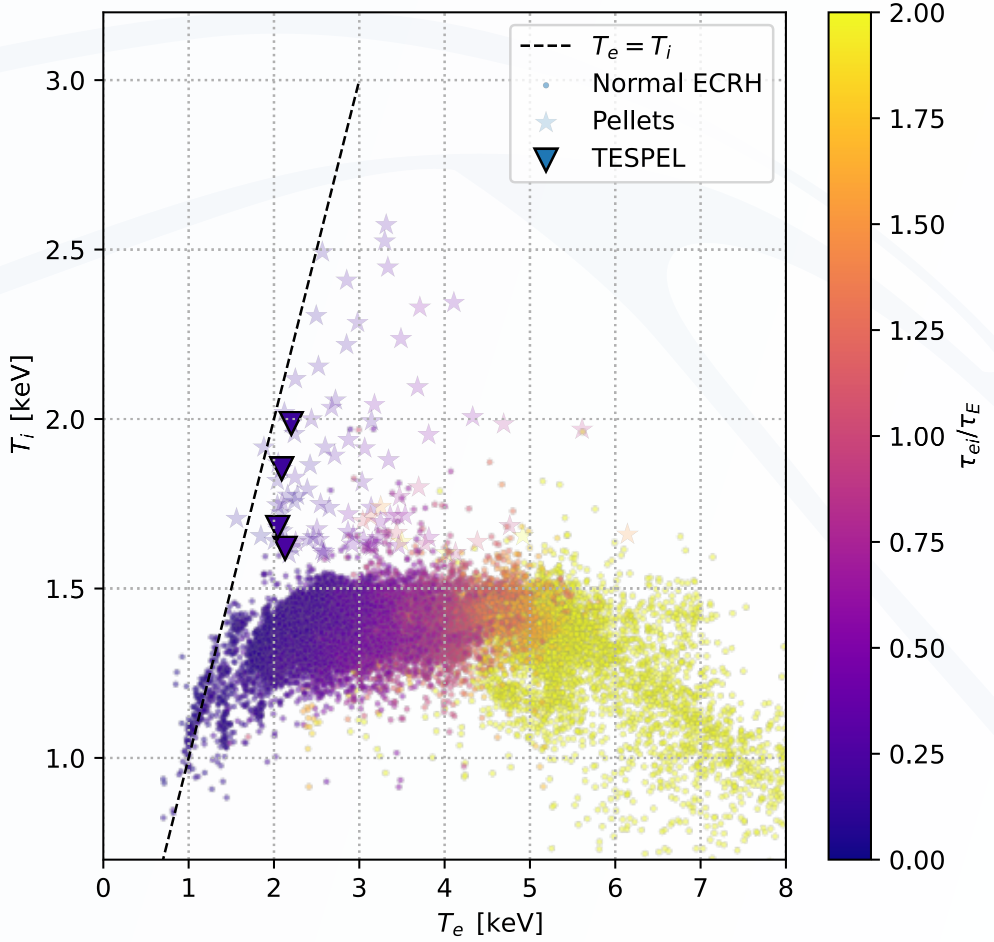

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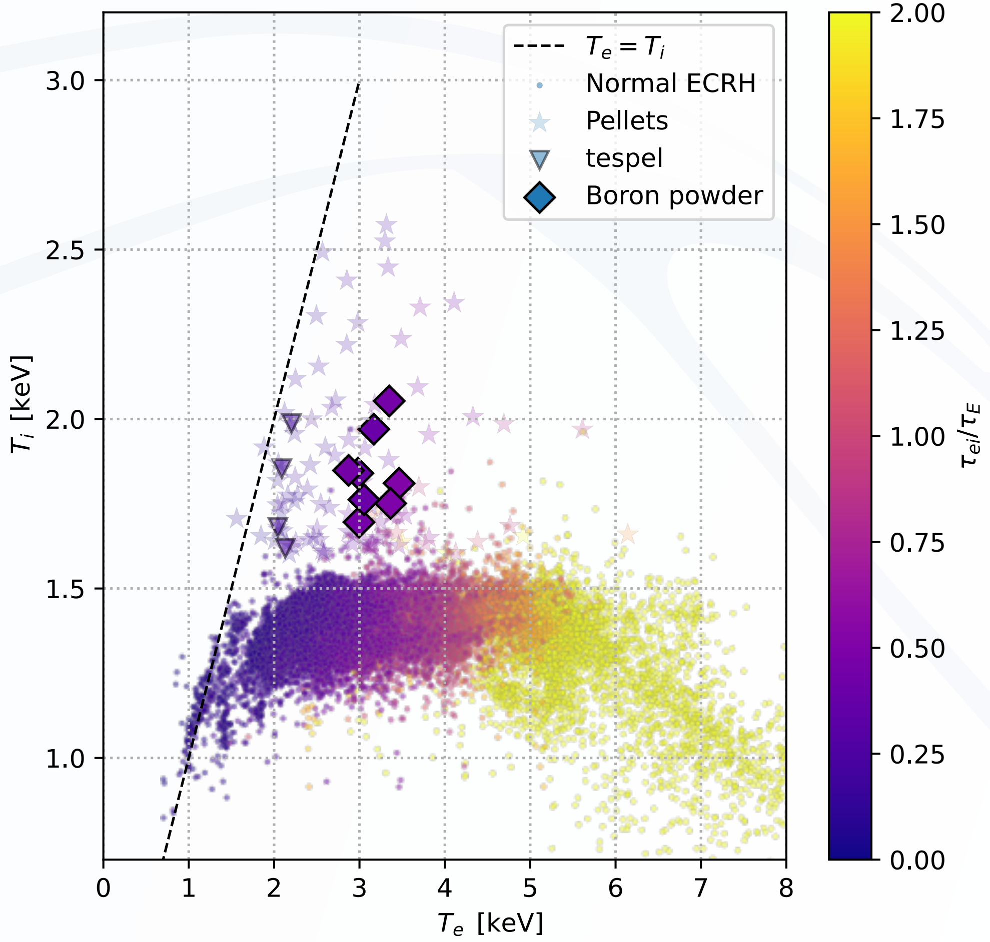

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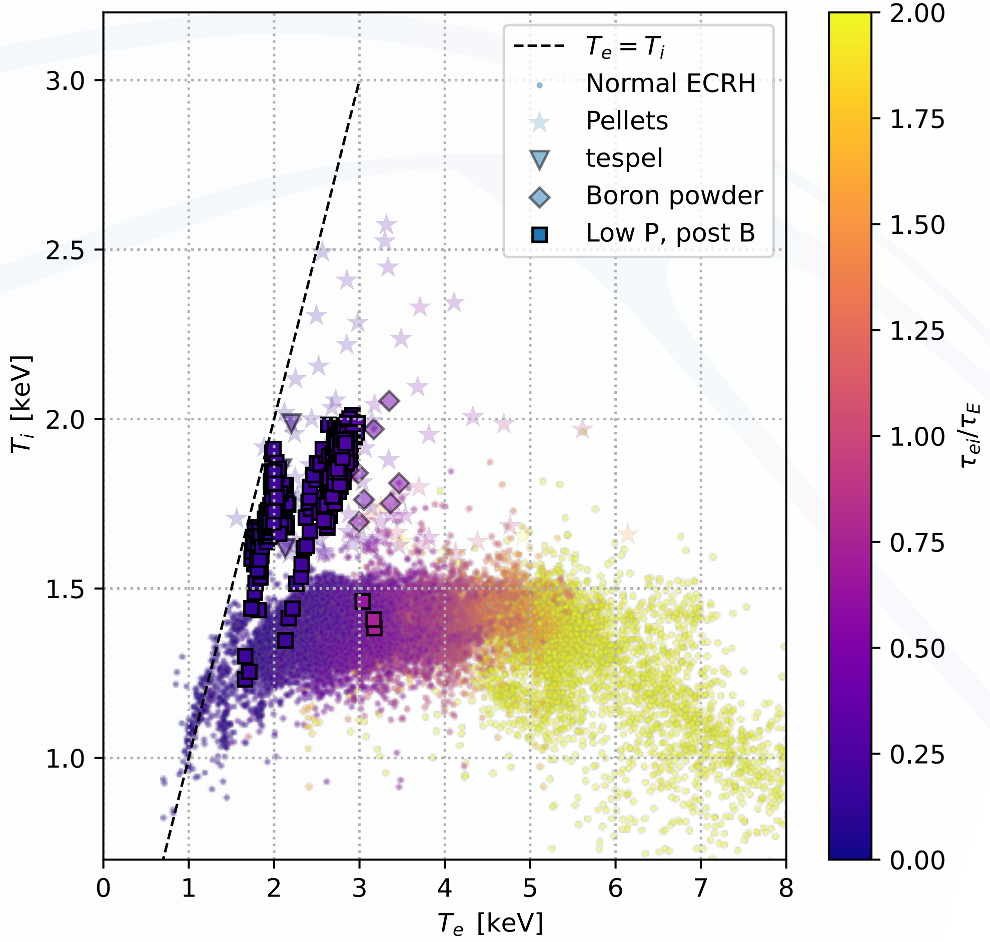

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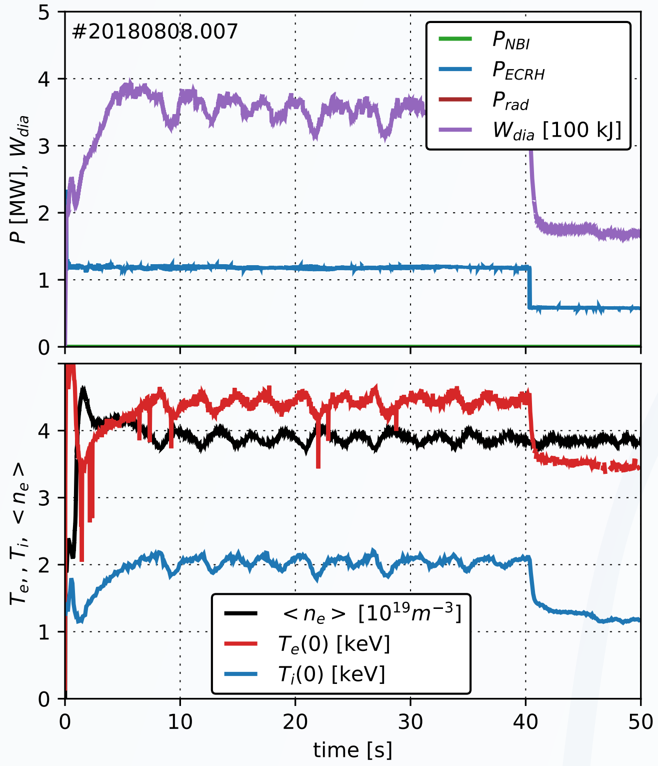

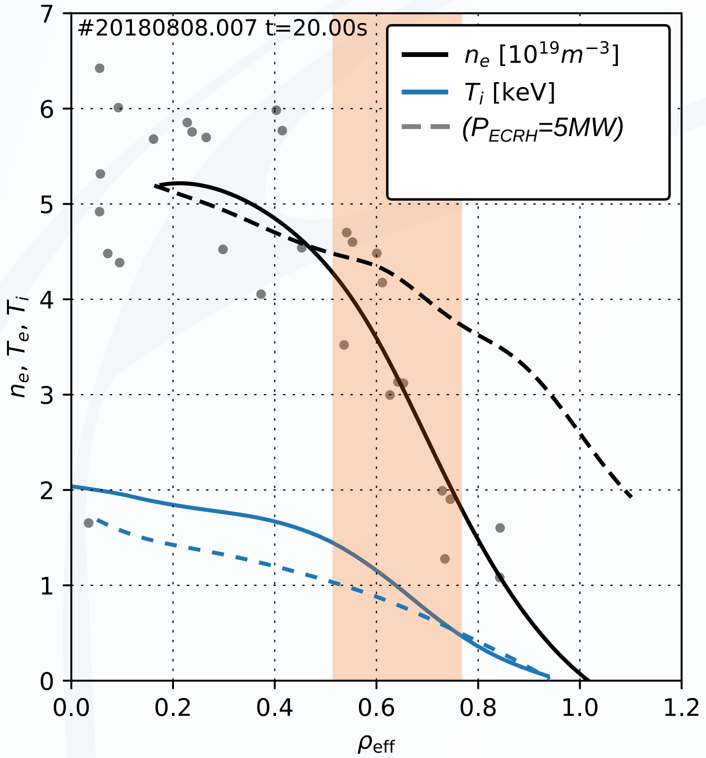

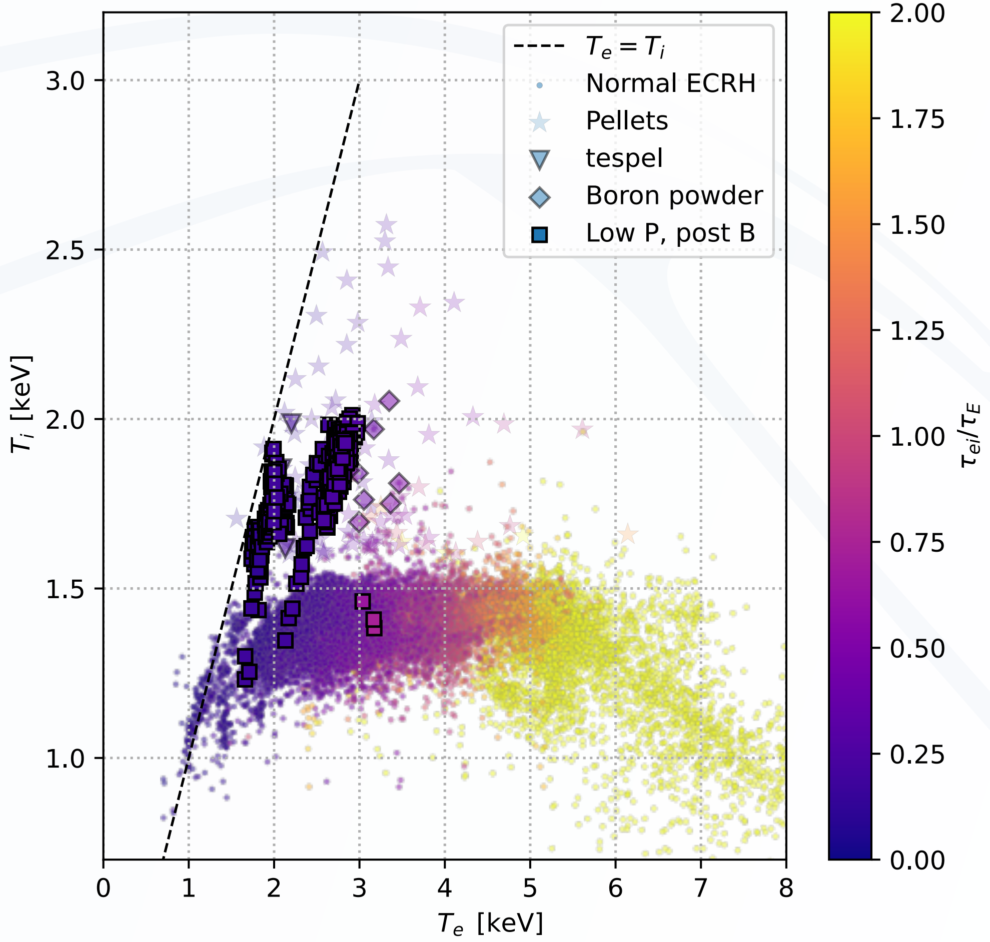

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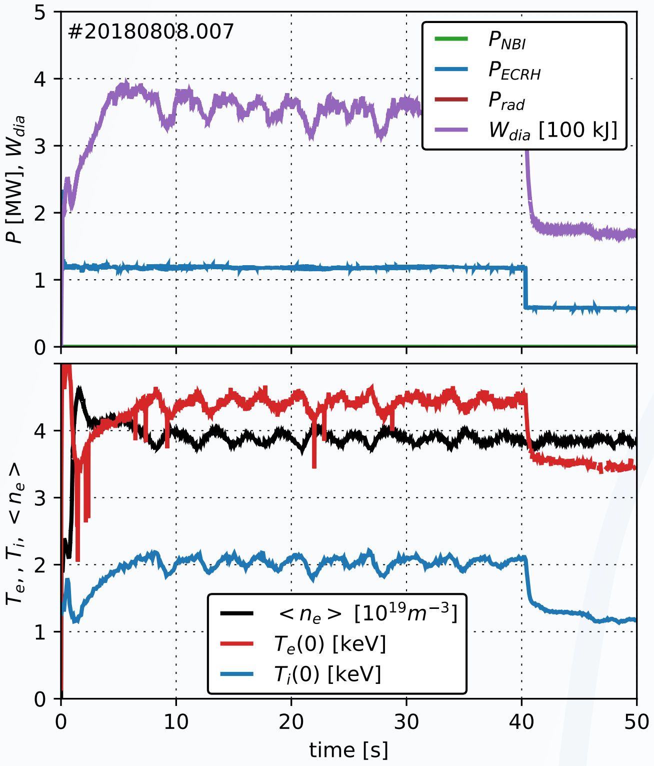
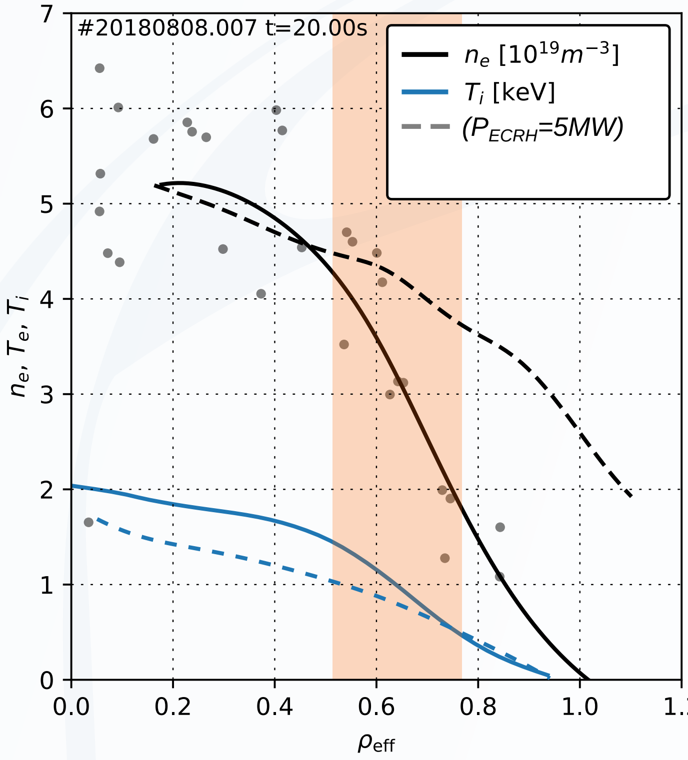
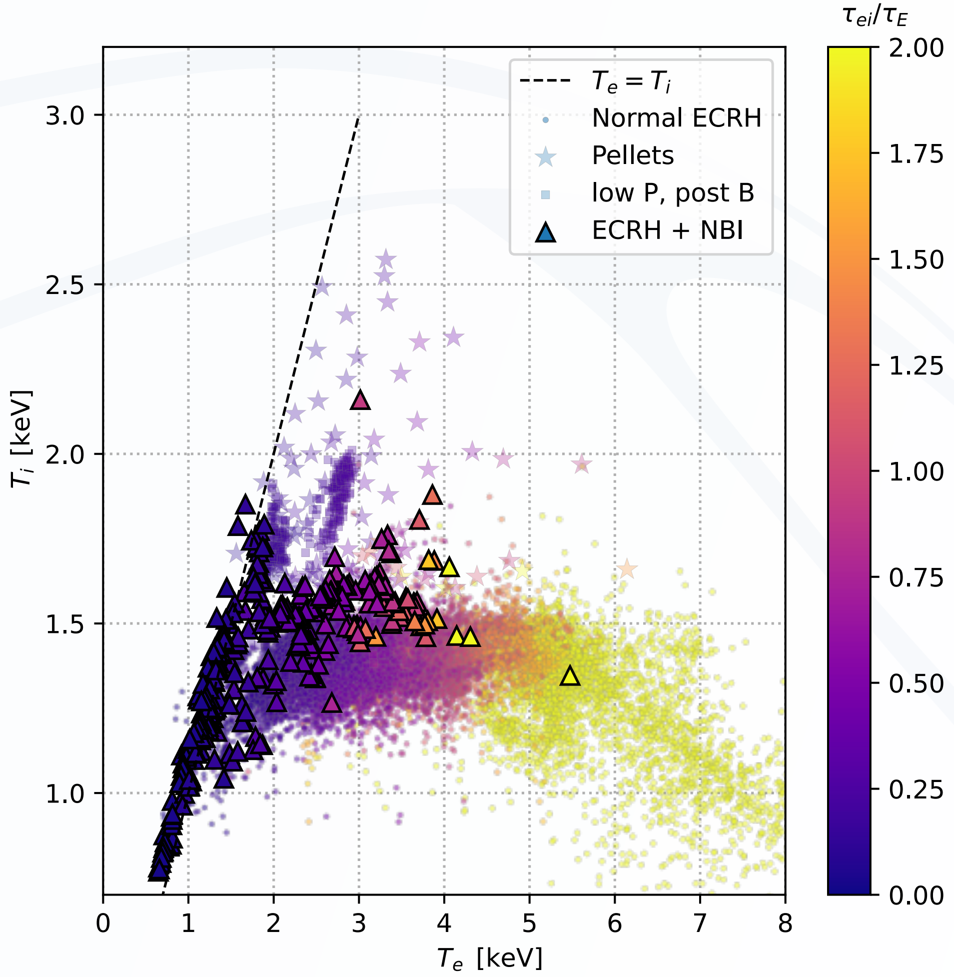
  - Low power long-duration discharges.
  - NBI core fuelling.





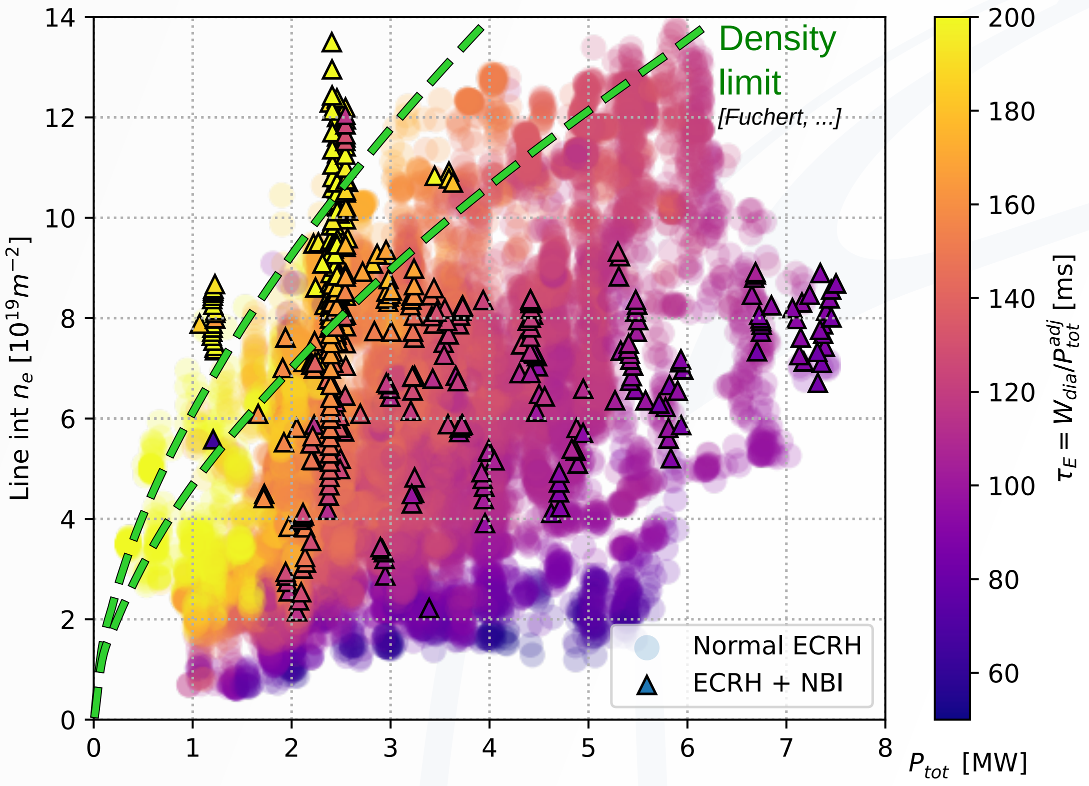


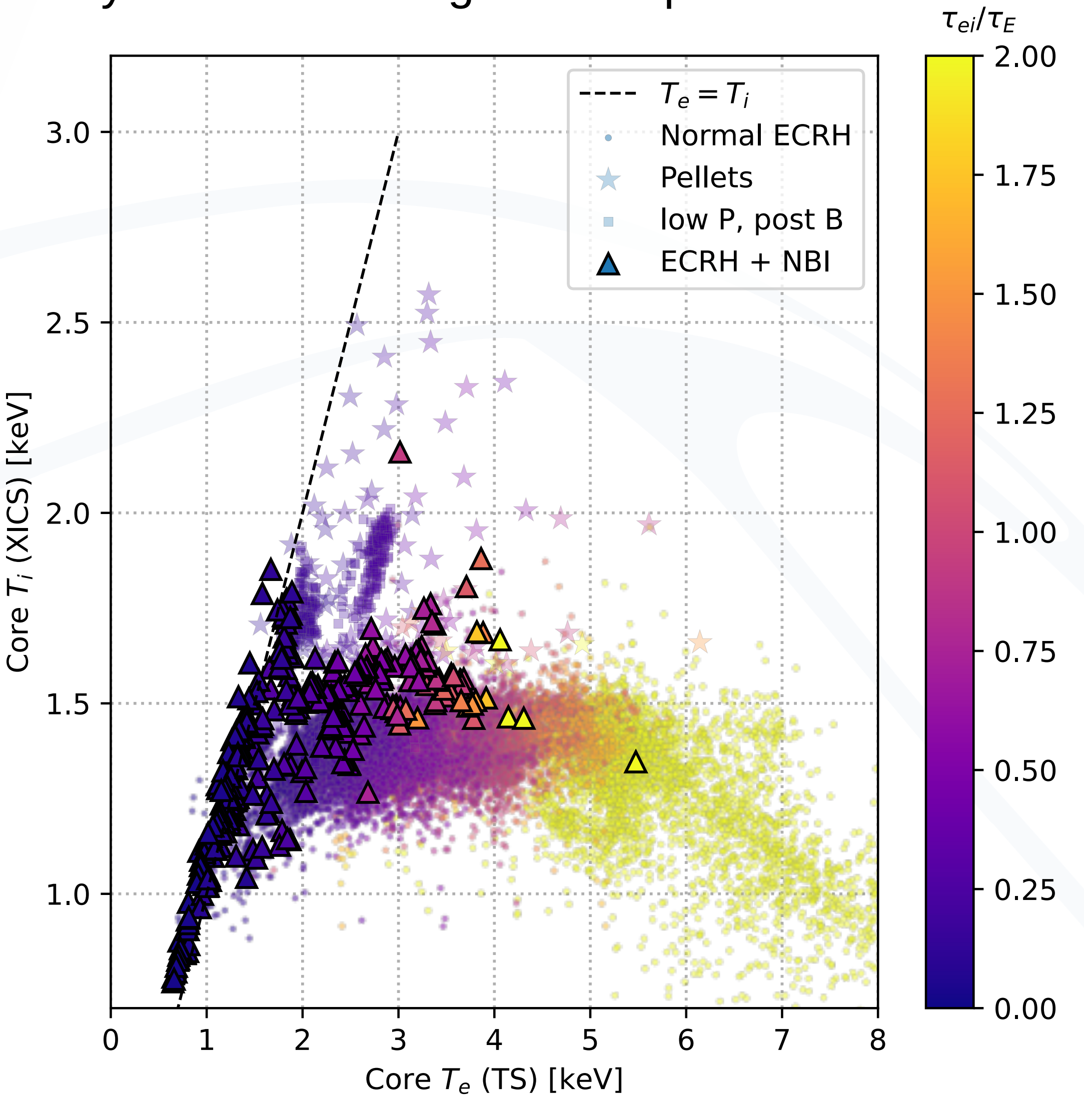
Neutral Beam Injection: Confinement

- NBI startup not possible on W7-X. Most beam injection is supplmentary to moderate-high ECRH power.
- Operation above ECRH radiative density limit [Fuchert, ...]
- Degradation with n_e relative to ISS04 stellarator scaling reduced.

$$\tau_{\mathrm{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} n_{\mathrm{e}}^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$

- T_i typically at only slightly above the T_i clamping limit.





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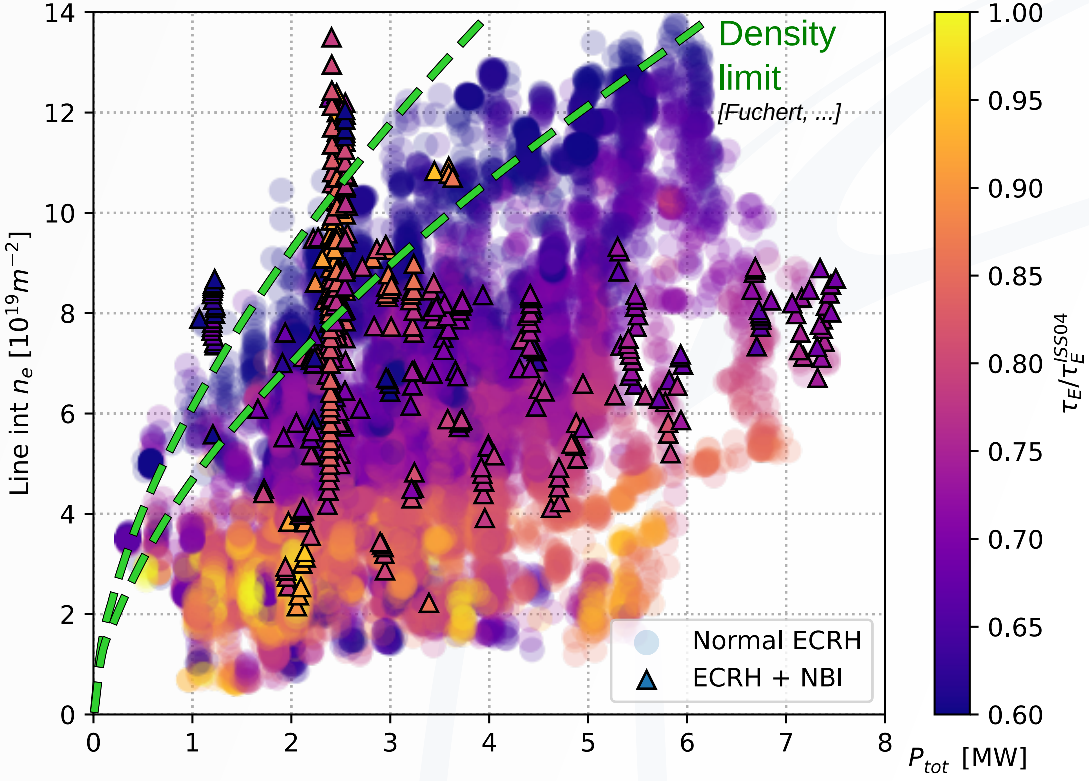

