Experimental validation of mechanisms for electron trapping and acceleration in magnetic islands and stochastic fields

Plasma Science Frontiers Program at DIII-D

Presented by

Evdokiya Kostadinova[1]

In collaboration with:

Dmitri Orlov[2], Bradley Andrew[1], Jessica Eskew[1], Evan Bursch[3], Mark Koepke[4], Frederick Skiff[5], Max Austin[6], Laszlo Bardoczi[7], Tyler Cote[8], Francesca Turco[9], Claudio Marini[2]

Space Science/CSPAR Colloquium
UAH, Huntsville, AL
Feb 2, 20234

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[2] Center for Energy Research, UCSD

[3] University of Notre Dame

[4] Dep. of Physics and Astronomy, West Virginia University

[5] Dep. of Physics and Astronomy, University of Iowa

[6] Institute for Fusion Studies, UT Austin

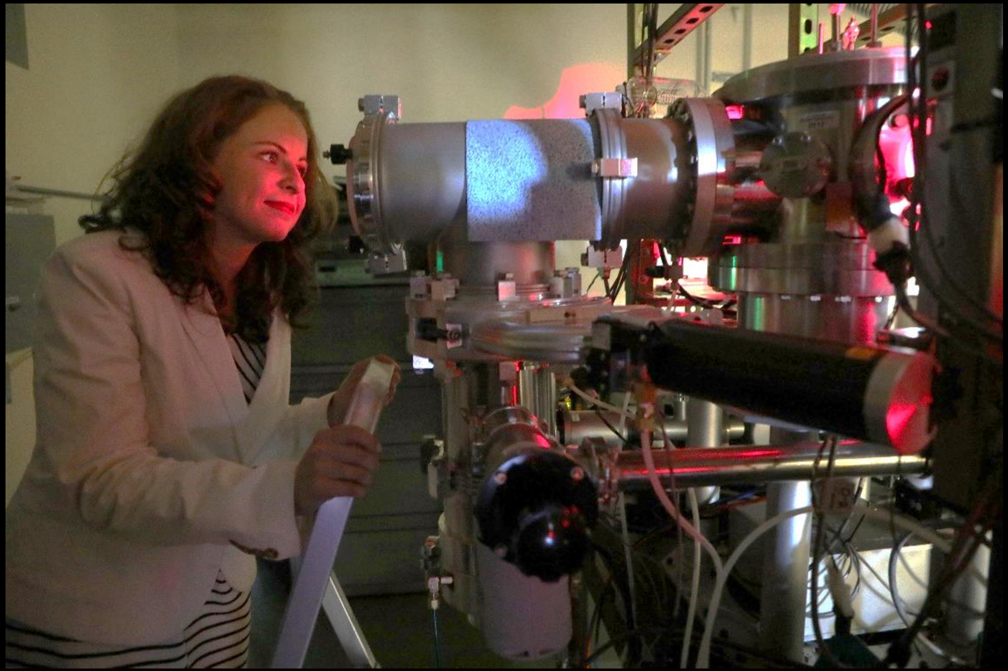
[7] UC Irvine

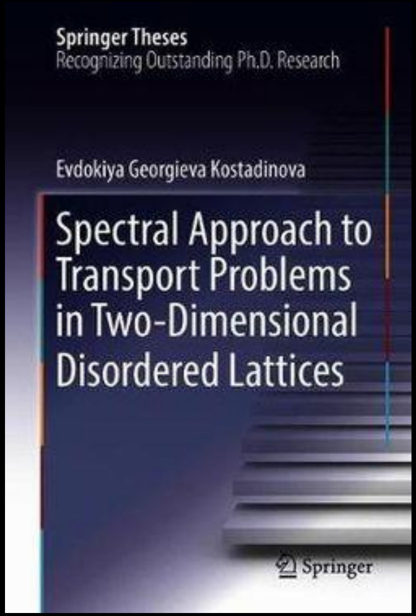
[8] General Atomics

[9] Columbia University

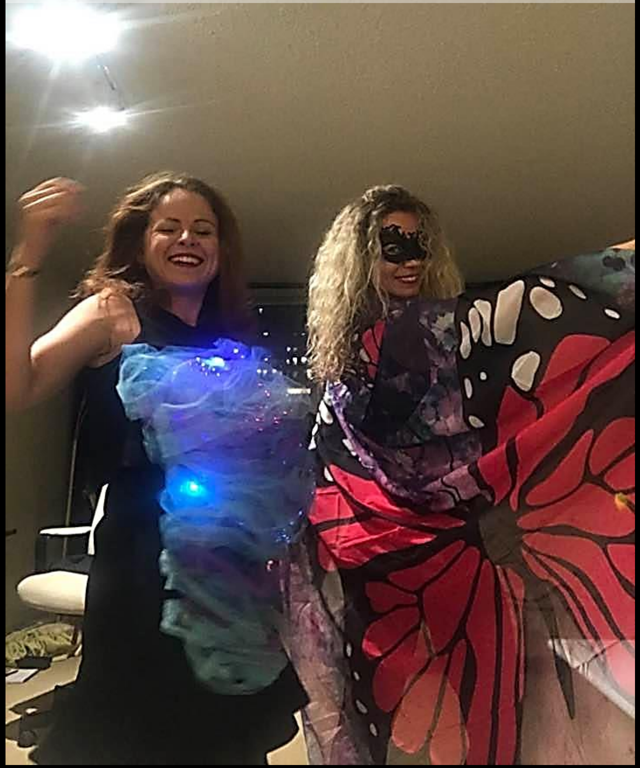
Evdokiya (Eva) Kostadinova

- Assistant Professor, Auburn
- PhD Physics, Baylor, Dec 2017
- Transport problems in disordered matter with nonlocal interactions → dusty plasma





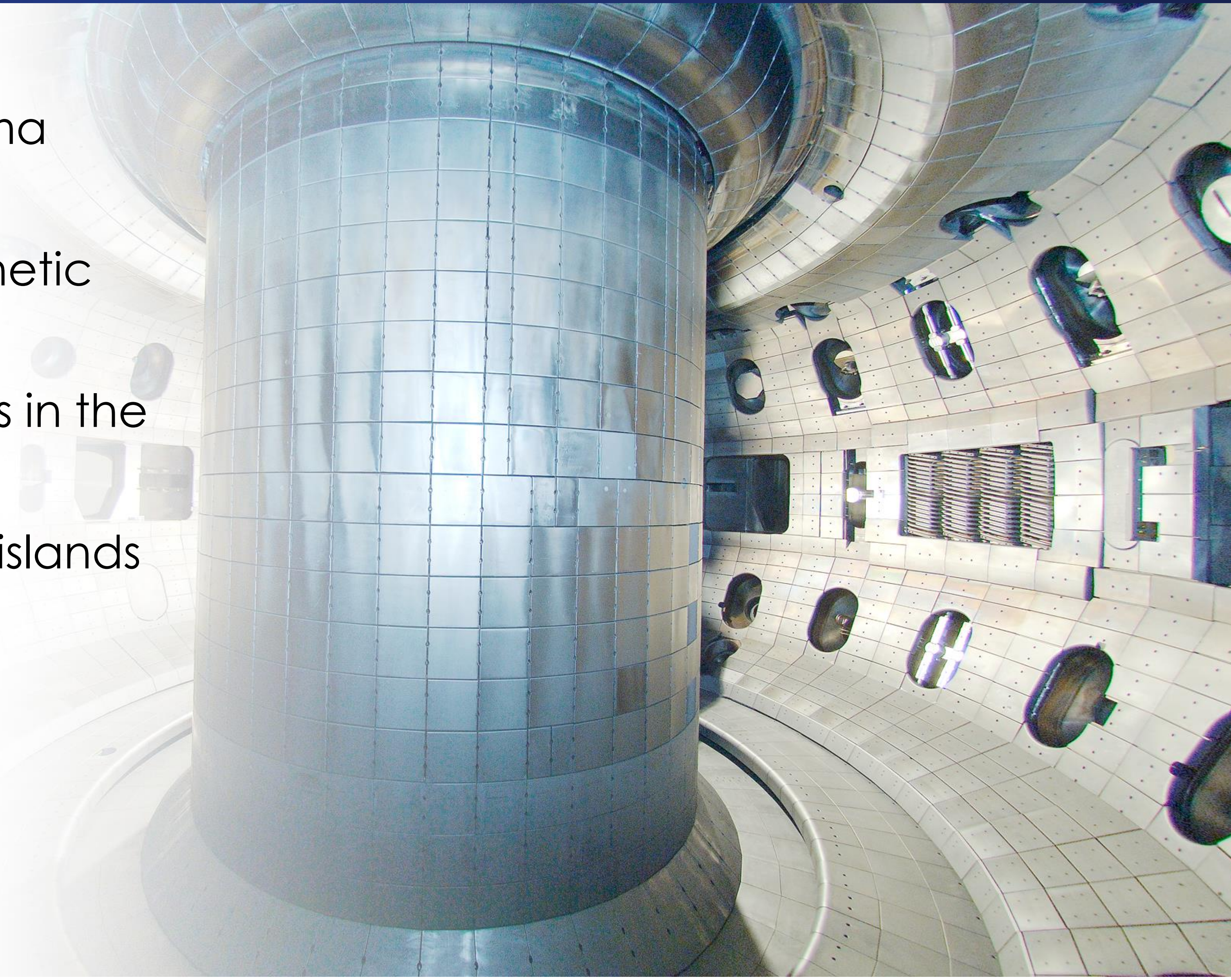
The Butterfly Effect



- Female international student
- BS from Furman University (small, liberal arts school)
- Interdisciplinary research b/w math and physics

Outline

- Interdisciplinary nature of plasma research
- Anomalous diffusion and magnetic topology
- Energetic Electrons Experiments in the DIII-D tokamak
- EEs interactions with magnetic islands and field stochasticity
- Concluding remarks



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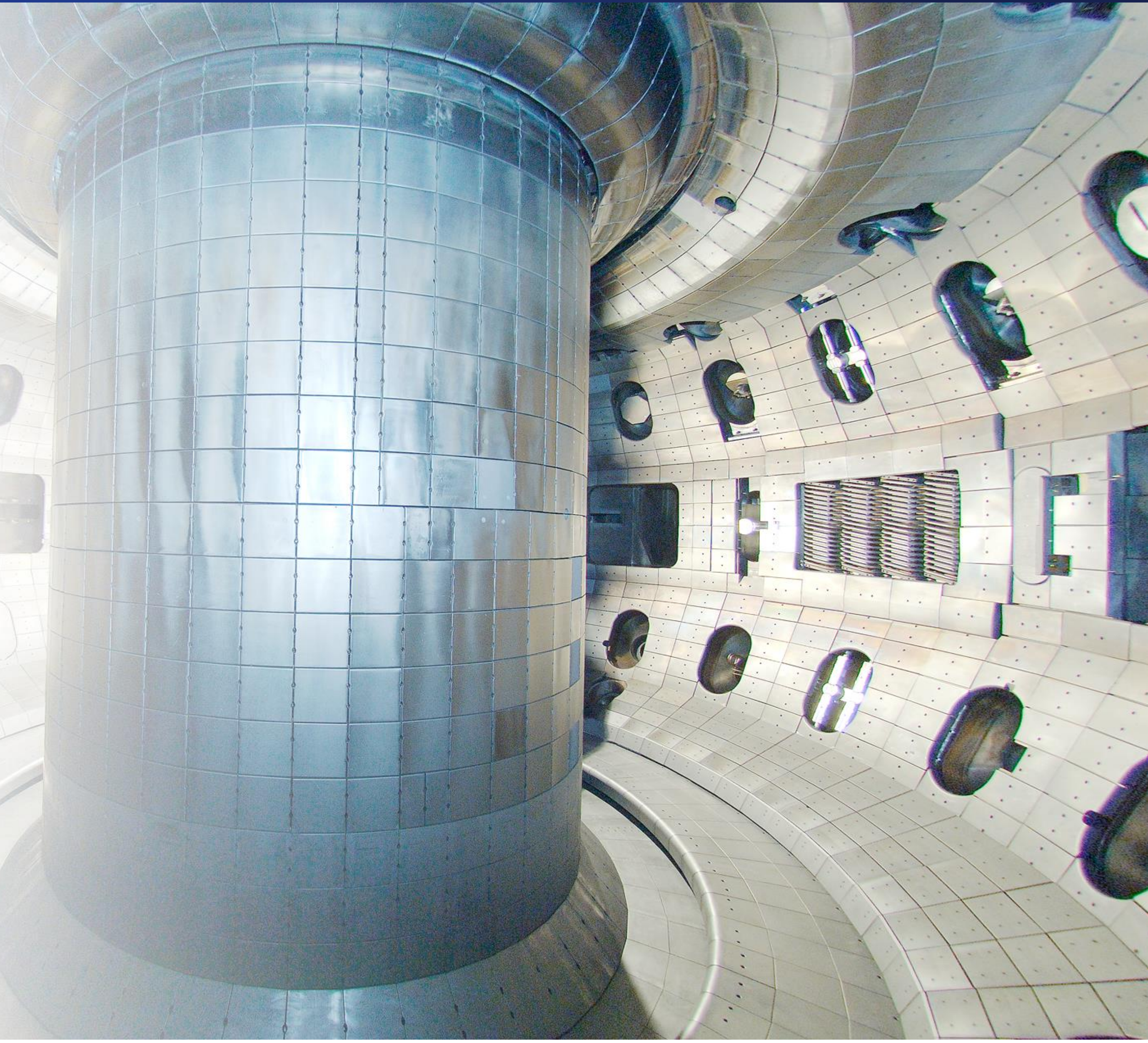

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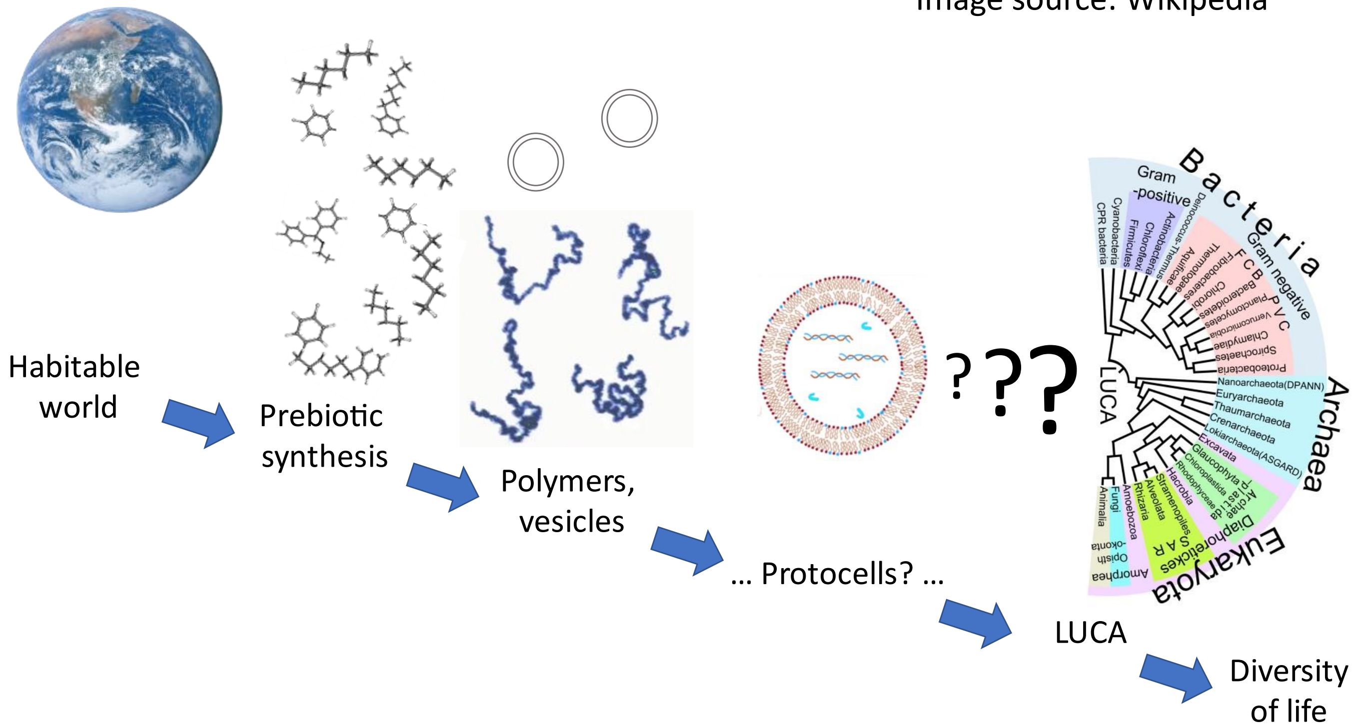
What do we work on?

