Non-diffusive transport of suprathermal ions in turbulent plasmas

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Why suprathermal ions? Why in basic devices?

In fusion plasmas, suprathermal ions are created by

- Fusion reactions (alpha particles) and additional heating (NBI, ICRH)
- Crucial for burning plasmas (heating, non-inductive current drive)

In space and astrophysical plasmas, suprathermal ions are ubiquitous

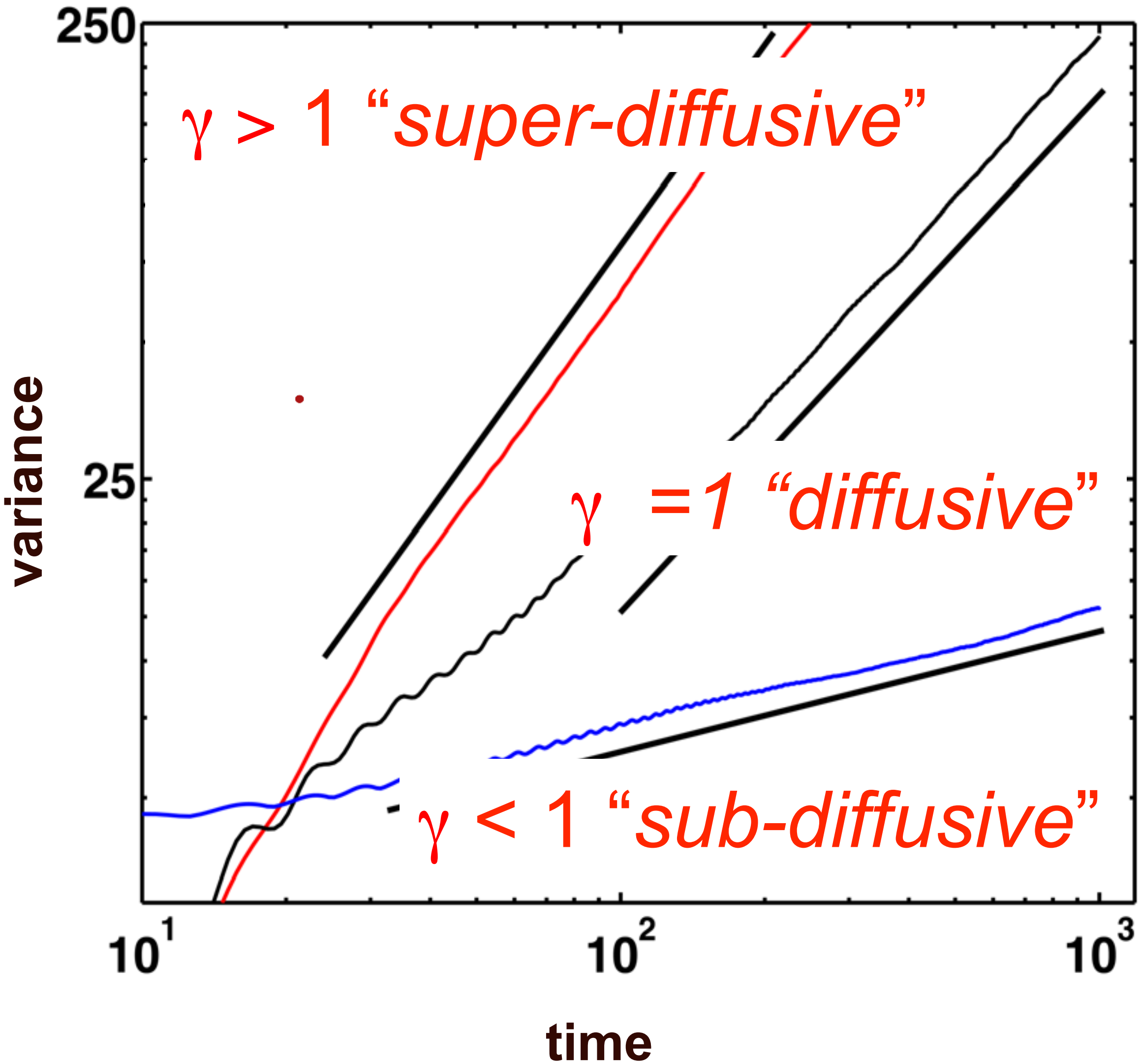
- Cosmic rays and solar energetic particles
- Can be harmful to spacecraft and are essential for Space Weather

Measurements in fusion devices or astrophysical plasmas are difficult

Basic plasma physics devices allow simpler investigations

- Many details of turbulence and suprathermal ions are directly measured
- Key experimental physics parameters can be varied systematically
- Direct comparison with numerical simulations ➔ code validation

Diffusive and non-diffusive transport



Spreading in time of the particle positions to extract an exponent:

$$\sigma^2 \propto t^\gamma$$

Are all these regimes accessible to suprathermal ions?

Which key elements determine the regime?

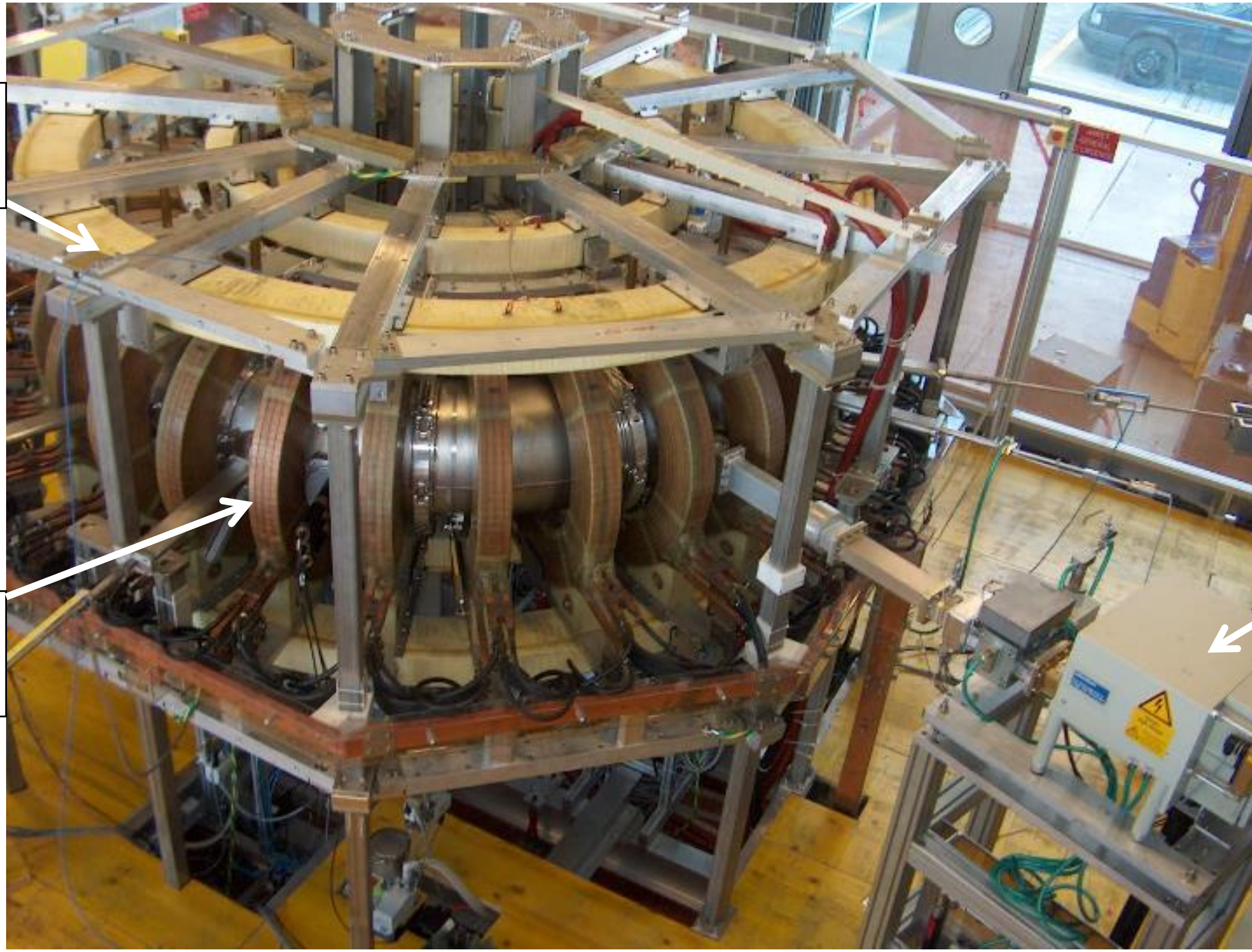
How can we identify them?

Outline

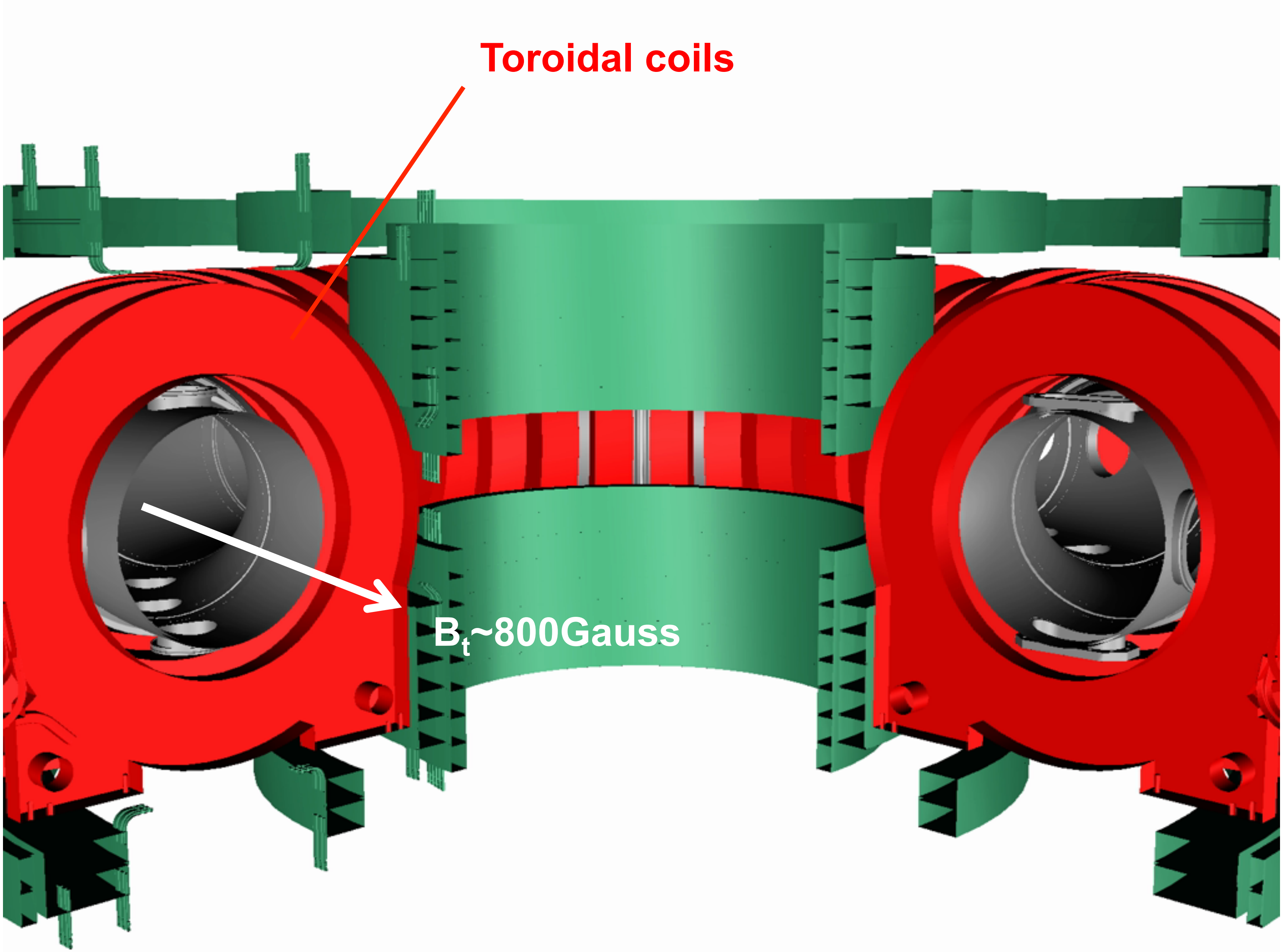
- **The TORPEX device, experimental setup and diagnostics**
  - ideal interchange turbulence
  - suprathermal ions source and detector
- **Experimental measurements**
  - energy dependence of suprathermal ion transport
- **Comparison experiments-simulations**
  - evidence for super- and sub-diffusive regimes
- **Time-resolved measurements**
- **Conclusions**