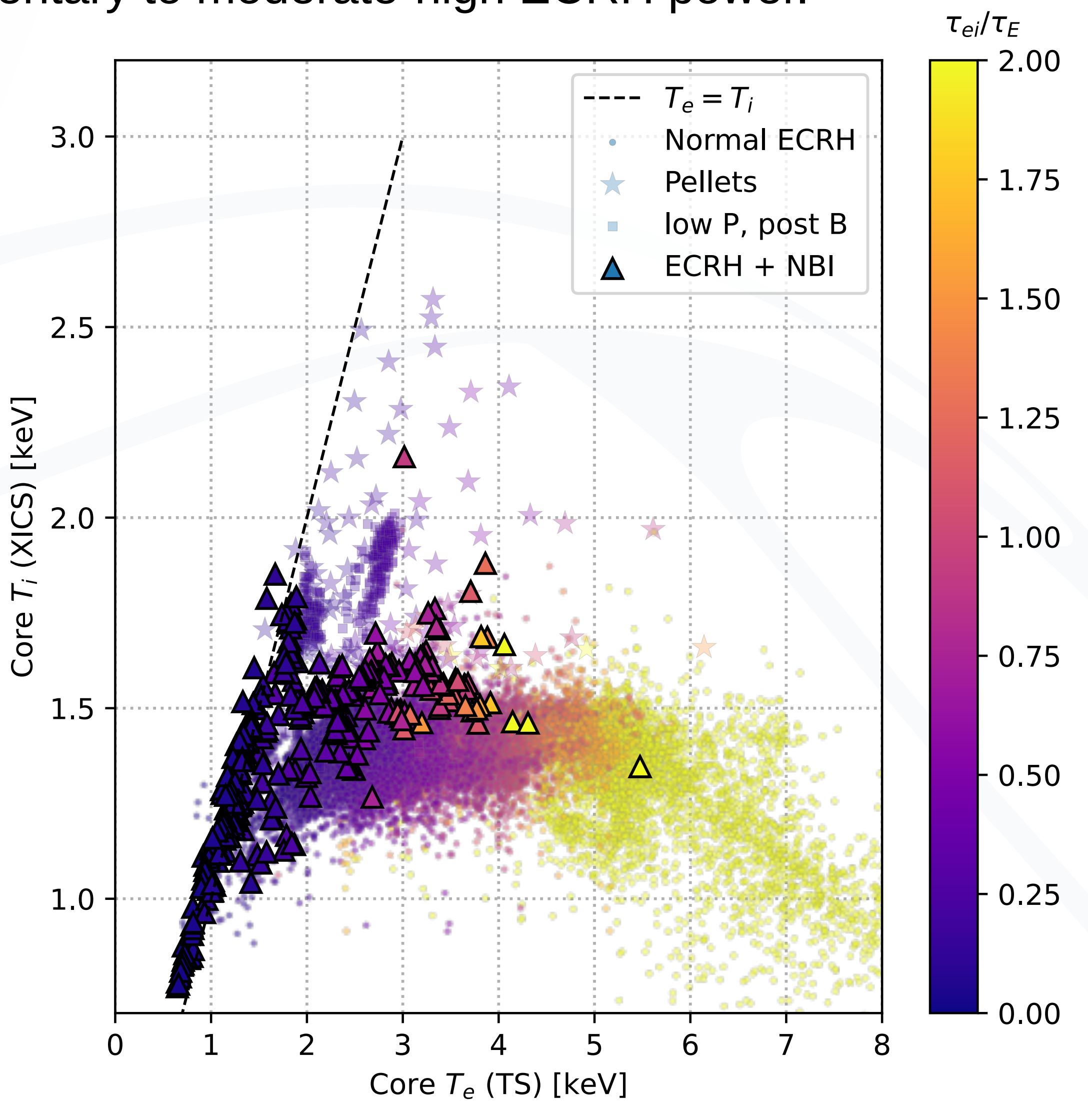

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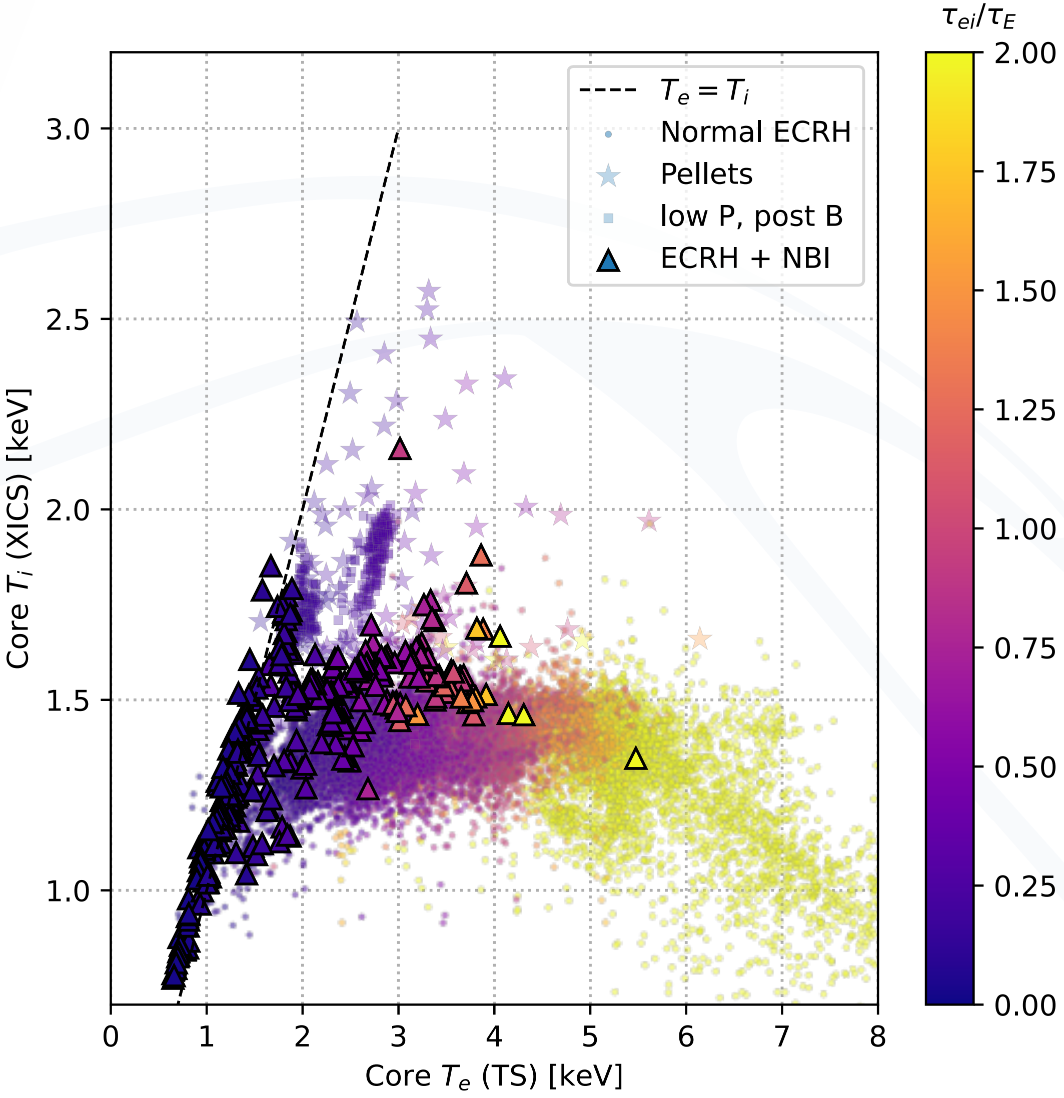

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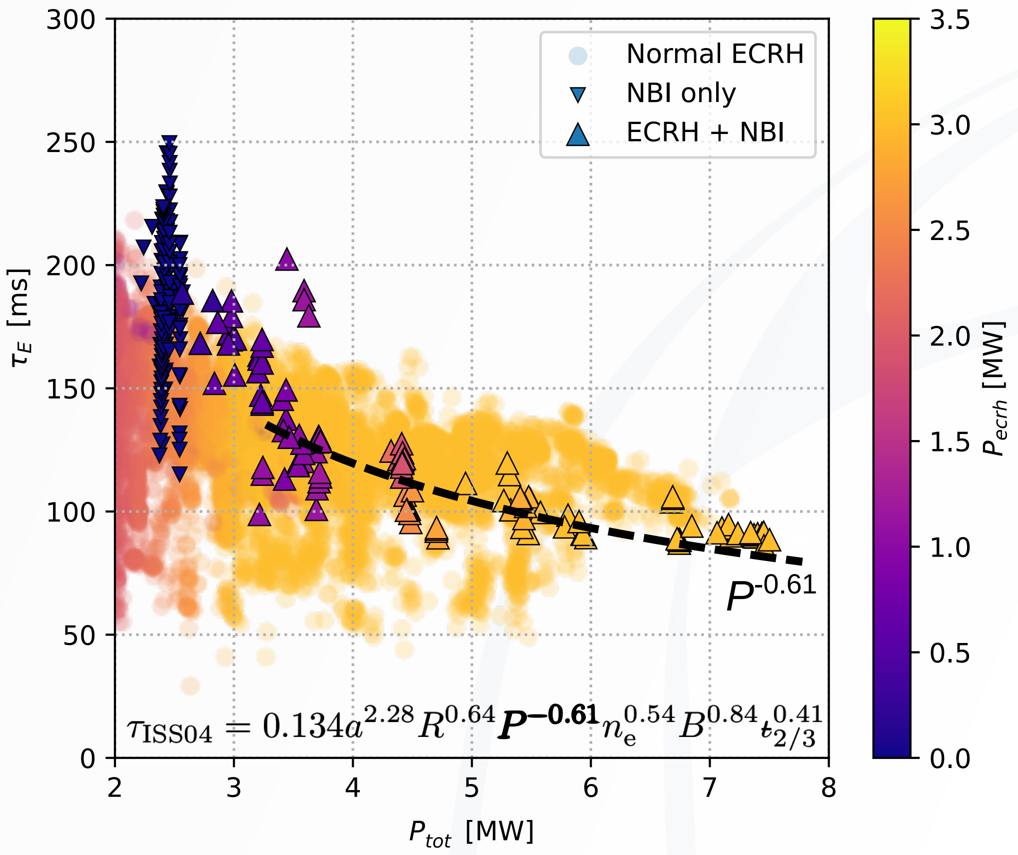

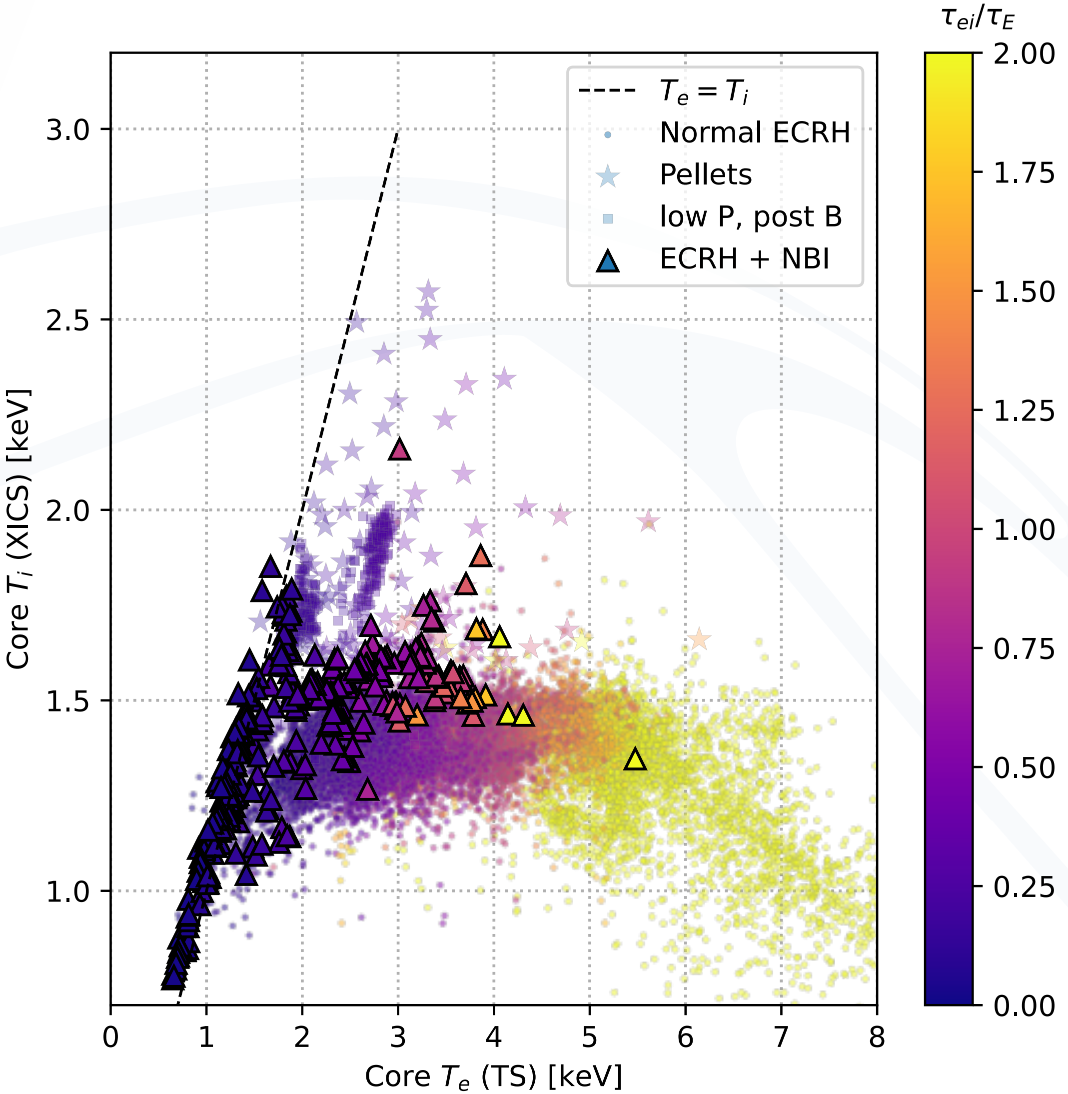

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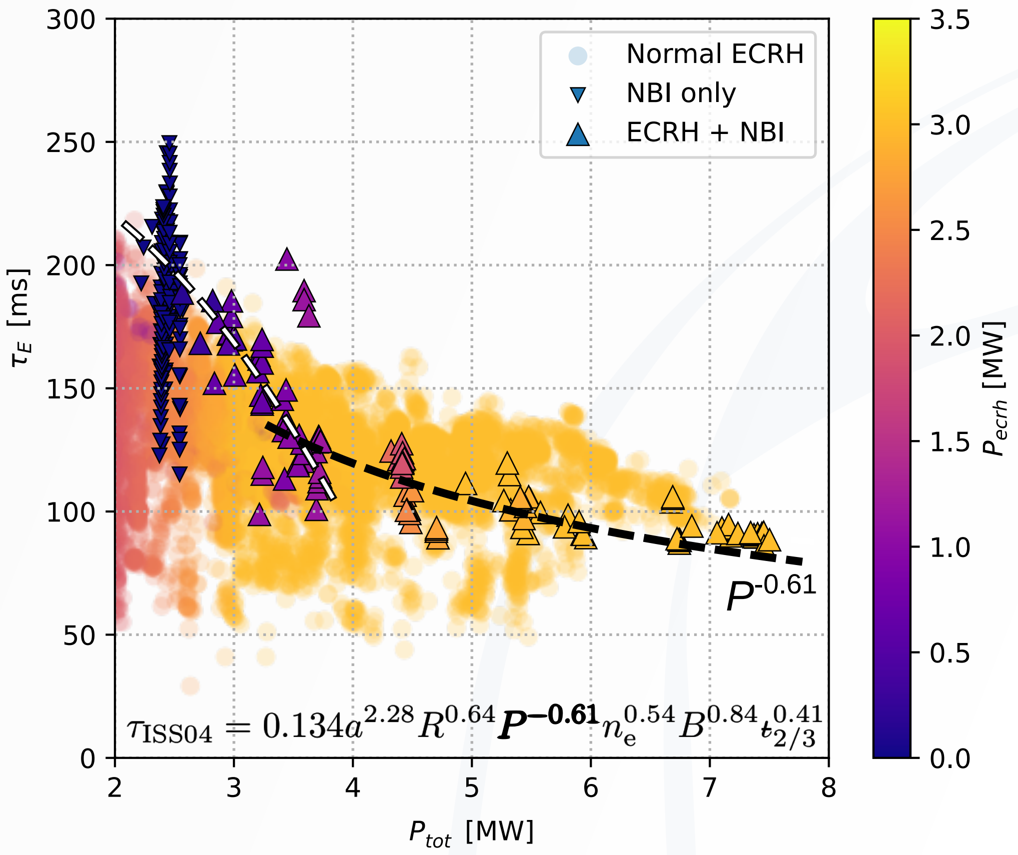

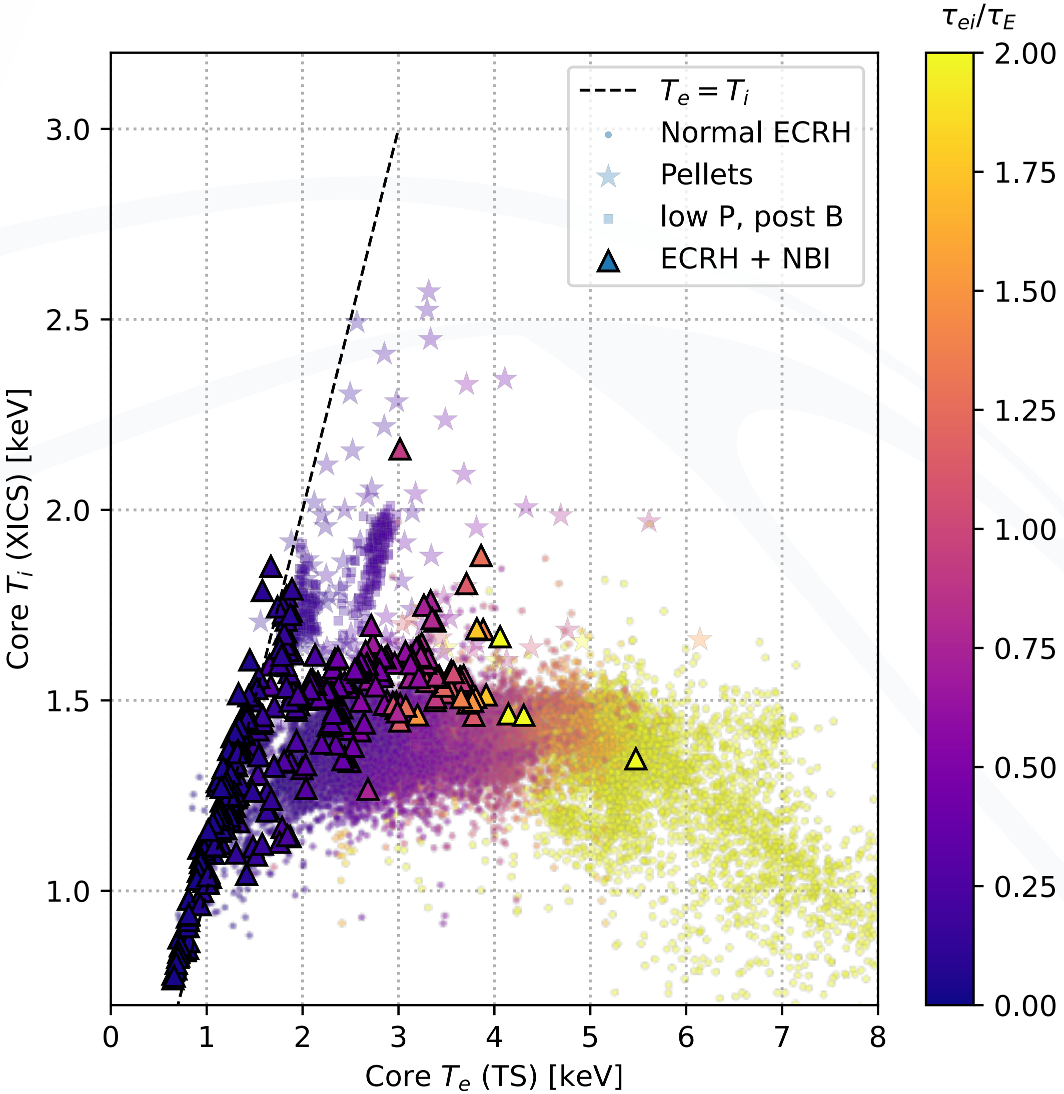

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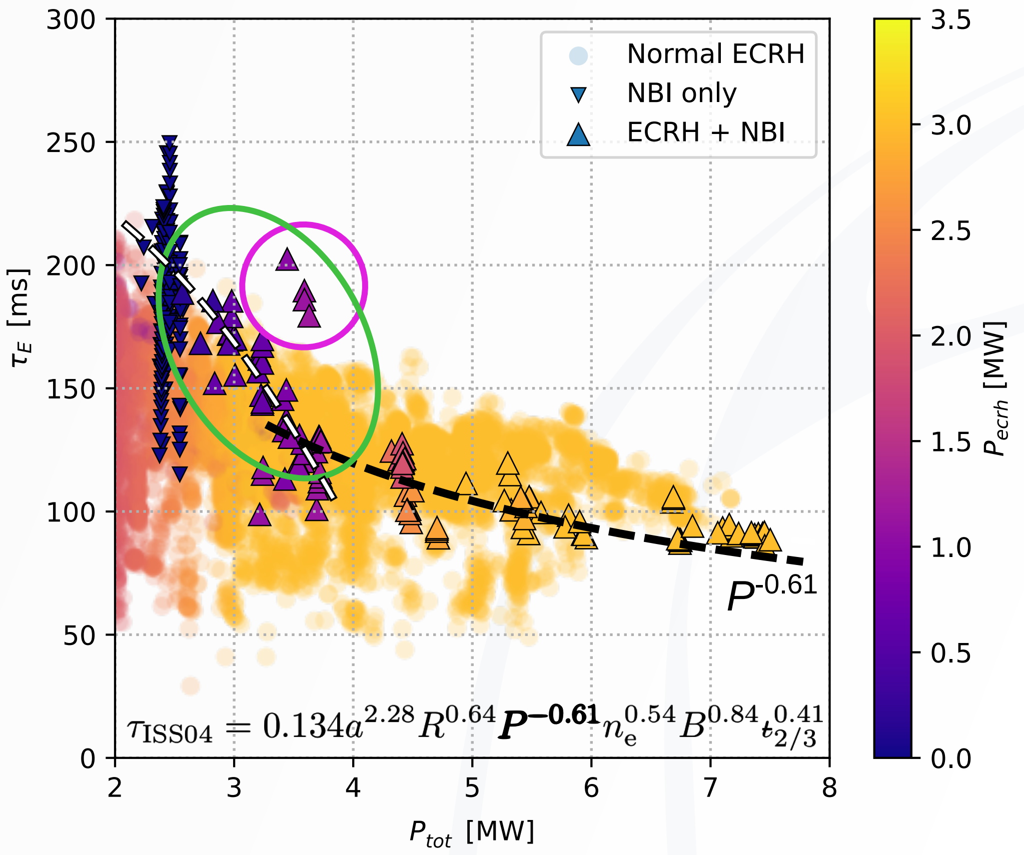
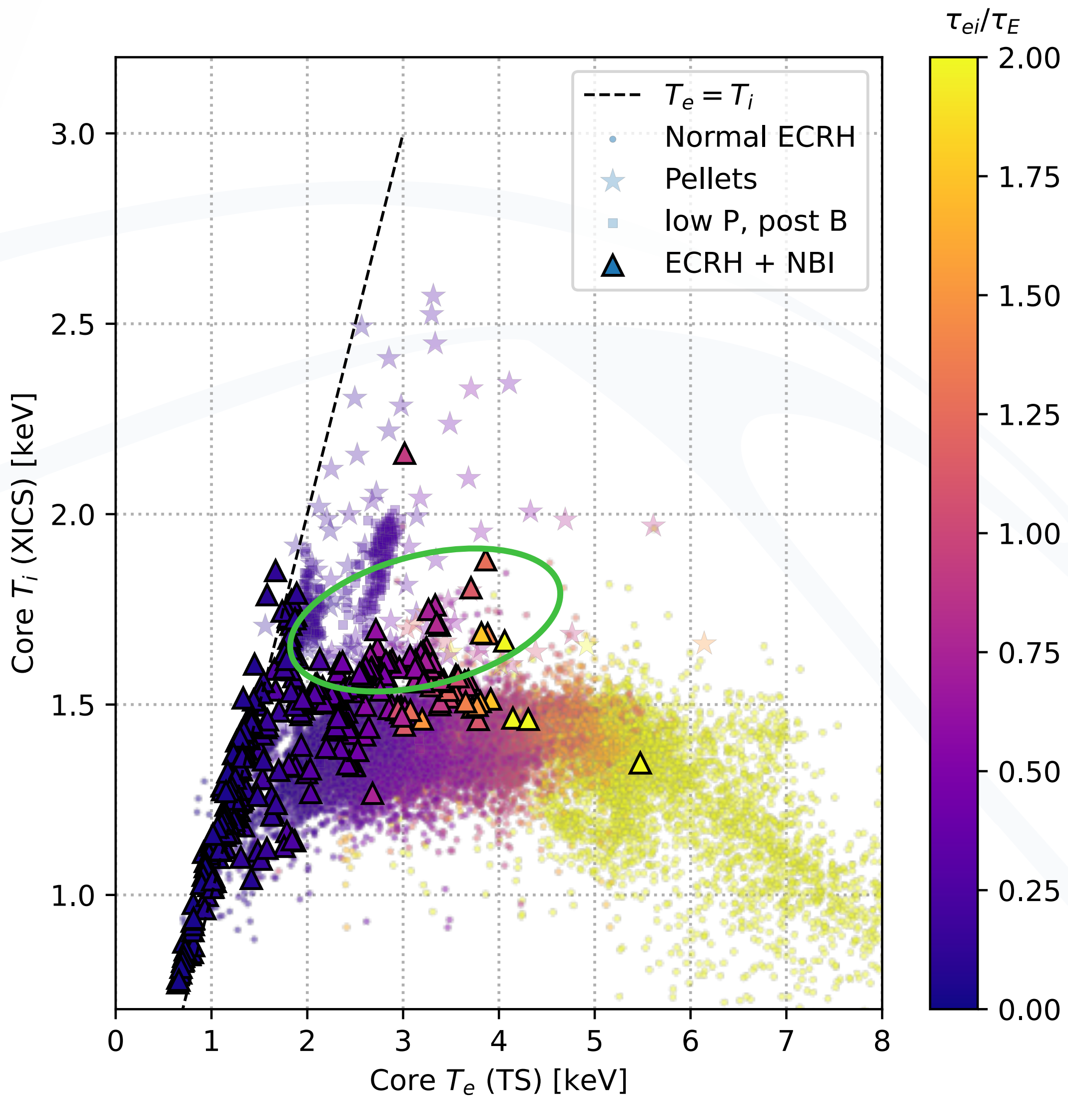
- Highest stationary T_i above clamping with NBI + 1MW ECRH.

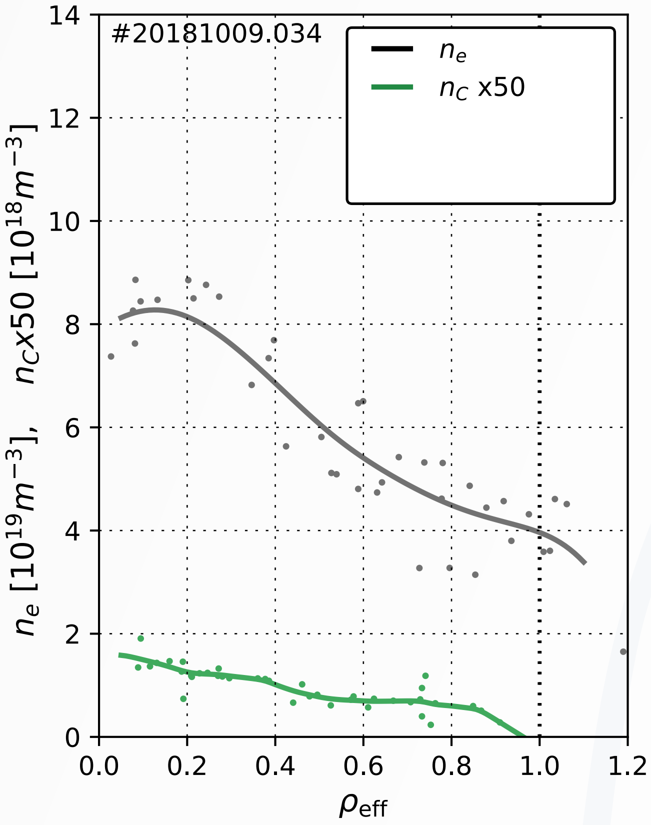


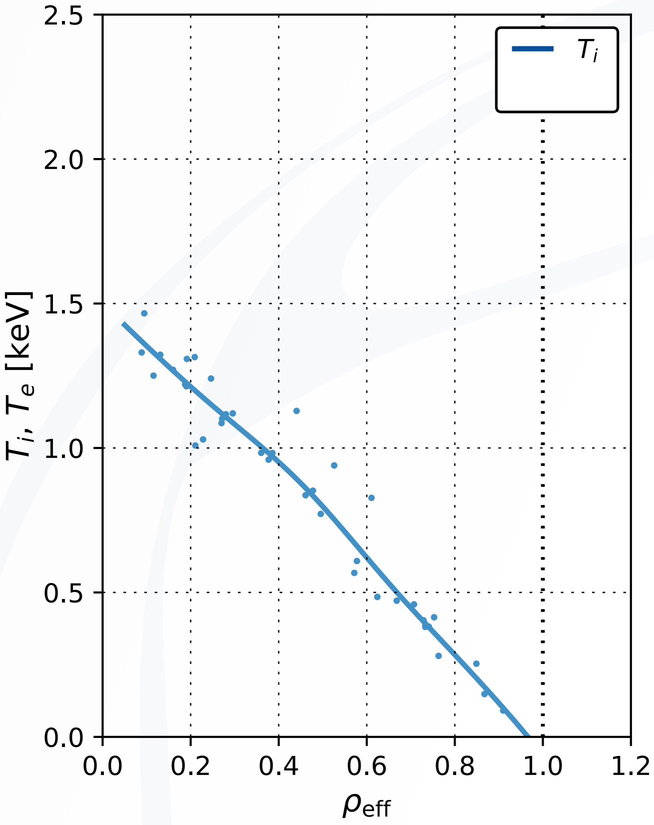


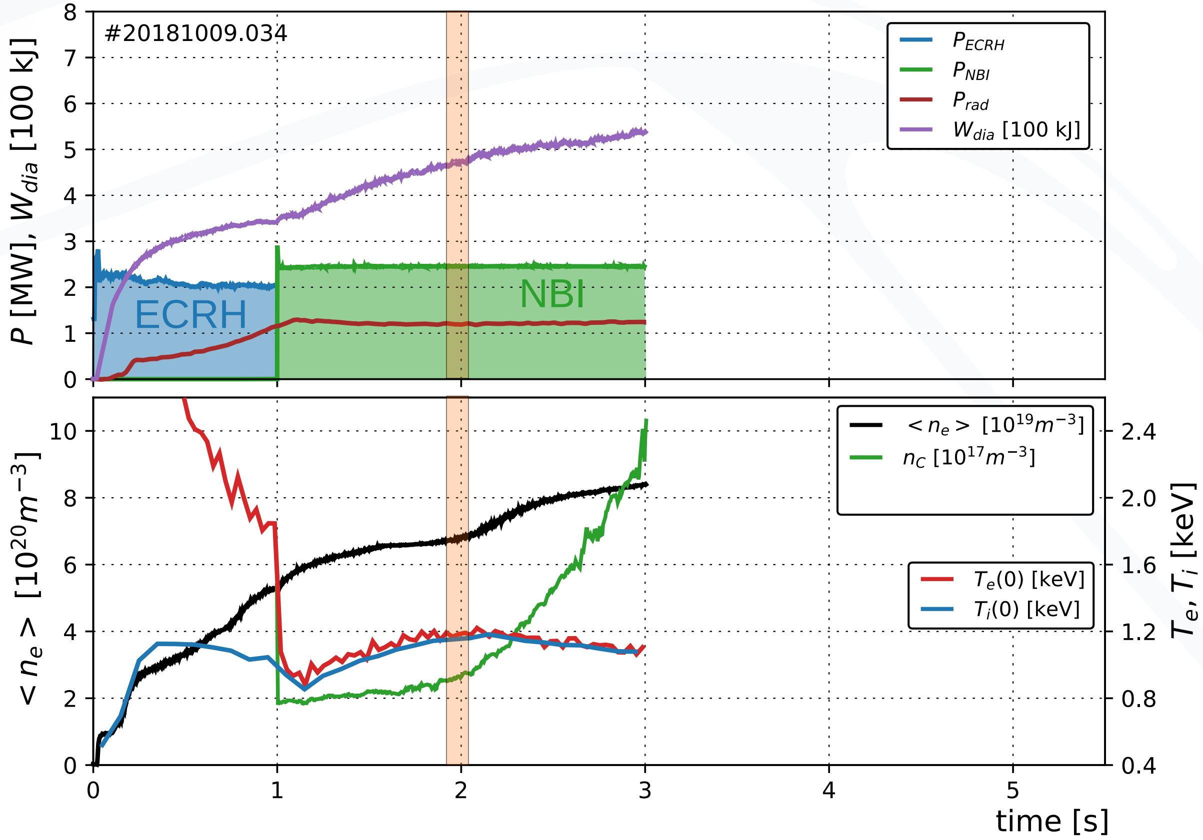
Mixed heating experiments

1: ECRH startup, switch to NBI only. Initial NBI phase shows moderate density peaking.

2: Density rise in $\rho < 0.5$ accelerates.