- Origins of life on Earth

Image source: Wikipedia



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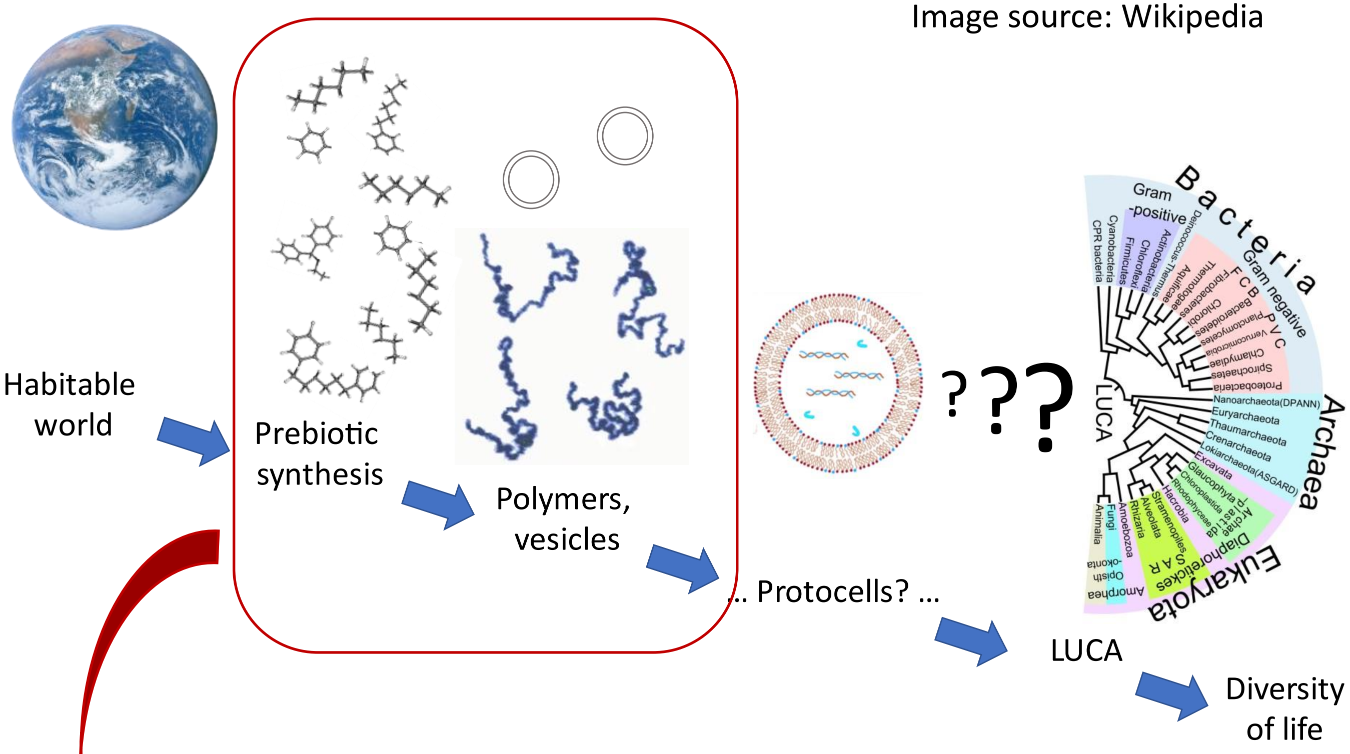
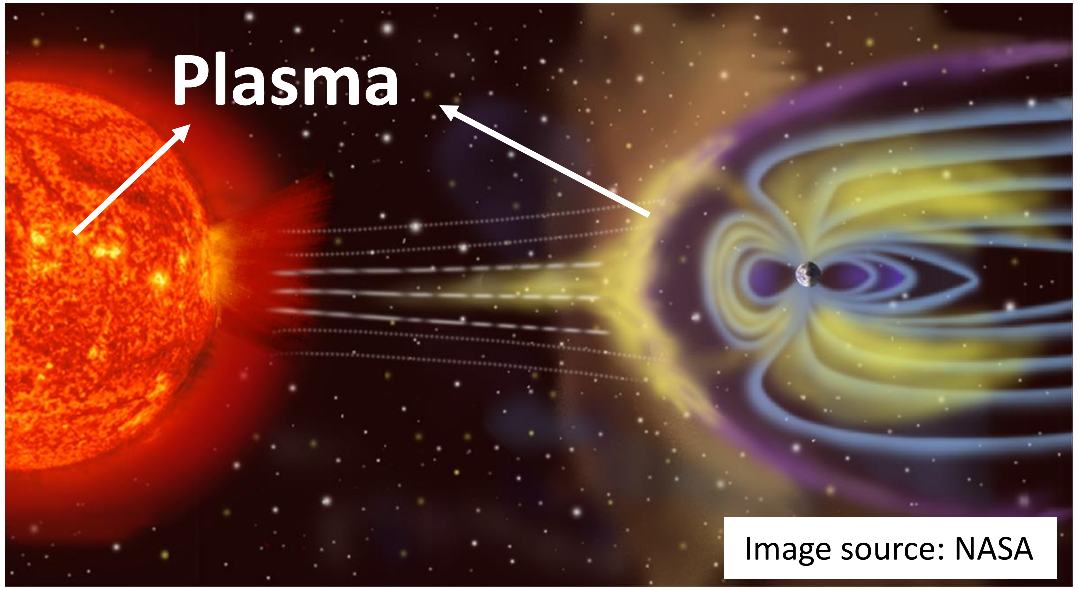


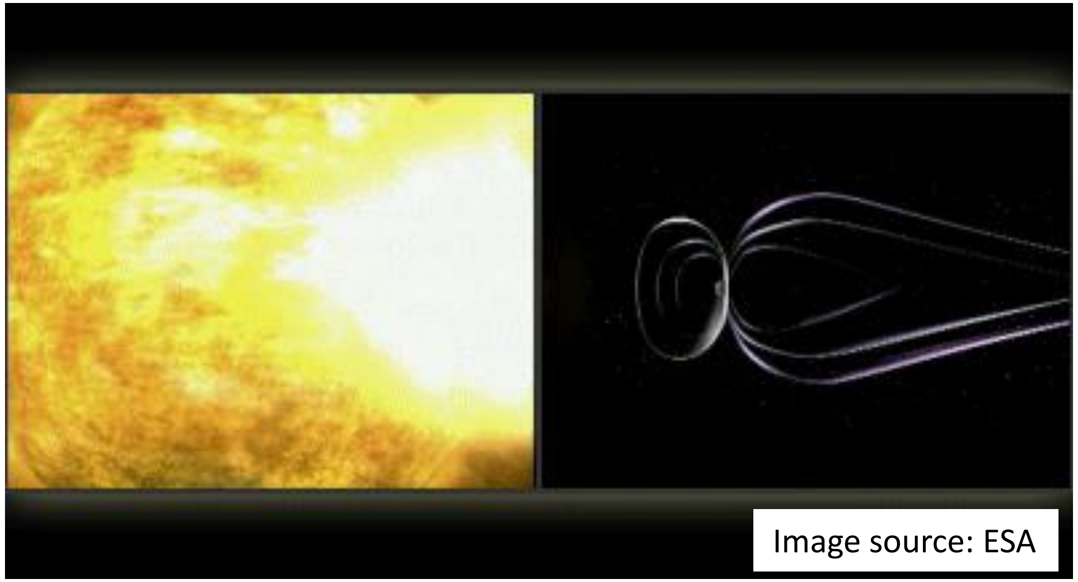
Q: How did simple molecules (like H_2, O_2, N_2, etc.) formed complex organic molecules - the building blocks of life?

H: Organics formed in the **plasma** tails of meteorites as they entered Earth

What do we work on?

- Origins of life on Earth
- Protecting life on Earth from space weather





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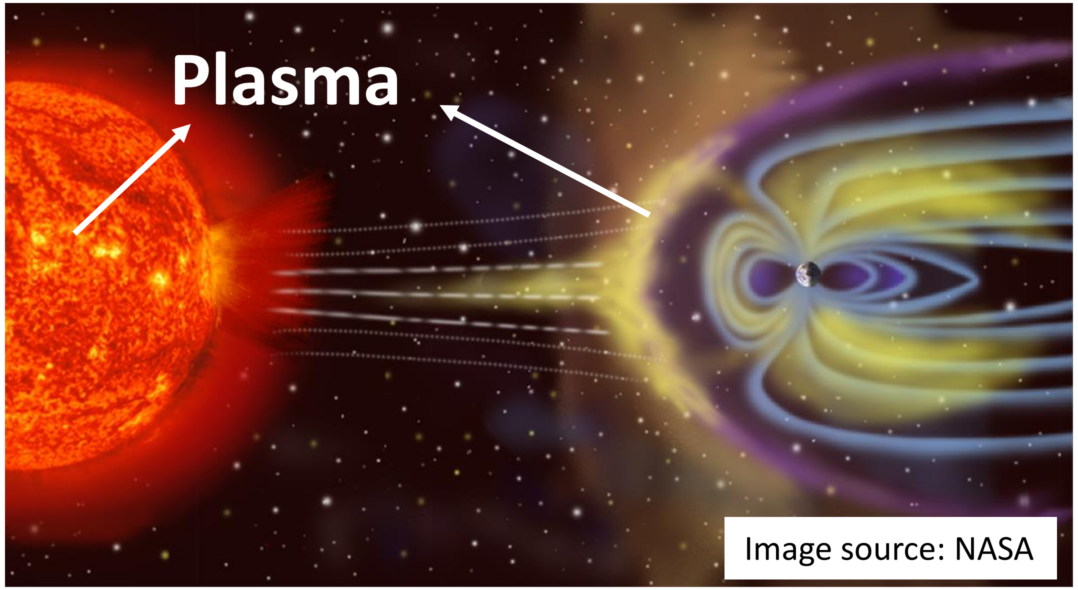
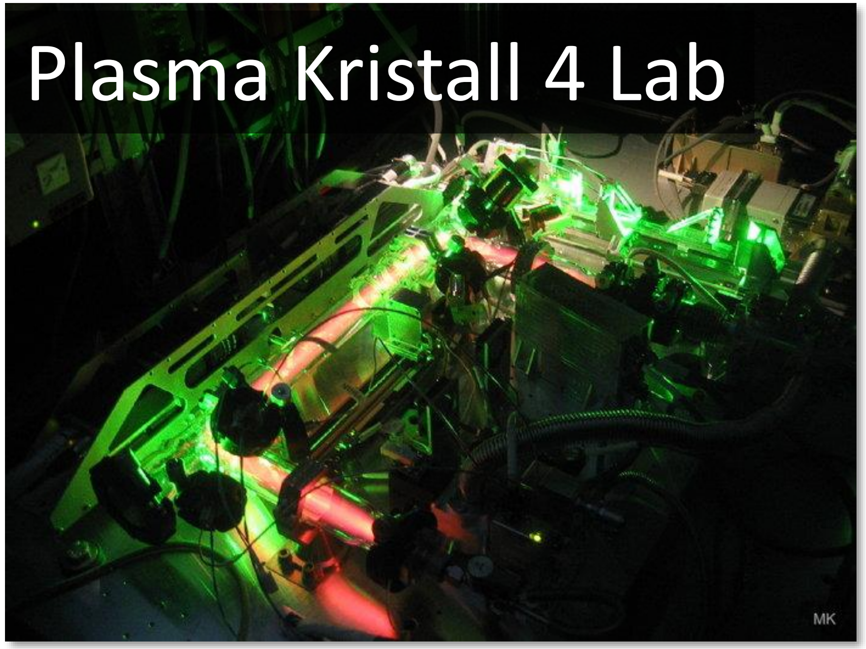


Q: How do twisted and chaotic magnetic fields in Earth's magnetosphere accelerate electrons to ultra-fast speeds causing geo-magnetic storms?

H: When magnetic fields interact with the solar wind, they form a standing wave structure that may trap and accelerate electrons.

What do we work on?

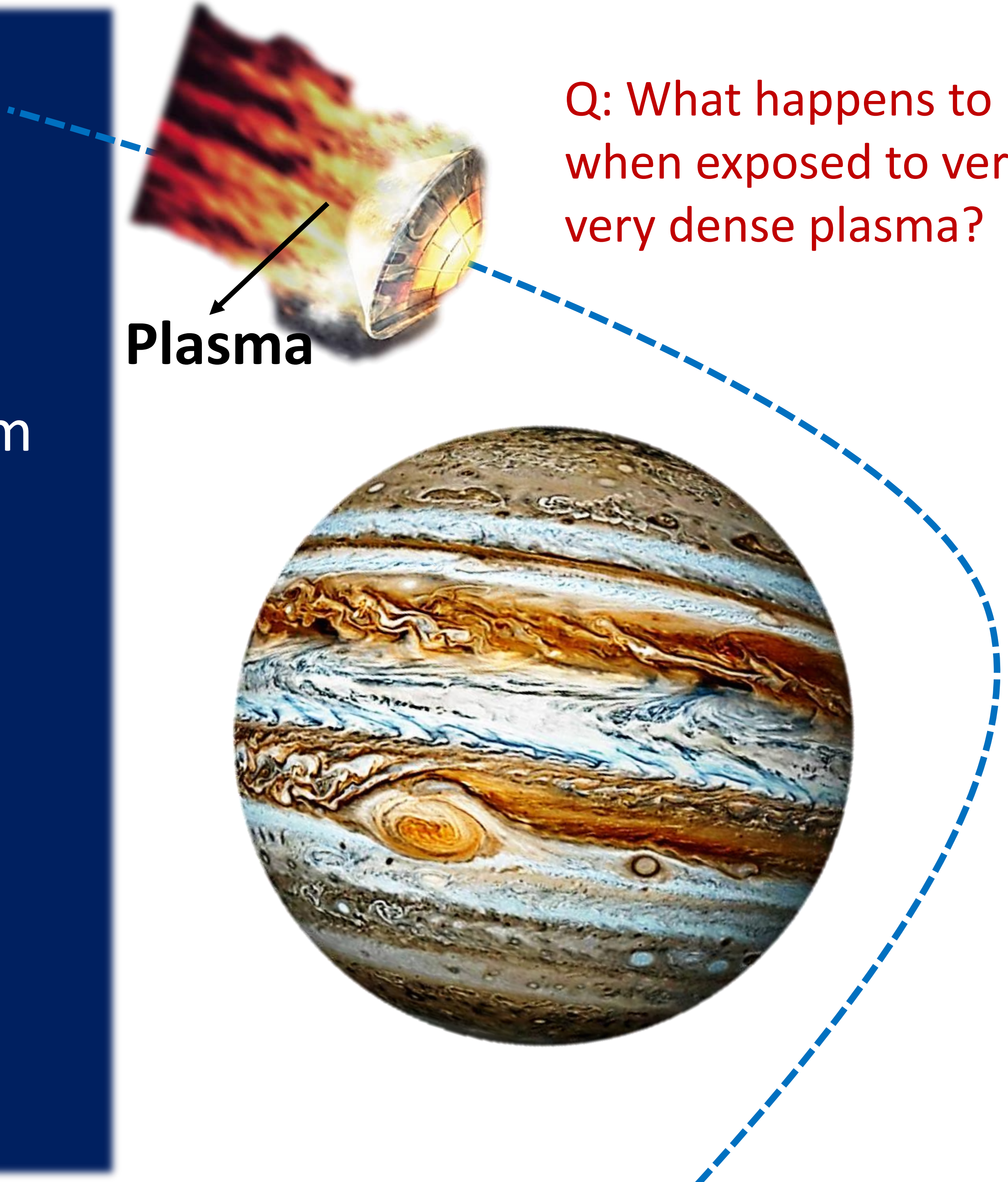
- Origins of life on Earth
- Protecting life on Earth from space weather
- Life beyond Earth
  - Reduced-gravity physics



Q: What happens to the laws of physics when we remove gravity?

What do we work on?

- Origins of life on Earth
- Protecting life on Earth from space weather
- Life beyond Earth
  - Reduced-gravity physics
  - Heat shields for spacecrafts

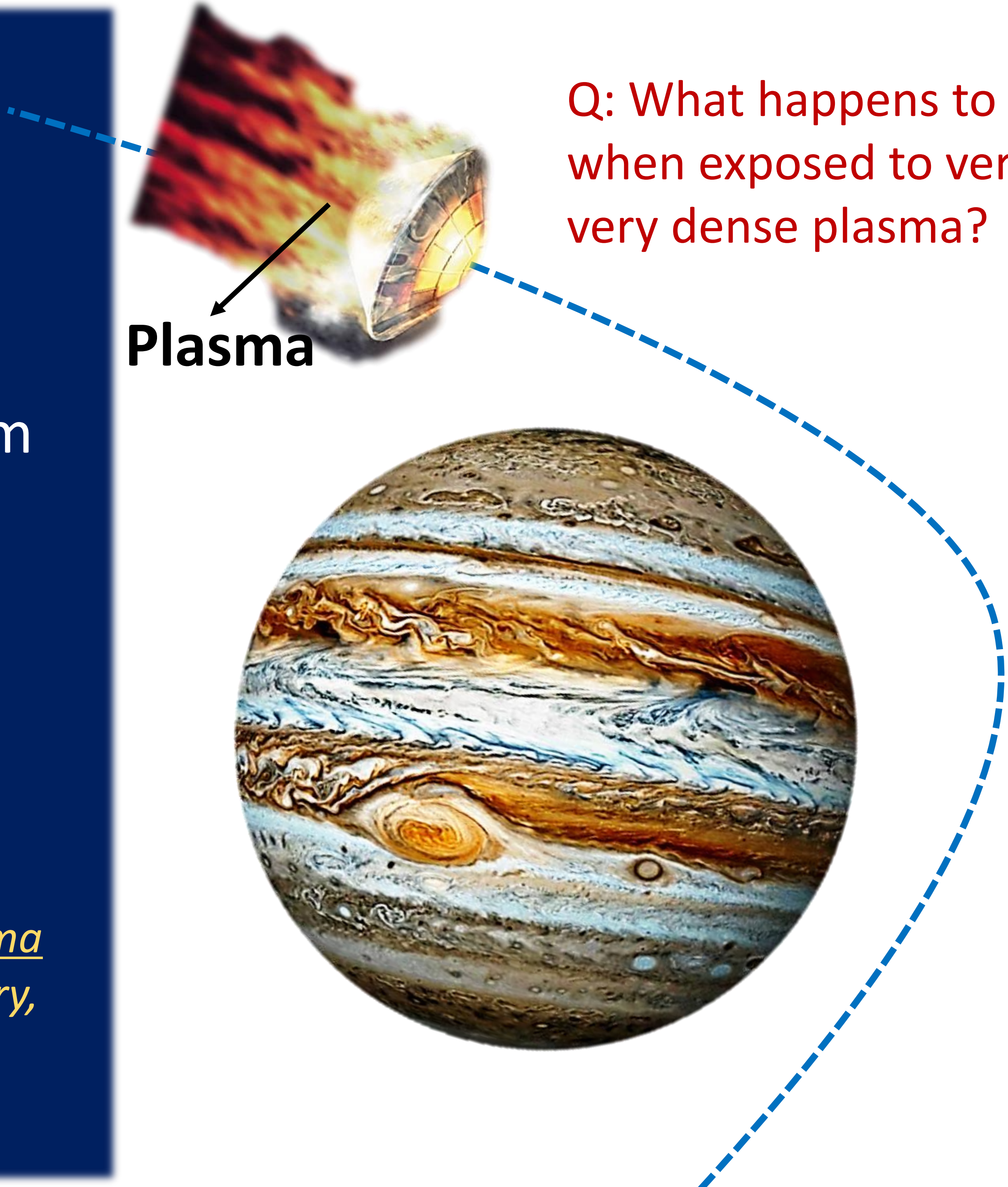


Q: What happens to materials when exposed to very hot and very dense plasma?

What do we work on?

- Origins of life on Earth
- Protecting life on Earth from space weather
- Life beyond Earth
  - Reduced-gravity physics
  - Heat shields for spacecrafts

These projects are at the interface of <u>plasma</u> and: space physics, applied math, chemistry, astrobiology, fusion energy, aerospace engineering



Q: What happens to materials when exposed to very hot and very dense plasma?