TORPEX (TORoidal Plasma EXperiment) at CRPP

major radius = 1m, minor radius = 20cm



TORPEX and the simple magnetized torus (SMT)



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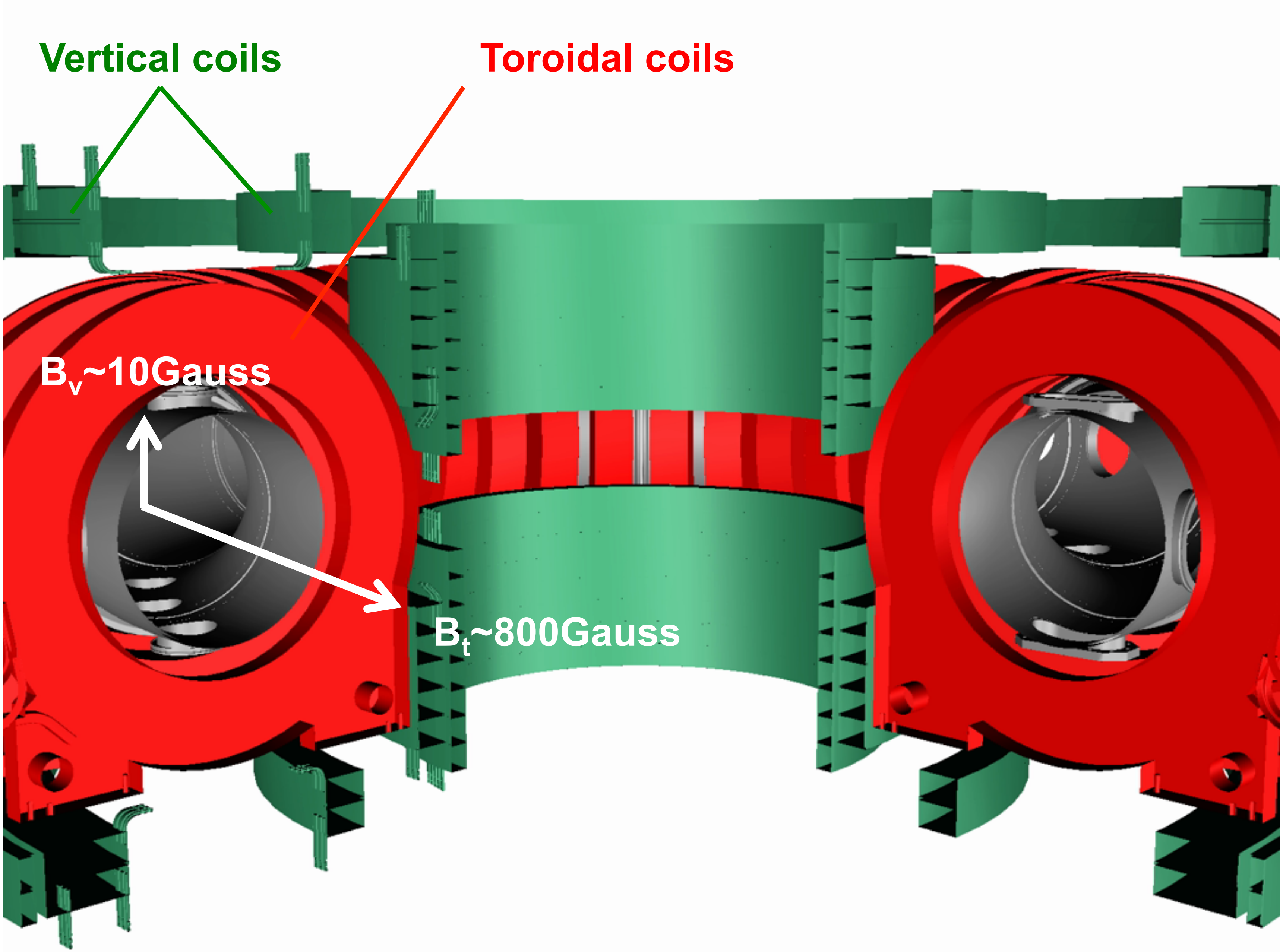
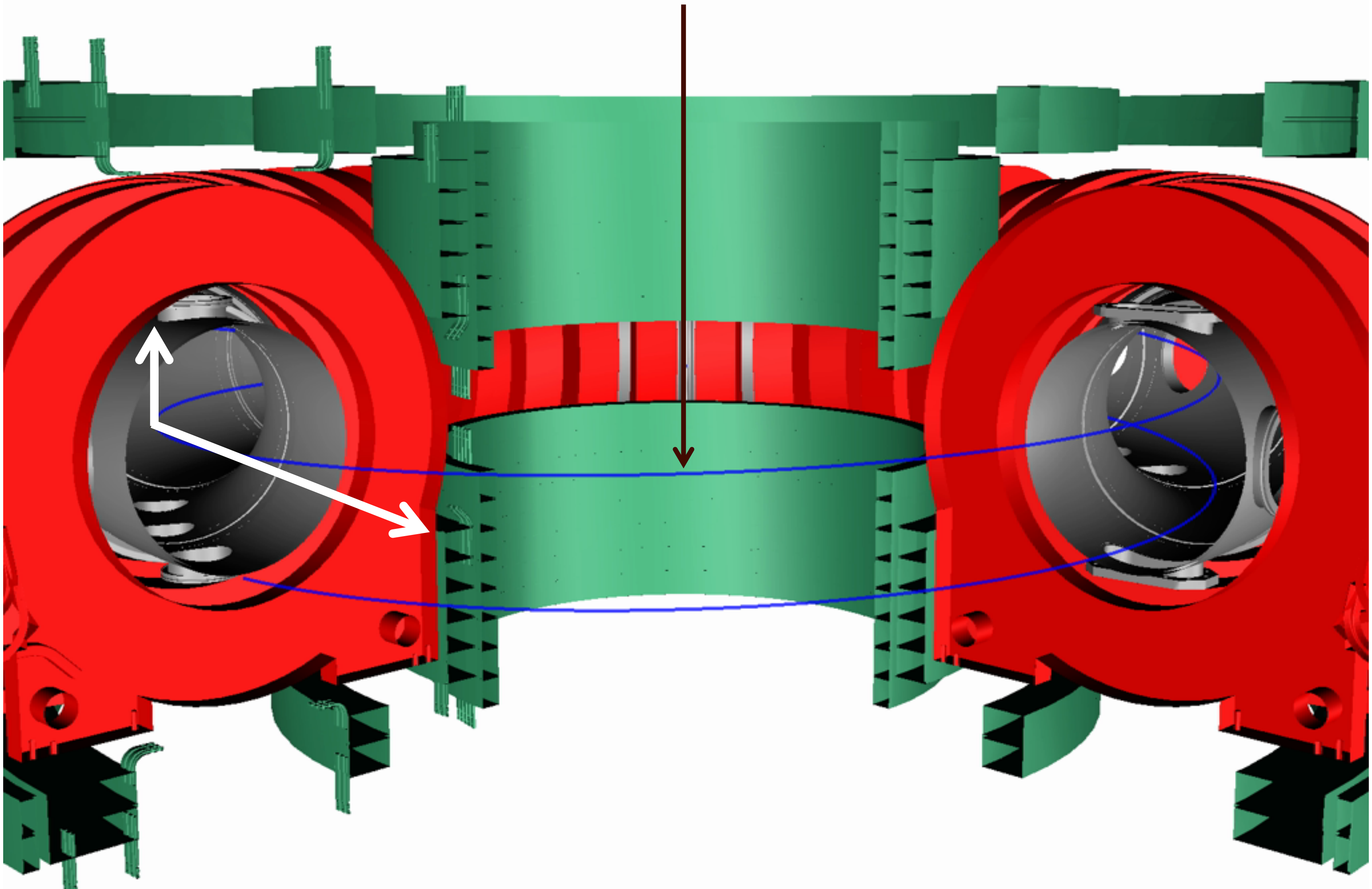
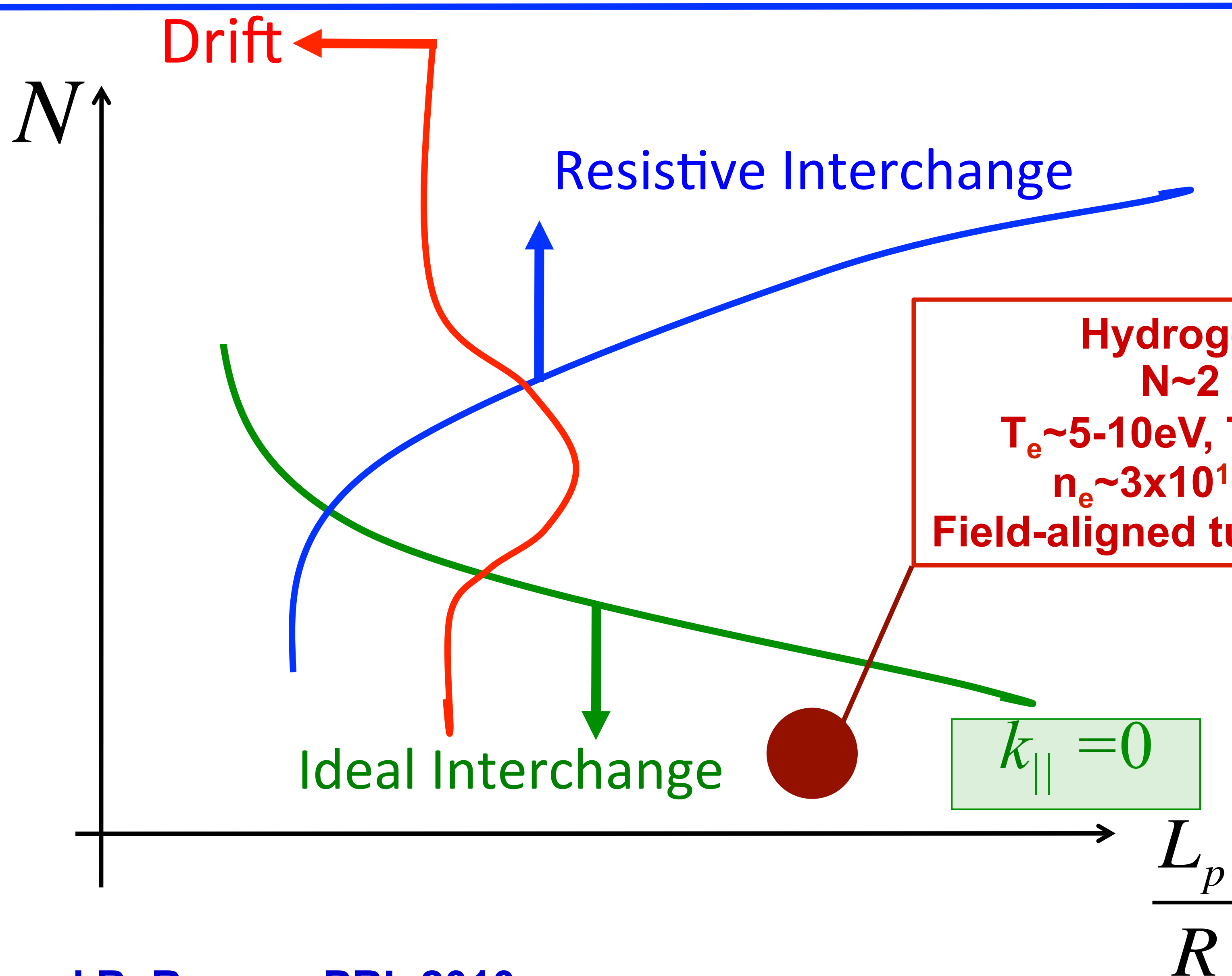


