Assessing runaway electron losses due to field stochasticity

K. Särkimäki, F.J. Artola, T. Fülöp, M. Hoelzl, and E. Nardon

sarkimk1@ipp.mpg.de

9th Runaway Electron Modelling Meeting
2.- 6. 5. 2022

EUROfusion

Max Planck Institute
for Plasma Physics

JOREK

We have enjoyed several intellectually stimulating presentations on complex topics.

We have enjoyed several intellectually stimulating presentations on complex topics.

This is not going to be one of those.

We have enjoyed several intellectually stimulating presentations on complex topics.

This is not going to be one of those.

This... is... spar... test particle physics!

We have enjoyed several intellectually stimulating presentations on complex topics.

This is not going to be one of those.

This... is... spar... test particle physics!

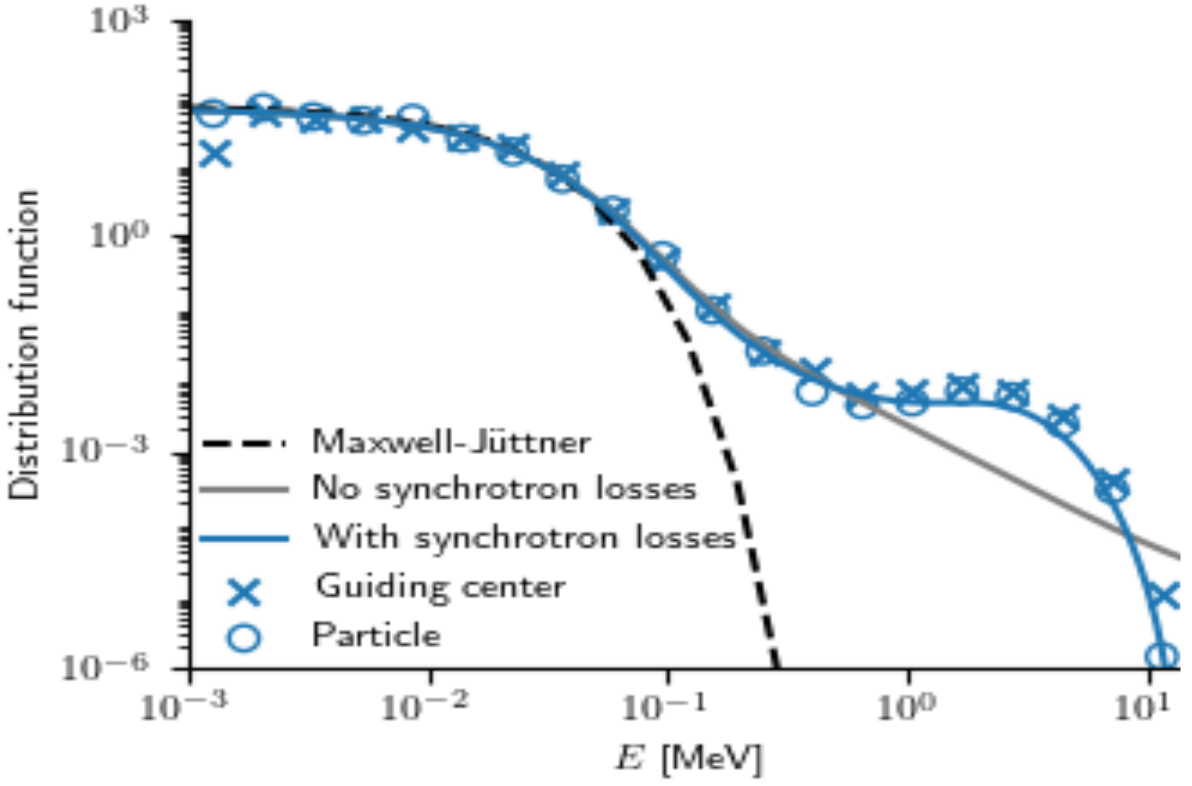
So no feedbacks, beam evolution, etc. - just orbits and losses.

MHD models have become increasingly better at simulating disruptions.
Tracing particles have become increasingly meaningful.

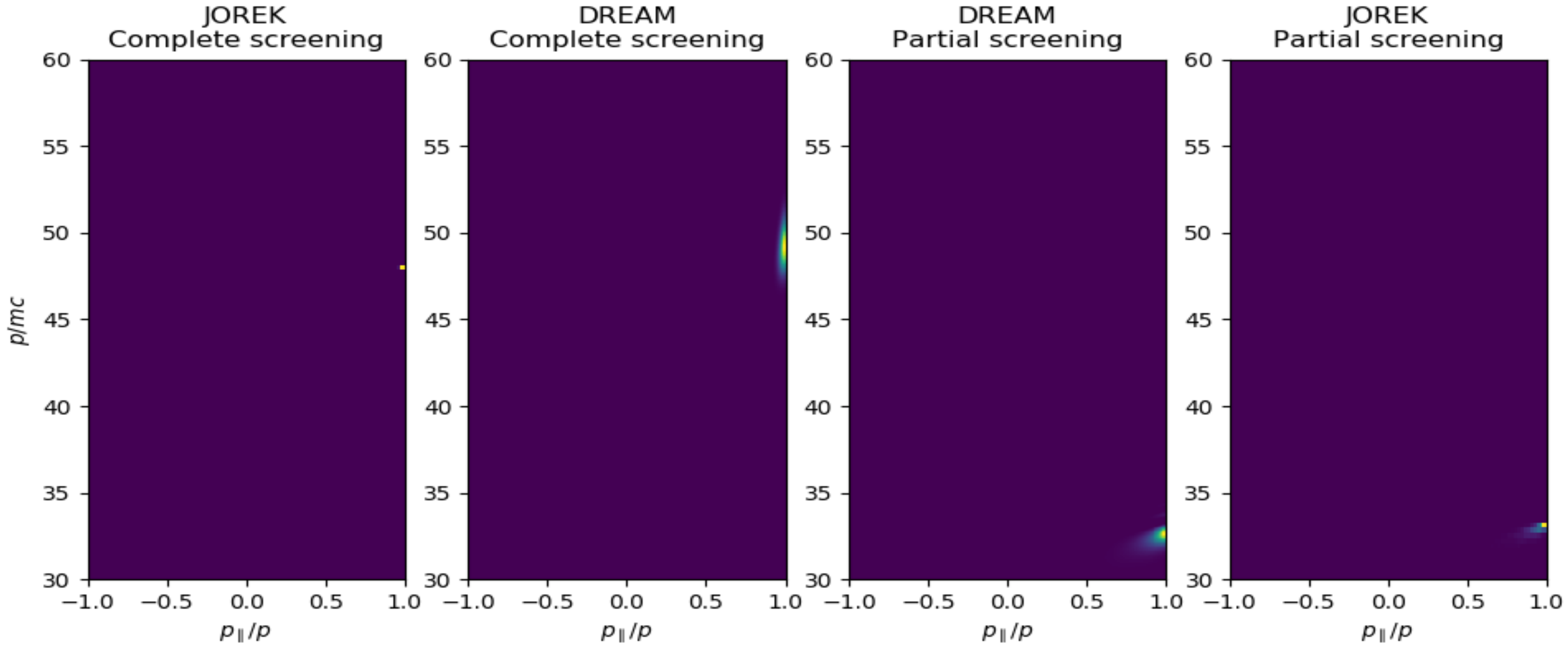
MHD models have become increasingly better at simulating disruptions.
Tracing particles have become increasingly meaningful.

Particle modelling itself is at least theoretically capable of predicting RE generation.

Verifying that JOREK-particle reproduces bump-on-tail distribution after implementing Coulomb collisions and synchrotron losses.



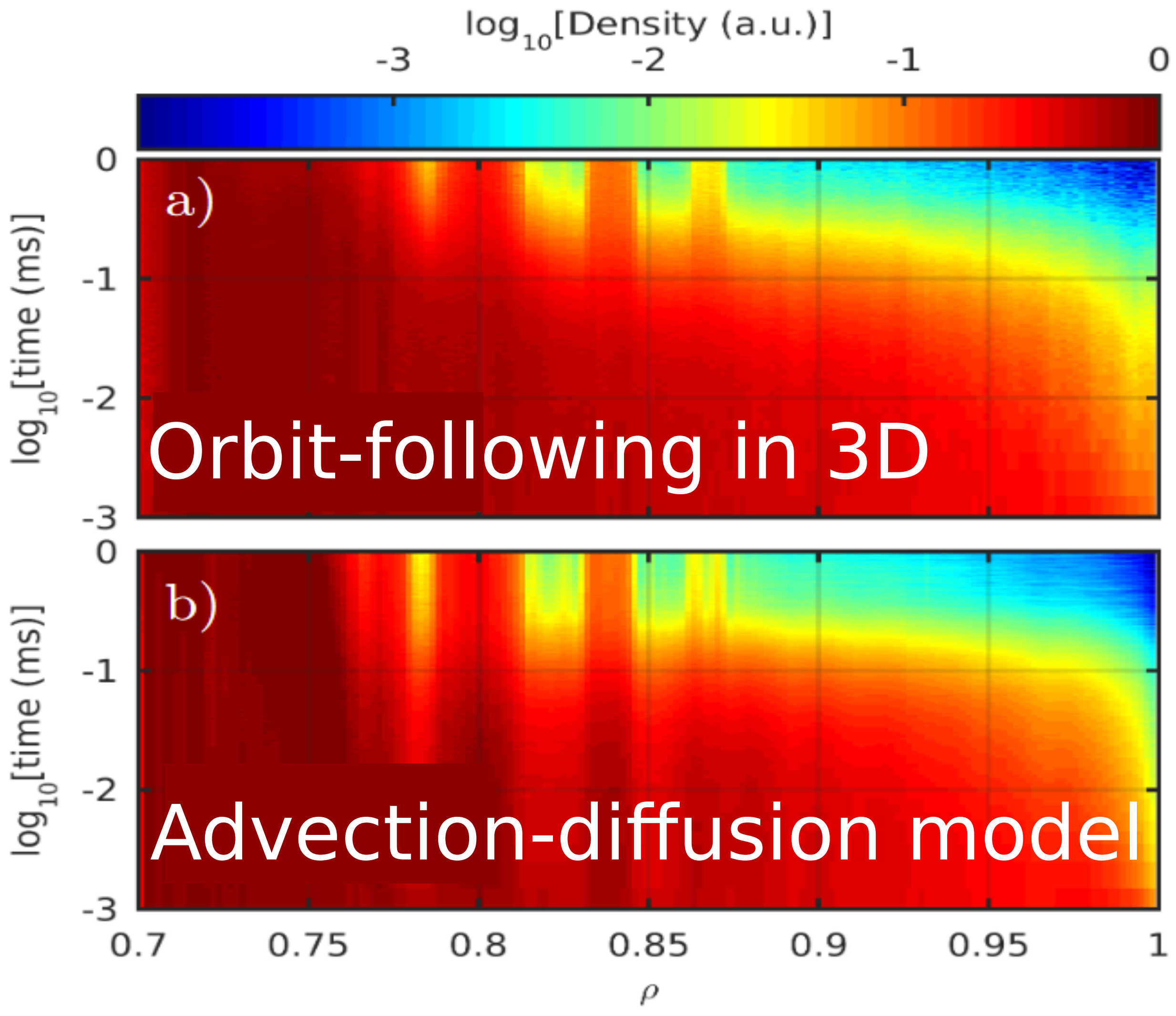
Partial-screening seems to work as well.



MHD models have become increasingly better at simulating disruptions.
Tracing particles have become increasingly meaningful.

Particle modelling itself is at least theoretically capable of predicting RE generation.

But test particle simulations alone cannot solve the RE problem.
Coupling to MHD, coupling to kinetic tools.



Transport coefficients from orbit-following simulations allow introducing stochastic field (losses) to reduced kinetic models.

First I'm going to convince you stochastic losses are important.
At least in a single ITER scenario.

Next its time to talk about trapped RE confinement.

...and then how passing RE transport depends on energy.