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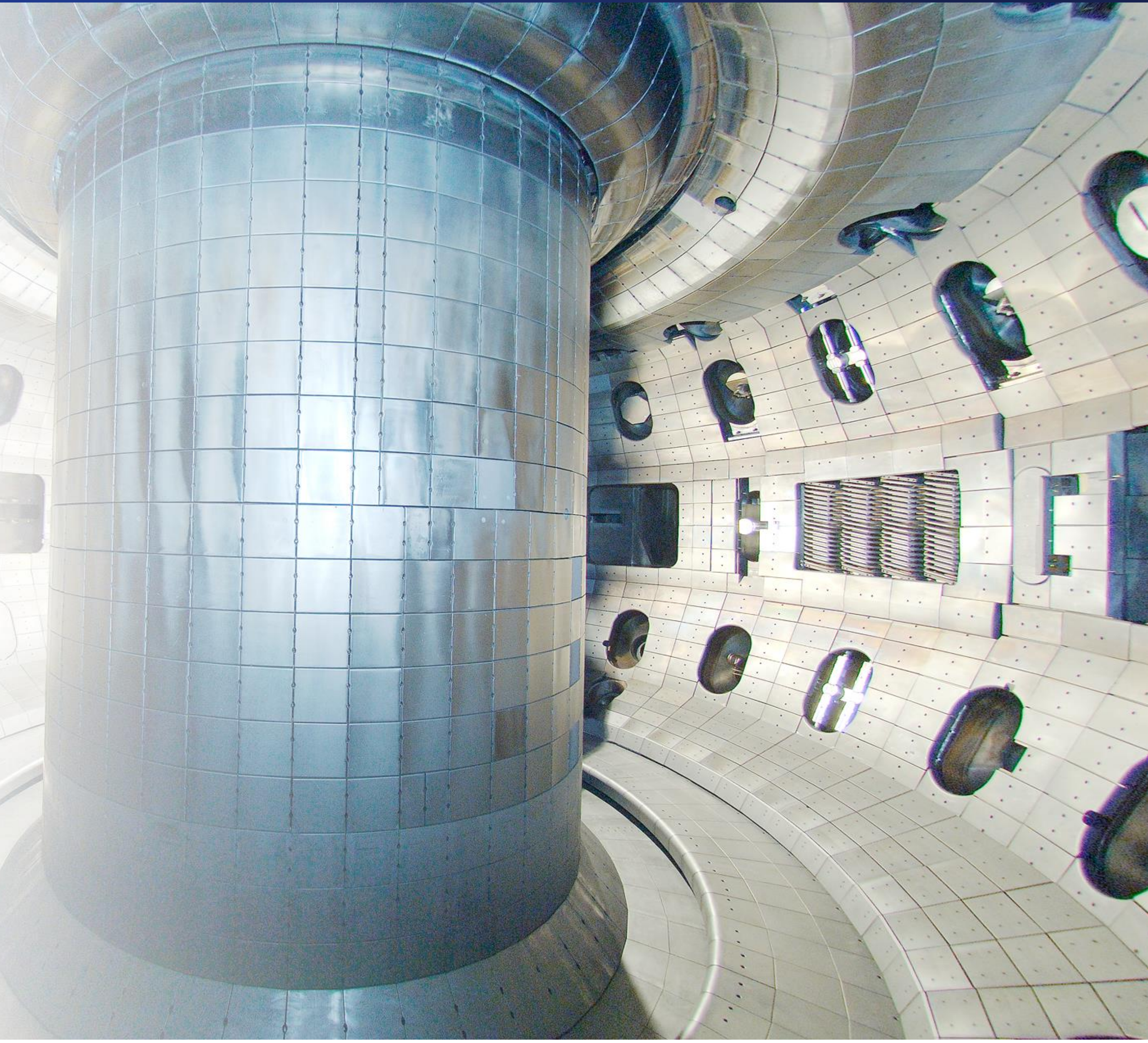

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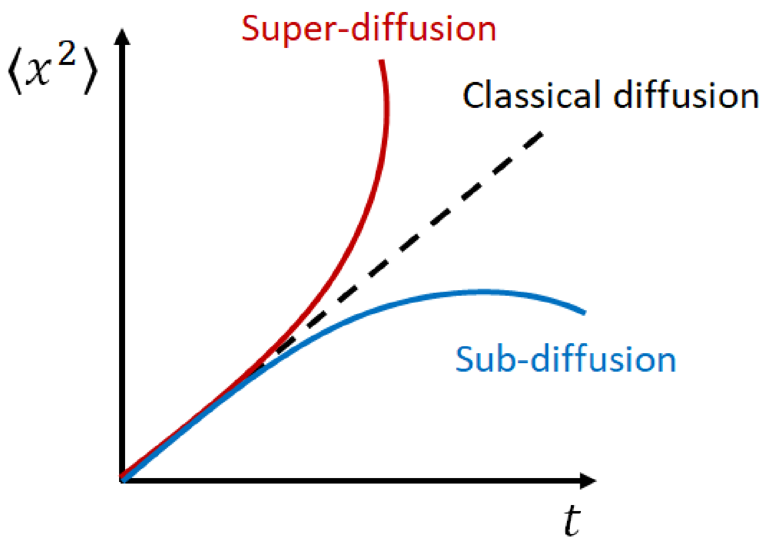
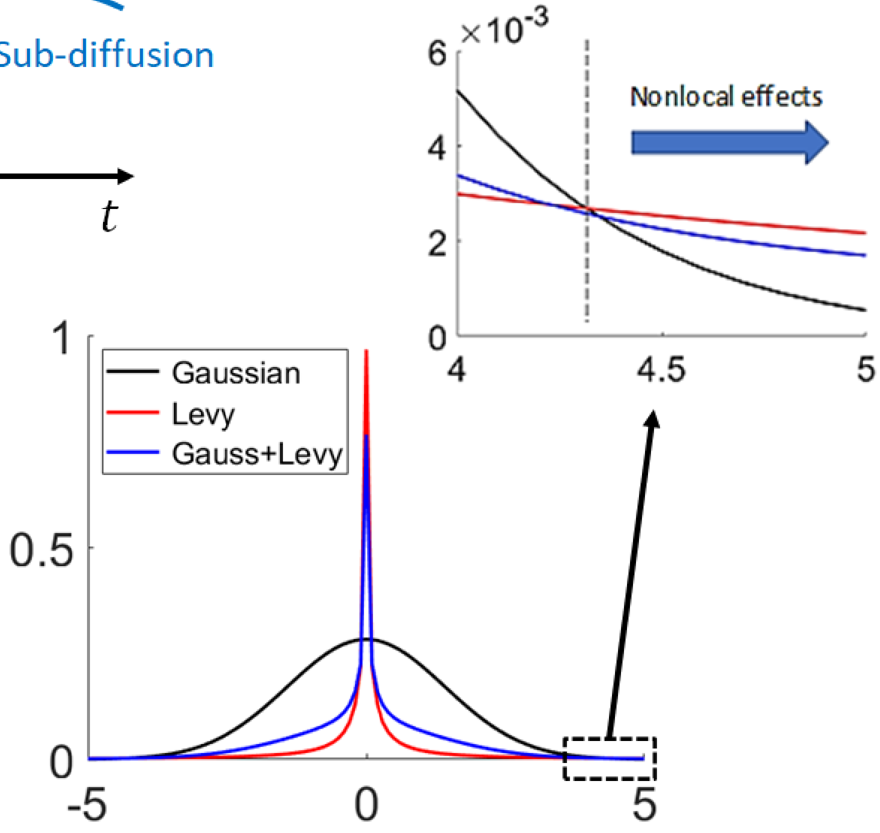
Definition and characteristics of anomalous diffusion

- **Classical Diffusion:** microscopic random motion due to a gradient (concentration, pressure, temperature, etc.)
- **Anomalous Diffusion:** microscopic non-deterministic motion due to non-local interactions (collisions and correlations)
  - **Observation 1:** mean square displacement (MSD) grows non-linearly as a function of time

    $$\langle x^2 \rangle \sim t^{\alpha}$$

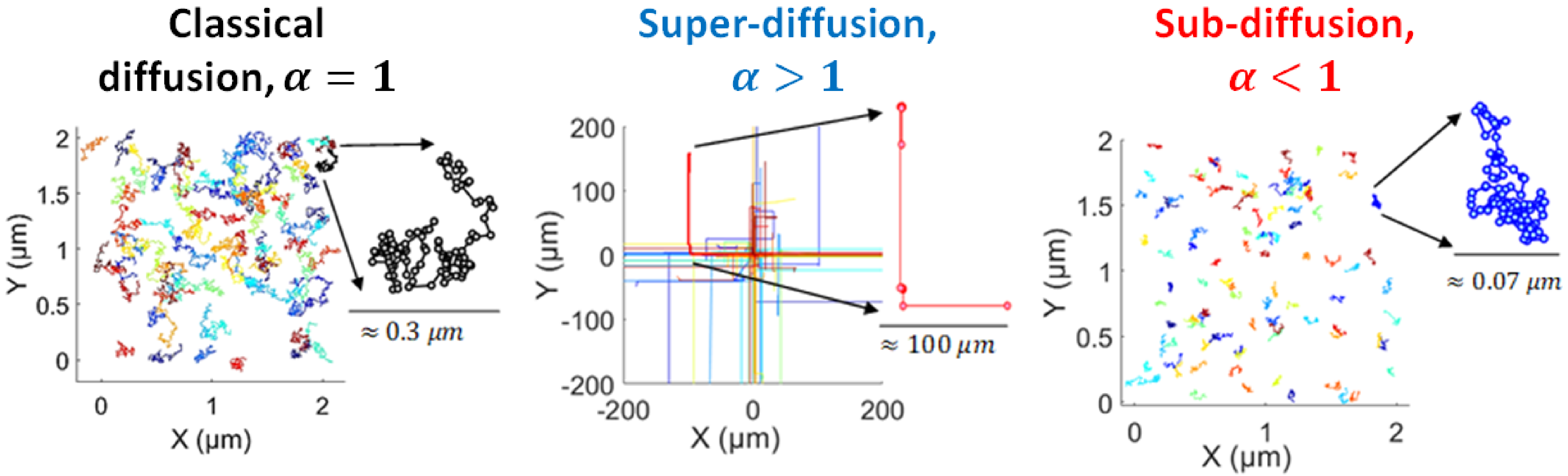
  - **Observation 2:** probability distribution functions (displacement/velocity) are non-Maxwellian





Visualizing different diffusion regimes using these principles

- The following trajectories were generated numerically using the probability distribution functions from the previous slide.

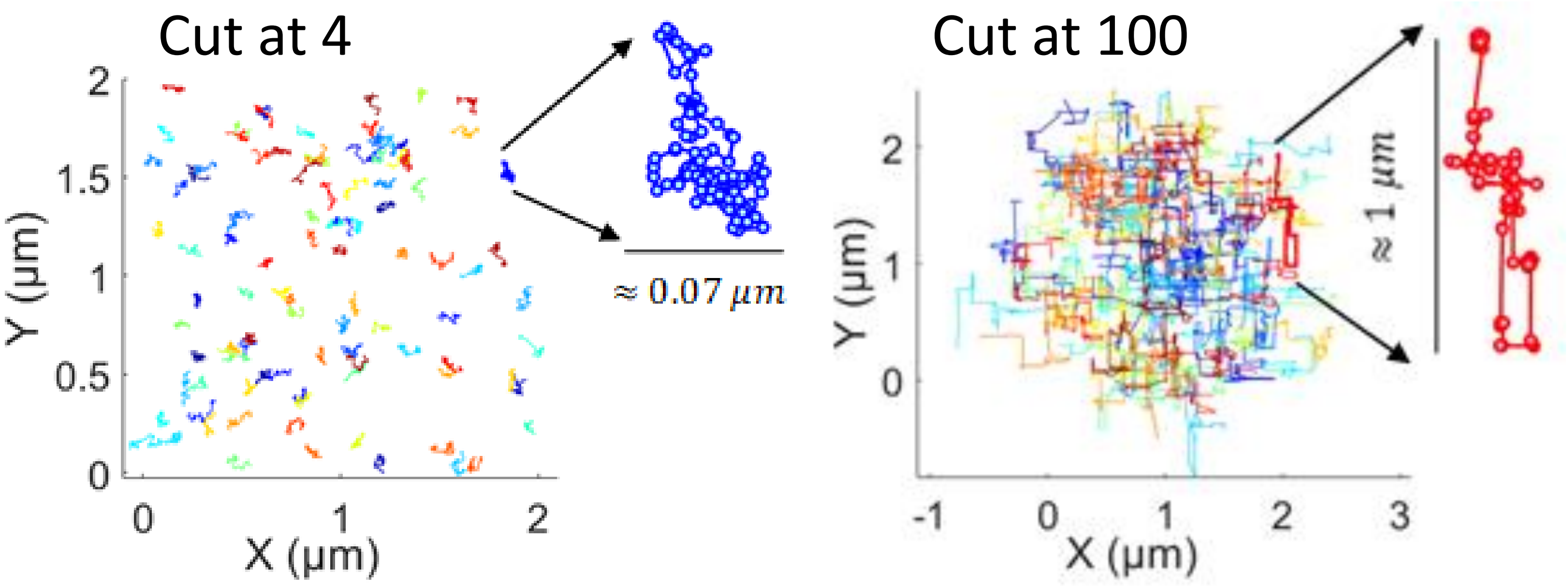


Particle trajectories generated using numerical techniques from: N. Tarantino et al., J. Cell Biol., vol. 204, no. 2, 2014

Sub-diffusion can be modeled as waiting times or as backward jumps (i.e., restricted super-diffusion)

- **Waiting times model:** requires PDF that spreads slower than a Gaussian
- **Backward jumps model:** requires a superposition of classical diffusion and superdiffusion

Sub-diffusion, $\alpha < 1$



- Anomalous diffusion can be modeled using a **fractional Laplacian**

$$(-\Delta)^s \equiv \left(\frac{\partial^2}{\partial r^2}\right)^s$$

Kostadinova, E., et al. "Fractional Laplacian spectral approach to turbulence in a dusty plasma monolayer." Physics of Plasmas 28.7 (2021): 073705.

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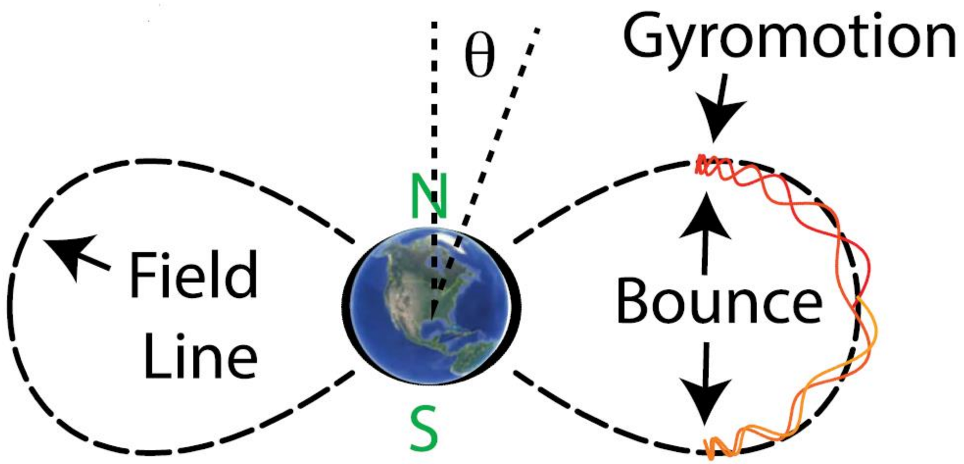
Anomalous diffusion is expected for energetic particles in Earth's magnetosphere

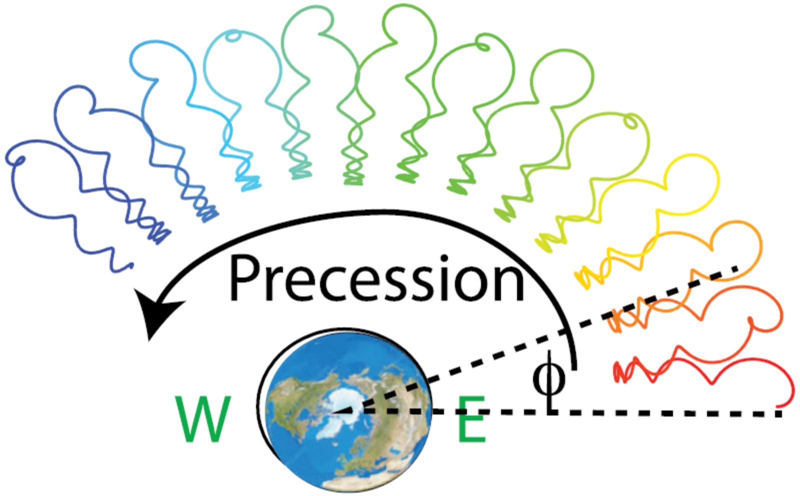
- Properties of energetic particles in B-fields in plasma:
  - Have **energy order of magnitude greater** than the thermal particles in the bulk plasma
  - EP trajectories **deviate further from B-field lines**
    → larger gyroradius (due to larger $v_\perp$)
    → larger drifts (due to larger $v_\perp$ and $v_\parallel$)

$$W_\perp = \frac{1}{2} m v_\perp^2 \qquad W_\parallel = \frac{1}{2} m v_\parallel^2$$

Grad-B drift: $\boldsymbol{v}_{\nabla \boldsymbol{B}} = \frac{W_\perp}{q} \frac{\boldsymbol{B} \times \nabla \boldsymbol{B}}{B^3}$

Curvature drift: $\boldsymbol{v}_{\boldsymbol{curv}} = \frac{2 W_\parallel}{q B^2} \frac{\boldsymbol{R_c} \times \boldsymbol{B}}{R_c^2}$





Heidbrink, W. W., and R. B. White. "Mechanisms of energetic-particle transport in magnetically confined plasmas." Physics of Plasmas 27.3 (2020): 030901.