TORPEX and the simple magnetized torus (SMT)

Helical field lines winding N times around the torus
∇B and curvature ➔ interchange drive

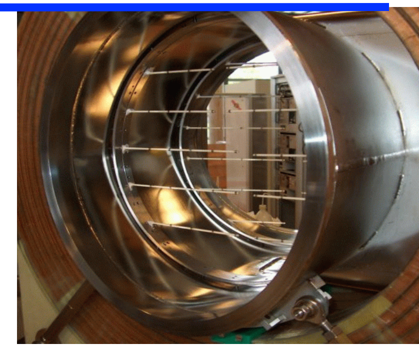


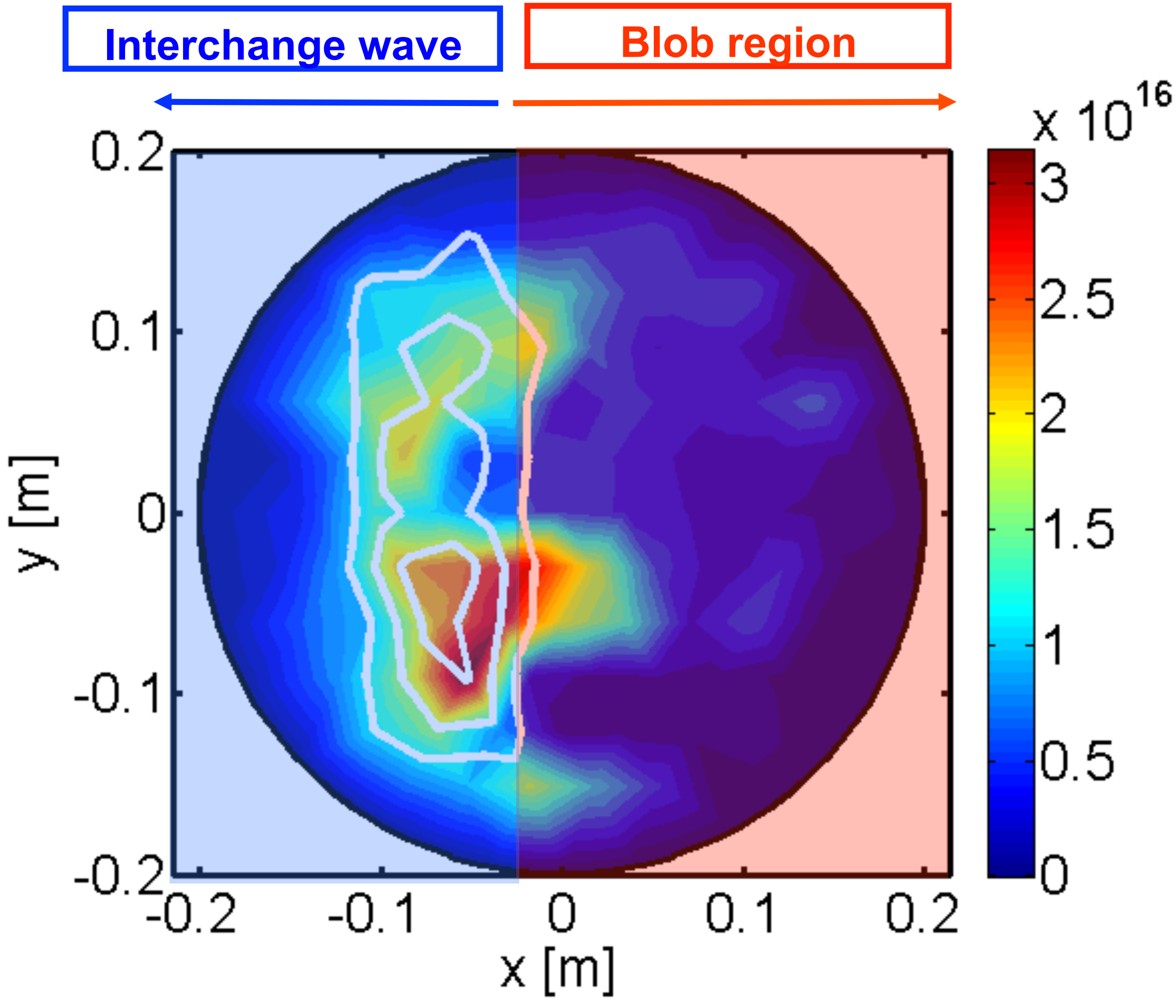
At low N, SMTs are dominated by field-aligned turbulence



P. Ricci and B. Rogers, PRL 2010

Ideal interchange regime: waves and blobs





I. Furno, PRL 2008

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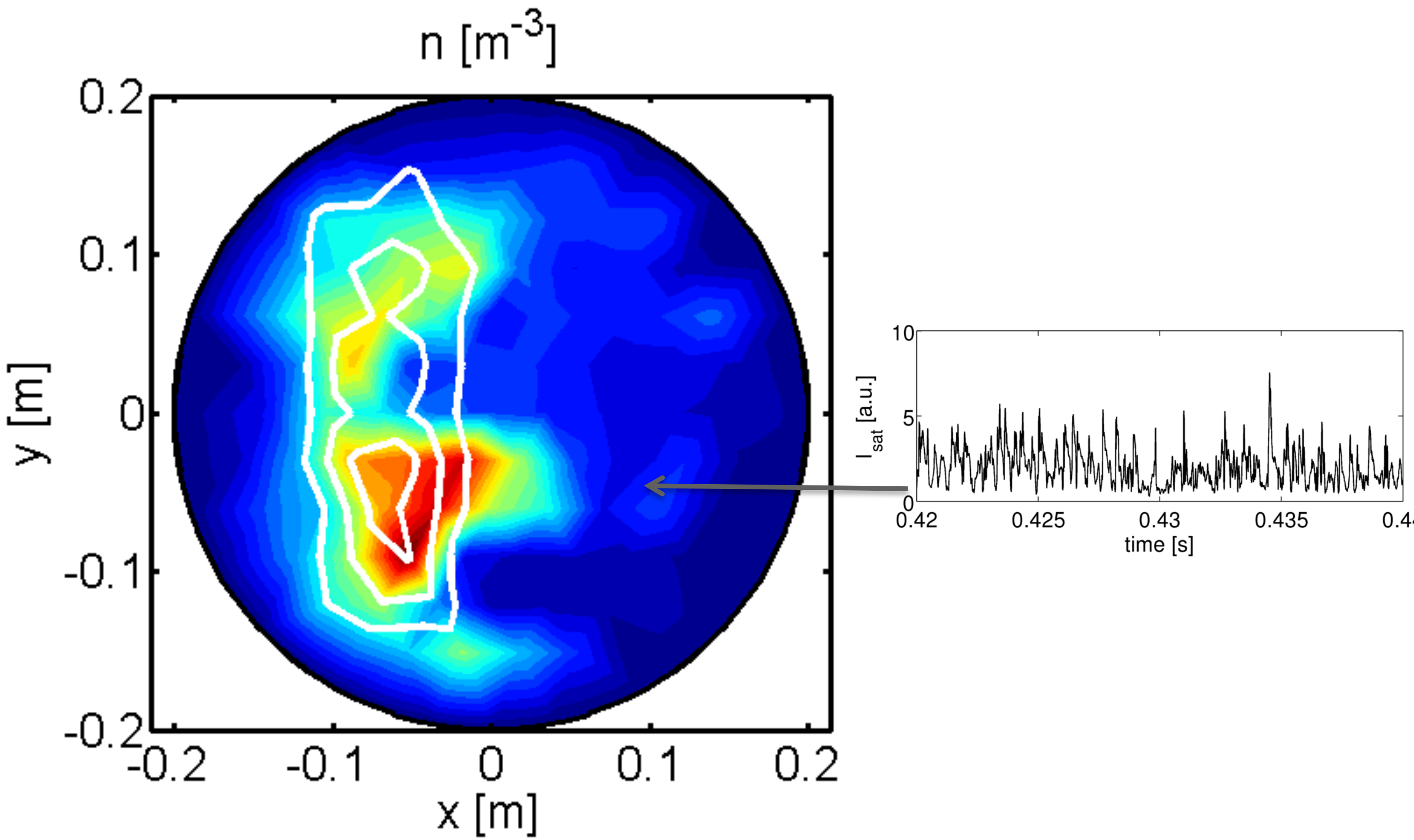
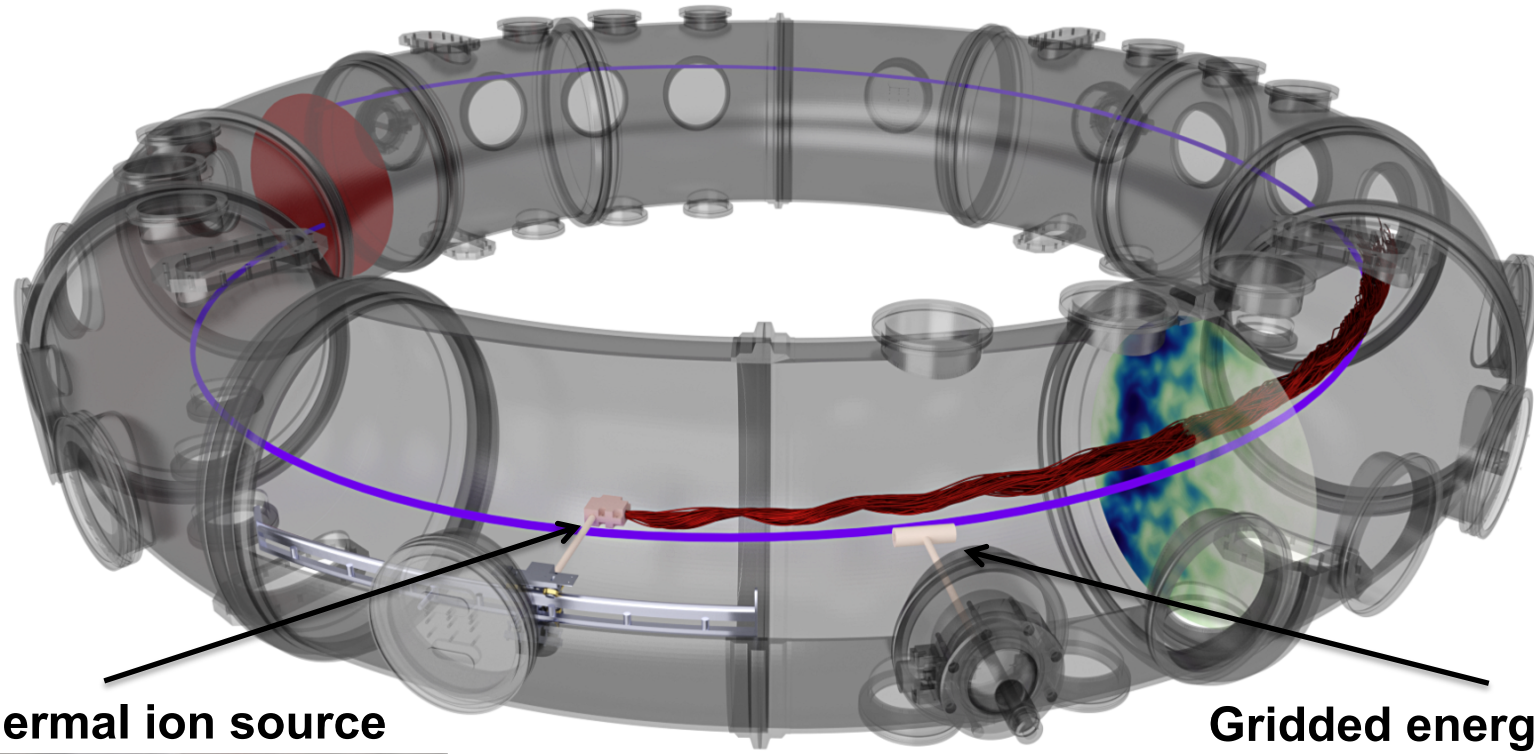