Finally, what I'm going to present at REM 2023.
Possible locations are listed below:

München

Göteborg

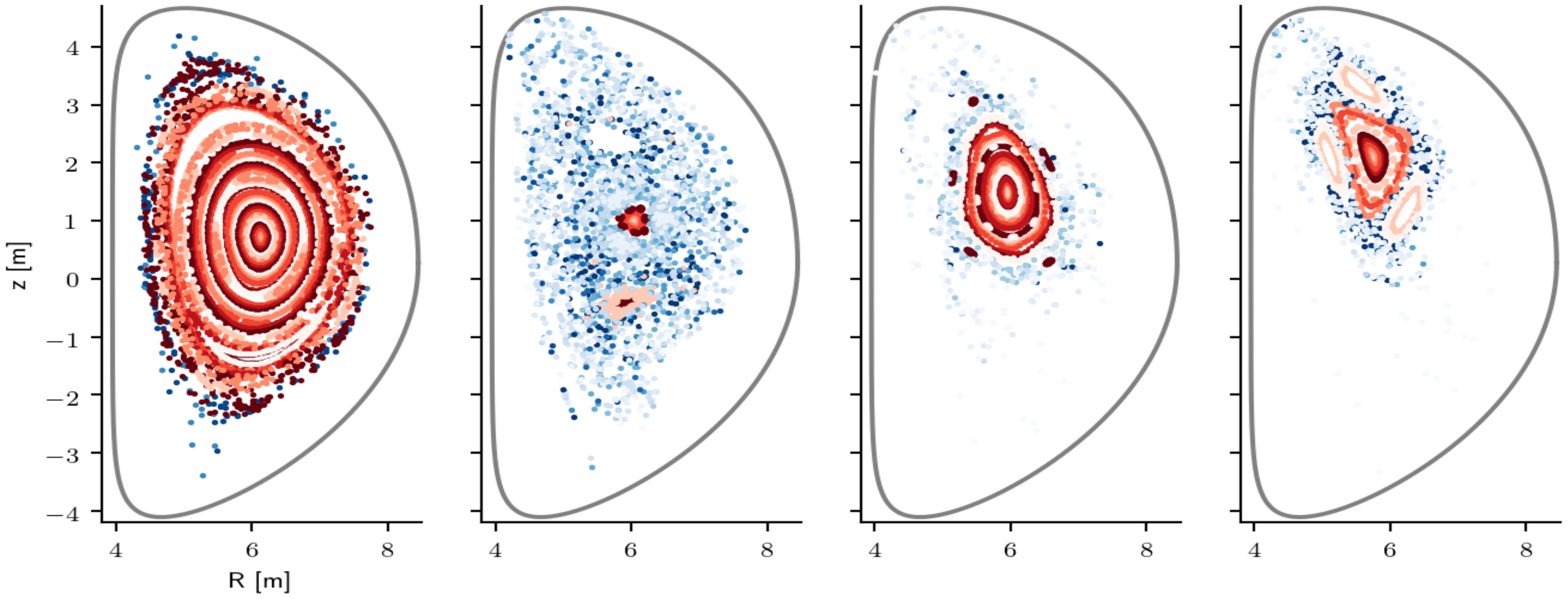
Helsinki

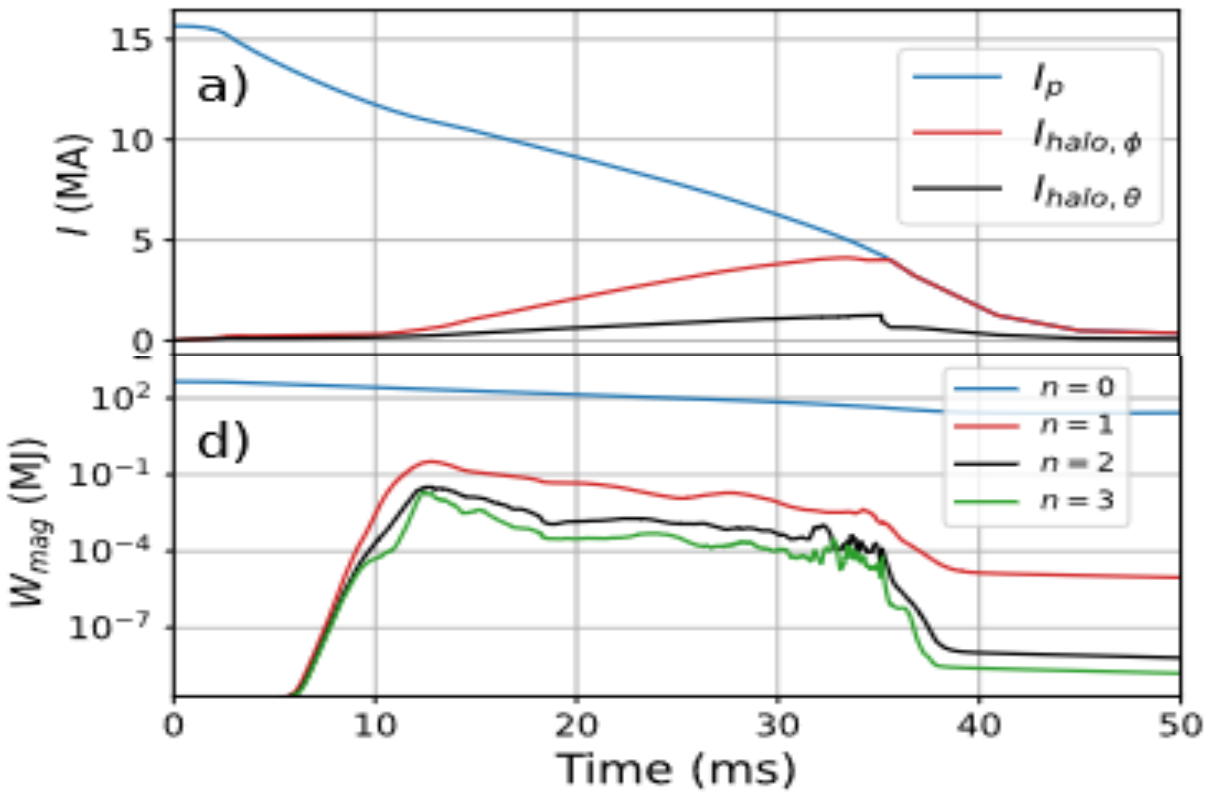
[Artola NF 2022] recently modelled cold VDE with JOREK
and the field was found to be quite stochastic.

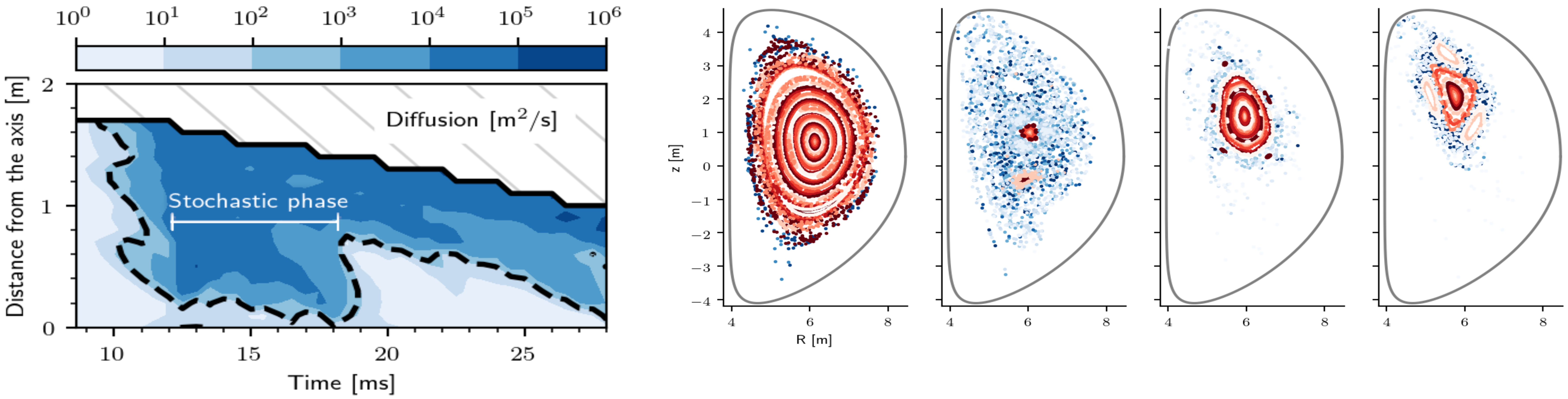
The stochastic phase lasts for ~8 ms.
Is is strong enought to affect REs?

Important!
Just a single case, unknown how
sensitive the results are
to the initial conditions.

TQ was not modelled.
Stochastization probably happens already during TQ.
-> Both hot-tail and avalanche are of interest.





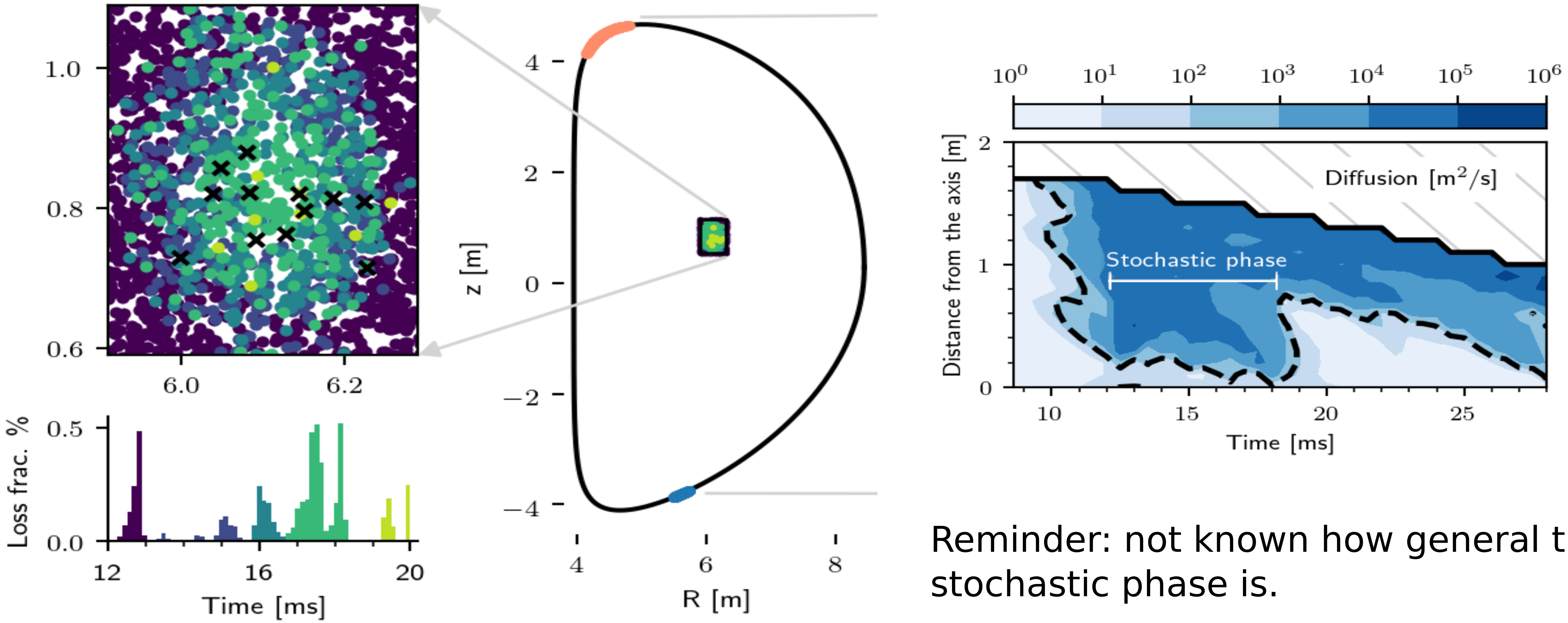


Computed transport coefficients as a function of time and radius.

-> Used to estimate RE loss rate.

-> If this is larger than avalanche gain, then no beam forms [Martín-Solís PoP 2021].
(Passing hot electrons also lost.)