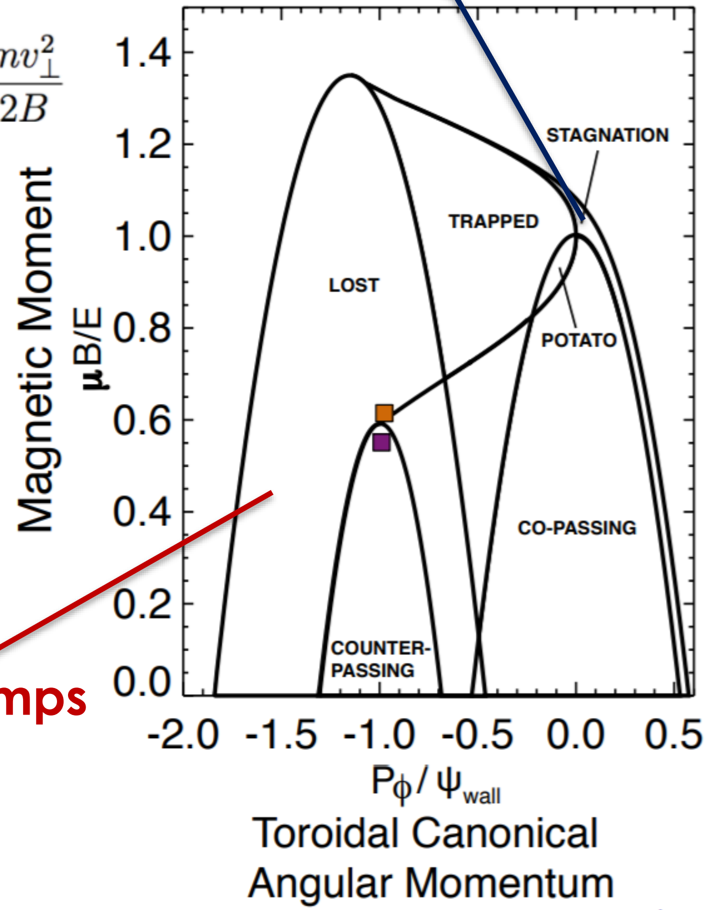
Anomalous diffusion is expected for energetic particles in laboratory plasma

- Properties of energetic particles in B-fields in plasma:
  - Have **energy order of magnitude greater** than the thermal particles in the bulk plasma
  - EP trajectories **deviate further from B-field lines**
    → larger gyroradius (due to larger $v_\perp$)
    → larger drifts (due to larger $v_\perp$ and $v_\parallel$)
  - **Coulomb collisions are negligible** on the timescale of a single orbit in the B-field

    → some trajectories become even more confined
  - EP distribution has complex dependence on energy
    → described by **non-Maxwellian PDF**
    → modeling Eps requires a **single-particle picture**

very trapped

$$\mu \equiv \frac{mv_\perp^2}{2B}$$



big jumps

Cami Collins talk for 2019 PPPL SULI prograam: https://suli.pppl.gov/2019/course/Collins_SULISingleParticleMotion_2019.pdf

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Anomalous diffusion results from particle's interaction with the plasma waves/instabilities and/or B-field topology

- **Poincare plot:** made by plotting positions in phase space at regular intervals
  → often used to trace B-field lines
  → can be used to trace single particle orbits
- For **toroidal geometry**, plot the (r, z) position of the field line every time it passes a particular toroidal angle
- **Large-scale perturbations** of the B-field (e.g., due to coils) can cause the formation of magnetic islands

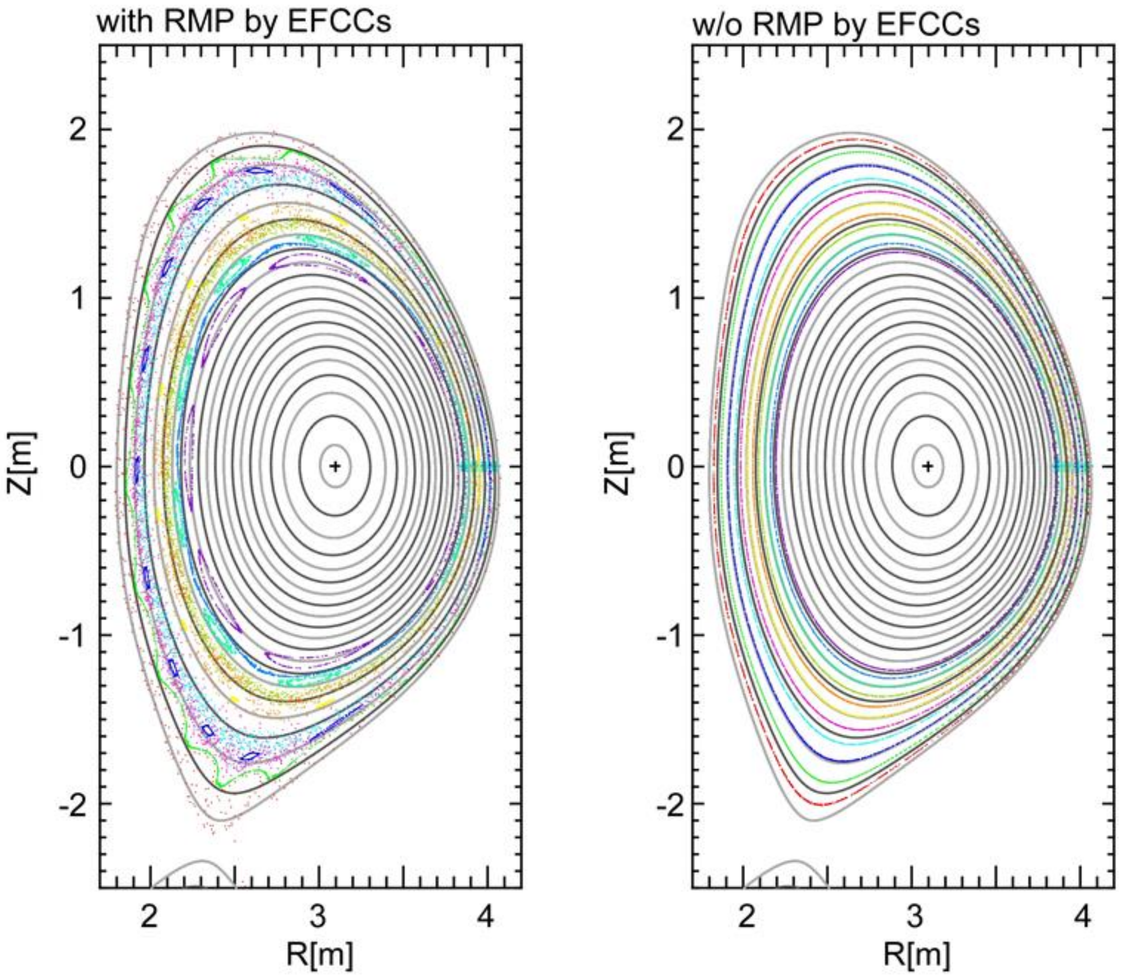


Image credit: JT-60SA Newsletter
https://www.jt60sa.org/b/news43/news43f.htm

Simple geometrical picture of a magnetic island

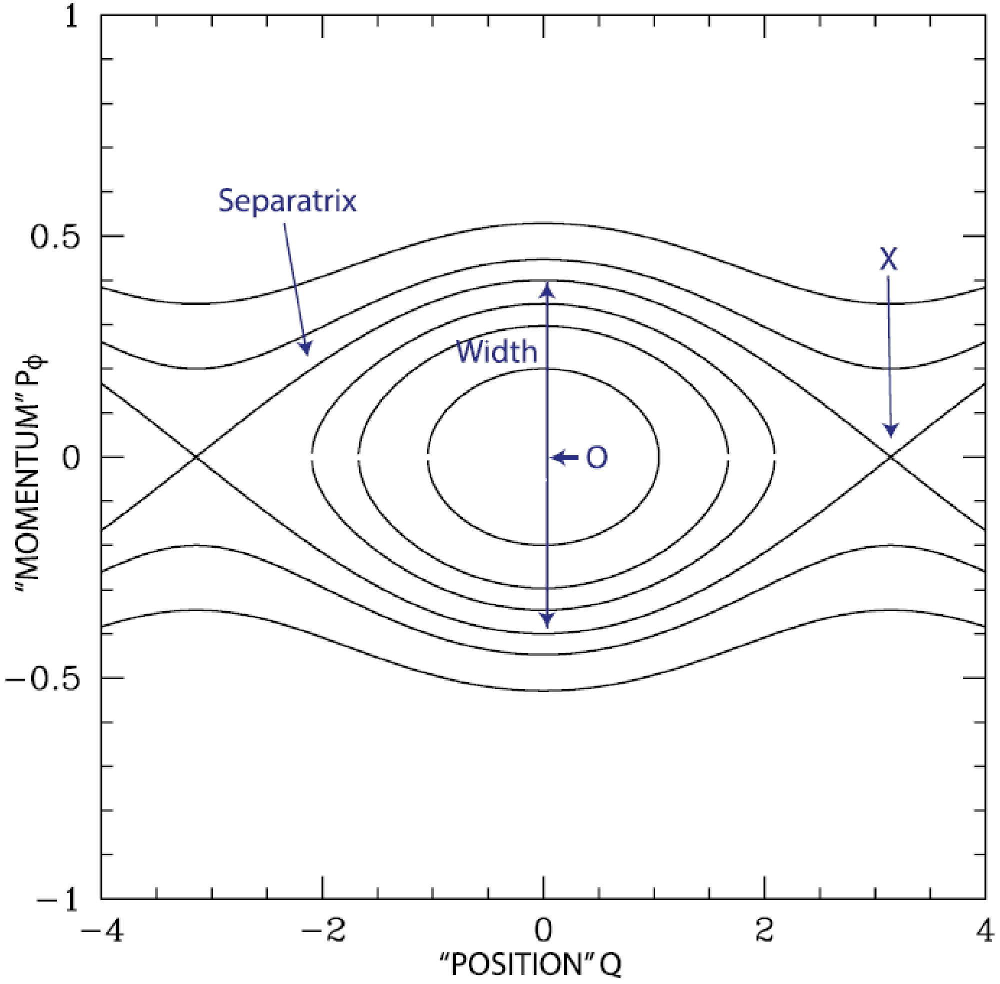
- **Magnetic island:** a closed magnetic flux tube bounded by a separatrix, isolating it from the rest of space

  → O-point corresponds to elliptical trajectory

  → X-point corresponds to hyperbolic trajectory

  → Separatrix – last closed flux surface

  → Island width ~ square rood of perturbation amplitude



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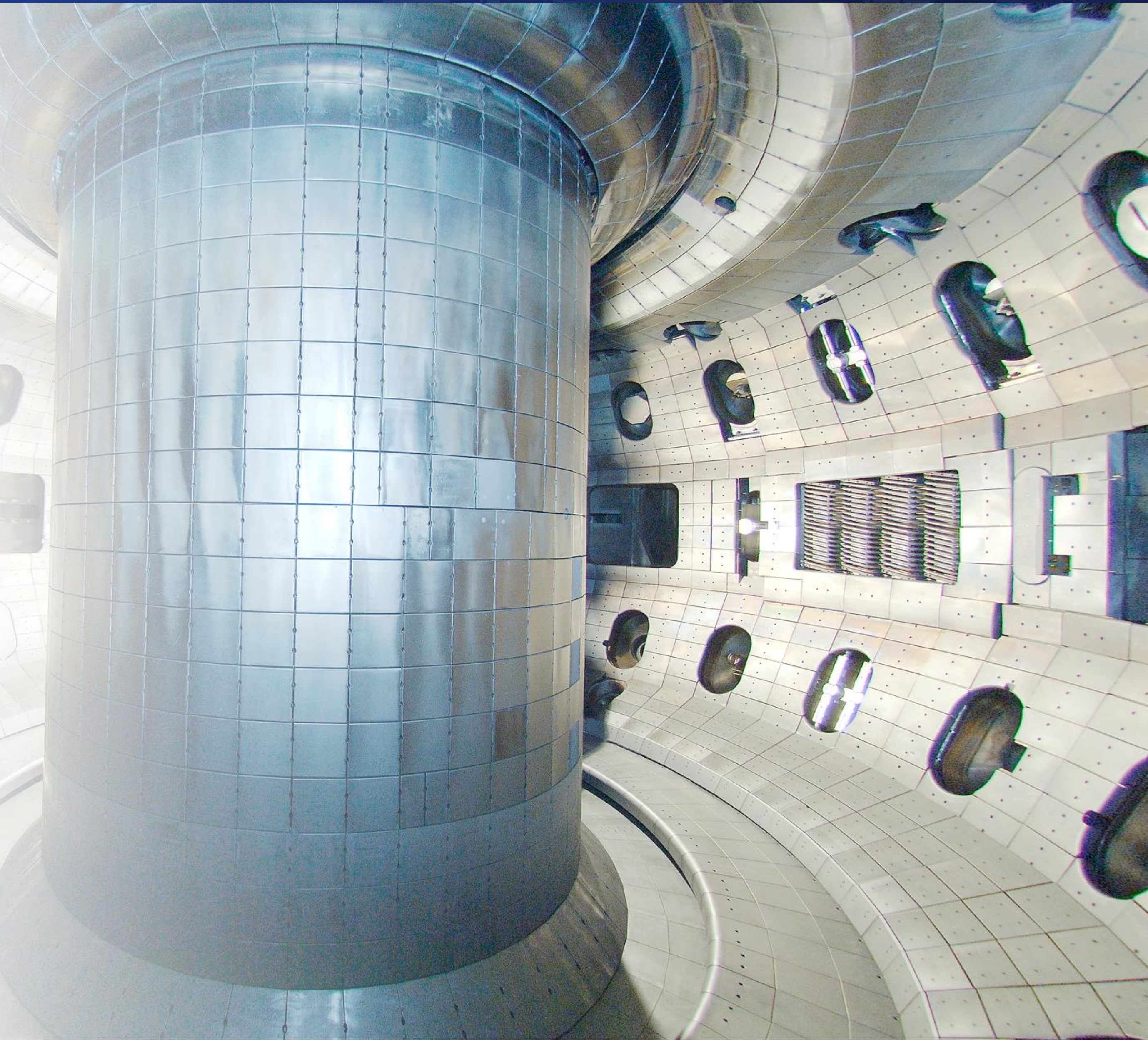
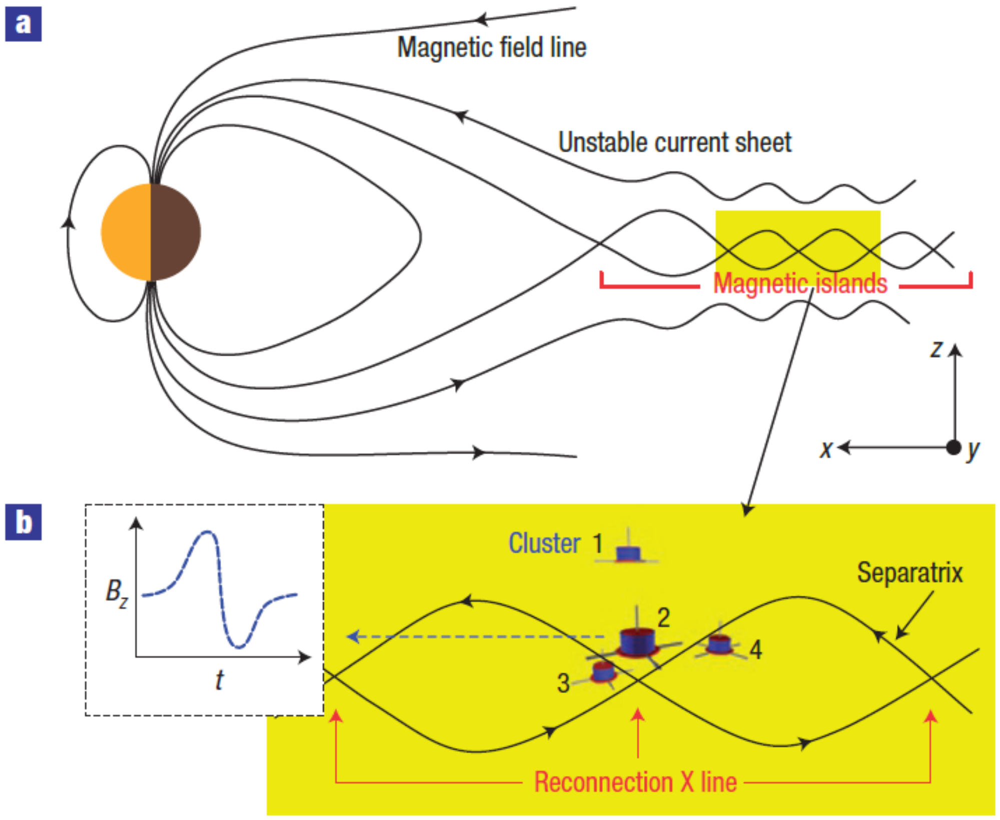


Spacecraft data suggests that energetic electrons (EEs) in Earth's magnetosphere originate from magnetic island chains

- **Motivation:** Up to 50% of the energy released in Earth's atmosphere during solar flares is carried by energetic electrons (EEs)
- **Question:** What causes EEs? How EEs interact with features of the Earth's magnetic field?
- **Hypothesis:** Magnetic islands interact with EEs
  1. **Islands trap EEs** (MeV energies)
  2. EEs **de-confinement at X-points** due to scattering/stochasticity
  3. **Contracting/expanding islands accelerate** electrons
  4. Island **overlap or bifurcation** cause formation of "fast channels" for EE transport



Chen, L-J., et al. "Observation of energetic electrons within magnetic islands." Nature Physics 4.1 (2008): 19-23.

Can we test this in a controlled lab plasma experiment?

