Alpha channeling, edge turbulence, A&M reactions: a journey into the physics of the tokamak

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ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Frascati, 26th February 2024

Career:

- **2008:** PhD in Relativistic Astrophysics, University of Rome “Sapienza”
- **2008-2016:** some postdocs across Europe (Universities of Rome “Sapienza”, Erlangen-Nürnberg, Wrocław)
- **2017-2019:** postdoc at University of Rome “Tor Vergata”
- **2019-2021:** postdoc at PIIM laboratory, CNRS/Aix-Marseille University
- **2021-2023:** postdoc at Jülich Forschungszentrum
- **2023-?:** researcher at ENEA Frascati

Summary

- Alpha Channelling

  EUROfusion grant at University of Roma Tor Vergata 2017-2019

- Simulations of Edge Plasma Oscillations

  Postdoc at PIIM Laboratory (CNRS, AMU) 2019-2021

- Collisional Radiative Models in EIRENE simulations

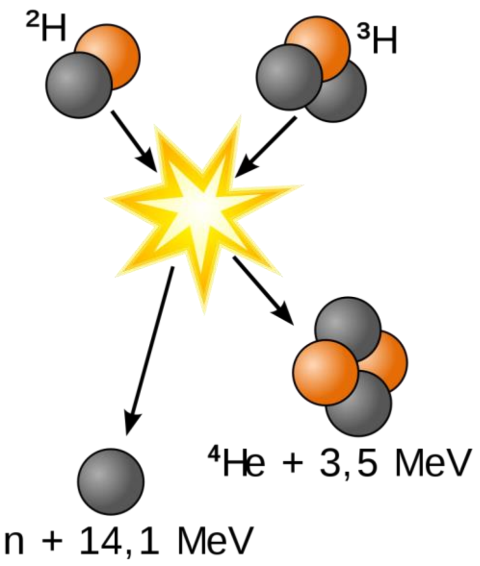
  Postdoc at Forschungszentrum Julich 2021-2023 (TSVV5)

- Turbulence simulations near the X-point

  ENEA (since June 2023)

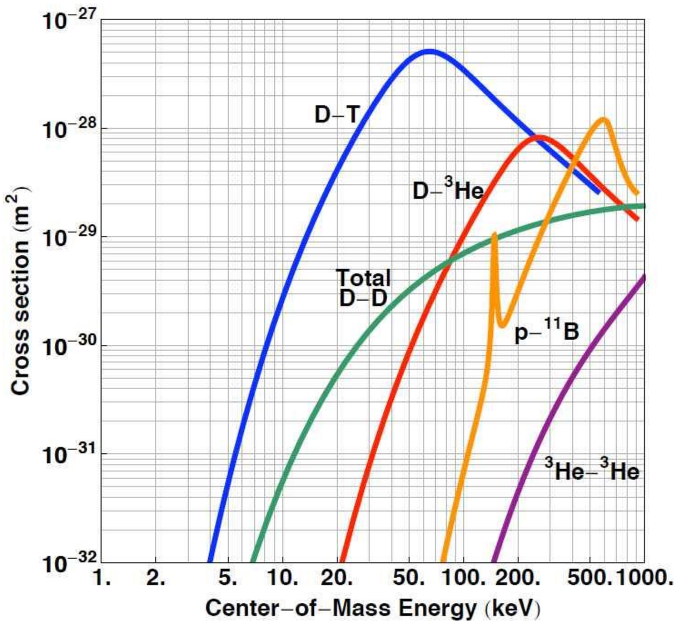
Alpha Channelling

Motivation: can we heat bulk ions directly through alpha particles?



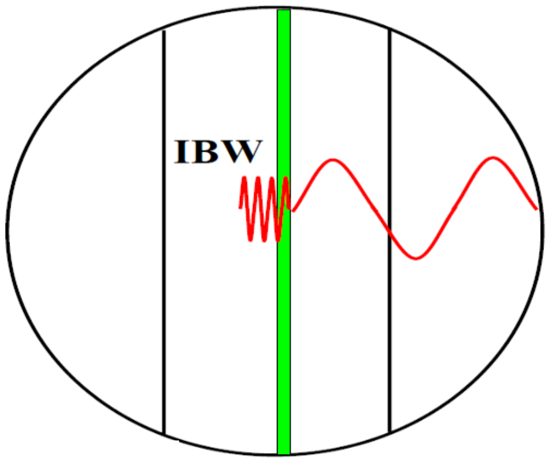
Fusion reactions:

$$D + T \rightarrow n + {}^4He$$



Classically alpha particles mainly slow-down on electrons, but in a reactor the best performance is achieved in HOT ION mode.

The idea of alpha channelling is to use some waves (IBWs) that can extract the kinetic energy of alpha particles (through stochastic interaction) and release it to bulk ions (via cyclotron interaction).



Stochastic cooling

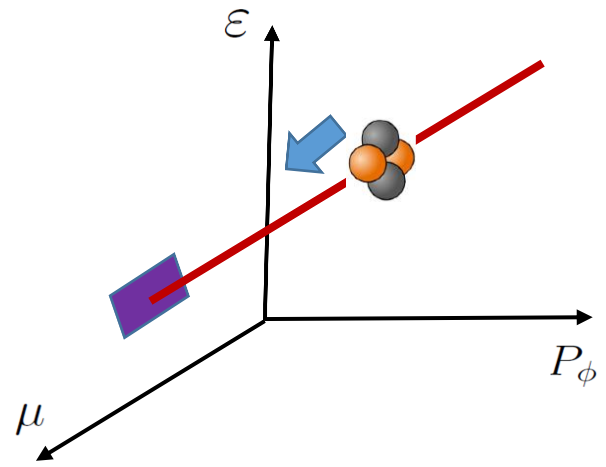
$$\Delta\mu = \frac{ZeN}{m\omega}\Delta\varepsilon \qquad \Delta P_\phi = \frac{n_\phi}{\omega}\Delta\varepsilon$$

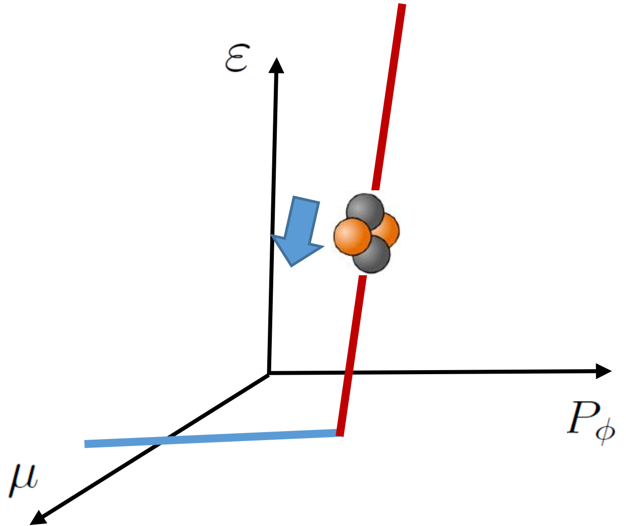
Original idea: drive most of alpha particles to the plasma boundary

$$\begin{cases} \Delta P_\phi \sim \frac{Ze}{c}\psi^w \\ \Delta\varepsilon \sim \varepsilon_\alpha \end{cases} \Rightarrow n_\phi \sim 1000$$

too high toroidal wave number (not realizable, not even efficient)

[Fisch and Rax *PRL* 92, Snyder, Hermann and Fisch *JFE* 94]





Two waves scenario: more advantageous to use two waves:

_ IBW to extract energy

_ low-frequency wave (TAE?) to move particles to the wall

[Fisch and Hermann *NF* 95, Hermann and Fisch *PRL* 97]

Goals of the EUROfusion research grant

Very limited evidences of alpha channelling have been found so far both in experiments and in numerical simulations. [Darrow et al *NF* 96, Clark and Fisch *PoP* 00, Wong at al. *PRL* 04] [Cook et al *PRL* 10, Cook et al *PPCF* 11, Ochs and Bertelli and Fisch *PoP* 15]

The goals of the project are:

- ***the quantitative determination of the amount of fusion alpha power that can be transferred to IBW***
- ***the determination of the conditions for minimal absorption by the electron and optimal transfer of the energy from IBW to the thermal ions and of the required injected power.***
- ***the optimization of the characteristic of the Alfvenic turbulence to maximize the effect of alpha channelling***

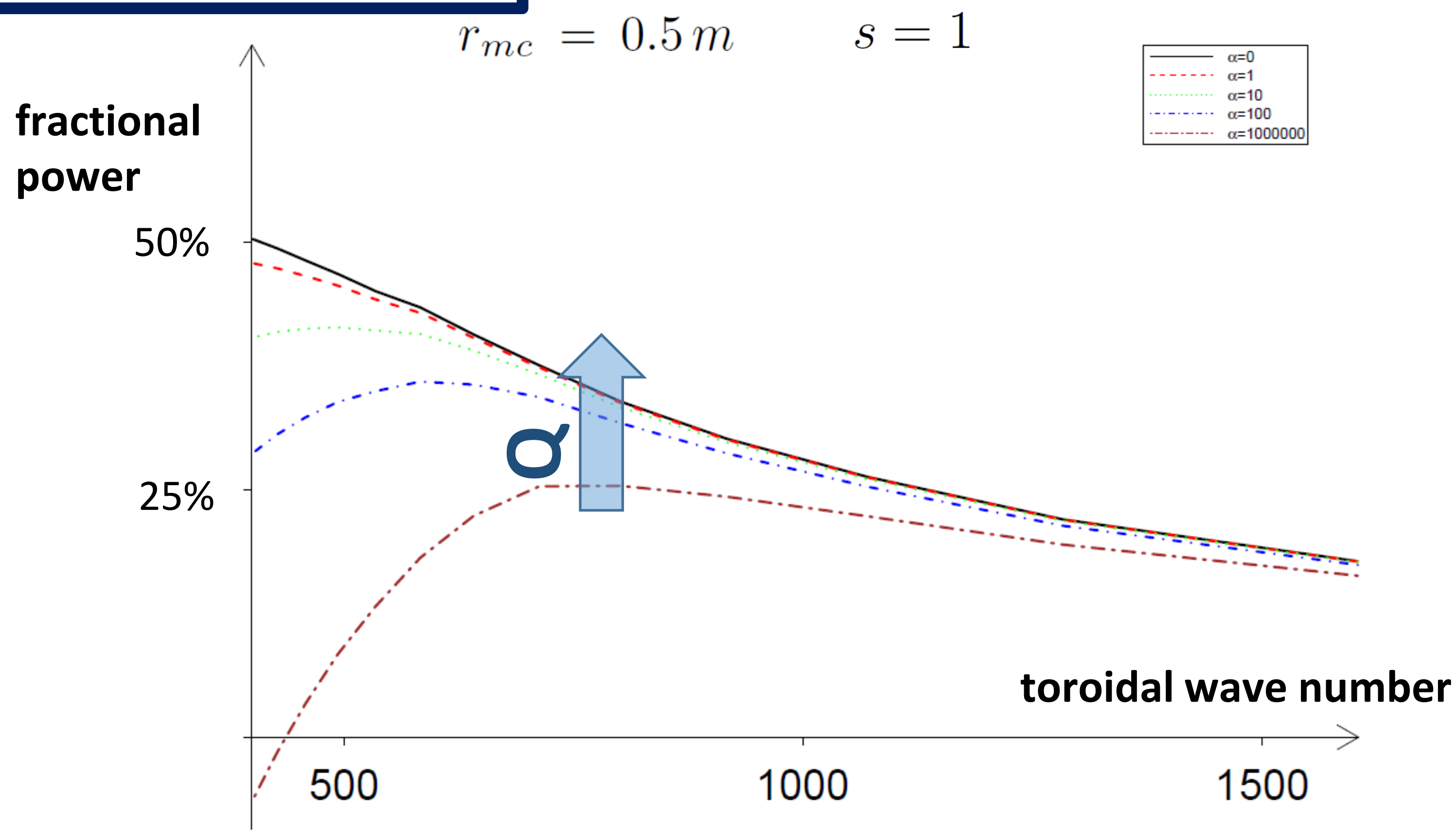
Results: fractional power vs toroidal wave number

Q: outward flux to model the low-frequency wave

By increasing the low-frequency wave flux the maximal power increases and moves towards low toroidal wave numbers.

Only the scenario with two waves can provide efficient alpha channeling.

In the optimal case, about **55% of alpha particle energy** can be extracted by IBWs.

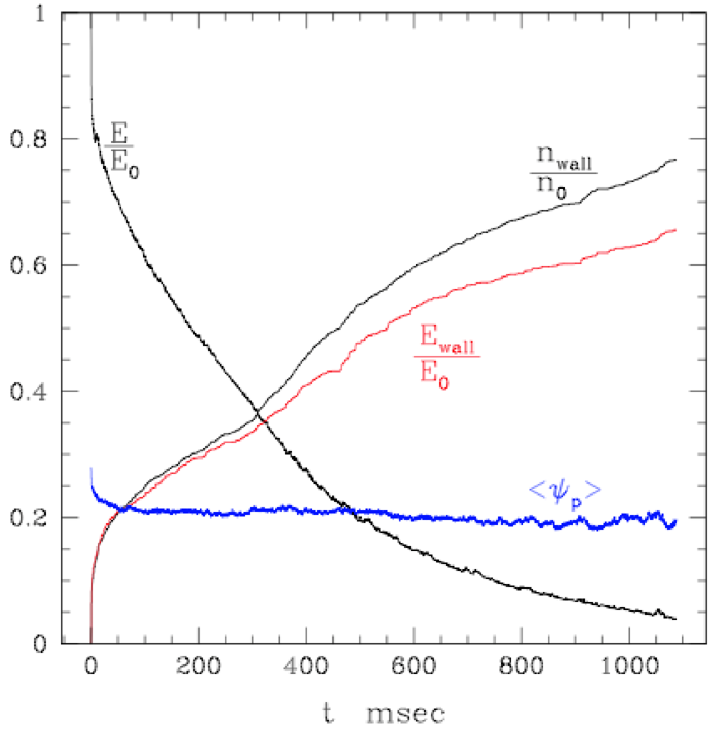


[Cianfrani and Romanelli *NF* 18]
[Cianfrani and Romanelli *NF* 19]

ORBIT simulations

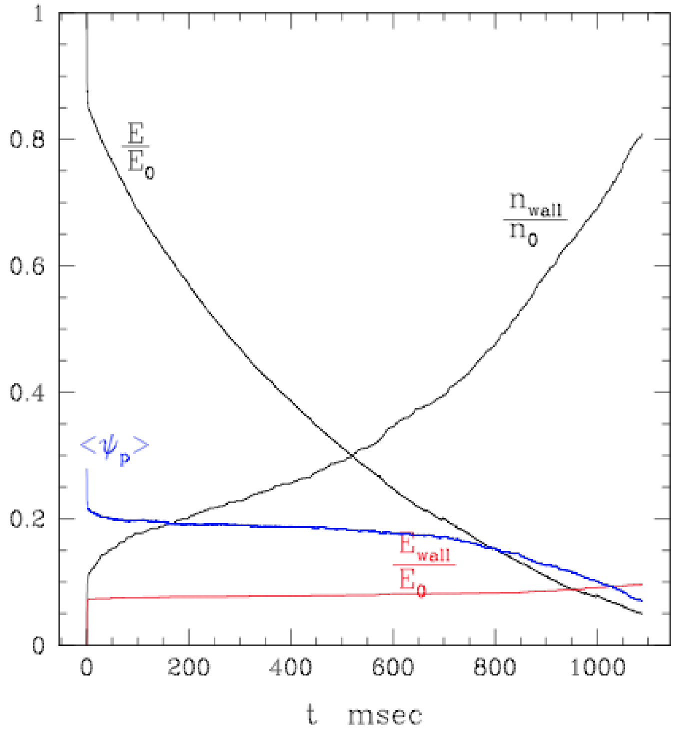
The results on the alpha particles cooling have been **confirmed** by the simulations performed via the ORBIT code.

[White, Romanelli, Cianfrani and Valeo *PoP* 21]



These simulations also outlines how **TAEs** provides **too high losses** of particle energy (over ten percent of the particle energy to be deposited on the walls).

high ash removal
high energy losses



Promising results with **micro-turbulence** playing the role of the second low-frequency wave.

high ash removal
low energy losses

Simulations of Edge Plasma Oscillations

EMEDGE3D: two-fluid code simulating the edge of a tokamak plasma (constant density, equal electron and ion temperatures and a constant toroidal external magnetic field).