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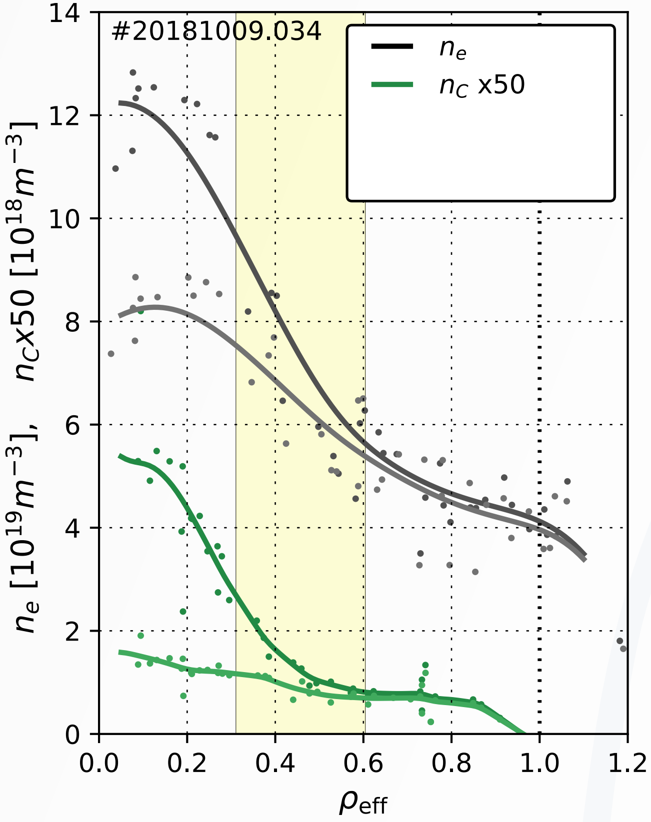

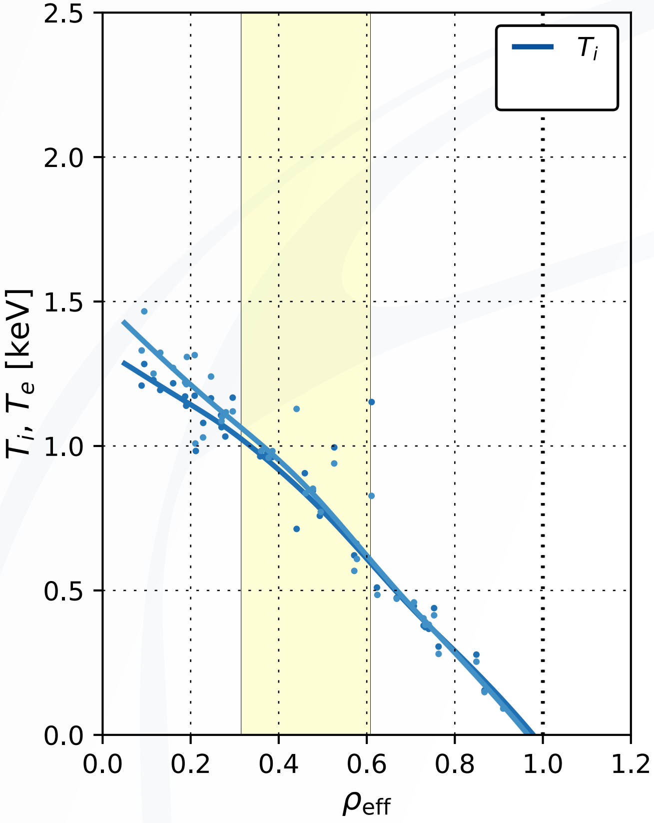

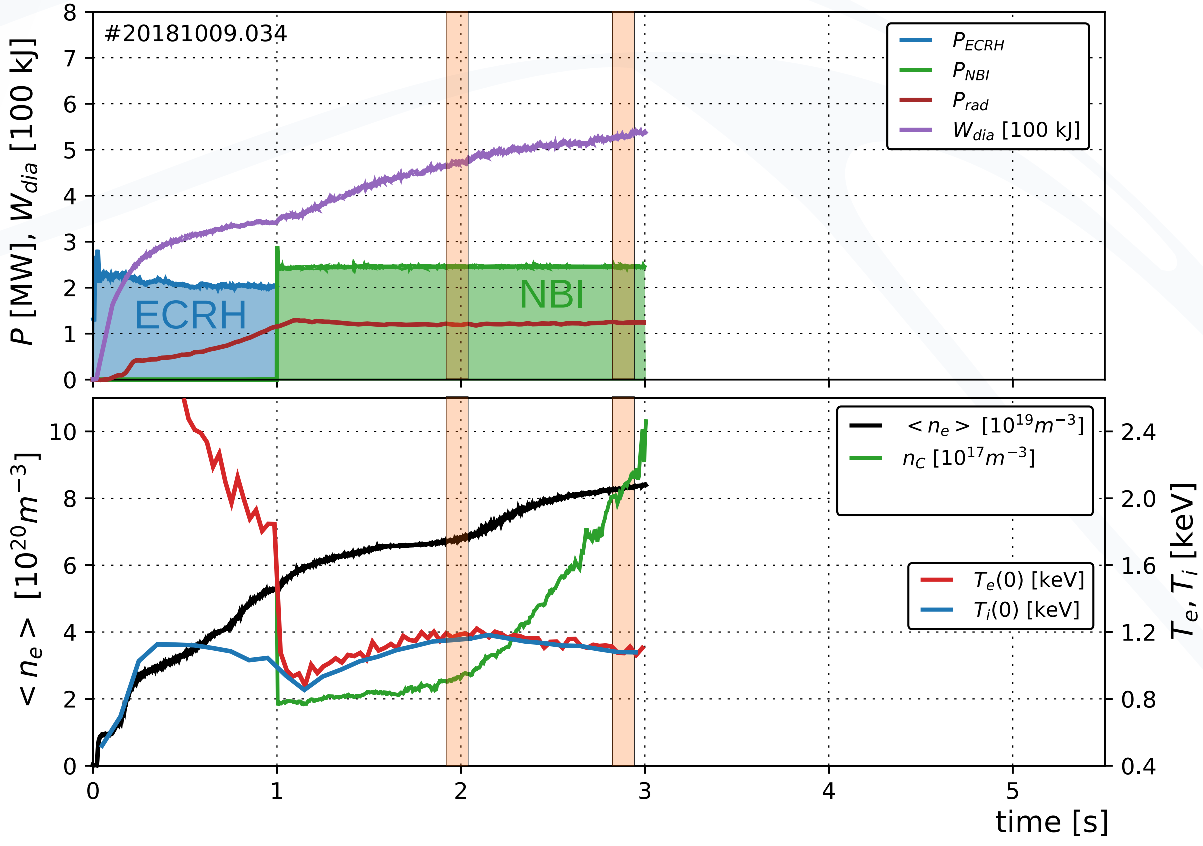

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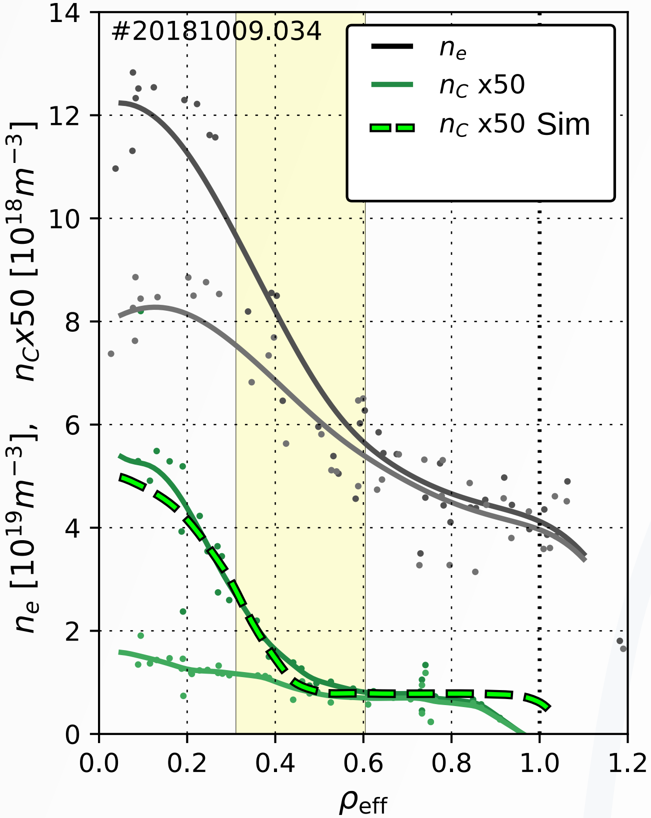

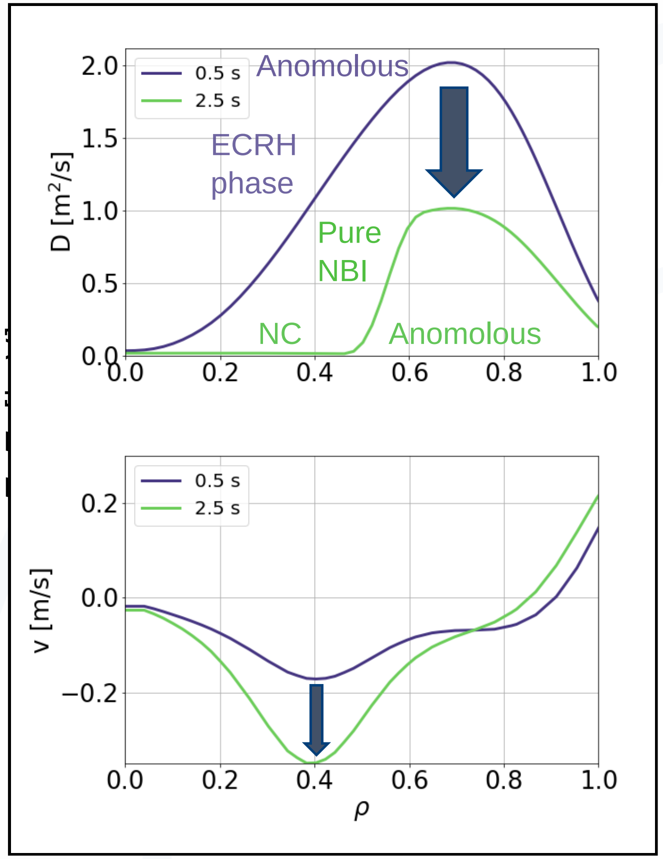

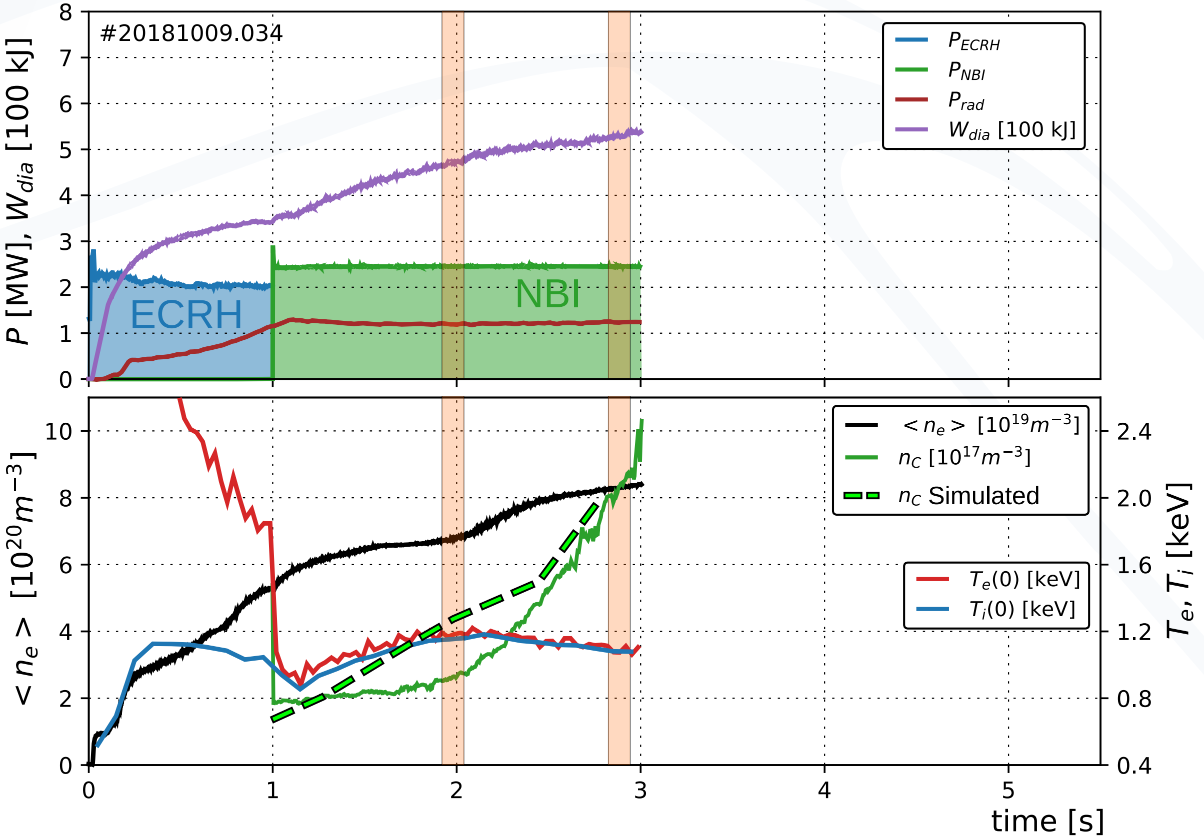

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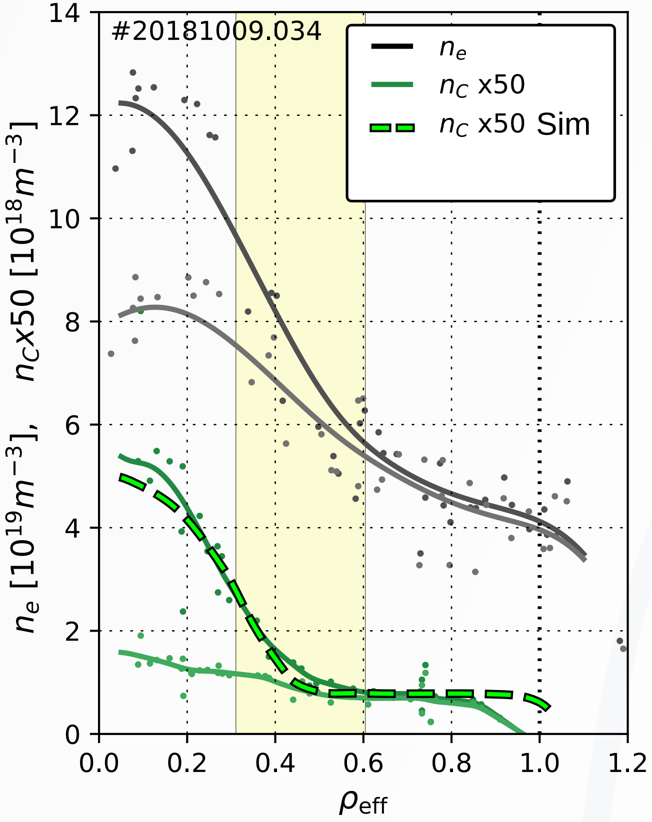

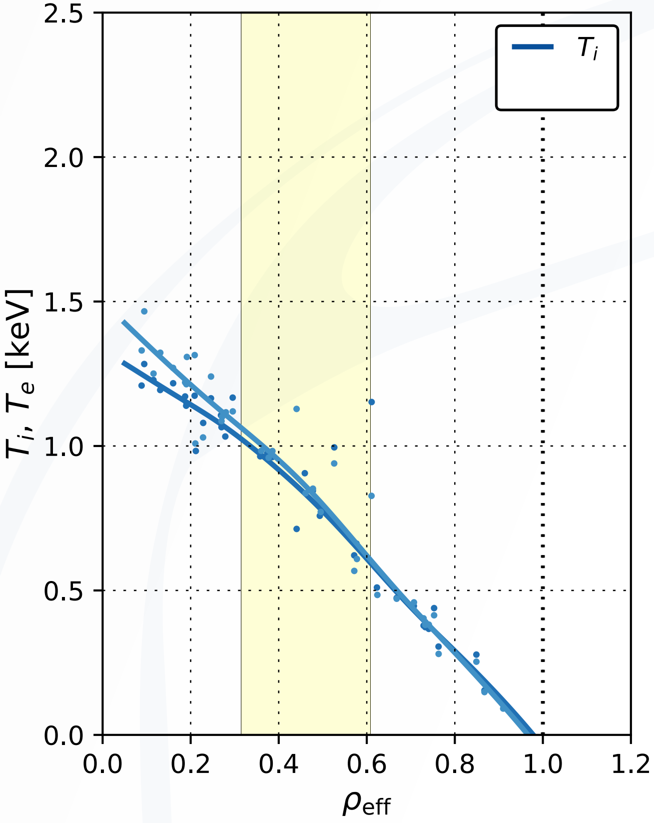

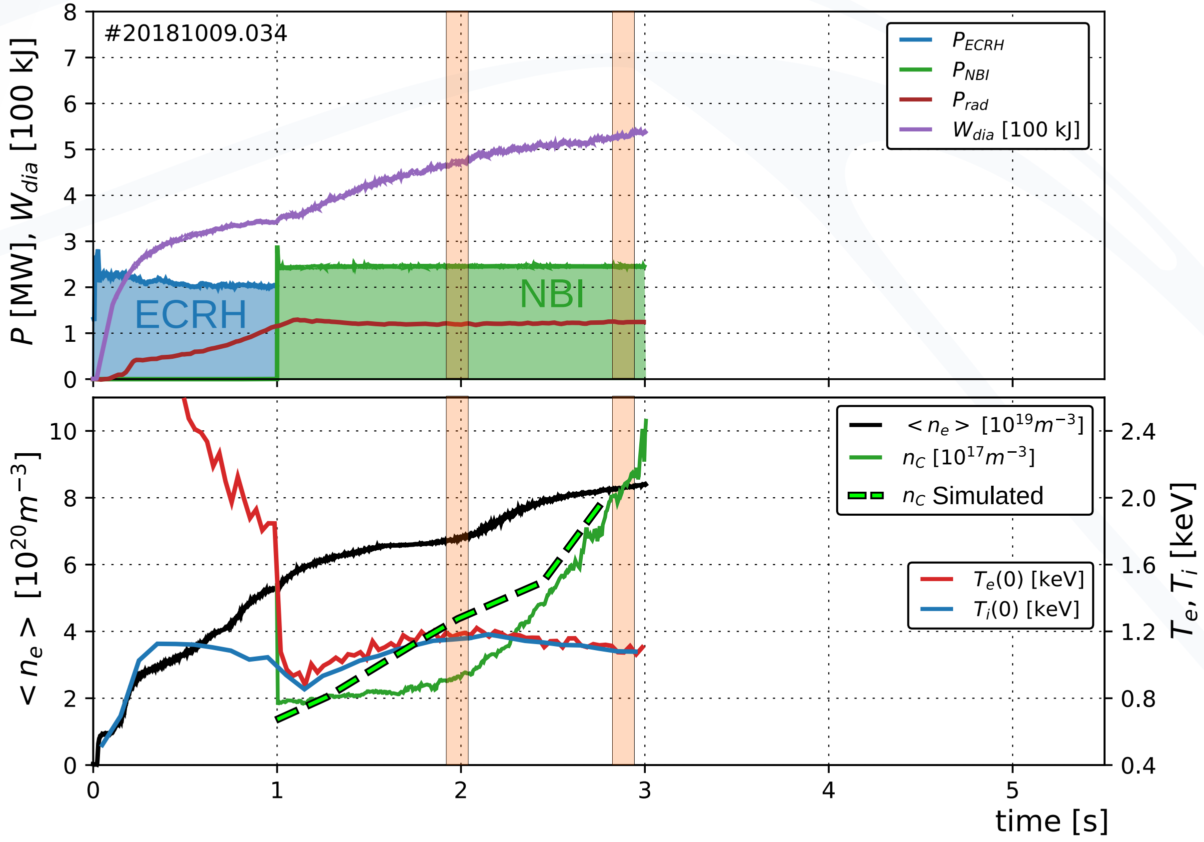

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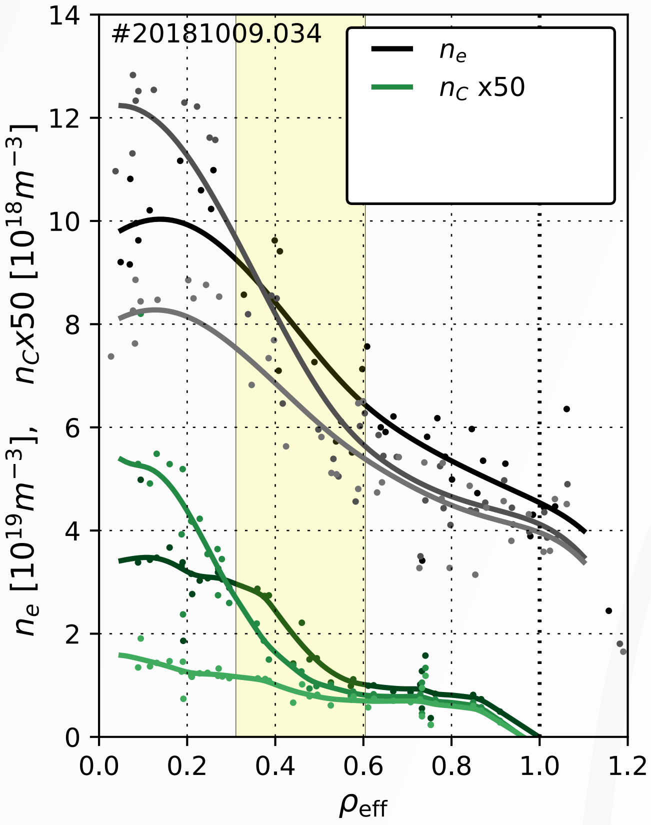

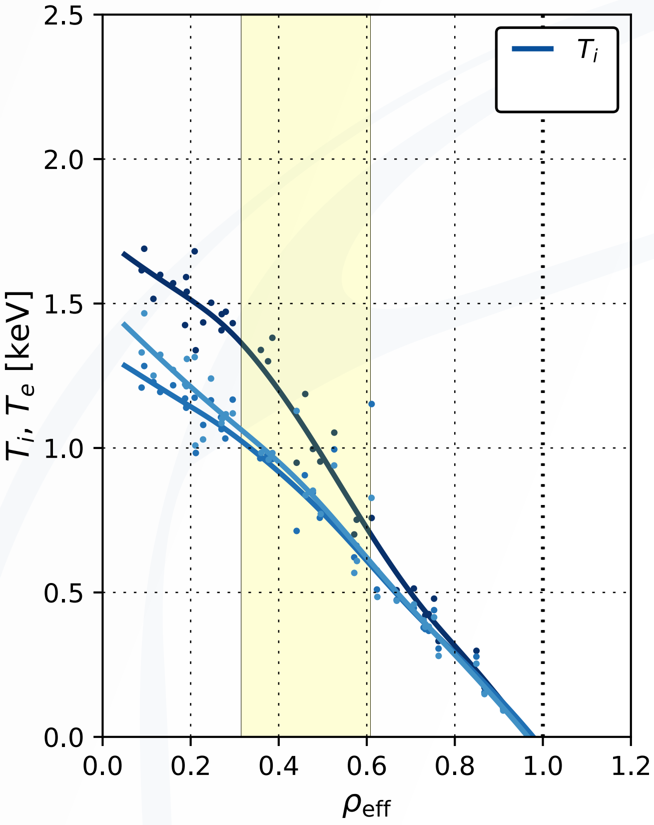

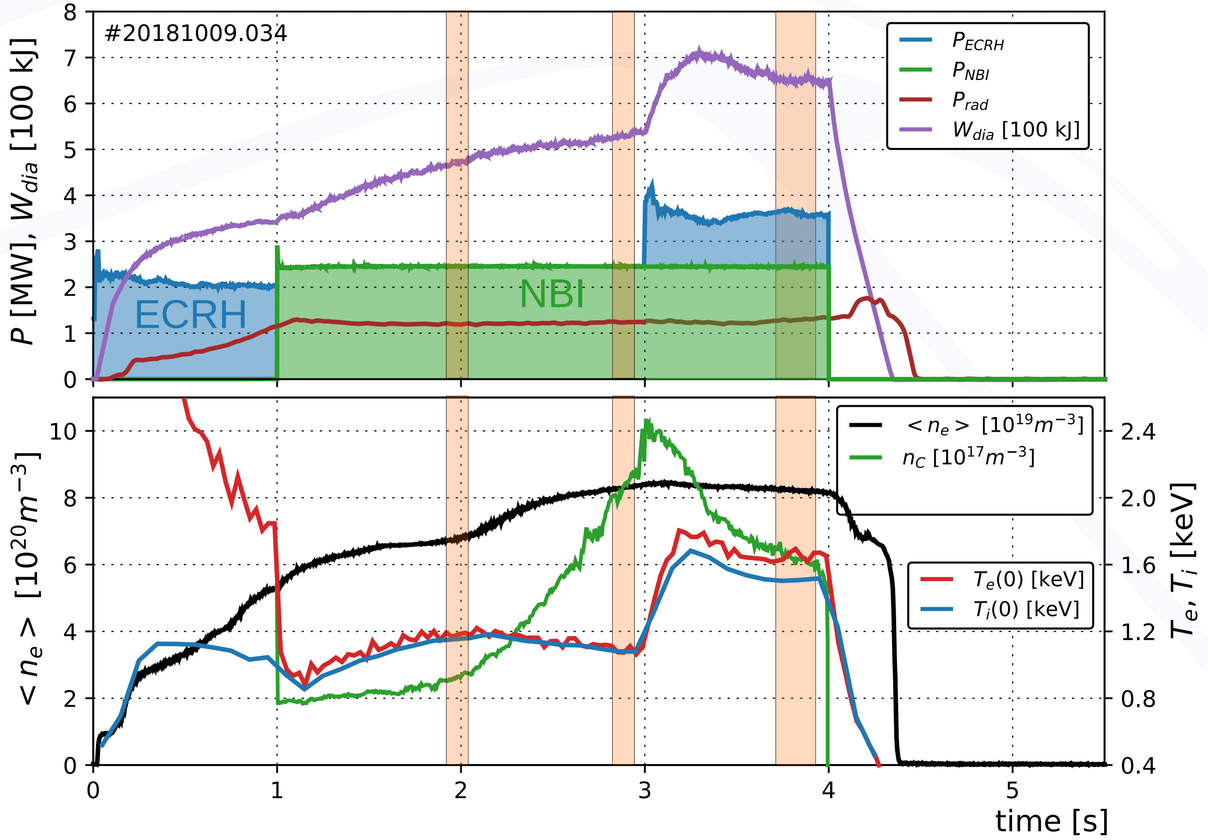

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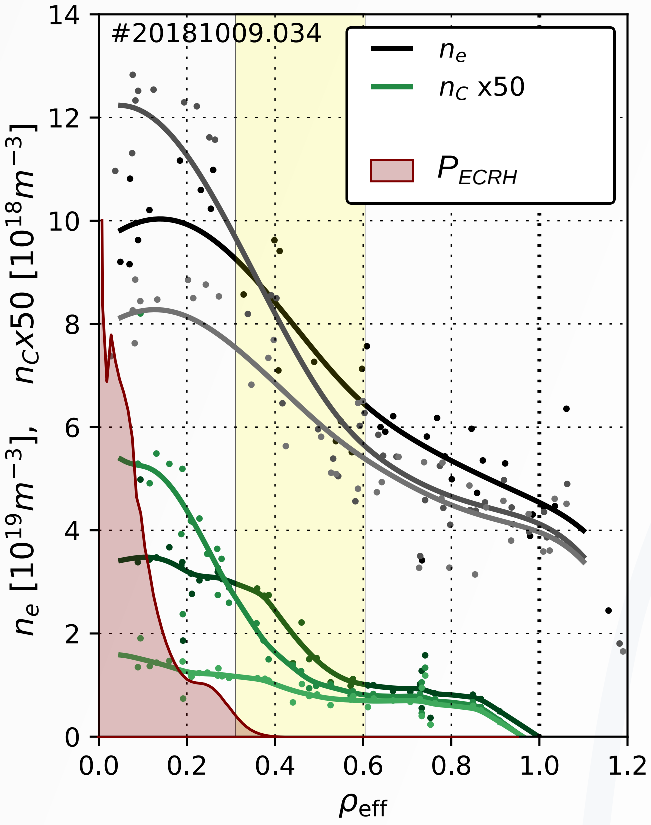
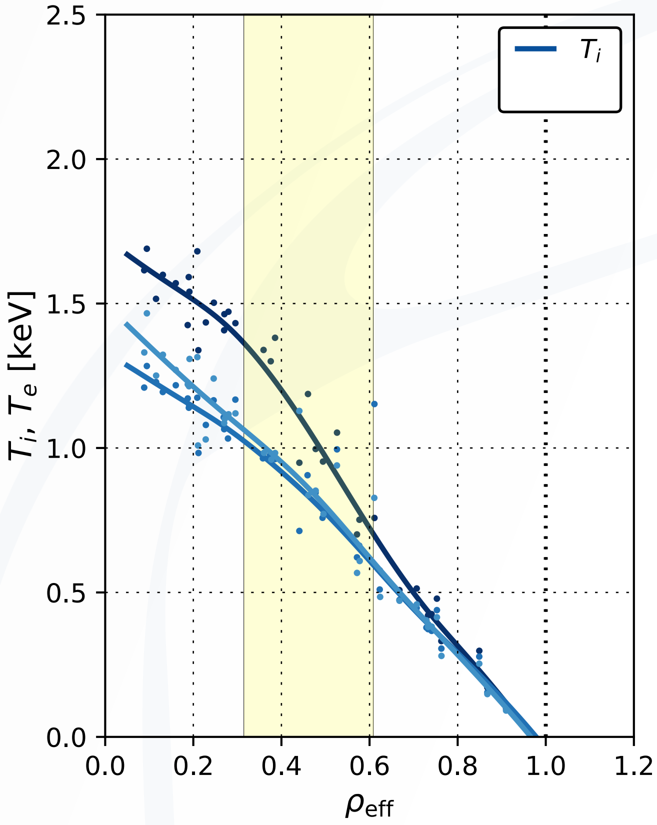
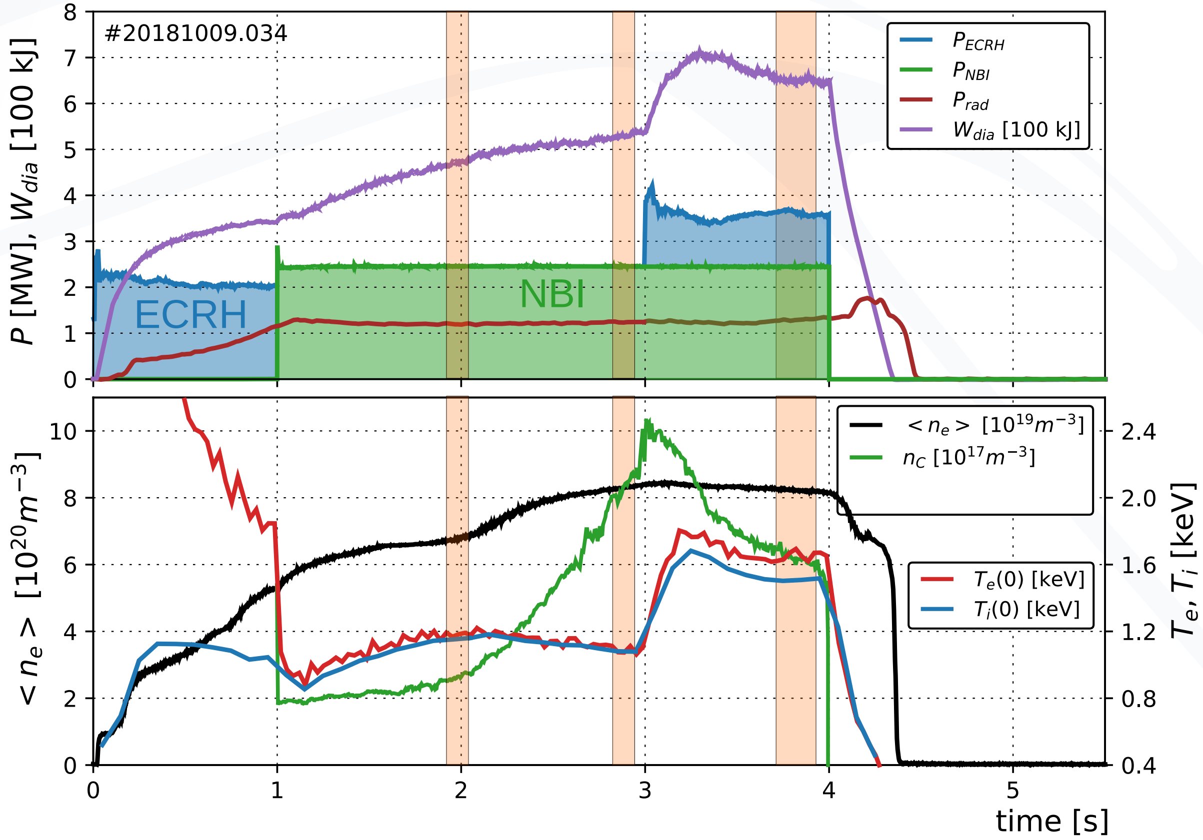
3: Add 1MW O2-mode ECRH raises temperature, slightly reduces density peaking and flattens impurity profile in deposition region.



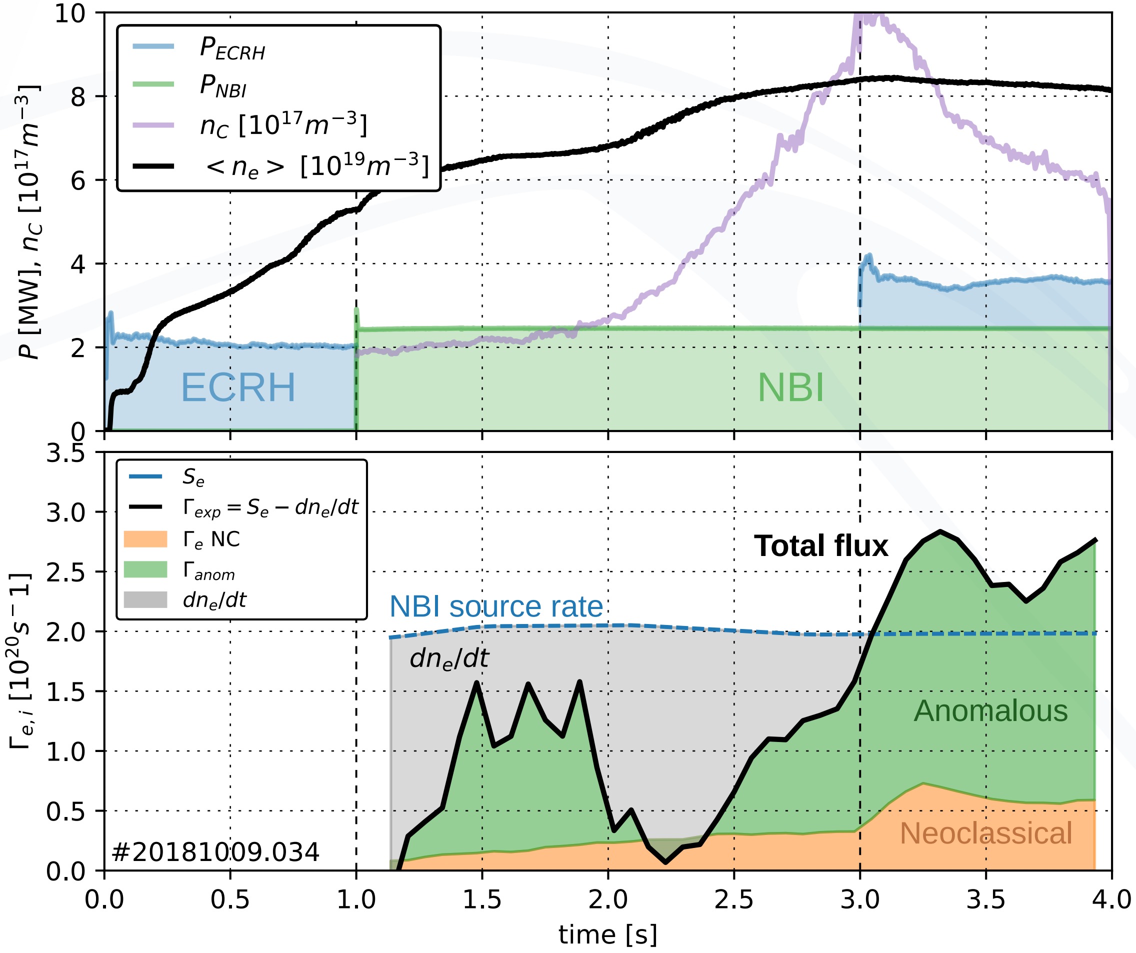




Electron/ion particle transport

- Particle flux reduces to neoclassical level inside mid-radius at onset of peaking.
  --> indicates strong suppression of turbulent flux in plasma core.
- Anomalous particle flux increases again as density gradient builds.
- Both neoclassical and anomalous increase with addition of ECRH, which stops density rise.