Suprathermal ion source and detector

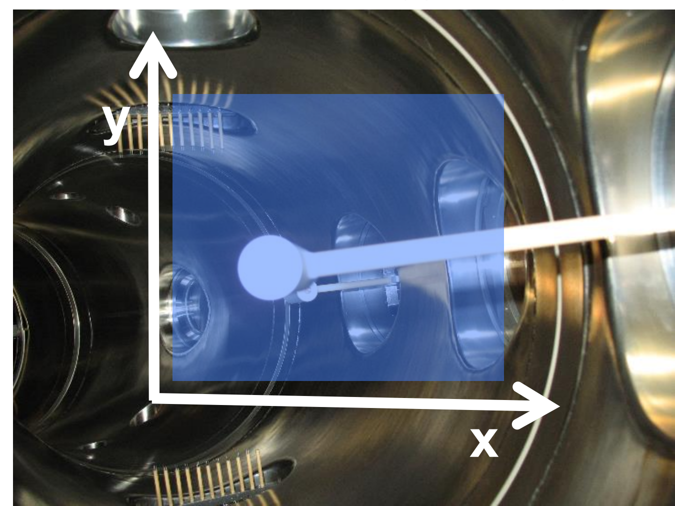


Suprathermal ion source

Gridded energy analyzer

Three-dimensional profile of the suprathermal ion beam

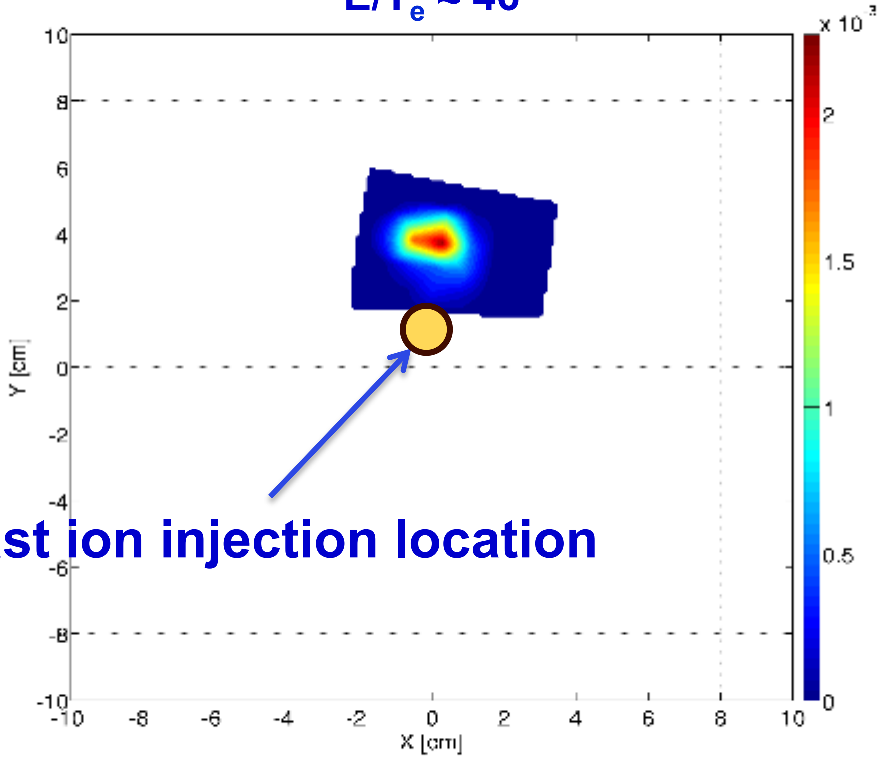
Time-averaged meas.
Time-resolved meas.

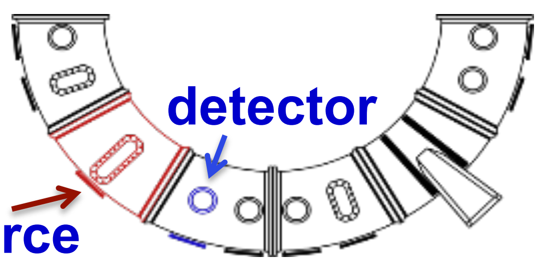


3D time-averaged profile at two fast ion energies

E = 70 eV

$E/T_e \approx 46$





Distance from the source = 0.2 m

3D time-averaged profile at two fast ion energies

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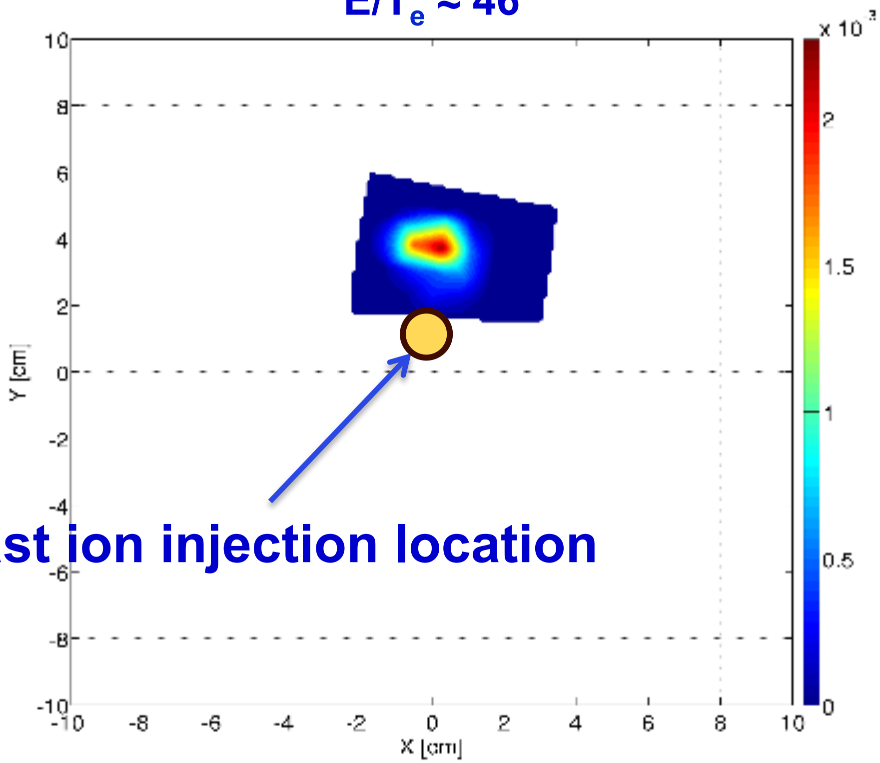
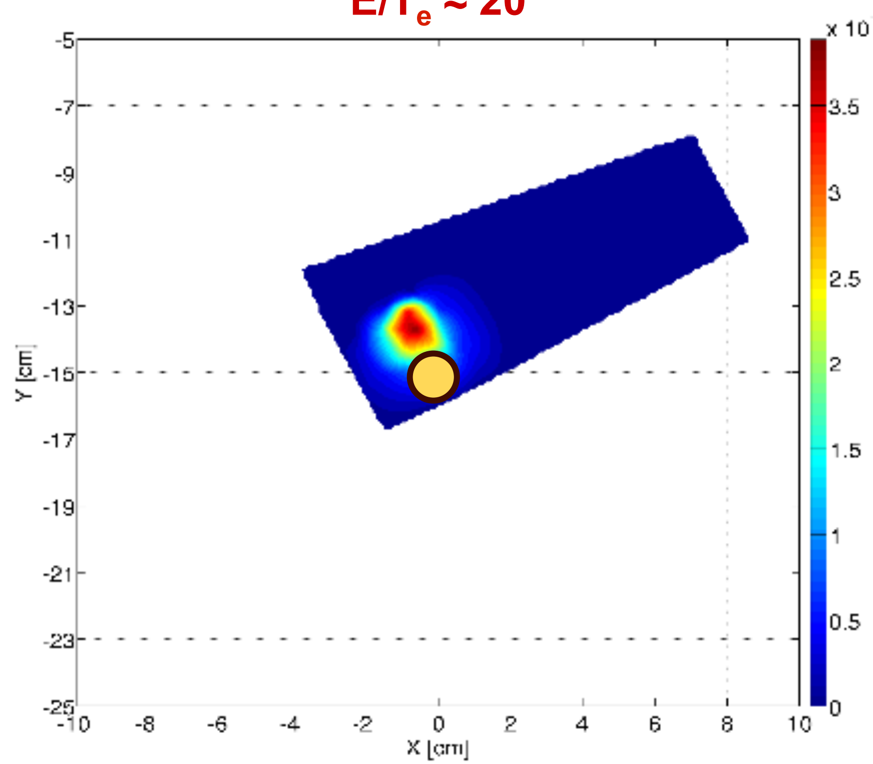
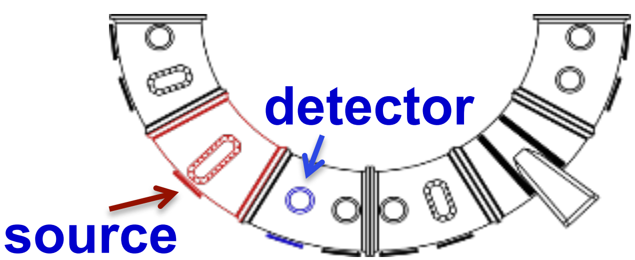


E = 30 eV
$E/T_e \approx 20$





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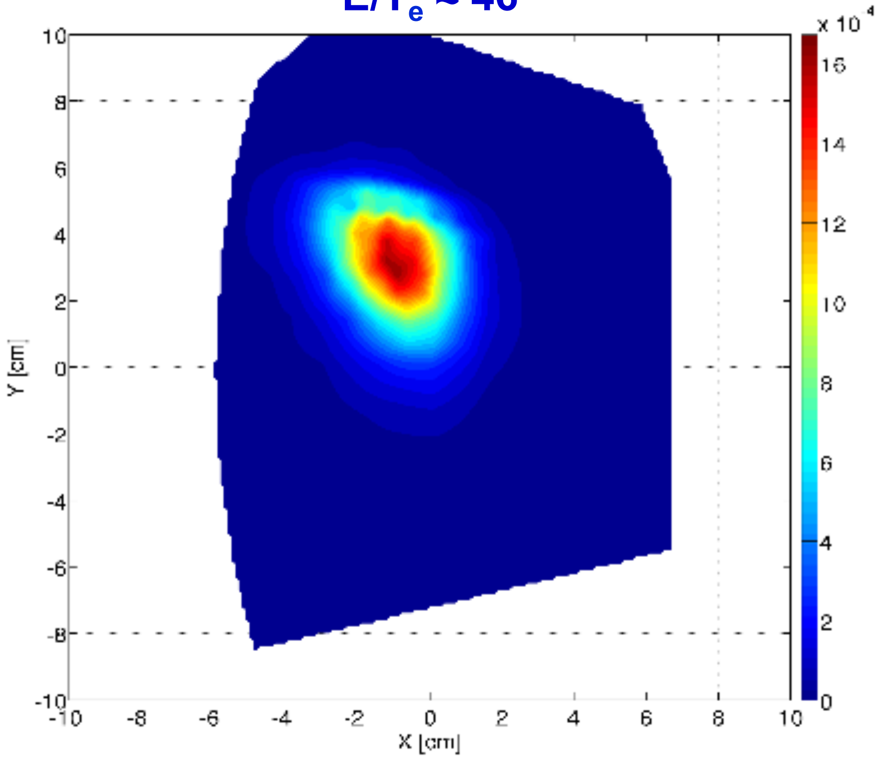

