Impurities in a Reactor

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Acknowledgements
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Overview

- Introduction
  - ⇨ Impurities in Fusion Plasmas
- Impurity limits
  - ⇨ Simple 0D and 0.5D approach
  - ⇨ 1D ASTRA model
- What Physics Issues Need to be Addressed?

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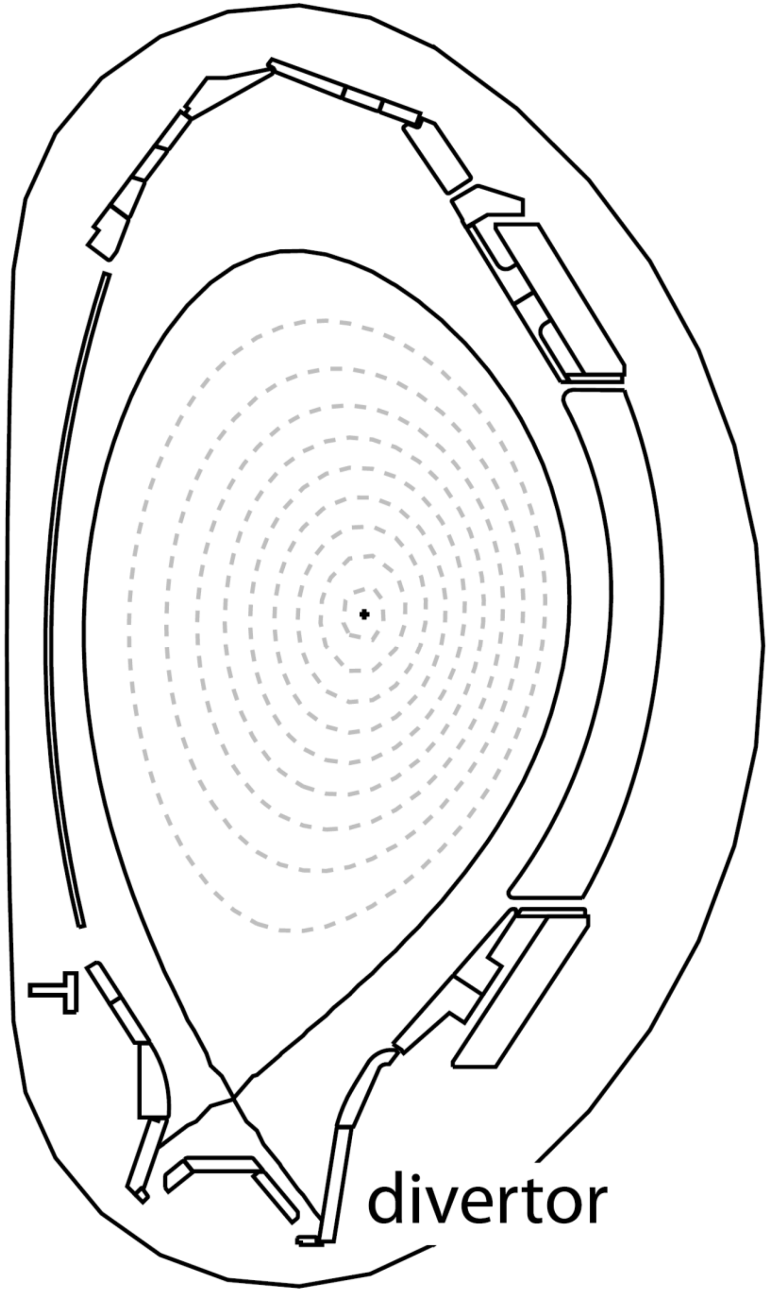
Impurity Sources



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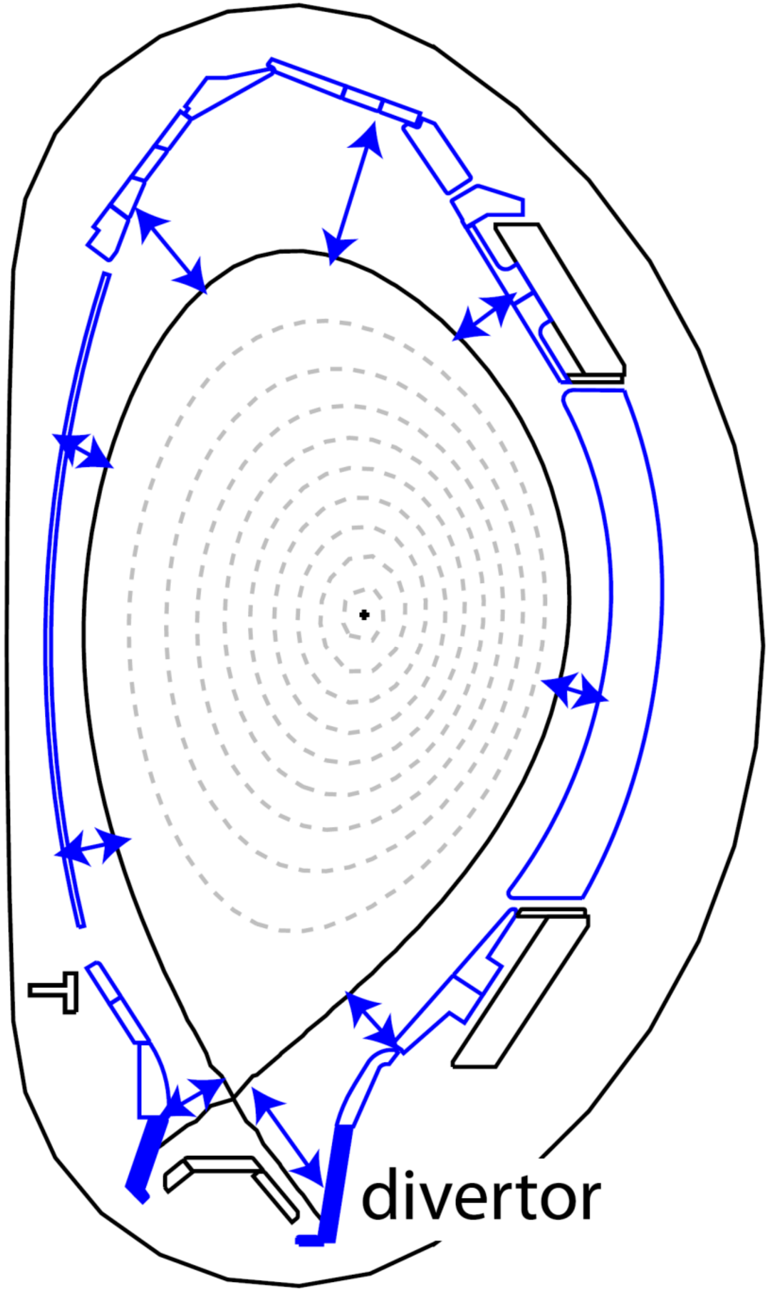

- Erosion from first wall
  (e.g. W, Be, C…..)

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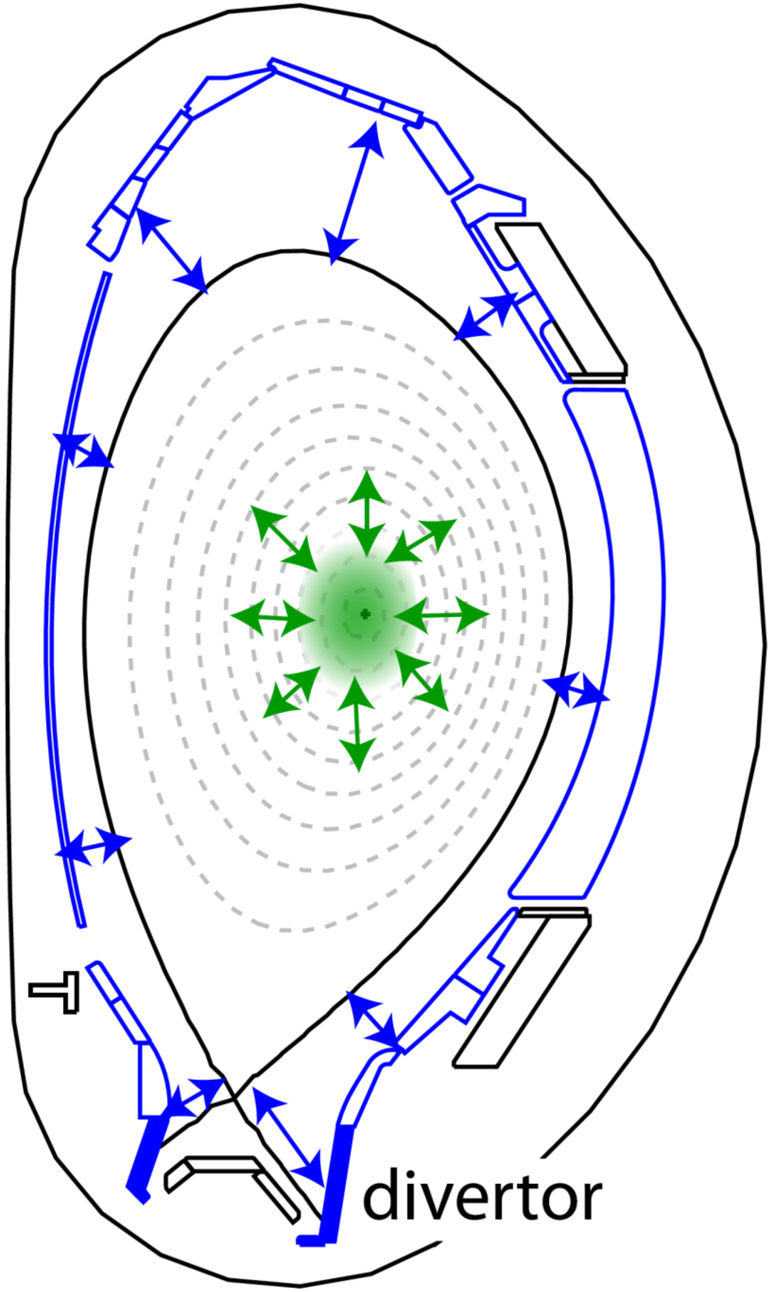


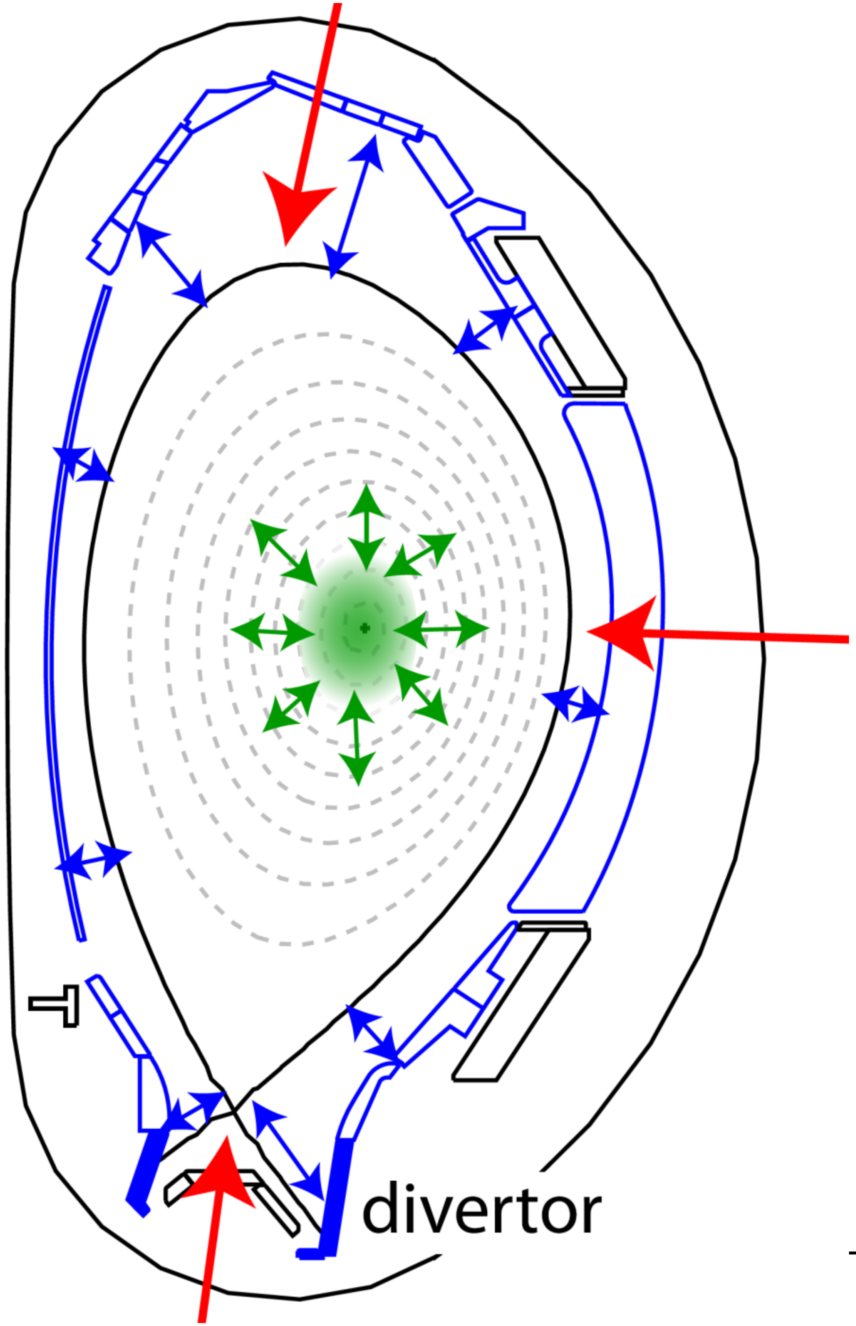
- Erosion from first wall
  (e.g. W, Be, C.....)