- NBI heat and particle source from Beams3D code [S. Lazerson, this conference]



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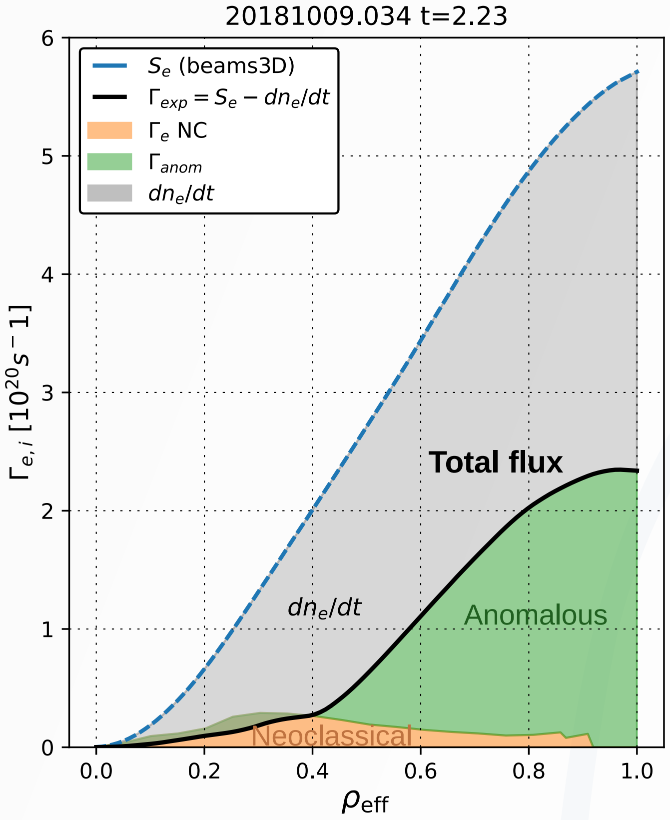

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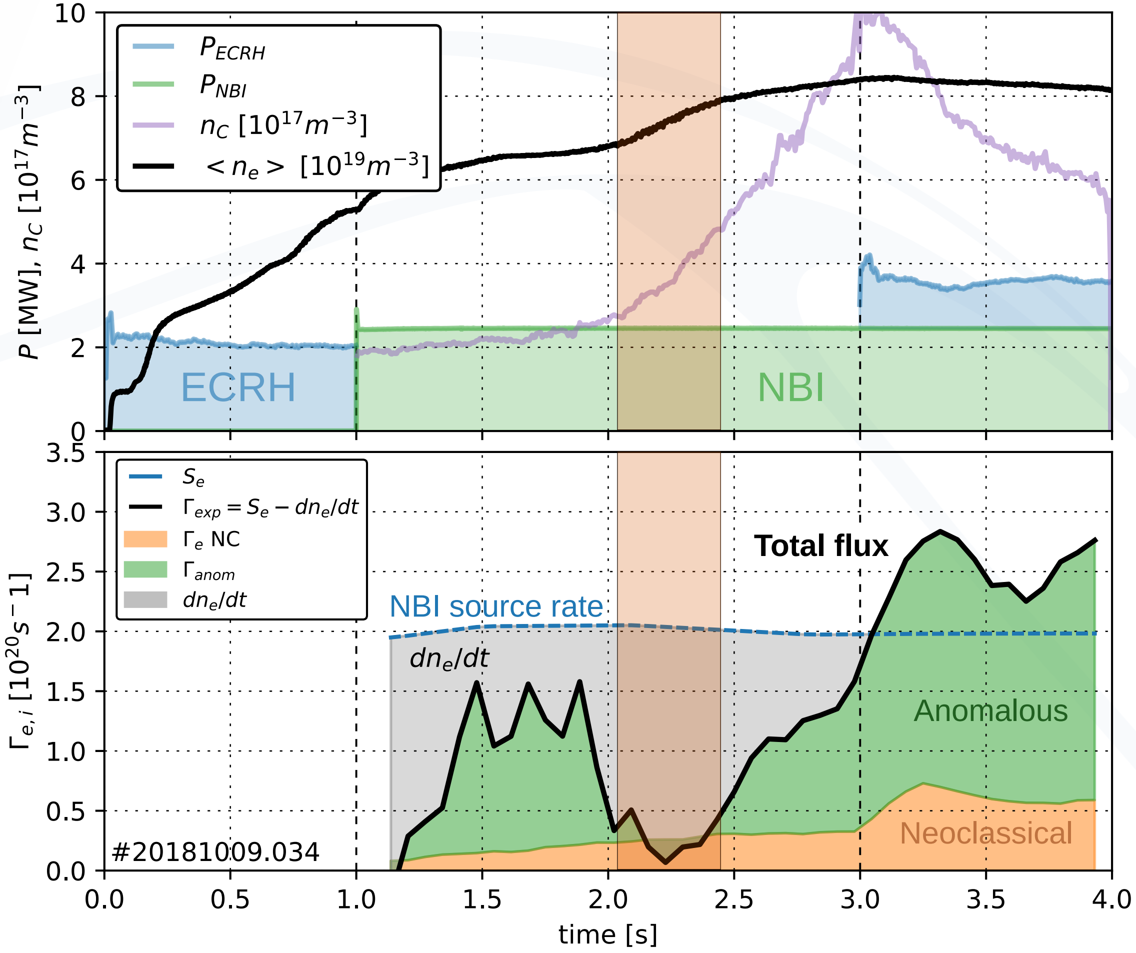

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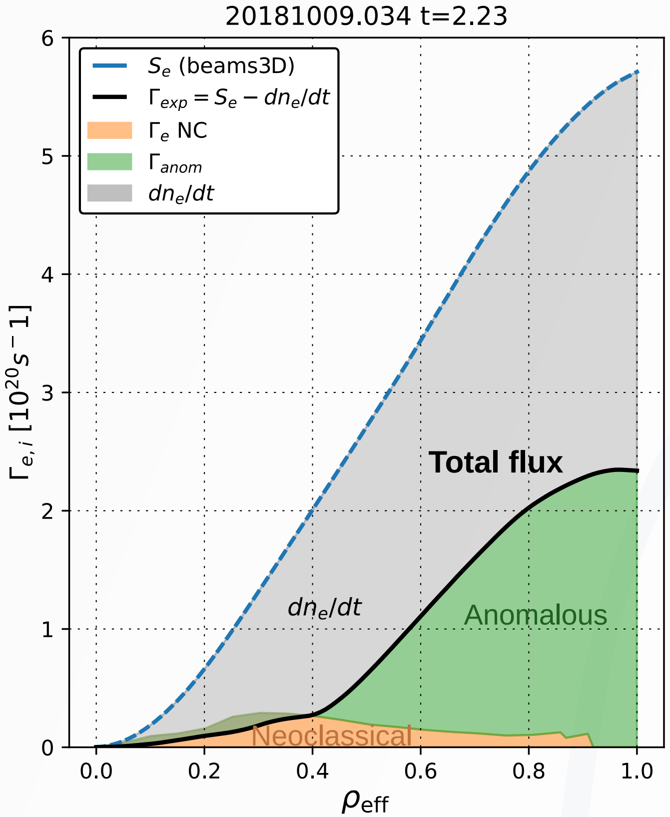

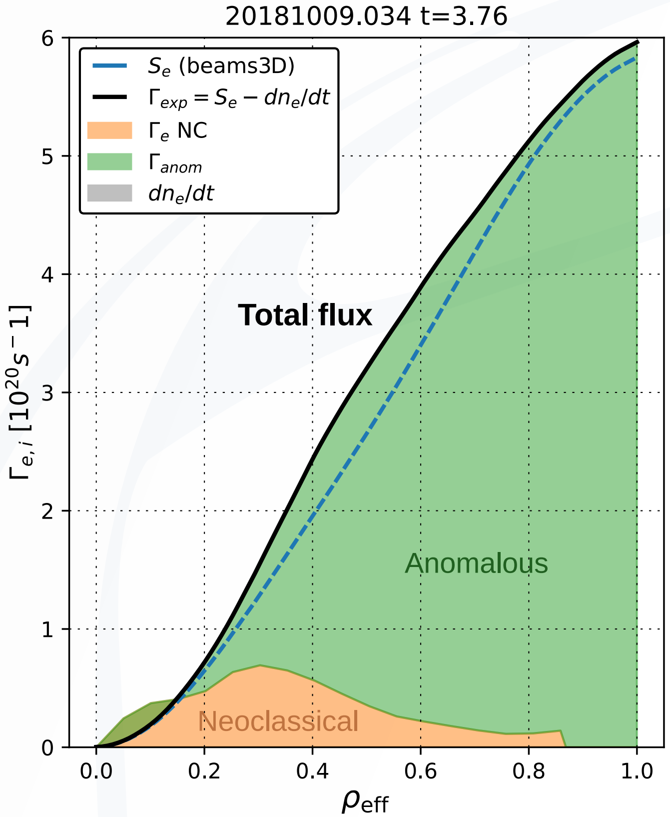

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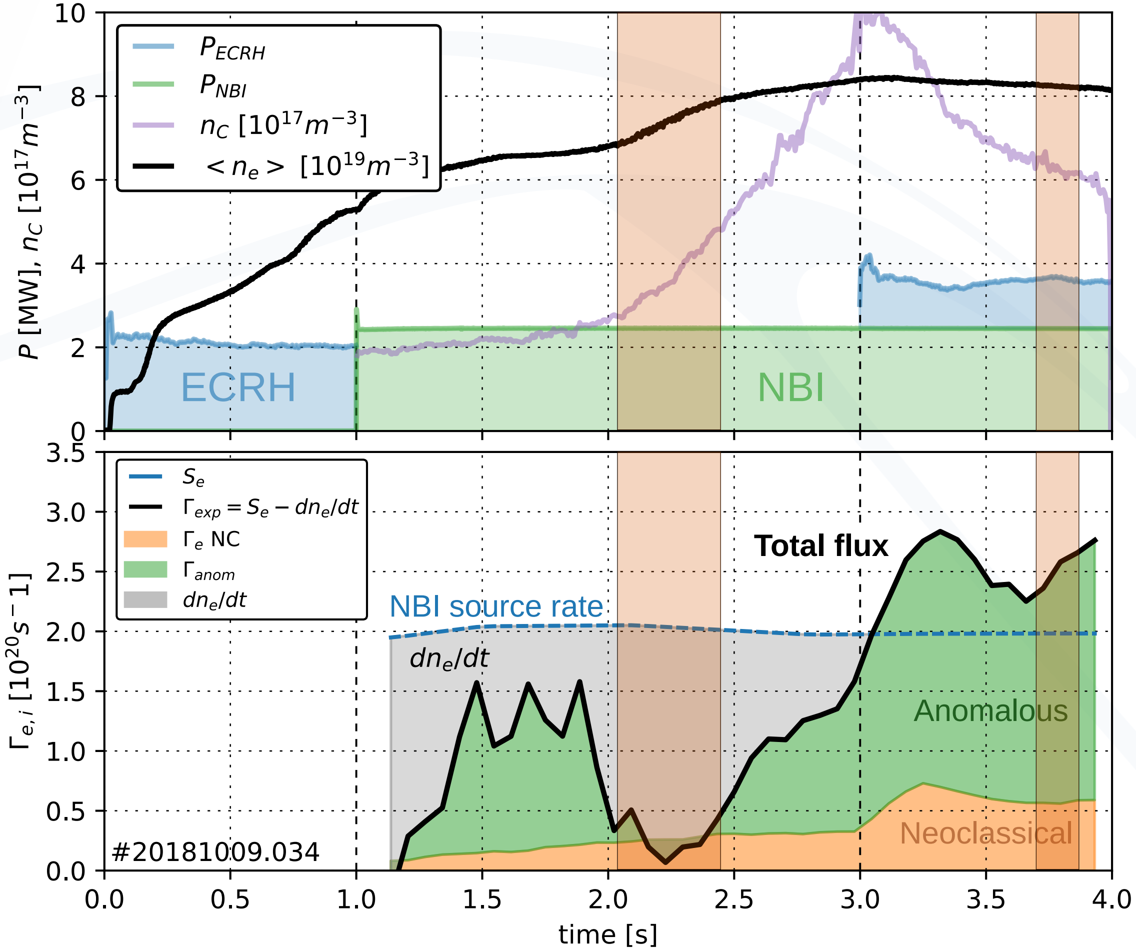
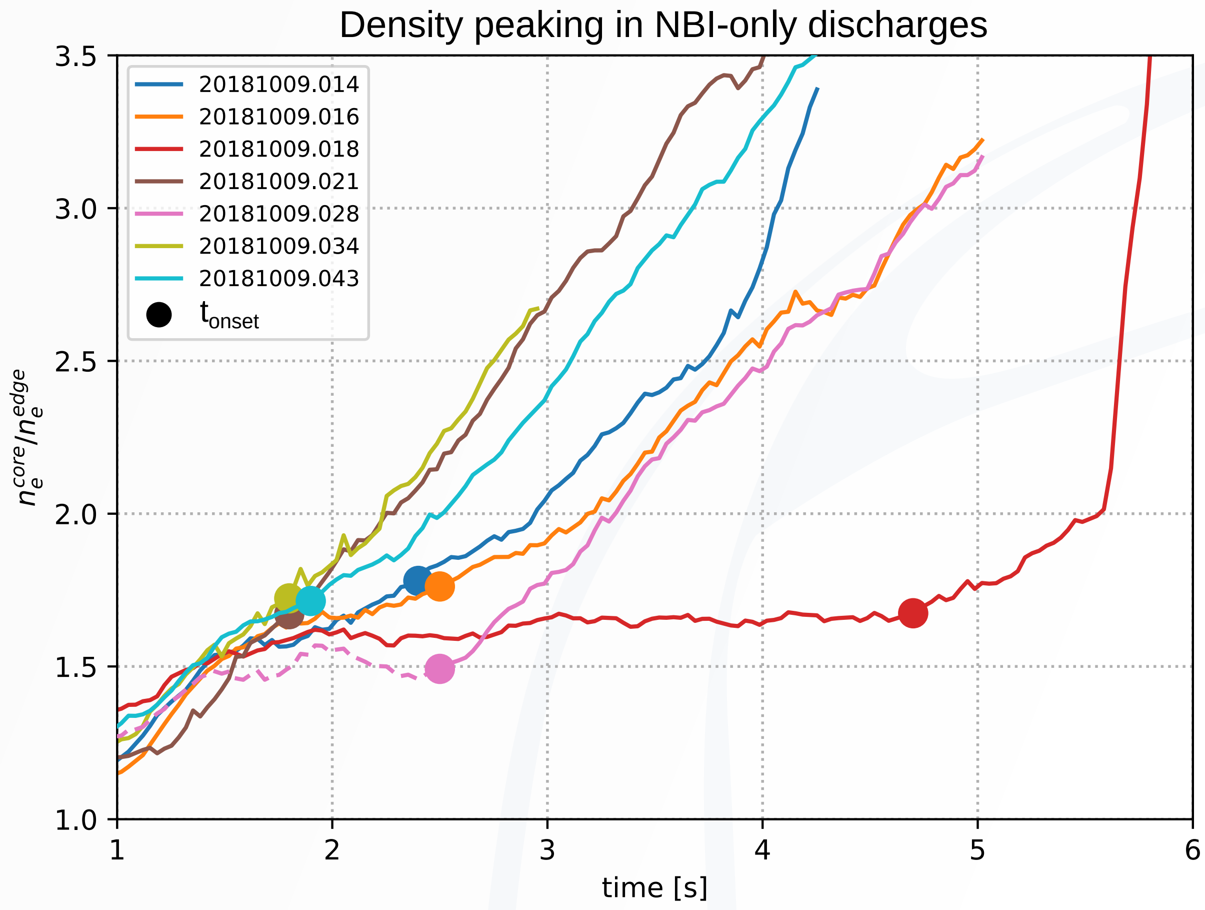
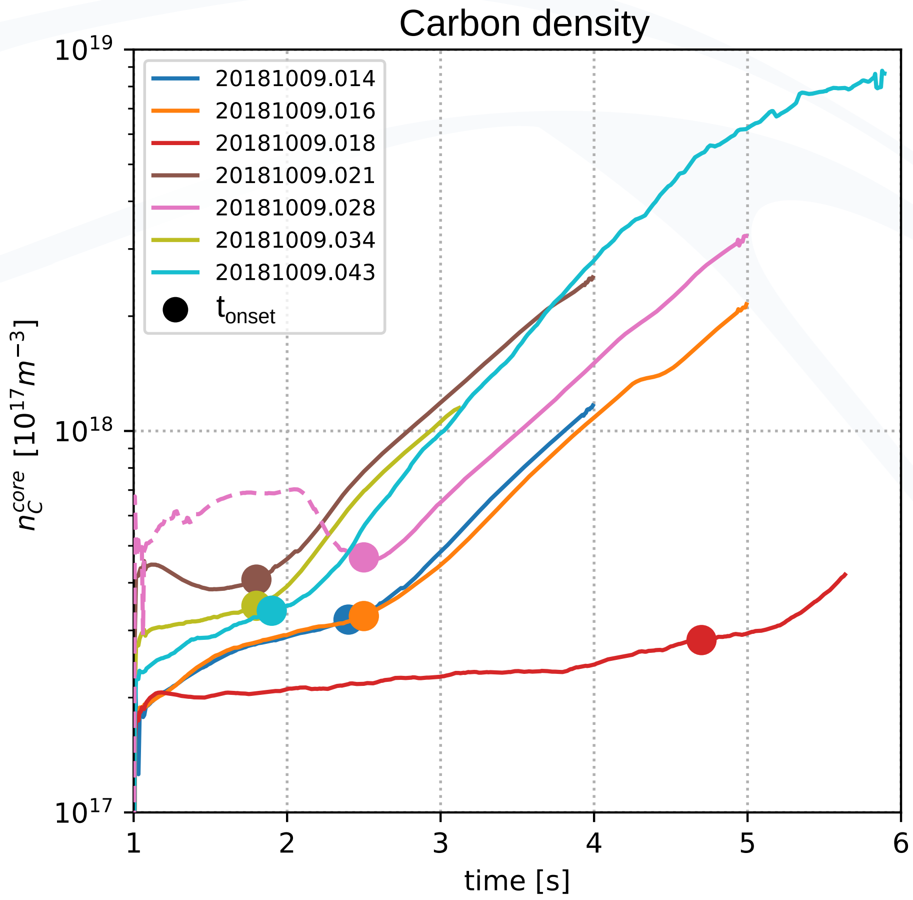


Electron/ion particle transport

- The onset time of the reduced particle and impurity anomalous fluxes varies between shots.
- No external events, no changes observed at plasma edge.
- Onset appears to occurs when *a/Ln*$_e$ reaches ~0.85 *(tentative)*

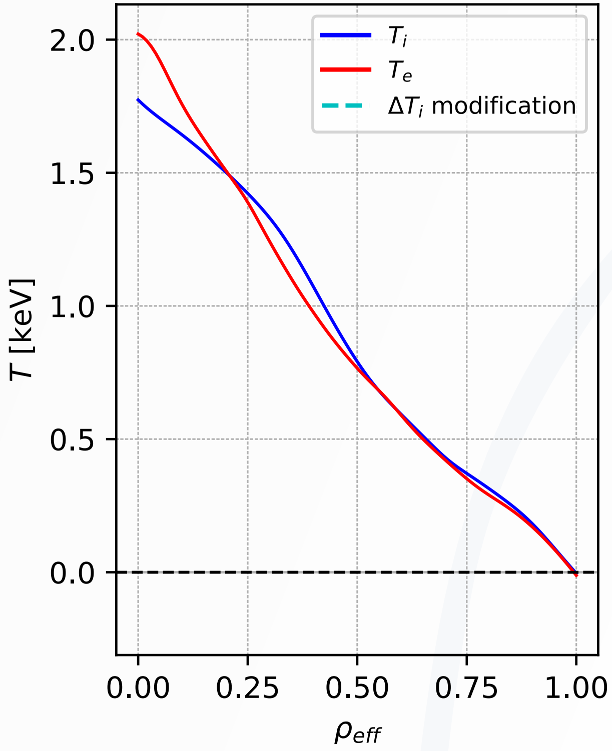




Energy transport: Species separation

- Separation of ion and electron energy fluxes requires determination of power exchange term.
- At high collisionality ($n_e \sim 10^{20}$), this requires O(10eV) accruacy of (T_e - T_i) profile, which has not yet been achieved.
- Best analysis so far for highest T_i gives range from: **A)** large Q_e with Q_i~Q_i^{NC} to **B)** $Q_i \sim Q_e >> Q^{NC}$.
- $Q_e >> Q_i \sim Q_{NC}$ would be consistent with with post-pellets experiments.
- However, neoclassical electron energy fluxes *not* supported by measurements.

--> Next campaign: Improvements in T_i profiles + heat wave measurements.



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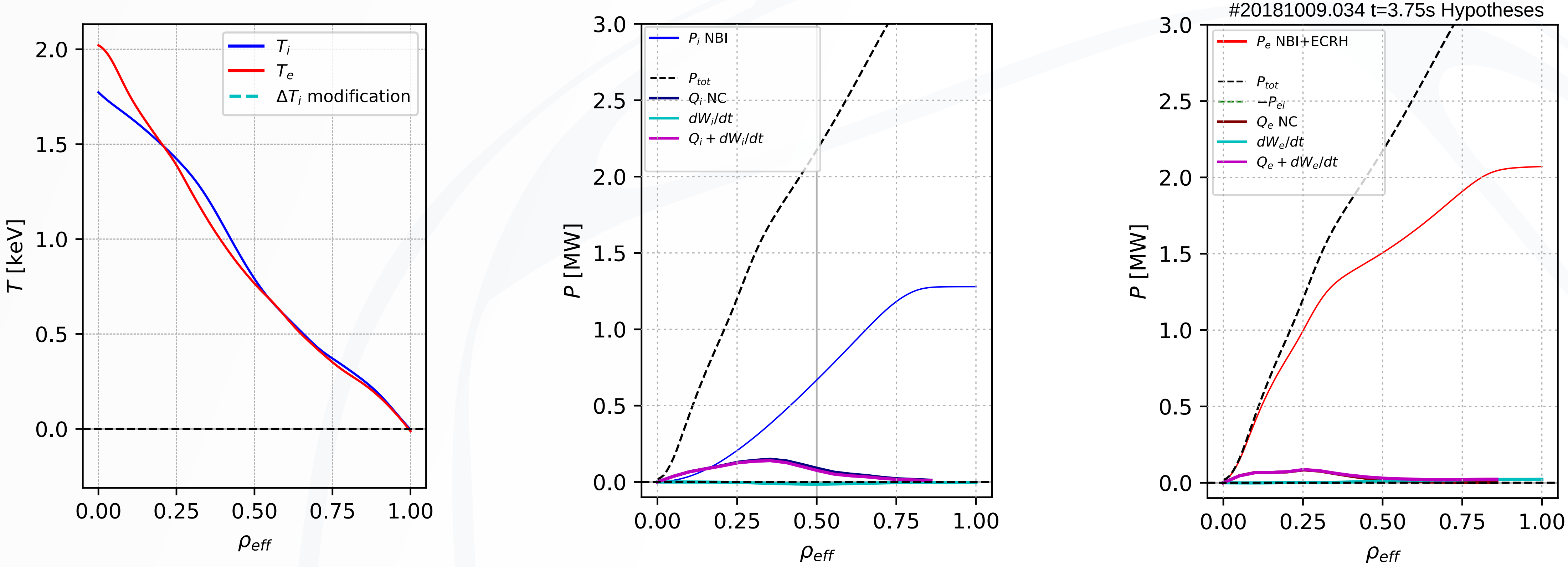

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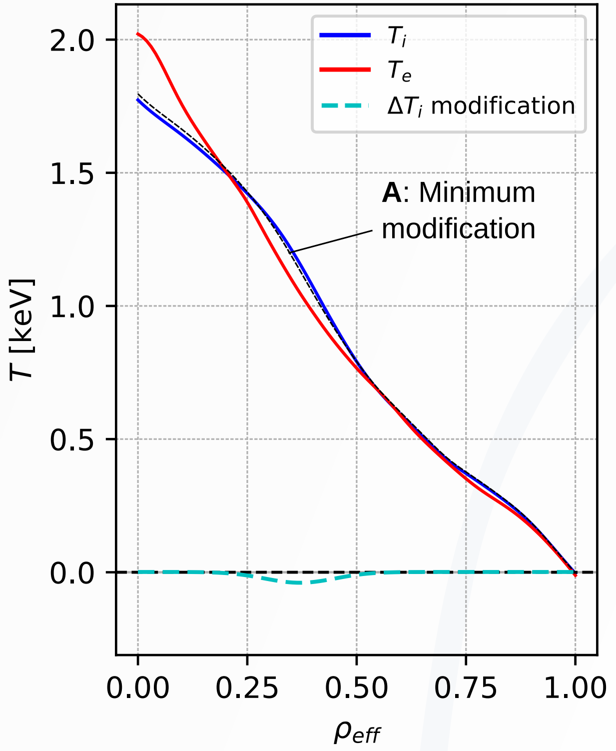

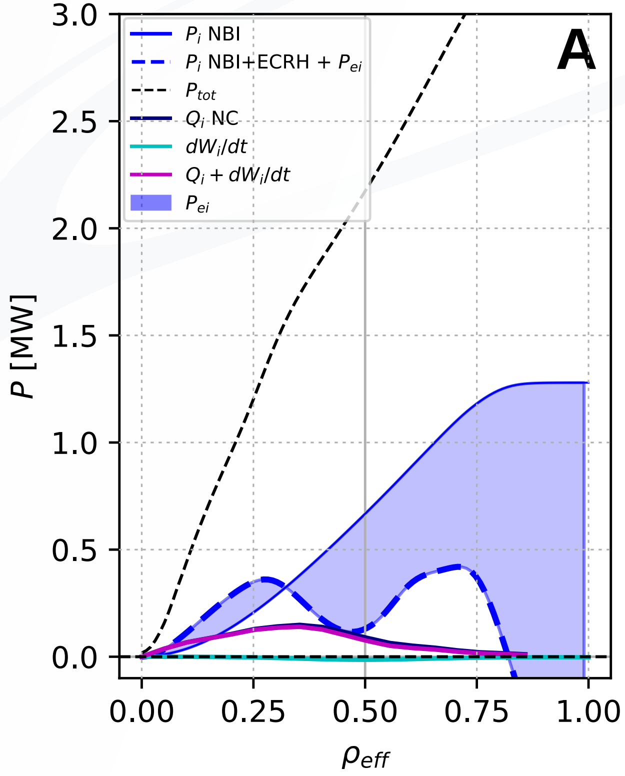

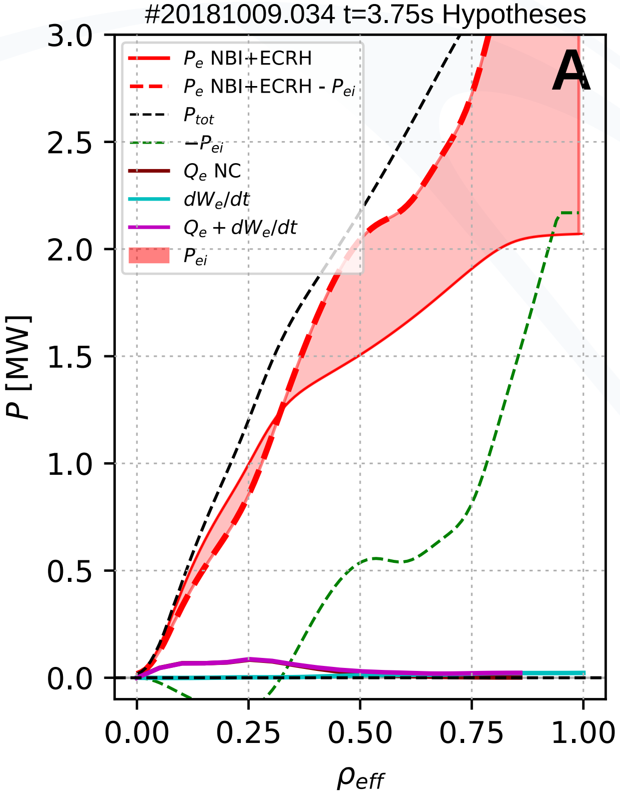

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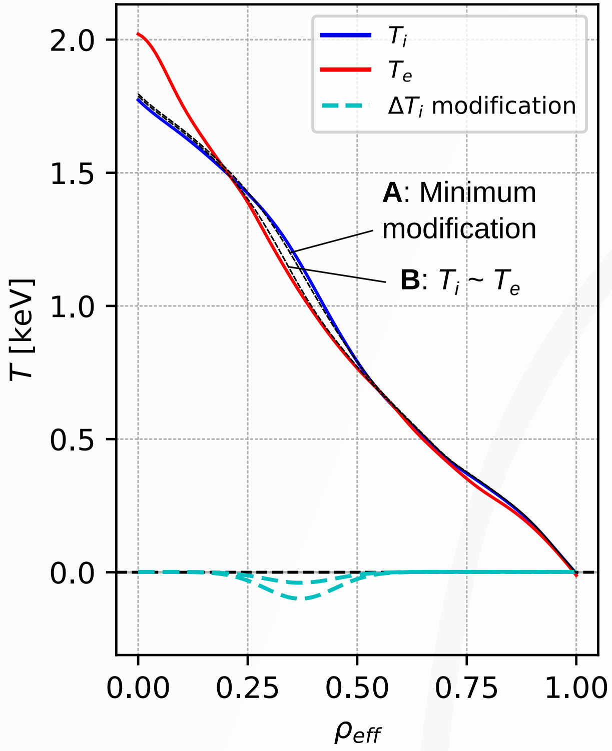

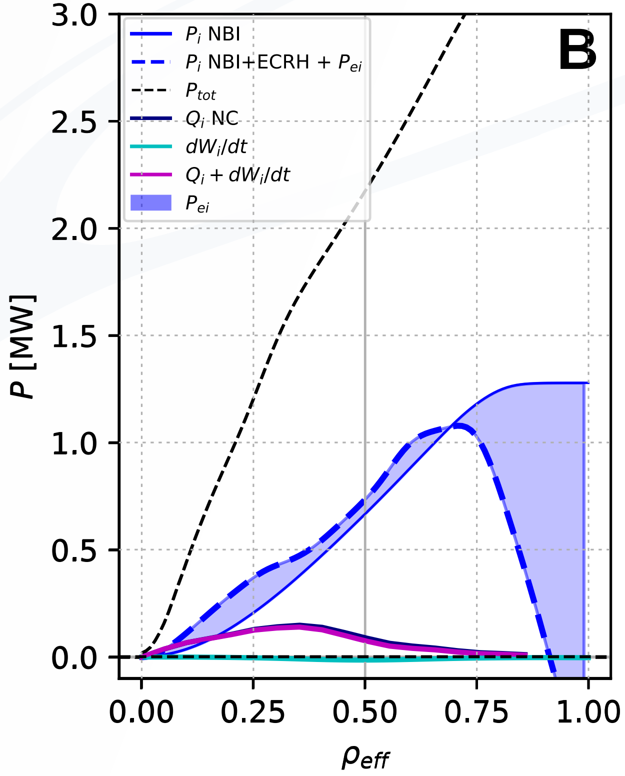

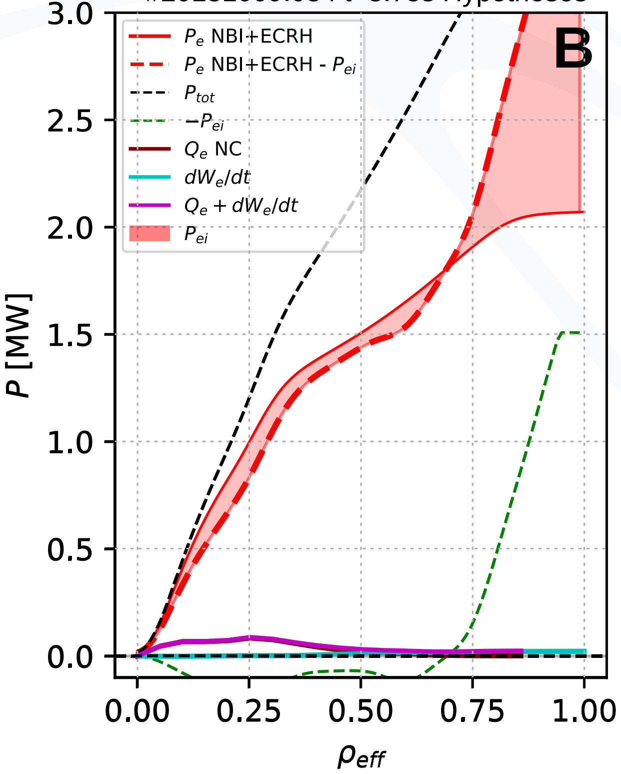

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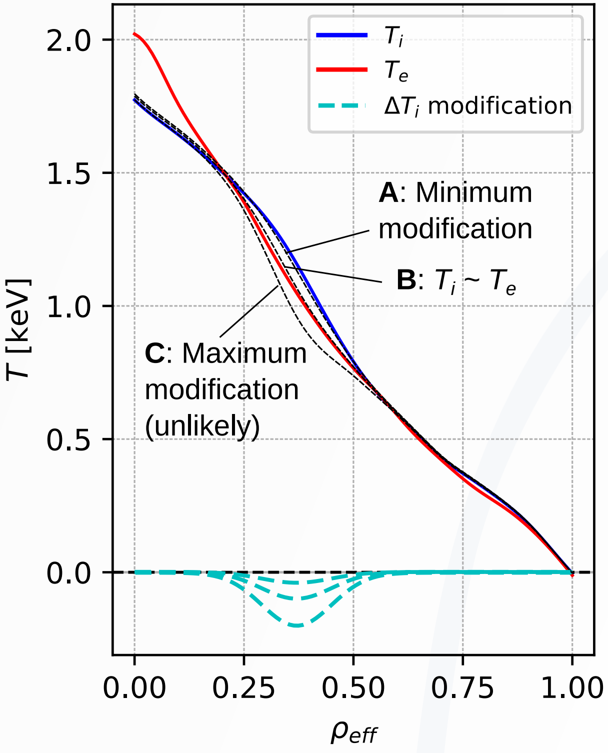