What about that region close to the axis?



Reminder: not known how general this stochastic phase is.

What about that region close to the axis?
Almost completely lost.

Beam might develop once the core is healed.

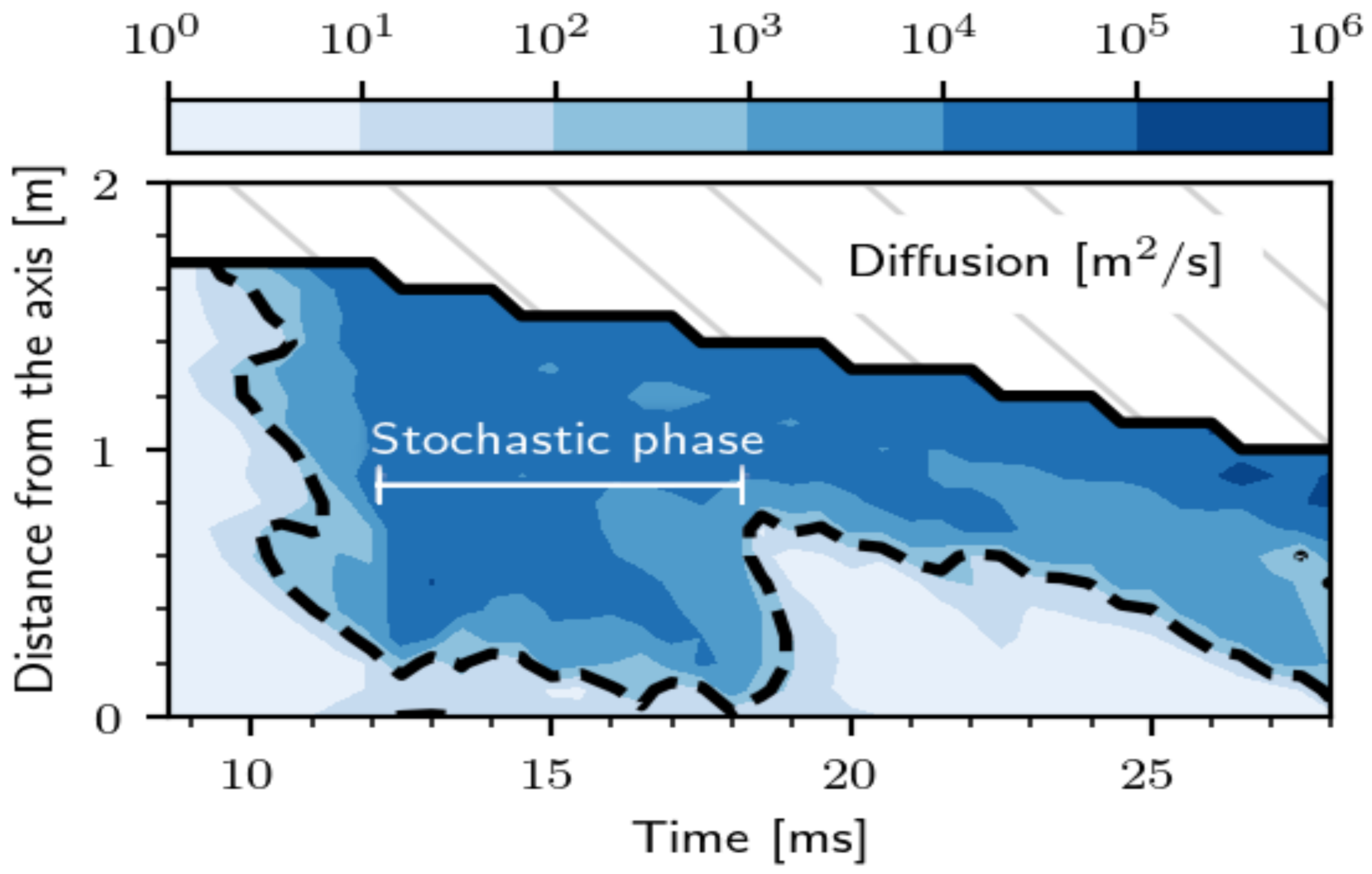
Trapped RE confinement

What causes trapped REs?
Hot-tail, collisional scattering (+ synchrotron radiation), knock-on collisions.

These do not trace stochastic field lines.

What if these survive the stochastic phase to form a new beam?
Trapped REs can become passing due via scattering or Ware pinch.

Probably more of an issue for a shorter stochastic phase.
However, the results shown here should be generalizable.

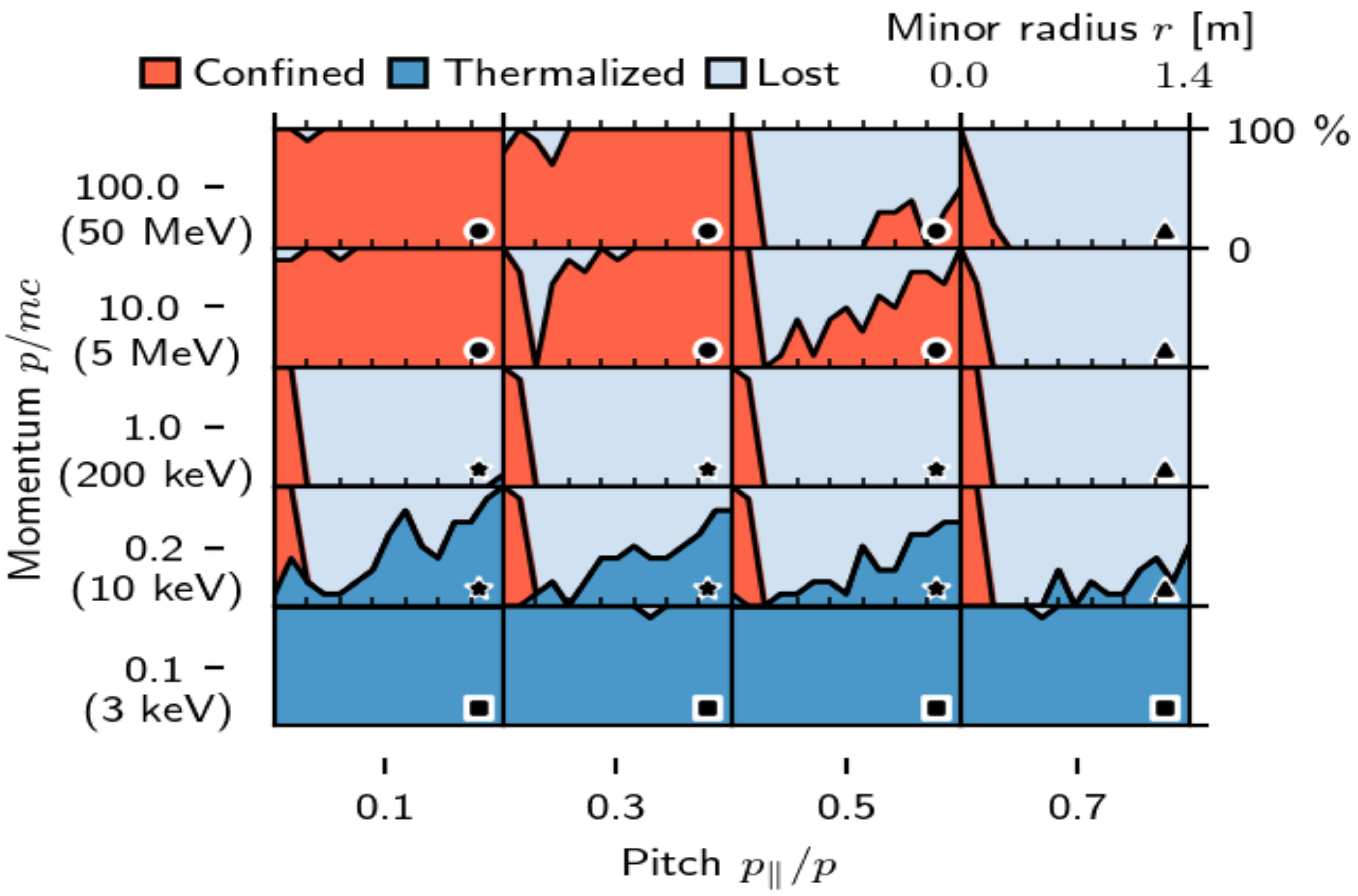


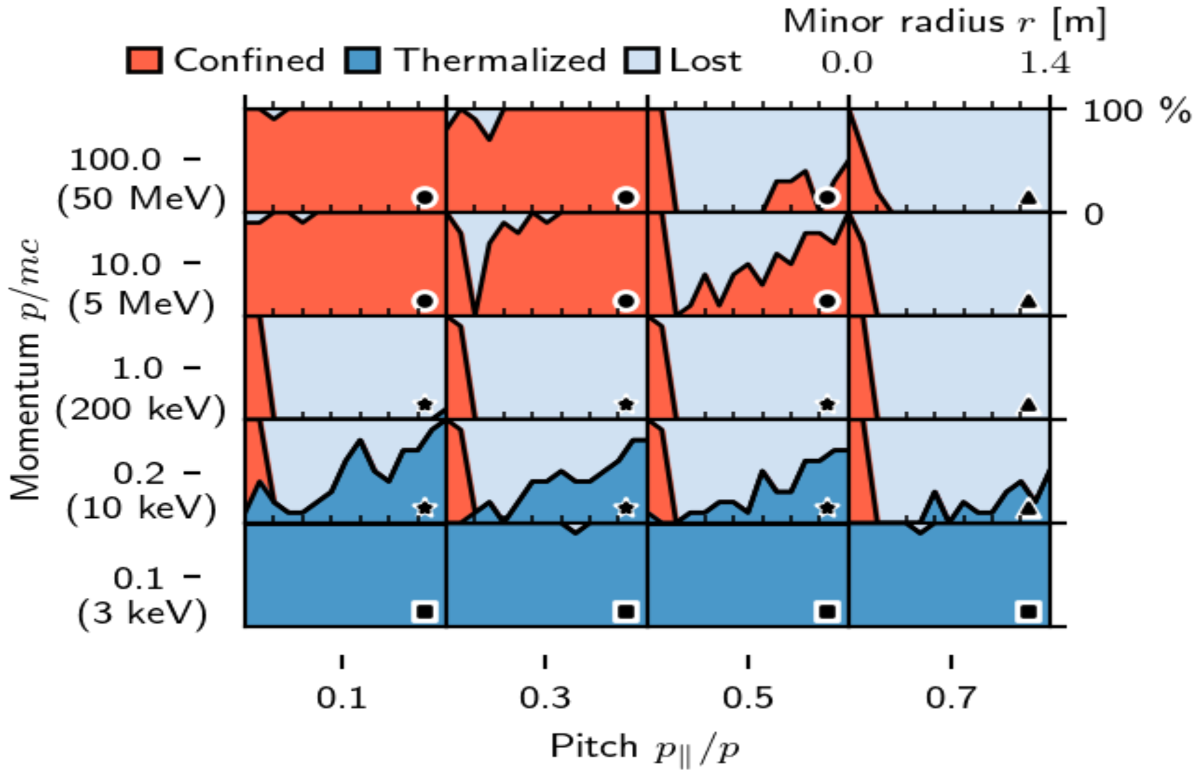
One phase-spaceful of REs traced for 1 ms during the stochastic phase.