Reduced MHD equations for electronic pressure, electrostatic potential, electromagnetic potential (drift ordering, including **DIAMAGNETIC VELOCITY**)

Charge Balance $$\partial_t \nabla_\perp^2 \phi + \{\phi, \nabla_\perp^2 \phi\} = -\nabla_\parallel \nabla_\perp^2 \psi - \omega_D \mathbf{G} p + \mu_\perp \nabla_\perp^4 \phi$$

Energy Balance $$\partial_t p + \{\phi, p\} = -\Gamma \nabla_\parallel \nabla_\perp^2 \psi + \delta_c \mathbf{G}(\phi - C_{dia}\, p) + \chi_\perp \nabla_\perp^2 p + S$$

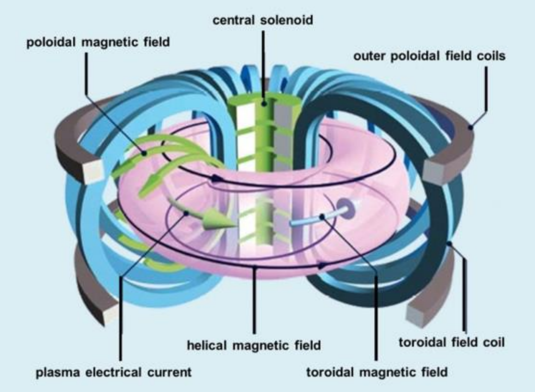
Ohm's Law $$\beta_e \partial_t \psi = -\frac{1}{\epsilon_\parallel^2} \nabla_\parallel (\phi - C_{dia}\, p) + \eta\, \beta_e \nabla_\perp^2 \psi$$

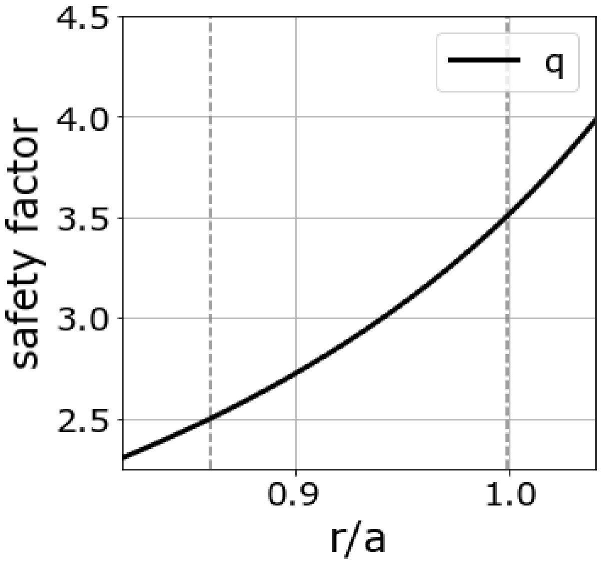
Curvature

ExB advection | Parallel current div | Viscosity | Diffusion | Resistivity | Source

Medium-size tokamak

$$B_0 = 1T \quad R_0 = 1.75m \quad a = 0.45m$$

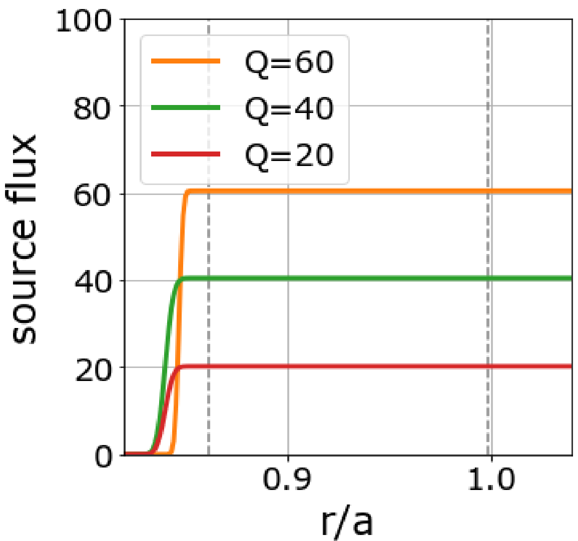




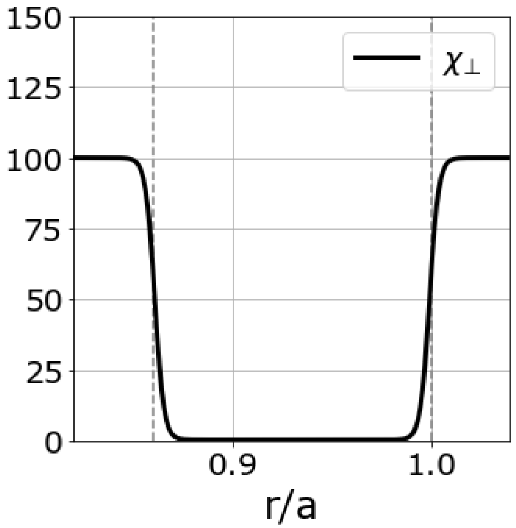
$$n = 2.5 \times 10^{19} m^{-3}$$
$$T_i = T_e = 50eV$$
$$\beta_e = 0.2\%$$

typical values for a JET discharge close to LH transition

[Bourdelle, NF 2014]

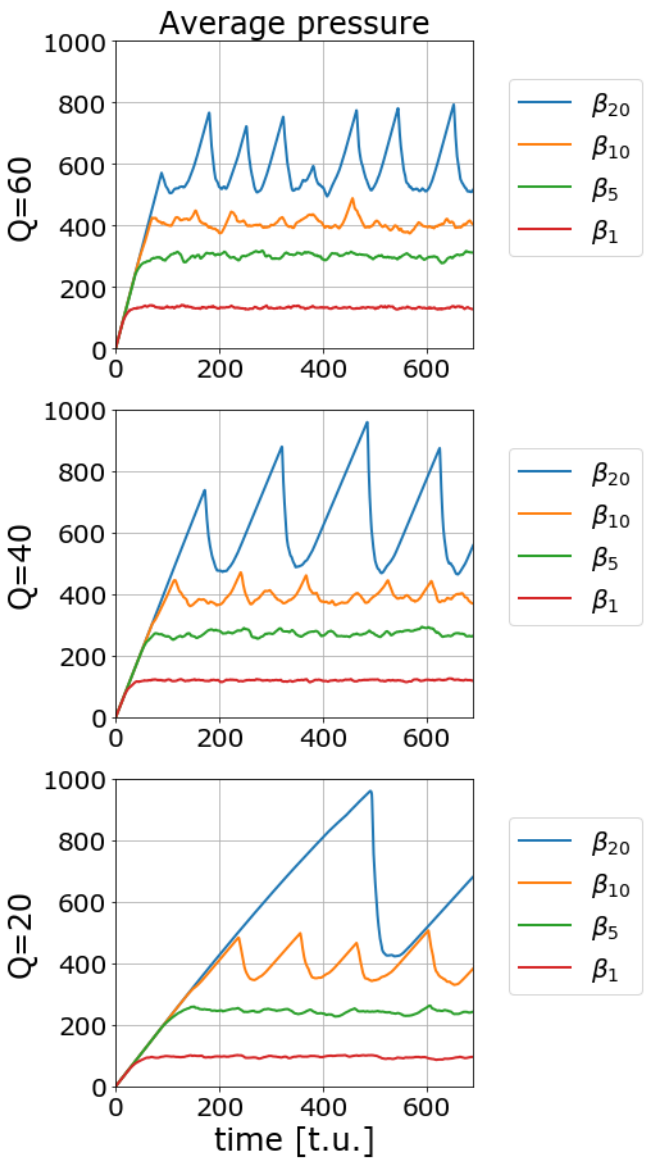


source in the inner buffer



dissipation is sharply increased in order to quench turbulence (high perpendicular diffusivity).

Results: oscillations at low β_e



$$\beta_d = \beta_e / d$$

low β_e

low density

$$100\, t.u. = 0.61\, ms$$

[Cianfrani, Beyer, Fuhr, PoP 2022]

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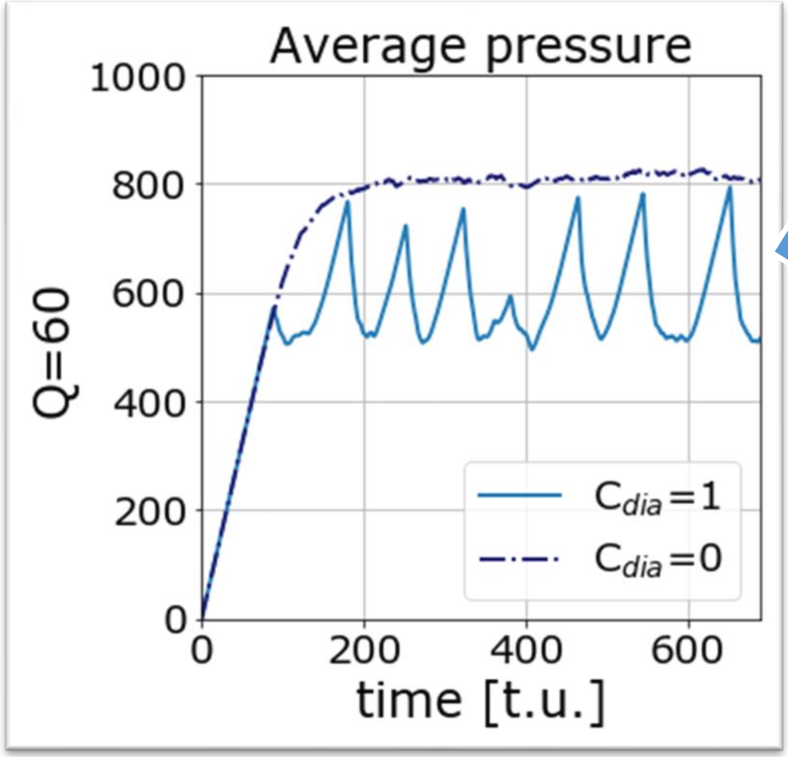
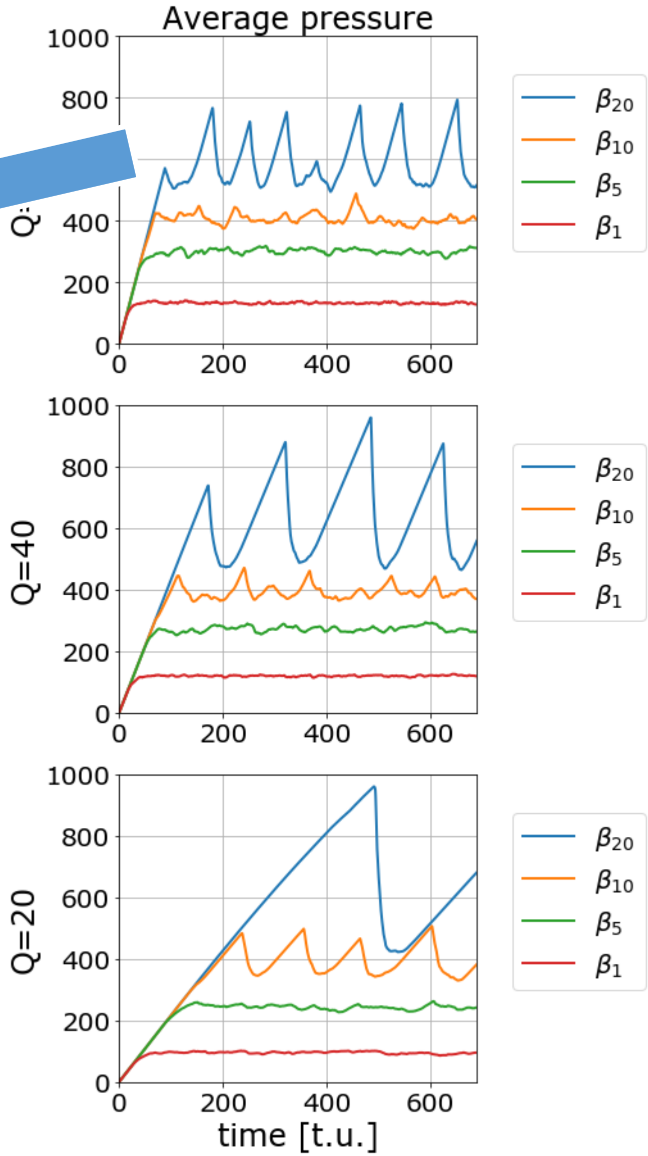




$$\beta_d = \beta_e / d$$

oscillations due to explosive growth of unstable modes previously stabilized by diamagnetic coupling (relaxation of a transport barrier).

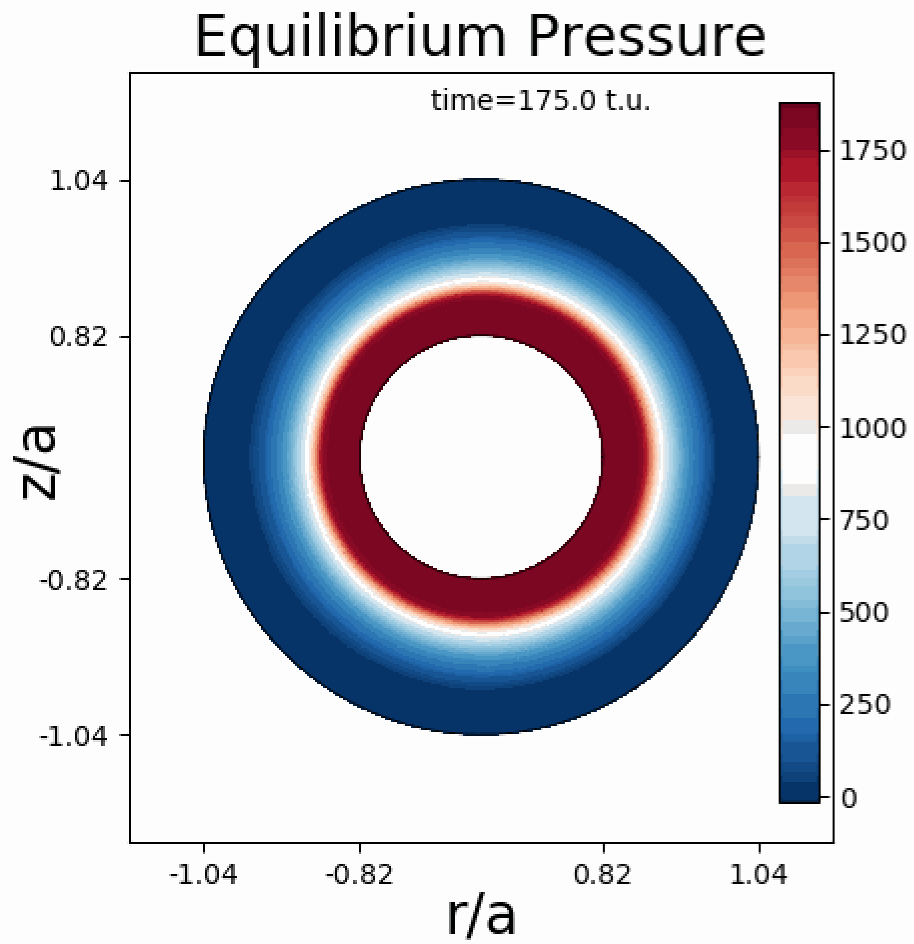
low β_e

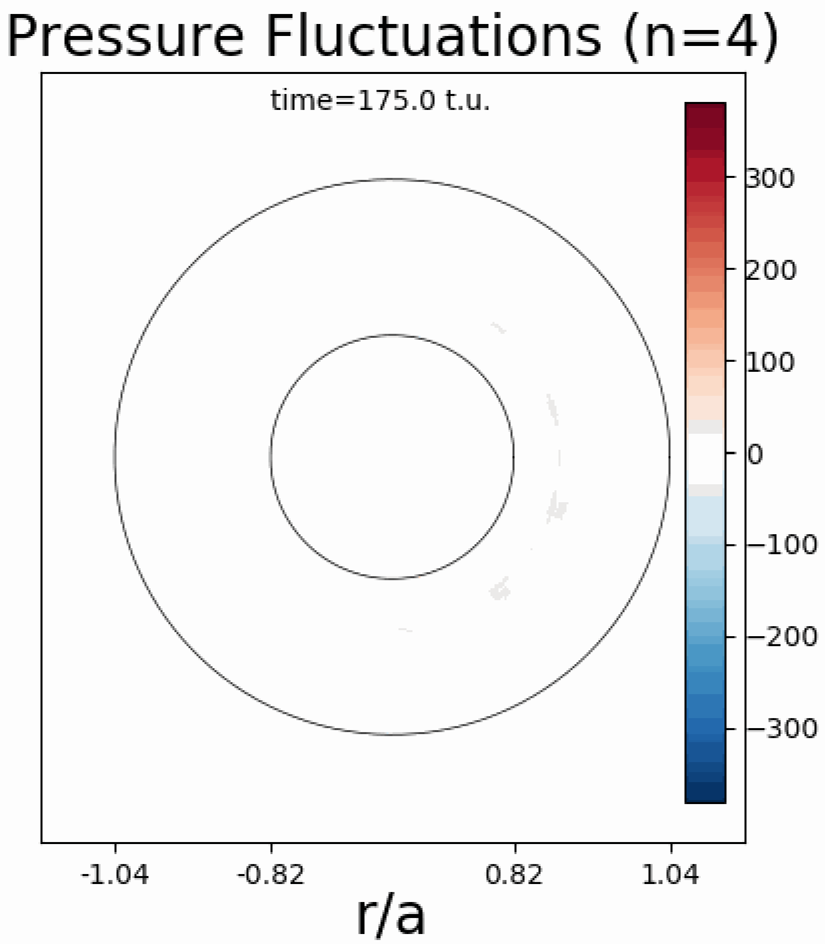
low density

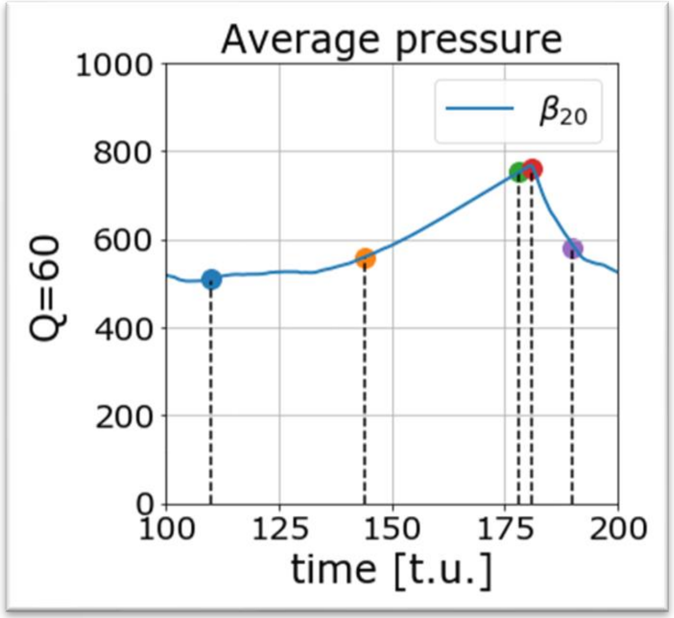
$$100\, t.u. = 0.61\, ms$$

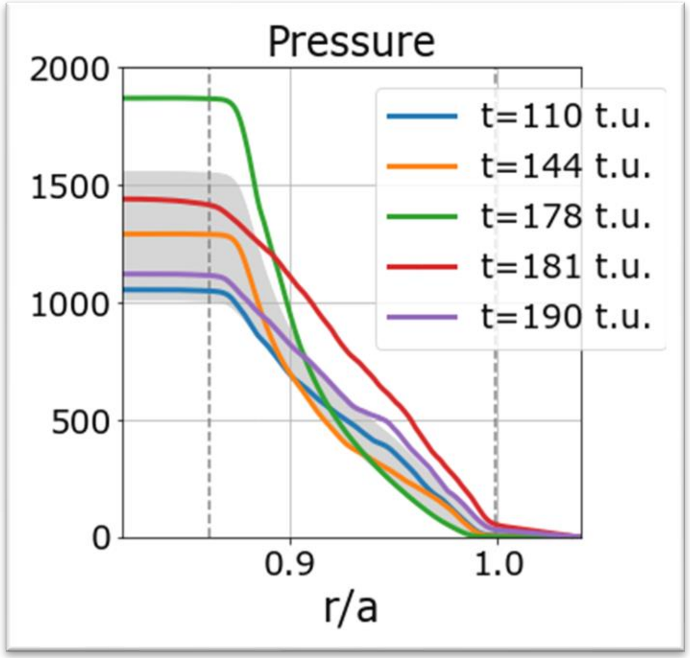
[Cianfrani, Beyer, Fuhr, PoP 2022]