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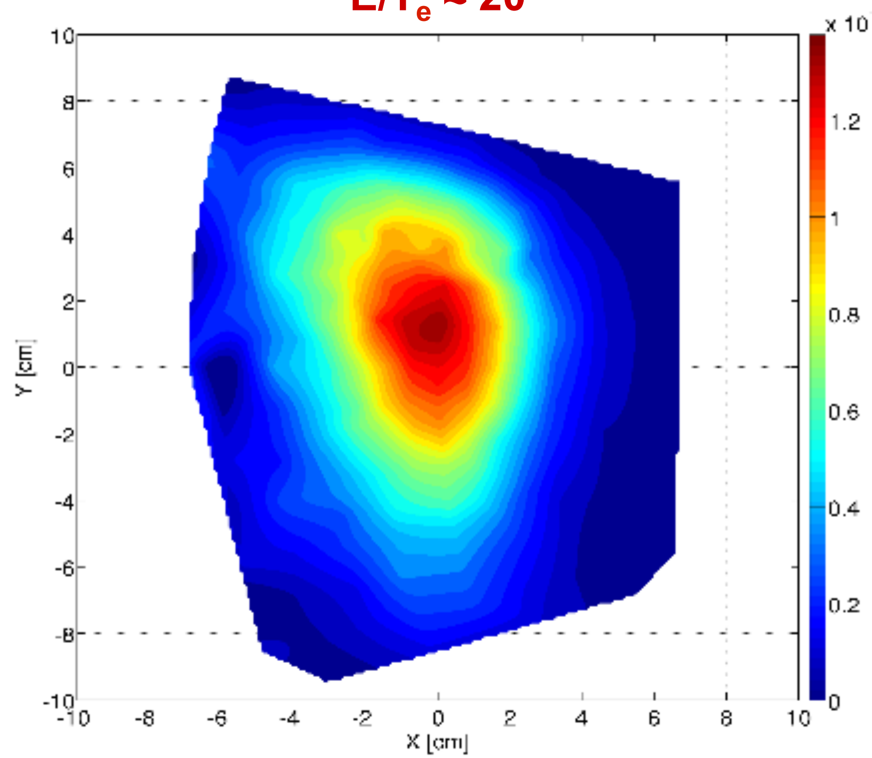
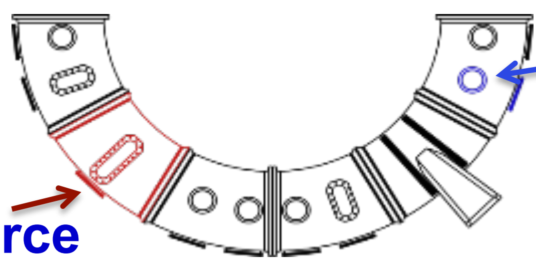
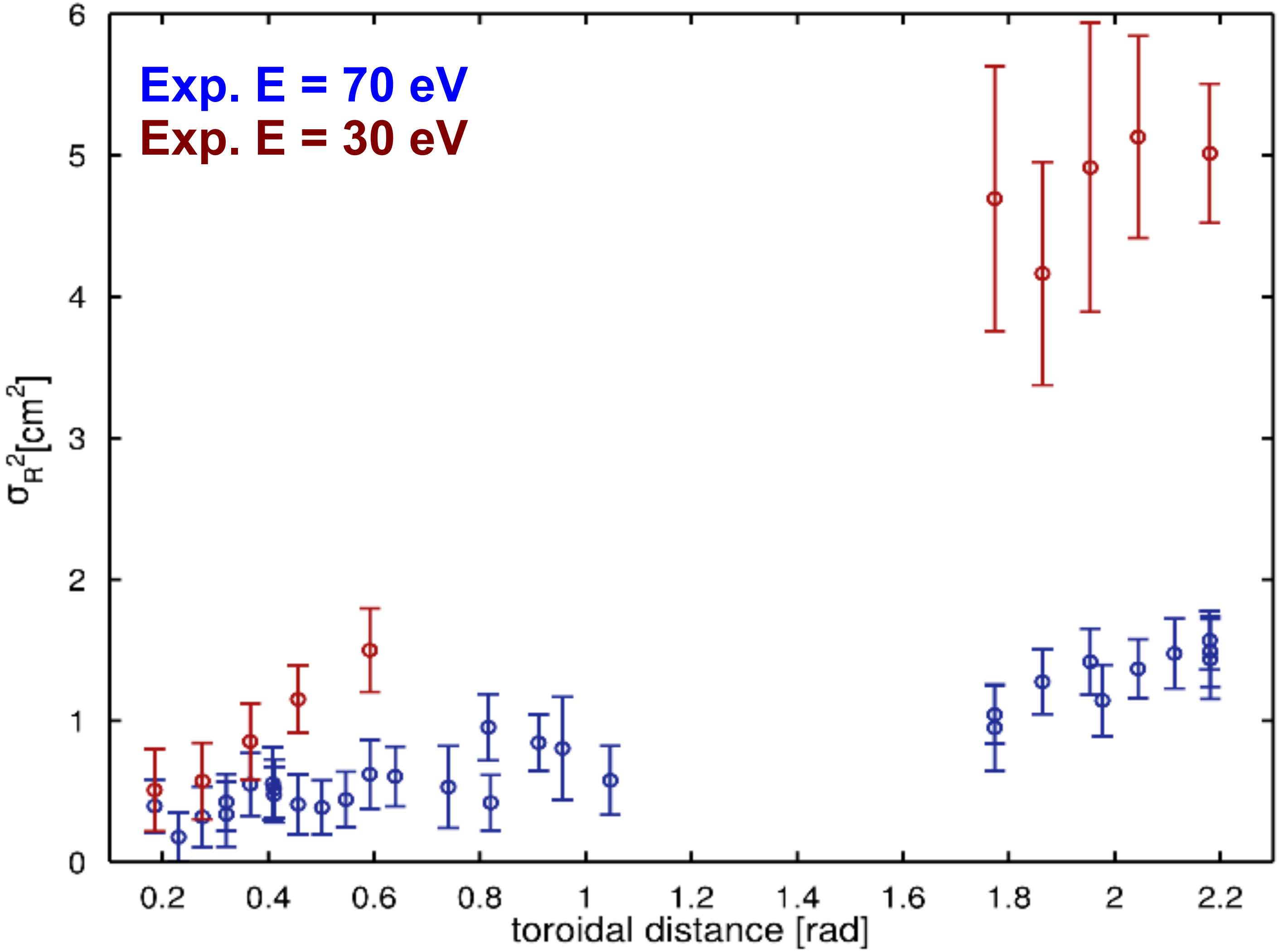


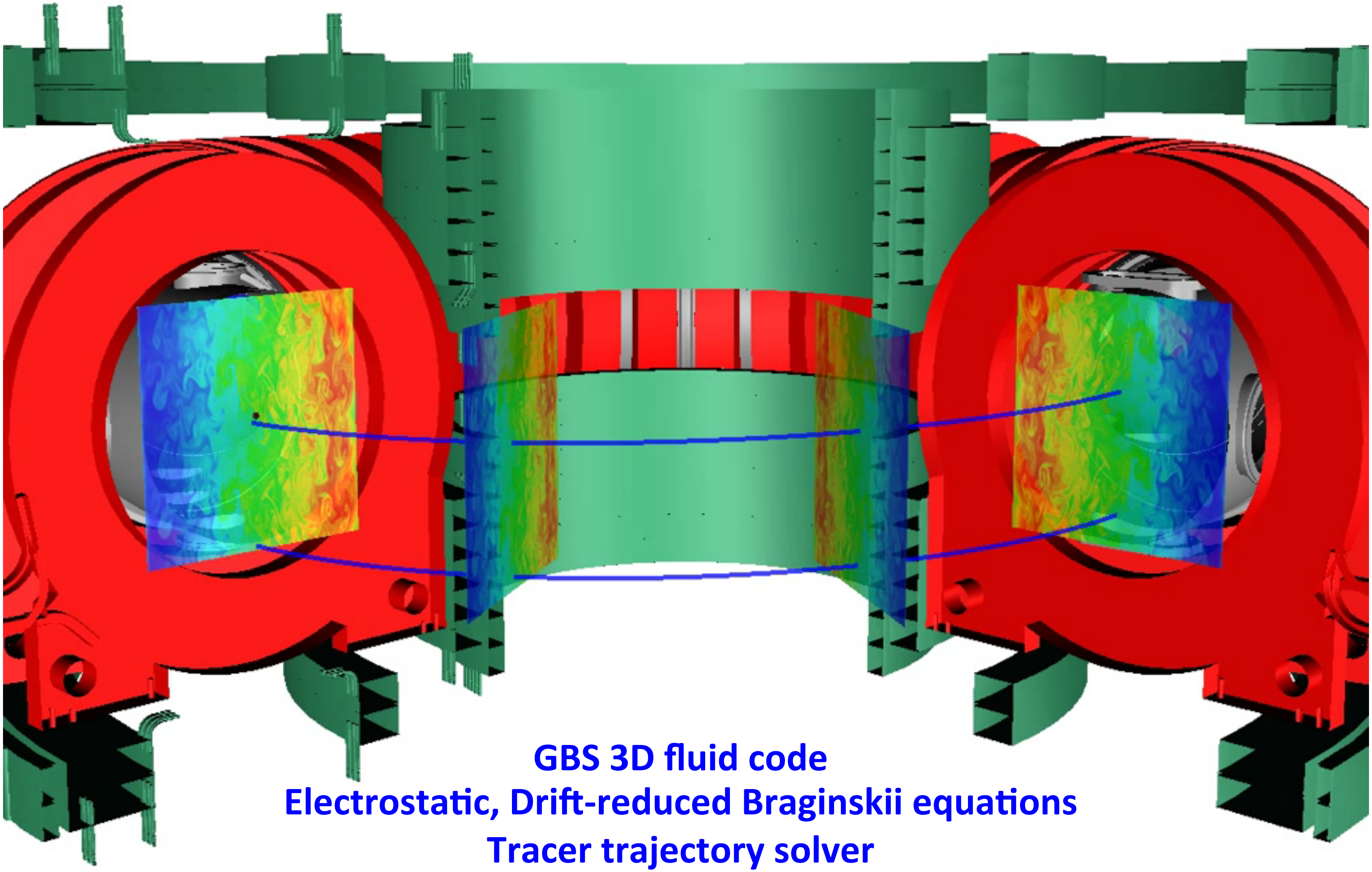


Distance from the source = 2.2 m

The beam spreading is different for different energies



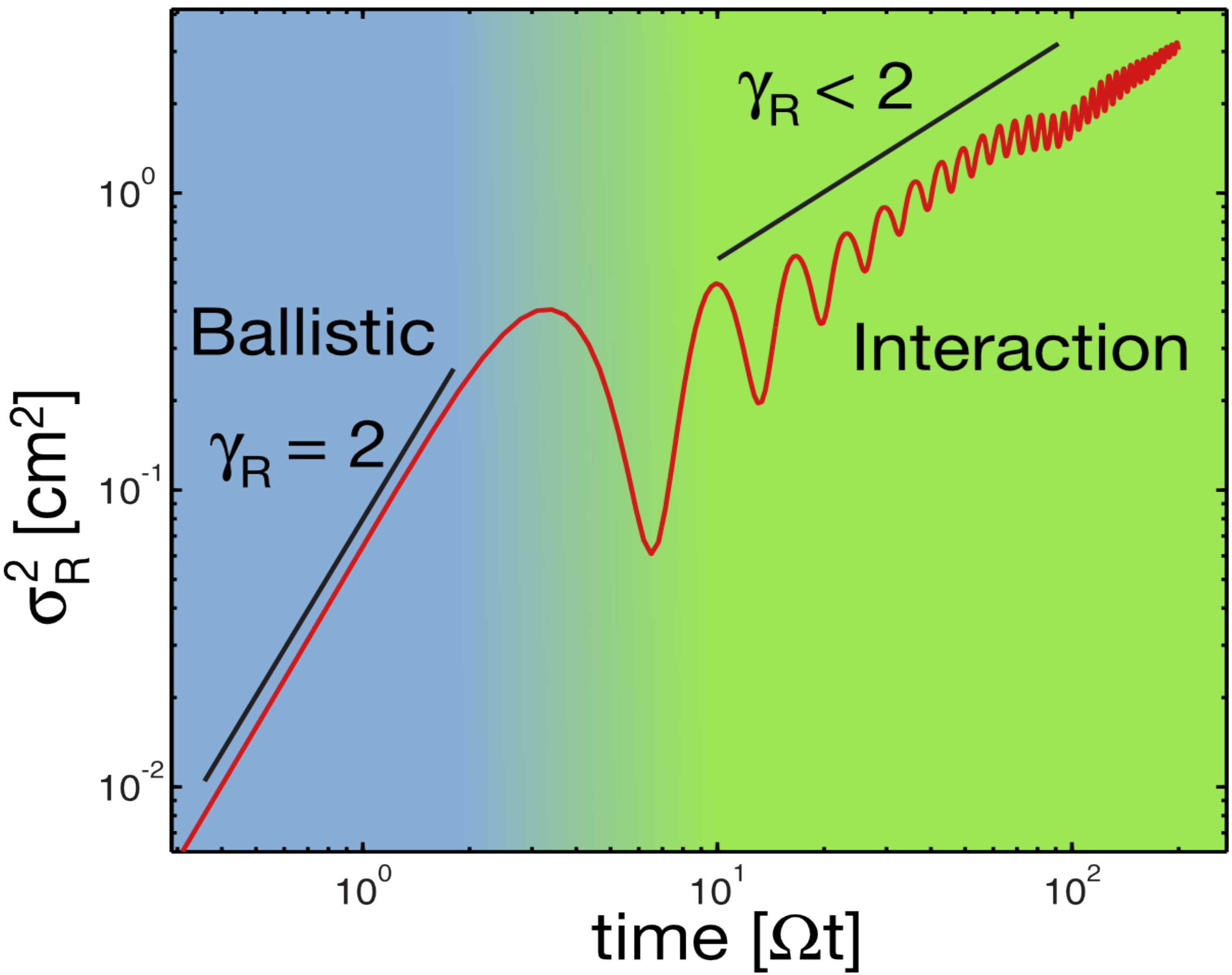
Ion tracers in simulated turbulent fields