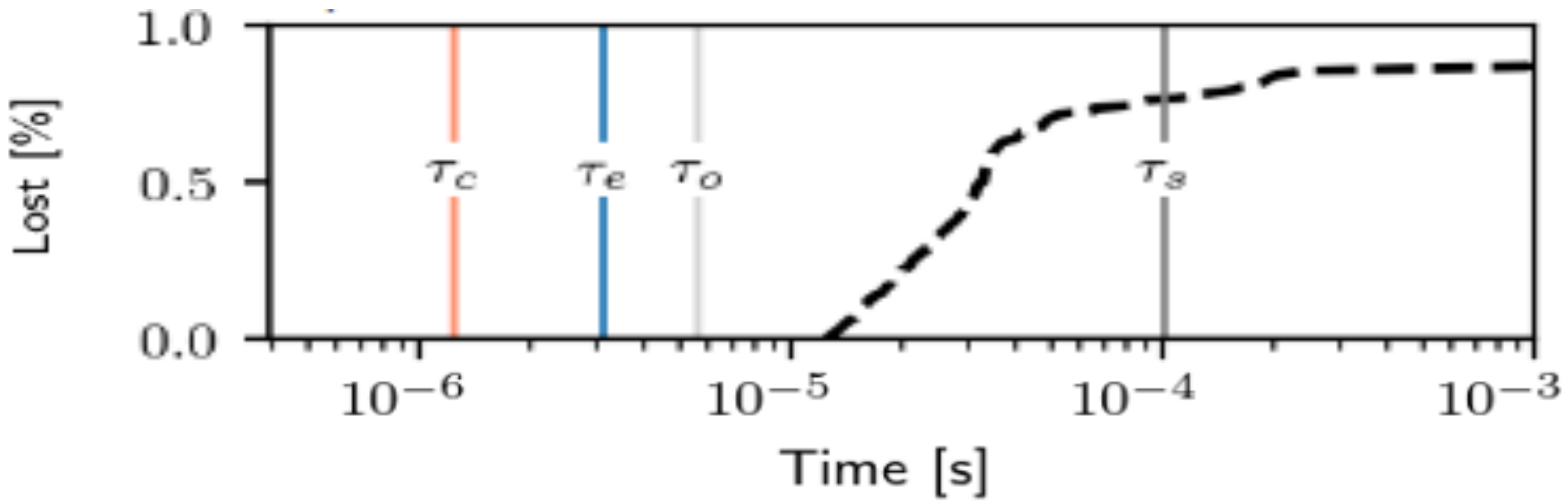
Collisions and synchrotron losses included.

REs are lost where it matters.

But why are they lost?



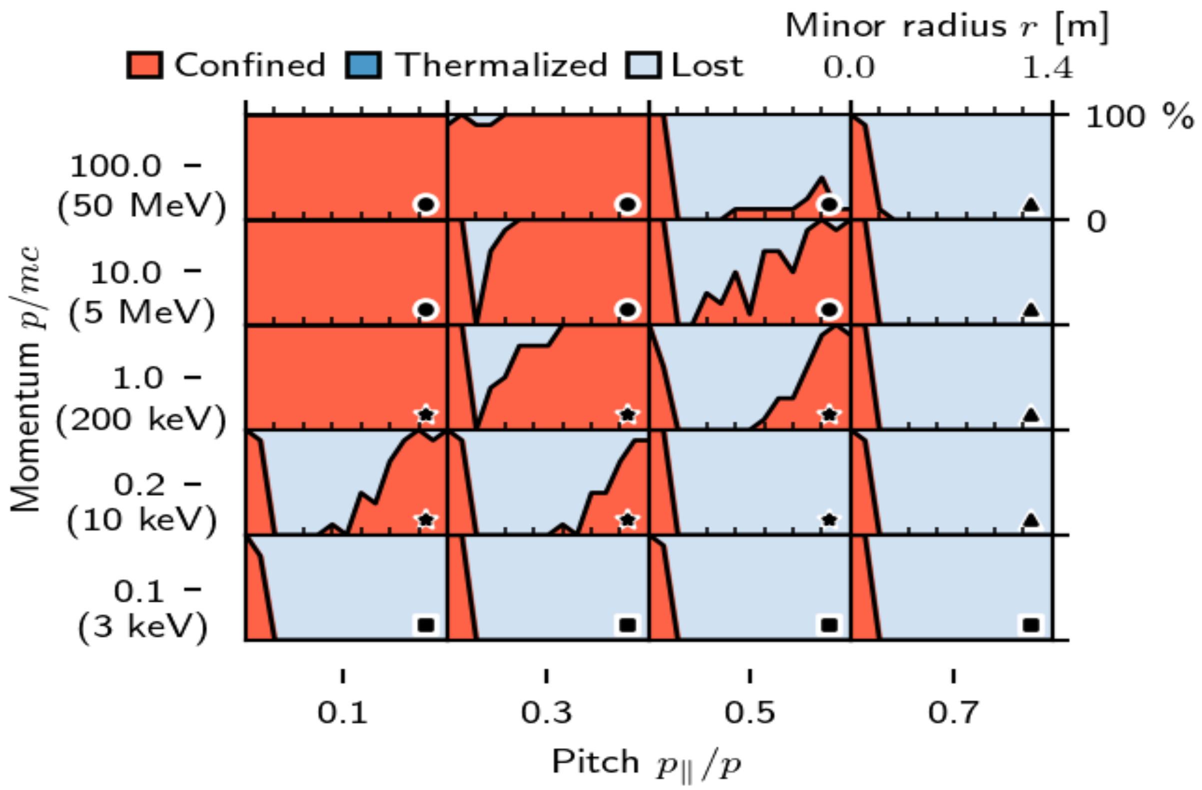


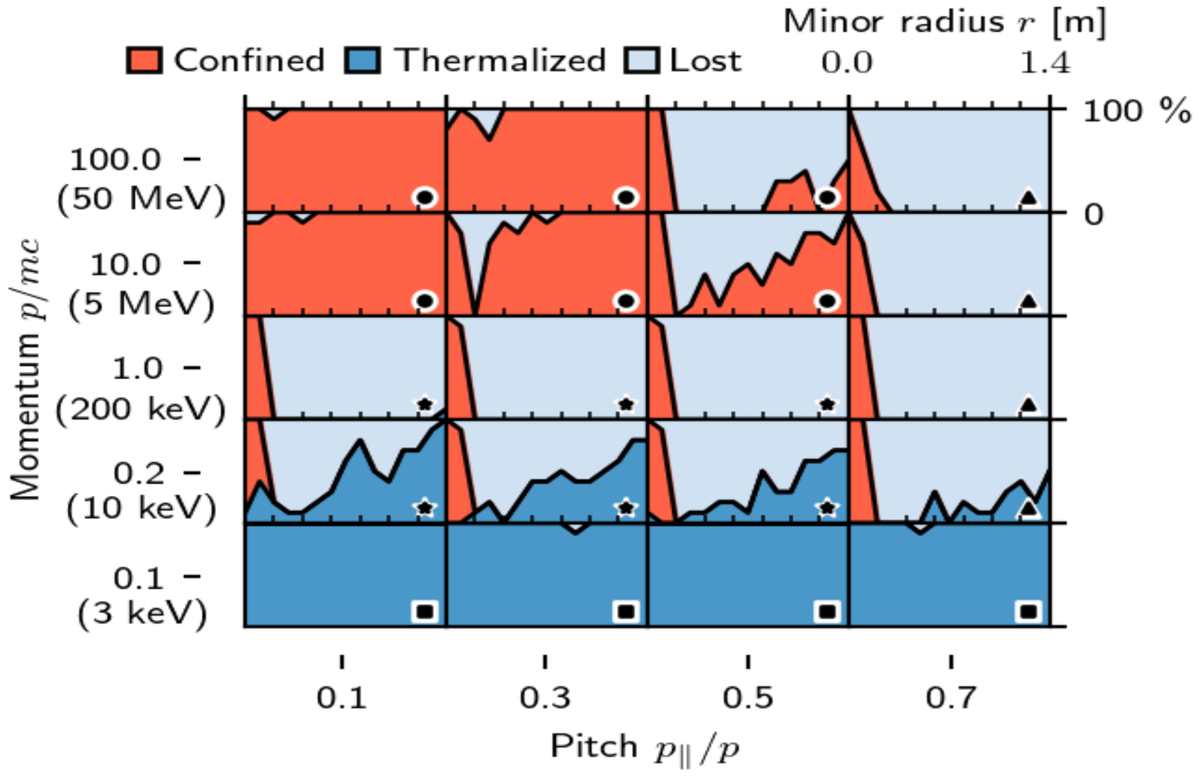


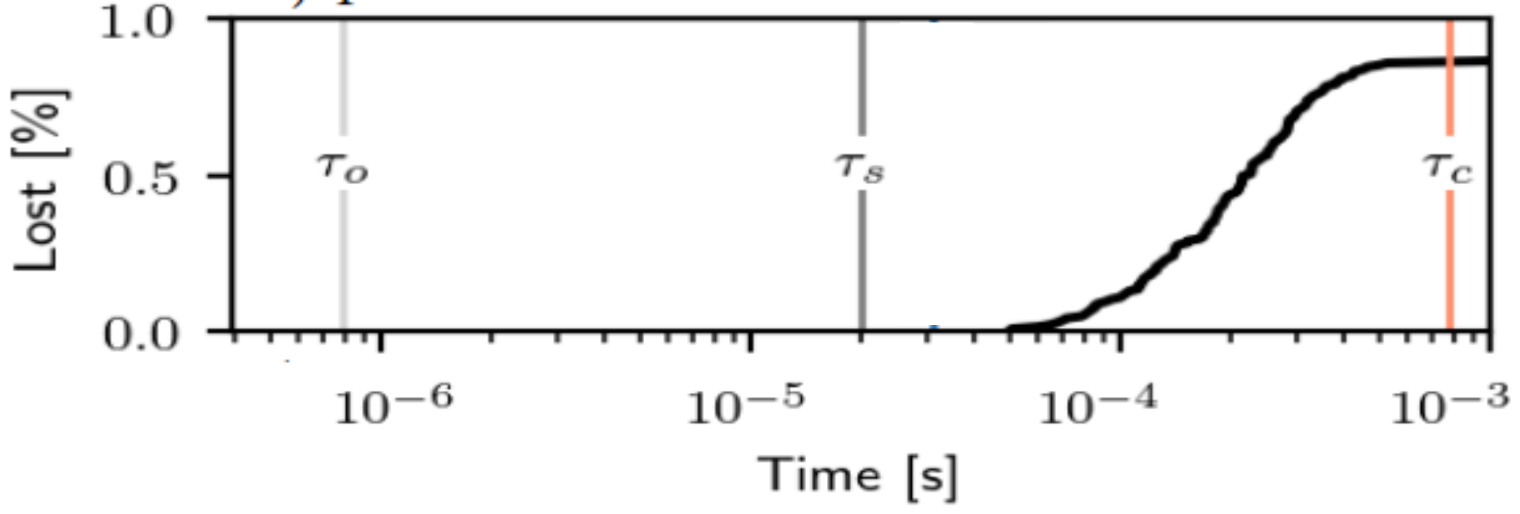
Below critical energy electrons just cool-down.

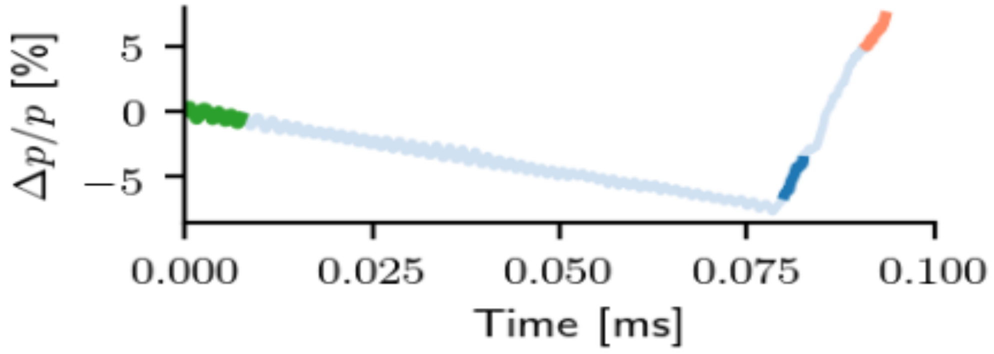
Semi-analytical estimates for the time-scales of different processes help to understand the whole story.