2D Animations

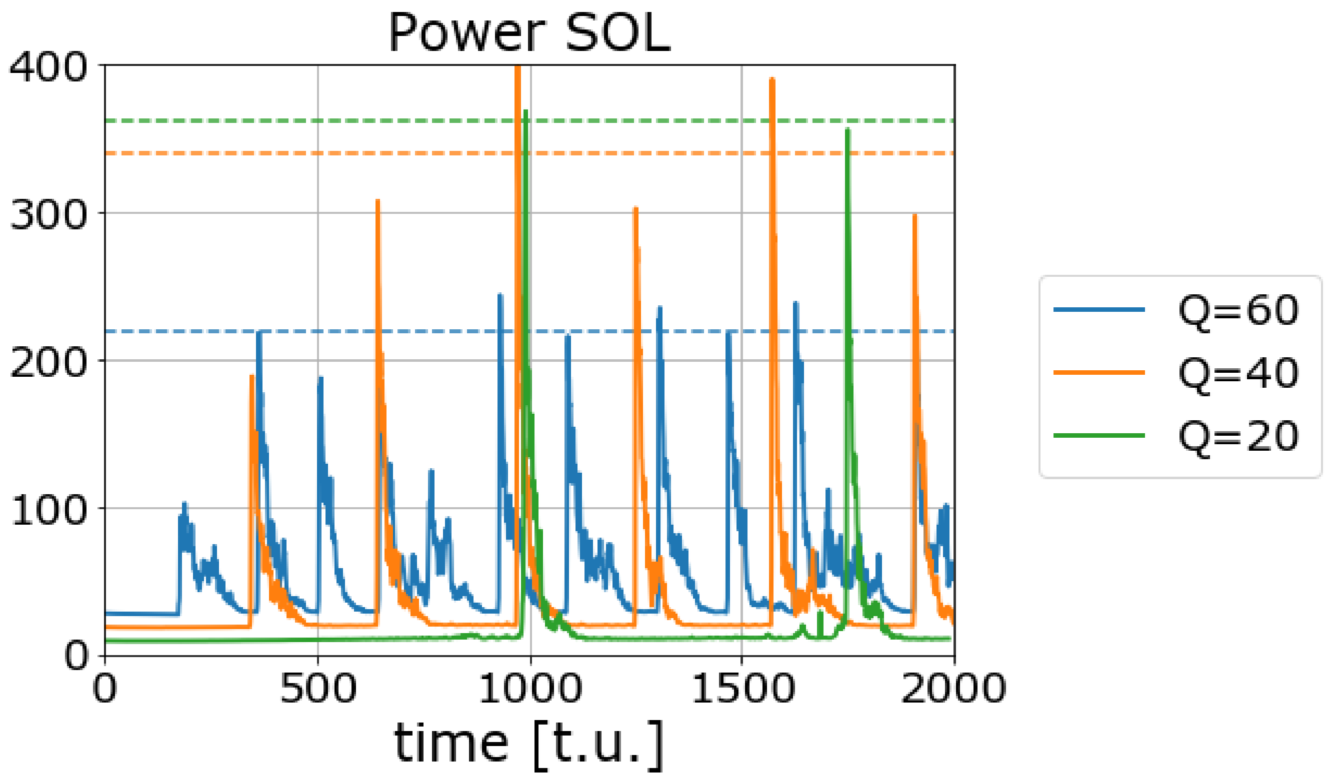








Results: type-III ELM

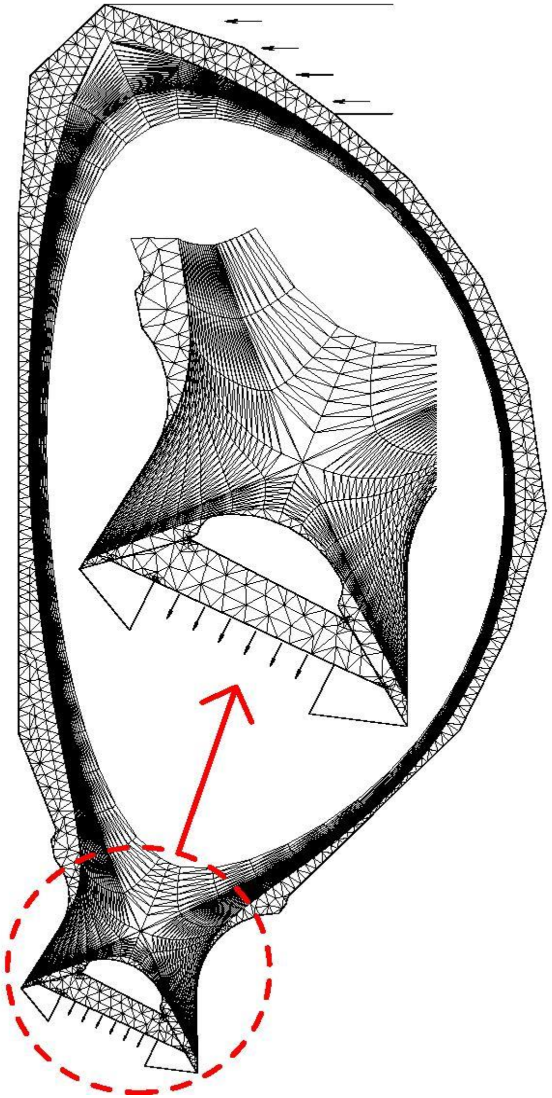


the oscillation frequency decreases
with increasing energy flux into SOL

[Cianfrani, Beyer, Fuhr, PoP 2022]

Collisional Radiative Models in EIRENE simulations

What is EIRENE in a nutshell (e.g. in SOLPS)?..



Macroscopic:

CFD codes (computational **fluid** dynamic):
B2, Edge2D, EMC3, SOLEdge3X, etc…

Plasma flow parameters

Microscopic

EIRENE-NGM: a 3D Monte Carlo multi-species transport code incl. radiation transfer, **kinetic** or **F-K** hybrid.

Source terms (Particle, Momentum, Energy)

CRMs for atomic and molecular neutrals H, H*, H_2, H_2(v), H_2*, H^-, H_2^+,…, impurities.
Ionisation, CX, recombination etc.

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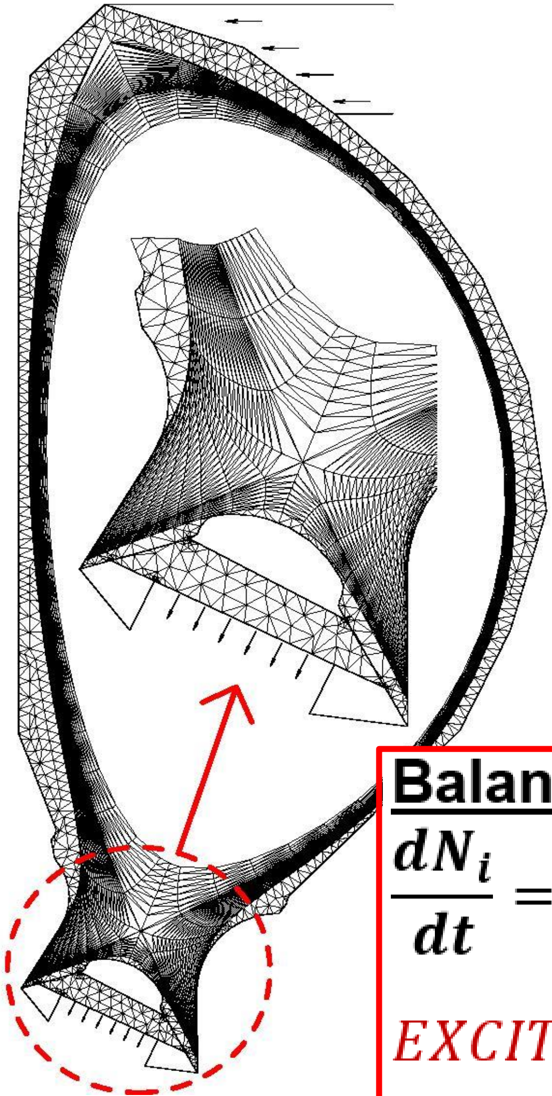

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Ionisation, CX, recombination etc.

Balance equations:

$$\frac{dN_i}{dt} = \sum_{j \neq i} A_{ji} N_j + n_e \cdot (EXCIT + IZ + CX + REC)$$

$$EXCIT = \sum_{j \neq i} \langle v\sigma_{ji} \rangle N_j$$

$$IZ = \sum_m \langle v\sigma_{mi} \rangle N_m^- + \sum_z \langle v\sigma_{zi} \rangle N_z^{2-} + \ldots$$

$$REC = \sum_k \langle v\sigma_{ki} \rangle N_k^+ + \sum_l \langle v\sigma_{li} \rangle N_l^{2+} + \ldots$$

CRM = list of states + transition data

Often used:

$\langle v\sigma_{ji} \rangle (T_e, n_e)$- effective Maxwellian averaged rates

PLOUTOS: what is inside?..

1) **CRM solver (transport excluded, pure A&M side of the problem) with extensive features**
2) **Plotting, solver results visualisation**
3) **Flexible reaction tables for EIRENE Databases (AMJUEL, HYDHEL, H2VIBR) interconnected with the solver and plotting**

TSVV5 Activities

- ***grouping of reactions:*** easier comparison btw data from different sources
- ***new column/features:*** sparse information now available
- ***default cases:*** testing purposes and model for **molecular decay**
- ***json output:*** reusability for new solver runs and other codes (EIRENE)

Conclusions Eirene Code Camp 22

we want to promote .. [PLOUTOS] .. as a standard pre-processing tool for Eirene

[Cianfrani, Borodin, Kuppers, EPJD 2023]

availabe in eirene.de
(for registered users only).

PLOUTOS: what is inside?..

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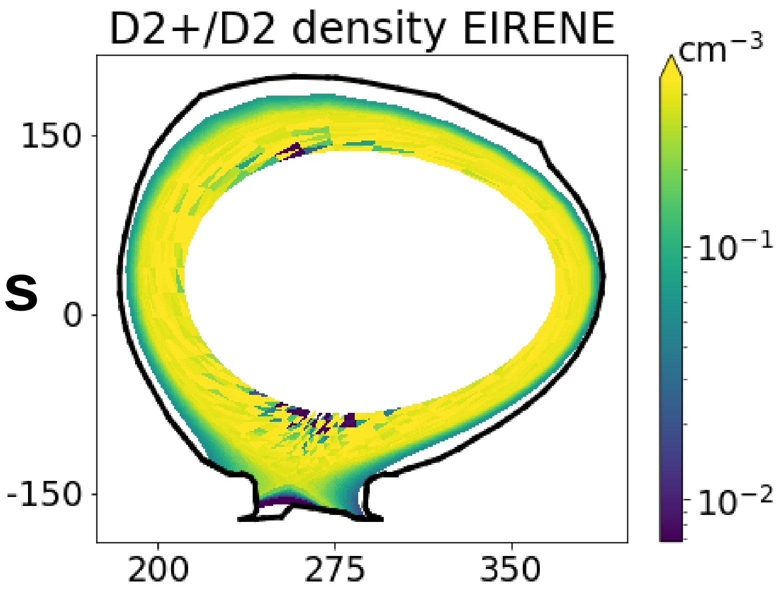
Conclusions Eirene Code Camp 22

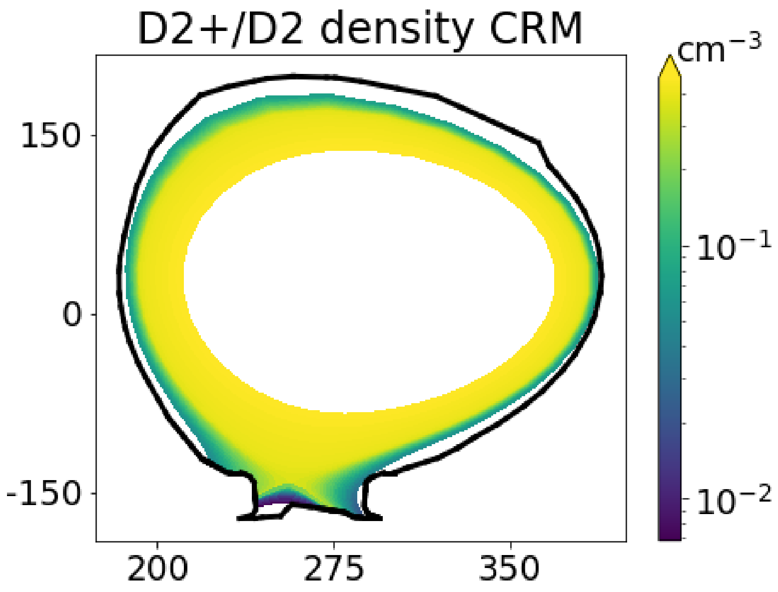
we want to promote .. [PLOUTOS

CRM vs EIRENE: TRANSPORT

EDGE2D-EIRENE simulations <u>JET shot 81472</u>:



vs



CRM in each simulation cell

CRM vs EIRENE: TRANSPORT

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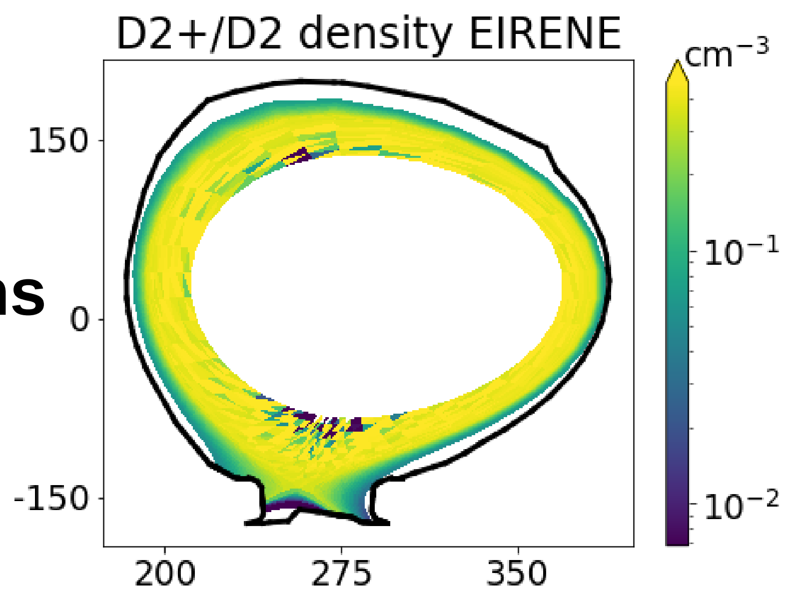

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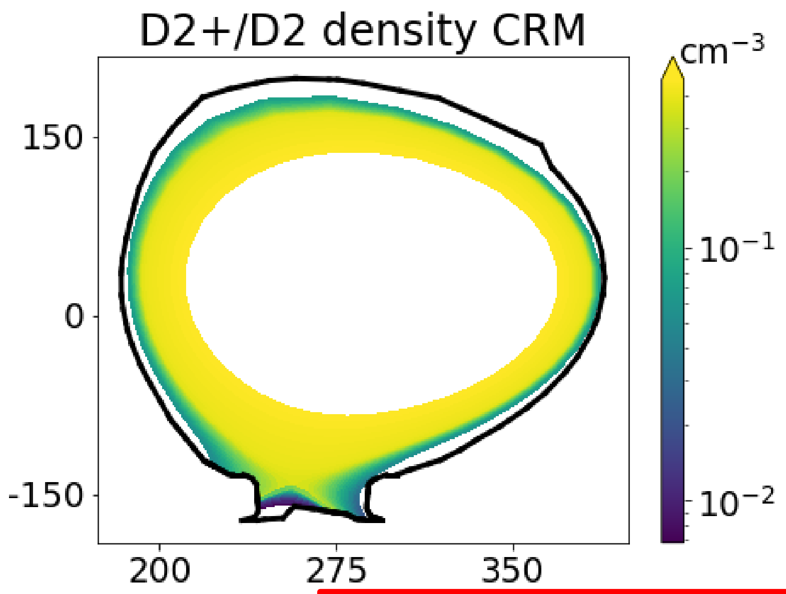
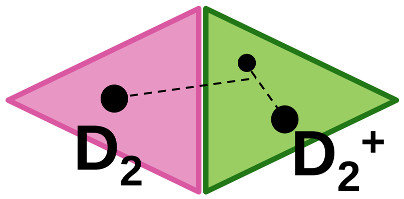
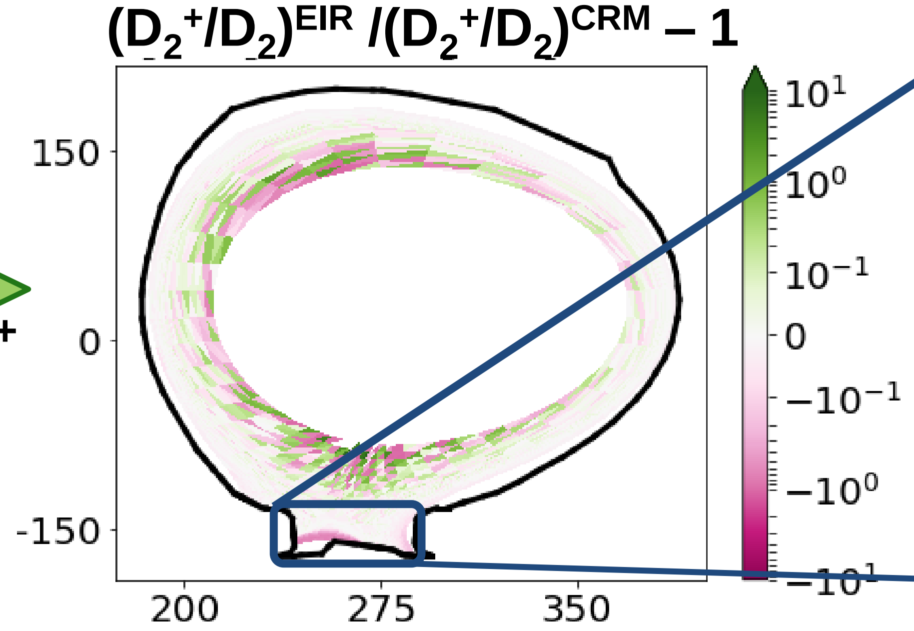
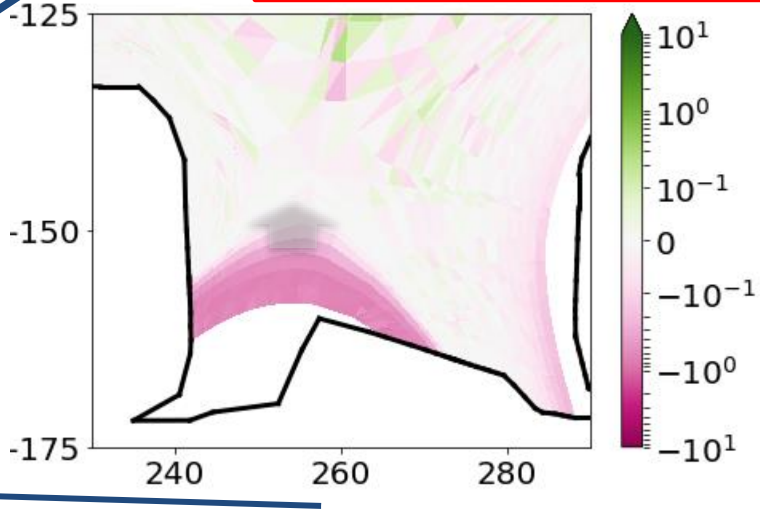


CRM in each simulation cell

CRM "quite good" in SOL..