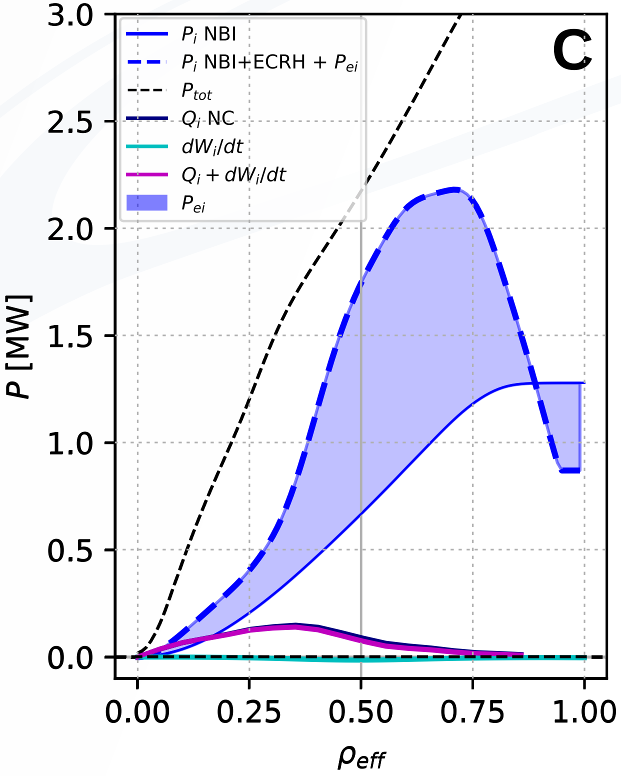

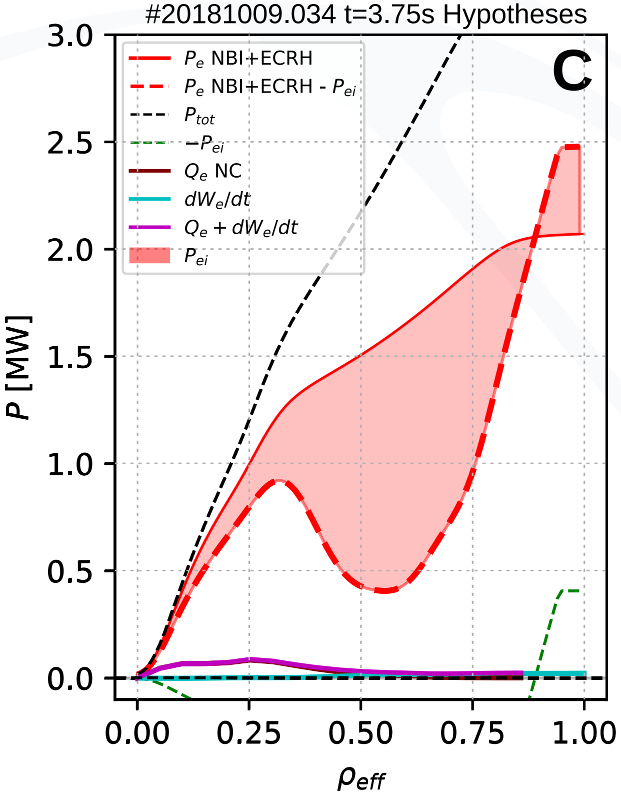

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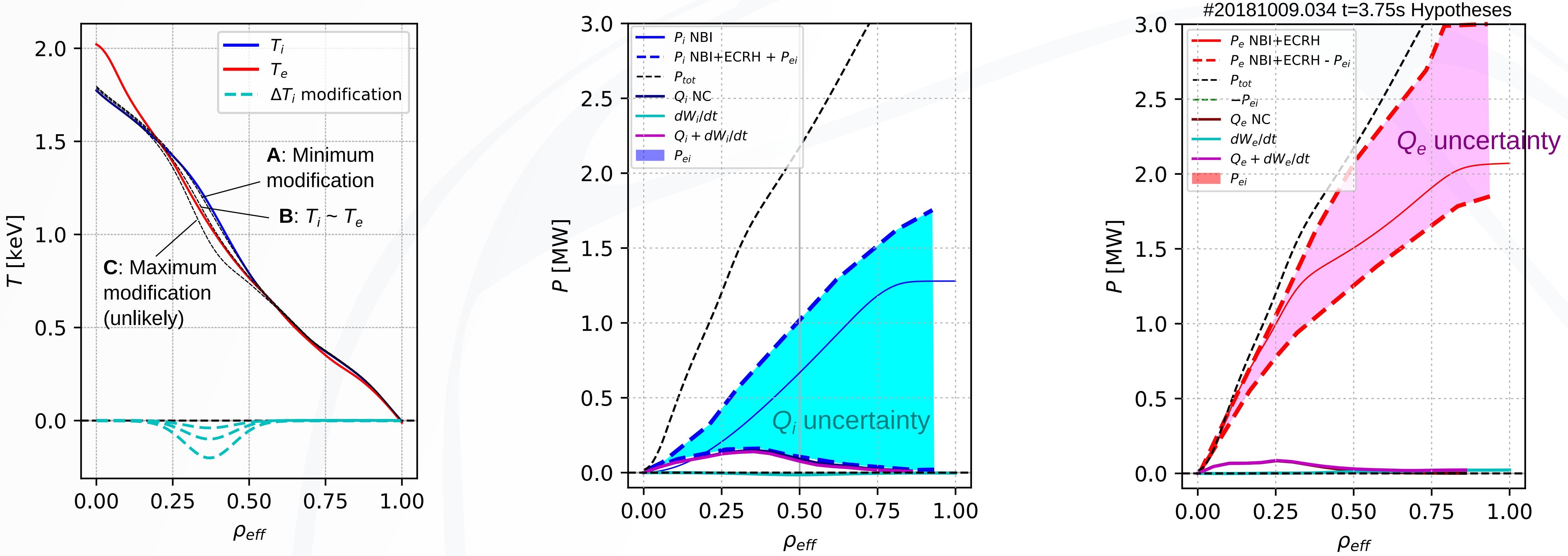

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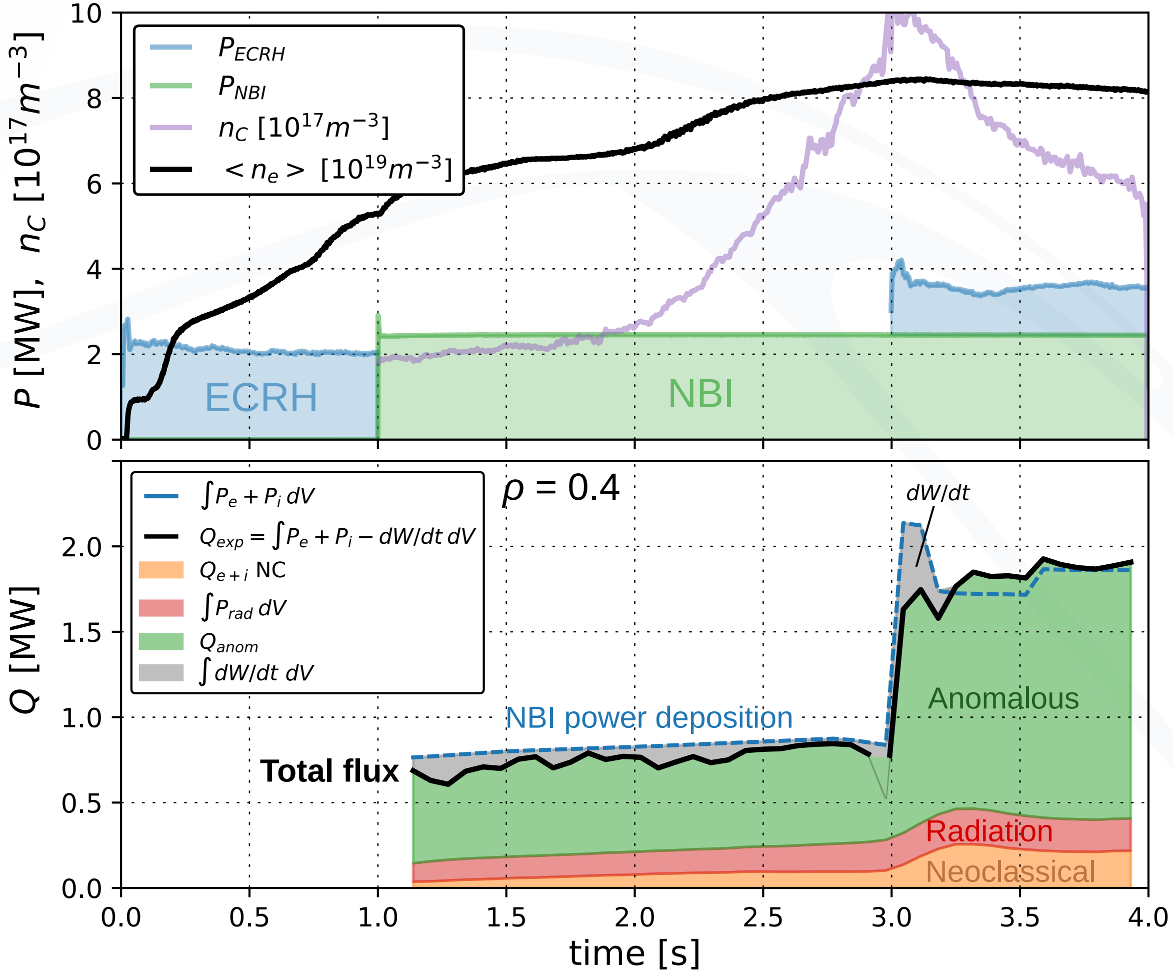

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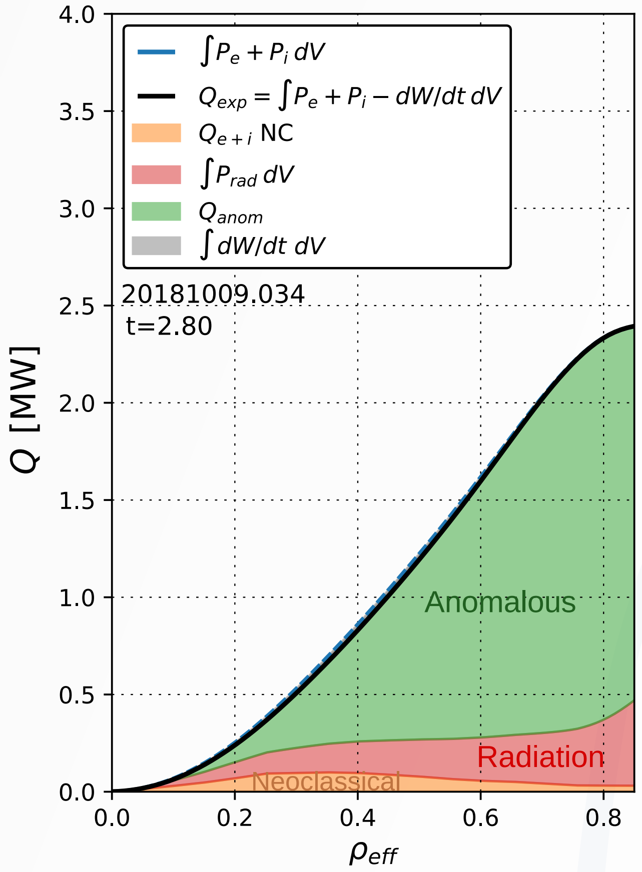

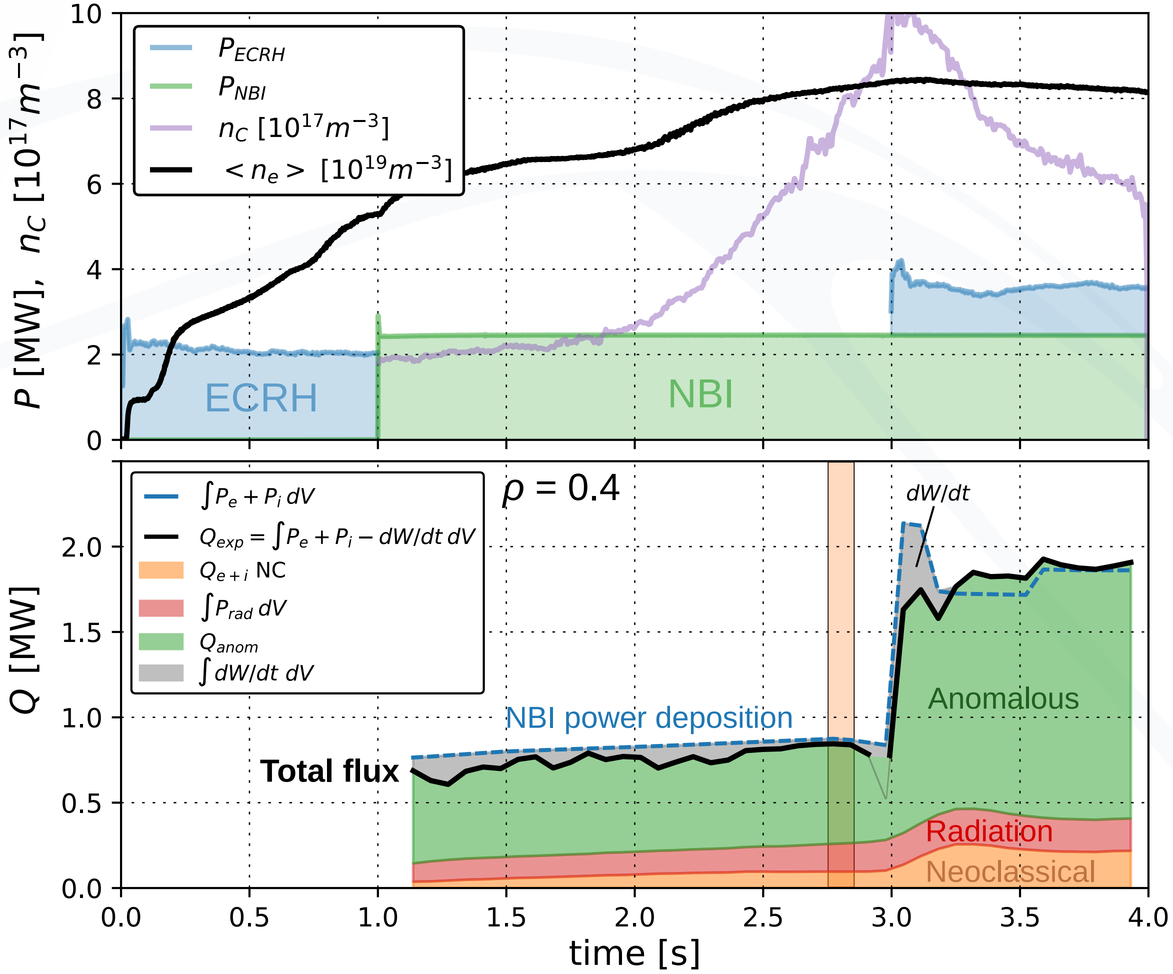

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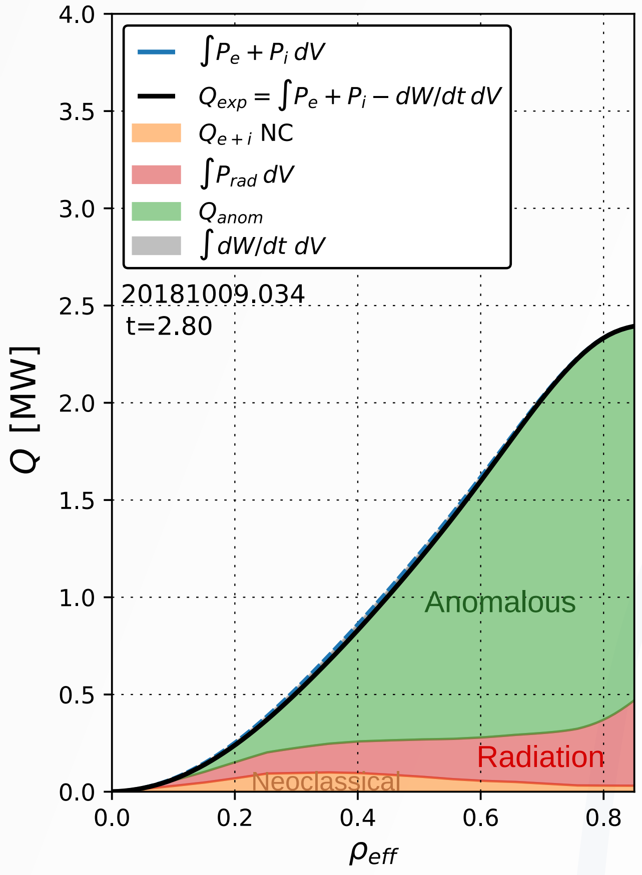

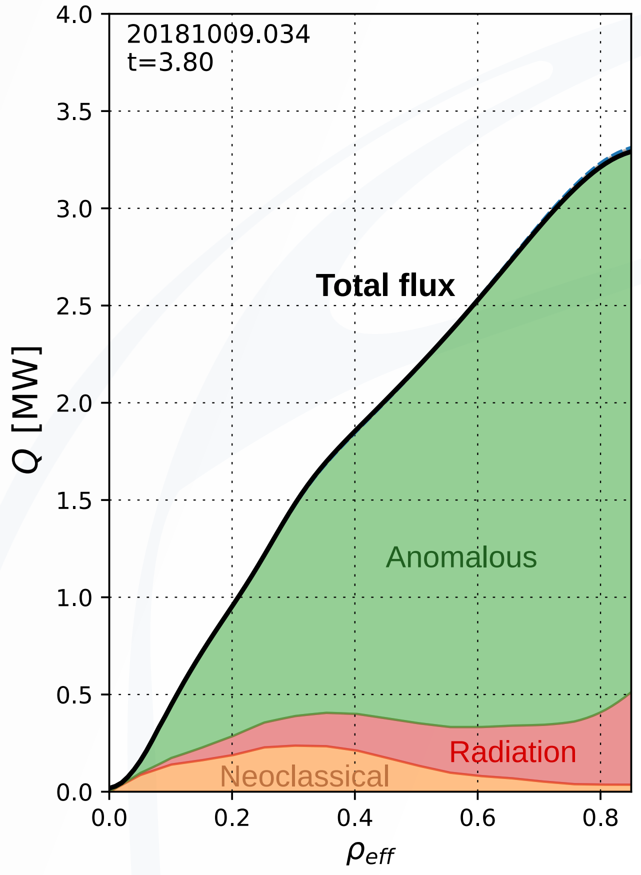

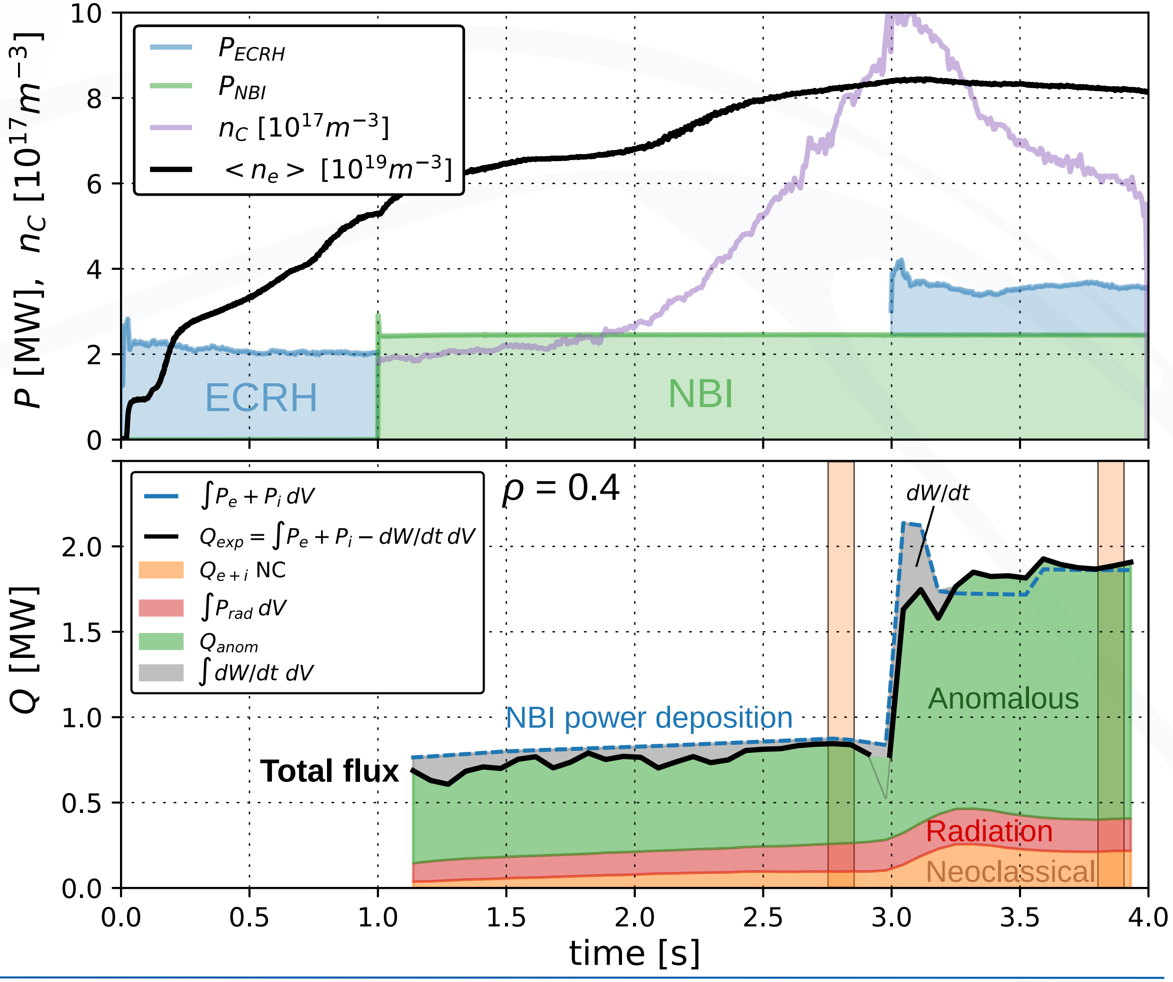

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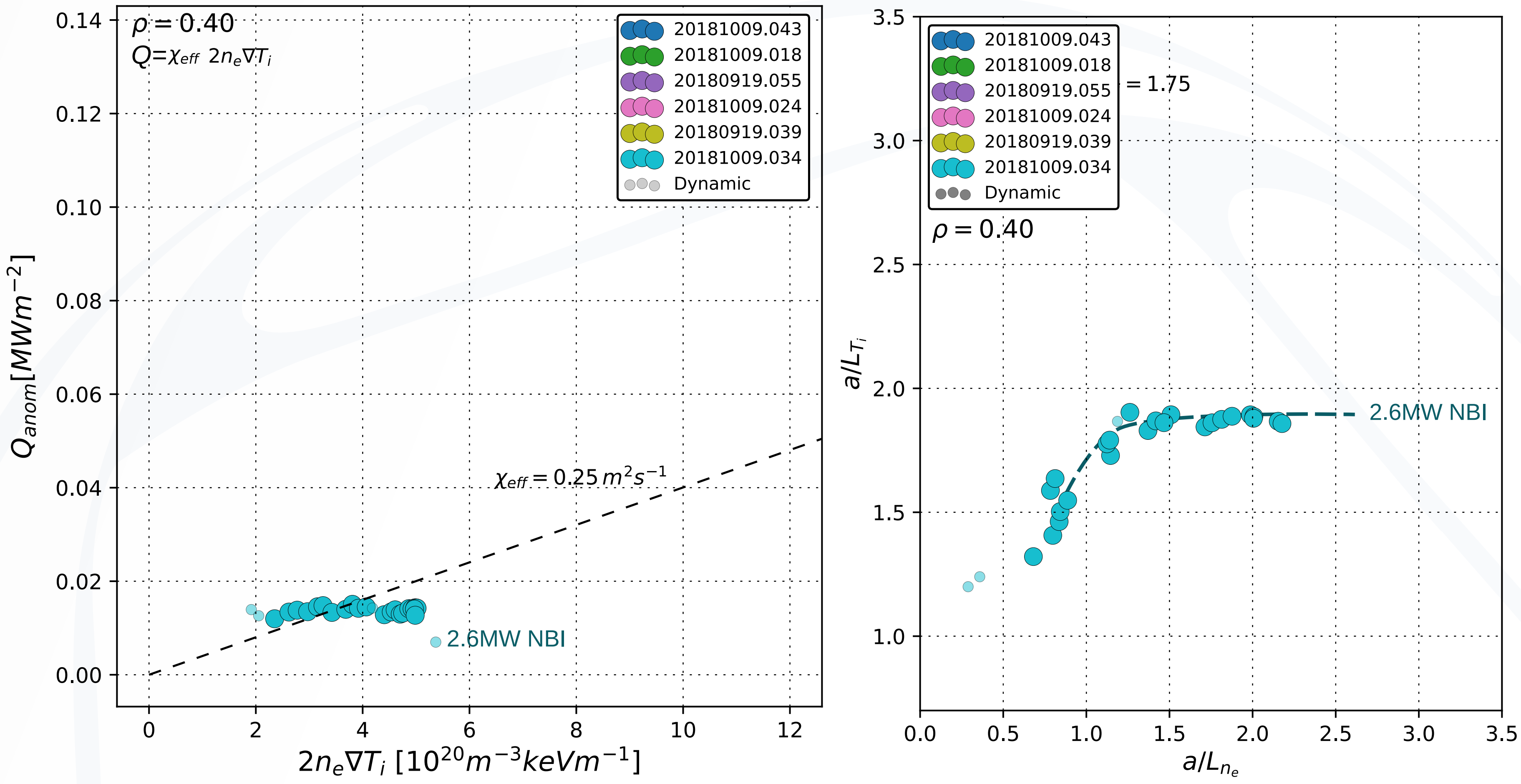

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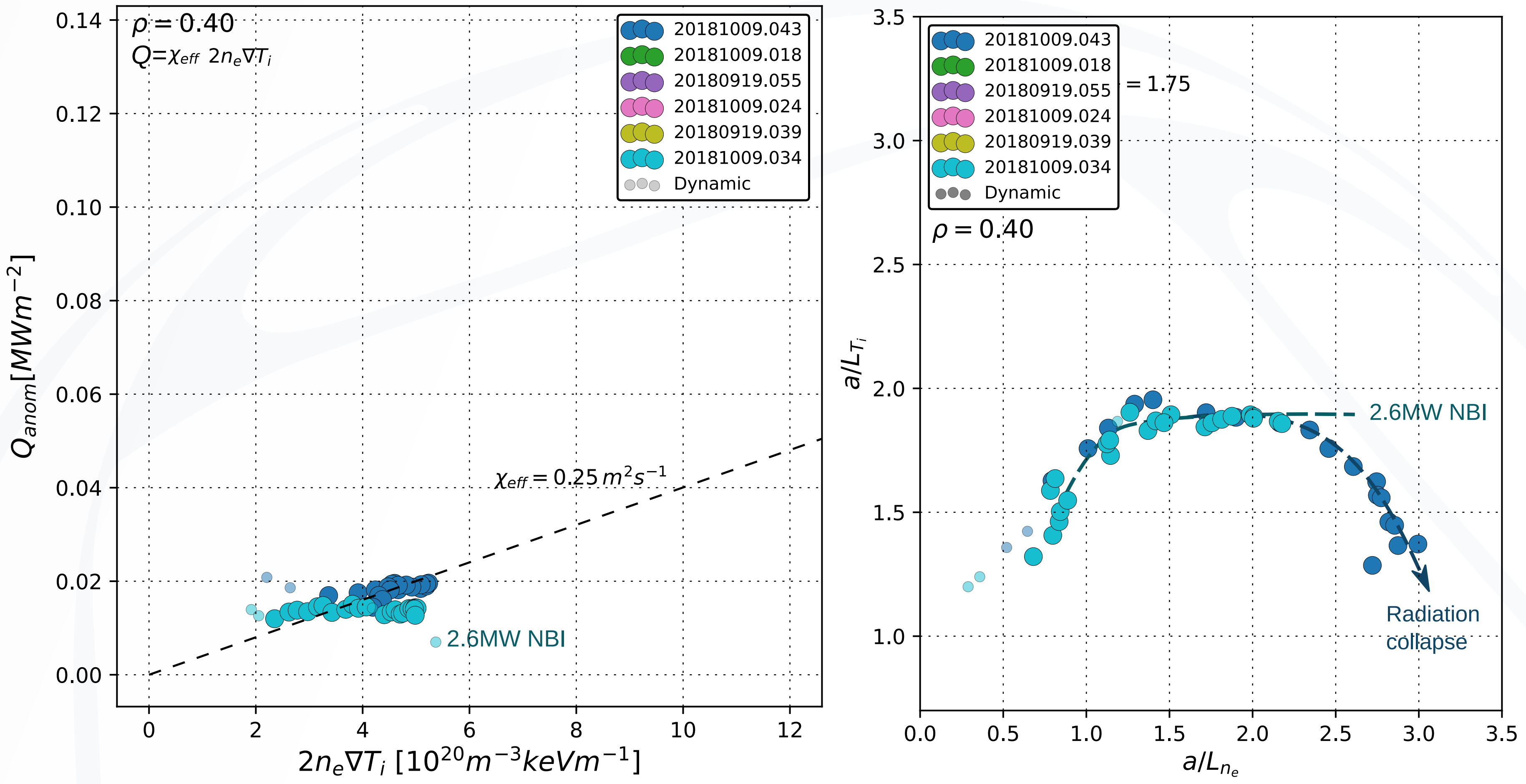

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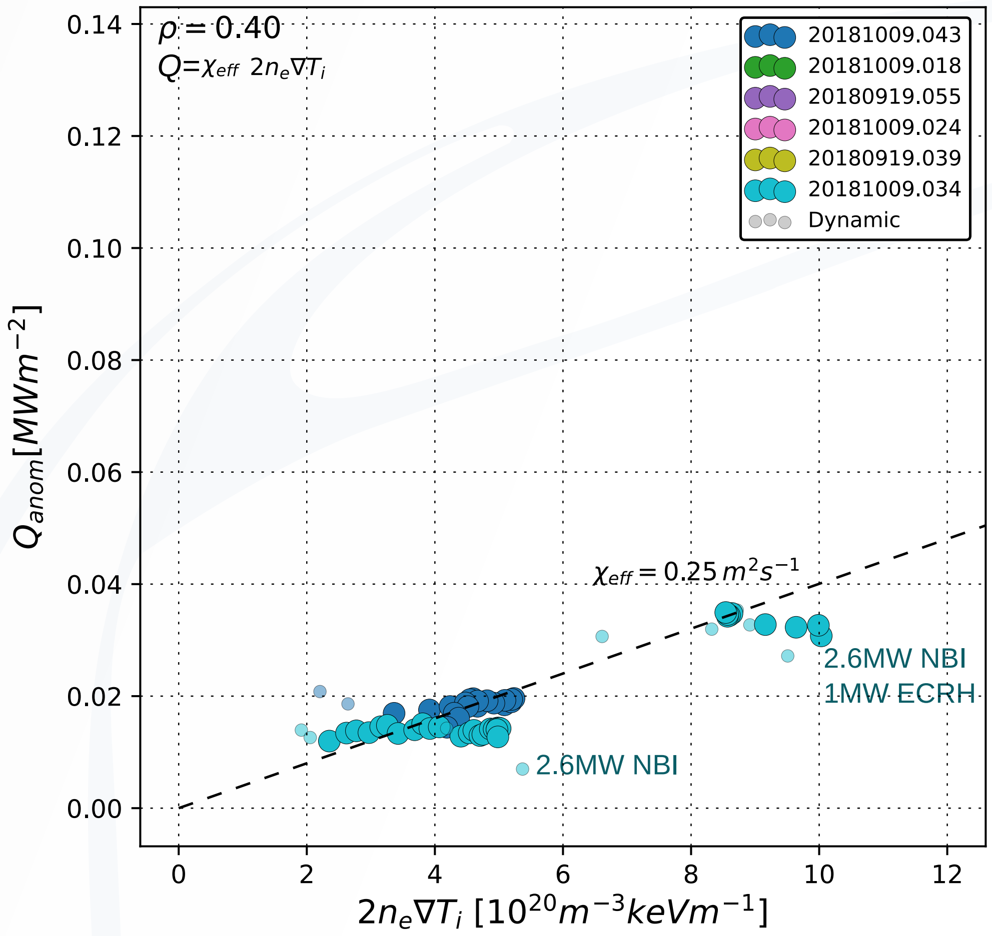