- Production of He in reactor core

$$ {}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}\mathrm{n} $$

3.5MeV 14.1MeV

Impurity Sources



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- Intentionally injected impurities
  (e.g. N, Ne, Ar, Kr…)

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0D-Model - Simple Power Balance

Reiter, NF 1990

A) Power balance: $P_\alpha = P_{rad} + P_{transp}$

$$\begin{aligned} P_\alpha &= \frac{n_e^2}{4}\langle\sigma u\rangle E_\alpha (1-2c_{He}-Z_ic_i)^2 \\ P_{rad} &= n_e^2((1-2c_{He}-Z_ic_i)L_H + c_{He}L_{He} + c_iL_i) \\ P_{transp} &= \frac{3kTn_e}{2\tau_E}(2-c_{He}-(Z_i-1)c_i) \end{aligned}$$

=> $\boxed{n_eT\tau_E = f(T, c_{He}, c_i)}$

B) He balance: production = losses

$$\frac{n_e^2}{4}\langle\sigma u\rangle (1-2c_{He}-Z_ic_i)^2 = \frac{n_ec_{He}}{\tau_{He}}$$

define: $\rho^* = \frac{\tau_{He}}{\tau_E}$

A+B

===>

$$\boxed{a_3(\rho^*, T, c_i)c_{He}^3 + a_2(\rho^*, T, c_i)c_{He}^2 + a_1(\rho^*, T, c_i)c_{He} + a_0(\rho^*, T, c_i) = 0}$$

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=> $\boxed{n_eT\tau_E = f(T, c_{He}, c_i)}$

- Fix ρ^*,T and c_i
- $\leq$ 2 meaningful solutions for c_{He}

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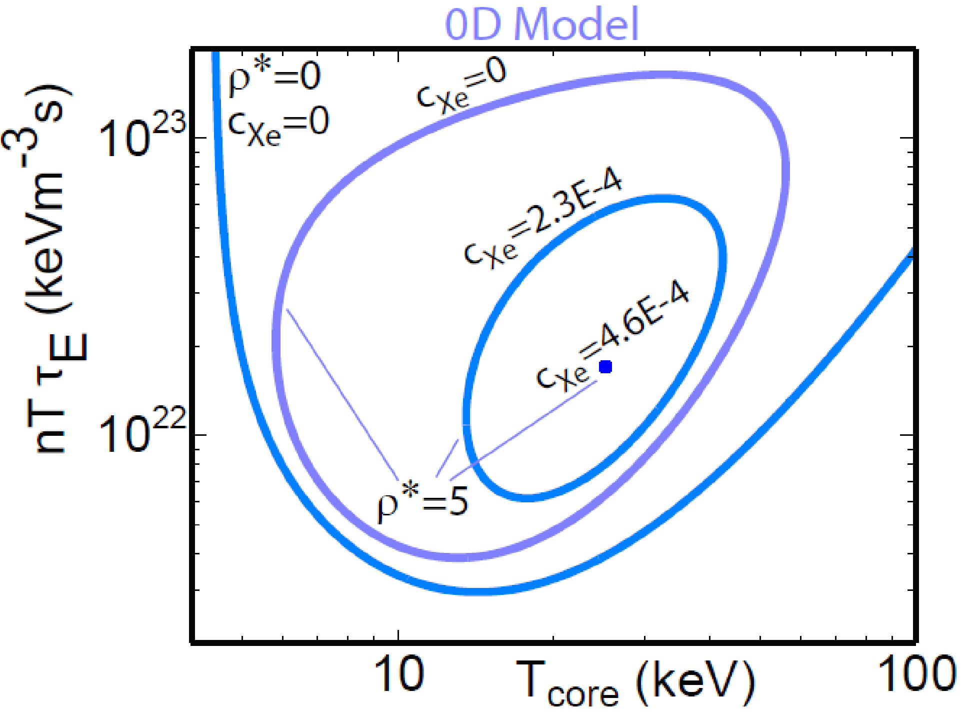
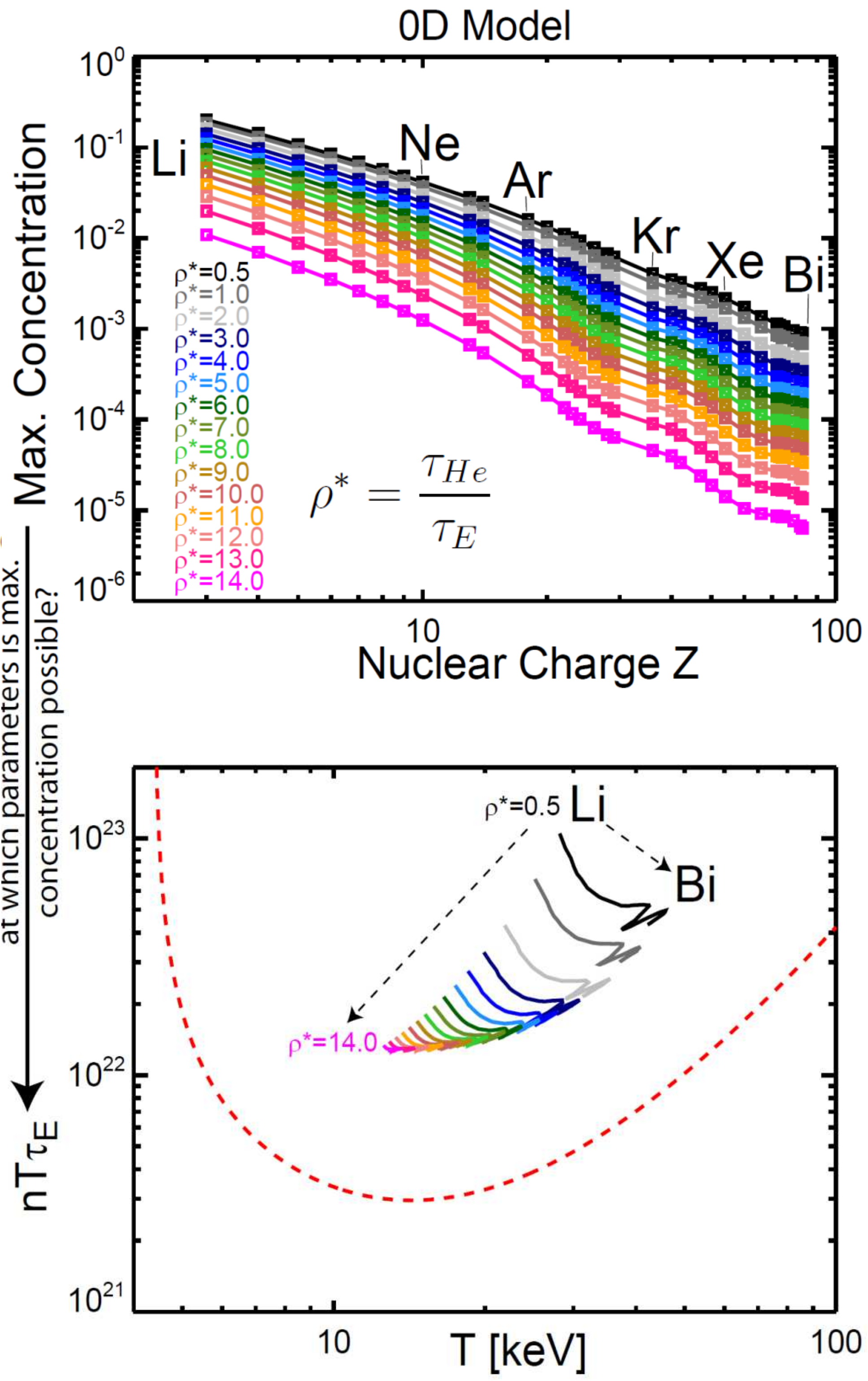


Pütterich, EPS 2015

- For fixed ρ* and variation of c_{Xe} => plots with burn curves
- Burn curves become a single dot for maximum impurity level
- low-Z impurities decrease P_α via dilution
- high-Z impurities increase P_{rad}



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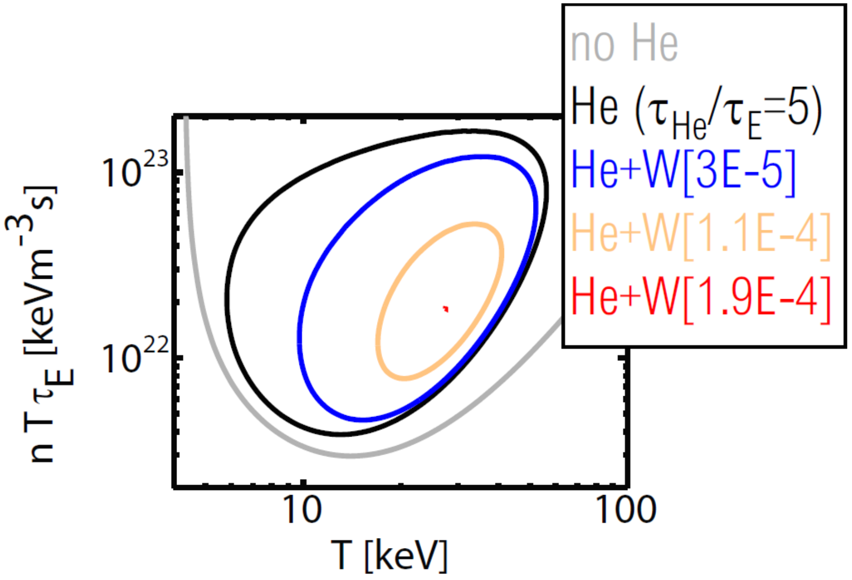
0D Model - Mixing Impurities

- W from wall, seeded impurities, He-ash



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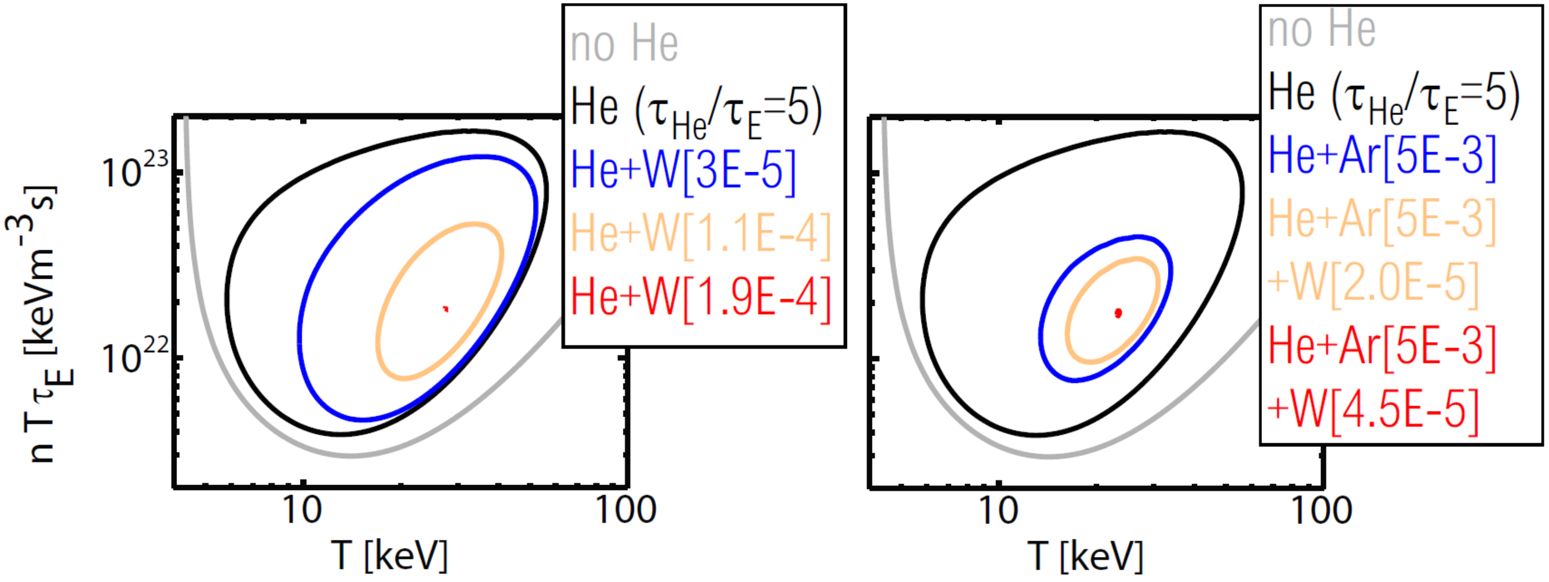

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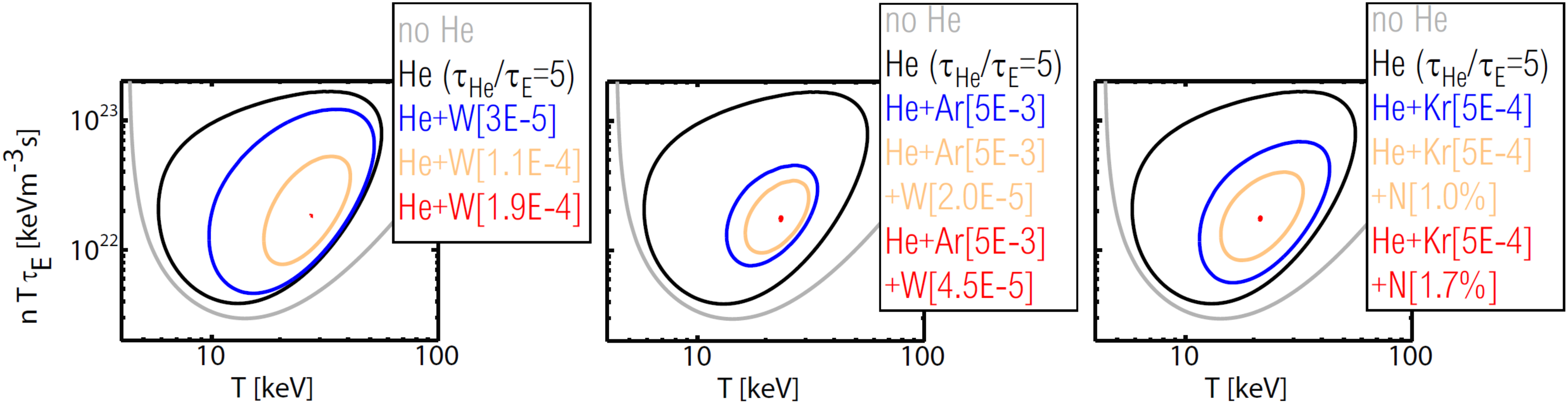