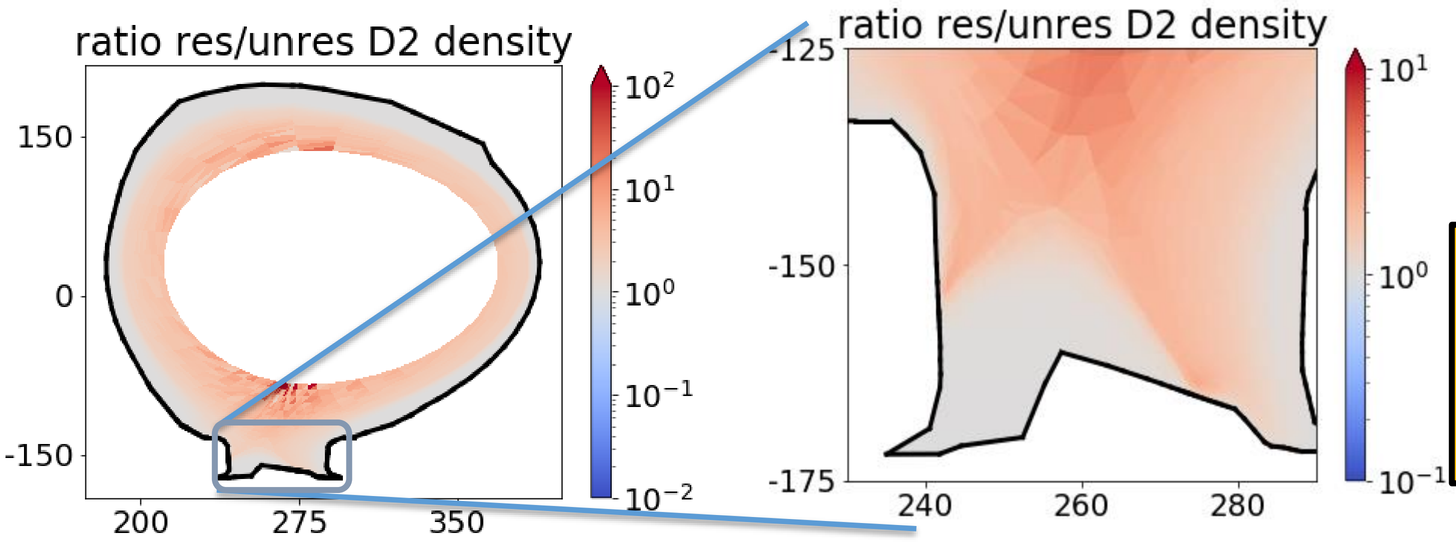




transport of molecules from private flux region

Impact of vibrational resolution

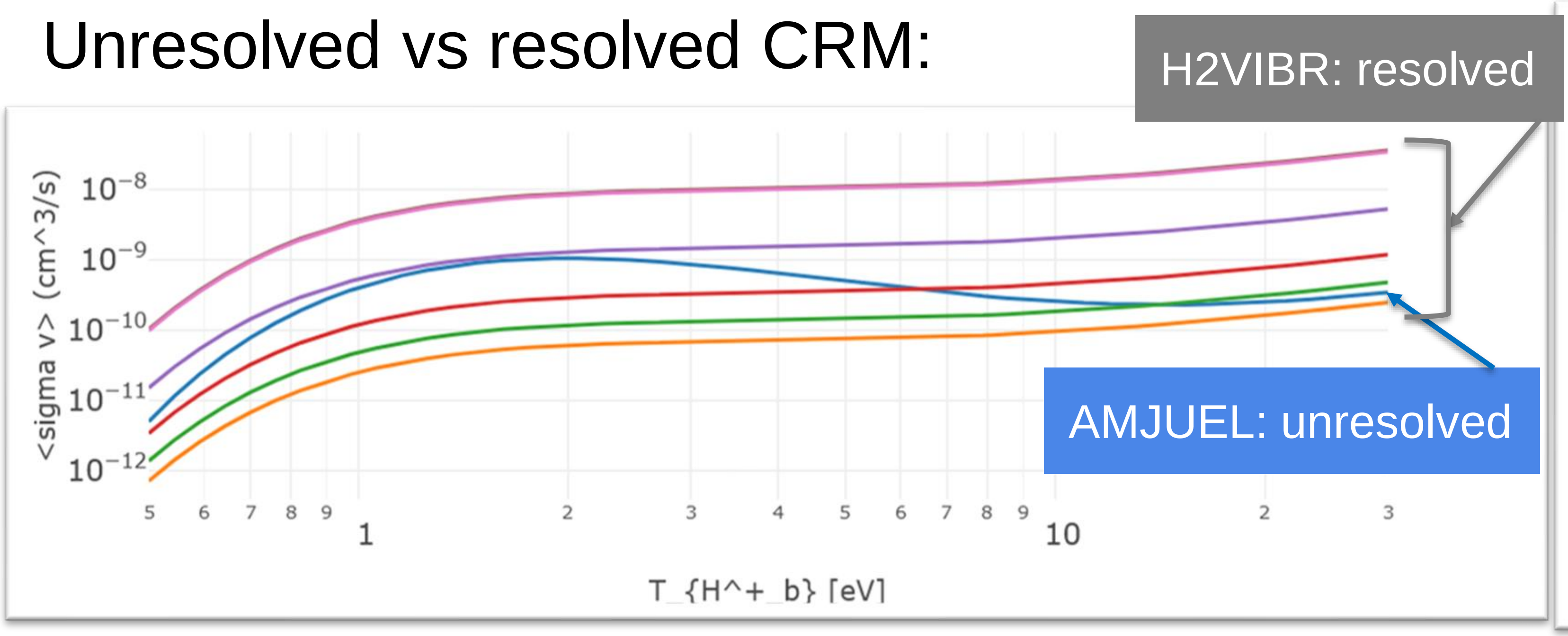
Unresolved vs resolved EIRENE simulations:

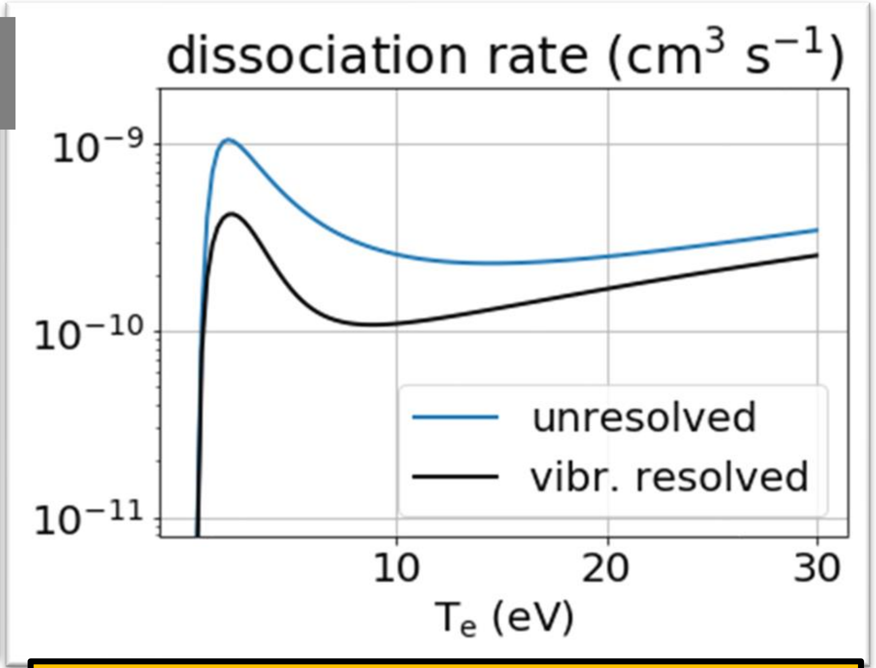


Larger molecular density (factor≃2÷3) along the separatrix with vibr. resolution.

Impact of vibrational resolution

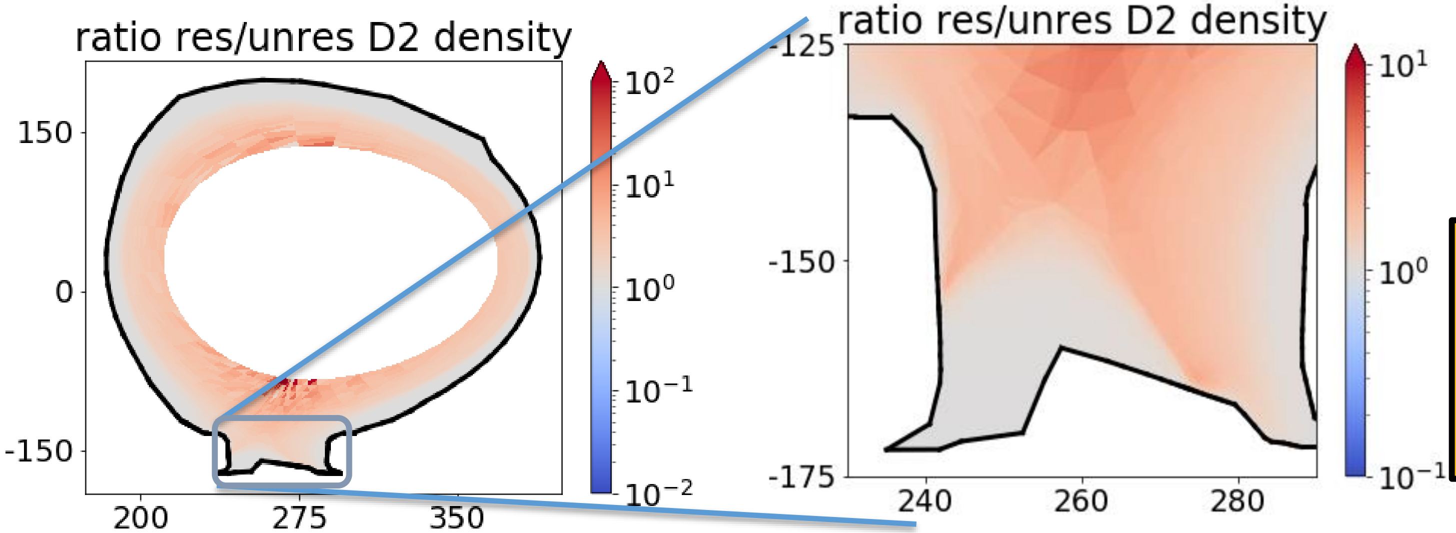
Unresolved vs resolved CRM:





reduced dissociation rate from vibr. resolved data.

Unresolved vs resolved EIRENE simulations:



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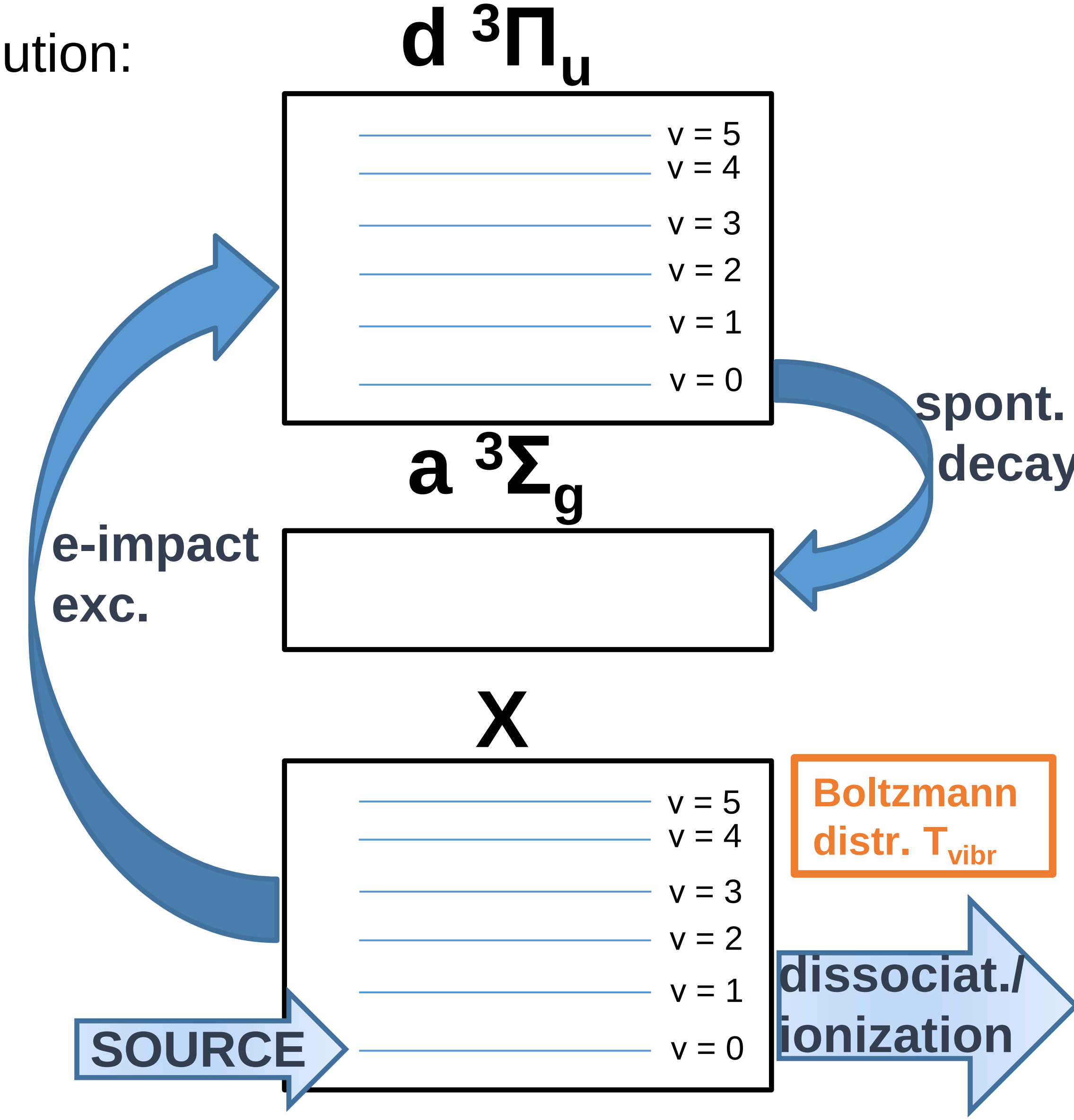
EXCITED MOLECULAR STATES:

Model for excited states on top of ground state distribution:

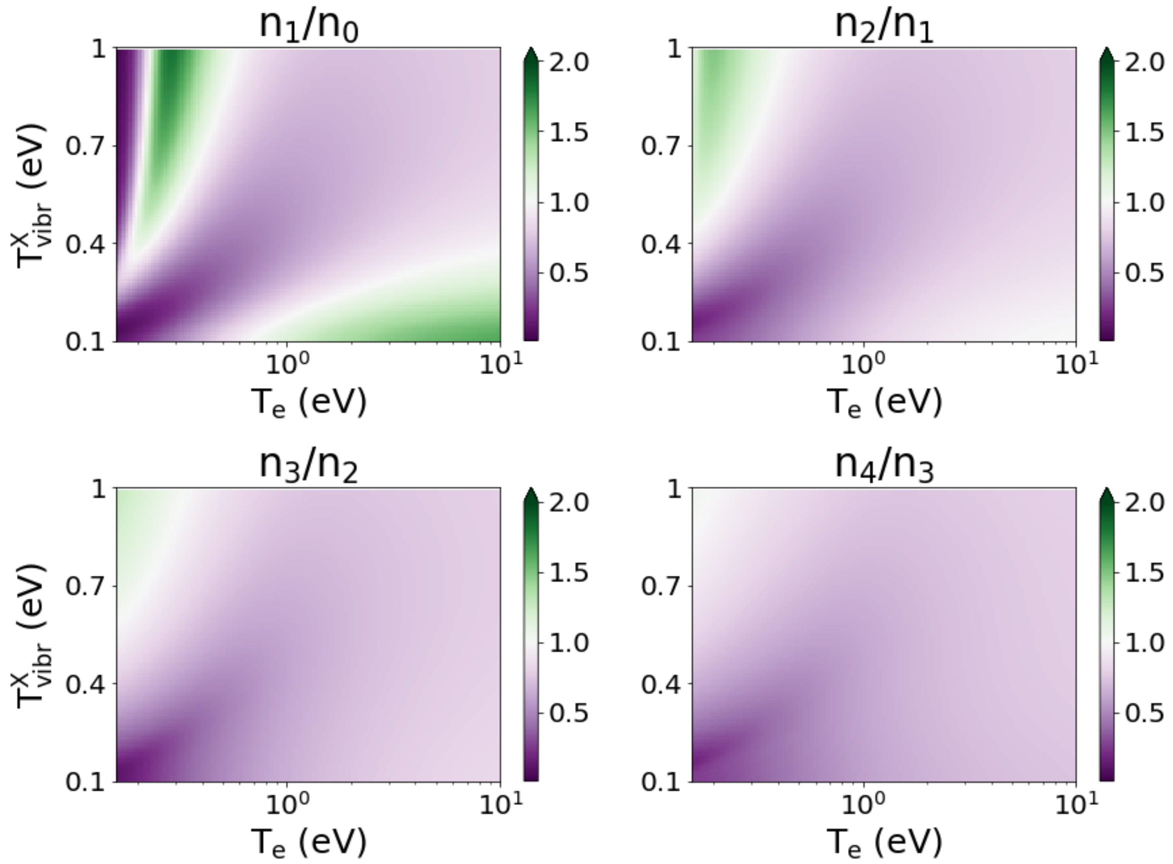


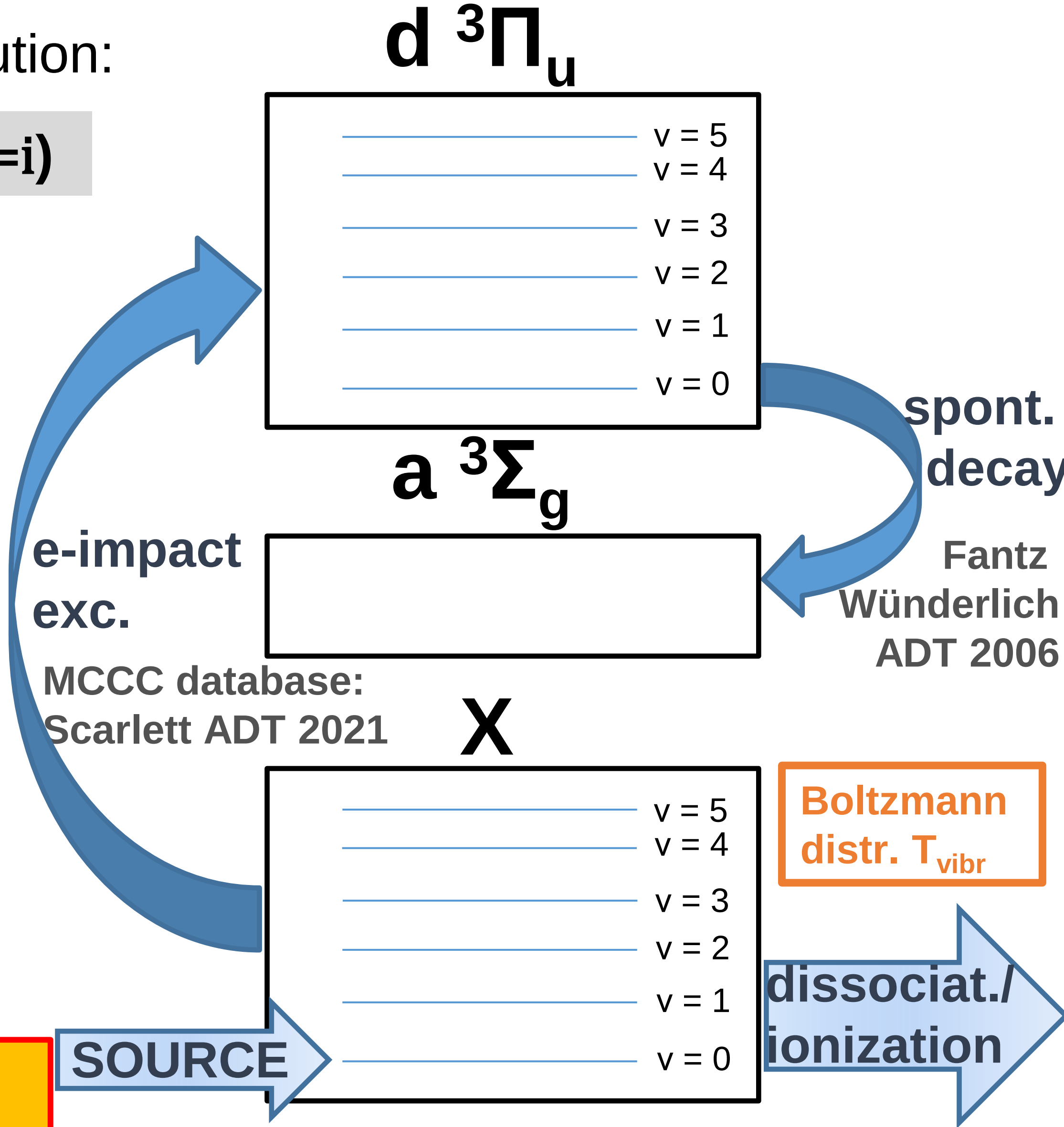
EXCITED MOLECULAR STATES:

MCCC database

Model for excited states on top of ground state distribution:

- population coeff. excited state **d $^3\Pi_u$:** $n_i = n(d,\nu=i)$





ratio of Fulcher band intensities as a proxy for ground state vibr. distribution

Actions:

- **ModCR:** CRM solver (CVODE) for integration with EIRENE
    - Ongoing

- **MCCC database:** inclusion into EIRENE
    - planned, not started yet

MCCC DATABASE

MCCC database - Molecular Convergent Close-Coupling e-molecule scattering cross sections
https://www.mccc-db.org/

Turbulence simulations near the X-point

Motivation: understand the physics of turbulence generation near the X-point through fast 3D simulations

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ASSUMPTIONS: constant temperature, ignoring curvature-parallel velocity-drifts-magnetic potential-diamagnetic terms, low frequency....