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Department of Energy Frontiers in Plasma Science Program

- **DOE Frontiers in Plasma Science** program stewards user/collaborative facilities at small and intermediate scales
  - Magnetized plasma facilities: **MPRL, LAPD, WiPPL, DIII-D**
  - Strong partnerships with the NSF and NNSA
- **MagNetUS** is an ecosystem for a broad scientific community interested in experimental magnetized plasma research
  - **Broaden participation** in magnetized plasma
  - Form a broad consortium of **affiliated facilities**
  - Maintain a broad and diverse **collaborator base**
  - Establish a strong program for **education and training**

2024 MagNetUS meeting is April 14-18th at Lake Arrowhead, CA

MagNetUS community

Call for facility runtime

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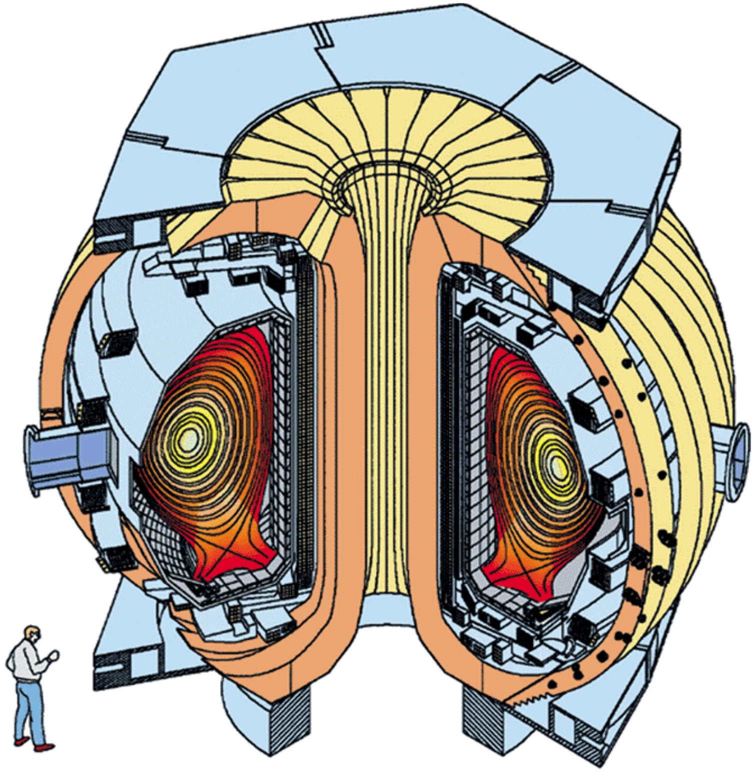
Data presented here is from the 2023 Frontiers Experiments at DIII-D

- **Frontiers Experiments at DIII-D**
  - Several days per year
  - Engaging new collaborators
  - Fundamental plasma experiments
- **DIII-D is a medium size tokamak**
  - R = 1.67 m, <a> ~ 0.67 m,
  - 5-7 seconds discharges
  - Magnetic field 2.2 T
  - $n_e \sim 10^{19} - 10^{20}\ m^{-3}, T_e \sim 10^3$ eV



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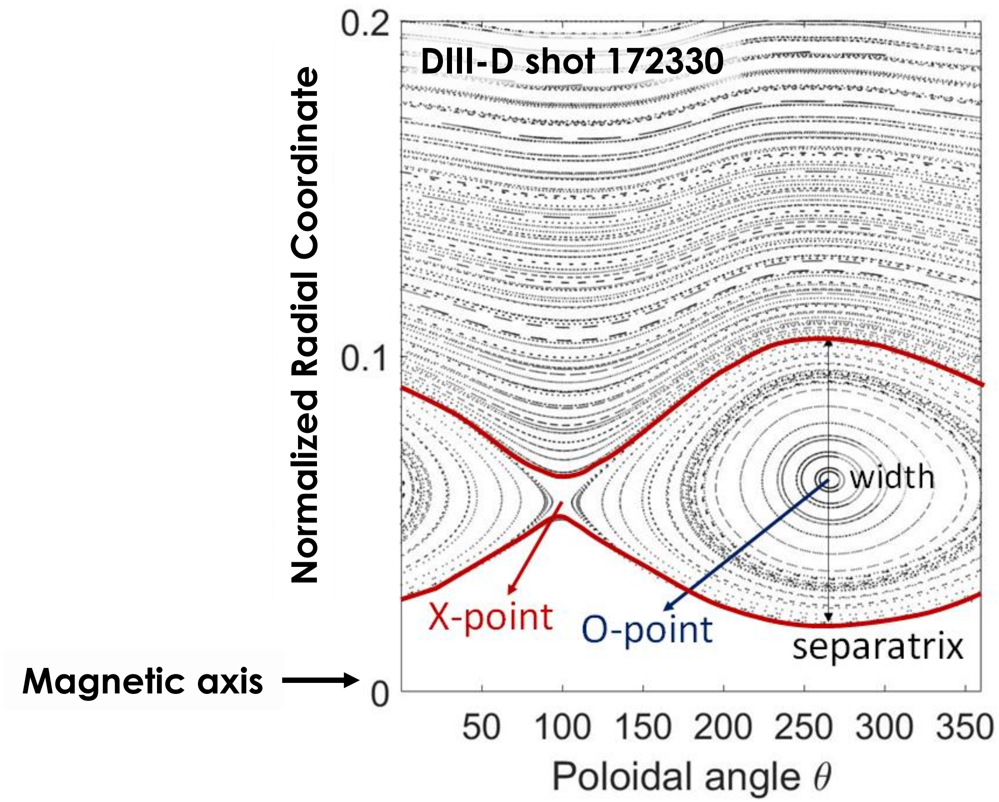
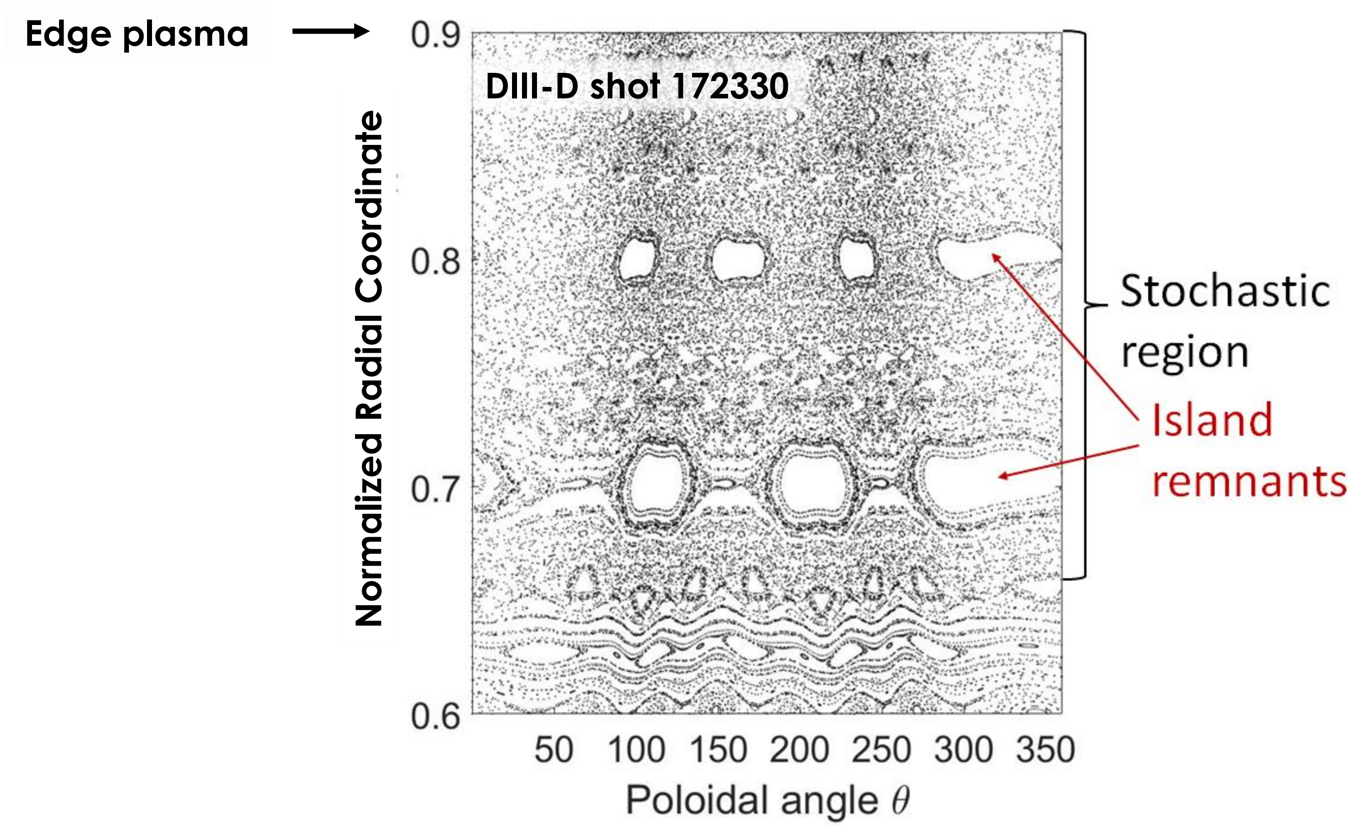
Magnetic islands often coexist with regions of stochastic fields. In the tokamak, this can be controlled with coil perturbations

- **A magnetic island** is a closed magnetic flux tube, characterized by a central elliptic point (O-point) and a separatrix surface.
- **A stochastic region** can form around island X-points and when islands overlap or bifurcate due to magnetic perturbations.



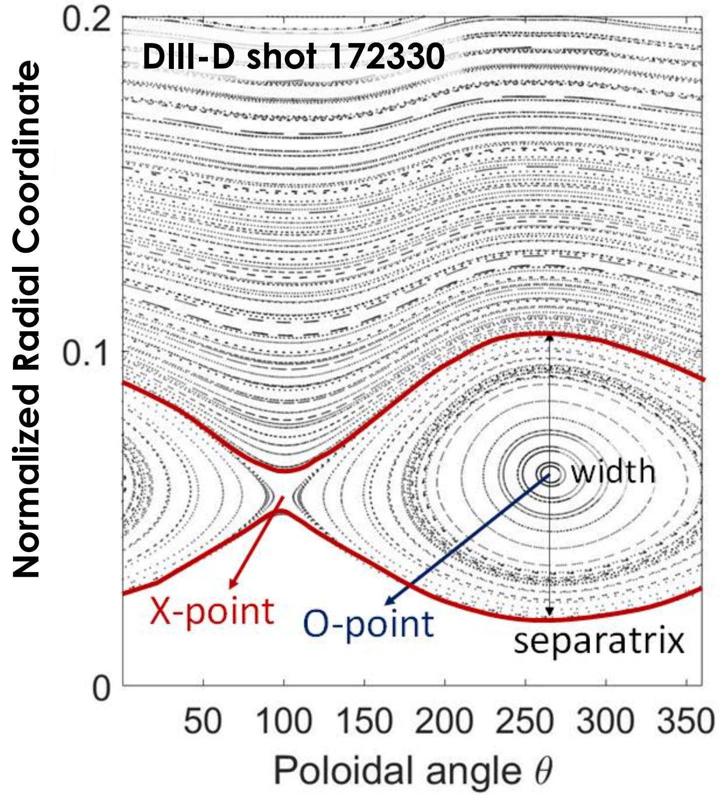


Note that all islands discussed here are fixed Resonant Magnetic perturbation (RMP) islands.

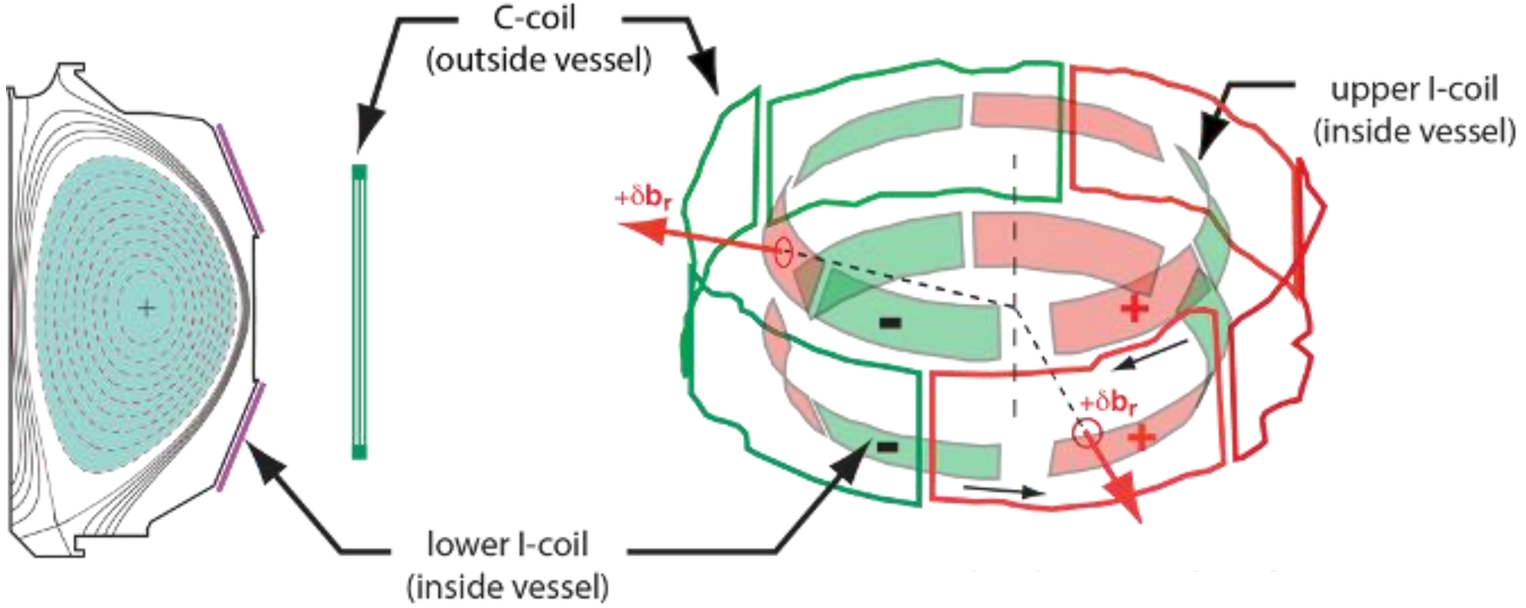
Poincare plots of the vacuum B-field were generated using TRIP3D

Controlled formation and rotation of magnetic islands in DIII-D was performed using set of non-axisymmetric magnetic perturbation coils

- **A magnetic island** is a closed magnetic flux tube, characterized by a central elliptic point (O-point) and a separatrix surface.

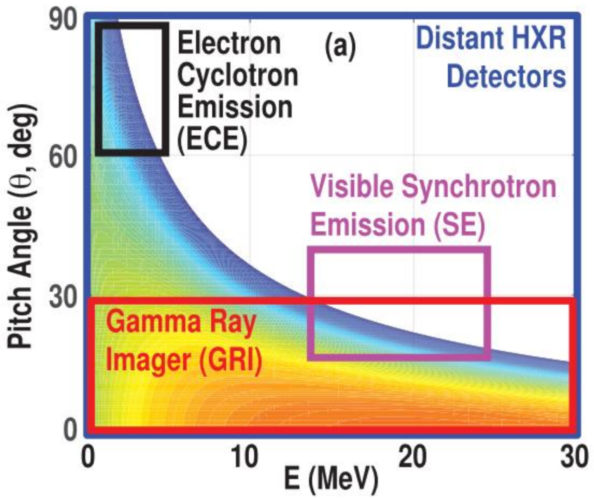


- **C-coils:** used for correction of error fields
- **I-coils:** used for growth and rotation of magnetic islands

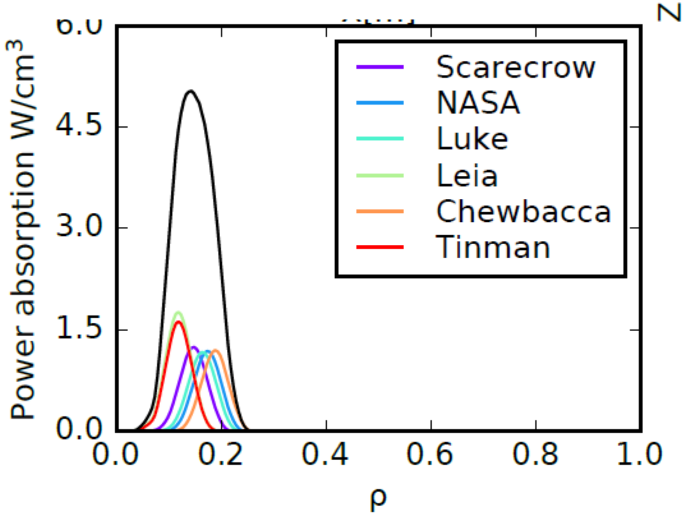


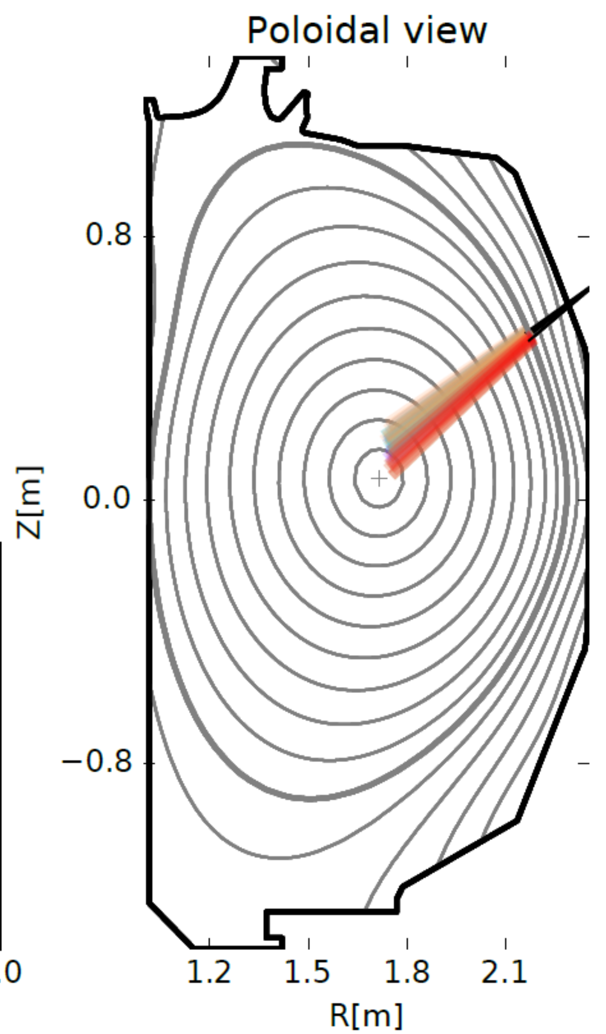
DIII-D experiments used ECH/ECCD pulses near and inside islands to probe for high energy tails on local electron distributions

- **Vlasov tagging:** Small perturbation is caused on the local electron velocity distribution → signal on emission diagnostics comes primarily from high-energy tails
- **Discharge:** Inner Wall Limited, L-mode, no Neutral Beam Injection, only Ohmic heating and ECH/ECCD pulses
- **Plasma conditions**
  $n_e \lesssim 1 \times 10^{19}\, m^{-3}$, $I_p = 0.72\, MA$, $B_t \approx -2\, T$, $q_{95} = 4.5 - 7$
- **ECH/ECCD:** $P_{ECH} \approx 2 - 3MW$, vary ρ_{ECH}, width $\Delta\rho \approx 0.1$
  1. long pulses ($\Delta t \approx 250\, ms$)
  2. modulated pulses ($f \approx 50Hz$)



Paz-Soldan, et al. PoP, 25.5 (2018).