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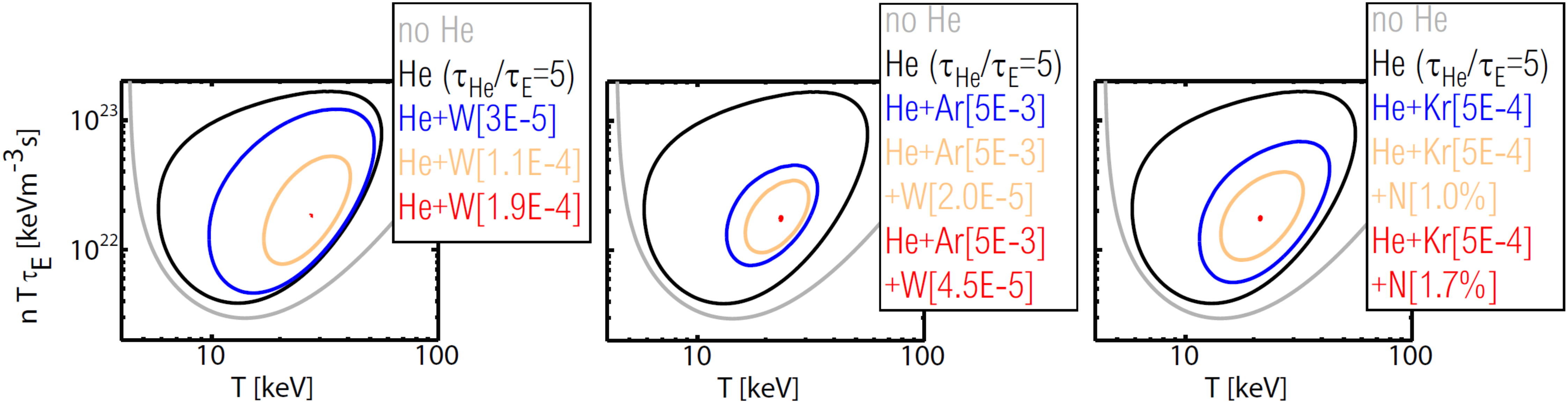
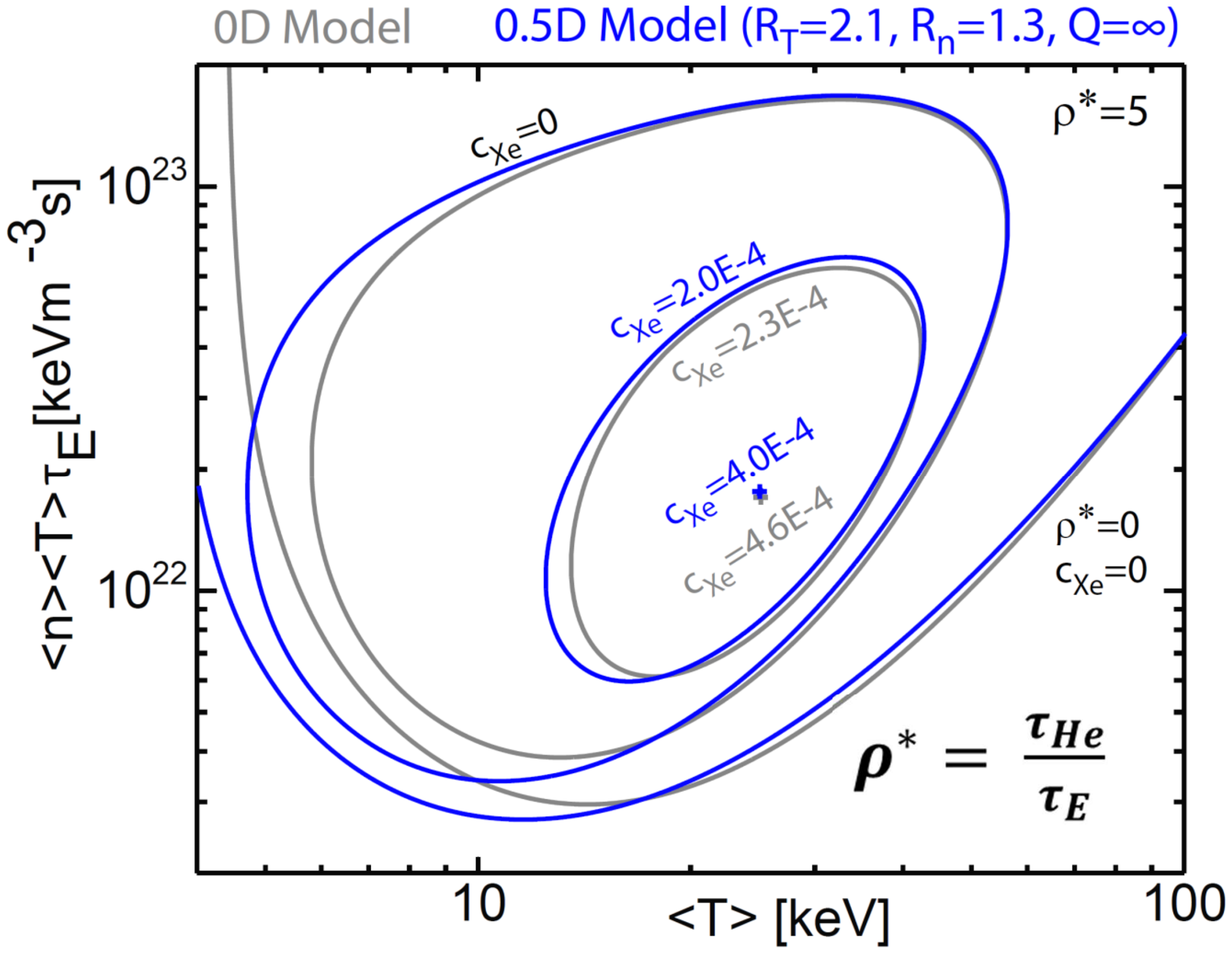


- Is the situation changing for more realistic assumptions?

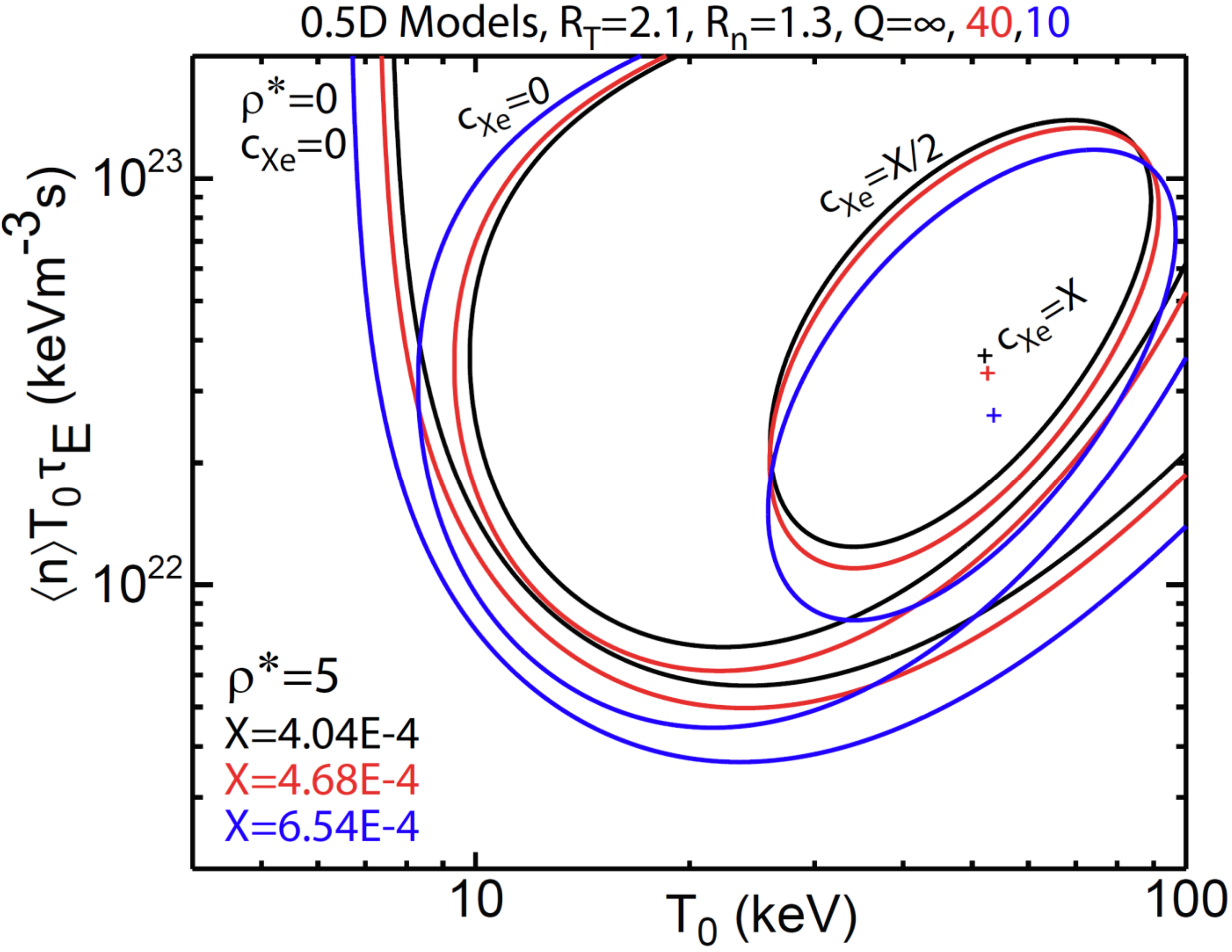
Implementation of T- and n-Profiles – Model Still Very General



- Profiles of n,T vs. r/a using circular plasma
- Any Plasma may be mapped onto a circular one
- Approximation: Linear Profiles, Flat Impurity Concentration
- Parametrized via peaking $R_T=T_0/<T>$, $R_n=n_0/<n>$
- Results are size independent
- For ρ*<5 small effect (<20%)

Pütterich, EPS 2015 – now improved model

Implementation of finite Q also Possible



$$\rho^* = \frac{\tau_{He}}{\tau_E}$$

Pütterich, EPS 2015 – now improved model

$$Q = \frac{P_{fus}}{P_{aux}} = \frac{5P_\alpha}{P_{aux}}$$

- Q>30 economically viable
- Finite Q can be seen as an artificially increased $P_{\alpha,eff}$

$$P_{\alpha,eff} = P_\alpha + P_{aux} = \frac{Q+5}{Q} P_\alpha$$

- Note: Fixed Synchrotron radiation can be taken into account, but depends on B_t & R

=> Talk today by E. Fable

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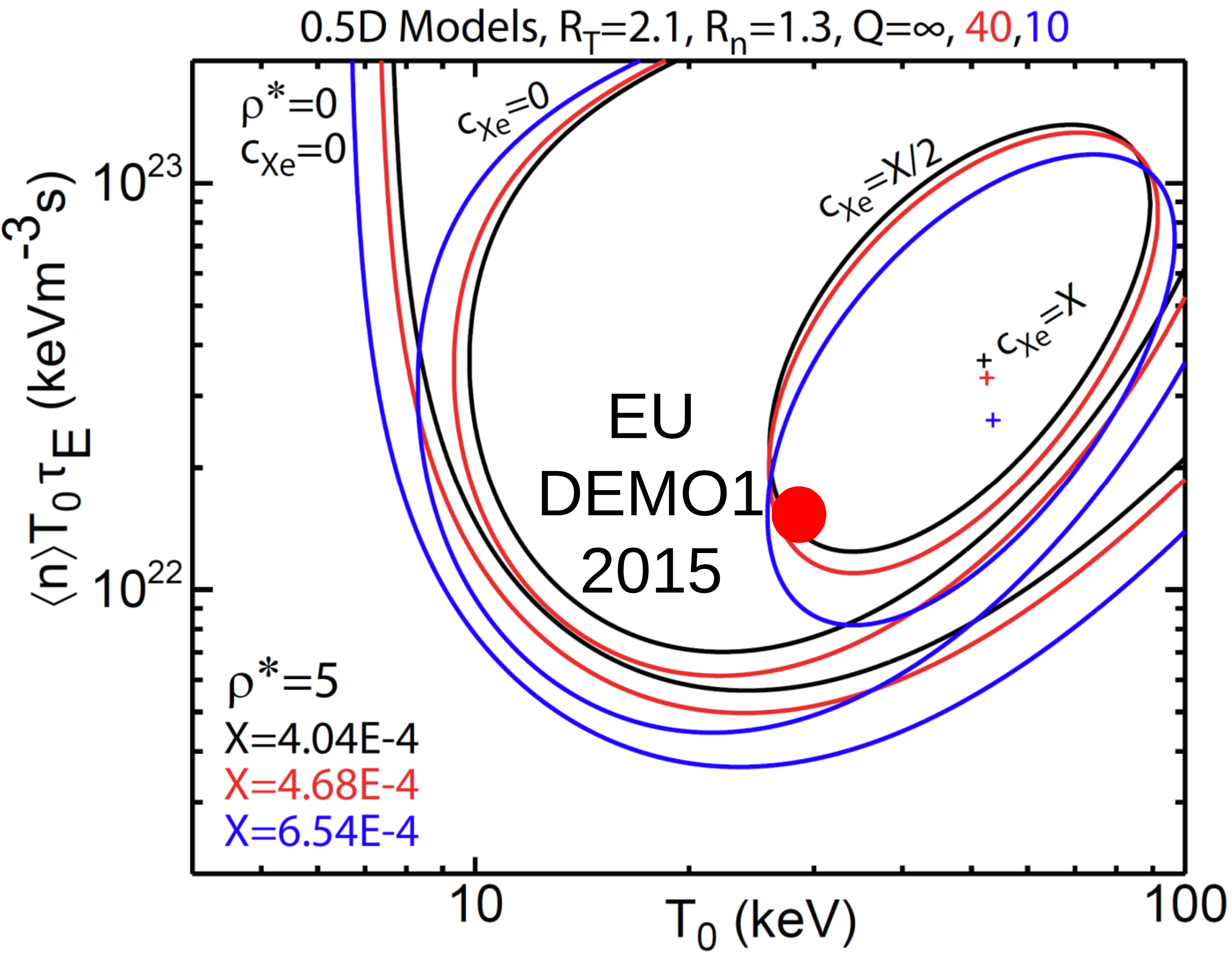

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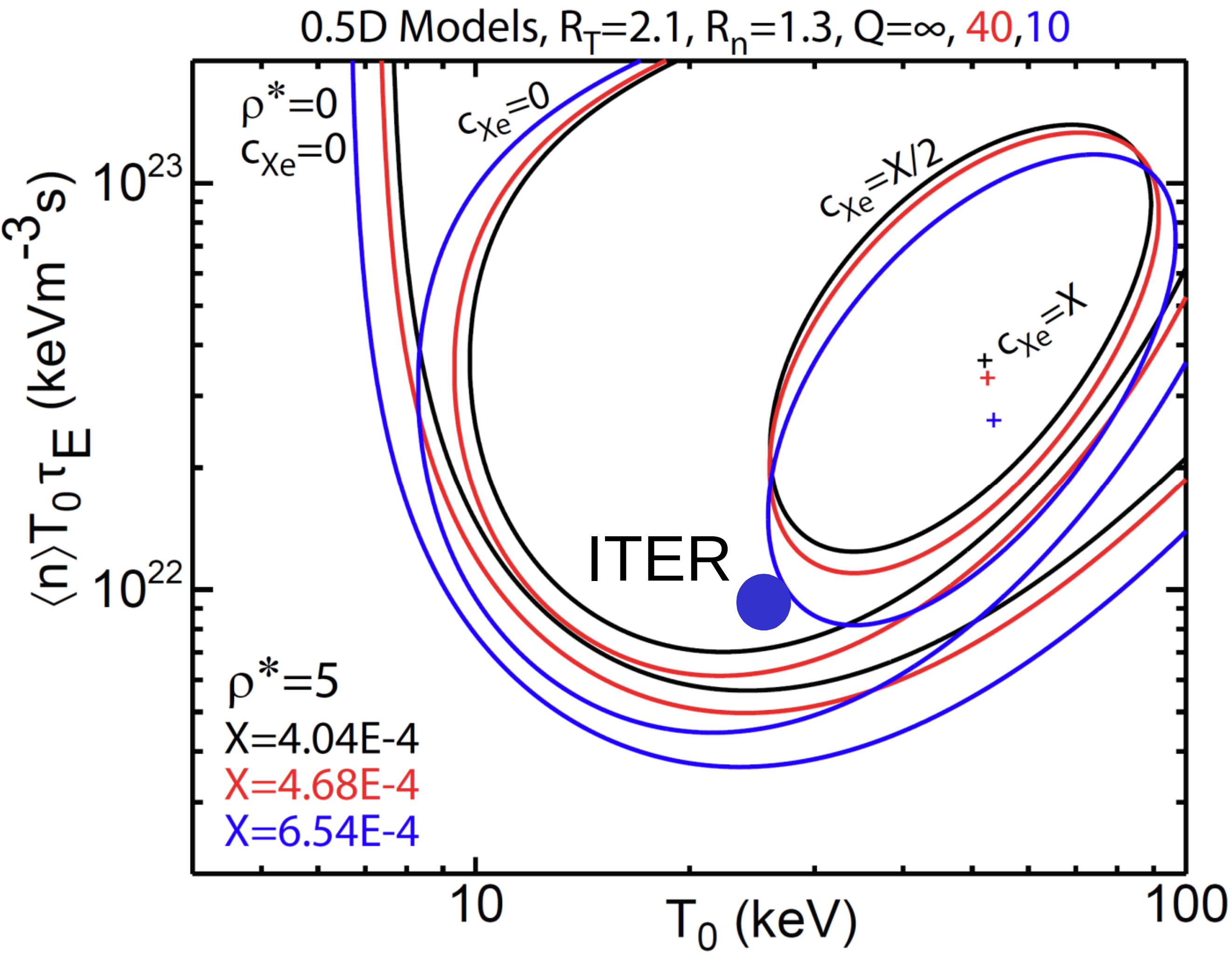