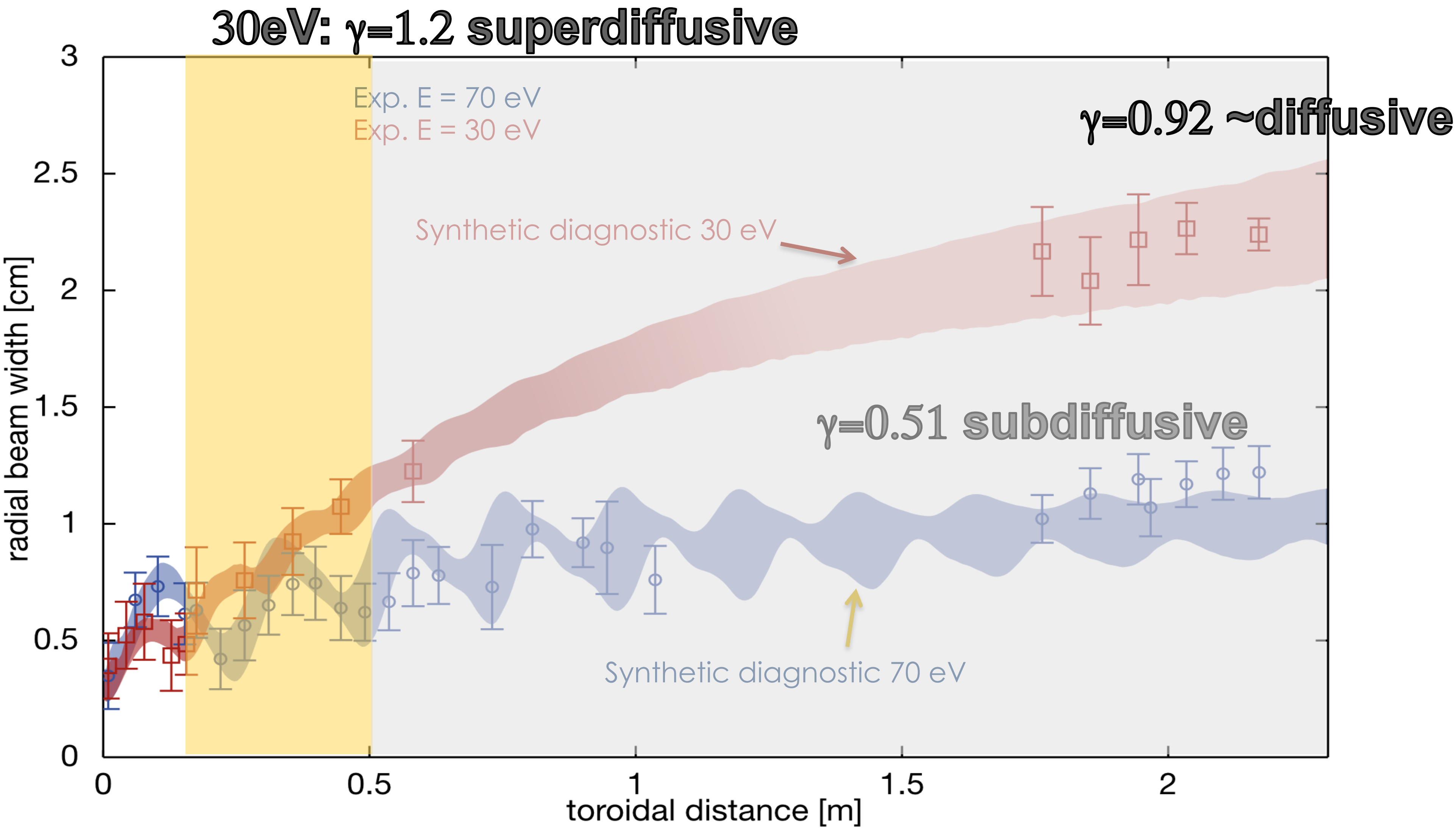
GBS 3D fluid code
Electrostatic, Drift-reduced Braginskii equations
Tracer trajectory solver

P. Ricci, PoP 2009

Particle spreading in time ➔ transport regime

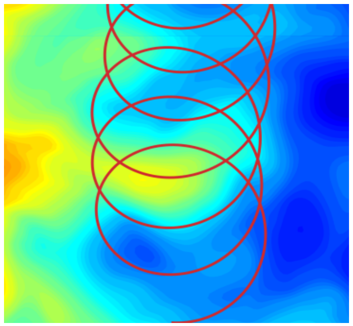


Two regimes for fast ion transport are revealed

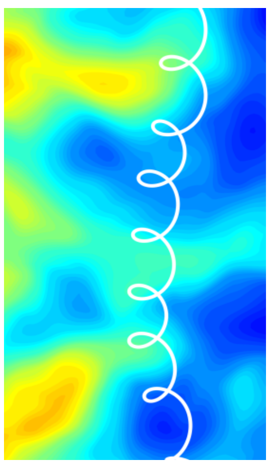


Gyro- and drift-averaging reduce transport

Gyro-averaging



Drift-averaging



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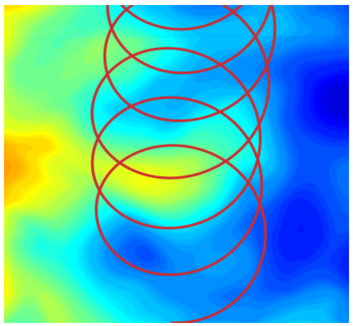
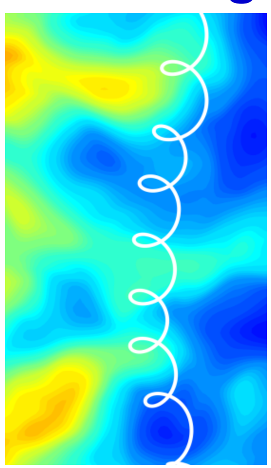
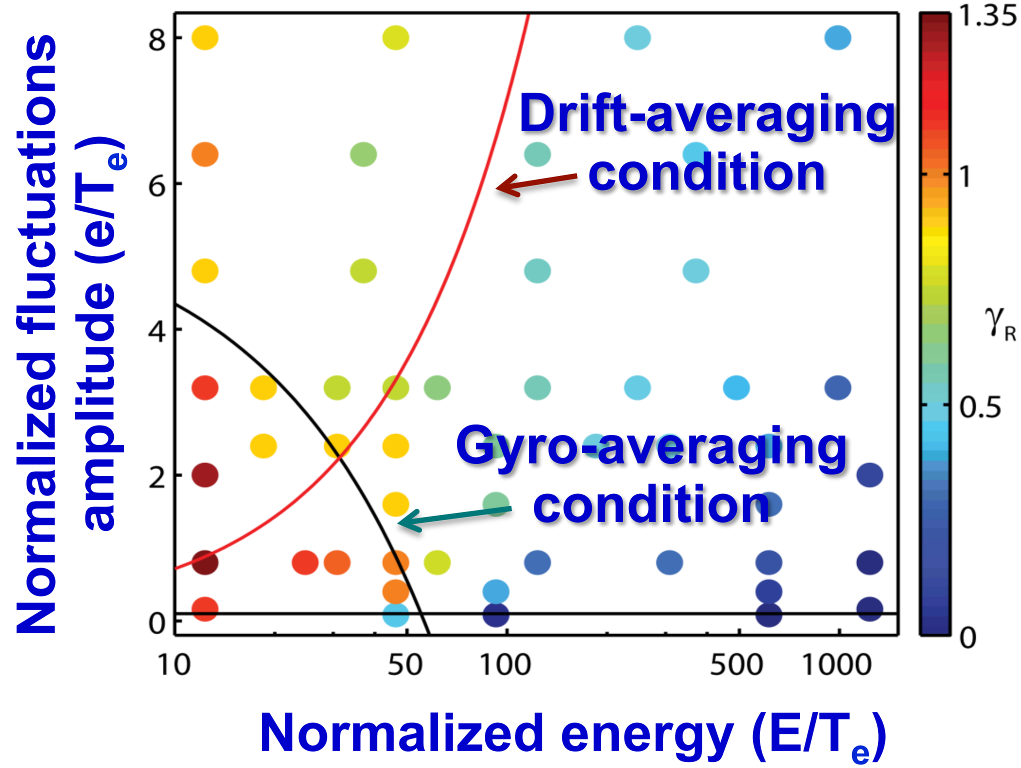


Drift-averaging





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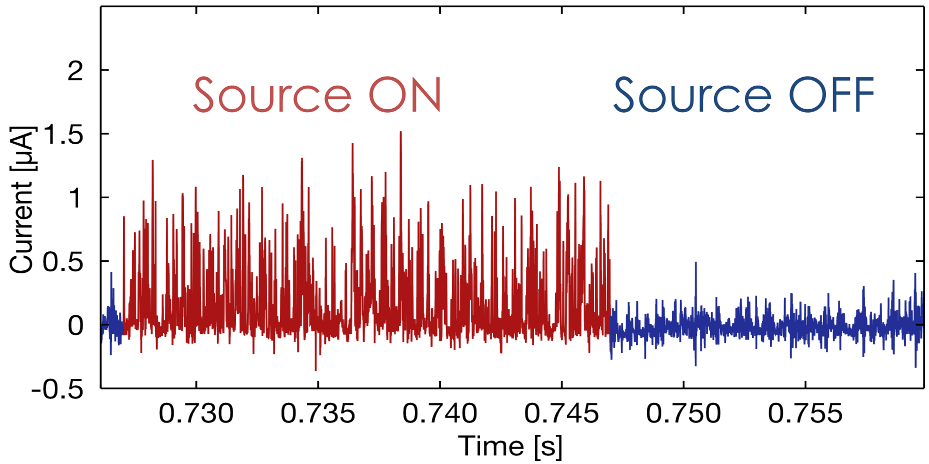
- **The TORPEX device, experimental setup and diagnostics**
  - ideal interchange turbulence
  - fast ions source and detector
- **Experimental measurements**
  - fast ion transport: energy dependence
- **Comparison experiments-simulations**
  - Evidence for super and subdiffusive regimes
- **Time-resolved measurements**
- **Conclusions**

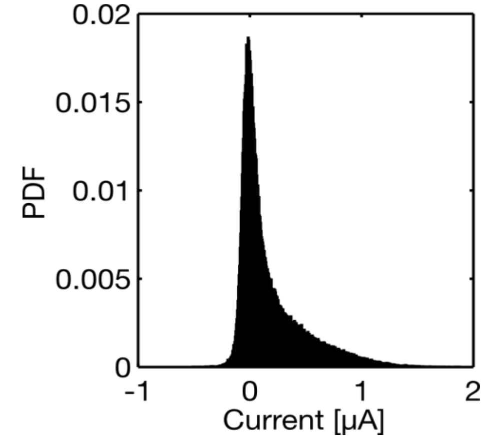
Time-resolved measurements in super- and sub-diffusive regimes