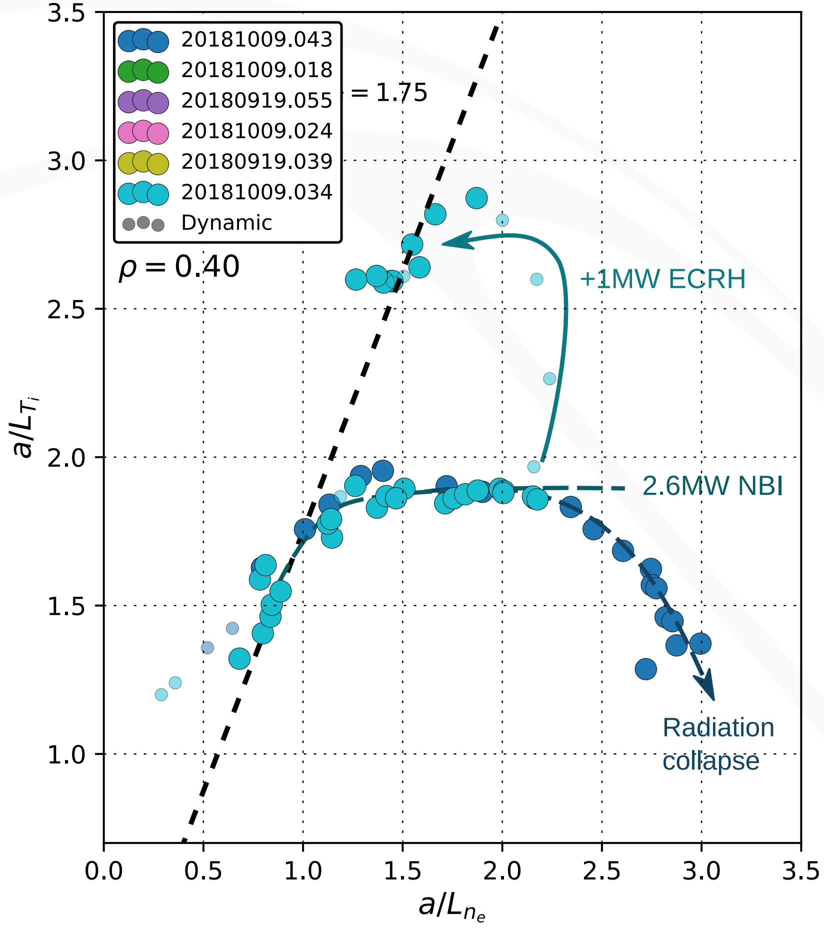

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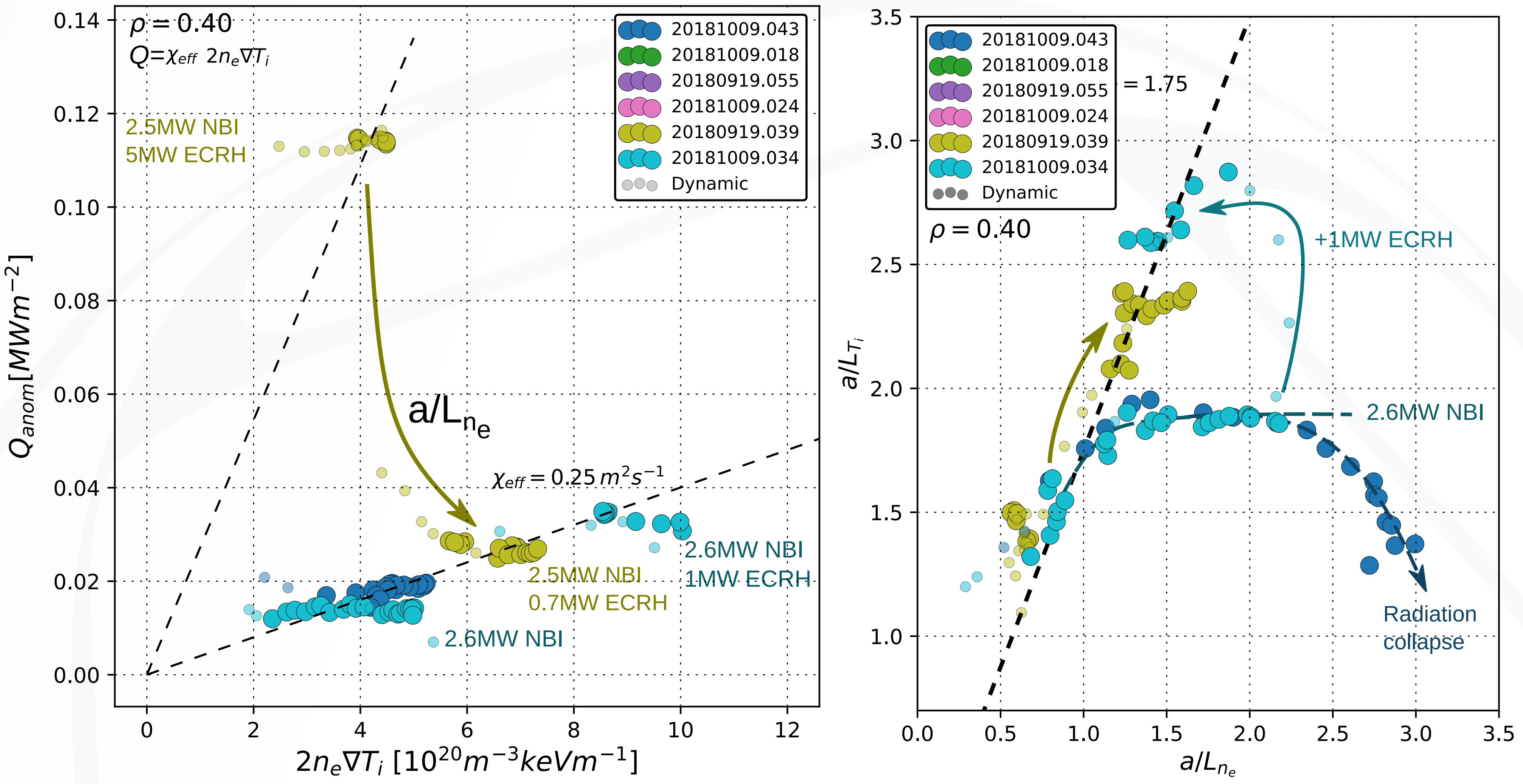

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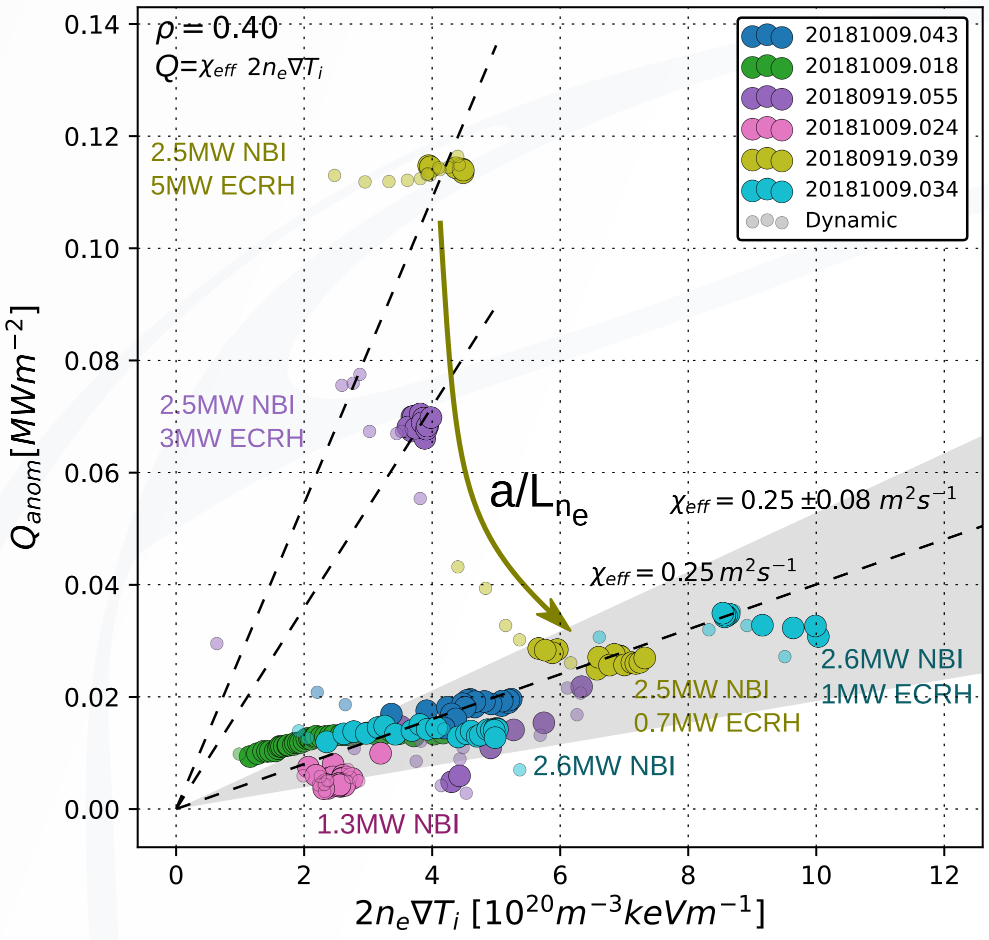

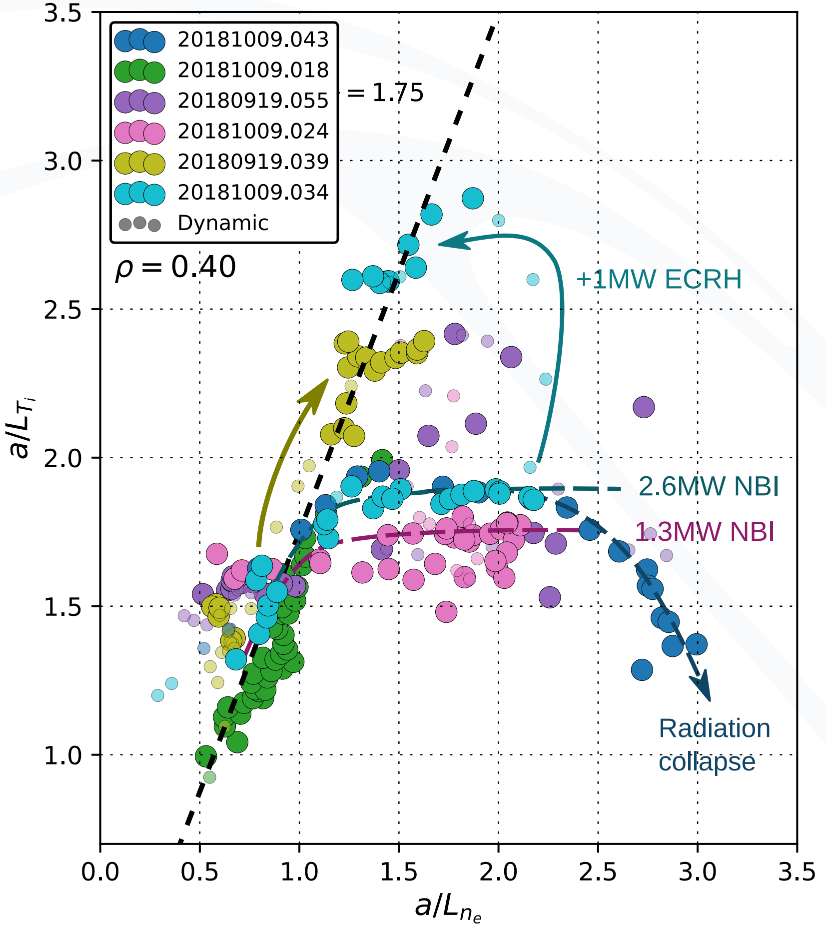

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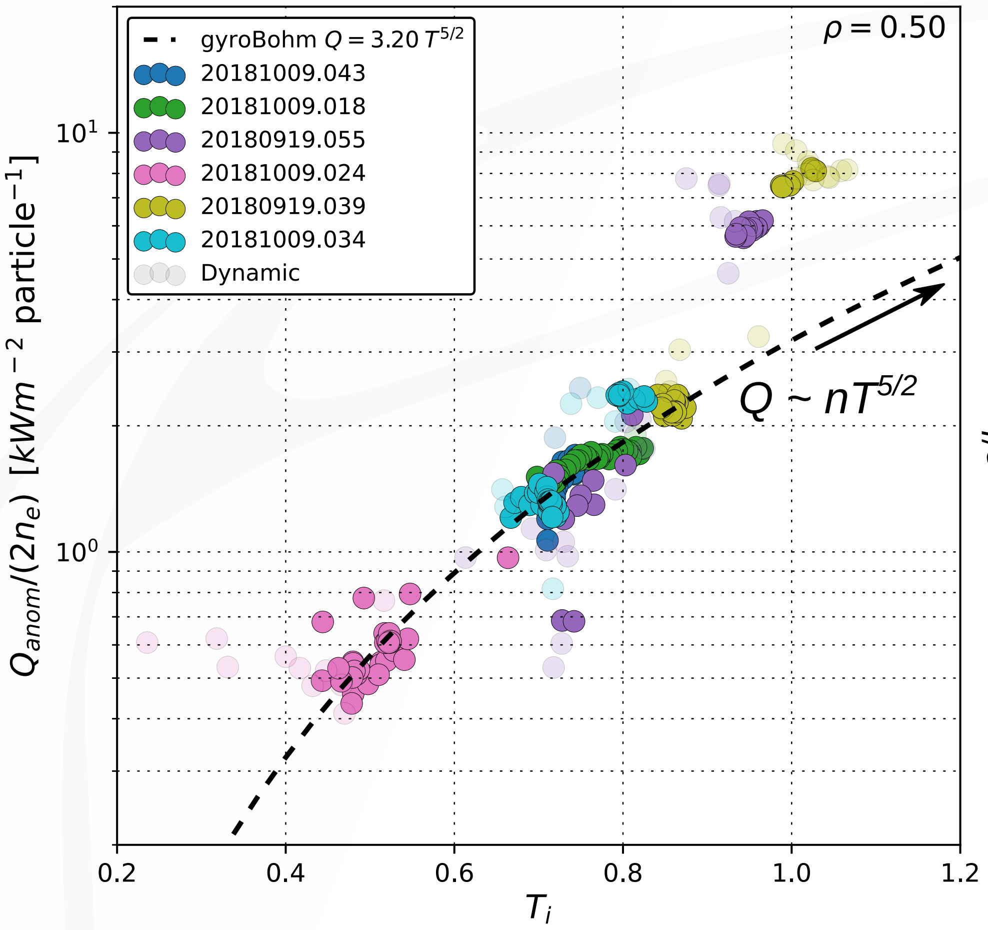

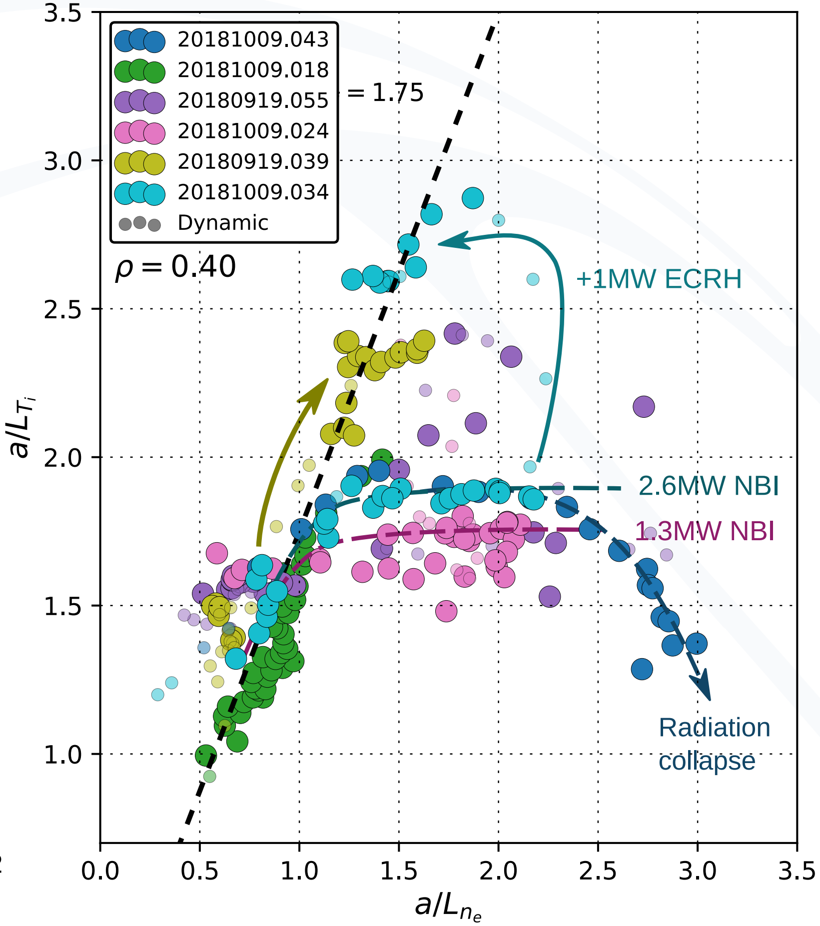

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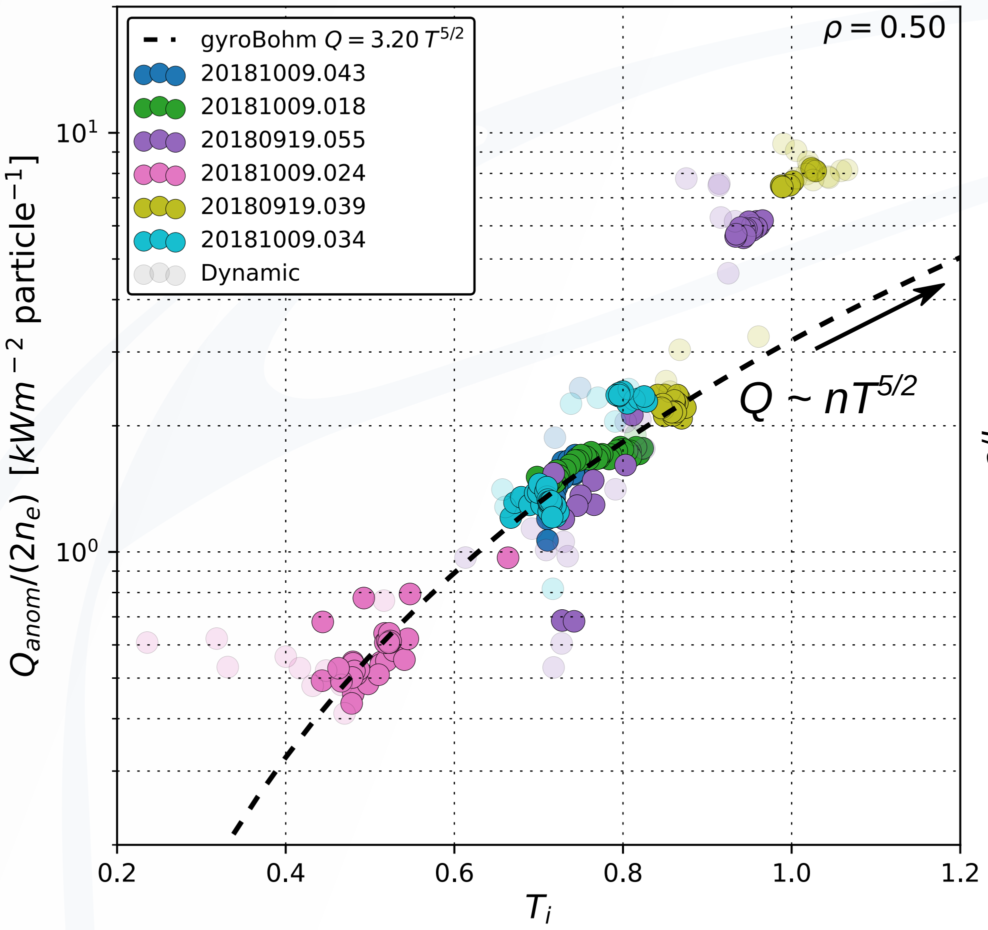
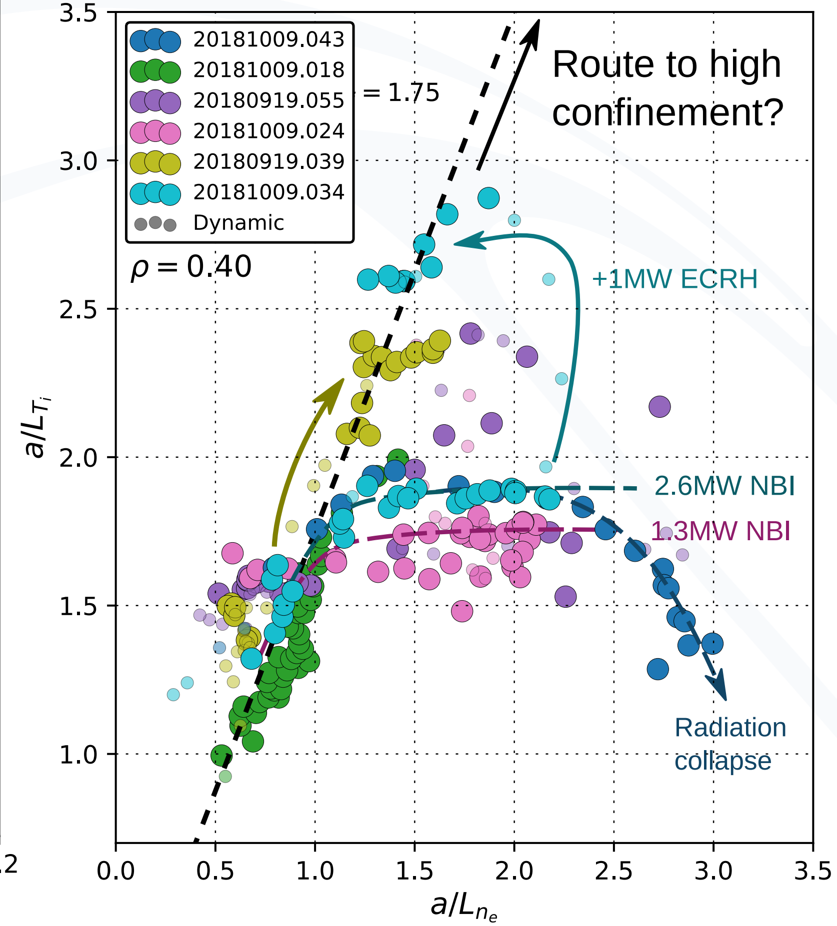
- If density gradient can be maintained, additional NBI power may lead to high n_e, high T_i plasmas.





Routes to high confinement

- Turbulence supression supported by reduced fluctuations in high a/Ln_e plasmas.
    - Doppler Reflectometer [D. Carralero et. al. this conference]
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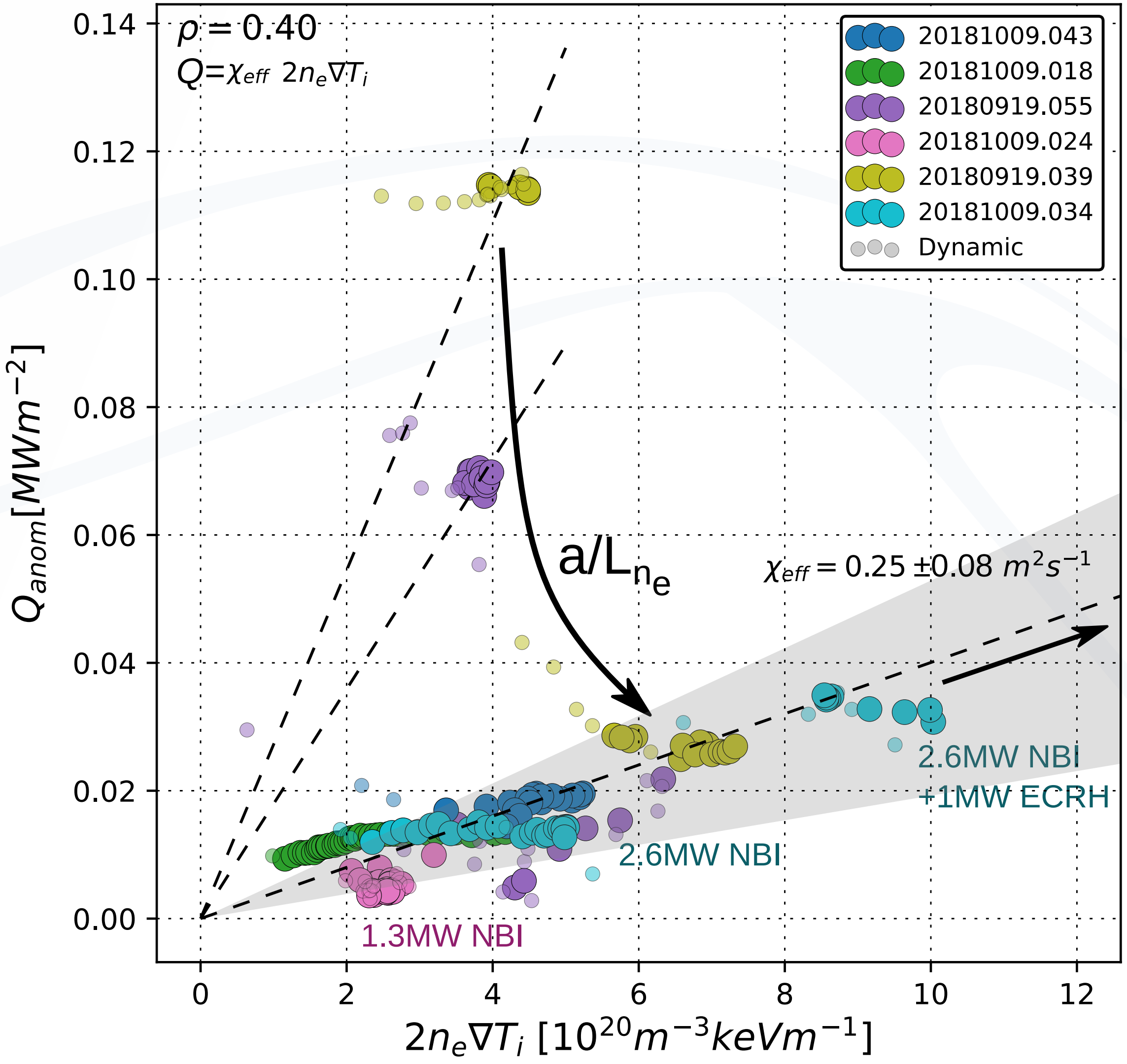

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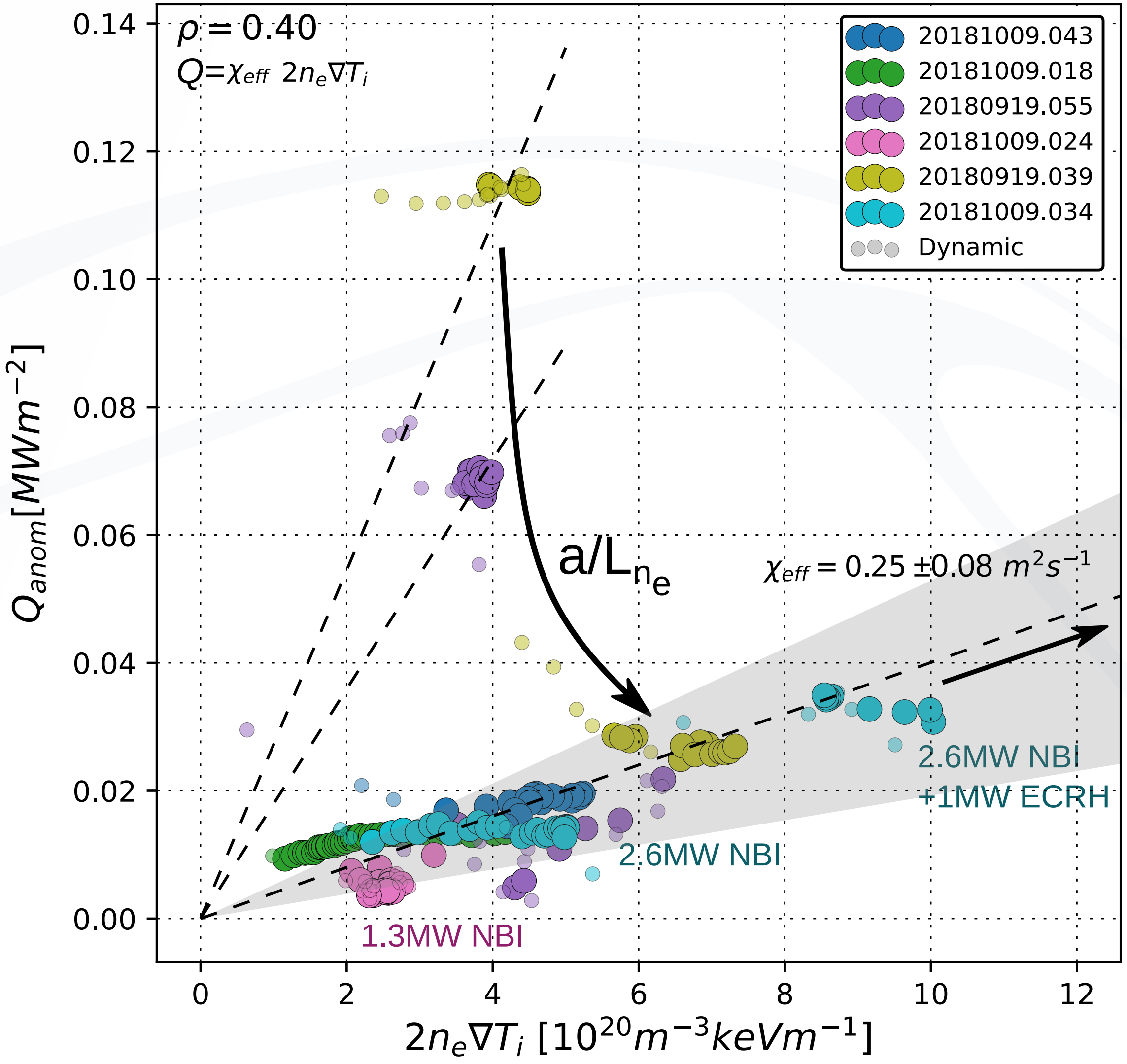

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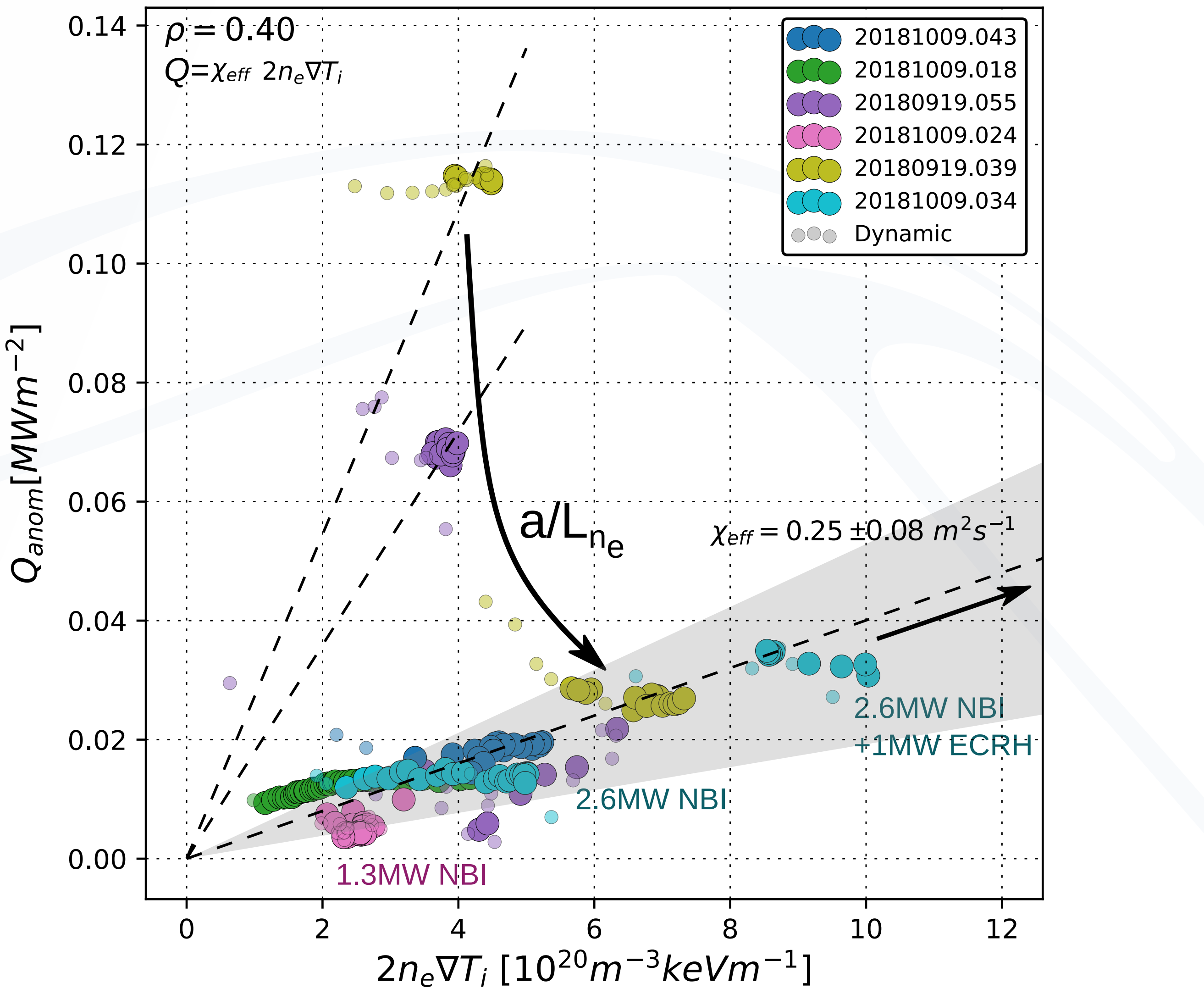
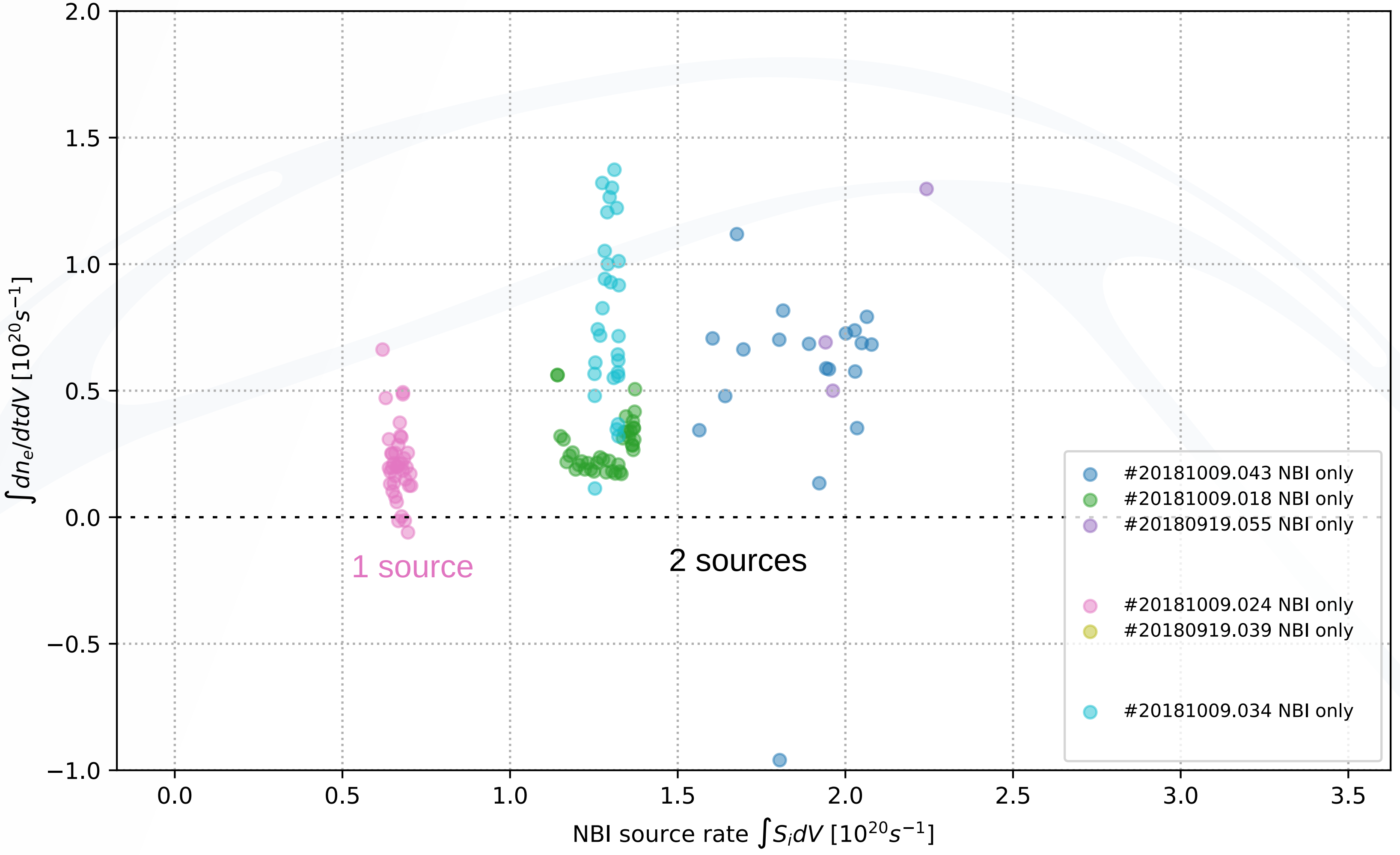
Open questions for 2022/3 campaign:
- Increase NBI power. What happens to a/Ln_e?
- Why does a/Ln_e decrease with ECRH?
- Can sufficient a/Ln_e be maintained while flushing out impurities?