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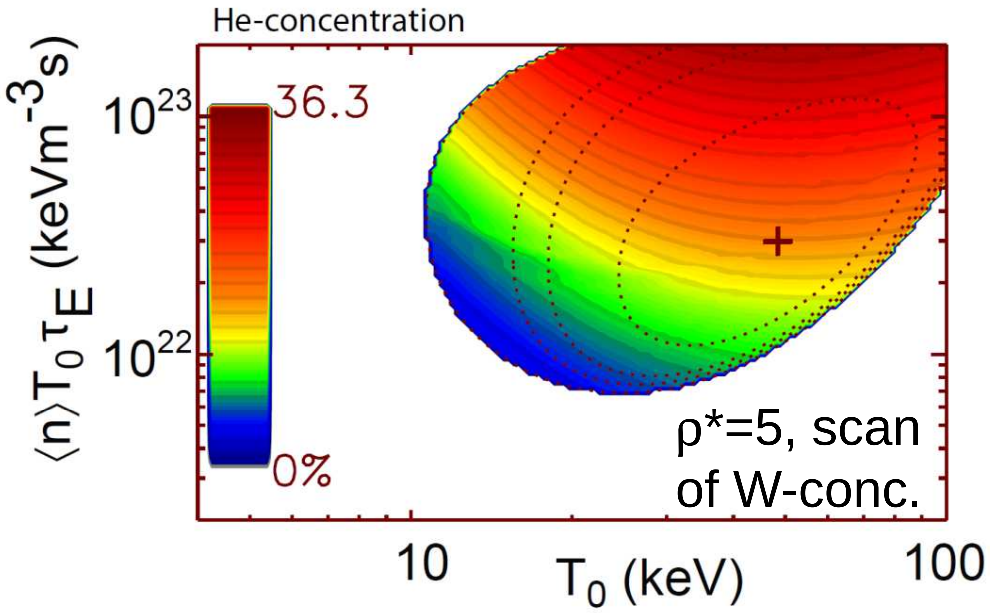
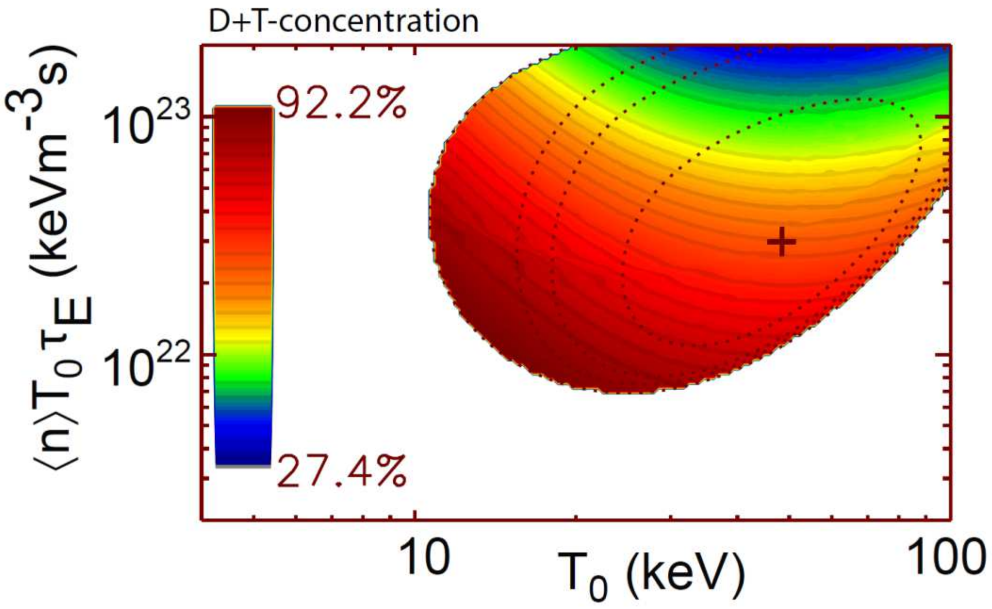
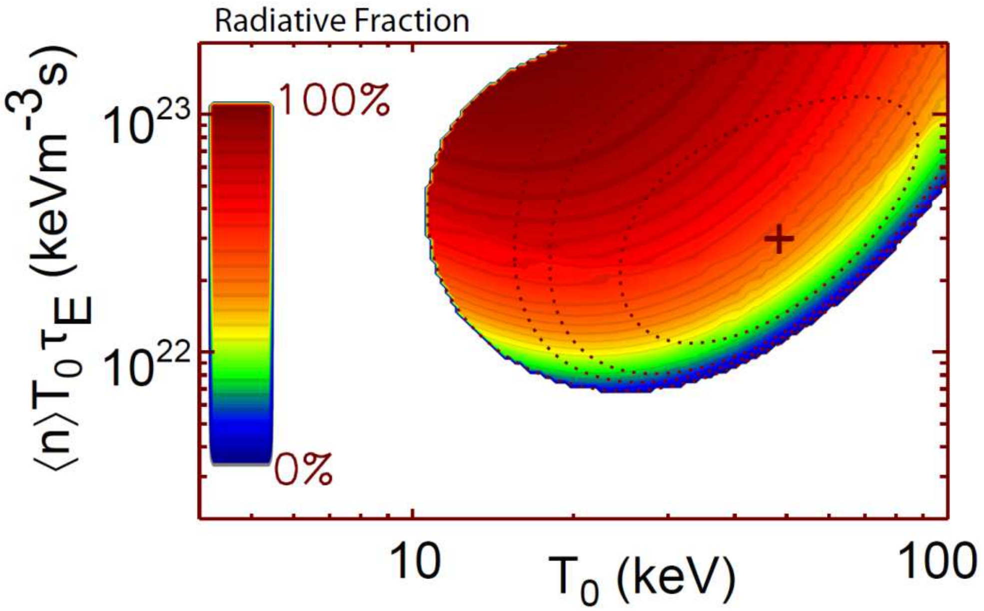
Realistic Boundary Conditions also Define Reactor Design: Dilution, Radiative Fraction





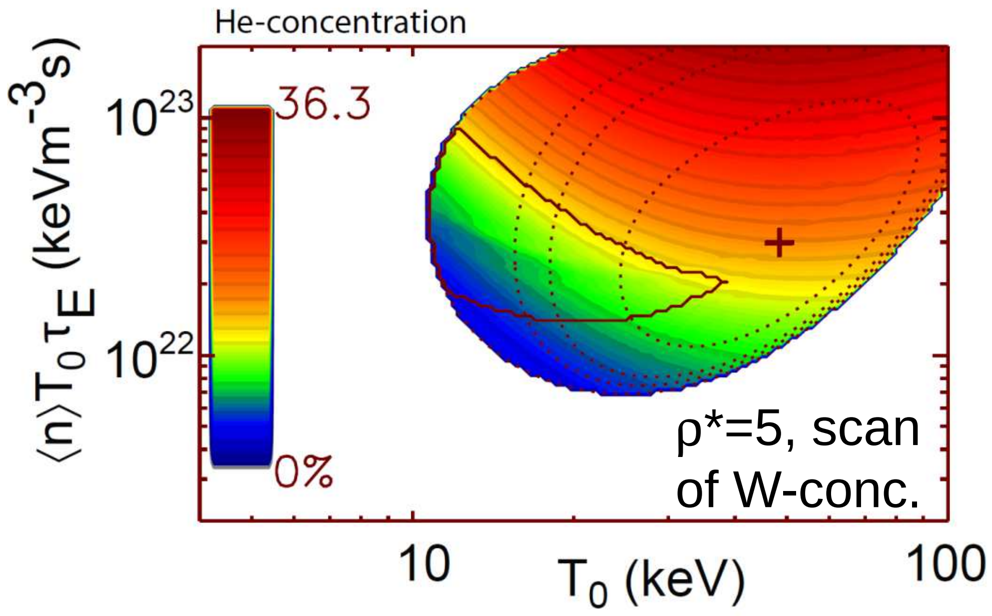


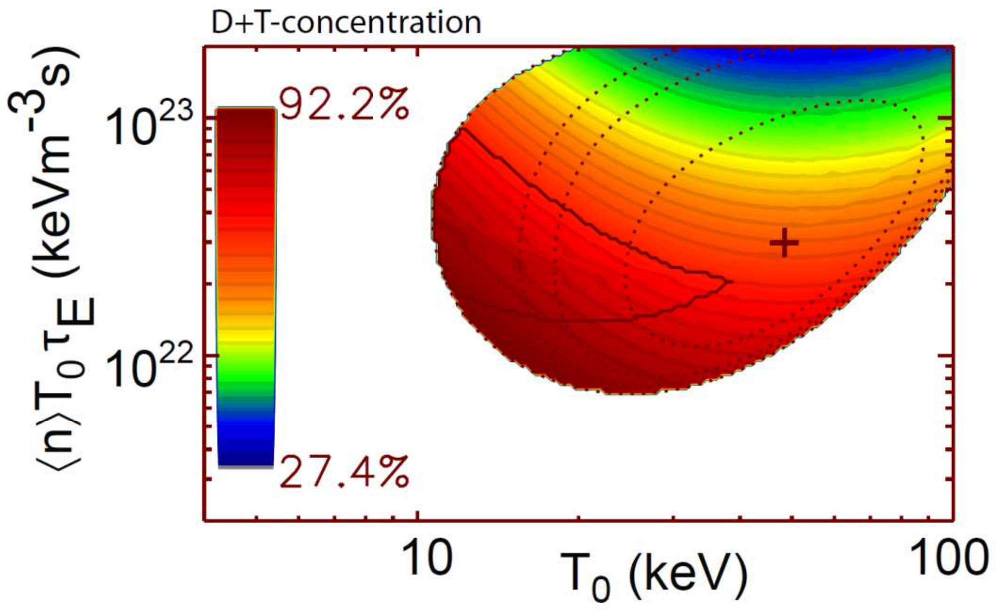
- Strong Dilution of fuel makes a fusion power plant inefficent

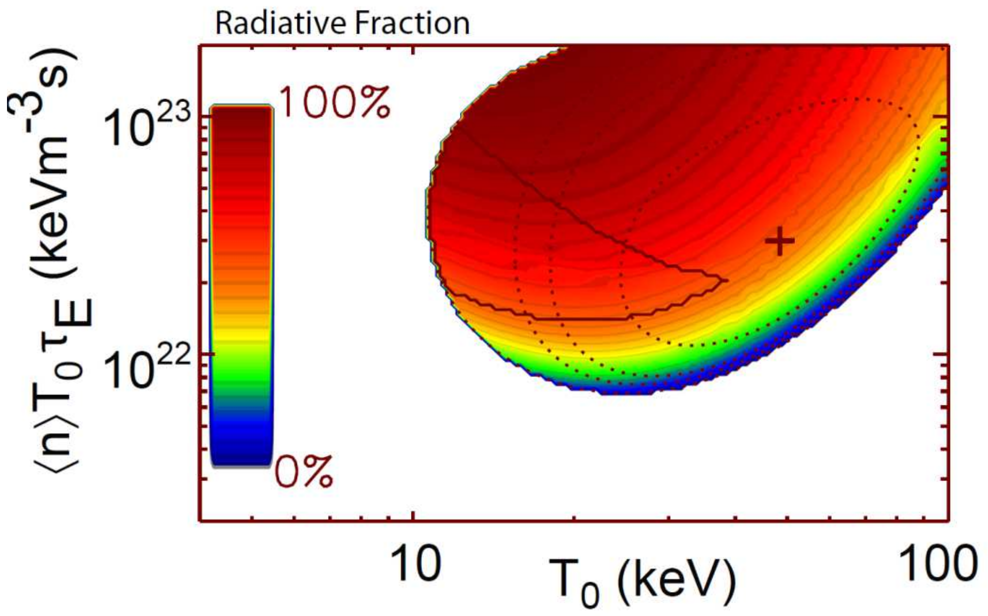
- Radiative Fraction must be considerble to provide power exhaust

(Q, sync. rad. and profile peaking match EU DEMO1 2015)

Realistic Boundary Conditions also Define Reactor Design: Dilution, Radiative Fraction


He-concentration


D+T-concentration


Radiative Fraction

- Strong Dilution of fuel makes a fusion power plant inefficent

  => assume >71% D+T

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=> assume >50% radiative fraction