--> **SIMPLEST SYSTEM FOR 3D TURBULENCE SIMULATIONS**

$$\begin{cases} \partial_t \Delta_\perp \phi + \{\phi, \Delta_\perp \phi\} = B\,\nabla_\parallel^2(\tilde{p} - \phi) + \mu\,\Delta_\perp^2 \phi \\ \partial_t \tilde{p} + \{\phi, \tilde{p}\} = -\hat{k}\,\partial_y \phi + D\,\nabla_\parallel^2(\tilde{p} - \phi) + \chi_\perp\,\Delta_\perp \tilde{p} \end{cases}$$

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--> SIMPLEST SYSTEM FOR 3D TURBULENCE SIMULATIONS

Viscosity

$$\begin{cases} \partial_t \Delta_\perp \phi + \{\phi, \Delta_\perp \phi\} = B \nabla_\parallel^2 (\tilde{p} - \phi) + \mu \Delta_\perp^2 \phi \\ \partial_t \tilde{p} + \{\phi, \tilde{p}\} = -\hat{k}\, \partial_y \phi + D \nabla_\parallel^2 (\tilde{p} - \phi) + \chi_\perp \Delta_\perp \tilde{p} \end{cases}$$

Drift coupling

Diffusion

<u>Advection:</u>

$$\{f, g\} = \partial_x f\, \nabla_{\hat{y}} g - \partial_x g\, \nabla_{\hat{y}} f$$

<u>Free energy source:</u> background pressure gradients

$$p = p_0 + \tilde{p}$$

$$-\,\partial_x p_0 = p_0 / l_0 \propto \hat{\mathbf{k}}$$

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Advection: nonlinear inverse energy cascade to large parallel scales (n=0)

Drift coupling: near the X-point it is toroidal, thus proportional to n.

? Turbulence suppression? HW effective model still valid? Is shear able to sustain drift response? What's the role of other parameters?

Geometry:

$$x = \frac{r - r_0}{L_\perp}, y = \frac{a\theta}{L_\perp}, z = \frac{R\varphi}{L_\parallel}$$

full toroidal
local in poloidal plane

$$k_\parallel \gg k_\perp$$

- **SLAB:** close X point

$$\nabla_\parallel = \partial_z \qquad \Delta_\perp = \partial_x^2 + \partial_y^2$$

- **TOKAMAK:**

$$\nabla_\parallel = \hat{b} \cdot \vec{\nabla} \qquad \Delta_\perp = (\nabla - \nabla_\parallel)^2$$

$$\hat{b} = \frac{\vec{B}}{B}$$

Laplacian and parallel derivative are non-linear in FS if B’s are not constant (shear).

Metodology: 4th order Runge-Kutta in Fourier space

- at each iteration pressure and vorticity are advanced

- electrostatic potential is computed inverting the Laplacian

  - **w/o shear:** inverse Laplacian is analytical in FS and can be easily inverted.
  - **with shear:** Laplacian and inverse are numerically pre-calculated before starting time iteration and stored as csr matrix.

- all non-linear terms are computed in real space with Fast Fourier Transforms (**FFT**) and pulled back in FS with inverse FFT (**pseudo-spectral**)

  - **w/o shear:** advection
  - **with shear:** advection + all terms with B's (drift,..)

Parameters:

Braginsky parameters for typical DTT case:

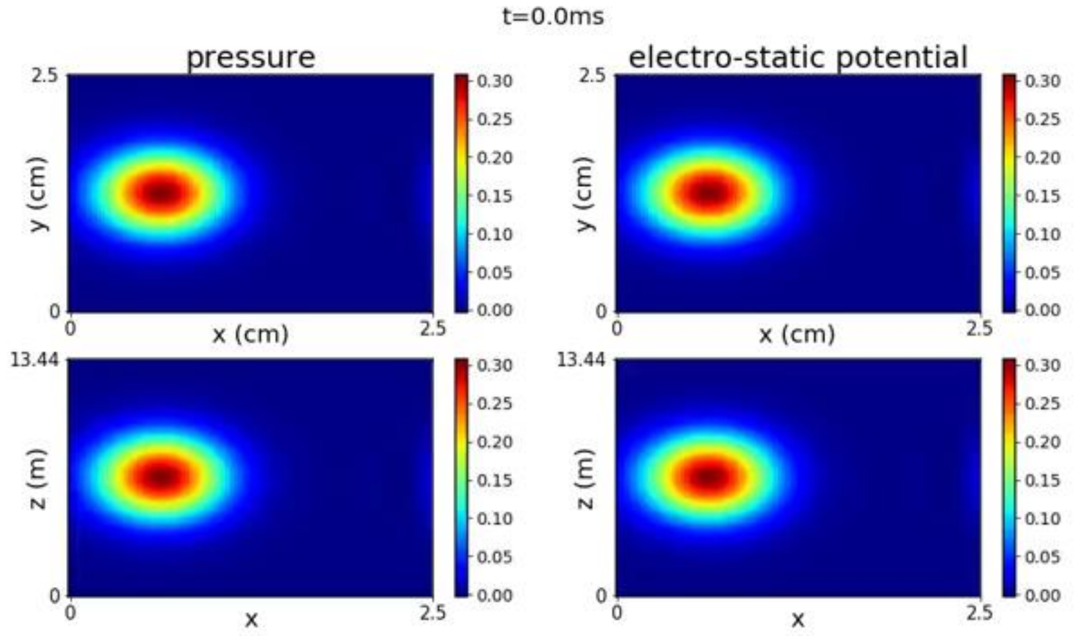
a=68cm *R=2.14m* $B=3x10^4Gs$ $n=5x10^{13}\ cm^{-3}$

Background pressure gradients: l_0=*40cm*

Two cases for diffusivity: Classical(*1.2m²/s*) vs Neoclassical (x10)

Initial values:

3D wave packet centered inside the simulation domain.



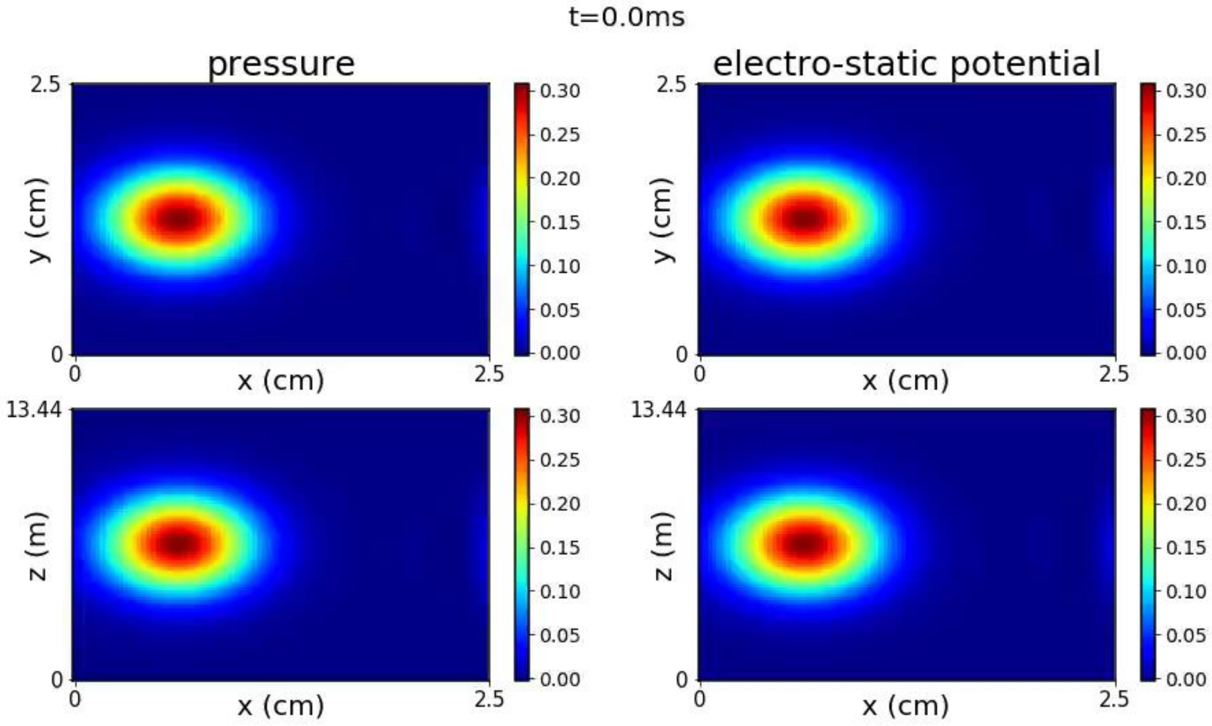
Boundary Conditions:

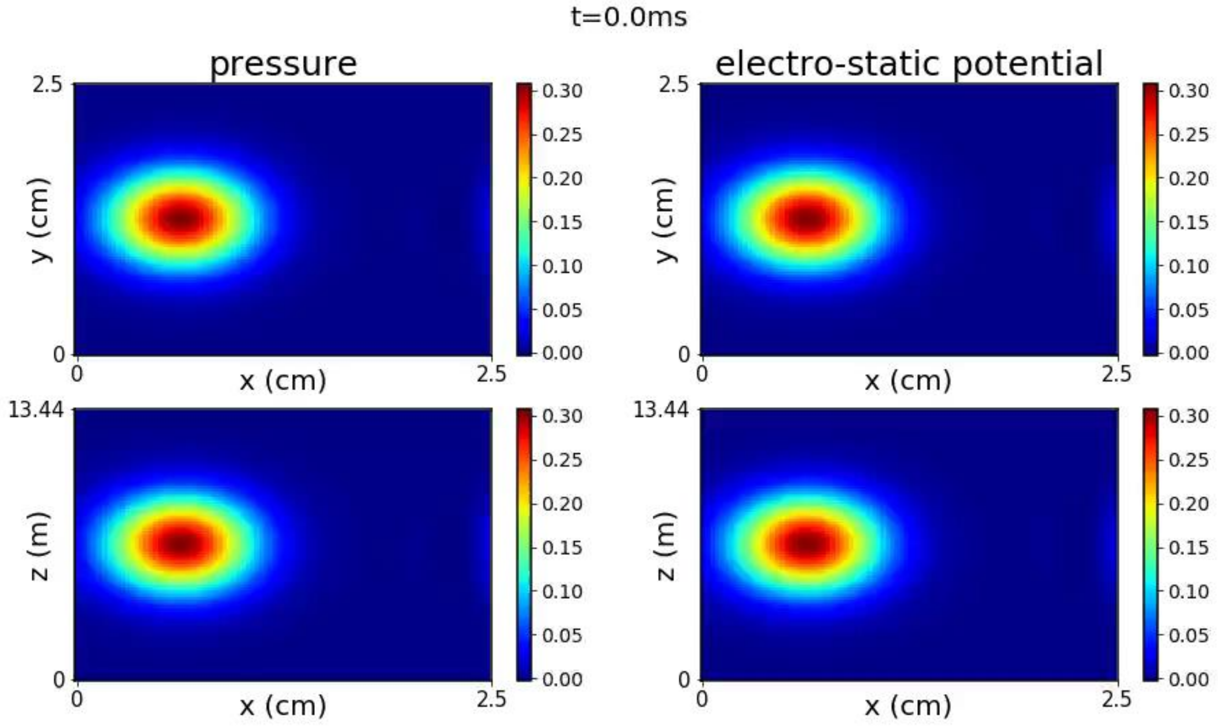
periodic boundary conditions

NEW: vanishing Dirichlet "radial" BC

Simulations: SLAB

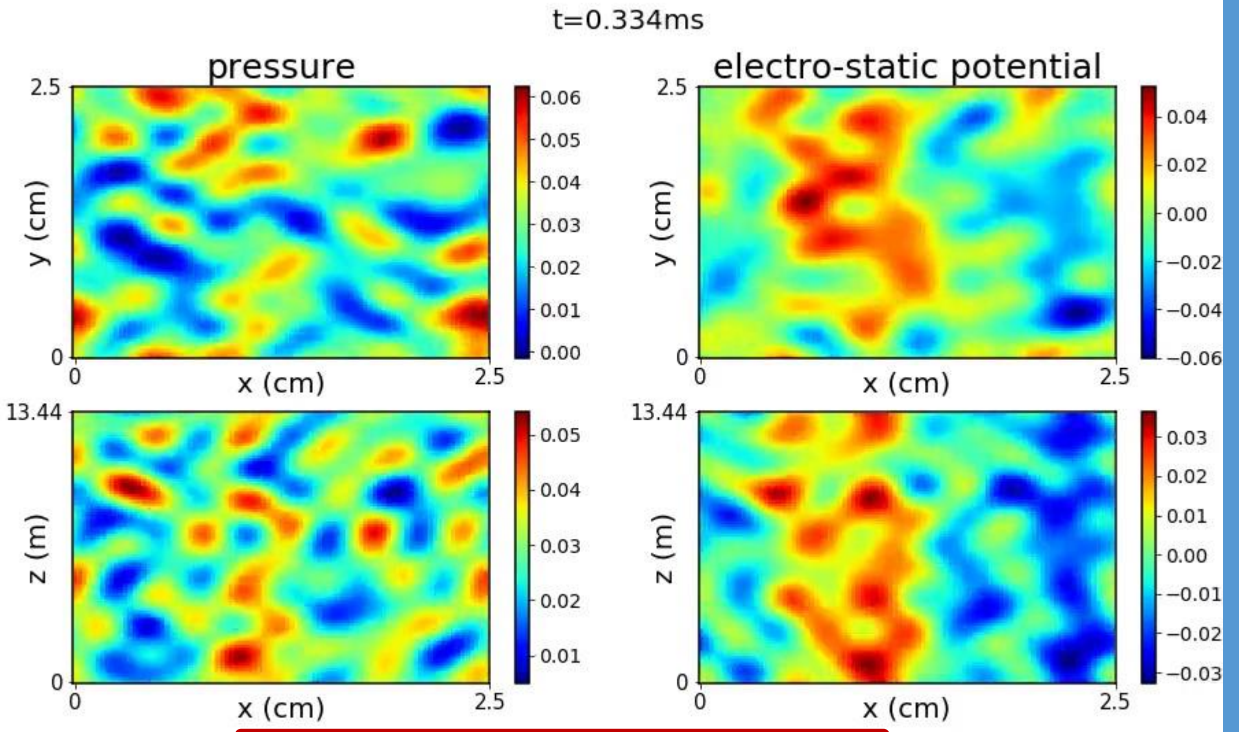
classical diffusivity vs neoclassical diffusivity

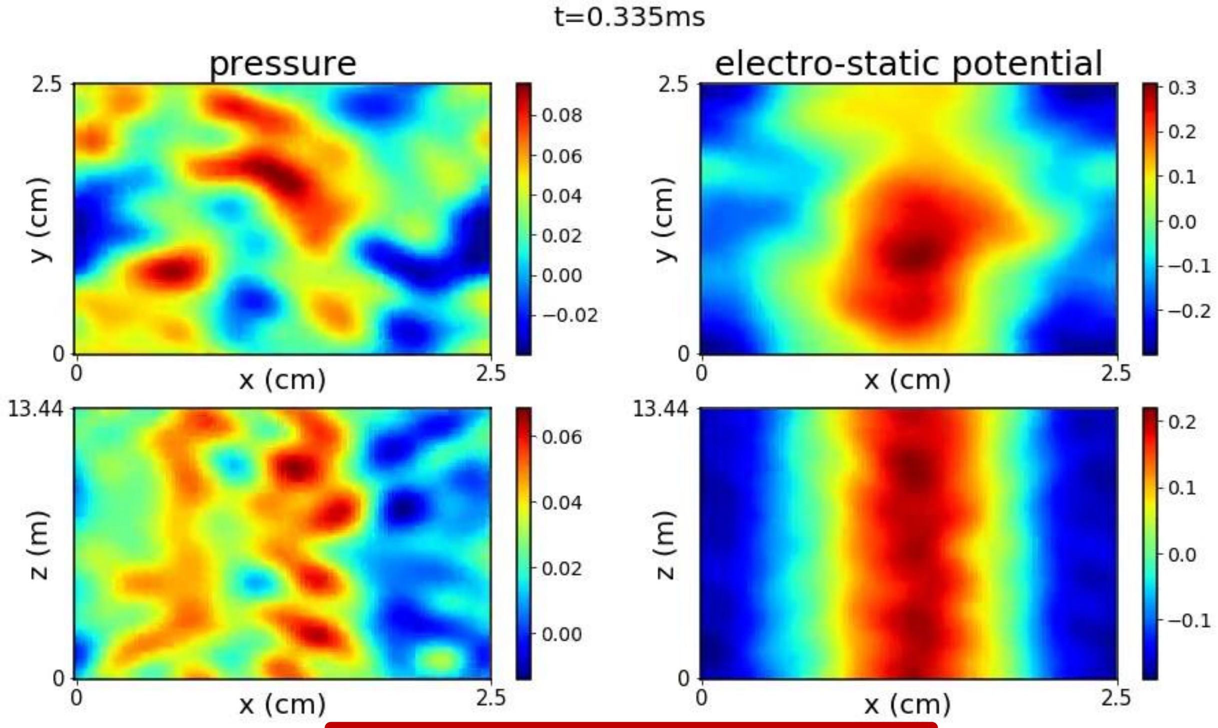




Simulations: SLAB

classical diffusivity vs neoclassical diffusivity





Stronger turbulence
large drift response
wider toroidal spectrum

Turbulence reduction
large diffusion
inverse cascade

Outlook:

- comparison between different magnetic geometries → X point
- inclusion of more effects (curvature, electro-magnetic, gyrofluid corrections,..)
- consistent diffusivity: test particle motion on turbulent scenario
- global (poloidal) simulations
- predictions for DTT

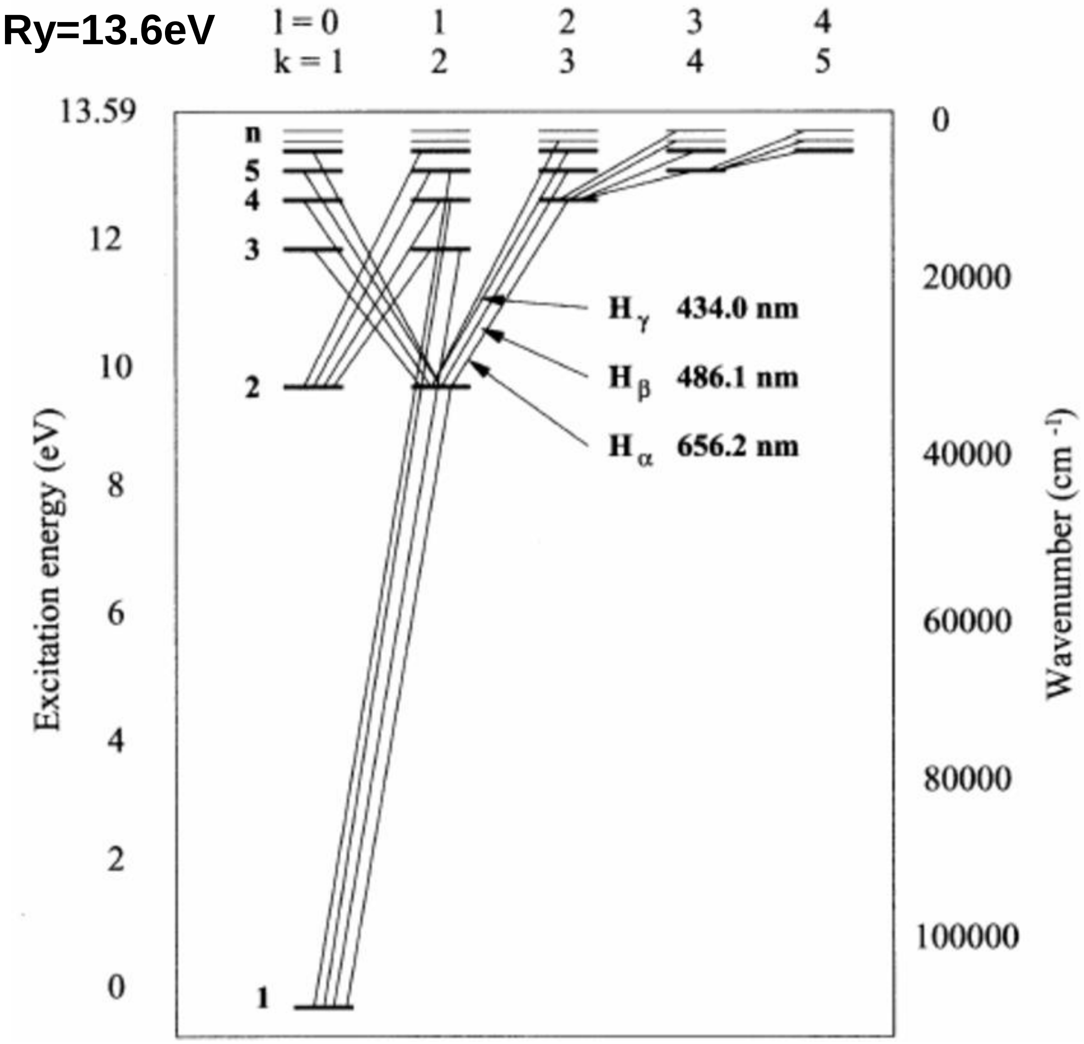
Fabio Moretti's talk..

Additional material

Collisional-Radiative Models (CRM)

Grotrian diagram for atomic H (D, T)

Ry=13.6eV



Balance equations:

$$\frac{dN_i}{dt} = \sum_{j \neq i} A_{ji} N_j + n_e \cdot (EXCIT + IZ + CX + REC)$$

$$EXCIT = \sum_{j \neq i} \langle v\sigma_{ji} \rangle N_j$$

$$IZ = \sum_m \langle v\sigma_{mi} \rangle N_m^- + \sum_z \langle v\sigma_{zi} \rangle N_z^{2-} + \ldots$$

$$REC = \sum_k \langle v\sigma_{ki} \rangle N_k^+ + \sum_l \langle v\sigma_{li} \rangle N_l^{2+} + \ldots$$

$\ldots$

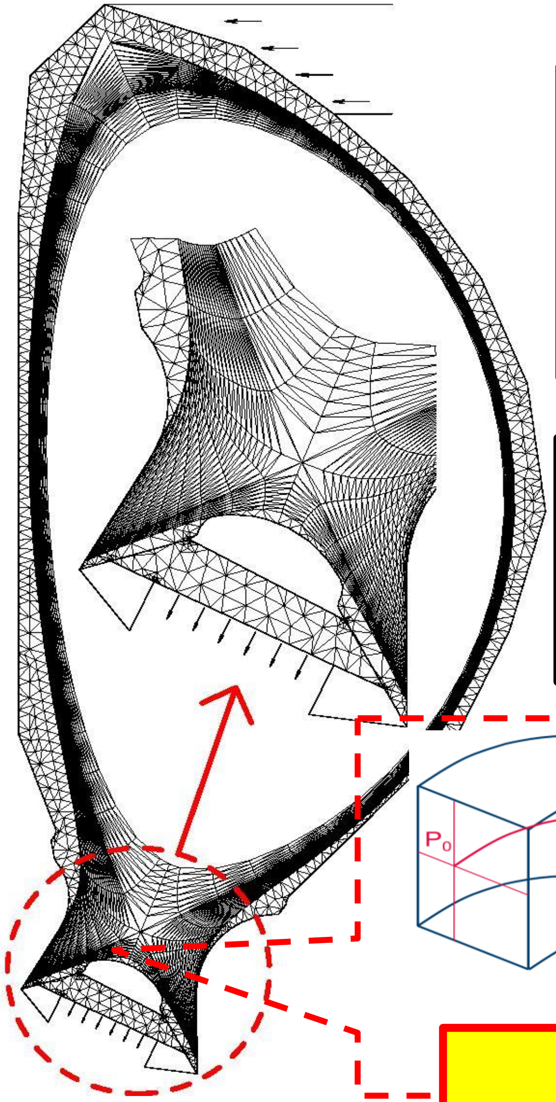
j, k, l, m, z, … states can be fine-superfine resolved or, opposite, bundled into few quasi-metastables (MS)

CRM = list of states + transition data

Often used:

$\langle v\sigma_{ji} \rangle (T_e, n_e)$- effective Maxwellian averaged rates

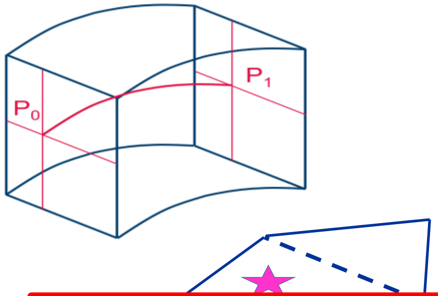
What is EIRENE in a nutshell (e.g. in SOLPS)?..



Macroscopic:

CFD codes (computational **fluid** dynamic): B2, Edge2D, EMC3, SOLEdge3X, etc…

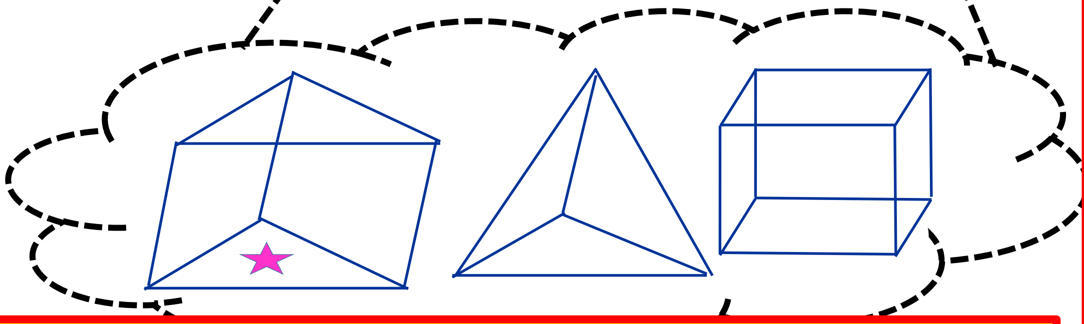
2D or 3D Volume grid (e.g. tetraeder) adopted for current magnetic configuration



Plasma flow parameters

3D EIRENE volume cell

Source terms (Particle, Momentum, Energy)



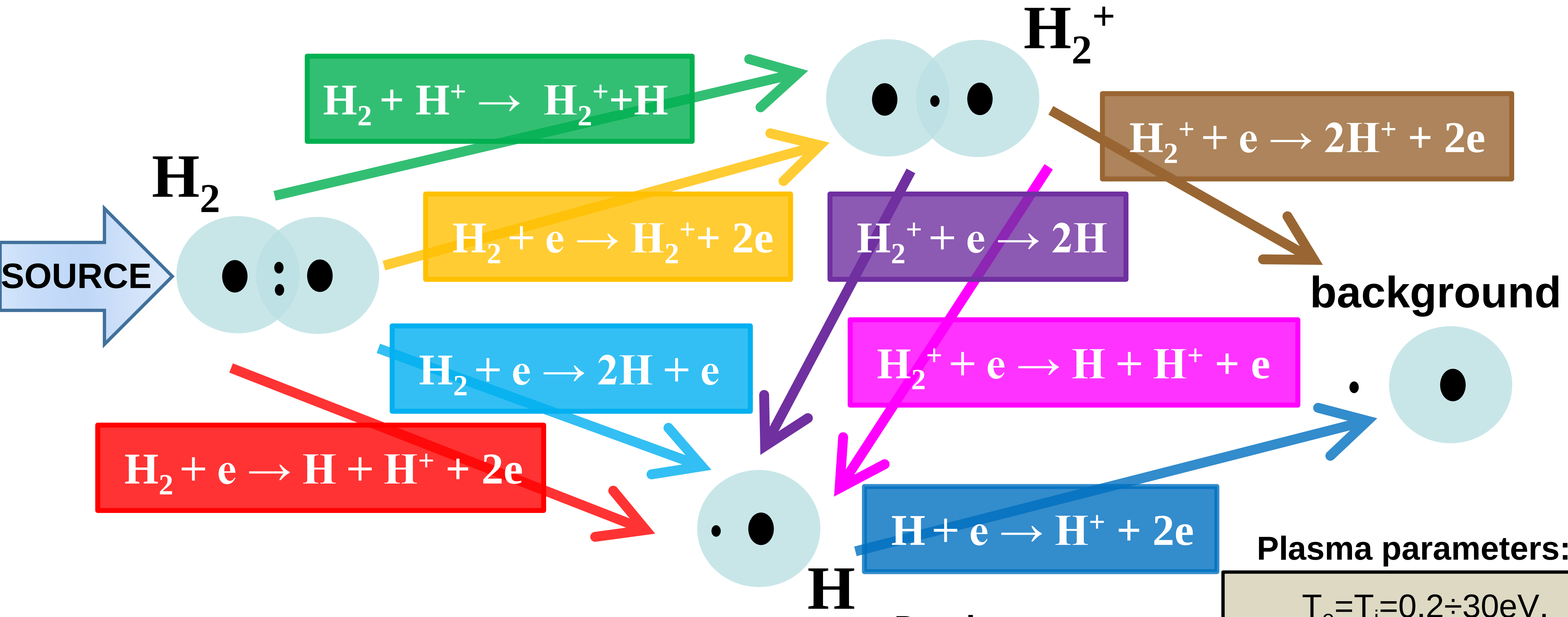
Microscopic

EIRENE-NGM: a 3D Monte Carlo multi-species transport code incl. radiation transfer, **kinetic** or **F-K** hybrid.

CRMs (HYDKIN, AMJUEL, ADAS, …) for atomic and molecular neutrals $H, H^*, H_2, H_2(v), H_2^*, H^-, H_2^+$,…, impurities Ionisation, CX, recombination etc.

Solving standalone CRM is necessary to understand the interplay between transport and local chemical reactions in full EIRENE simulations

CRM FOR MOLECULES



Databases:

AMJUEL, HYDHEL

Plasma parameters:

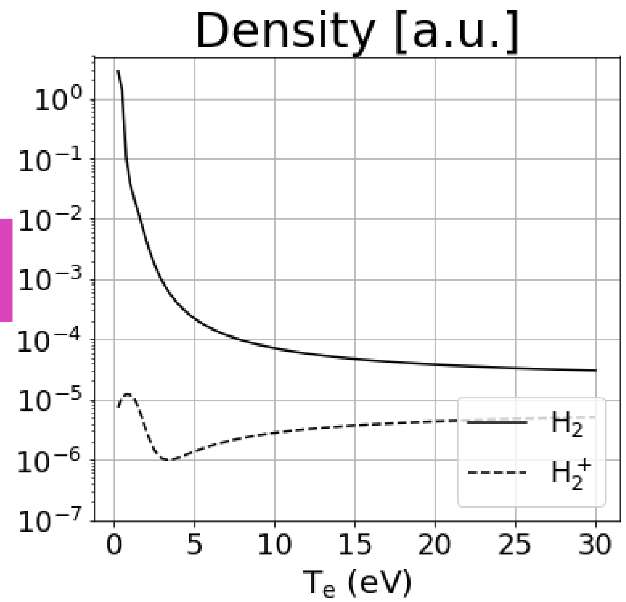
$T_e = T_i = 0.2 \div 30$ eV.