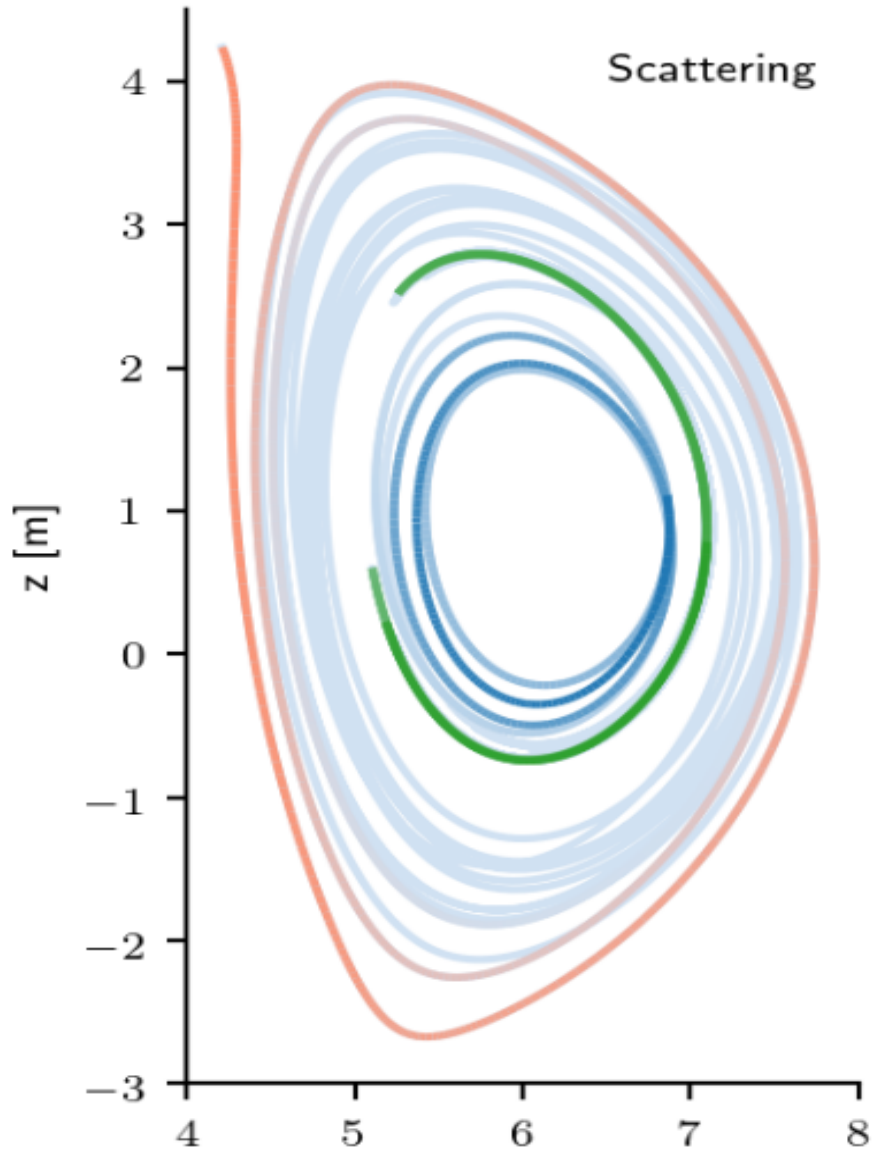
Same case without collisions.



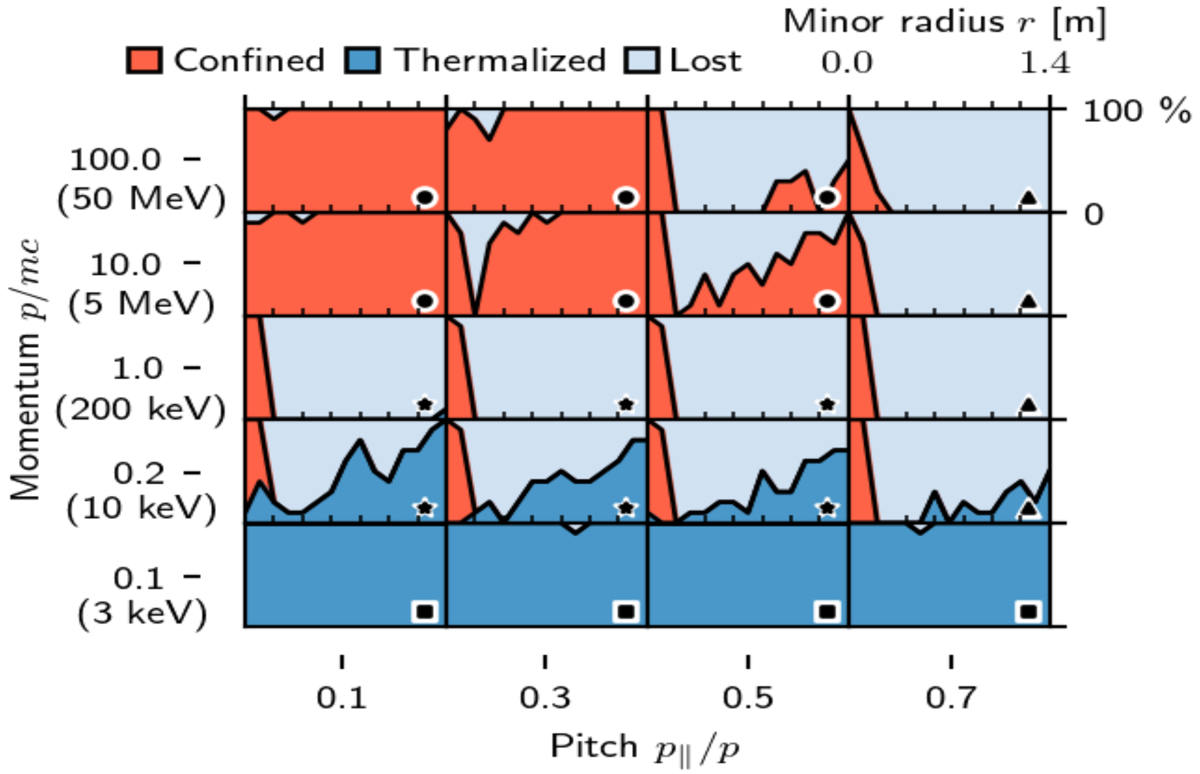


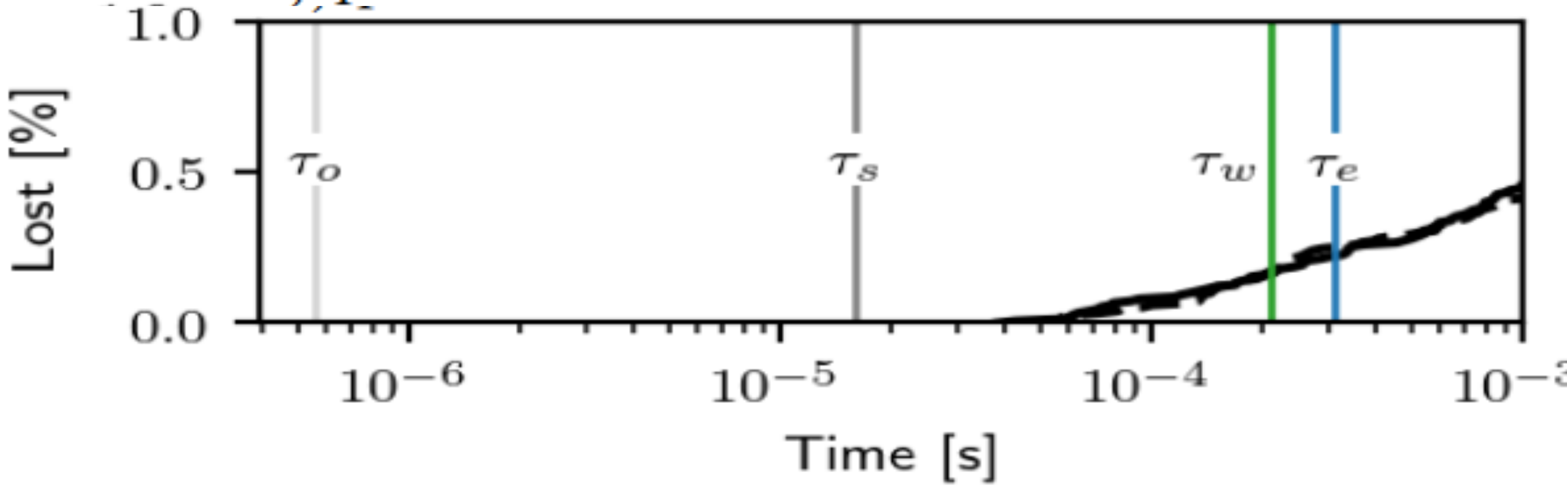


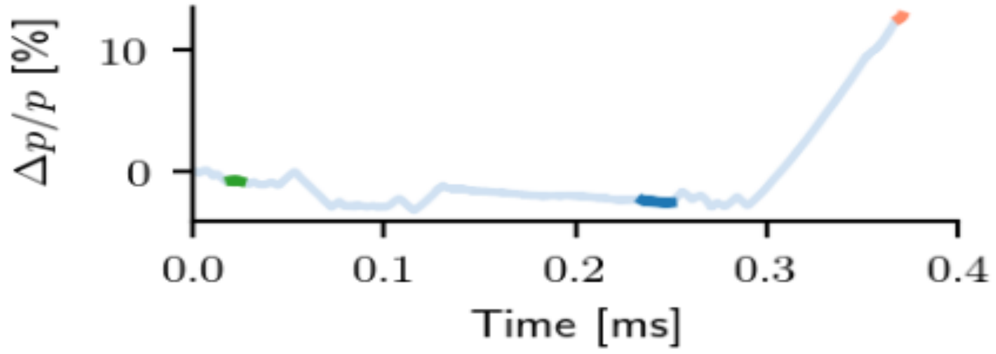


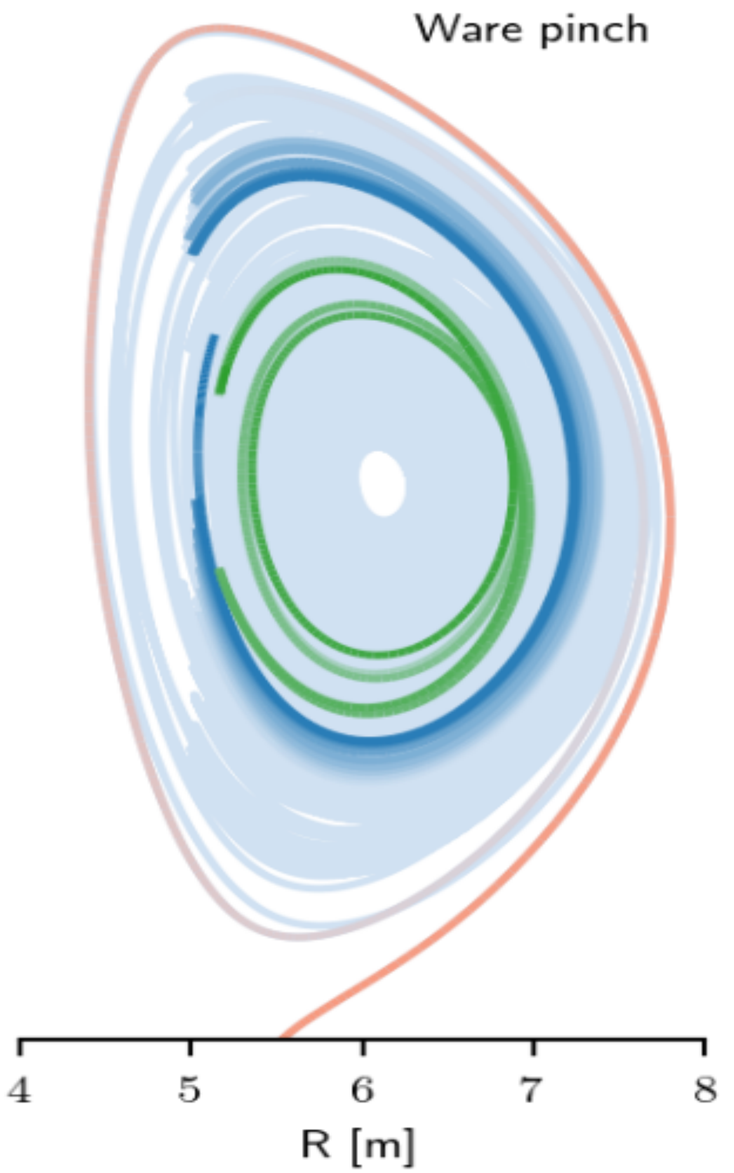


Low-energy REs scatter to passing regime and are promptly lost.