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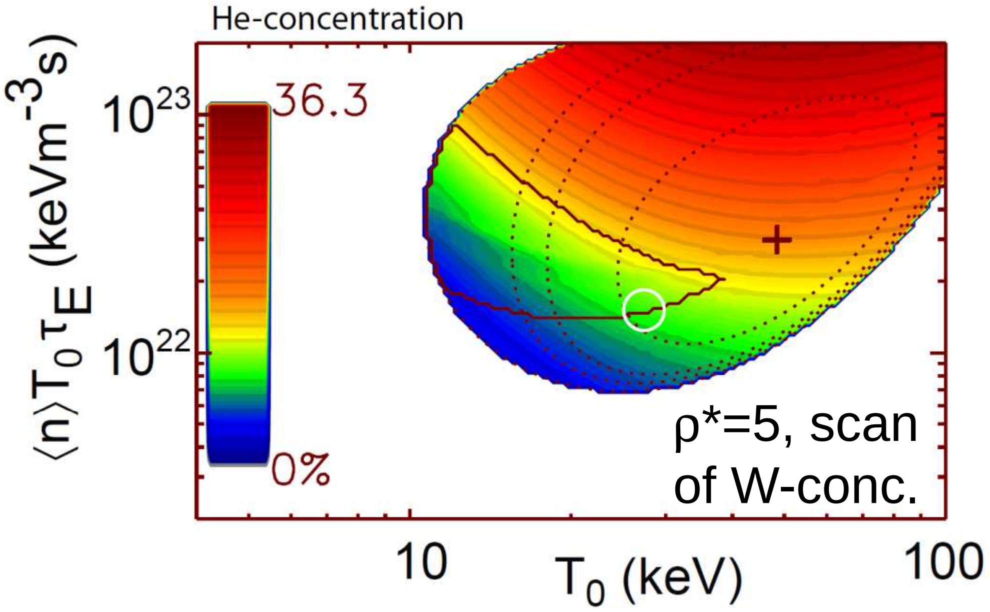
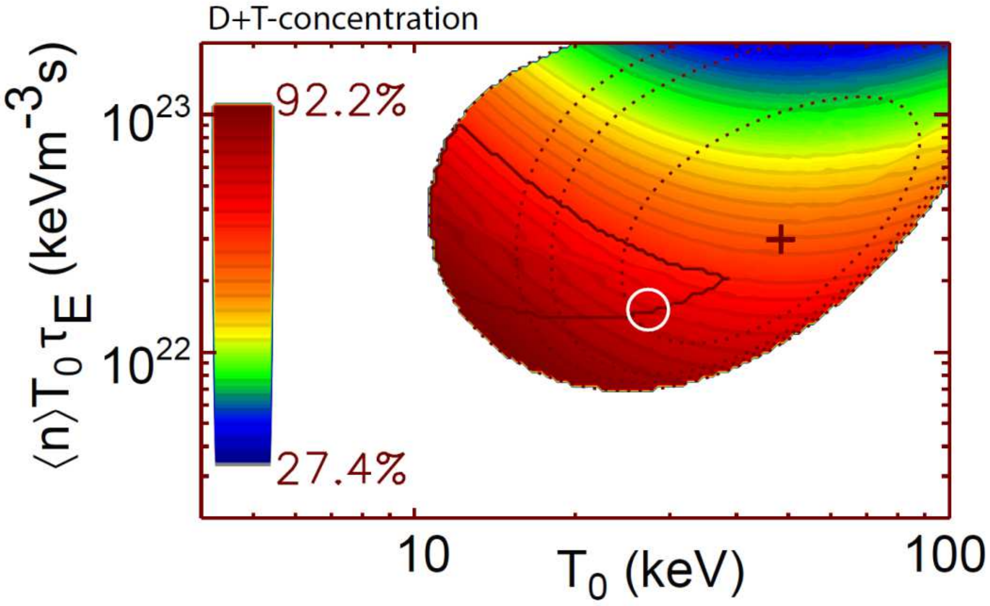

He-concentration

ρ*=5, scan of W-conc.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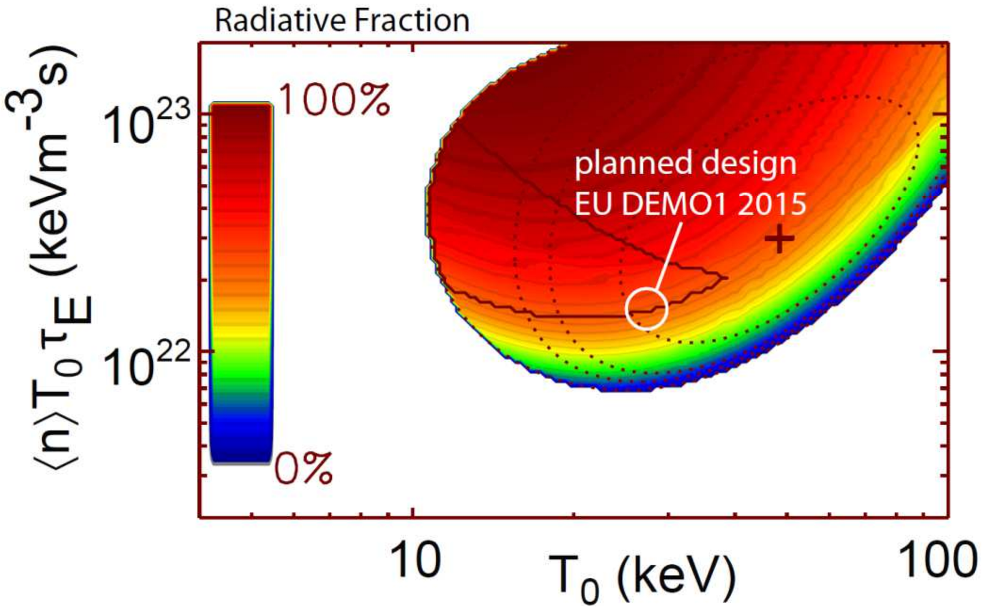
Radiative Fraction

planned design EU DEMO1 2015

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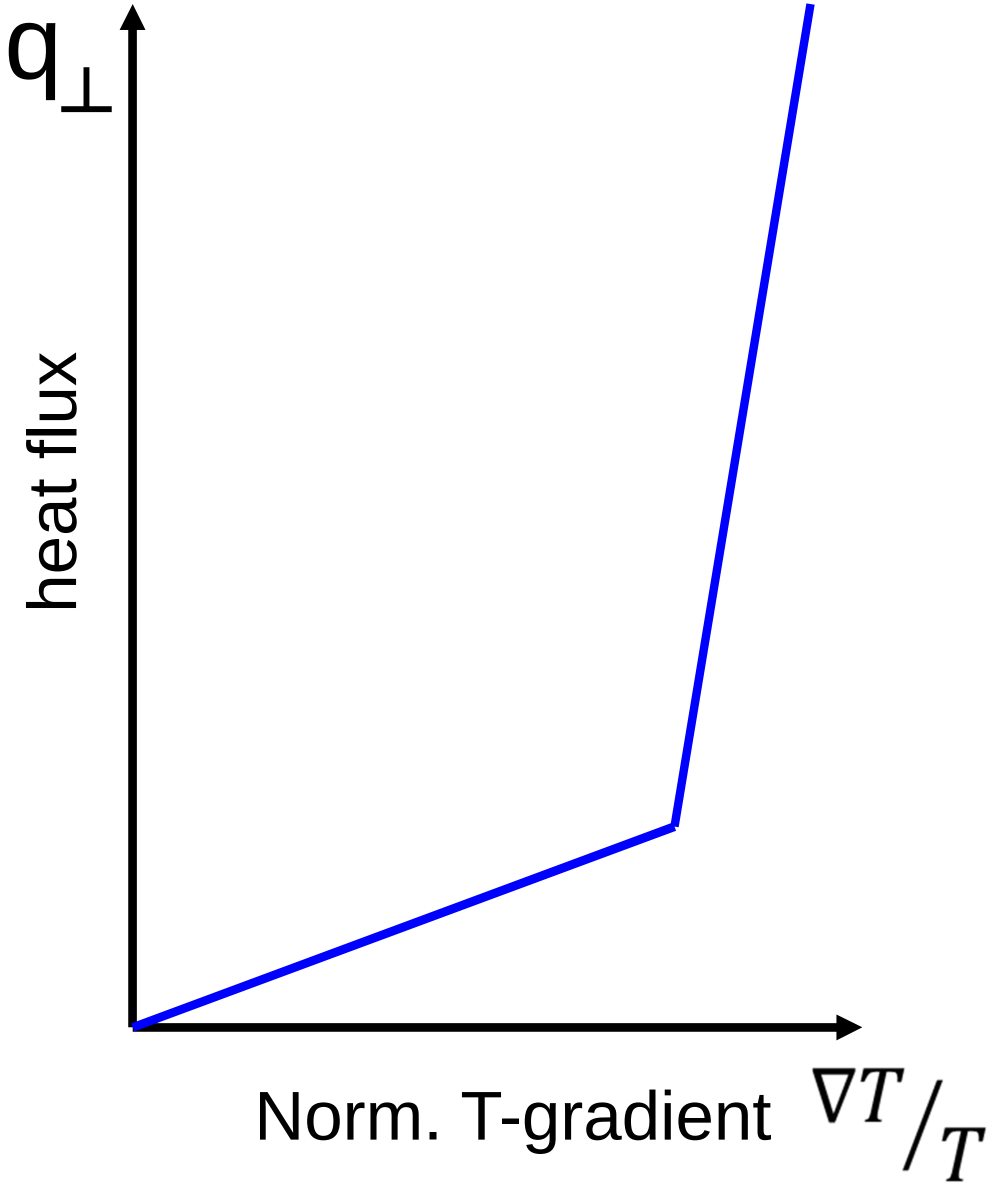
  - ⇨ 1D ASTRA model (fusion+radiation profile, transport, $Q < \infty$)
- What Physics Issues Need to be Addressed?

Why does radiation in a reactor not degrade confinement?



- Wall protection necessary
- ~500MW of alpha power
- Threshold in Turbulence Activity
  - ⇨ Stiff gradients for power fluxes above threshold
  - ⇨ Power flux may be reduced down to threshold, wo. confinement degradation

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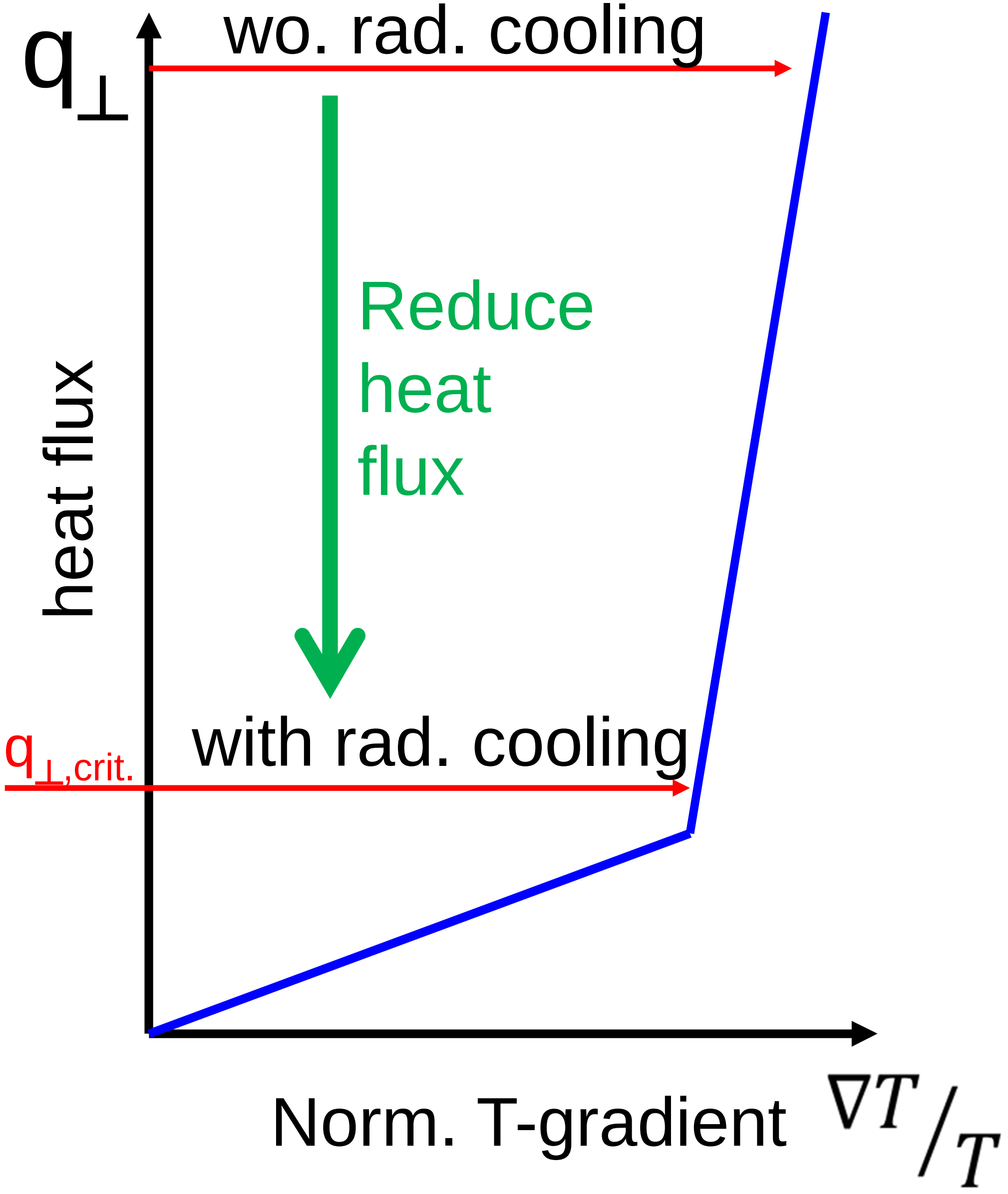

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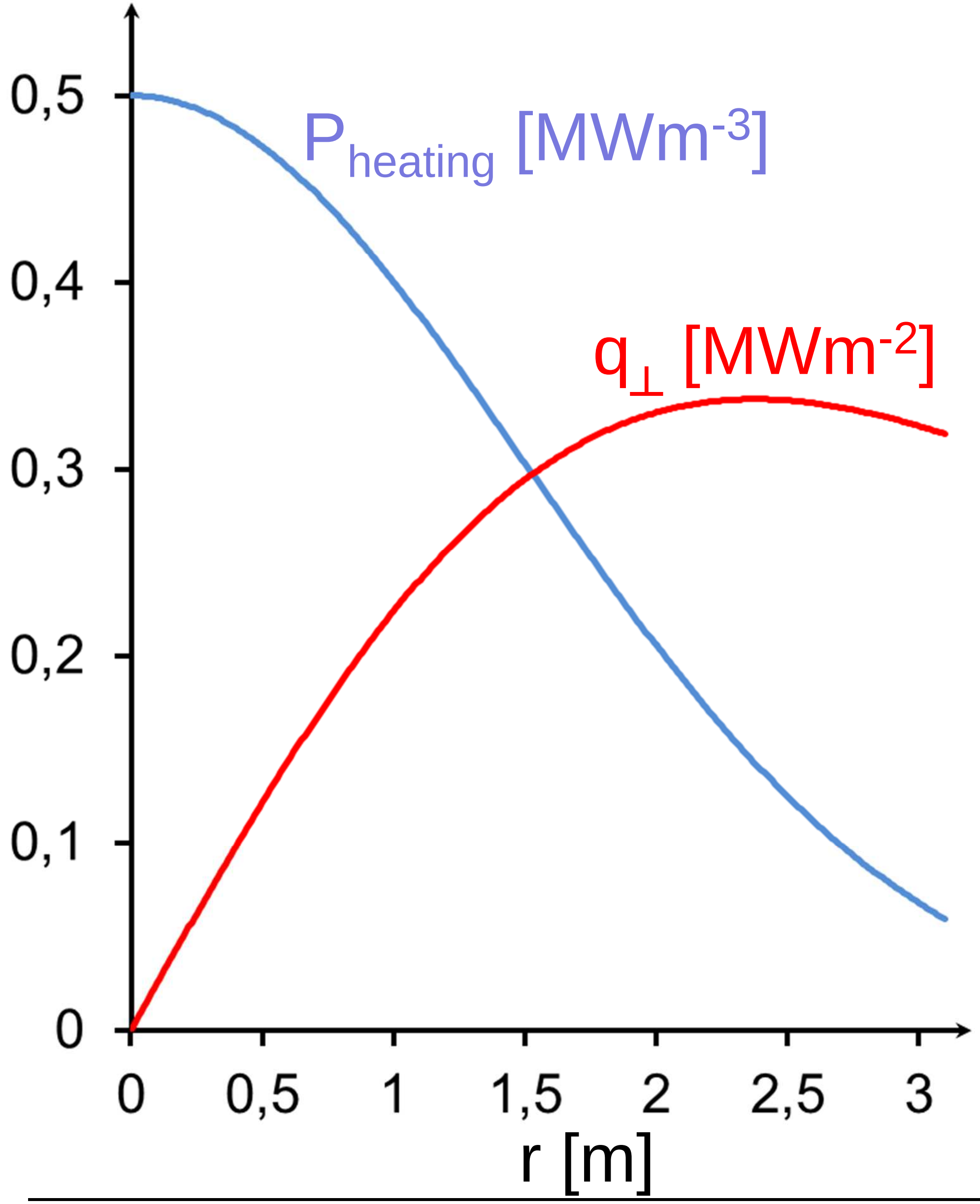
Reactor Core is more Vulnerable to Radiation