OMFIT, TORAY, # 172330 at 2600 ms

Three types of experiments were conducted to assess the interaction between EEs and magnetic islands

1. **Island toroidal/poloidal rotation** via toroidal rotation of magnetic perturbation fields with long-duration ECH/ECCD pulse.

   → Test for electron (de)trapping

2. **Island growth and shrinking** via changes in the perturbation coil current amplitudes with long-duration ECH/ECCD pulse.

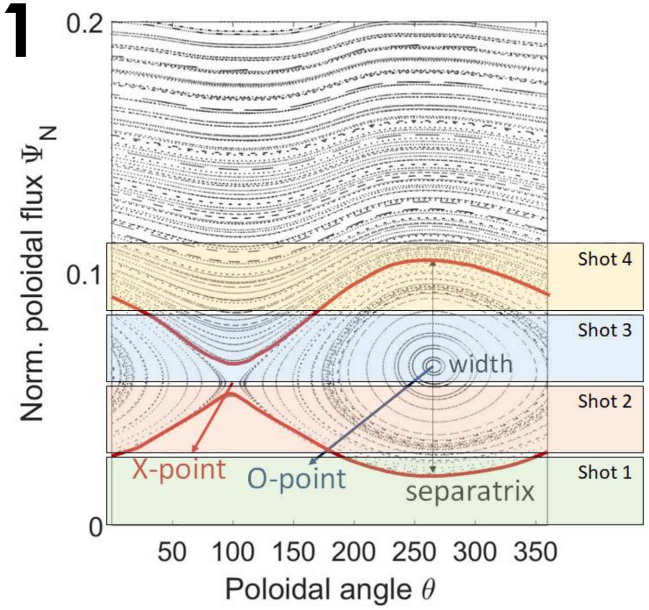
   → Test for electron acceleration

3. Fixed-size island with **high-frequency** modulated electron cyclotron **(MEC) pulse**.

   → Test for island bifurcation

Evans, T. E., et al. Comparative studies of static edge magnetic islands in DIII-D and LHD. No. NIFS--1124. National Inst. for Fusion Science, 2014.

1



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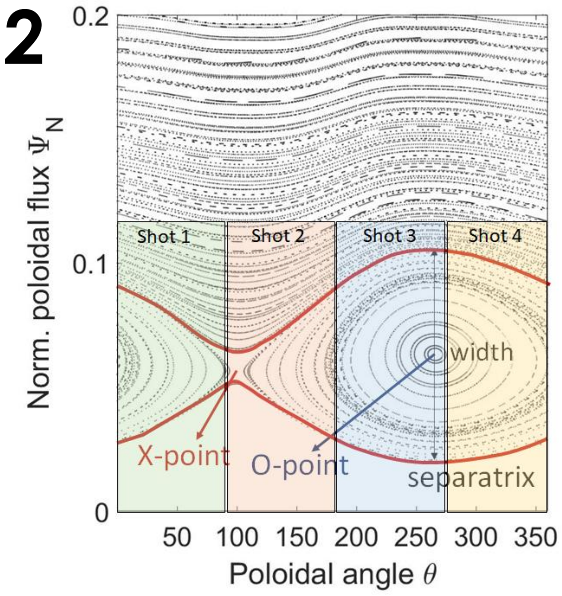
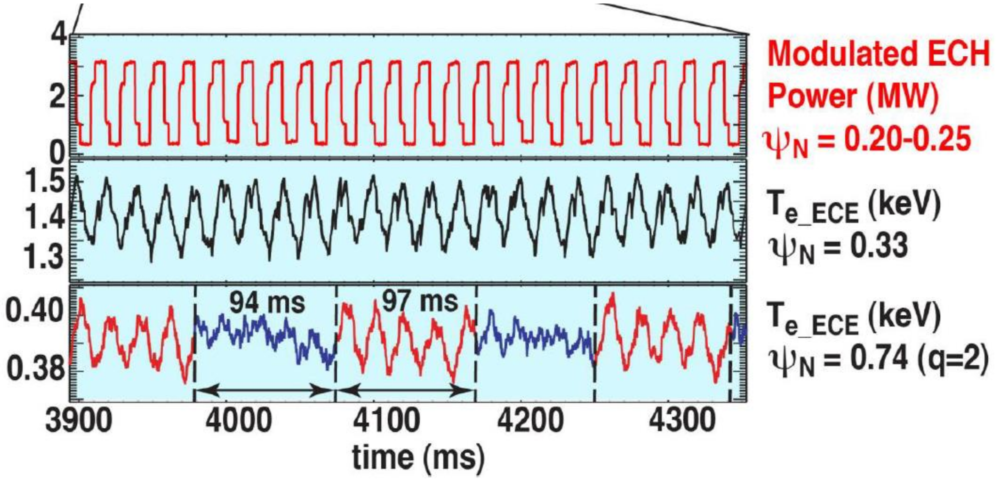


3

No island →

q=2 island →



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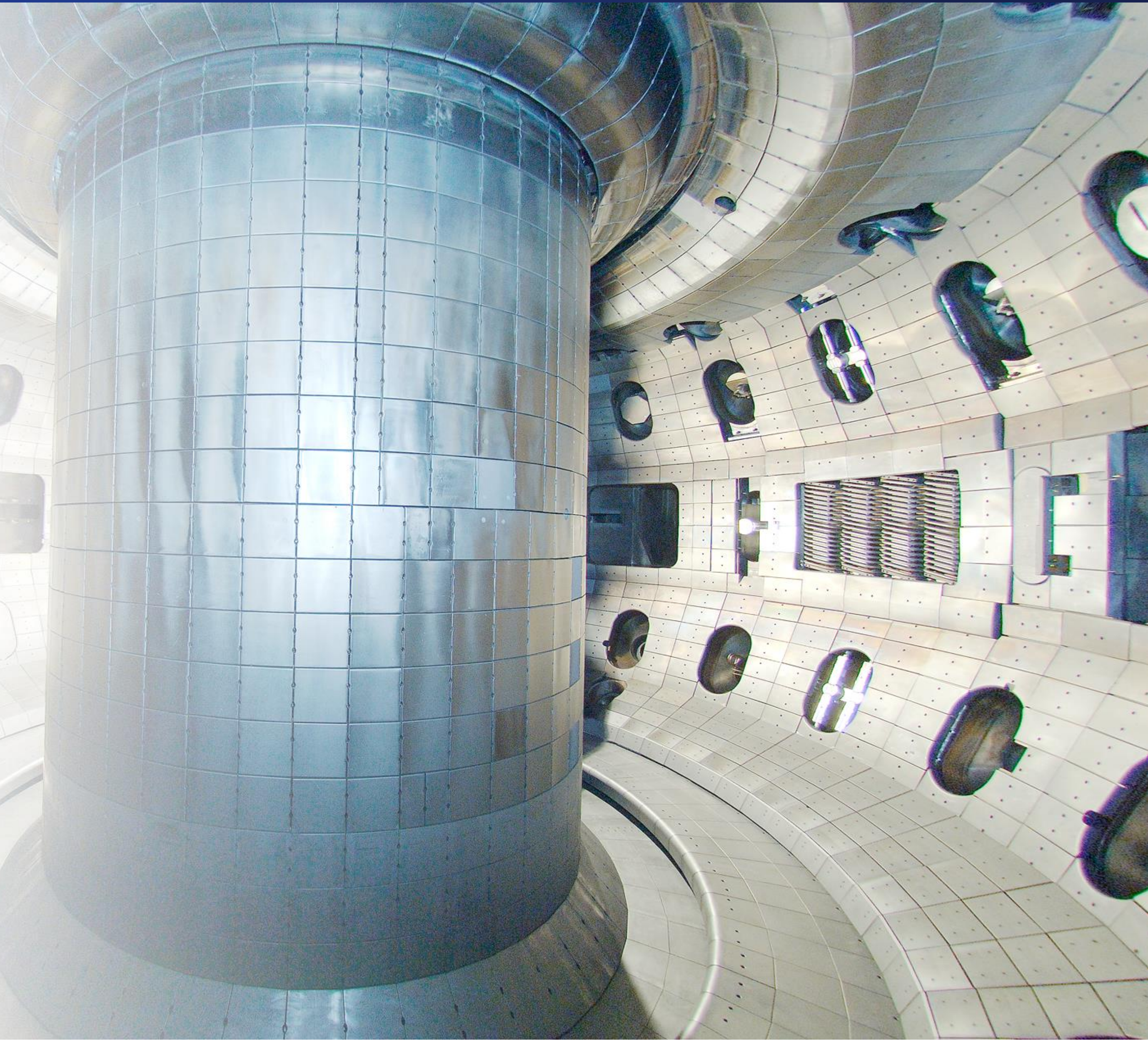

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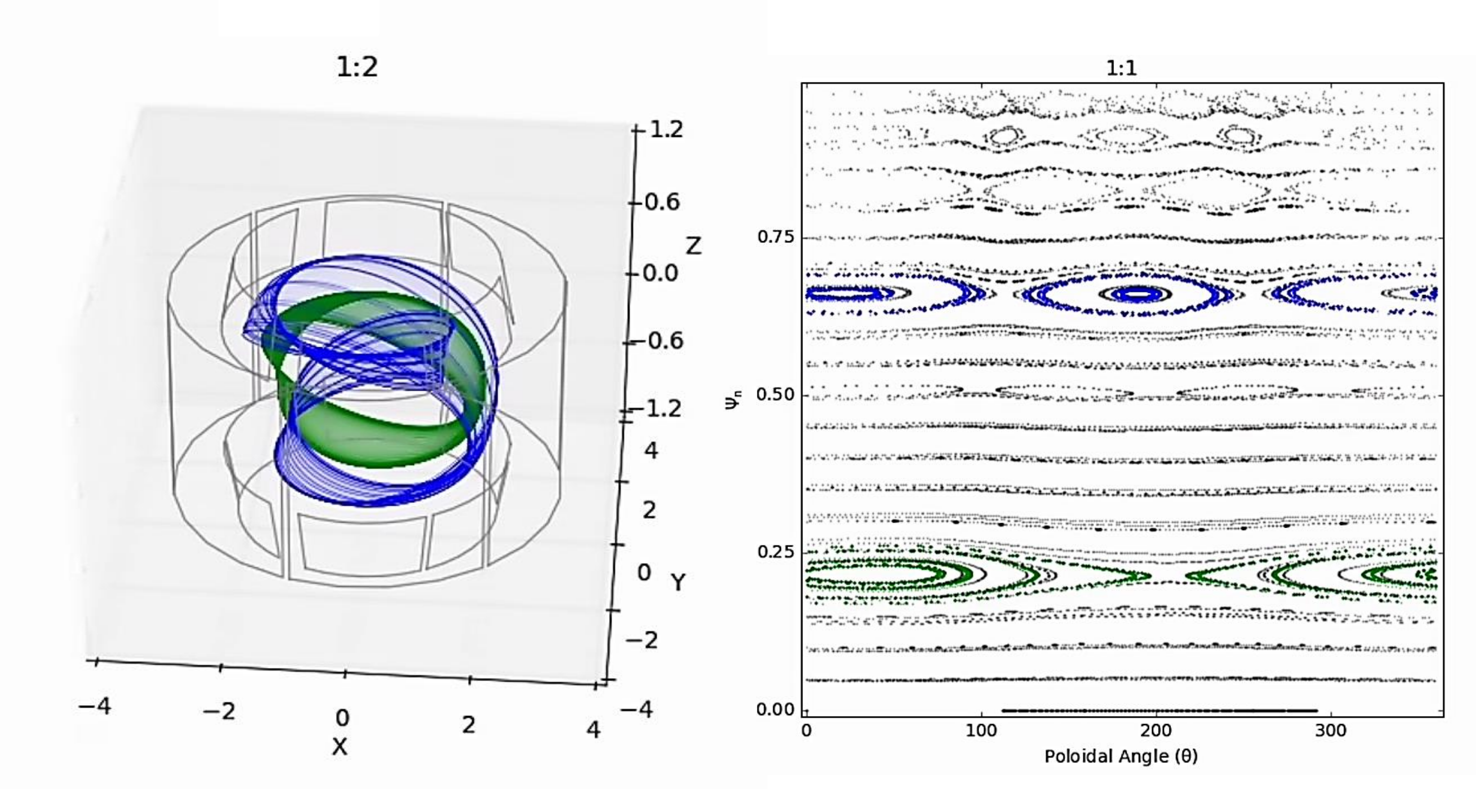
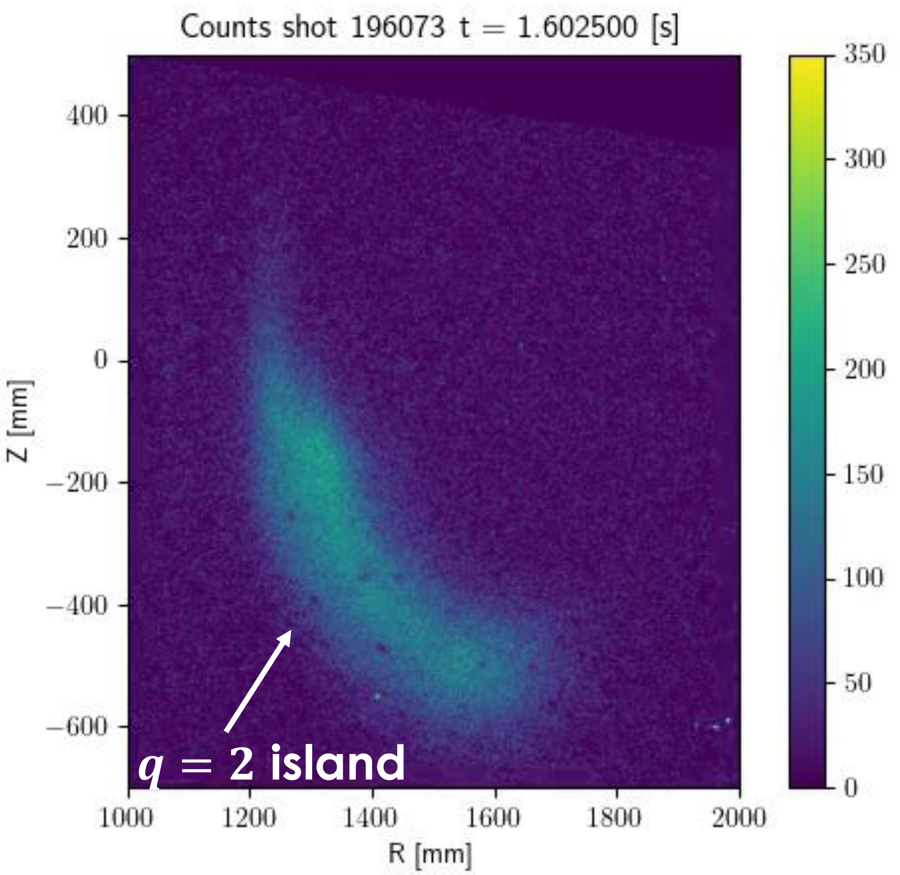
EE trapping observed: 10-20 MeV electrons were trapped in n=1 resonant magnetic perturbation islands.

- TRIP3D vacuum field simulations were used to confirm the island locations.



Plots were generated using TRIP3D code and data from DIII-D shot 196073 at 2500 ms



Data from Visible Synchrotron Emission

These observations provide direct evidence that magnetic islands affect energetic electron transport → implications to both lab and space magnetized plasma research

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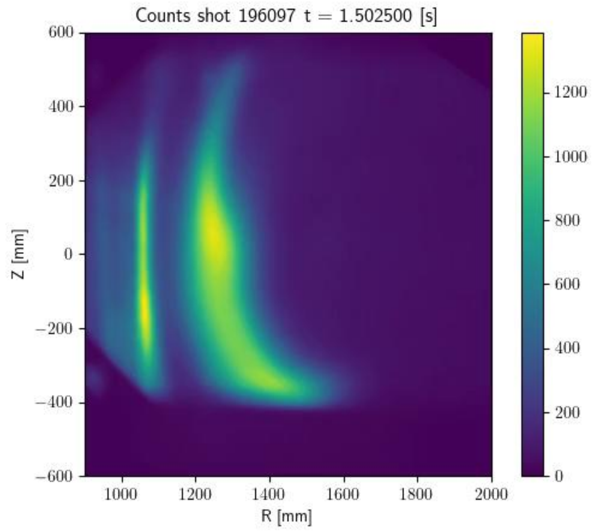
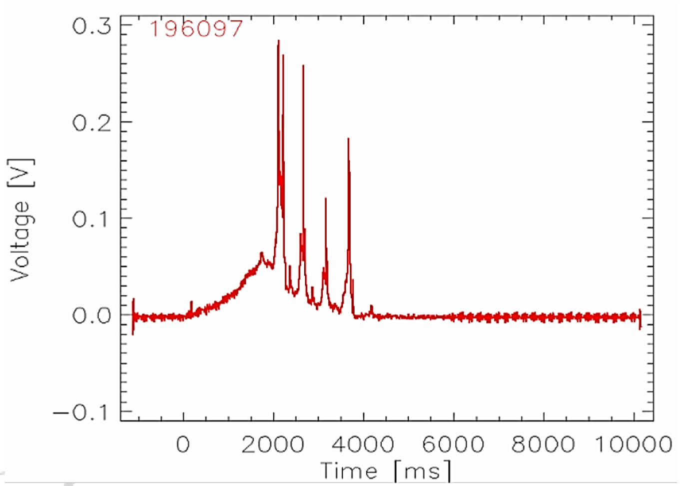
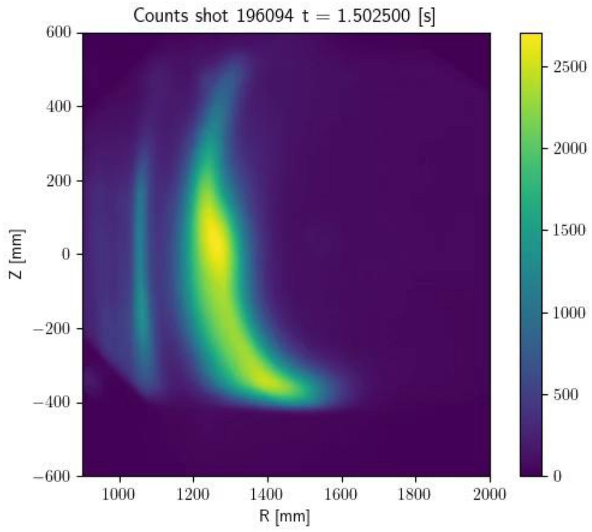
EE de-confinement observed: Periodic peaks in Hard X-ray data show that bursts of EEs are released during island rotation with I-coils