Time traces of the detector at 40 cm

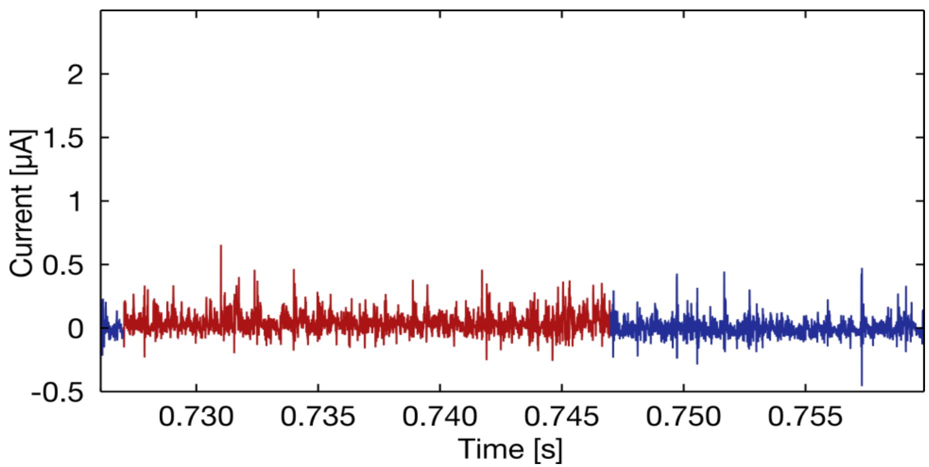
Probability density functions

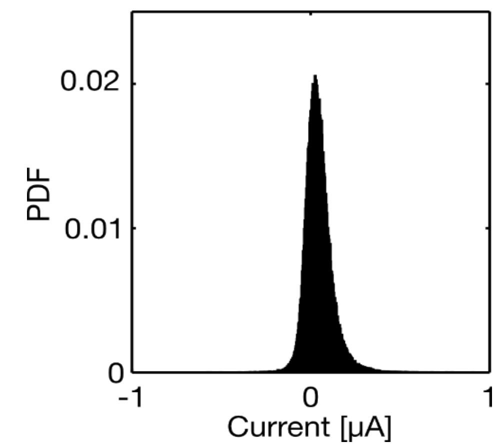
E = 30 eV
superdiffusive





E = 70 eV
subdiffusive





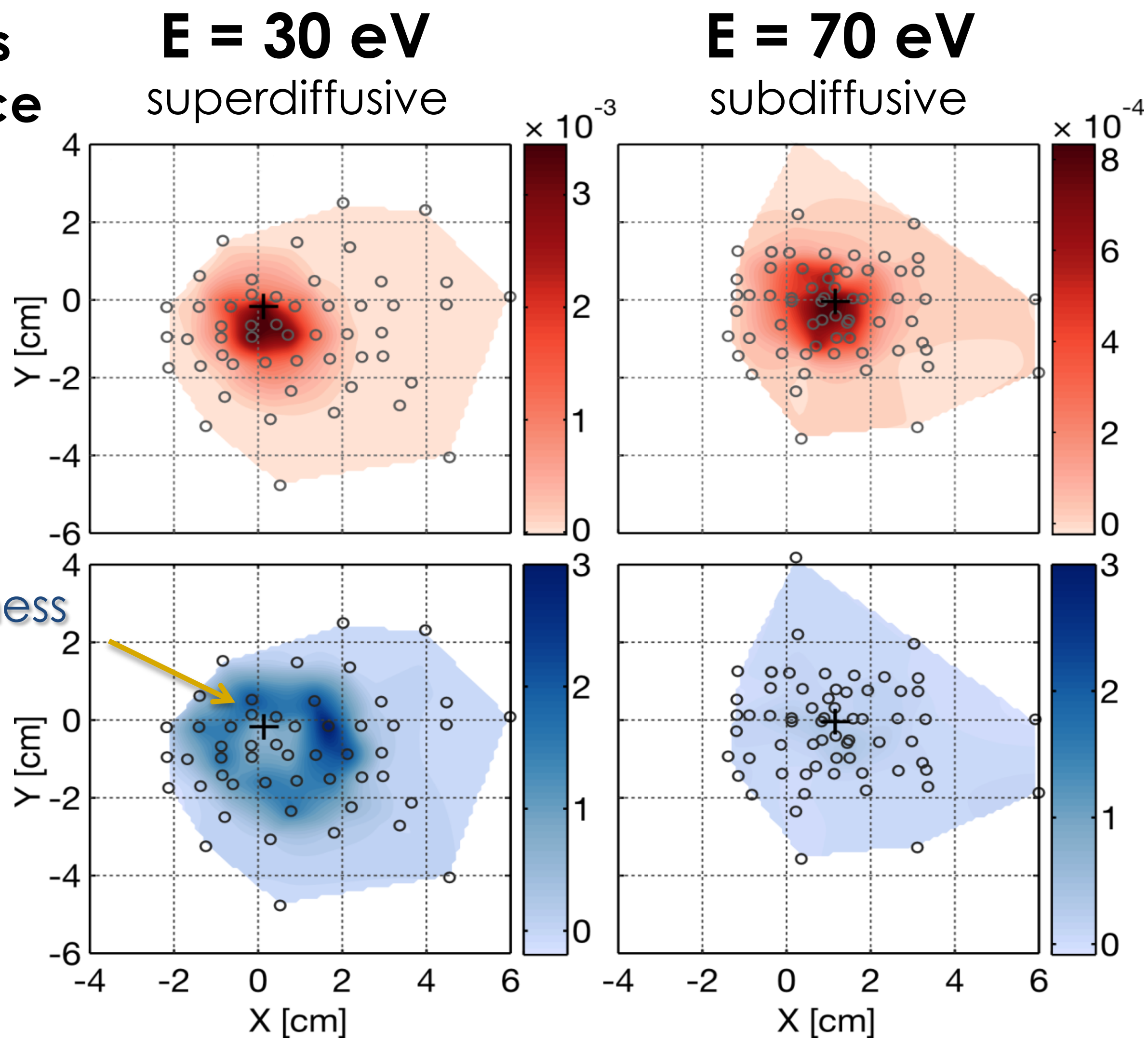
Different statistics in different transport regimes

Poloidal cross sections at 40 cm from the source

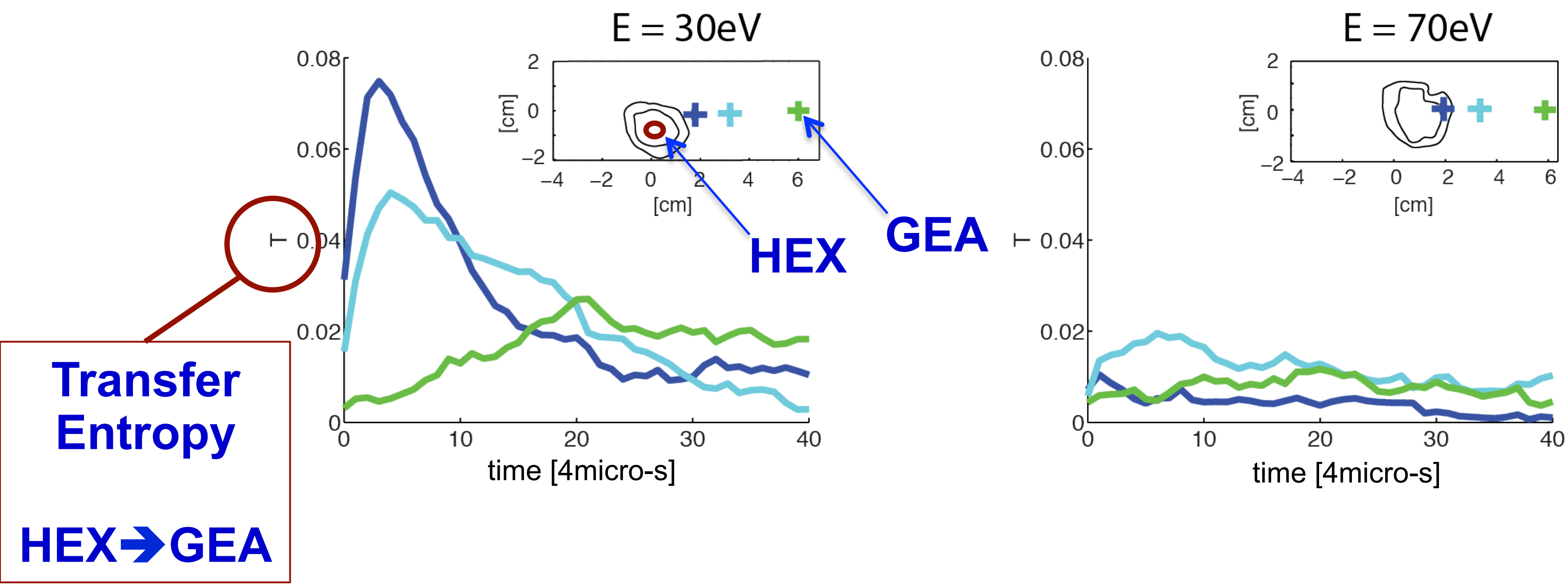
Time-averaged Current density [A/m^2]

«Crown» of high skewness

Skewness profile



The ion intermittency is causally related to turbulence



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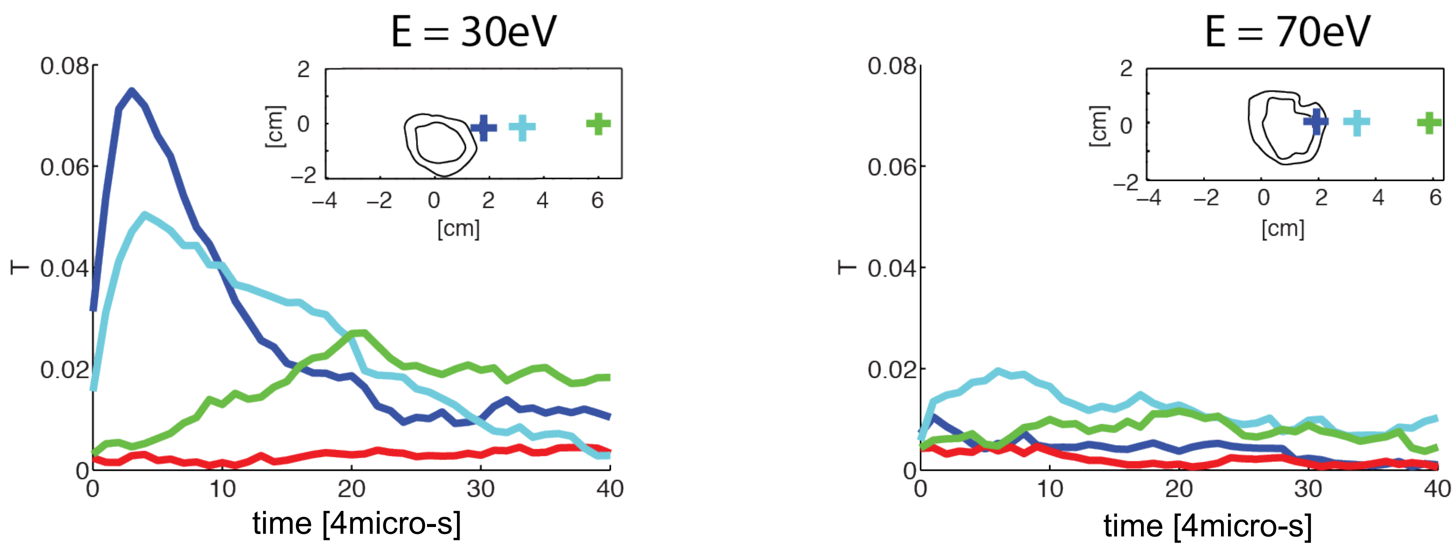