- Power flux at mid radius larger than in center
  - ⇨ Volume vs. Surface for flux surface

$$V_{circ.} = 2\pi^2 R r^2$$

$$S_{circ.} = 4\pi^2 R r$$

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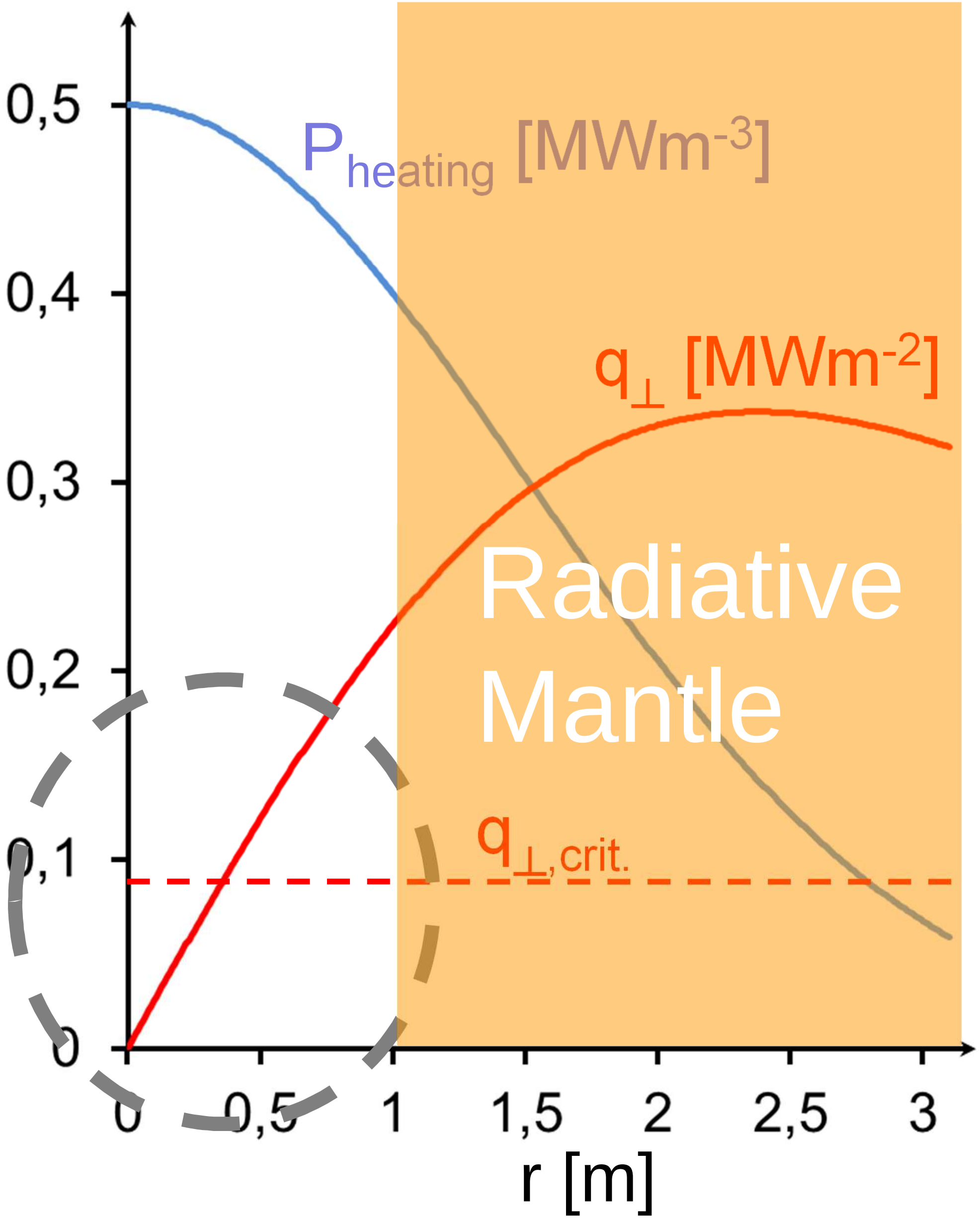

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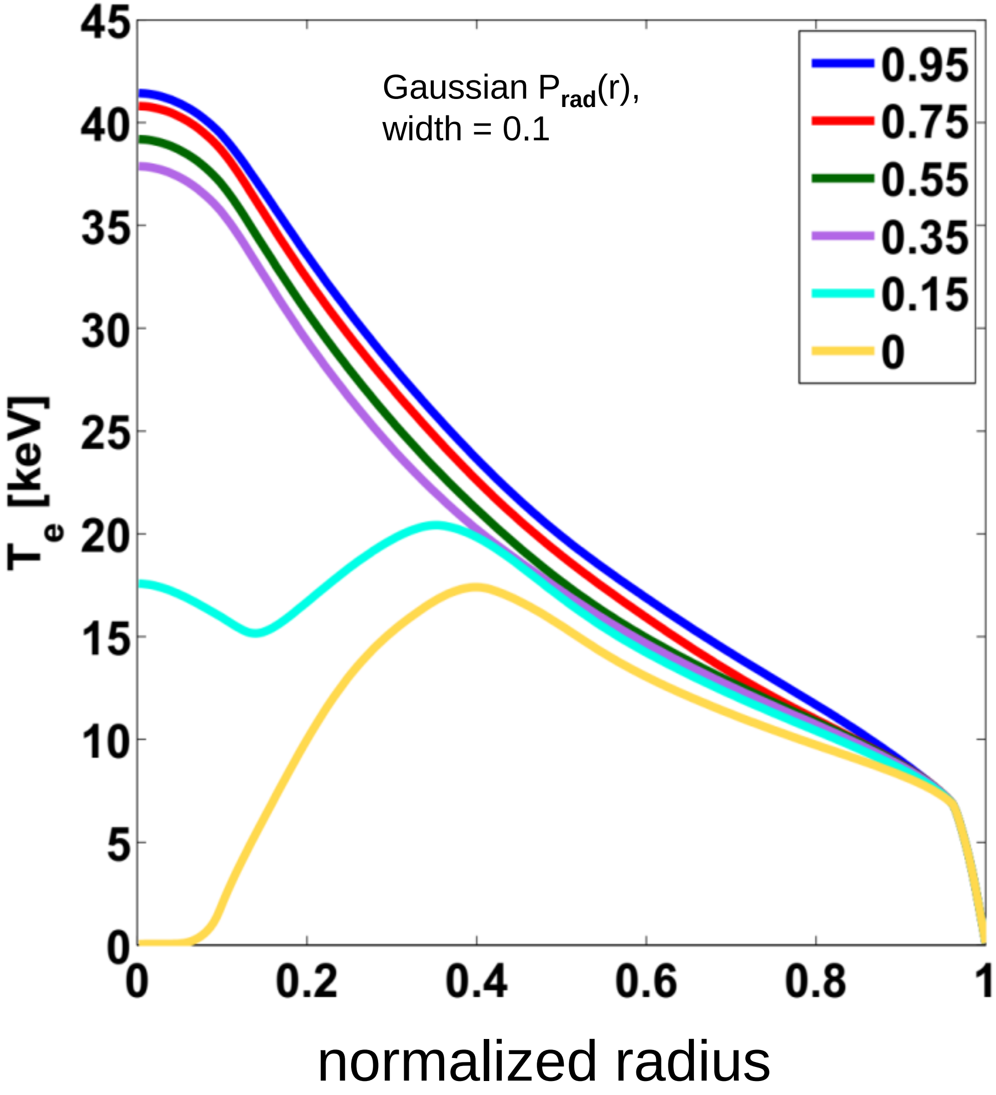
- Seeded Impurities should radiate at the plasma edge

Core Radiation May Damage Temperature Profiles

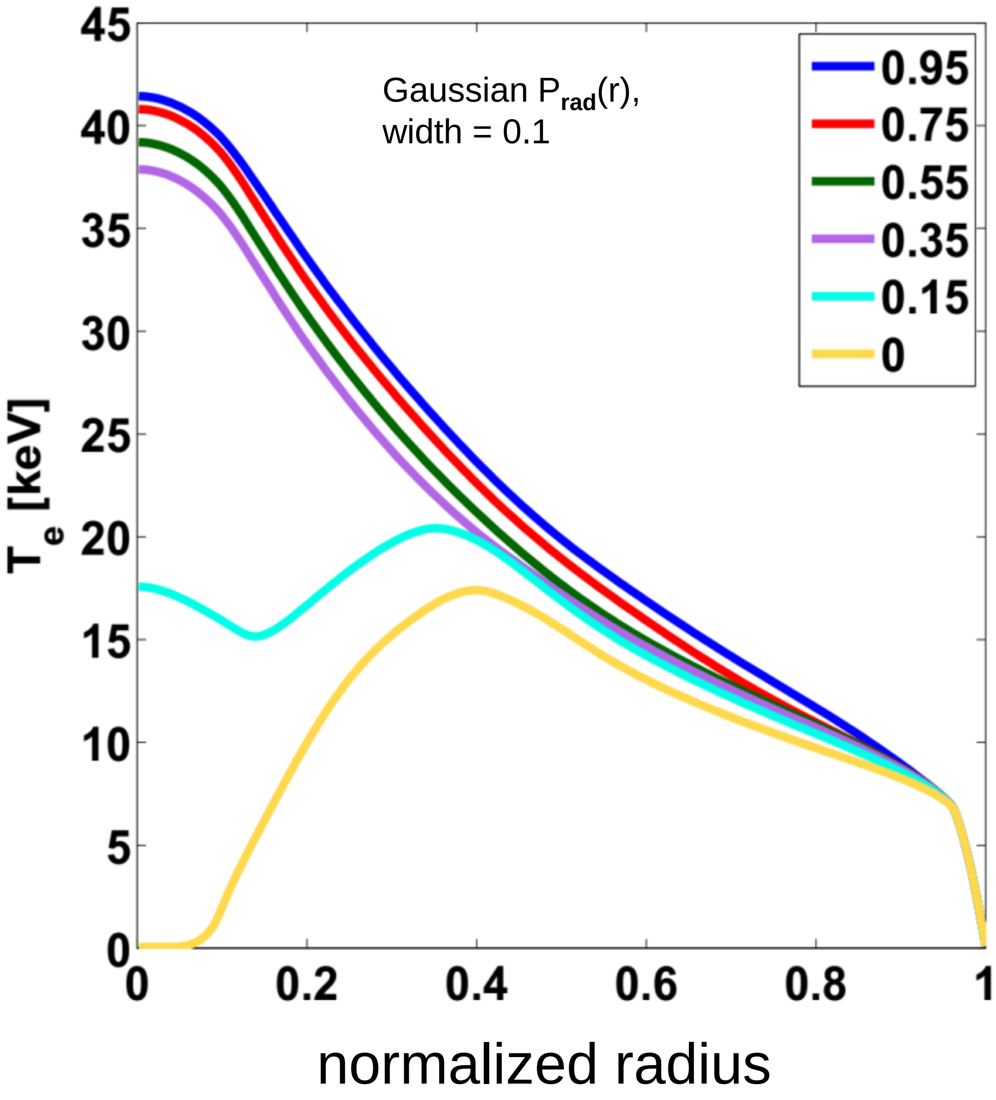


E. Fable NF 2017

- ASTRA simulations of a DEMO-like reactor
- T-profiles calculated using TGLF

  (Staebler PoP 2007)
- Localized radiative cooling
  - ⇨ Core cooling damages T-profiles
  - ⇨ Edge cooling with small impact

Core Radiation May Damage Temperature Profiles



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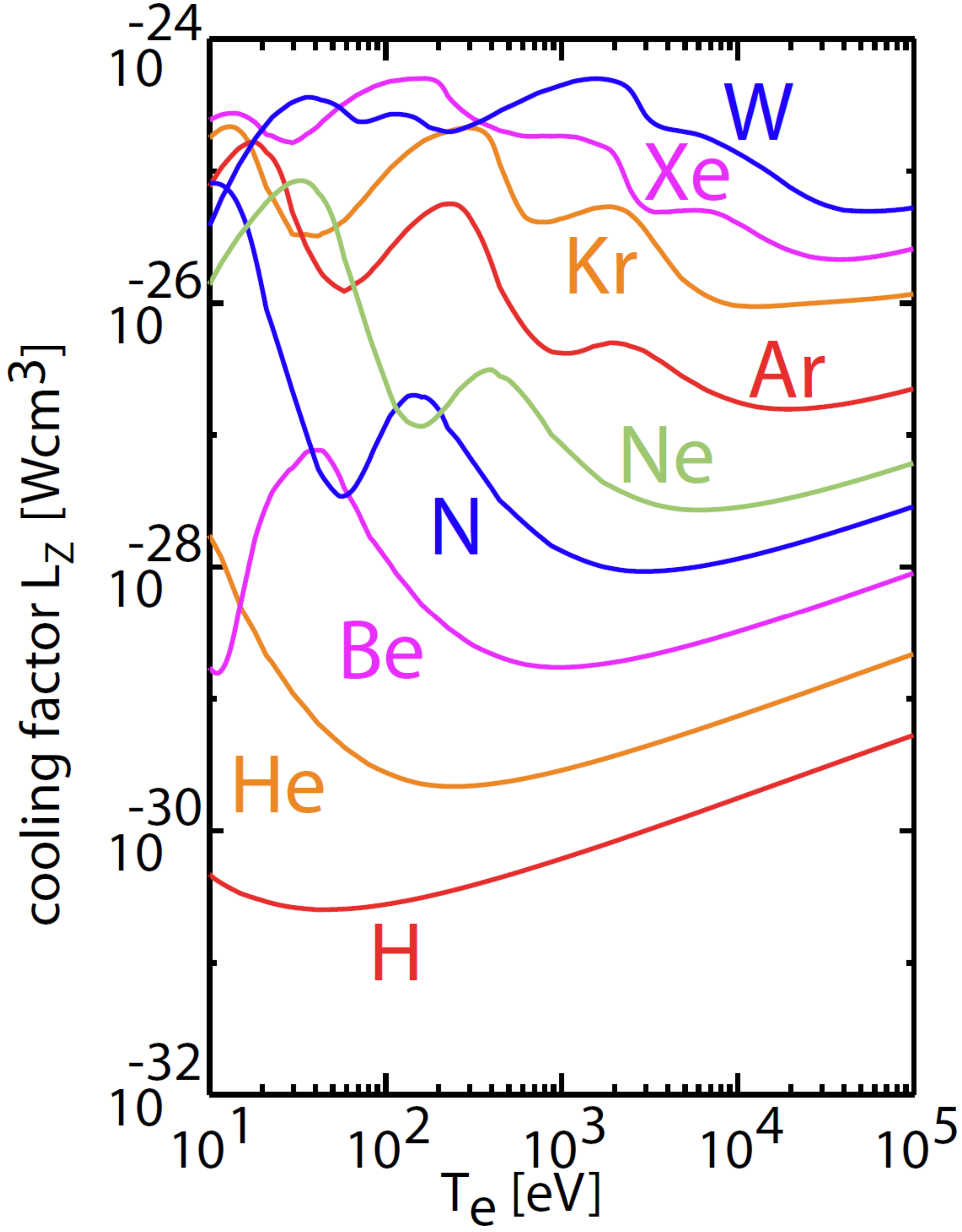
Are Xe, Kr and Ar better ‚Mantle Radiators‘ than W?