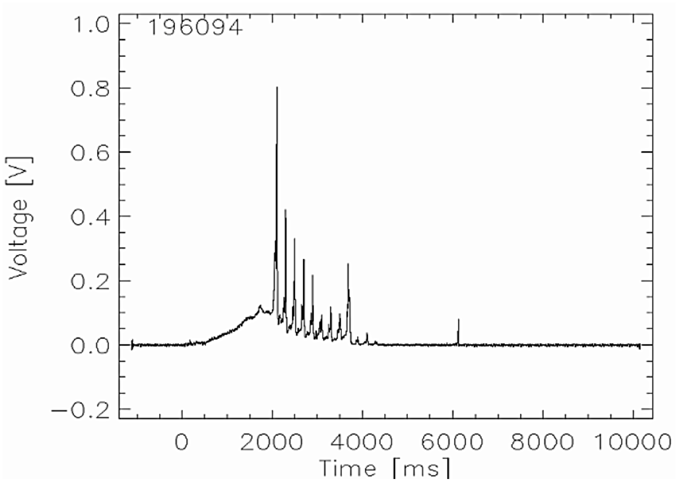
2 Hz rotation



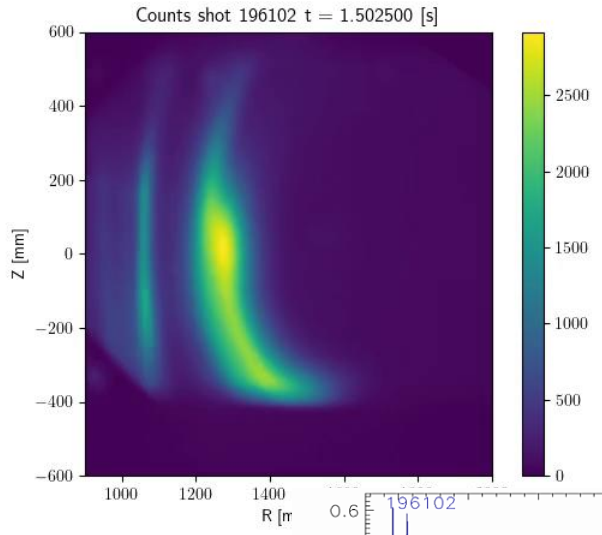


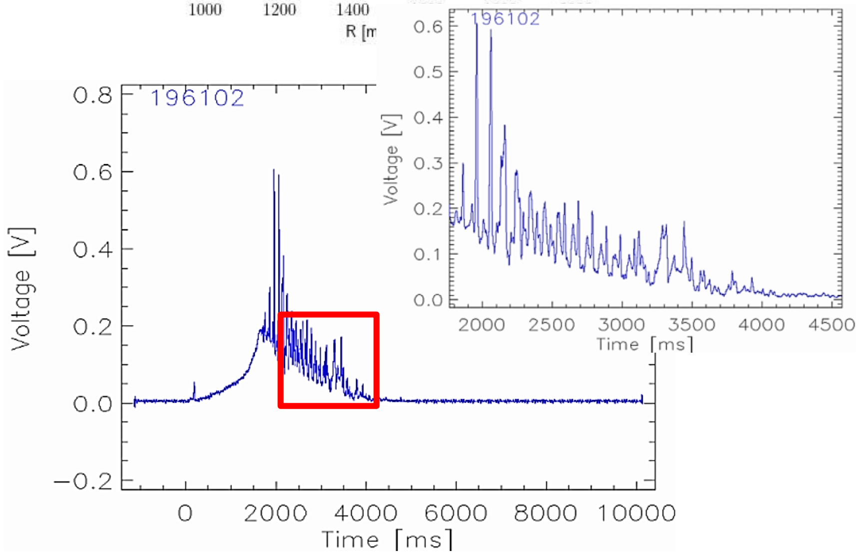
5 Hz rotation





10 Hz rotation





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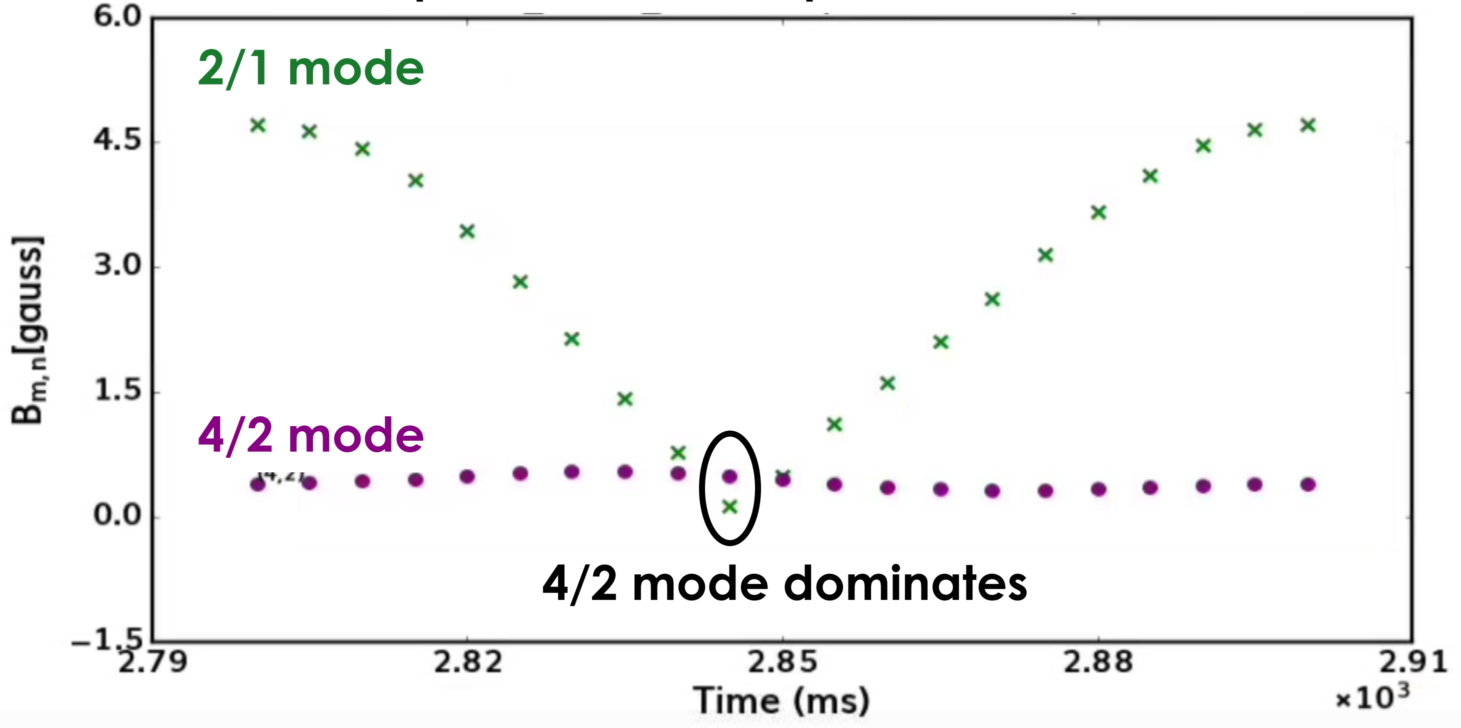
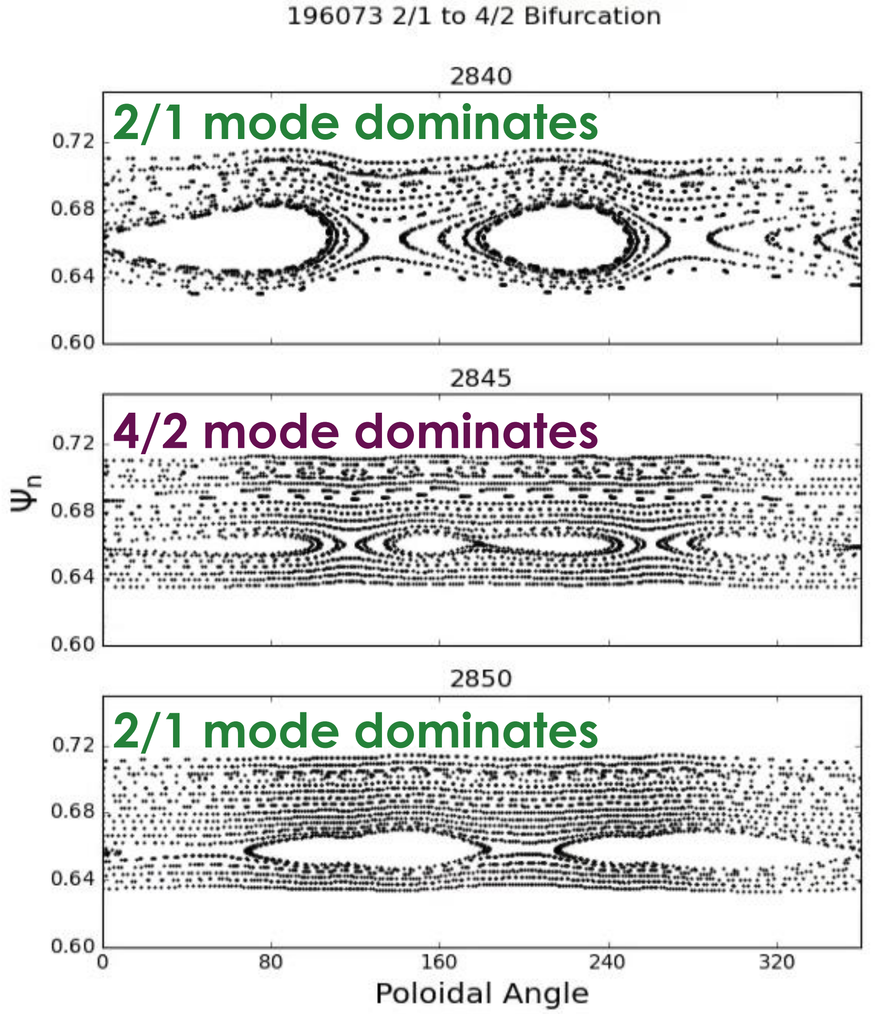
Periodic RMP island bifurcation from 2/1 to 4/2 occurs due to destructive coupling of coil perturbations during island rotation

- Coil perturbation at the q=2 magnetic surface results in a superposition of wave modes: 2/1, 4/2, 8/4, etc.

Total perturbation on q=2 surface, #196073





Plots were generated using TRIP3D code

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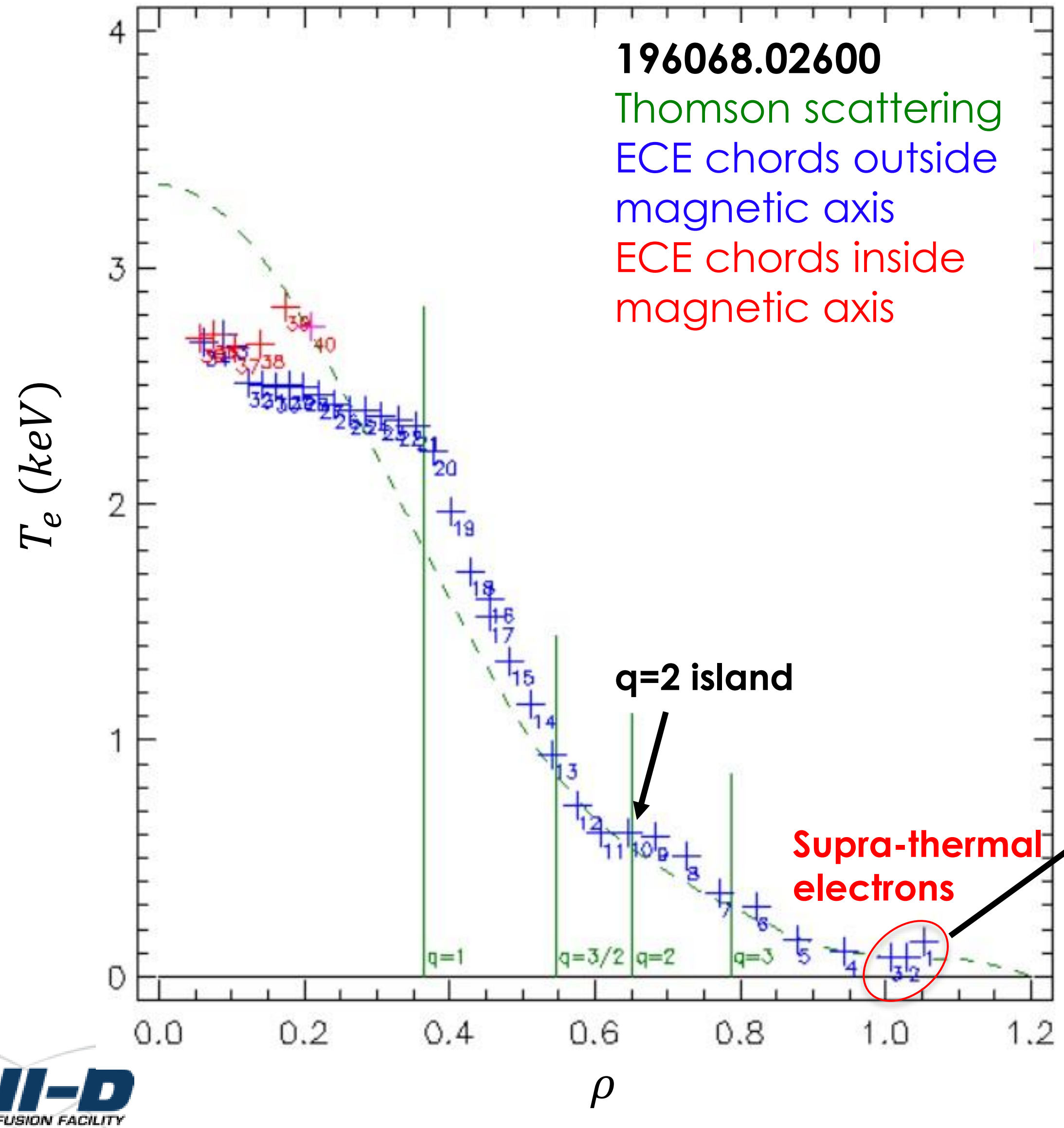
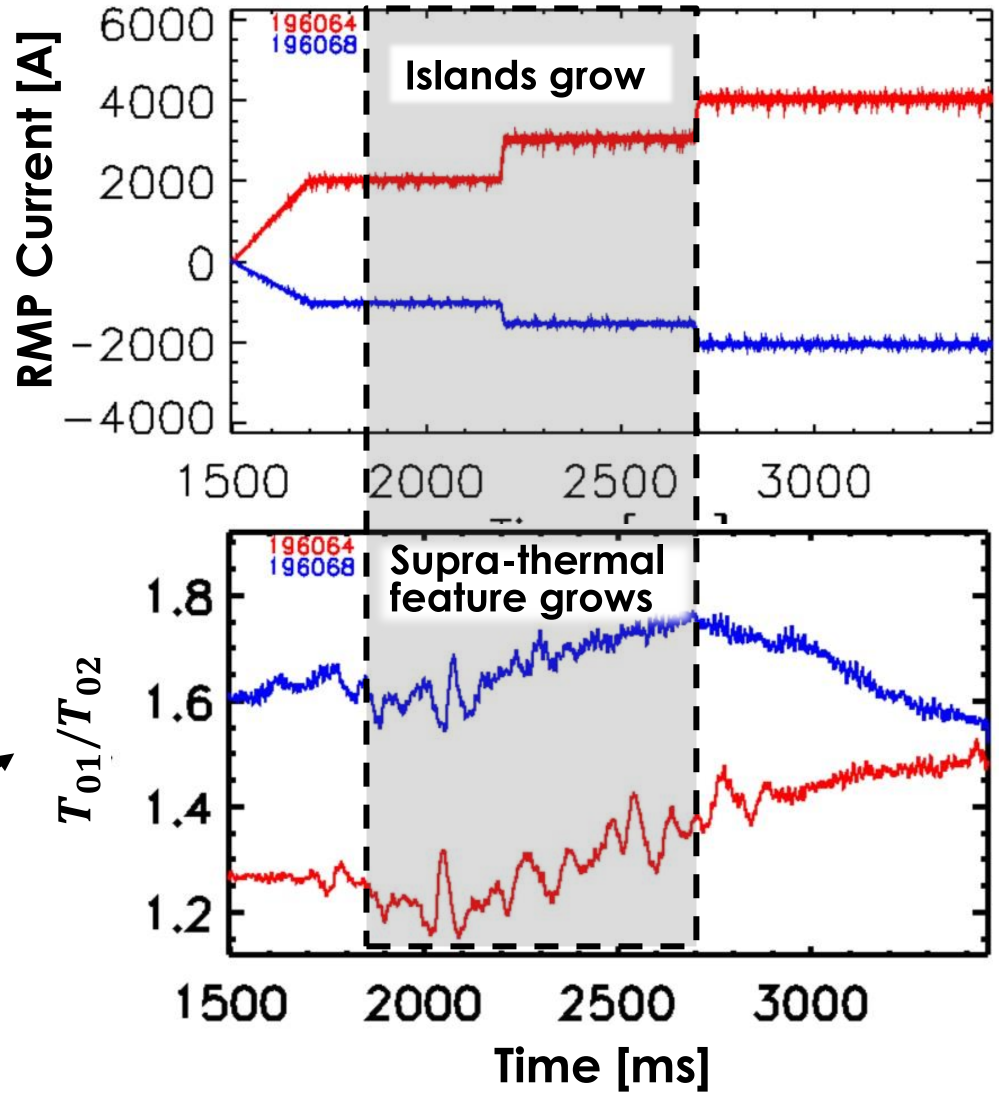
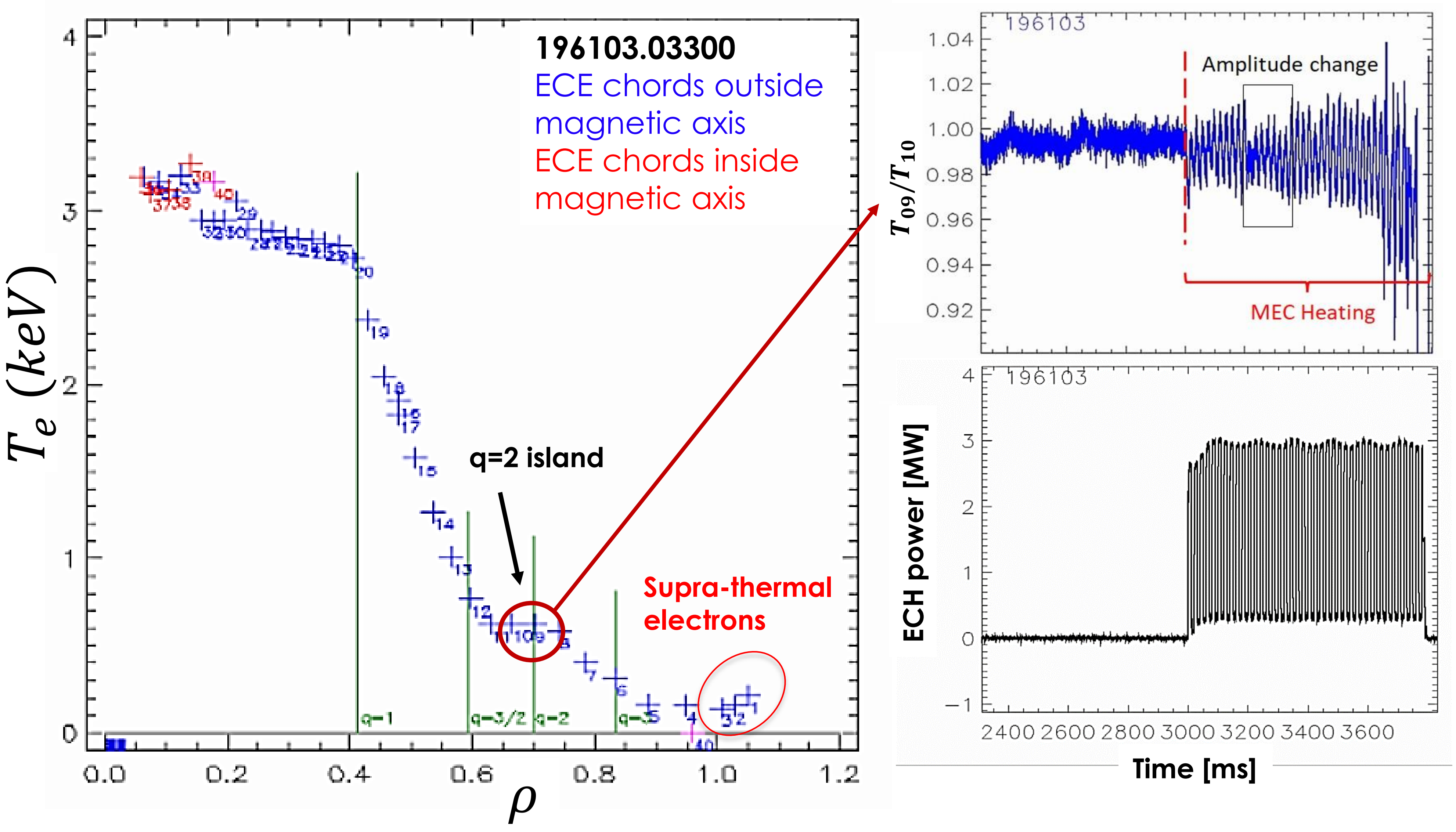
Enhanced transport during island growth observed: I-coil current ramp-up grows the islands leading to enhanced ECE temperatures in edge plasma