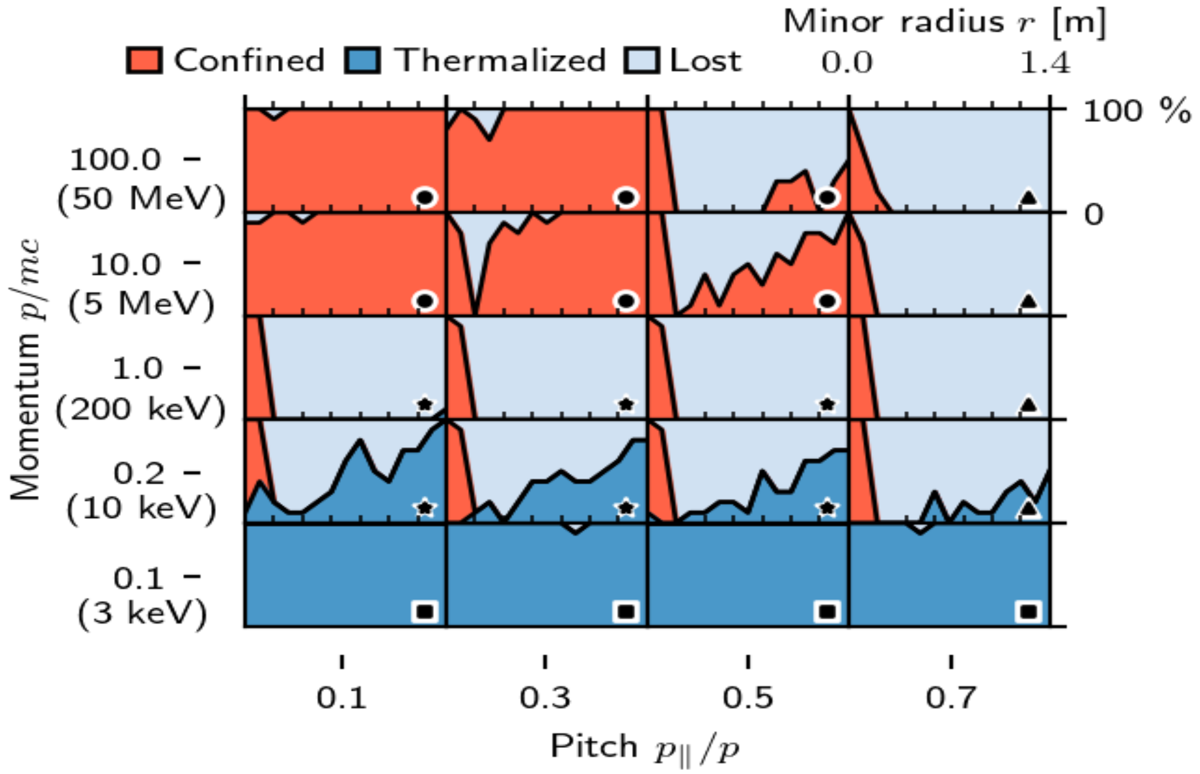






At mid-energy, REs go through de-trapping (Ware pinch) and trapping (stochastic field) before they are lost.

Note the Ware pinch time-scale does not take this into account.

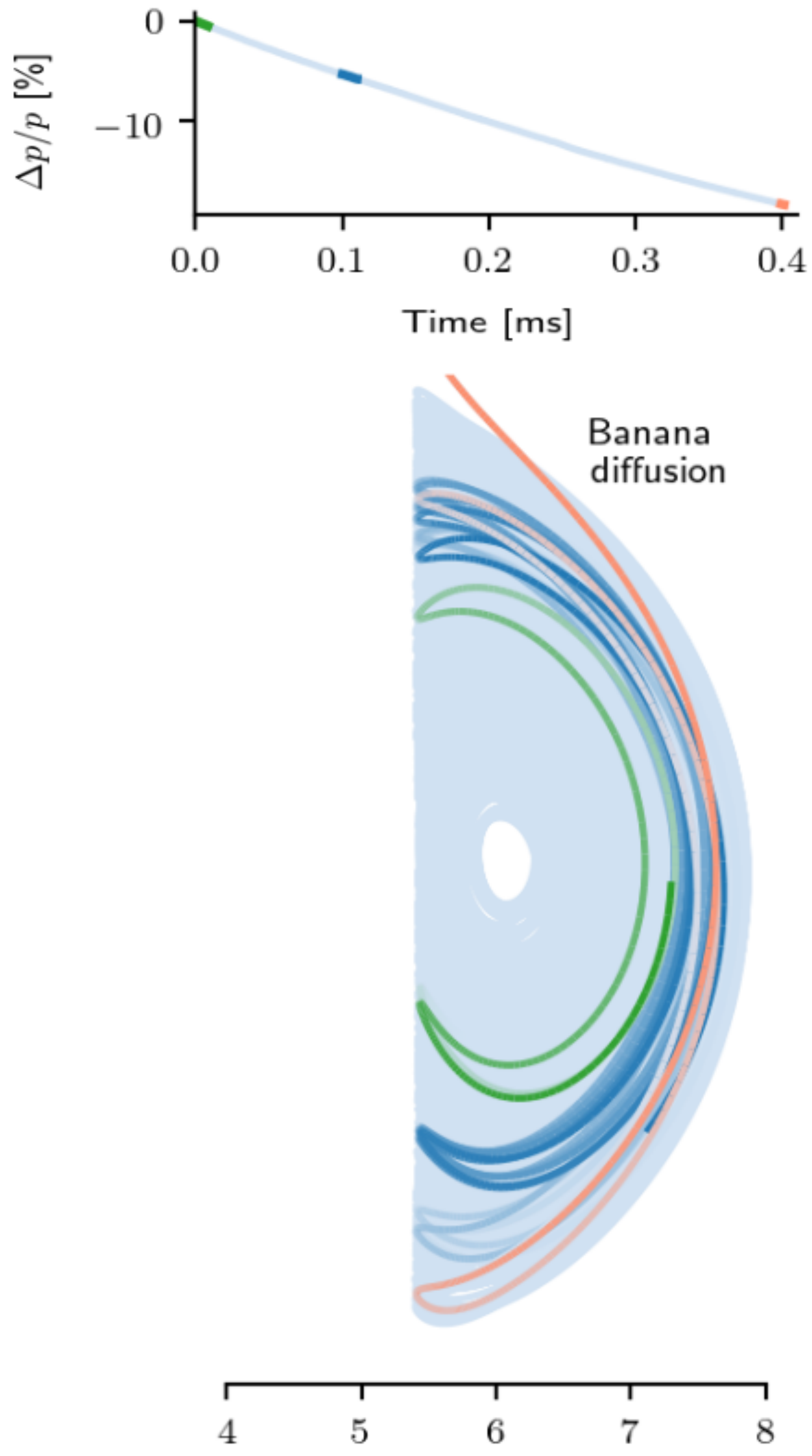


At high energy we have banana diffusion.

No estimate for the time-scale.

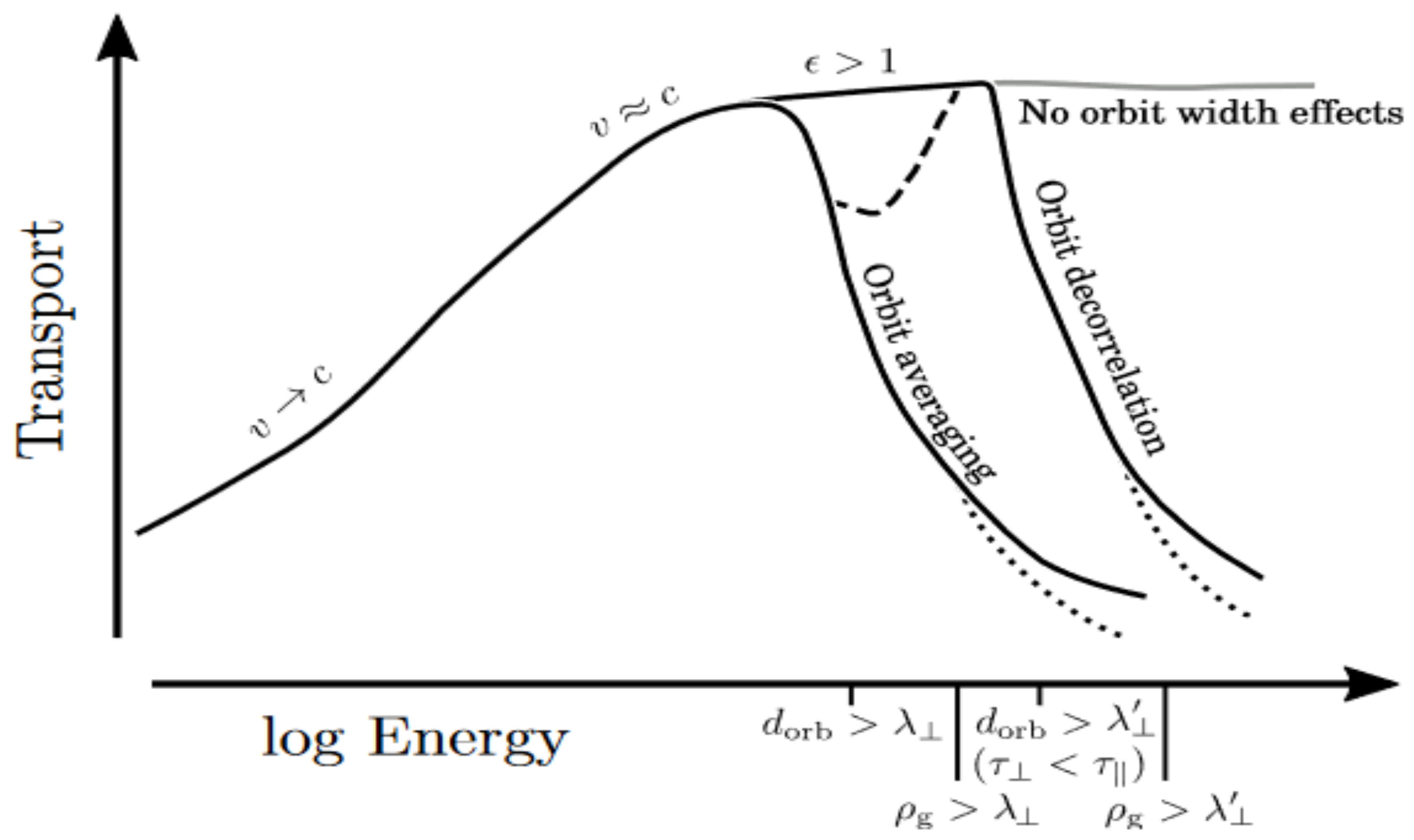
Analogous to toroidal ripple diffusion (here due to toroidal variation of the poloidal field).

Stronger for marginally trapped particles, probably more relevant for fast ions.



Transport of trapped particles depend on energy so what about passing particles?