Pütterich, EPS 2015 / paper in preparation

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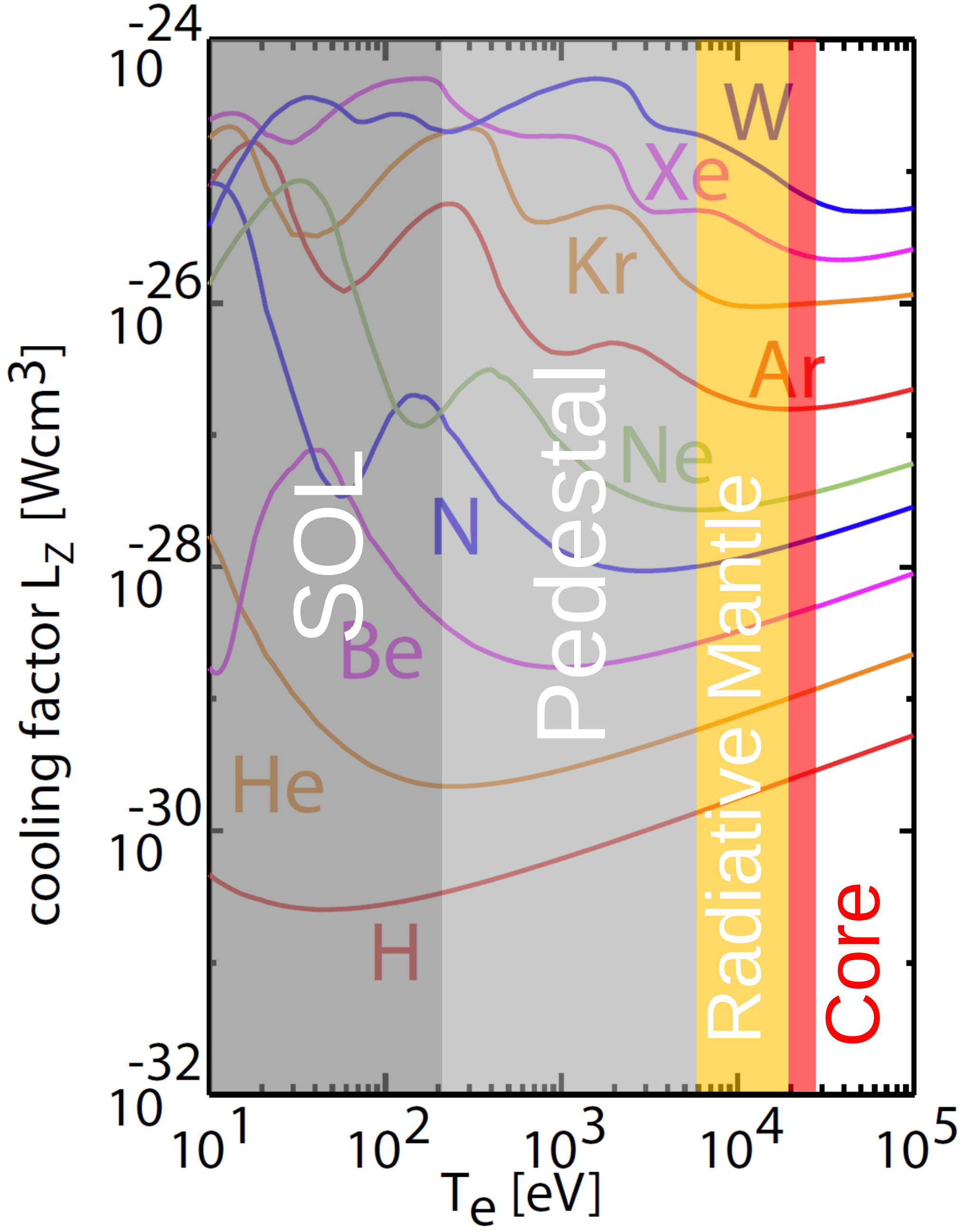


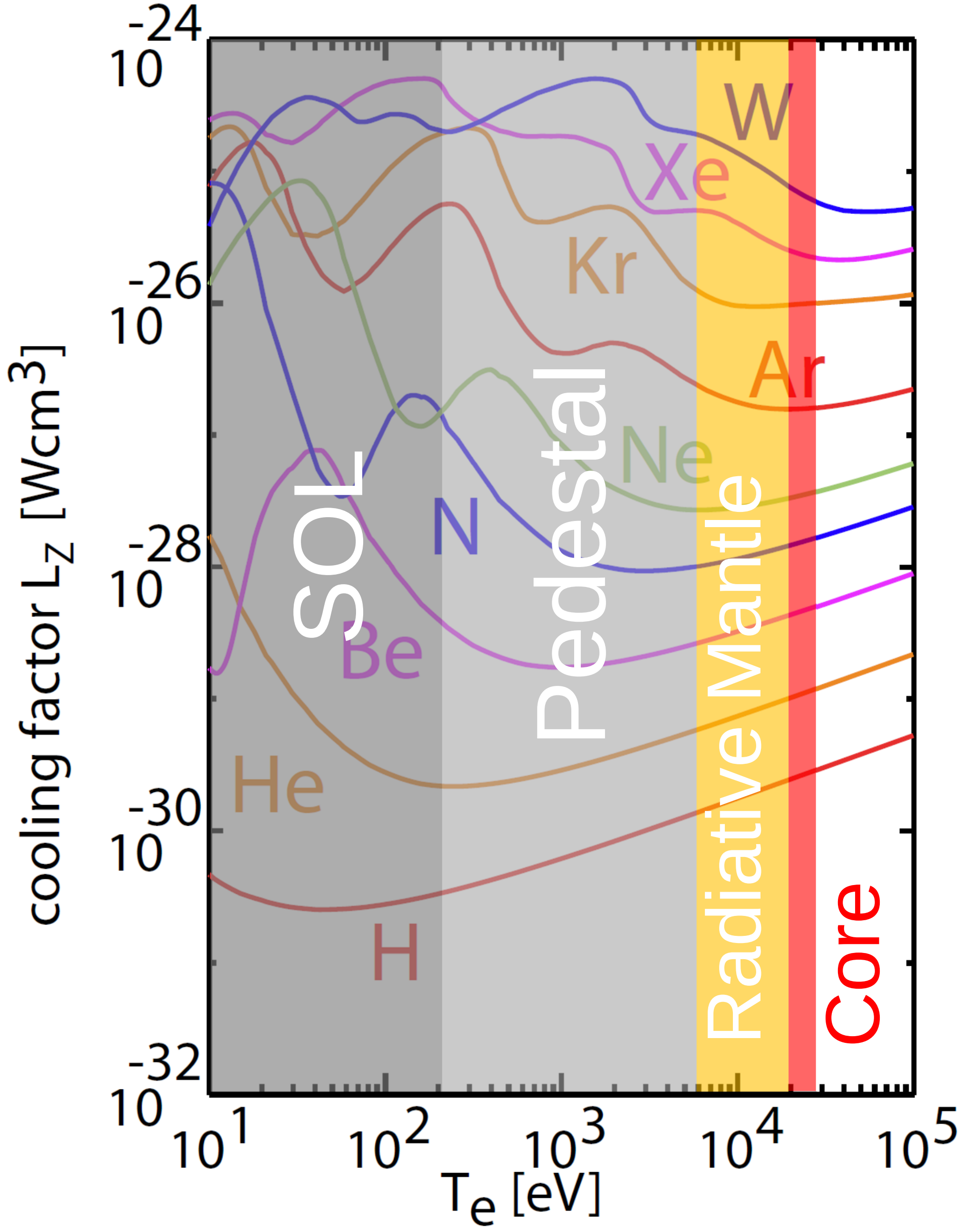
- In Reactor, the radiative mantle is between ~5keV and ~20keV

- What is the best radiator at the mantle for a certain ‚damage‘ in the plasma core?
  - ⇨Ratio of core vs mantle radiation
  - ⇨W is slightly better than Xe, Kr and Ar!
  - ⇨Differences between radiators

  less than factor 2 (~uncertainties)

Are Xe, Kr and Ar better ‚Mantle Radiators‘ than W?

No



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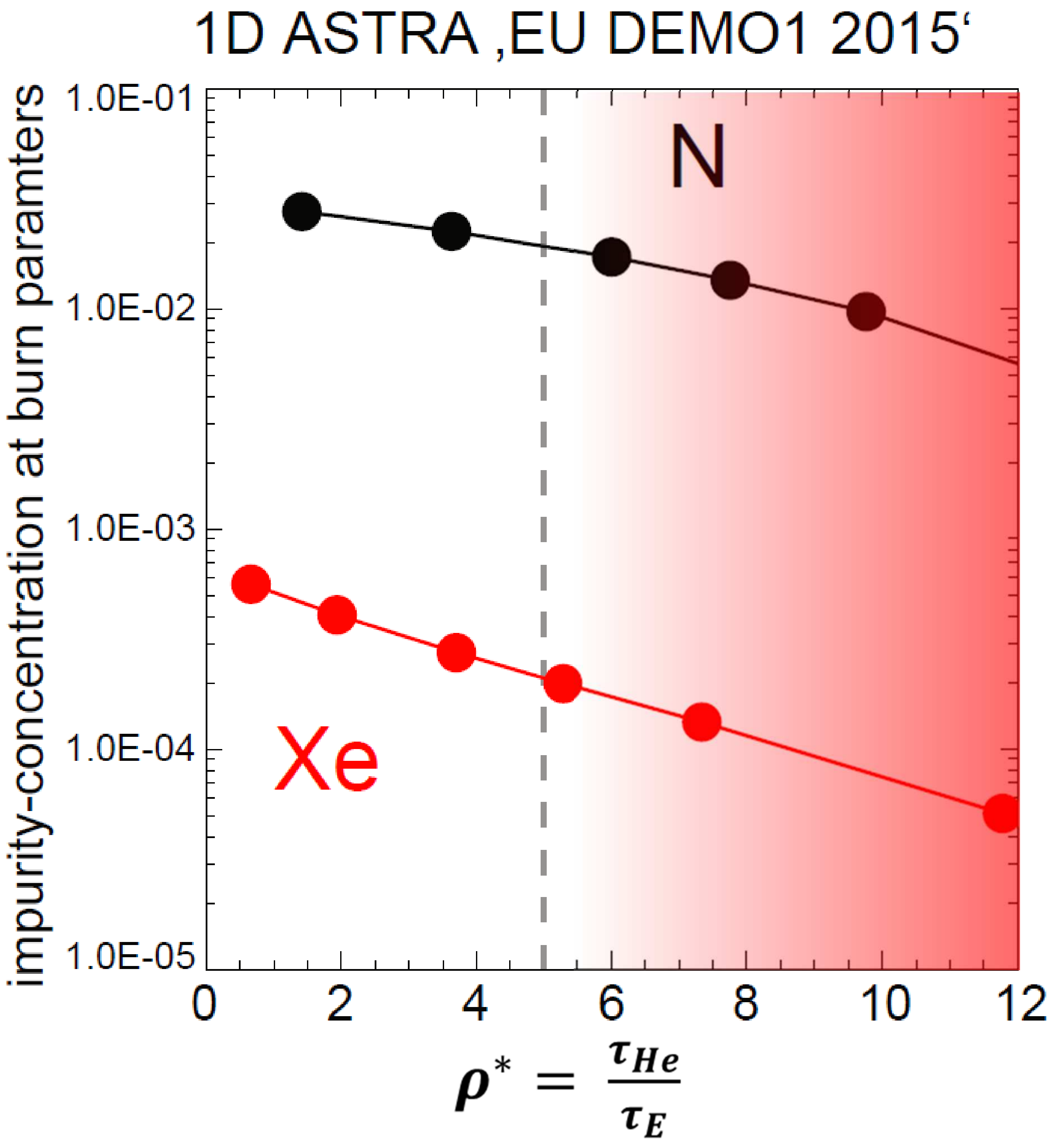
  - ⇨Differences between radiators less than factor 2 (~uncertainties)
- Note: core impurity transport is easily as important

EU-DEMO1 design 2015 modelled with ASTRA

	EU DEMO1 2015
$R[m]$	9.1
A	3.1
B_T [T]	5.7
I_P [MA]	20
H (rad. cor.)	1.1
$\beta_{N,tot}[\%]$	2.6
$f_{bs}[\%]$	35
$P_{sep}/R[MW/m]$	17
$\tau_{burn}[h]$	2
P_{fusion} *[MW]*	*2037*
Q	*40*

- Full 1D ASTRA model (Wenninger NF 2014)
- EU DEMO 2015 design (Wenninger NF 2017)
- Profiles of 50MW auxiliary heating and radiation
- P_{fusion} calculated => fusion yield $Q = \frac{P_{fusion}}{P_{aux.heating}}$
- Impurity seeding to obtain $P_{separatrix} = 160MW$
- Heat & particle transport may be modelled, here: fixed density profiles, ad-hoc heat transport

1D ASTRA: Operational Space Larger at Cost of Q



- Find Condition:

Reduce power flux to $1.2 {*} P_{LH}$ at pedestal-top

- Steady-State operation possible for large

$$\rho^* = \frac{\tau_{He}}{\tau_E}$$

- But: Sacrifices in Q
  - ⇨Efficiency of power plant
  - ⇨Cost of electricity

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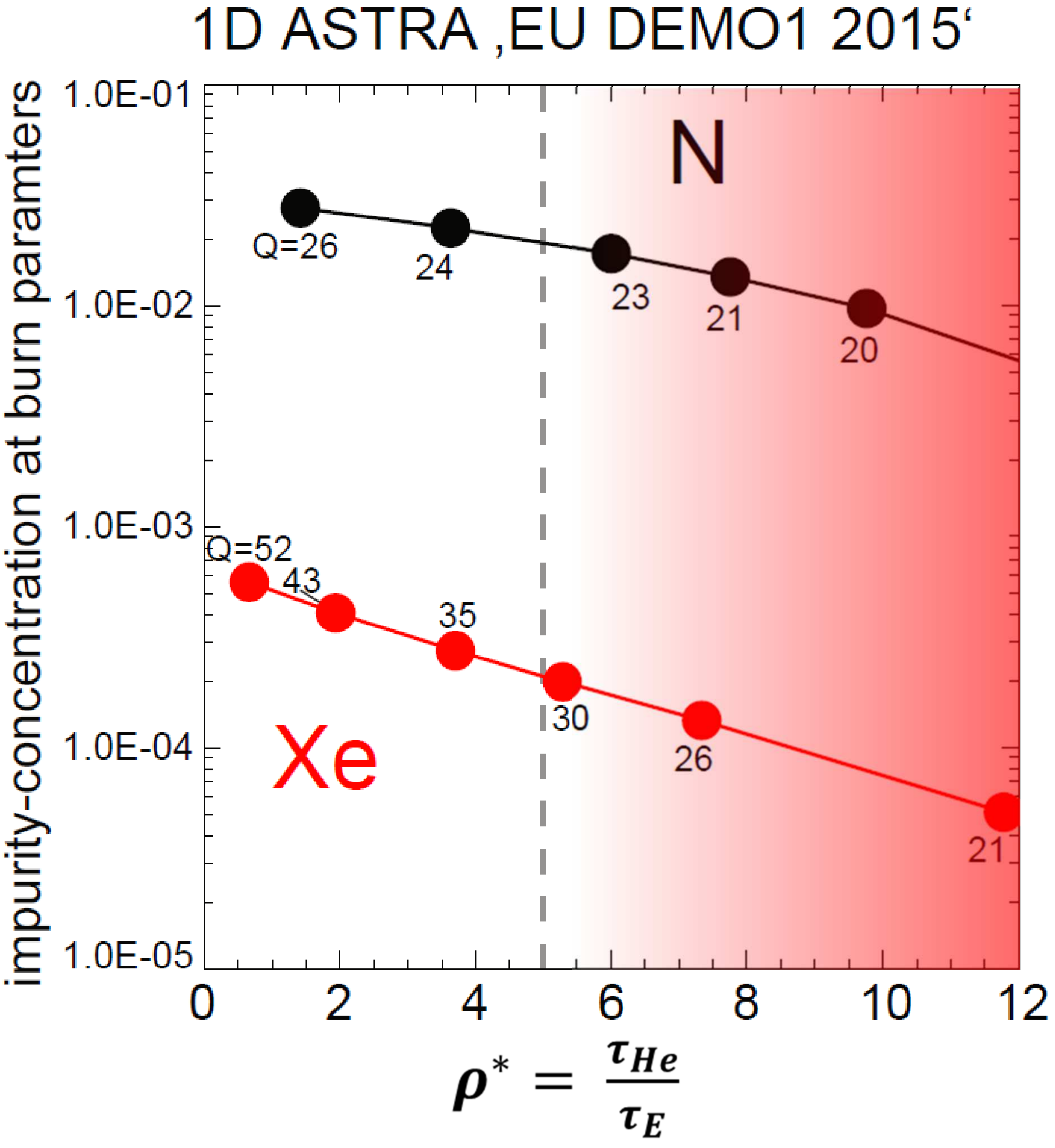

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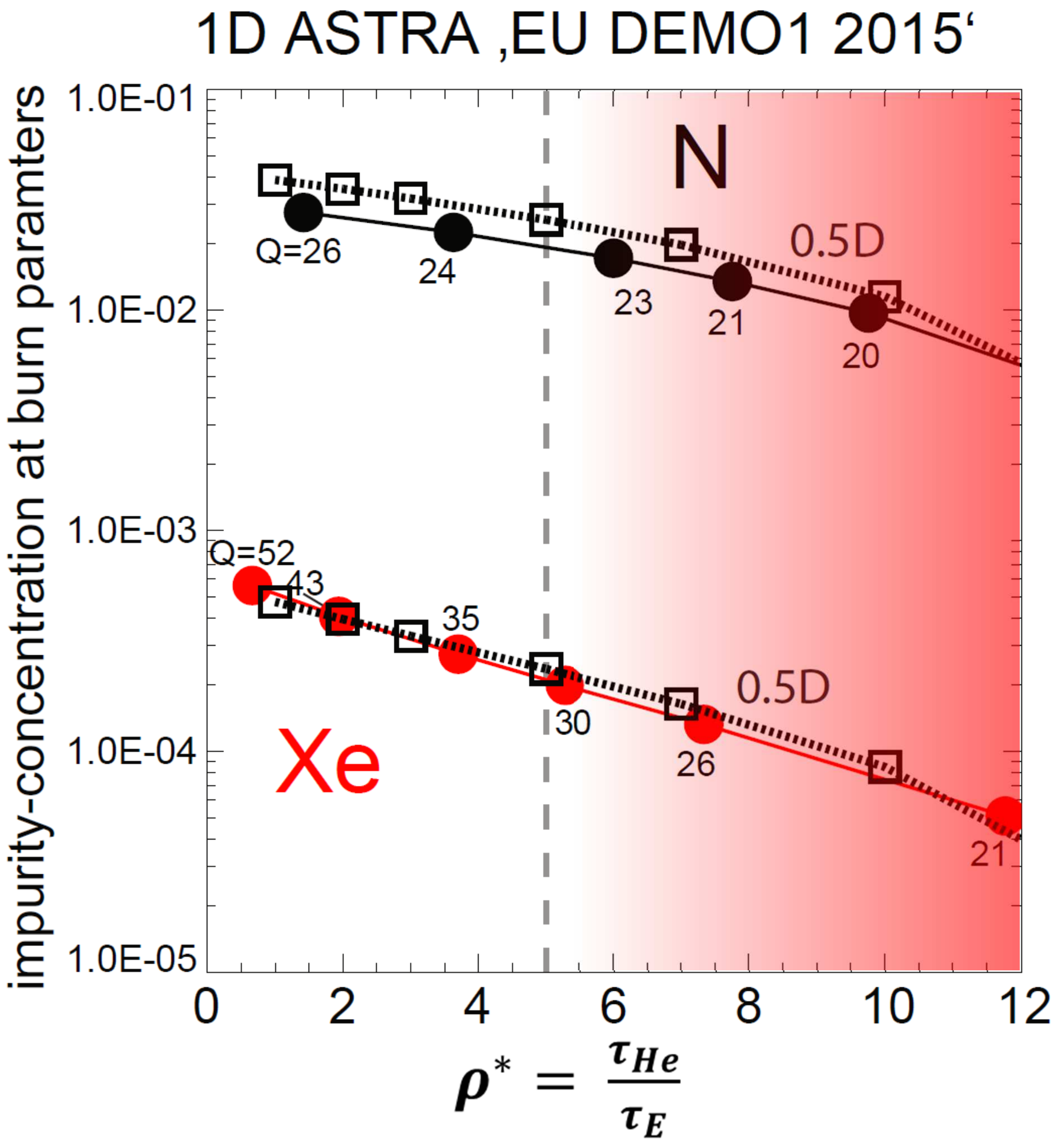

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  - ⇨Efficiency of power plant
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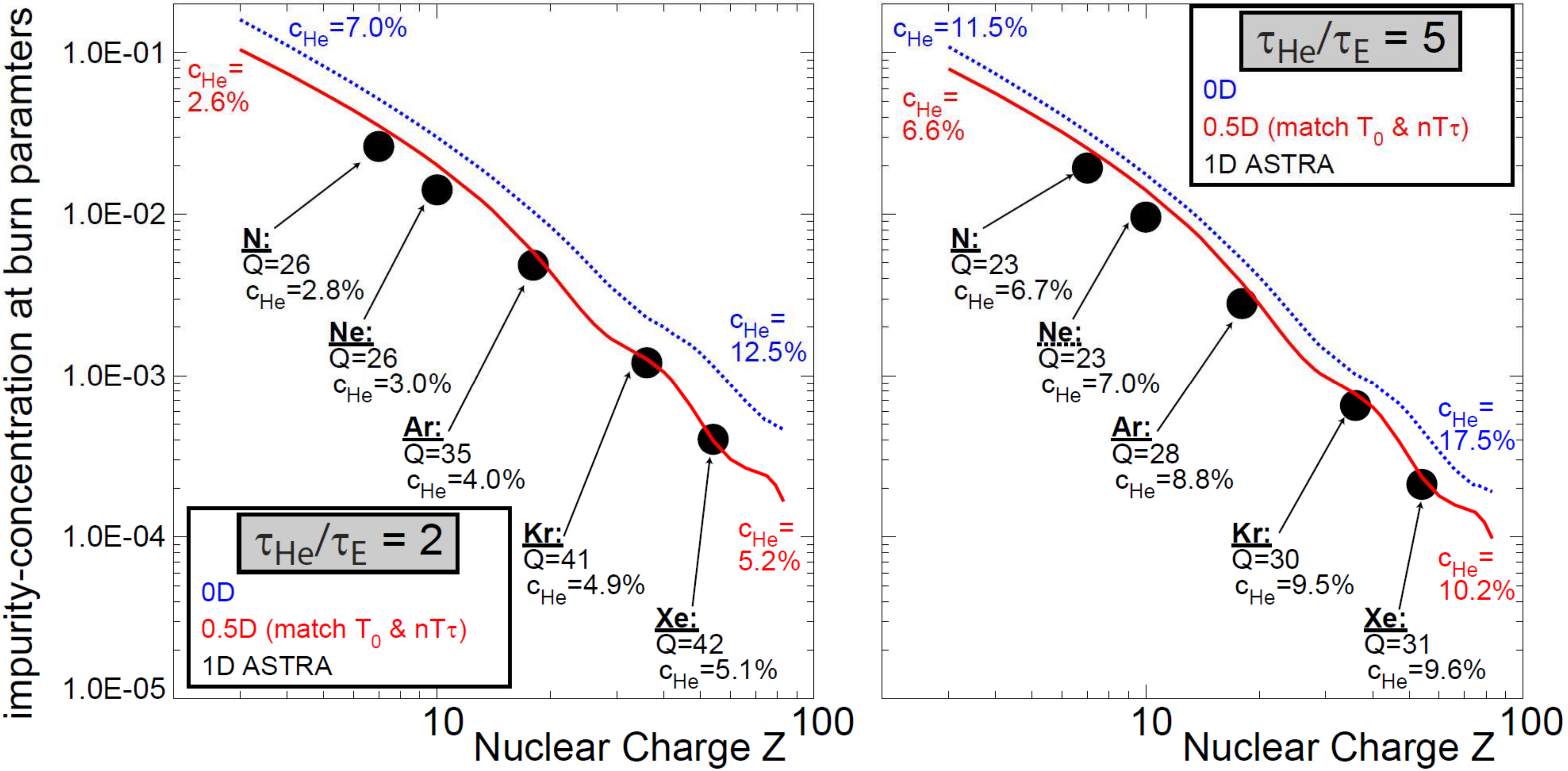
⇨Small difference to 0.5D!

0.5D and 1D ASTRA Give Similar Answers



Pütterich, EPS 2015 - now improved model

What Physics Issues Need to be Addressed?

- Core radiation from Xe, Kr and Ar is as good/bad as from W
  - ⇨ Impurity profiles should be preferably hollow (high-Z)

- How do the plasma profiles look in a reactor?
  - ⇨ Realistic plasma transport

- Combine reactor performance (Q) with radiative cooling
  - ⇨ Impurity profiles should be preferably hollow (low-Z)

  - ⇨ Avoid divertor radiator in main plasma
    - ⇨ divertor compression of N, Ne, Ar…
    - ⇨ High-Z radiation (if tolerable) is preferable to low-Z dilution

  - ⇨ Pump He well (divertor compression of He)

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- Core radiation from Xe, Kr and Ar is as good/bad as from W
  - ⇨ Impurity profiles should be preferably hollow (high-Z)

    true if turbulent transport dominant (Angioni NF 2017)

- How do the plasma profiles look in a reactor?
  - ⇨ Realistic plasma transport

(Impurity) Transport
Influenced also by Rotation

- Combine reactor performance (Q) with radiative cooling
  - ⇨ Impurity profiles should be preferably hollow (low-Z)

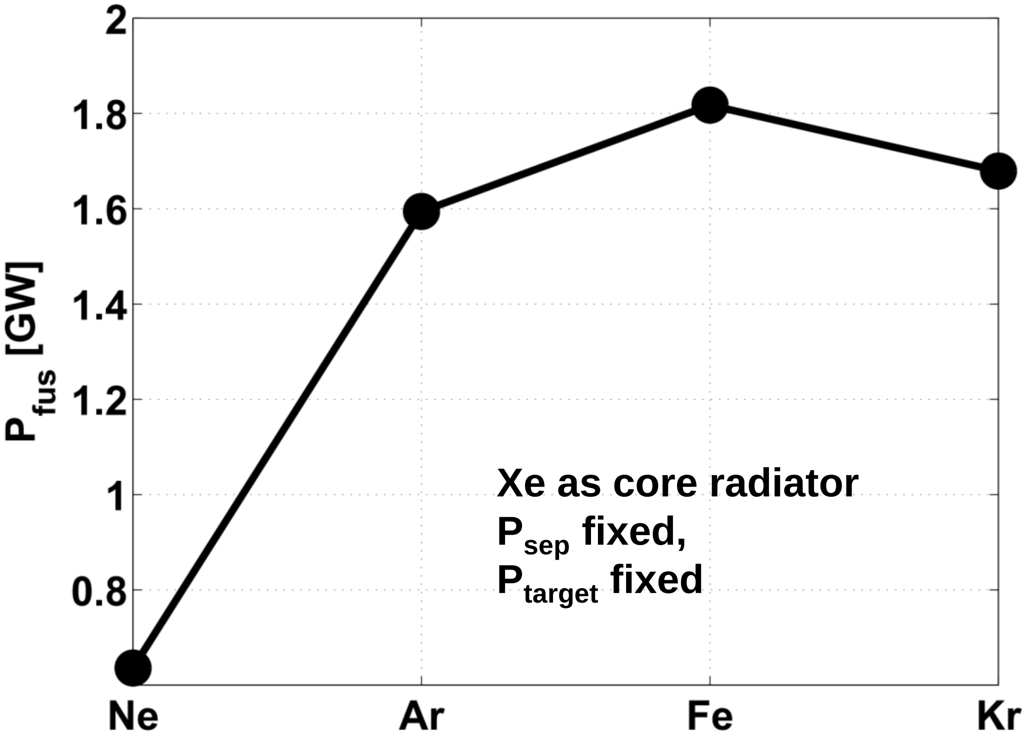
    true if turbulent transport dominant (Angioni NF 2017)

  - ⇨ Avoid divertor radiator in main plasma
    - ⇨ divertor compression of N, Ne, Ar…
    - ⇨ High-Z radiation (if tolerable) is preferable to low-Z dilution
  - ⇨ Pump He well (divertor compression of He)

Pedestal
SOL/Divertor Physics

Divertor Compression Crucial

ASTRA + SOL model



M. Siccinio, PPCF 2016

- If low-Z radiatiors leak into main plasma, fusion losses may be large
- Surprising solution may be mid-Z radiator for divertor radiation
- Too few divertor compression of He-ash is a danger independently of solution for radiative cooling

Core radiator (here Xe) may have to be complemented by edge radiator