Fuelling scaling

- No clear correlation of density rise with fuelling rate. Changes dramatically during shots (transport barrier).
- Not yet able to predict asymptotic density or scaling with 4 sources.
- Maybe possible with deeper particle transport analysis.



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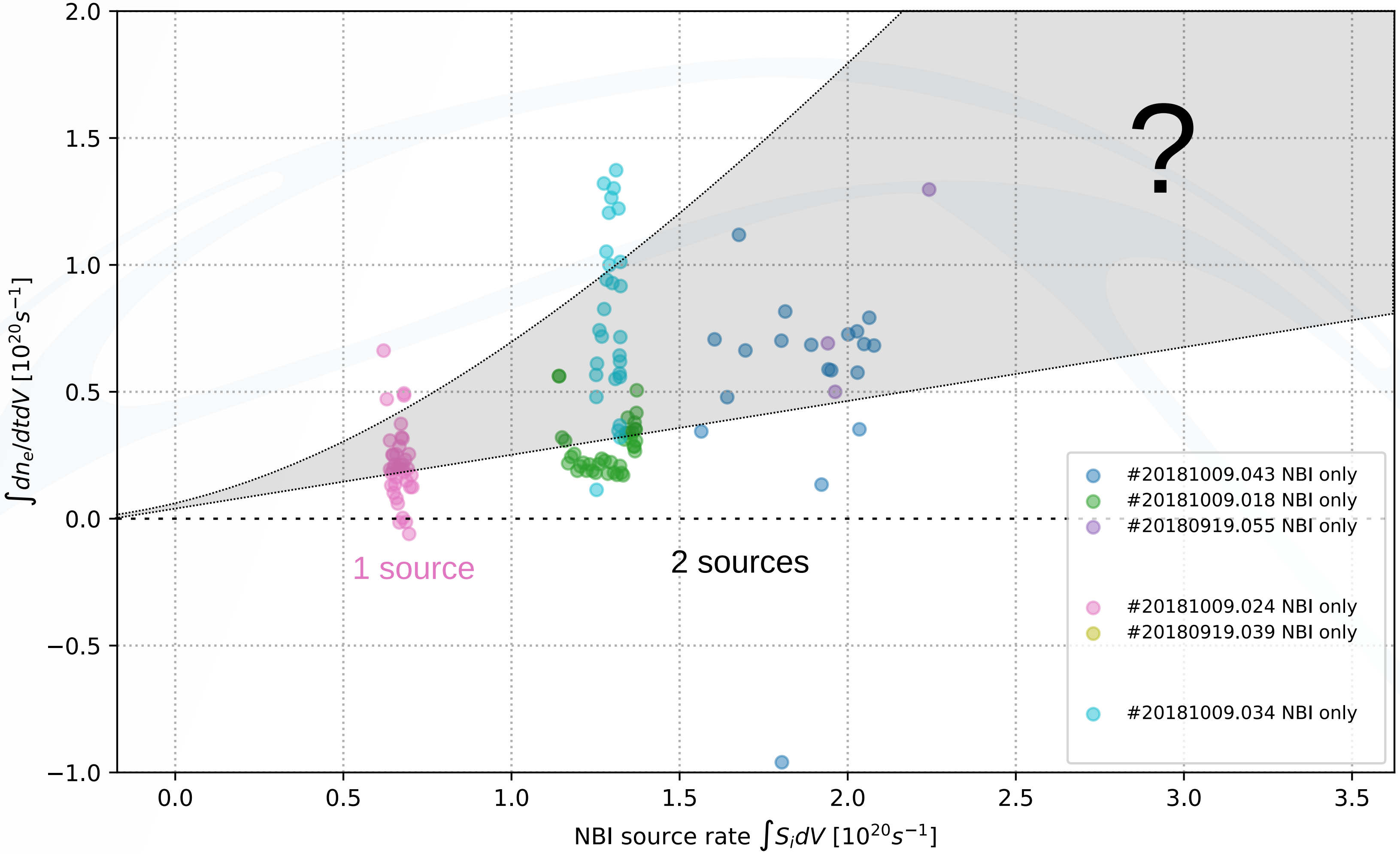

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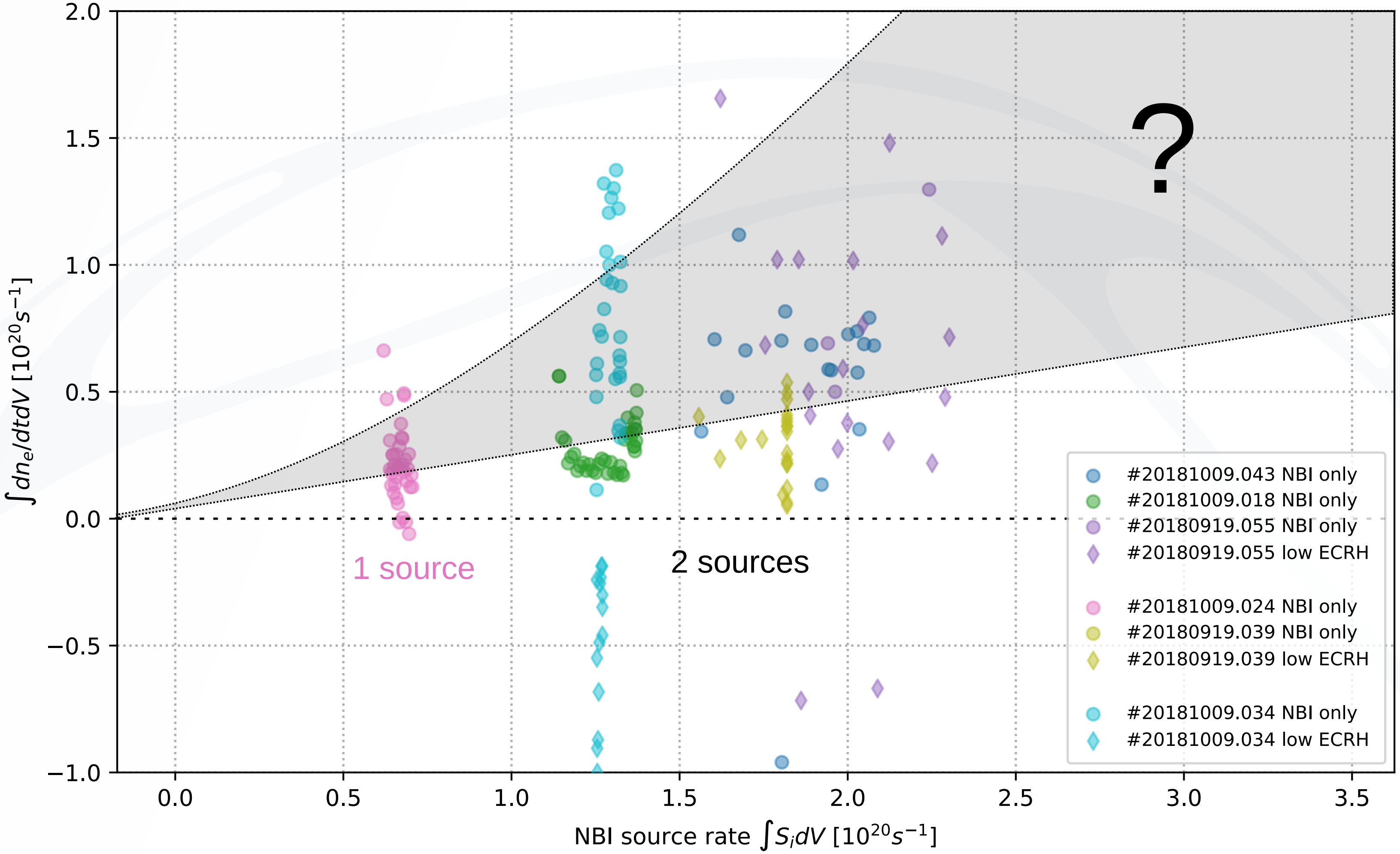

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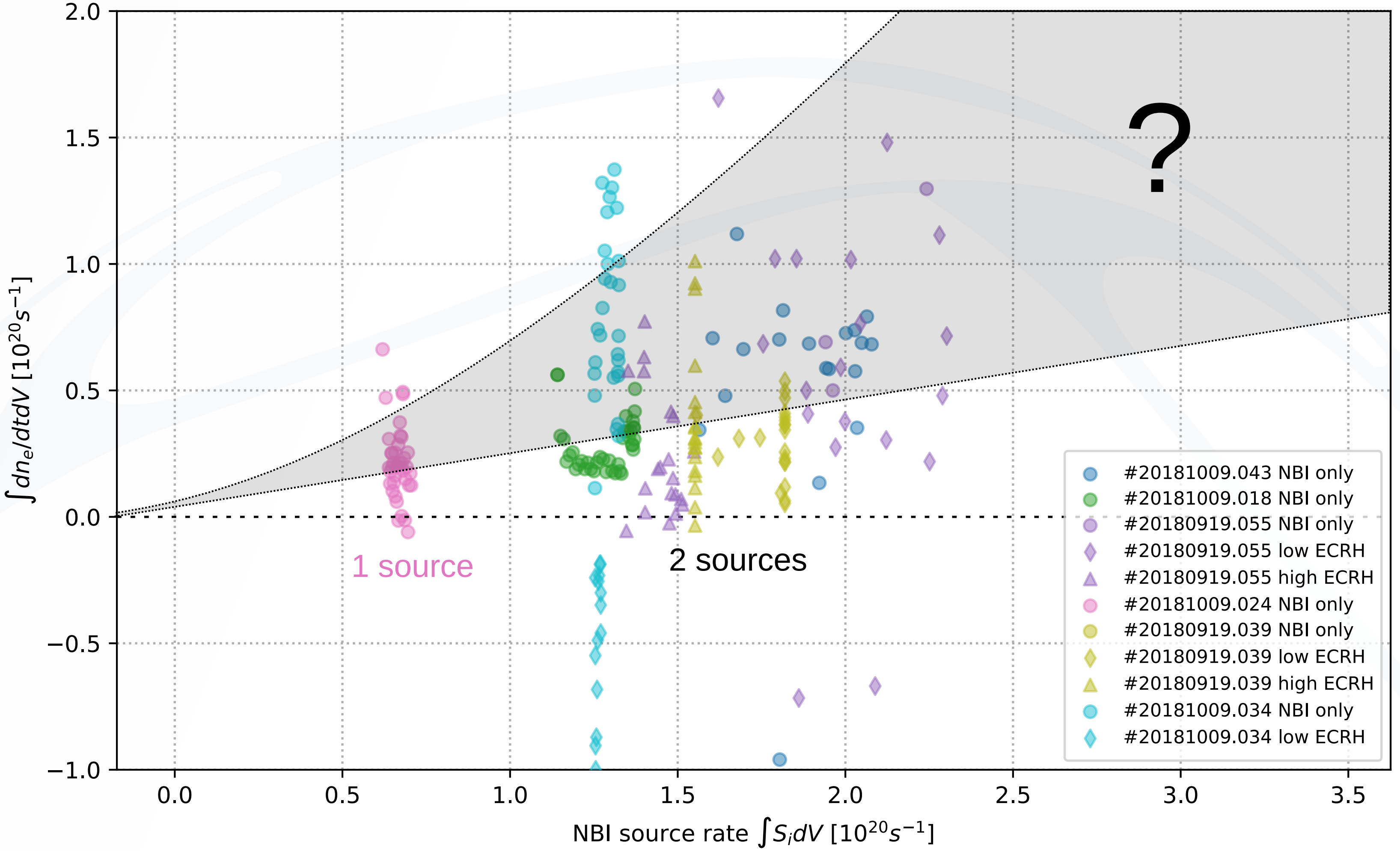

Initial comparison with LHD

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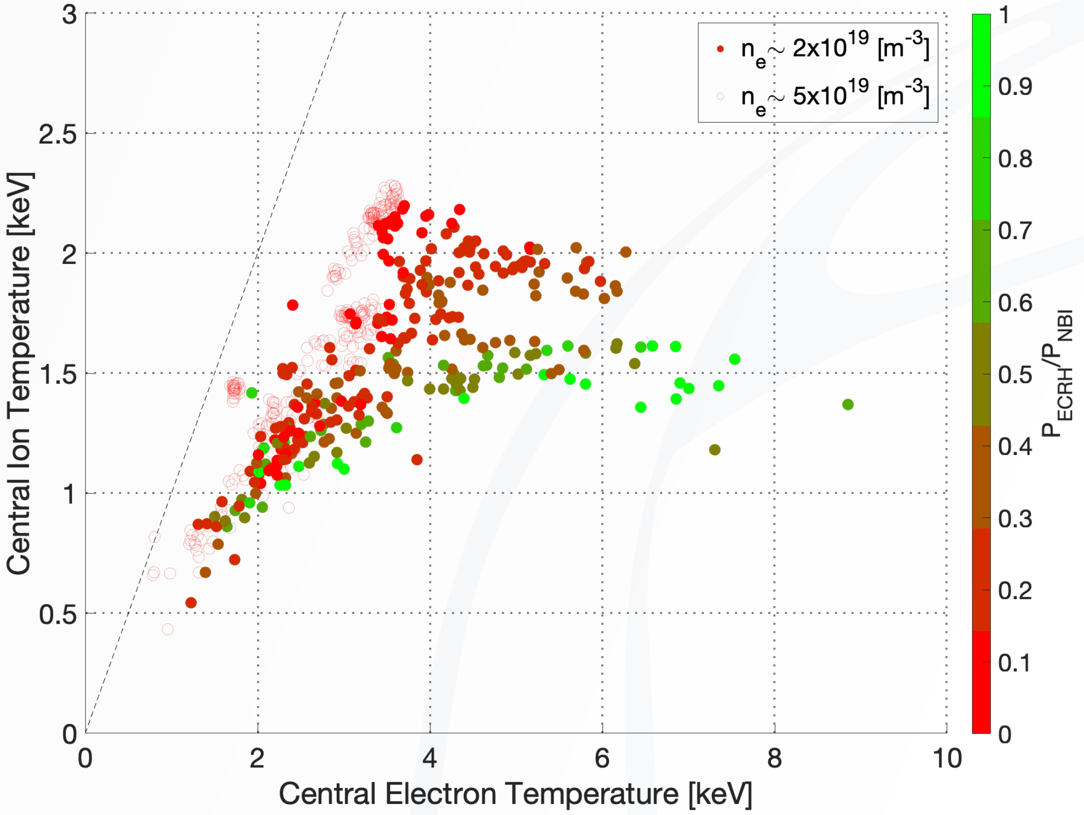

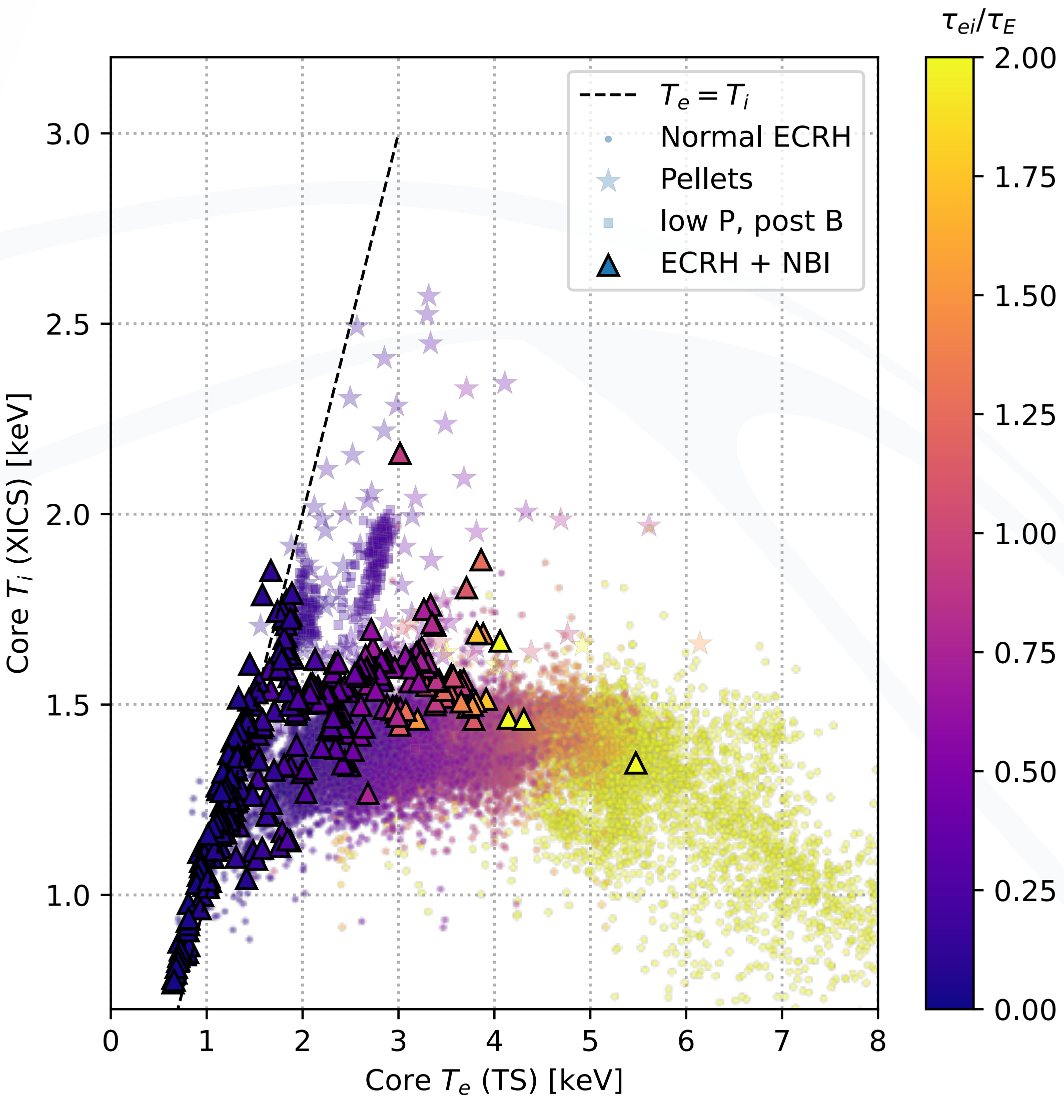

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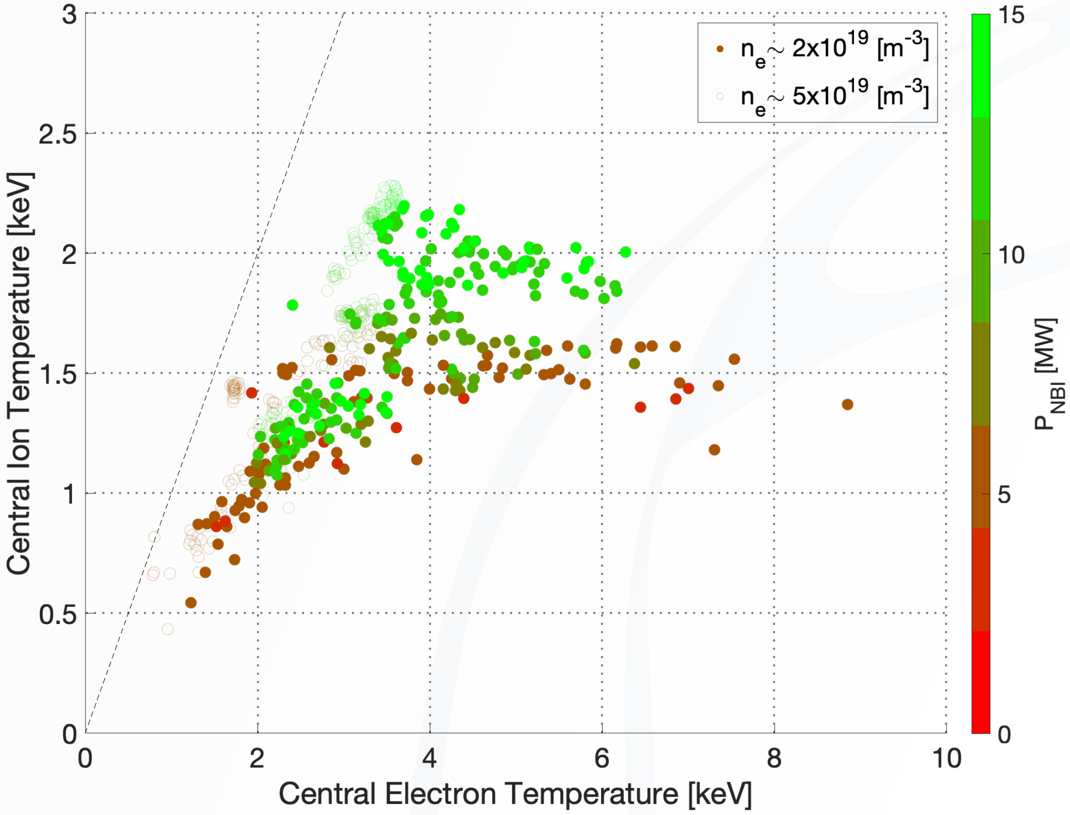

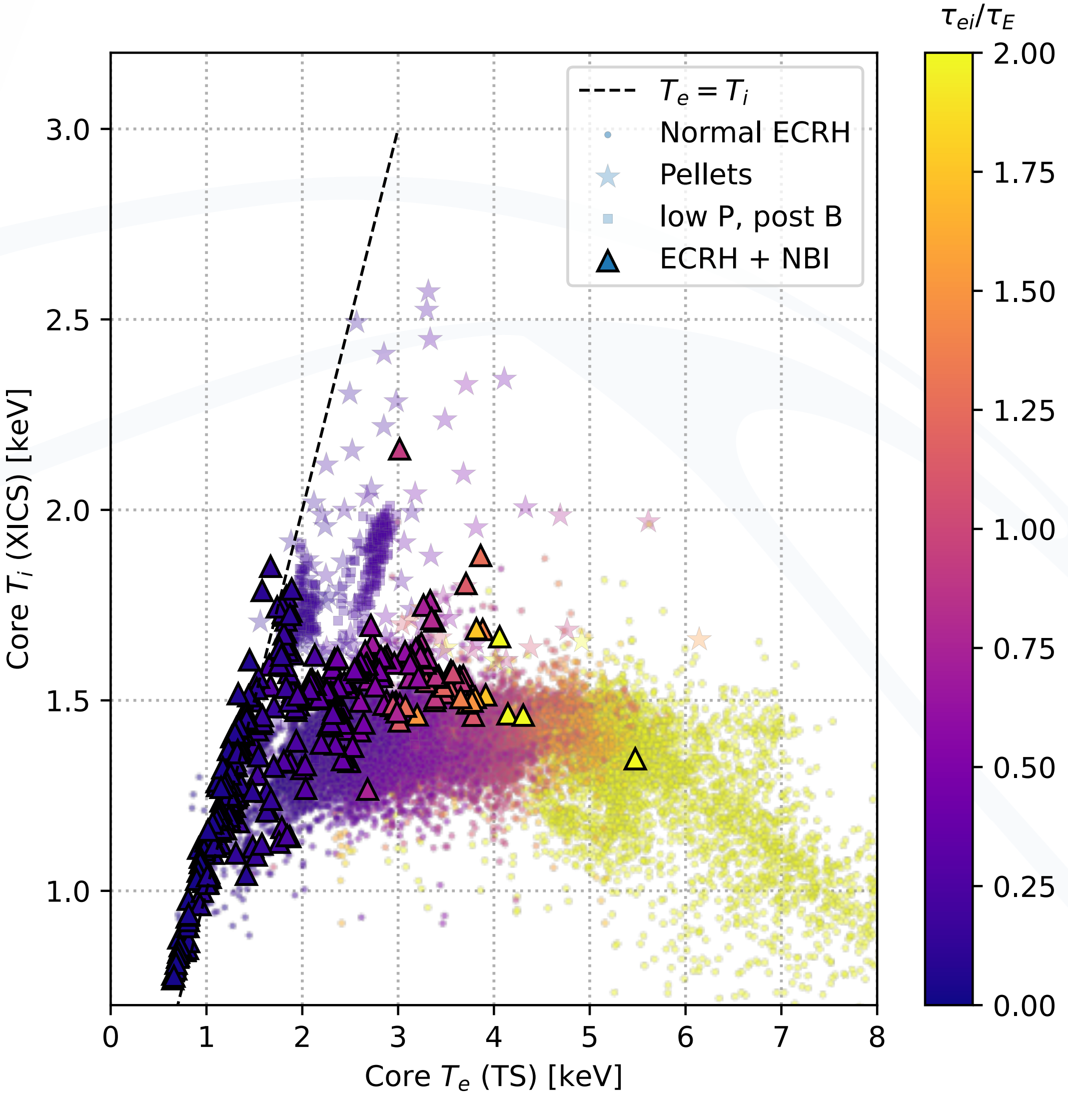

Exploration and exploitation

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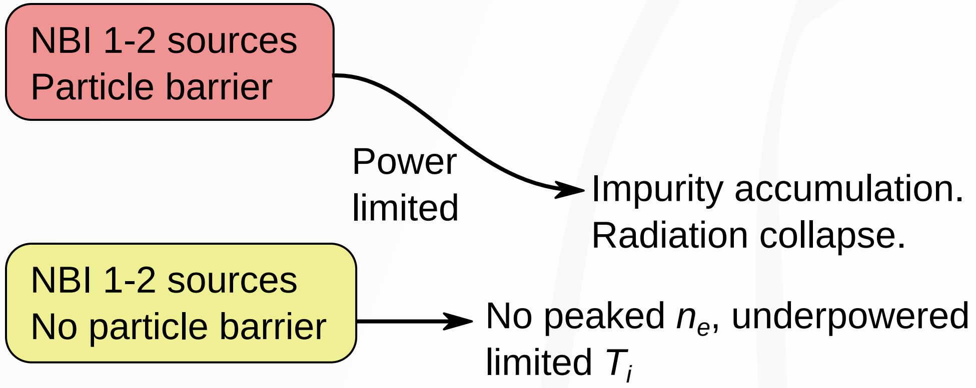

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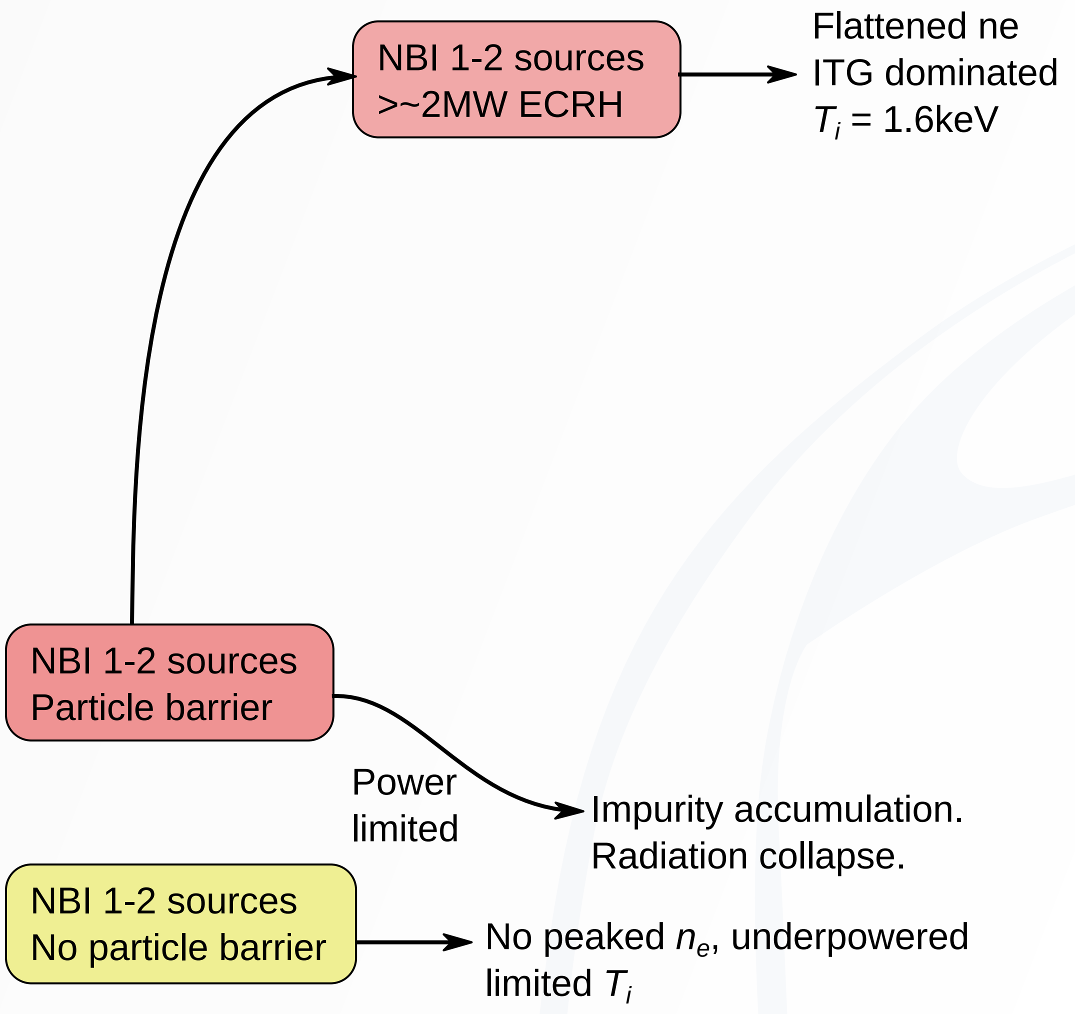

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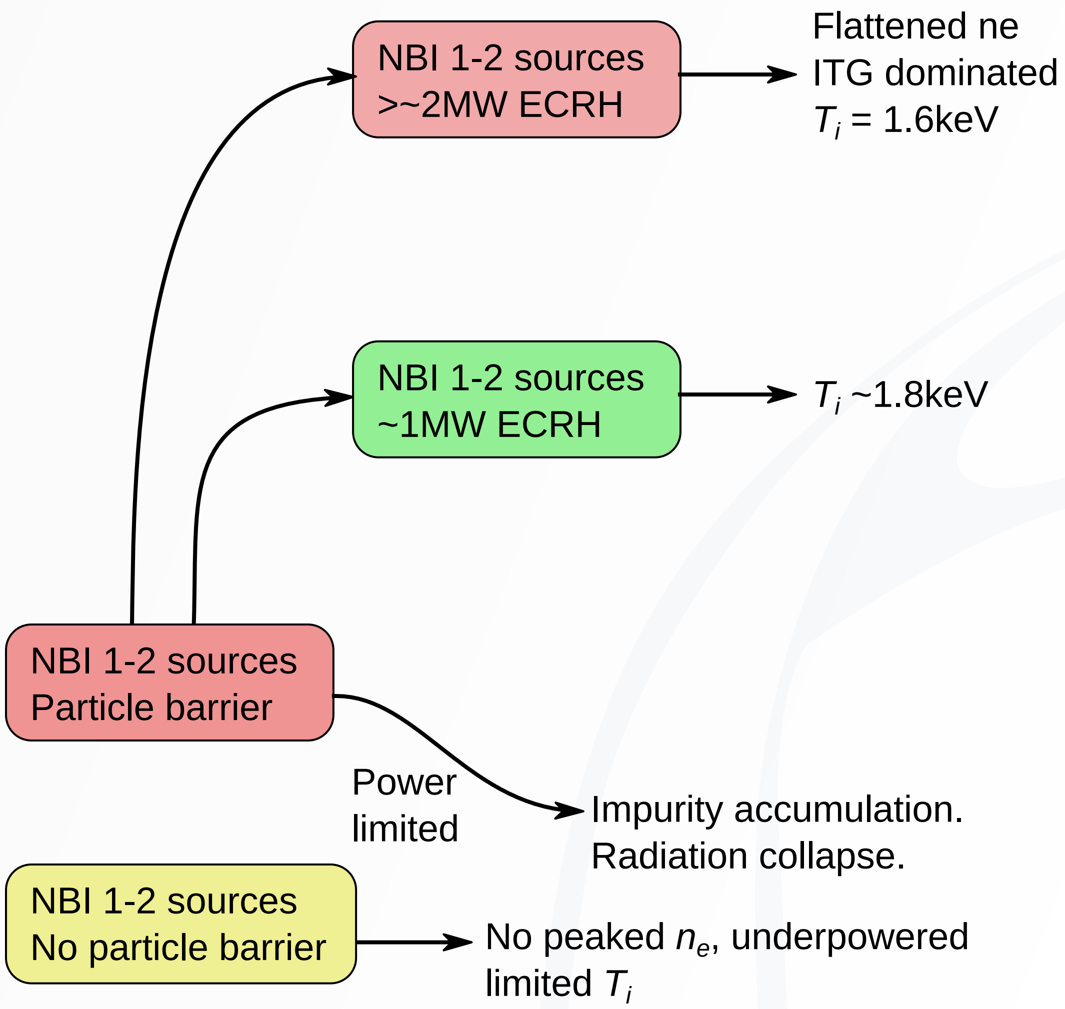