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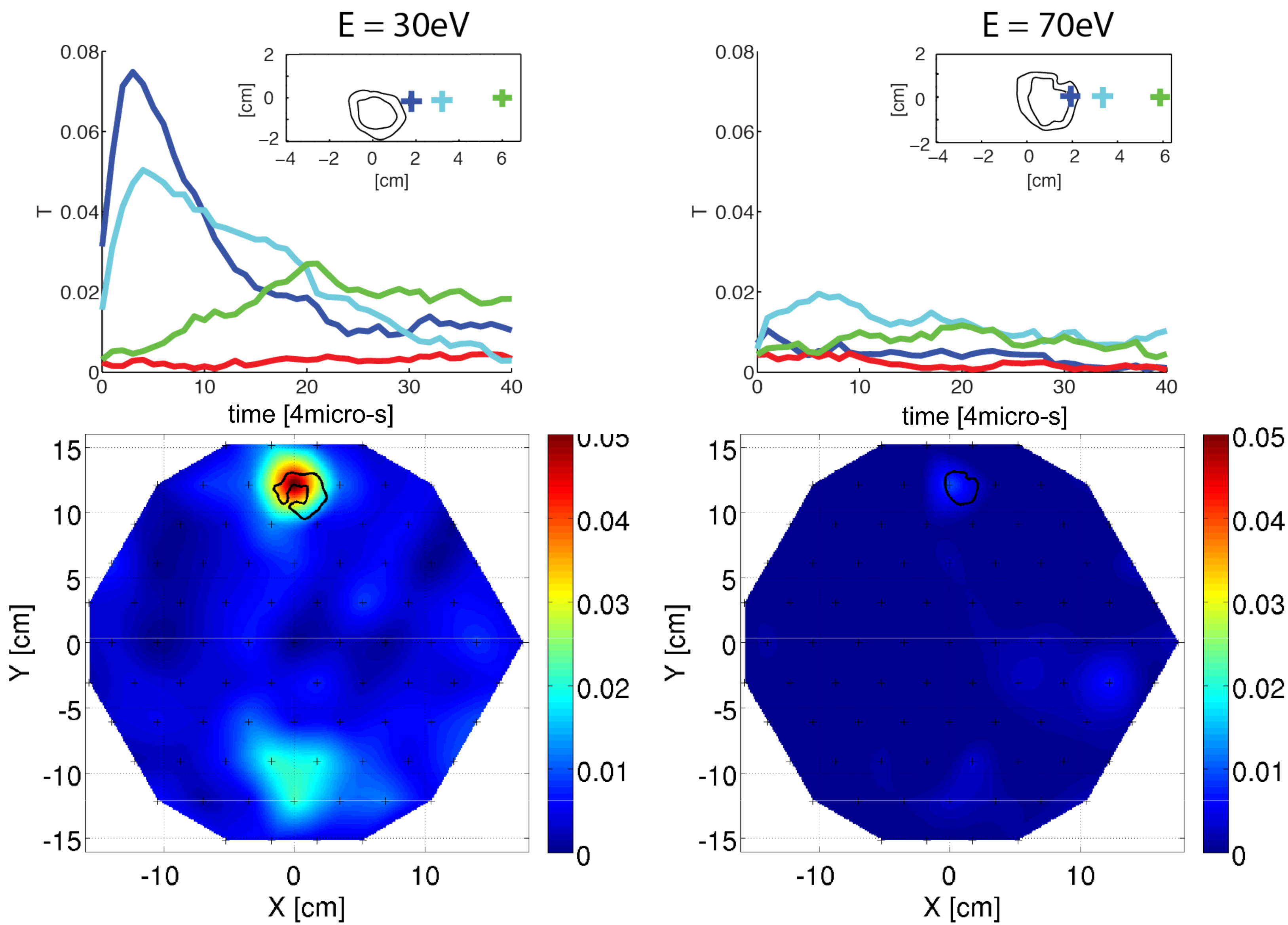
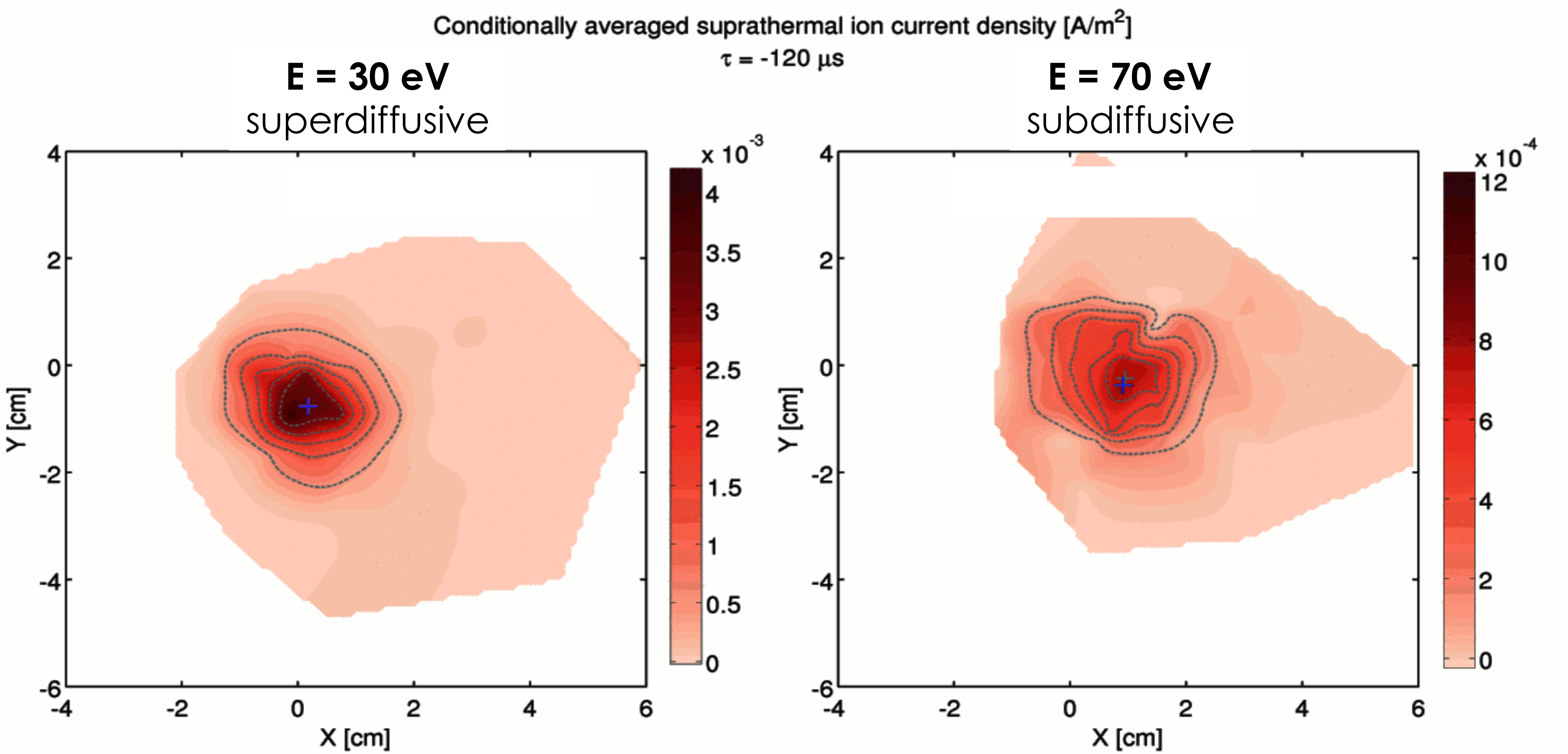


The entropy transfer is mediated by blobs



A. Bovet, PRL 2014

Conclusions

Simple plasma devices offer **great possibilities** to investigate the fundamentals of suprathermal ion – turbulence physics

On TORPEX, experiments and numerical simulations reveal different **non-diffusive regimes** for suprathermal ions depending on their energy and turbulence amplitude

Gyro- and **drift-averaging** can effectively reduce turbulent transport

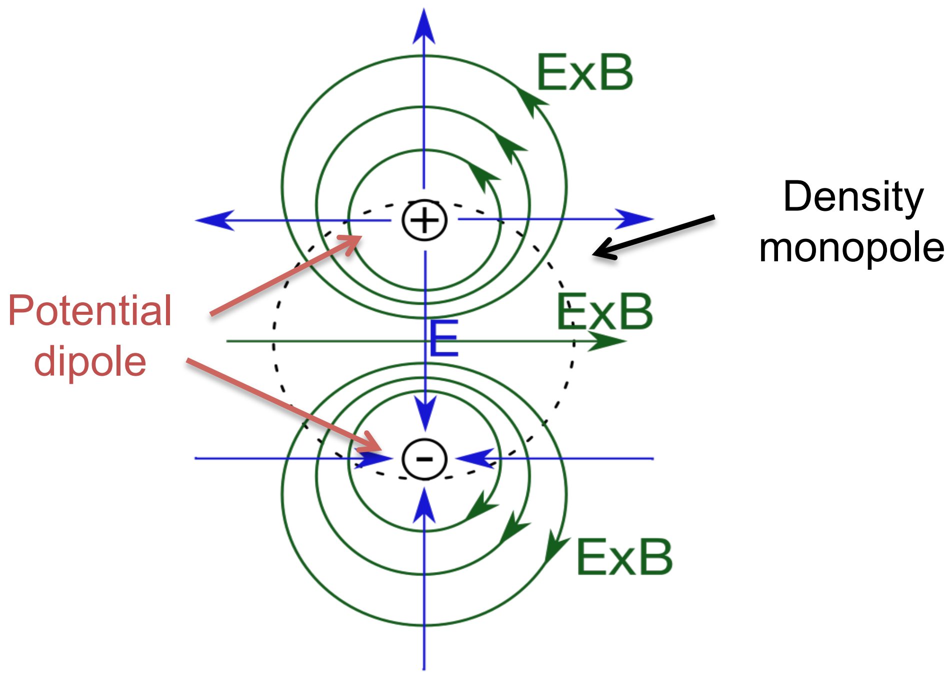
Time-resolved measurements reveal the effect of **blob transport**

Link between Eulerian time-resolved measurements (tokamaks, spacecrafts) and 3D time-averaged measurements

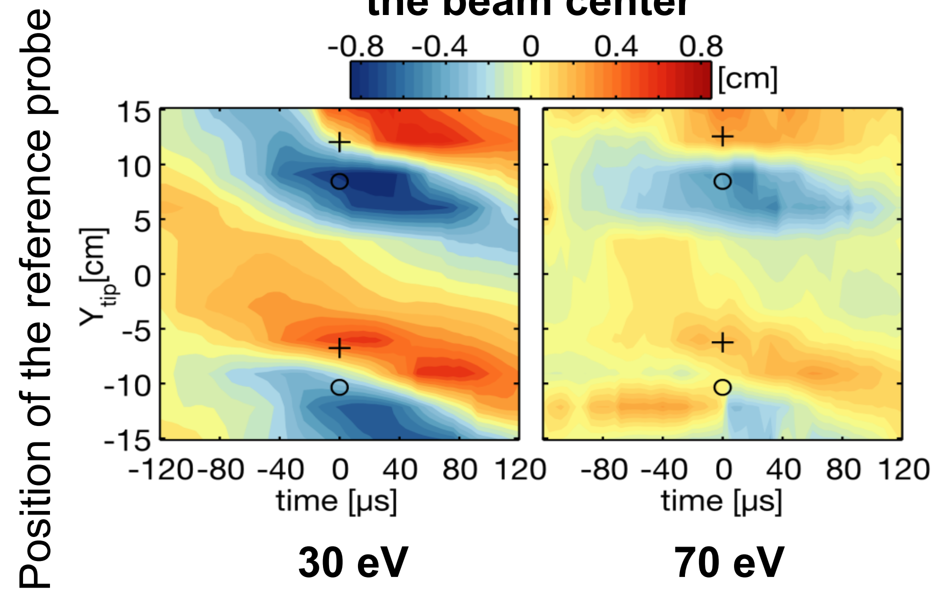
Upcoming TORPEX experiments will explore more complex magnetic geometries of direct relevance to tokamaks

The beam is displaced inwards/outwards by the blob ExB

Blobs are associated with a **potential dipole**



Radial displacement of the beam center



30 eV superdiffusive

70 eV subdiffusive

The 30 eV ions are systematically more displaced than the 70 eV ions
The displacement is inwards or outwards depending of the position of the blob
Larger blobs cause a larger displacement