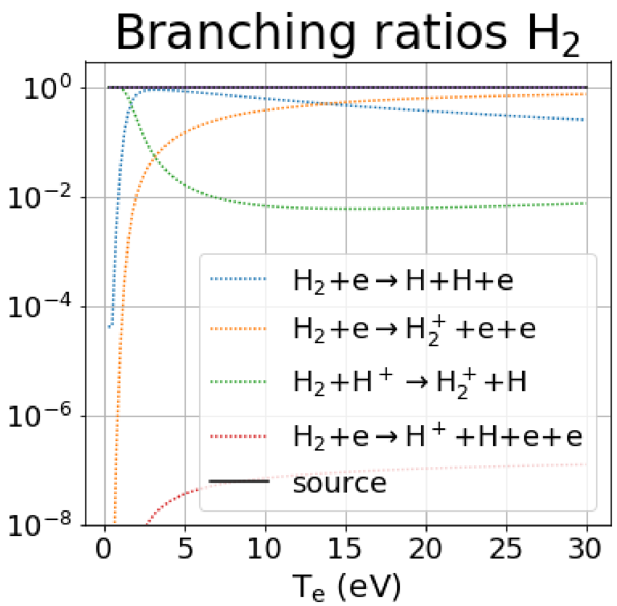
$n_e = n_i = 10^{19} m^{-3}$ JET

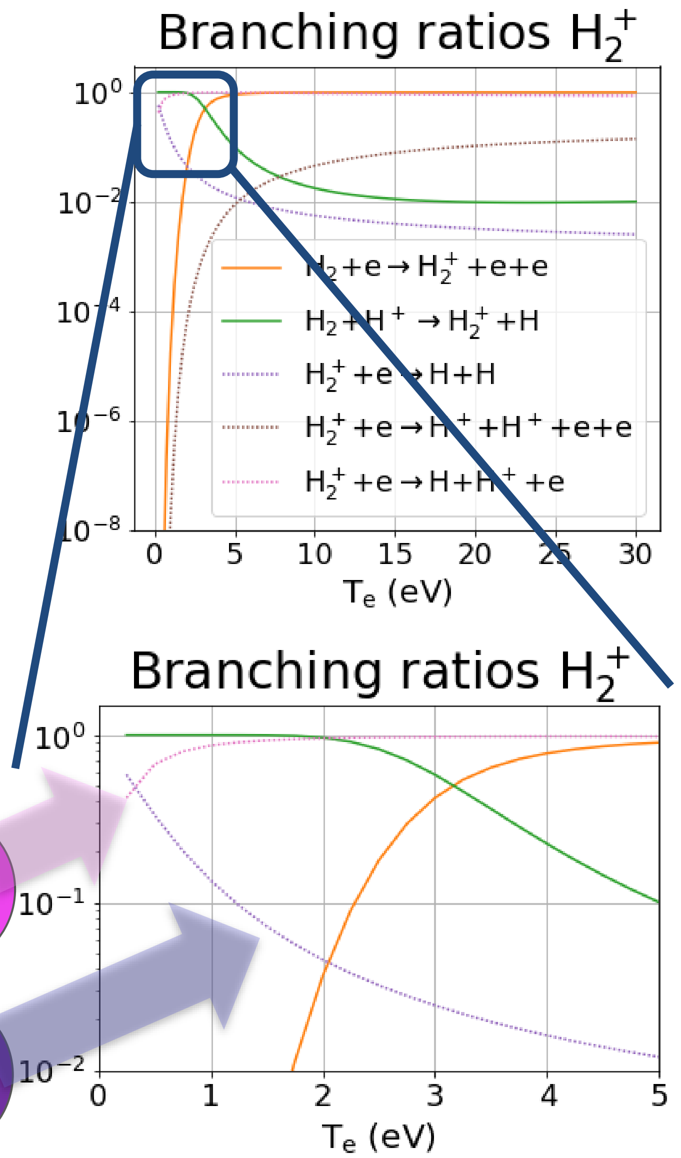
$n_e = n_i = 10^{21} m^{-3}$ EU-DEMO

CRM FOR MOLECULES: leading reactions with temperature

EU-DEMO







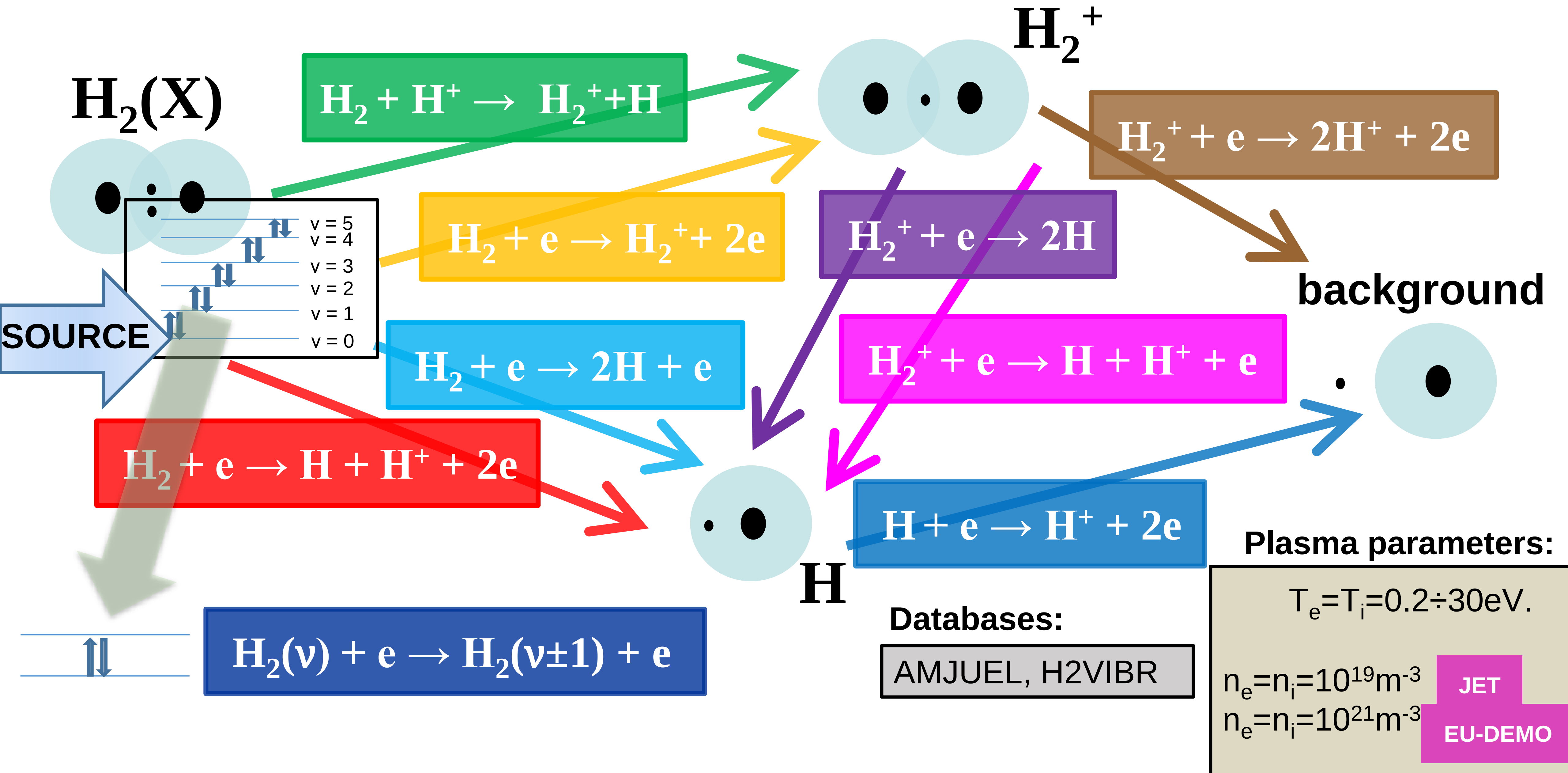
low temperature (T < 2eV) leading reaction chains:

MAR/MAD competition at very low temperature

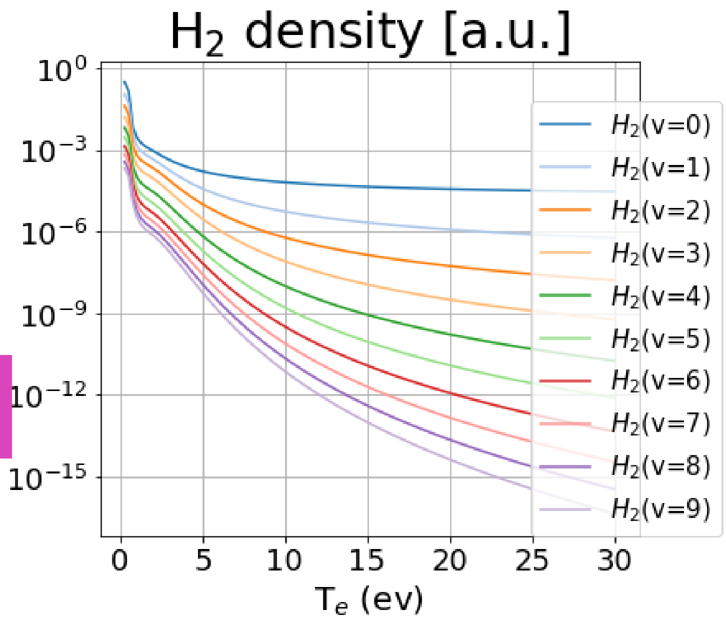
$H_2+H^+ \rightarrow H_2^+ + H$ **MAD** $H_2^+ + e \rightarrow H+H^+ + e$

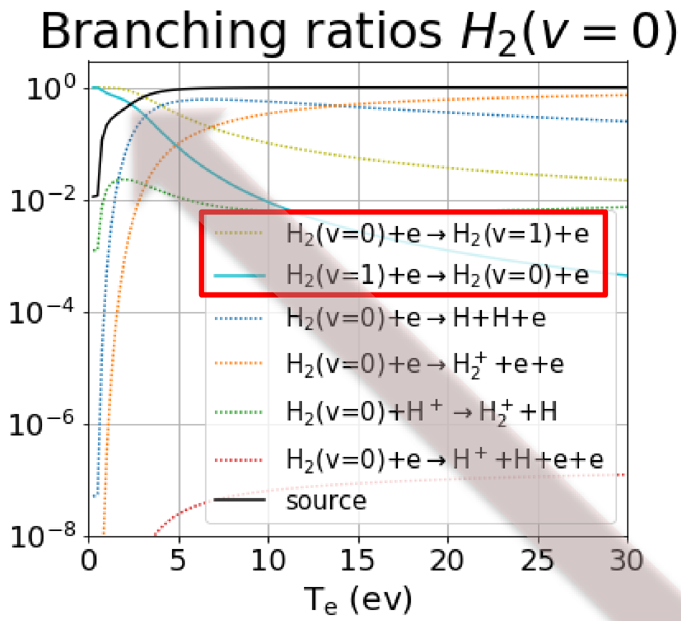
$H_2+H^+ \rightarrow H_2^+ + H$ **MAR** $H_2^+ + e \rightarrow H+H$

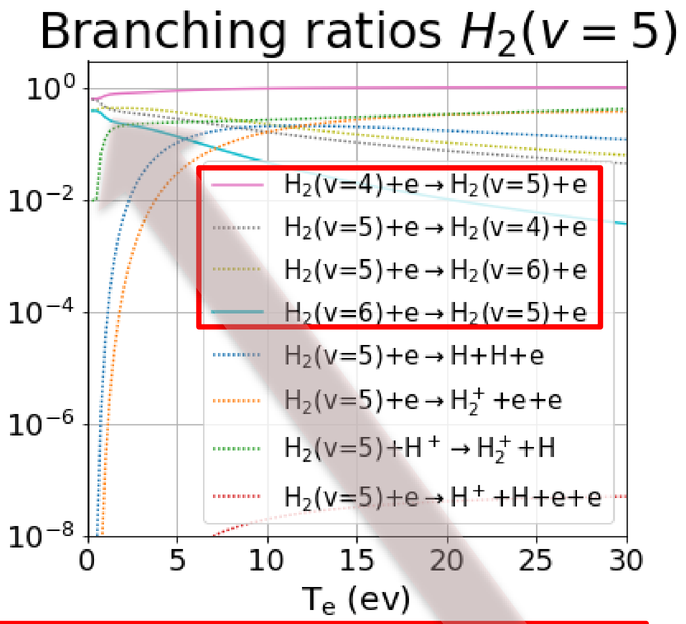
CRM FOR MOLECULES (vibr. resolved)



CRM FOR MOLECULES: leading reactions with temperature



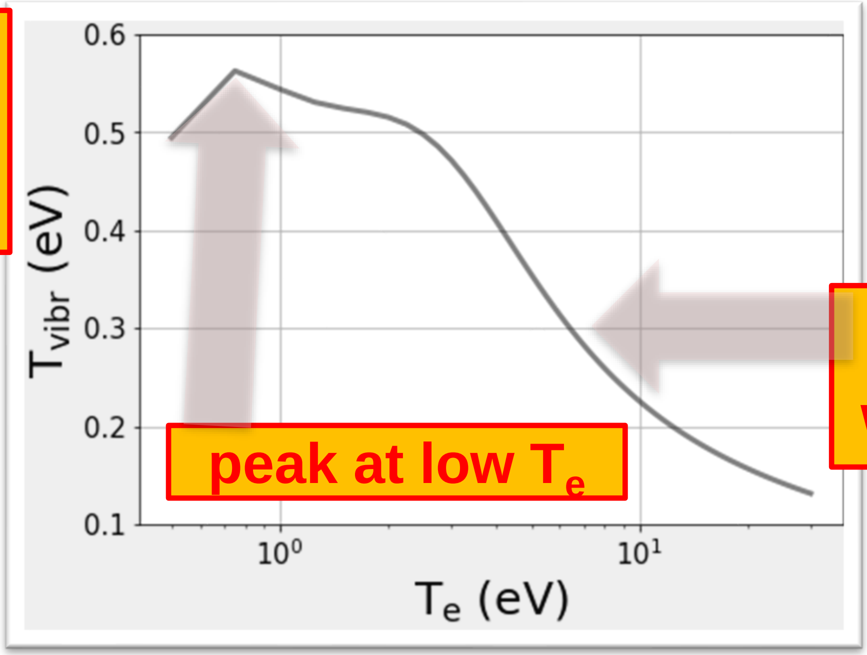




EU-DEMO

vibrational transitions are the main reaction channels at low temperatures

Maxwellian distribution (not obvious..)

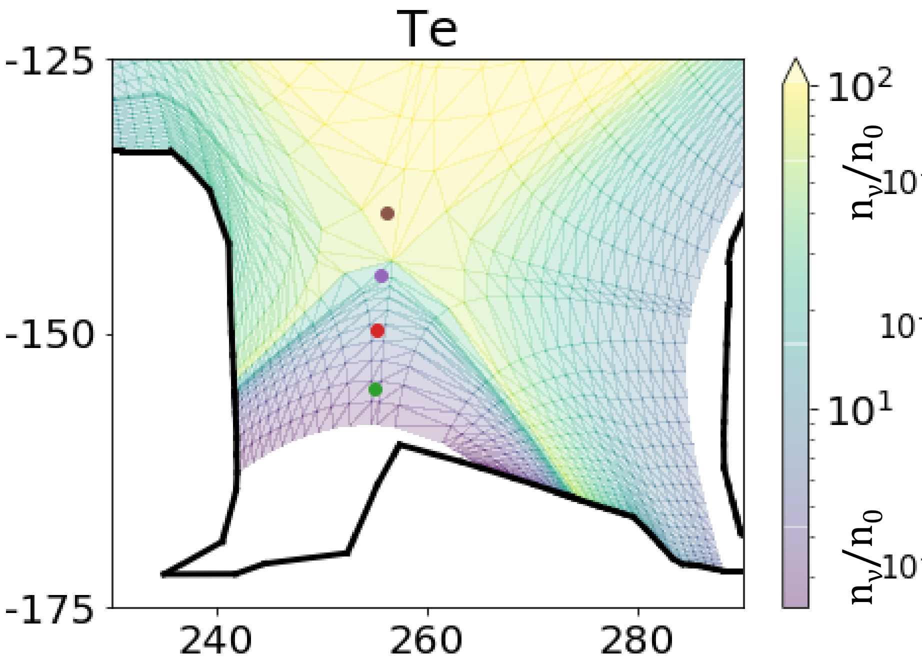


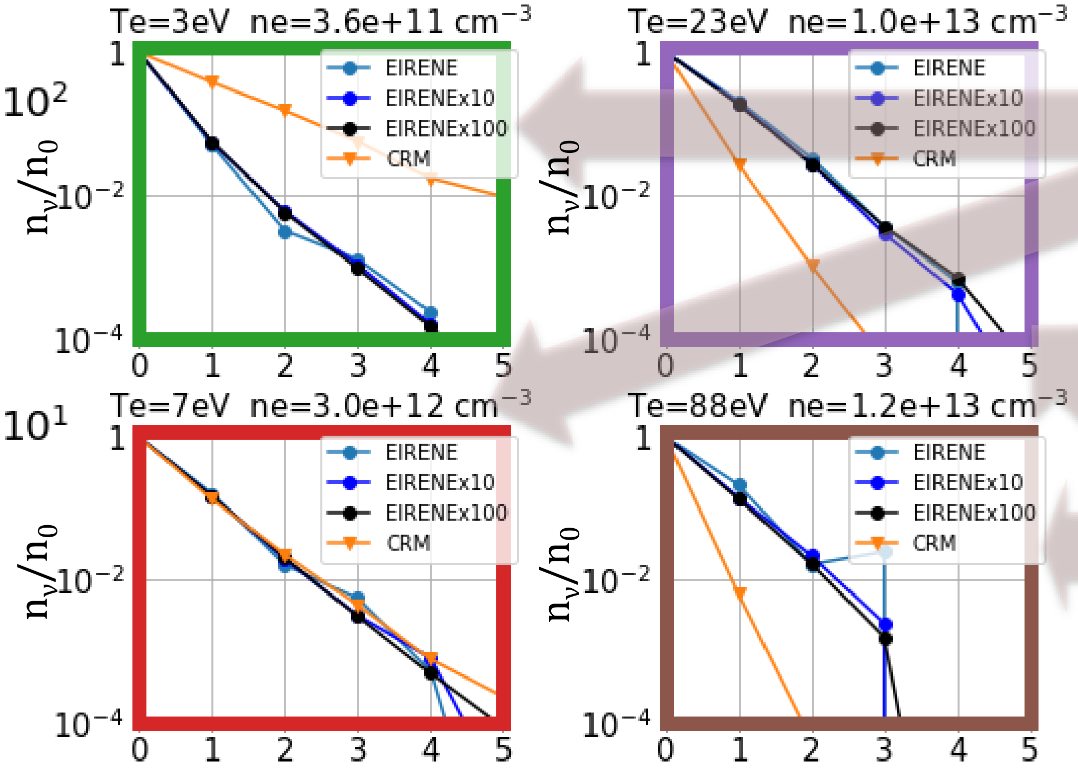
T_{vibr} increases with decreasing T_e

CRM vs EIRENE (vibr. resolved):

Simulations: **SOURCE v=0**

EIRENE: 793’300 histories
EIRENEx10: 7’933’000 histories
EIRENEx100: 79’330’000 histories





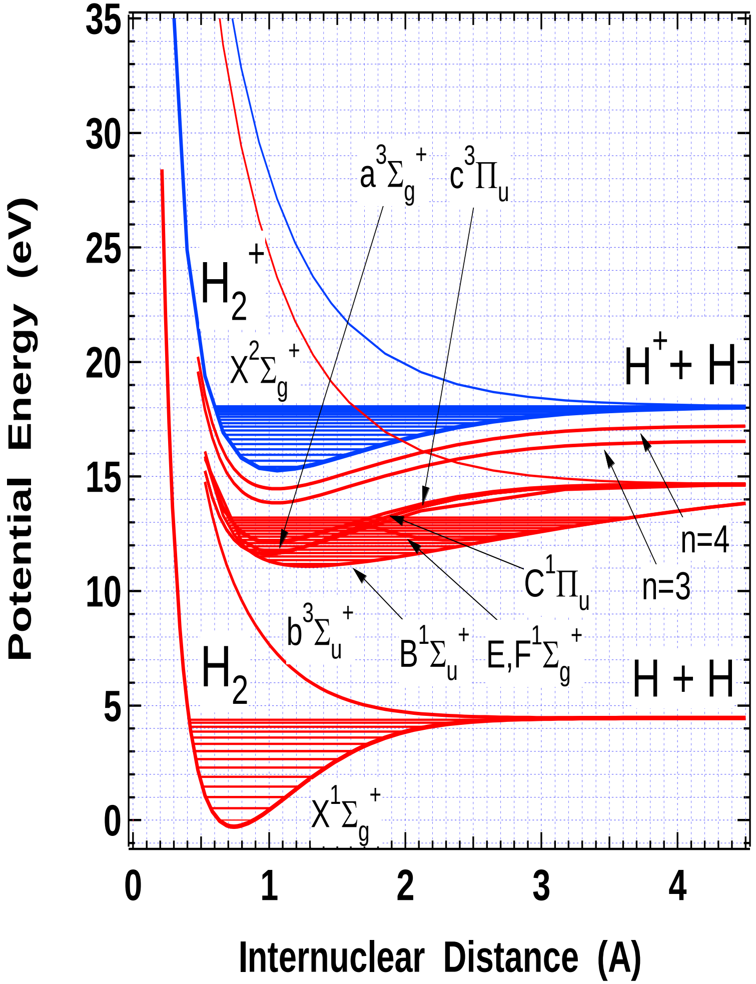
CRM overestimates excited state population at low temperature

CRM underestimates excited state population at large temperature

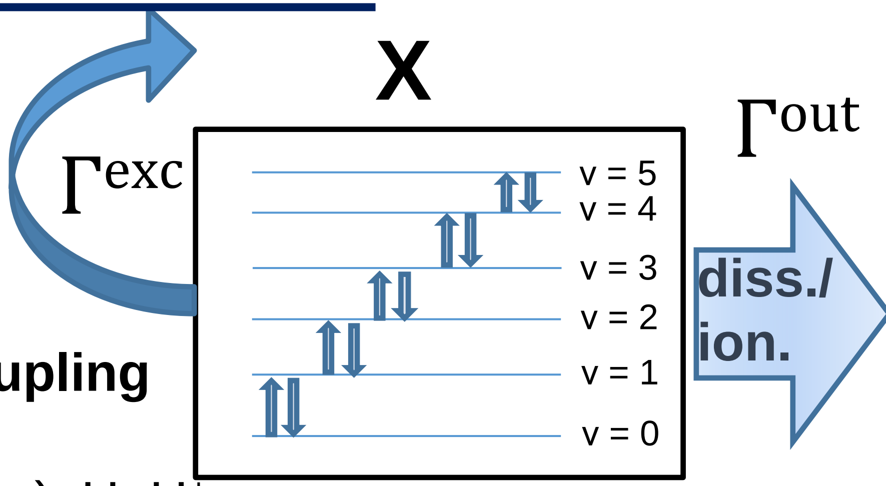
transport is important for vibrational distribution- full particle simulations (long and heavy)...