When poloidal orbit width is larger than perturbation scale length, the transport should drop as 1/p. [Hauff PoP 2009]

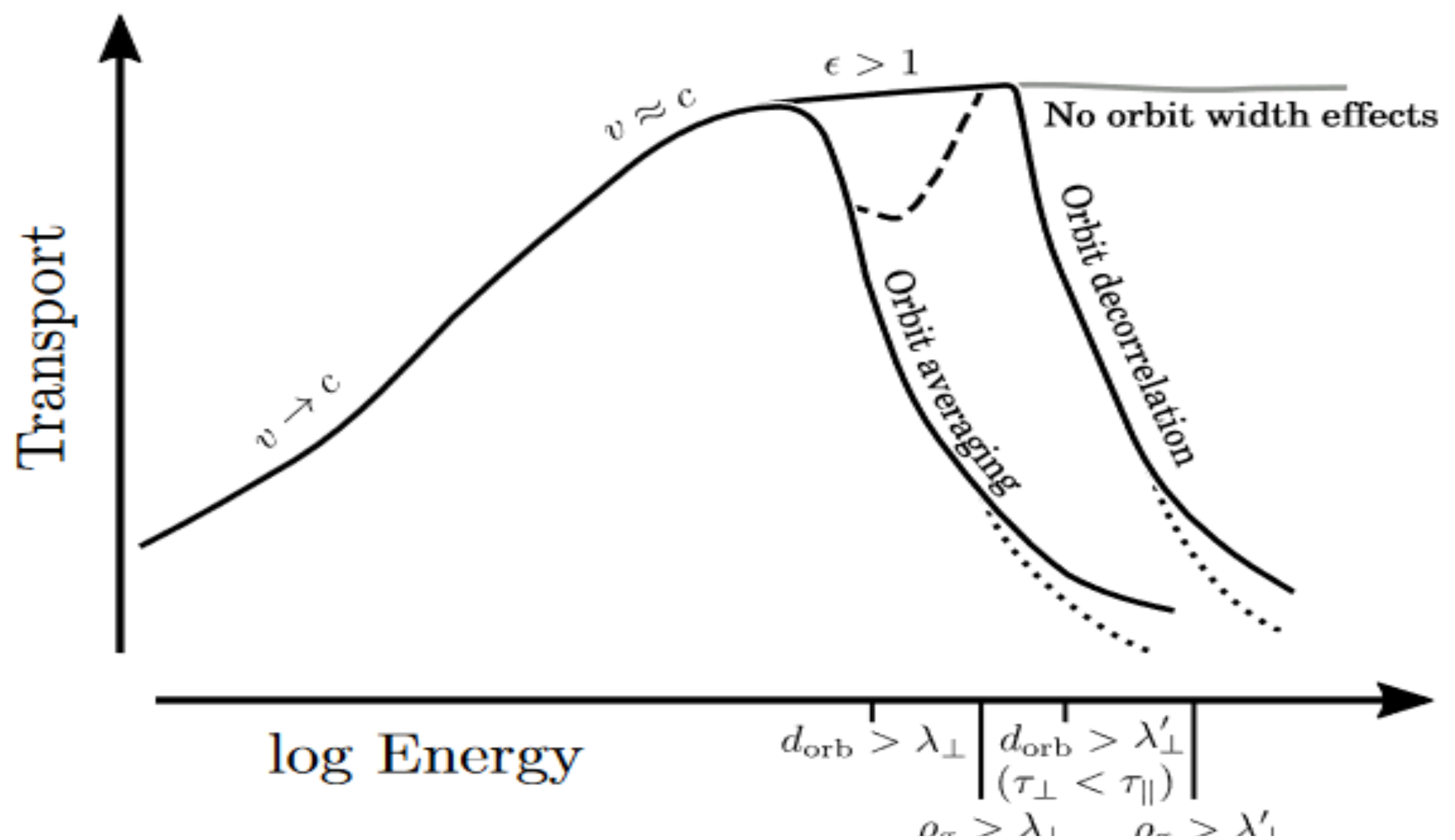


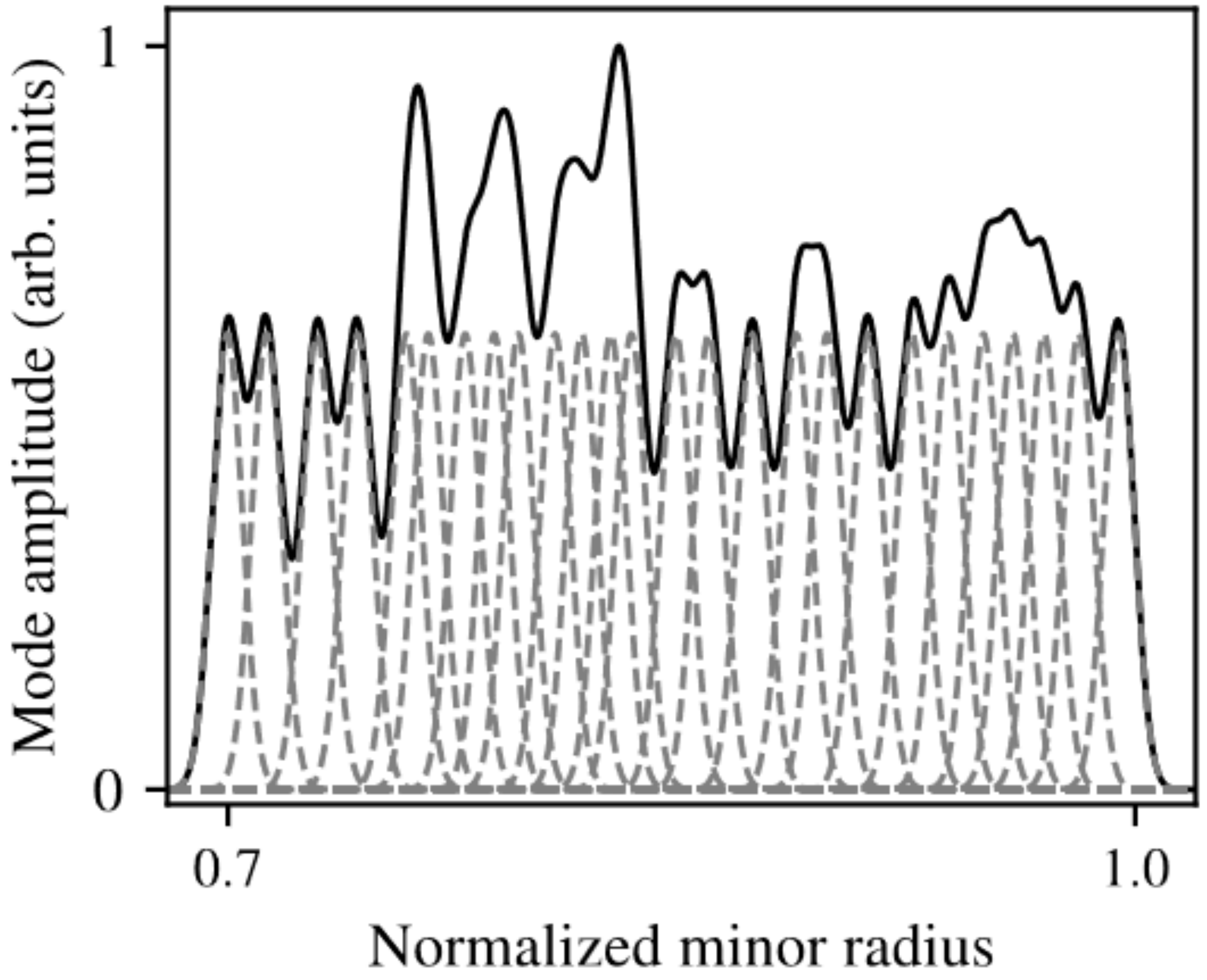
Transport of trapped particles depend on energy so what about passing particles?

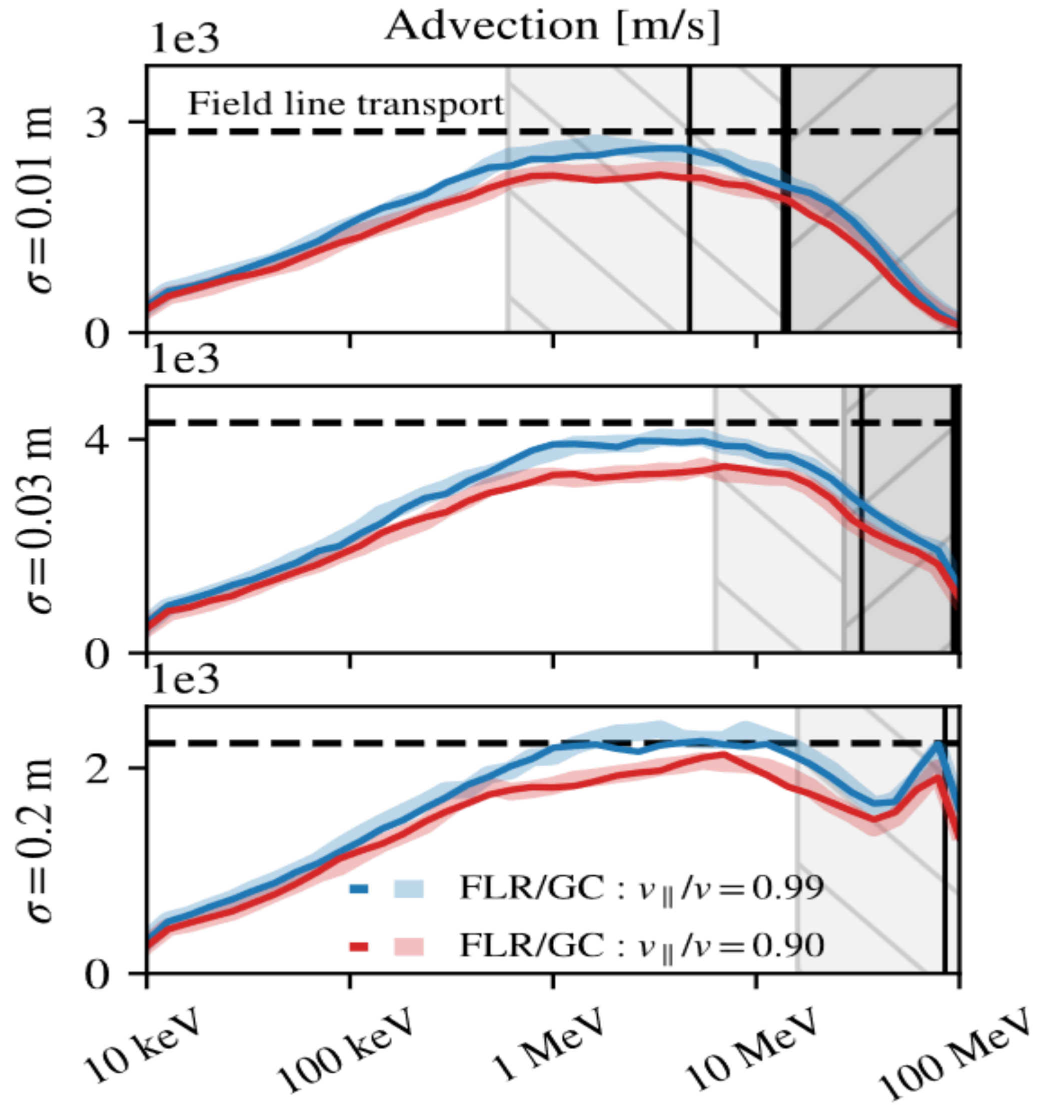
When poloidal orbit width is larger than perturbation scale length, the transport should drop as 1/p.

Orbit-following simulations show that this is true in an ideal field.

Perturbation scale ~ mode width.