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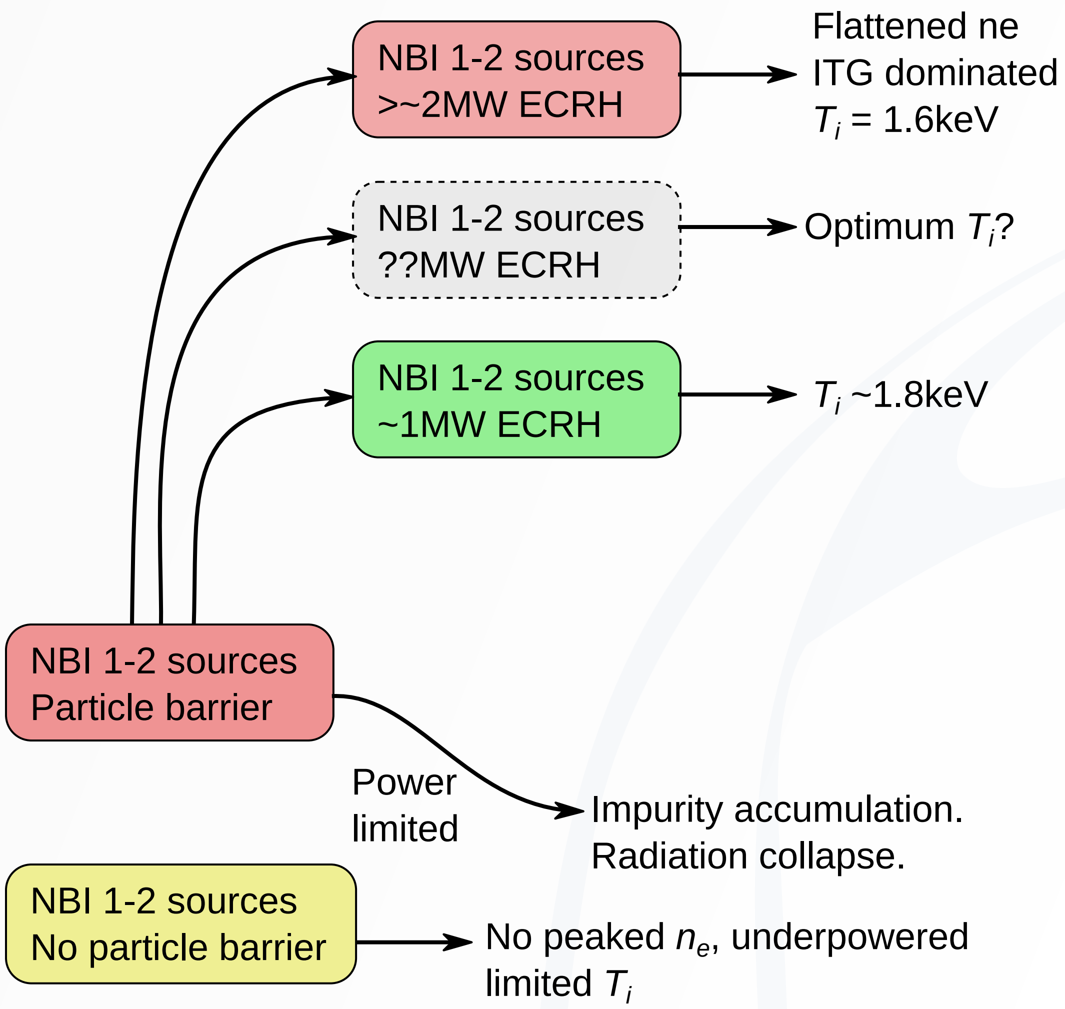

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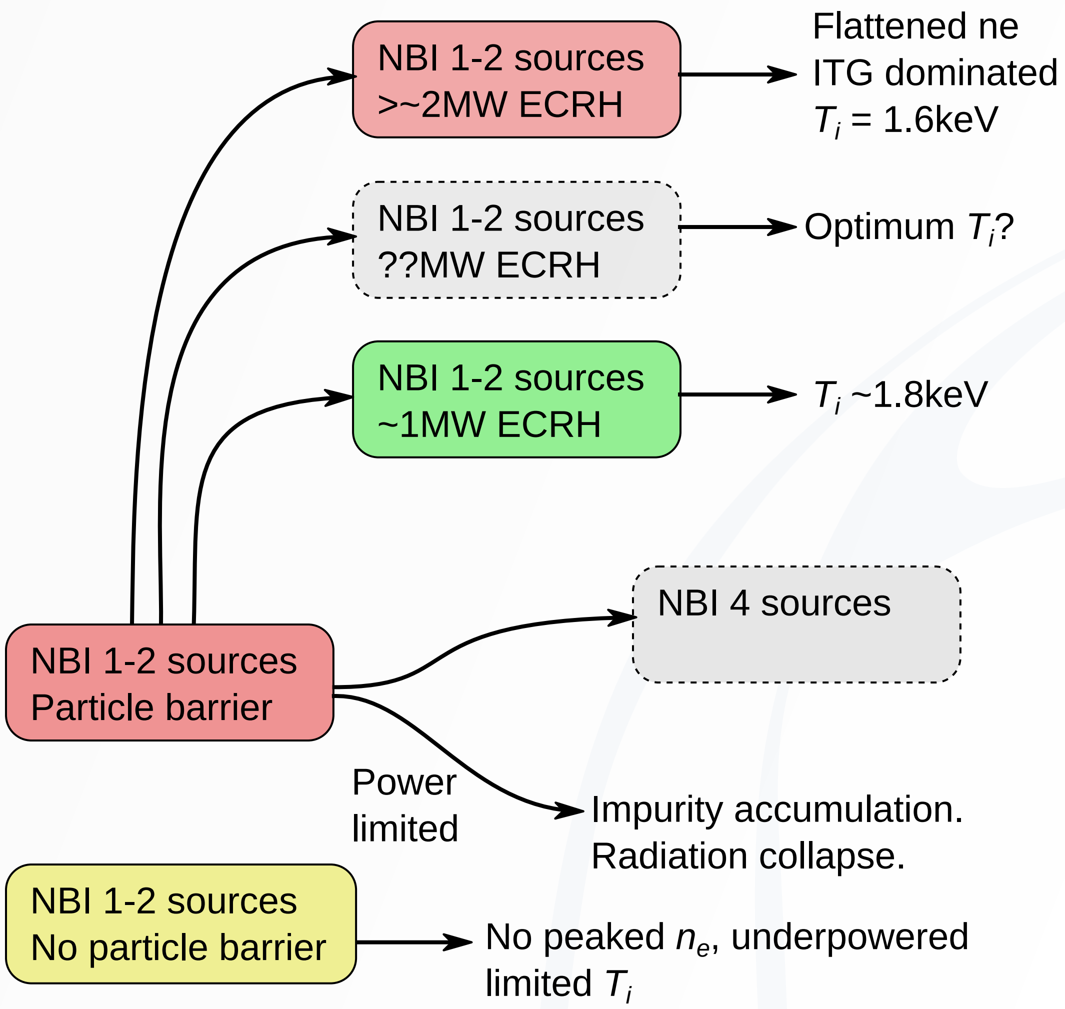

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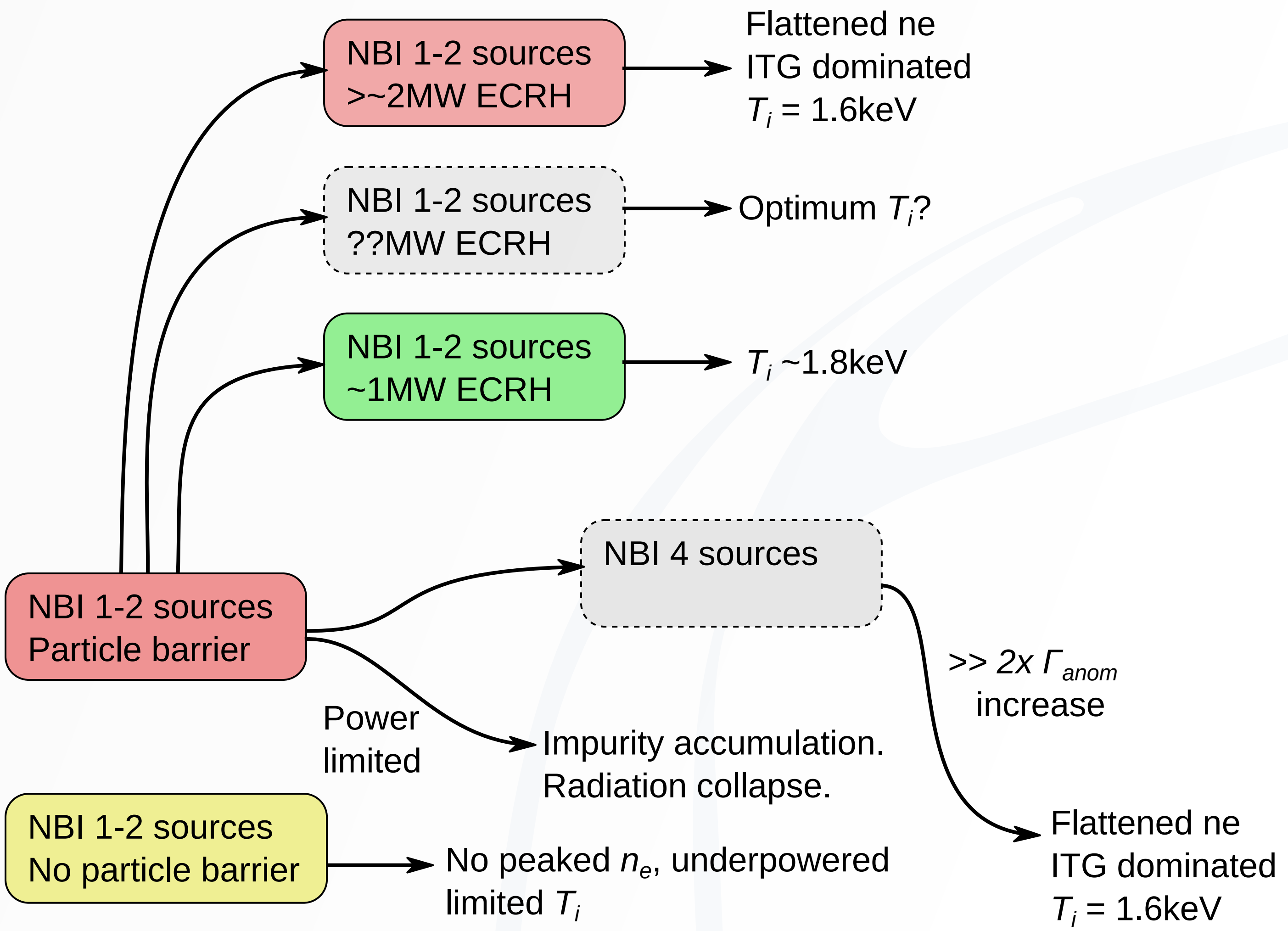

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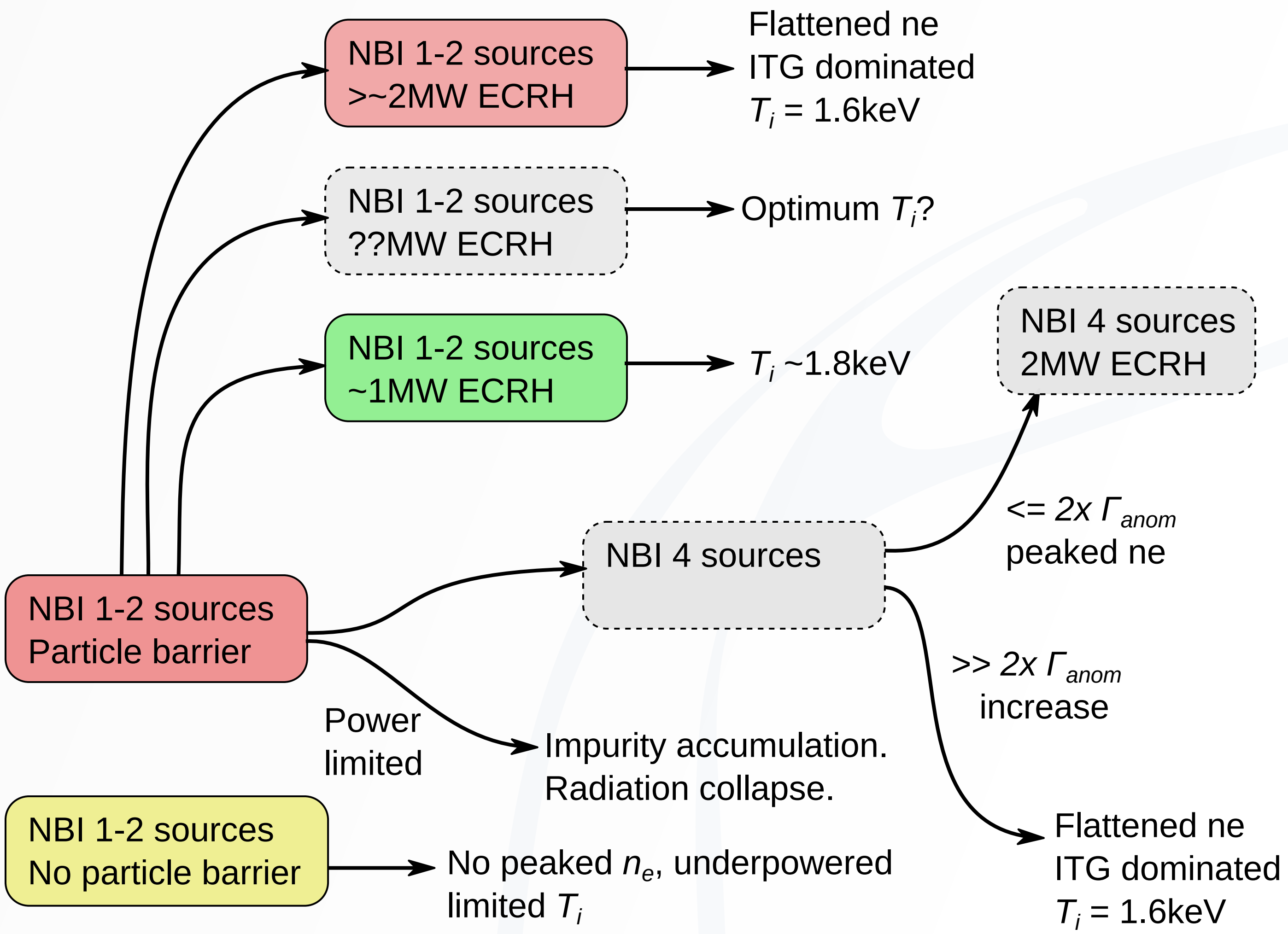

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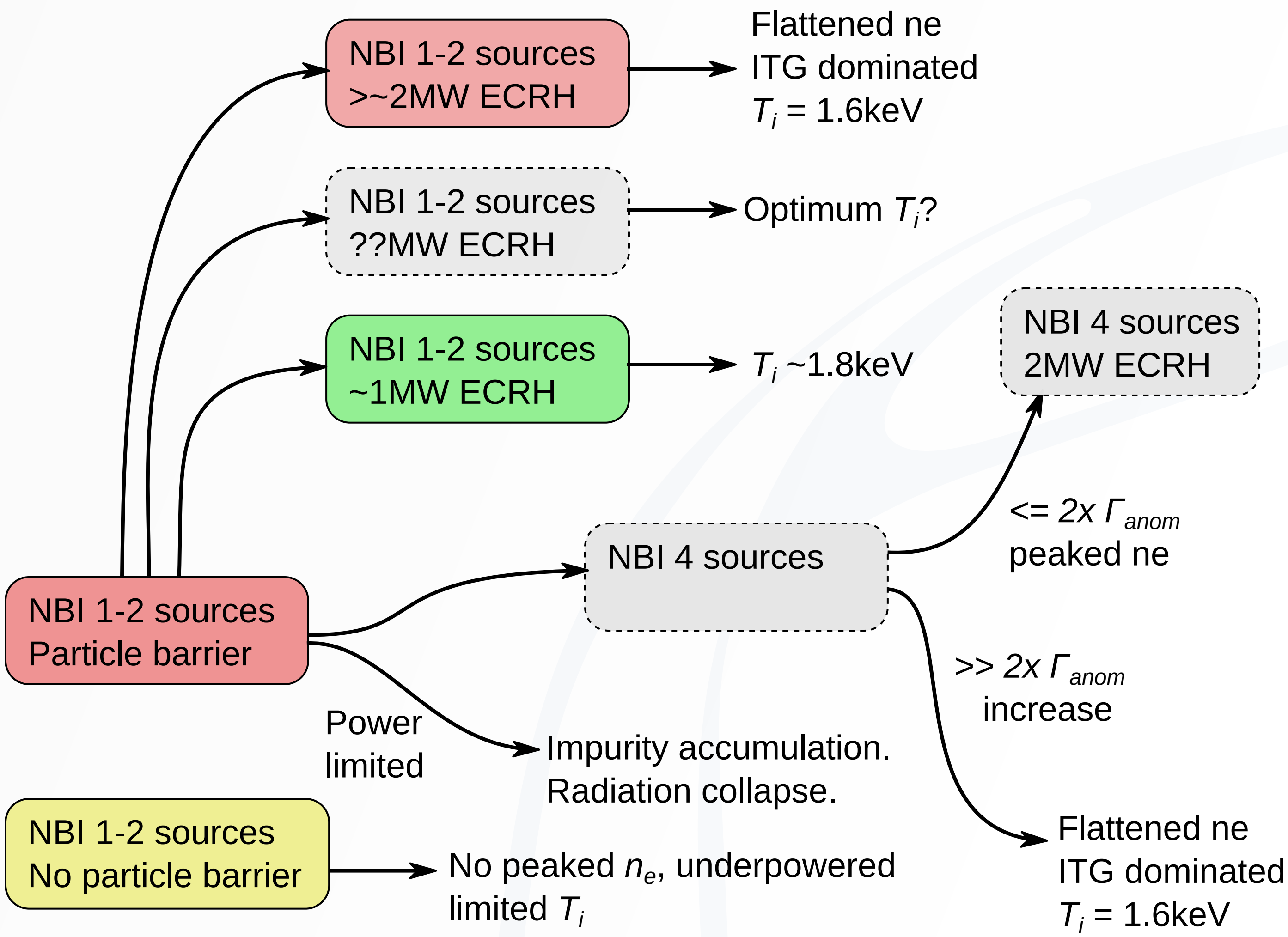

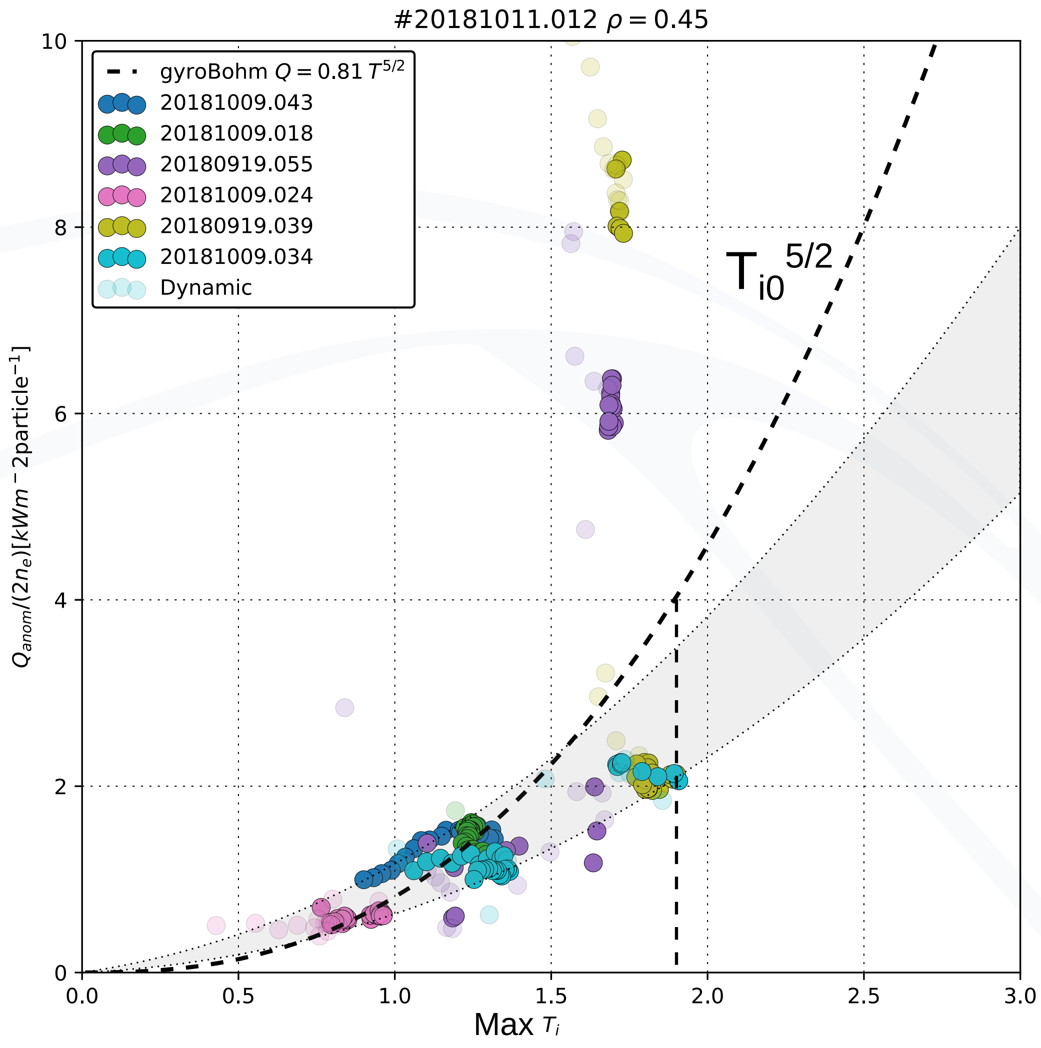

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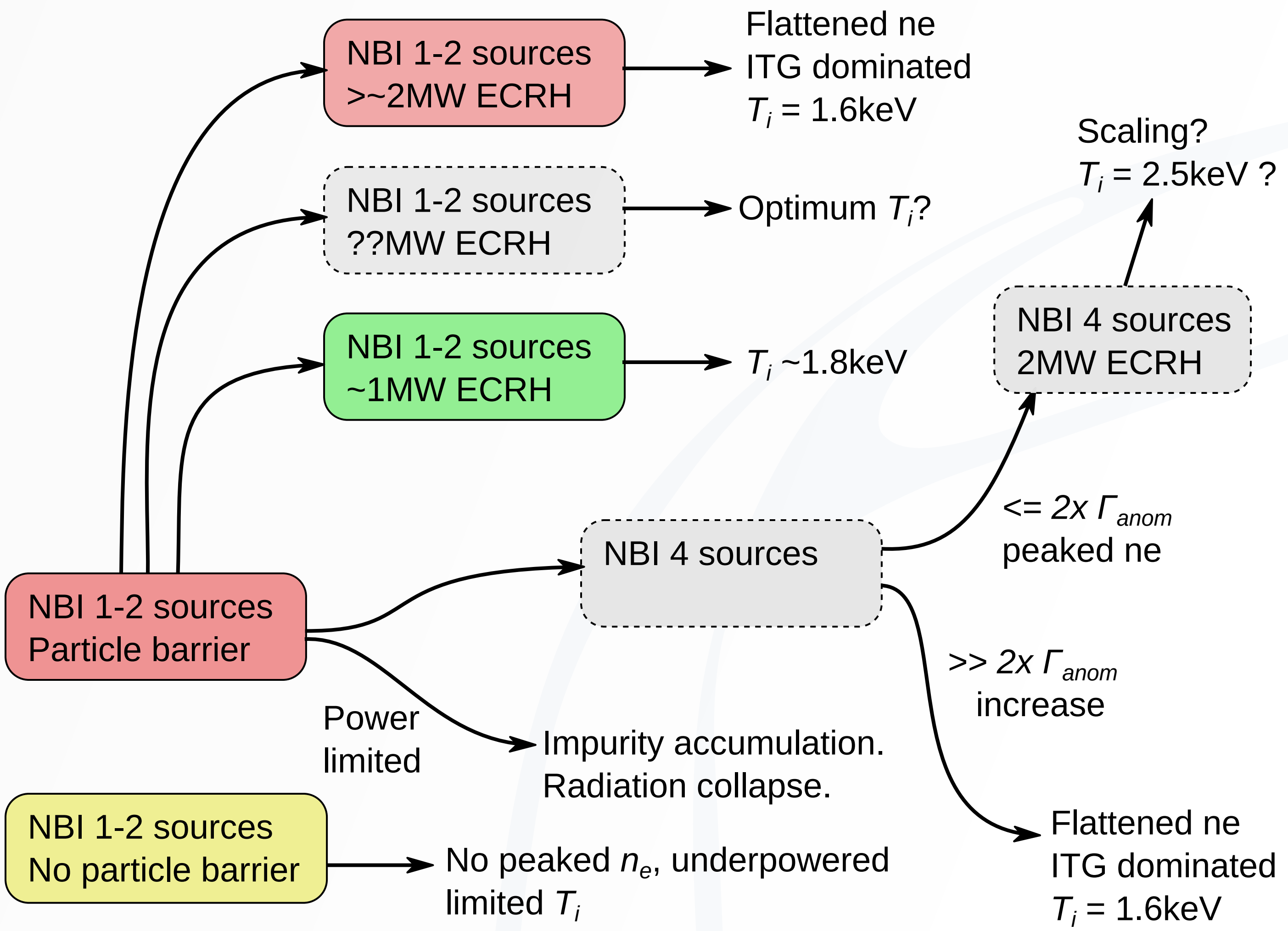

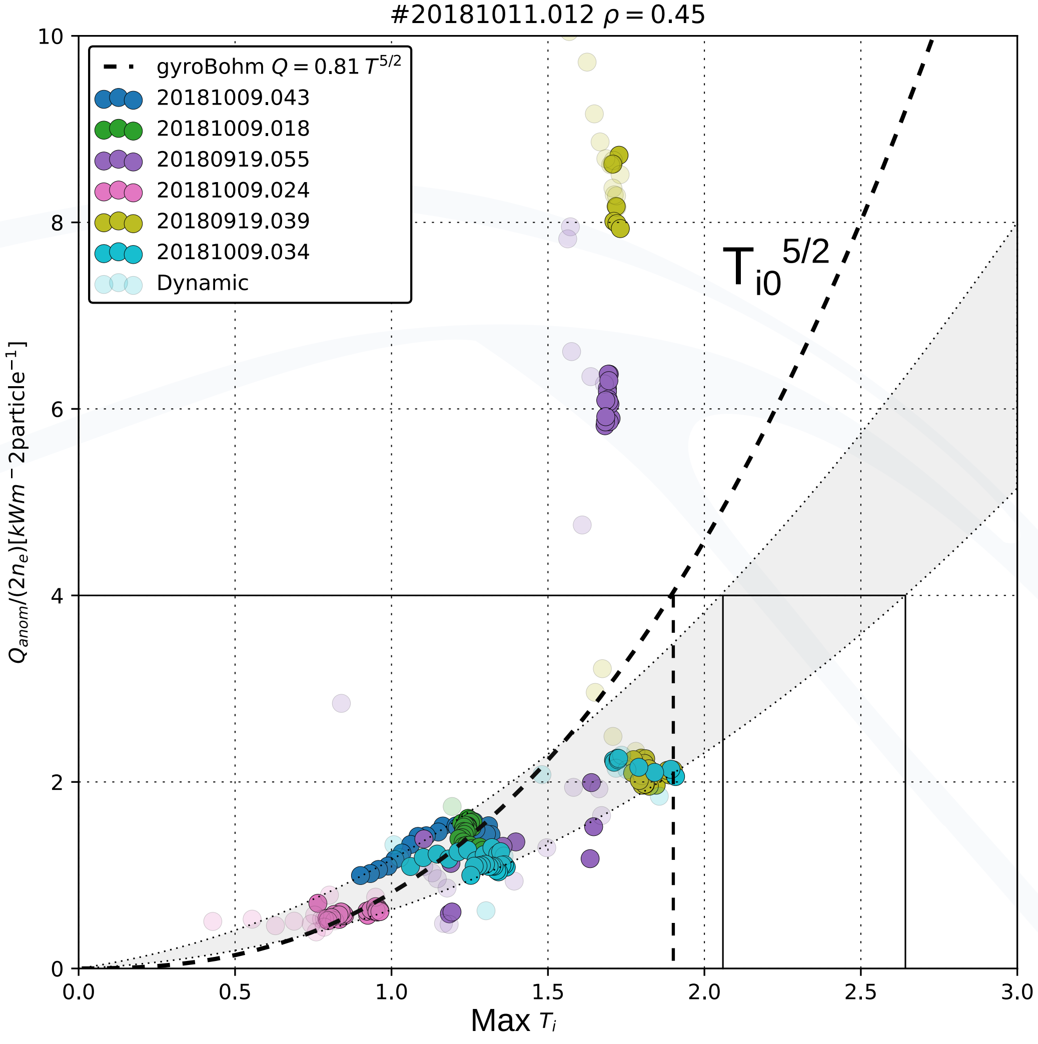

Summary and outlook

- Limited T_i and performance in standard ECRH heated gas fuelled plasmas understood as combination of: limited electron-ion coupling, strong ITG turbulence exacerbated by T_e / T_i ratio.

- Turbulence supression observed in many cases of density gradients:
    - Pellets - now well studied and understood, but might be difficult to achieve in steady-state.
    - Spontaneous peaking. Very stable but only in low power ECRH.
    - Edge n_e reduction by boron powder injection.
    - NBI core fuelling and reduced particle flux.

Summary and outlook

- Limited T_i and performance in standard ECRH heated gas fuelled plasmas understood as combination of: limited electron-ion coupling, strong ITG turbulence exacerbated by T_e / T_i ratio.

- Turbulence supression observed in many cases of density gradients:
  - Pellets - now well studied and understood, but might be difficult to achieve in steady-state.
  - Spontaneous peaking. Very stable but only in low power ECRH.
  - Edge n_e reduction by boron powder injection.
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- NBI with low-ECRH plasmas show stable density gradients and favorable gyroBohm like scaling $Q \sim nT^{5/2}$ providing possible steady state scenario with high T_i in W7-X plasmas.
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Strong n_e gradients = turbulence supression = higher T_i.
Why? ITG, ETG, TEM, iTEM .... --> E5
How can we best use it?
Why do we get n_e gradients? Why are n_e profiles not hollow? Why does ne peak in NBI/pellets?
Why does ECRH flatten n_e? What role does edge fuelling/pumping play?
Why do low P and boron droper plasmas have low edge n_e? How can this be used?
Are all these low/high edge n_e scenarios compatible with detachment?

CXRS OP2 status and upgrades

- Primary measurements: (mostly as OP1.2b)
  - T_i, E_r, n_C ~50 channels on NI21
  - NBI blips in almost all discharges: 20ms blips at 5Hz for 15s
  - E_r analysis development by PhD student from CIEMAT.
  - 2 variable spectrometers of 40 points on 2 impurities selected from B, C, N, O, Ar, Fe, ...

    (Select C for highest resolution --> 160 T_i, n_C, E_r points)

    (Gratings not upgraded due to lack of funds - 10k€)
  - FIDA measurements [Poloskei]

	Blips	Continuous NI21
T_i	< 2 minutes	Poor quality in 2 minutes. Validated on request only.
n_C	n_e available + 1 minute	
n_Z	n_e available + 1 minute	
E_r	On request	Difficult, special request only

Upgrades:

1) **18x high-speed T_i for Q_i via heat-pulse-propagation** [Univ. WISC: Geiger].
2) 30x extra carbon (T_i, n_C, E_r) measurements [NIFS: Ida, Yoshnuma]
3) Upgrade to passive spectrometer for C^{VI}
   --> Reliable T_i, n_C, E_r measurements in continuous NBI
   --> Inverted edge T_i, n_C measurements without NBI
4) Spectral MSE for ι profile measurements [E3: Zanini], (15k€ funds for camera uncertain).
5) **Passive Hα spectrometer for neutral hydrogen profiles** [E5: Reimold],
   (Currently no camera)
6) Coherence imaging of T_i, n_C [Univ. Seville: Viezzer; E4 Perseo]
7) *Passive FIDA spectrometer... to be considered, no camera (15k€)*