EXCITED MOLECULAR STATES: MCCC DB

- Preliminarily:

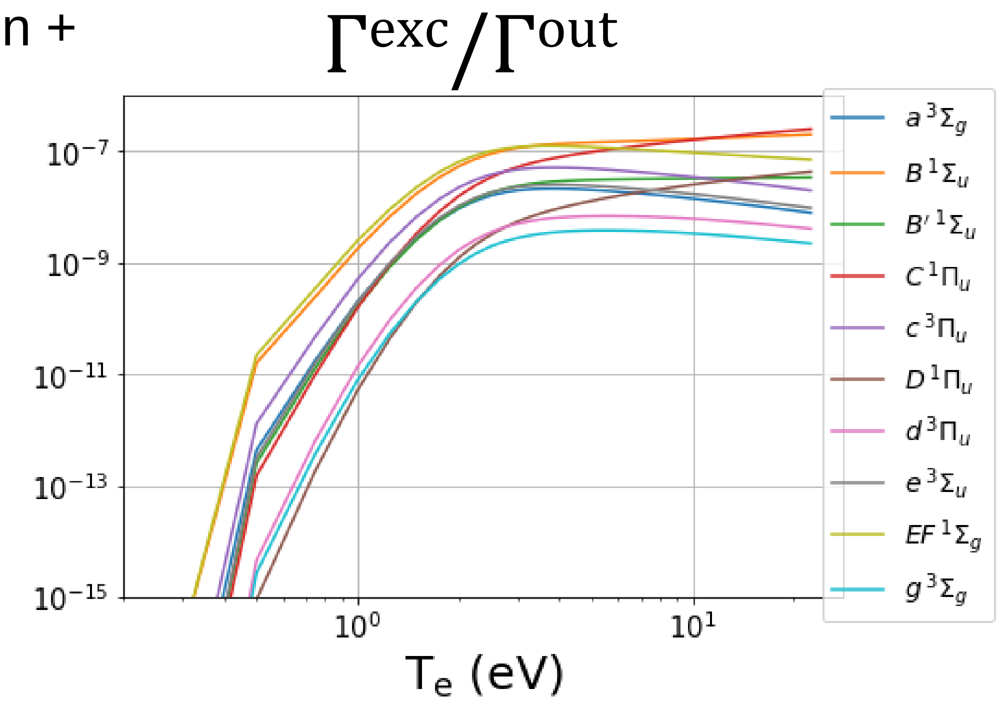


MCCC database:
Scarlett ADT 2021



- **Molecular Convergent Close-Coupling**
- electron and positron collisions
- target: H_2 (**isotopes**), H_2^+ (**isotopes**), HeH^+
- dissociation, ionizat., excitation + **vibrational resolution**
- output: **tabular**

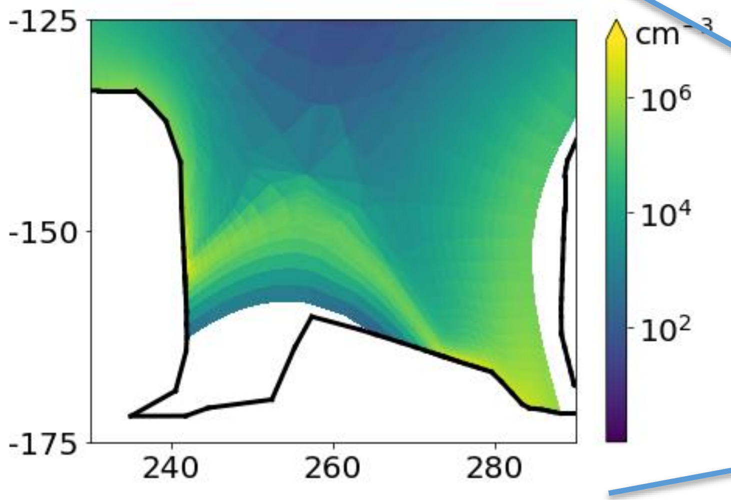
$$\Gamma^{exc} \ll \Gamma^{out}$$

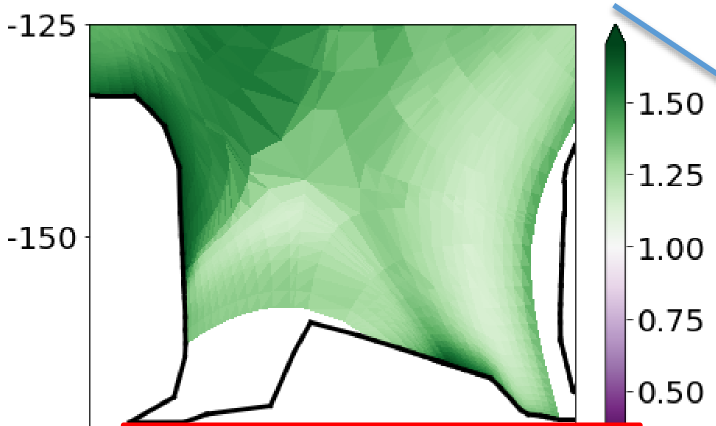


Model for excited states on top of ground state distribution

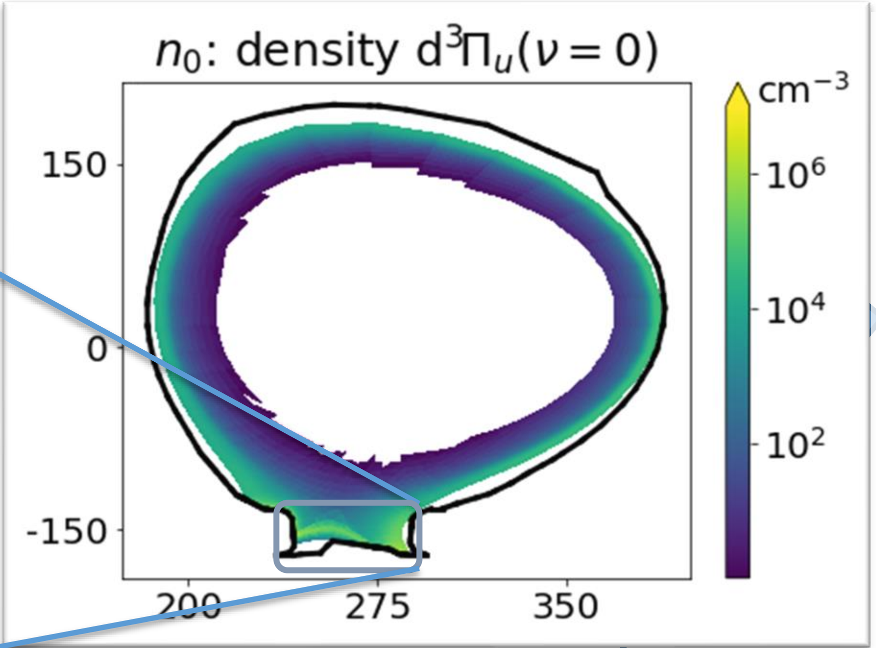
EXCITED MOLECULAR STATES: EIRENE

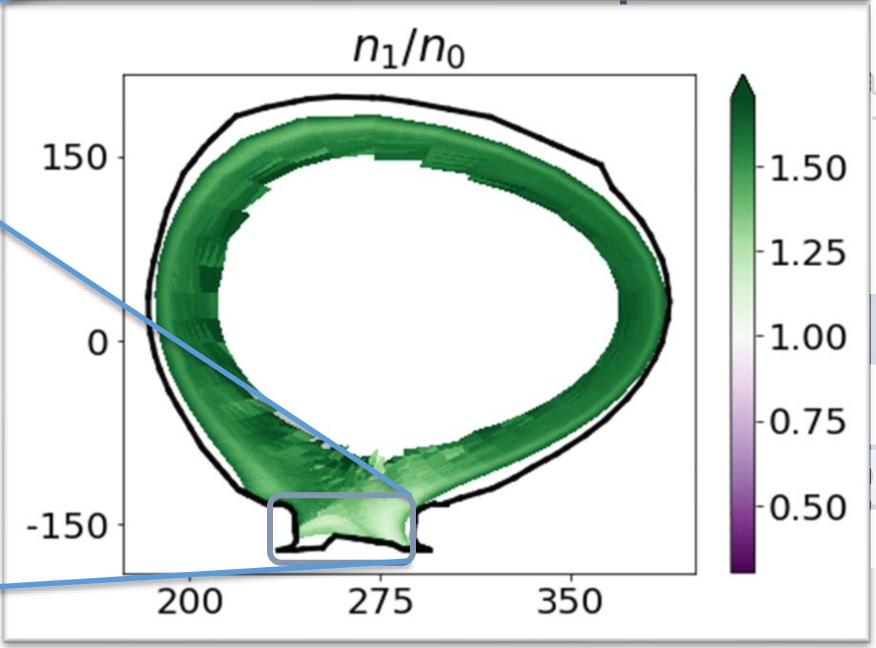
- excited state **d $^3\Pi_u$**:

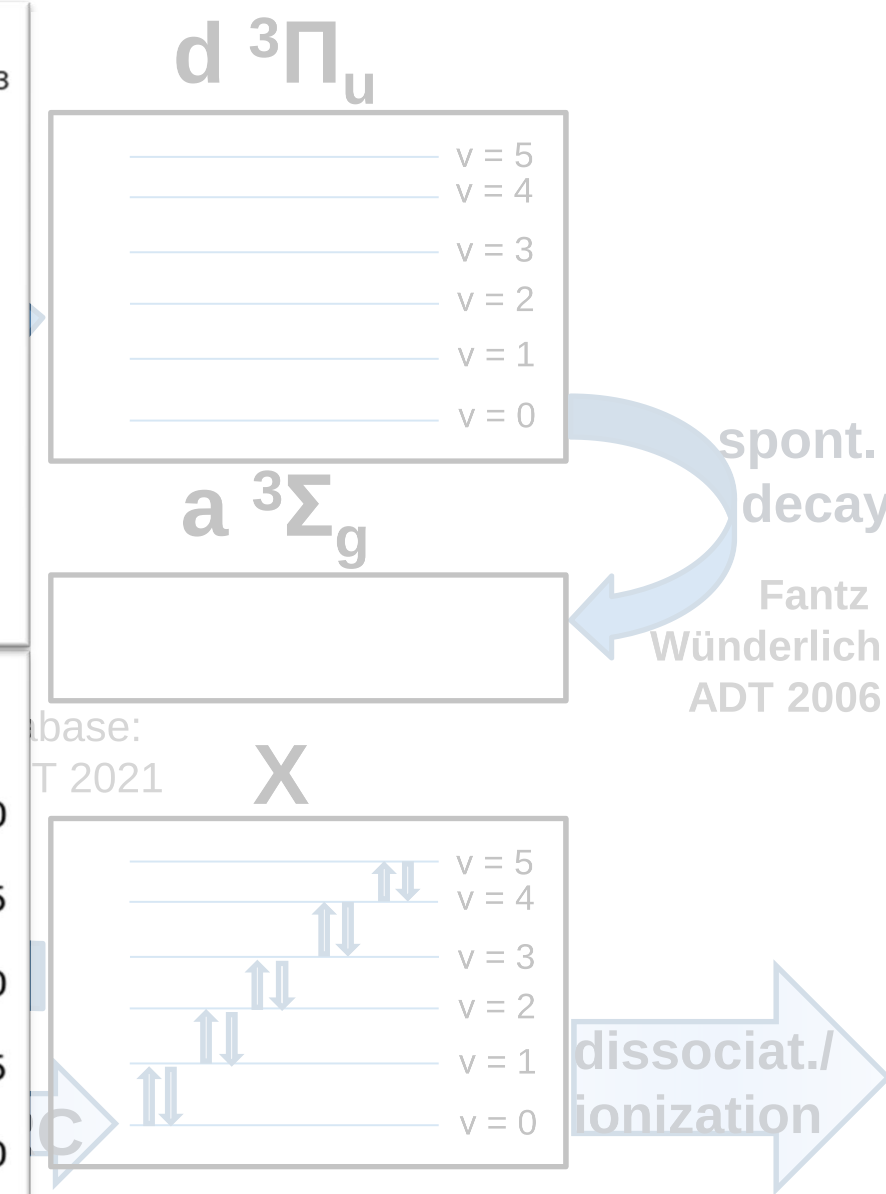




divertor population coefficients≃1.2

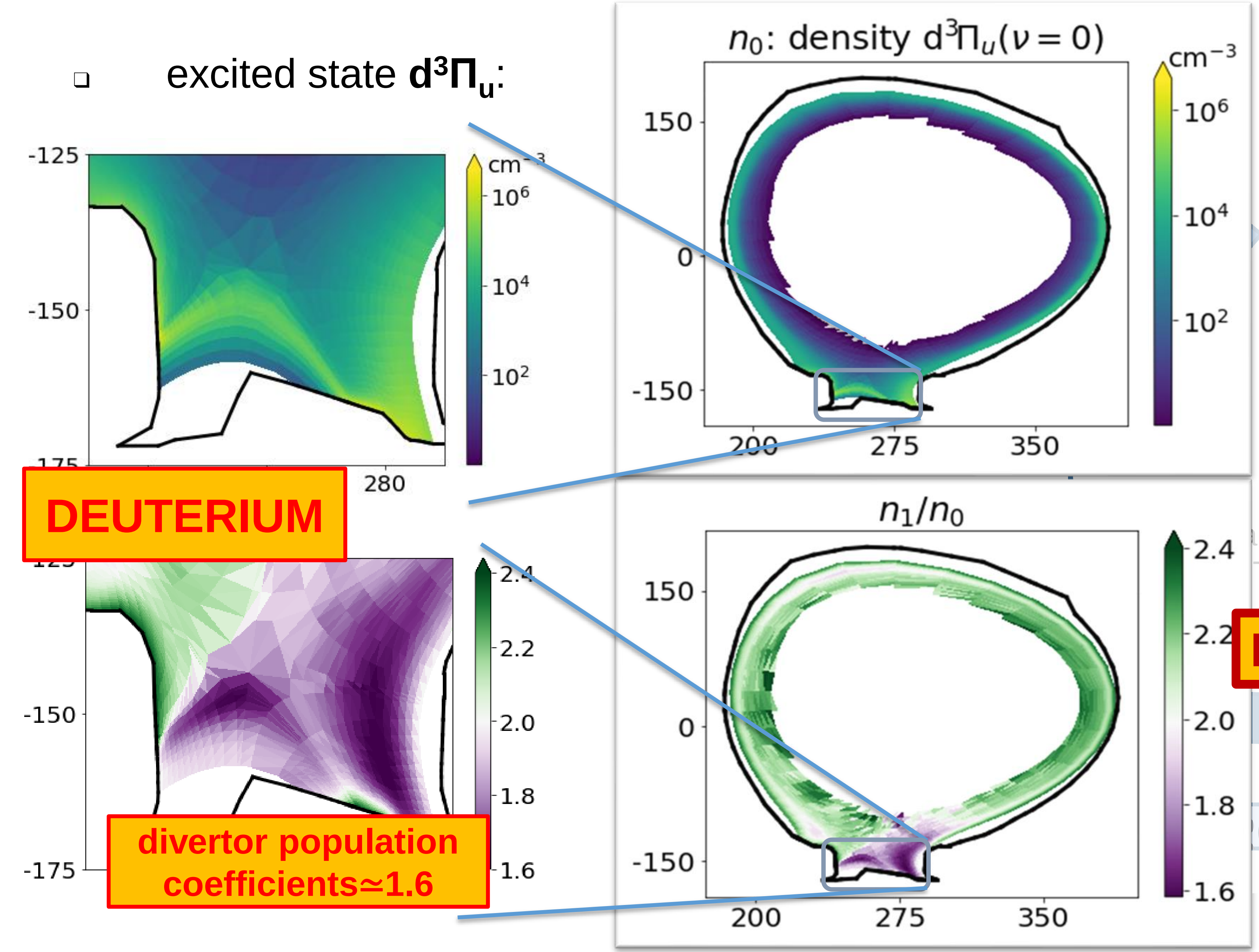






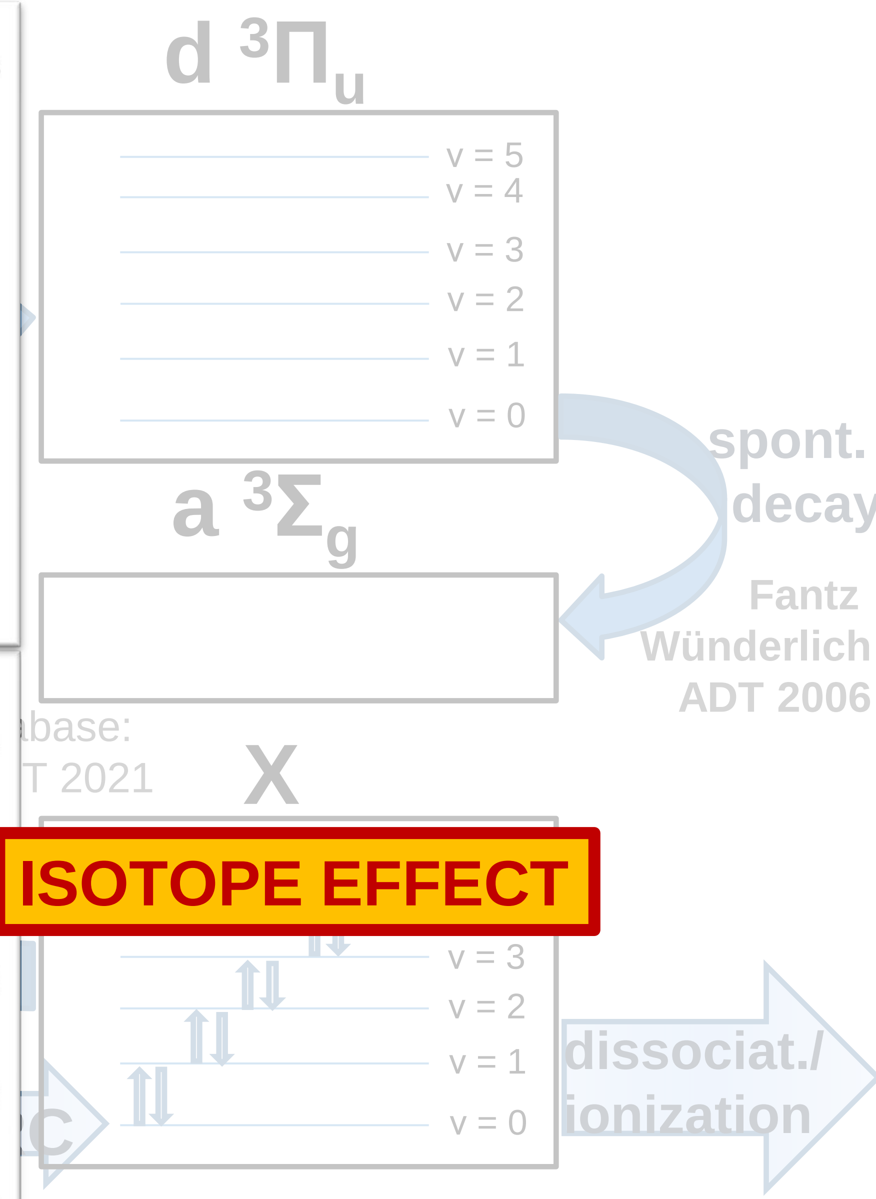
EXCITED MOLECULAR STATES: EIRENE

- excited state $d^3\Pi_u$:



DEUTERIUM

divertor population coefficients≃1.6



ISOTOPE EFFECT