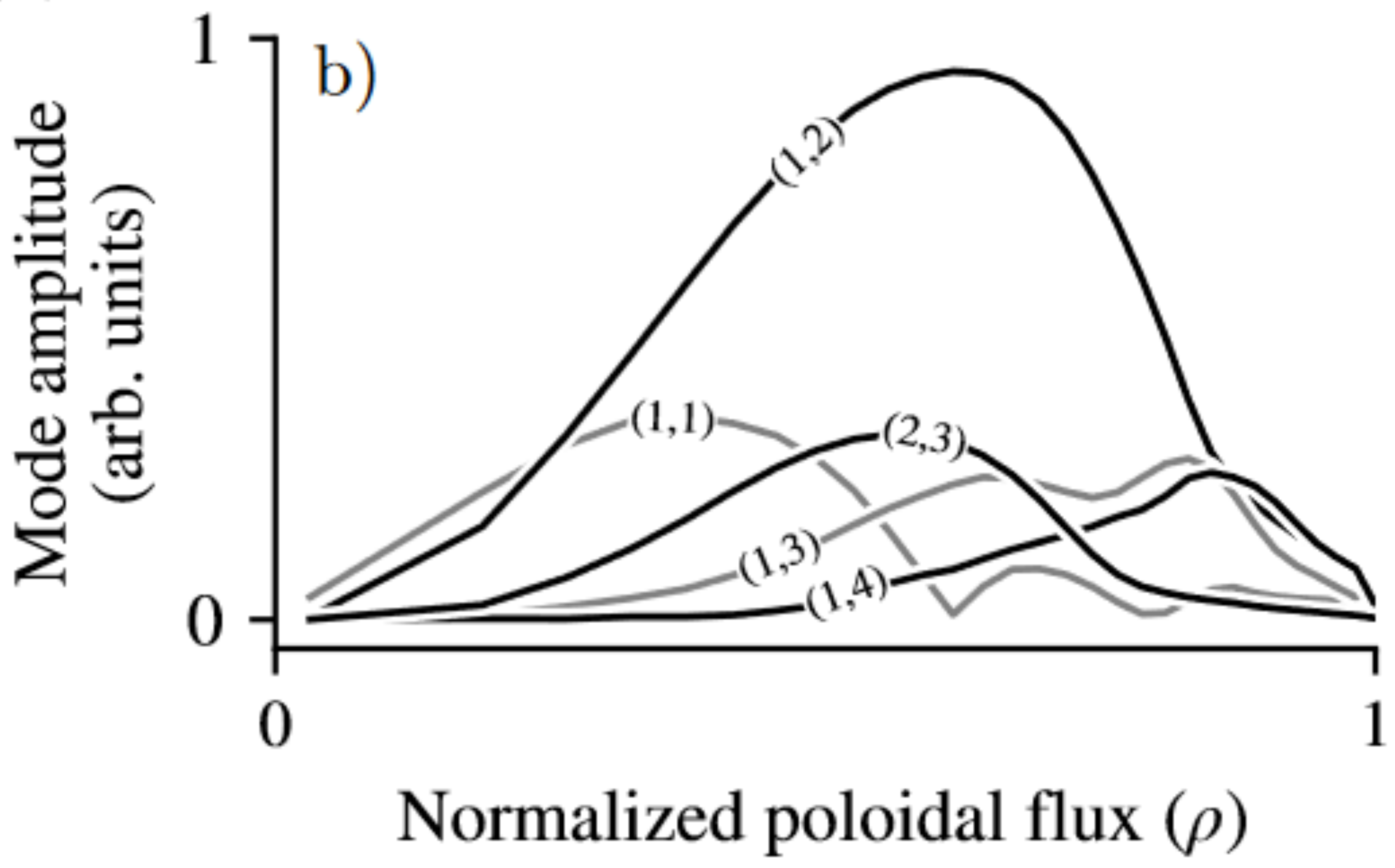
Transport of trapped particles depend on energy so what about passing particles?

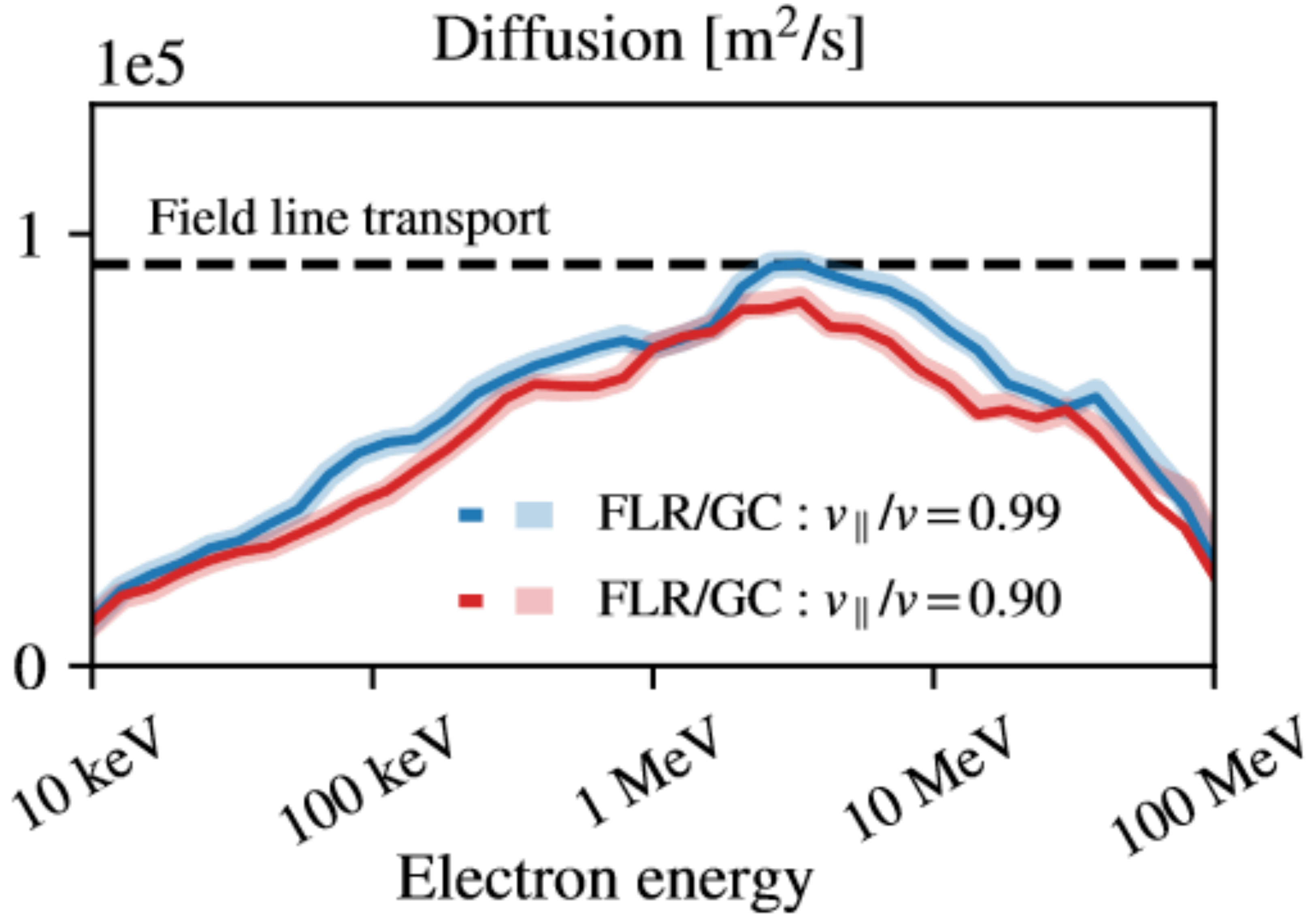
When poloidal orbit width is larger than perturbation scale length, the transport should drop as 1/p.

Orbit-following simulations show that this is true in an ideal field.

Perturbation scale ~ mode width.

Transport reduction can be observed in a real JET disruption simulation as well. Though at quite large energy; due to mode width? Negligible for ITER? More relevant for turbulence.





Transport of trapped particles depend on energy so what about passing particles?

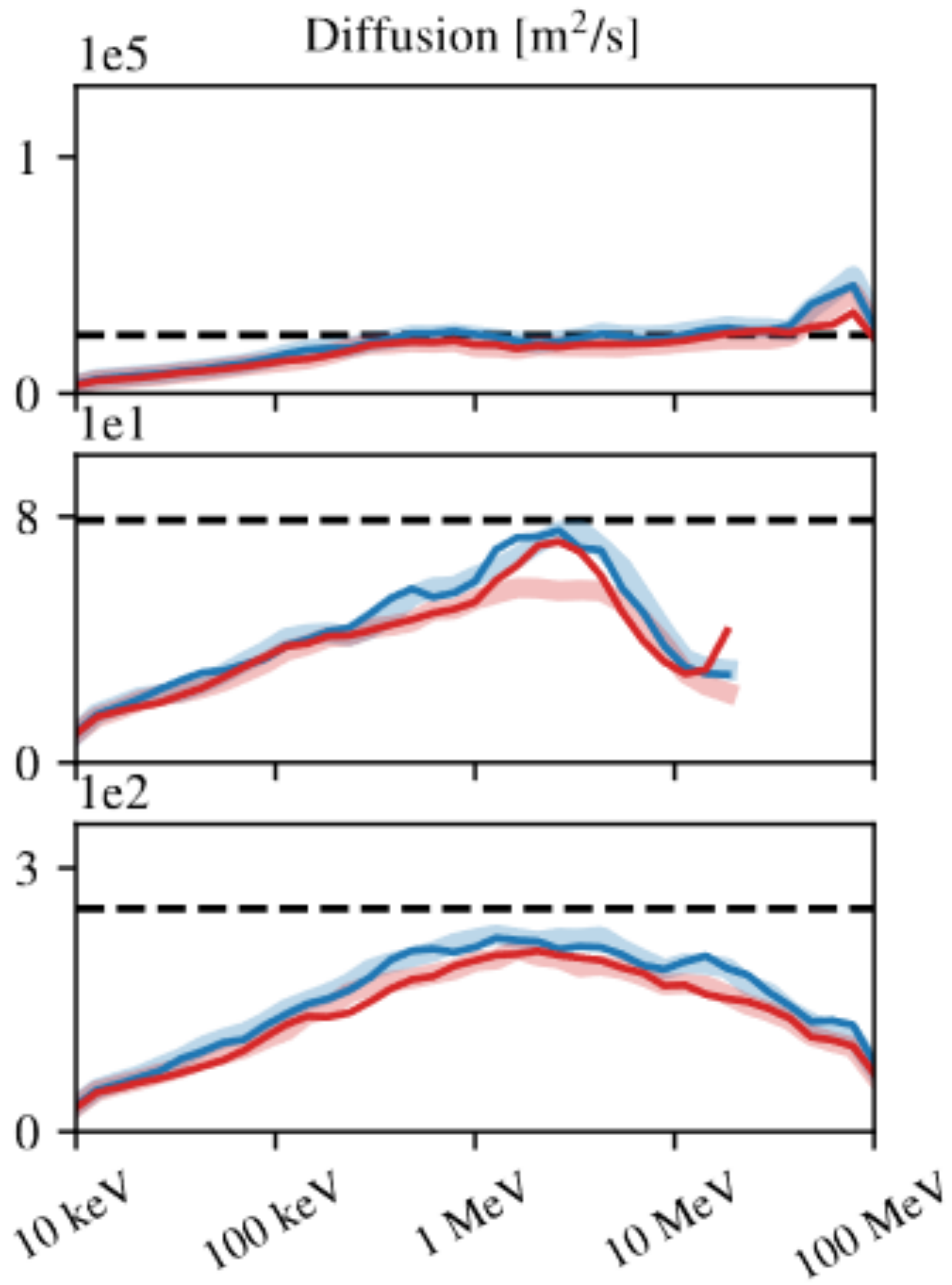
When poloidal orbit width is larger than perturbation scale length, the transport should drop as 1/p.

Orbit-following simulations show that this is true in an ideal field.

Perturbation scale ~ mode width.

Transport reduction can be observed in a real JET disruption simulation as well. Though at quite large energy; due to mode width? Negligible for ITER?

Non-uniform dB/B also relevant but has to be captured numerically.



Summary

Stochastic field transport in ITER can be sufficiently strong to lose hot-tail/suppress avalanche until flux surfaces reform.
Not known how general this is, how TQ affects this, and what the final RE beam will be.

Trapped REs can become deconfined depending on what the characteristic time-scales for the loss-mechanisms are.
Depends on collisionality, E-field, dB/B, duration of the stochastic phase...

Passing particle transport reduced when orbit width > perturbation scale length.
For disruptions in larger machines probably not relevant until > 100 MeV.

"Confinement of passing and trapped runaway electrons in the simulatio of ITER current quanch", submitted to NF, https://arxiv.org/abs/2203.09344

"Assessing energy dependence of the transport of relativistic electrons in perturbed magnetic fields with orbit-following simulations", NF 2020

Confirming the presence/absense of REs with particle module.

Understanding the transport barrier seen in some cases.

RE acceleration due to 3D fields. [Sommariva NF 2018]