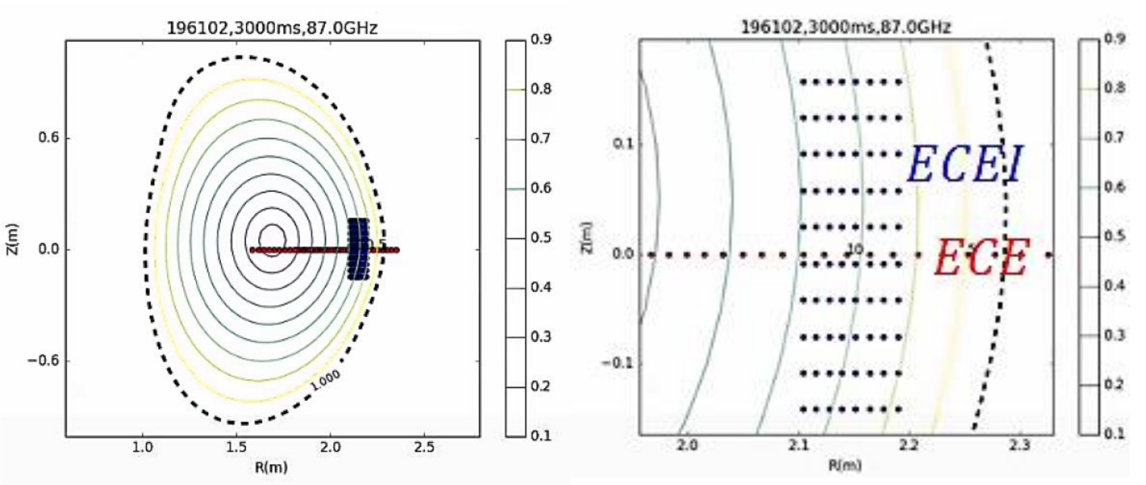


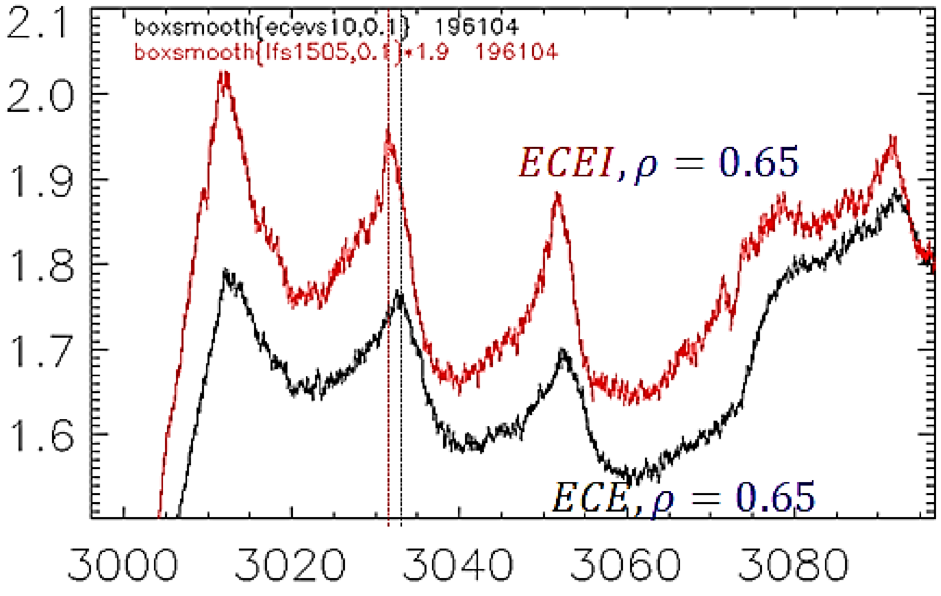
Possible spontaneous island bifurcation: during modulated EC heating of the q=2 island changes amplitude with time



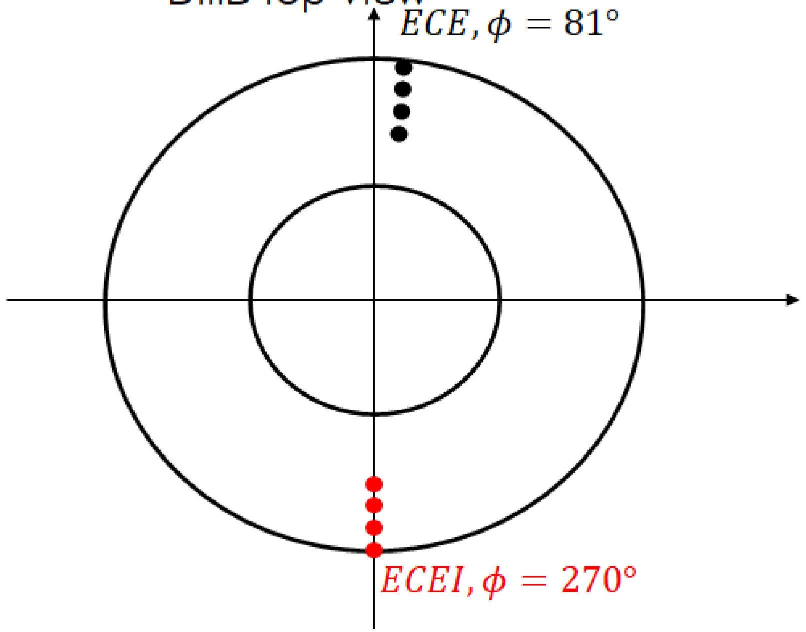
There is time delay (~1ms) of on-axis ECH heat propagating to the island center ($\rho = 0.65$) between ECEI and ECE

- Electron cyclotron Emission (**ECE**) and ECE Imager (**ECEI**) have radially overlapping chords, but different toroidal locations
  → Can detect time delay between heat pulses going through O-points vs X-points





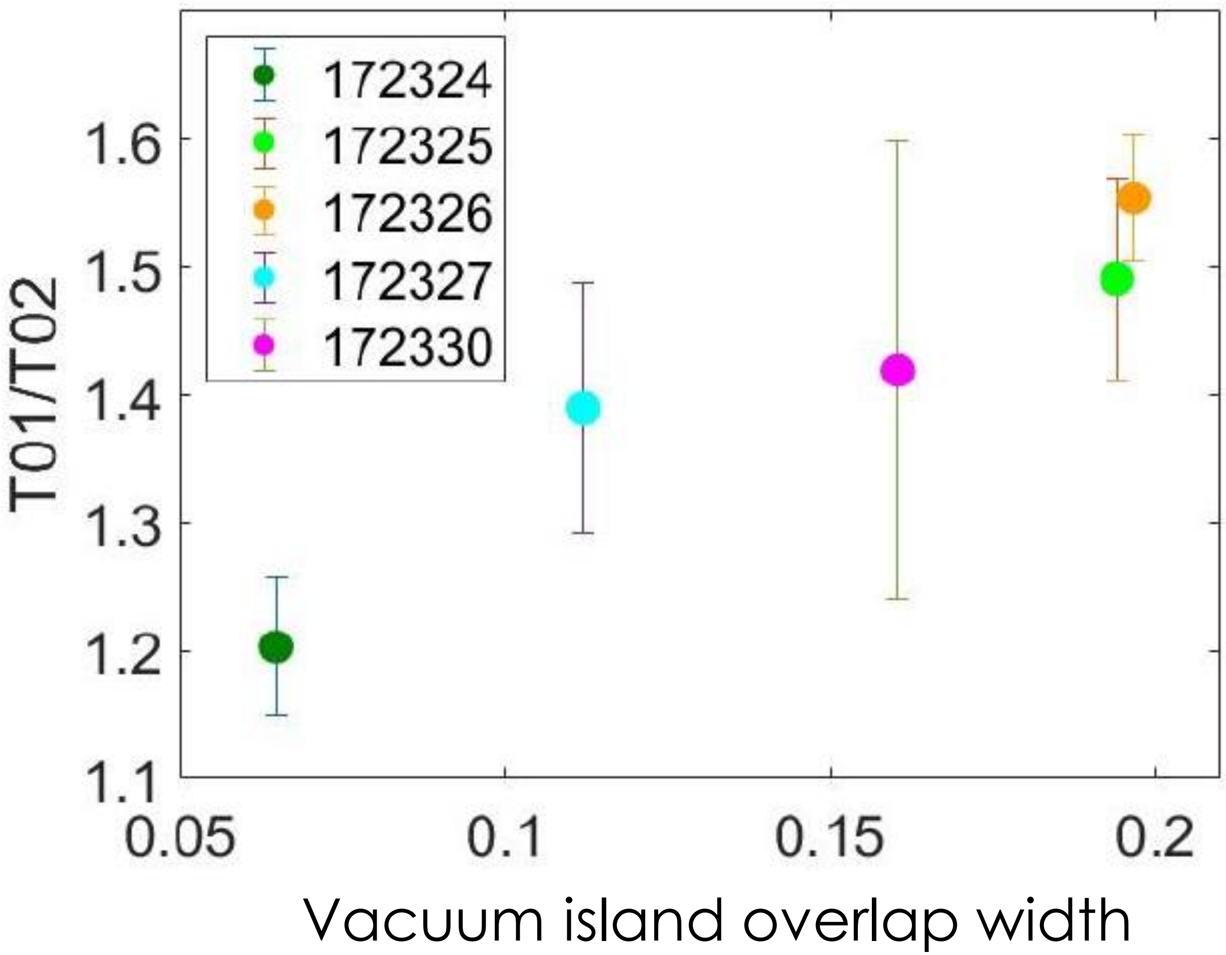
The Te change is caused by the 50 Hz ECH modulation



Enhanced transport in stochastic edge observed: ECE edge temperature increases with increased width of the stochastic region in edge plasma

- Vacuum island overlap width due to RMP coil perturbation
→ shots with similar perturbation current are shown

- T_{01}/T_{02} is the ratio between temperature measured by ECE cords 01 and 02
→ EEs are observed for $T_{01}/T_{02} > 1$



Kostadinova, E., Orlov, D., Koepke, M., Skiff, F., & Austin, M. (2023). Energetic electron transport in magnetic fields with island chains and stochastic regions. *JPP, 89*(4), 905890420. doi:10.1017/S0022377823000879

Energetic Electrons Conclusions

- DIII-D experiments were used to assess the interaction between energetic electrons and magnetic islands in magnetized plasma
  - **10-20 MeV EEs were trapped** and rotated with RMP islands
  - The **EEs** were **de-confined** from the islands during island rotations → caused by 2/1 **island bifurcating** into two 4/2 islands
  - **Island growth** observed to **accelerate electrons**
  - Edge plasma **stochasticity** creates "fast channels" **enhancing EE transport**
- Analysis needed to confirm all observations
- Next steps: **compare to spacecraft data**

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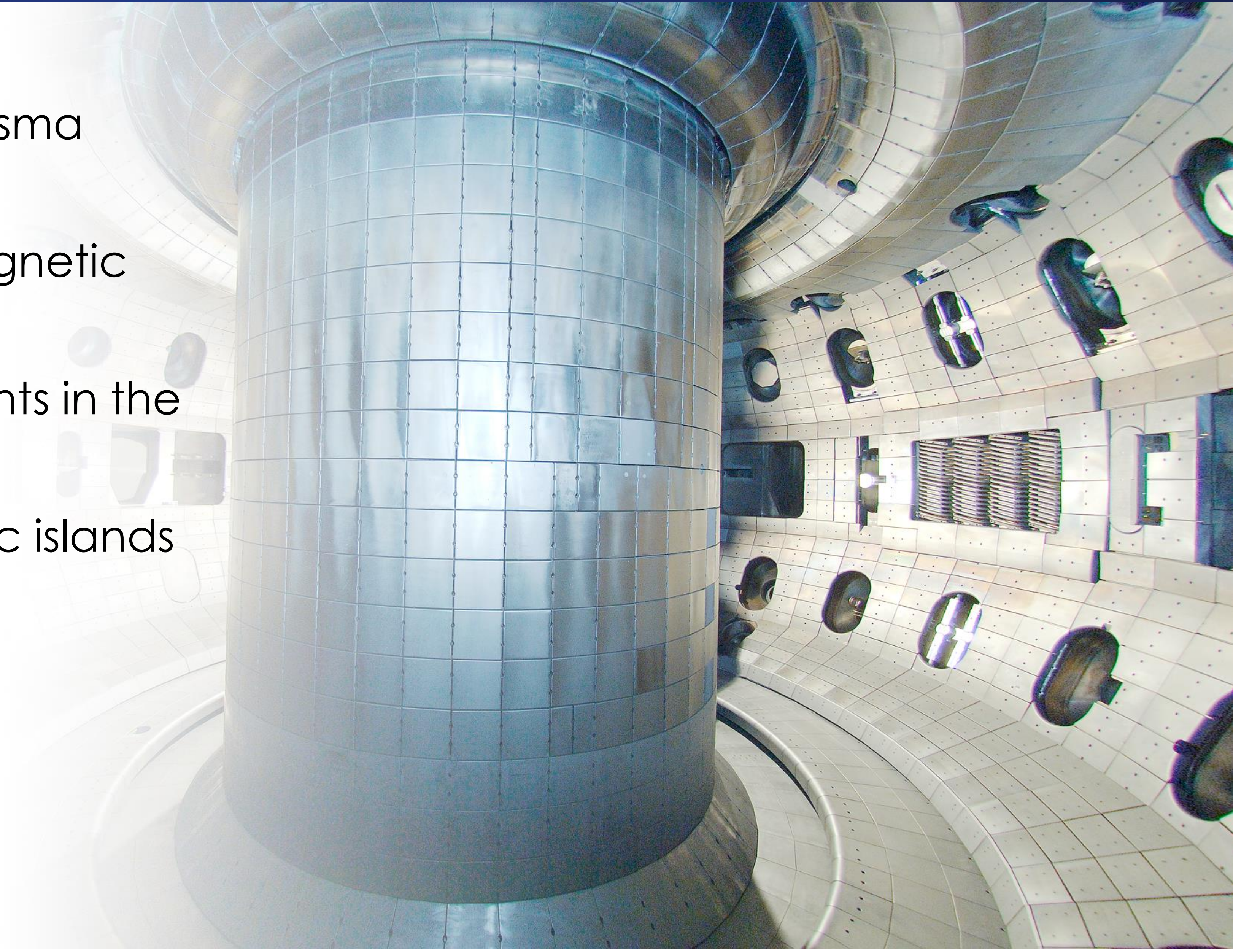
Outline

- Interdisciplinary nature of plasma research
- Anomalous diffusion and magnetic topology
- Energetic Electrons Experiments in the DIII-D tokamak
- EEs interactions with magnetic islands and field stochasticity
- Concluding remarks



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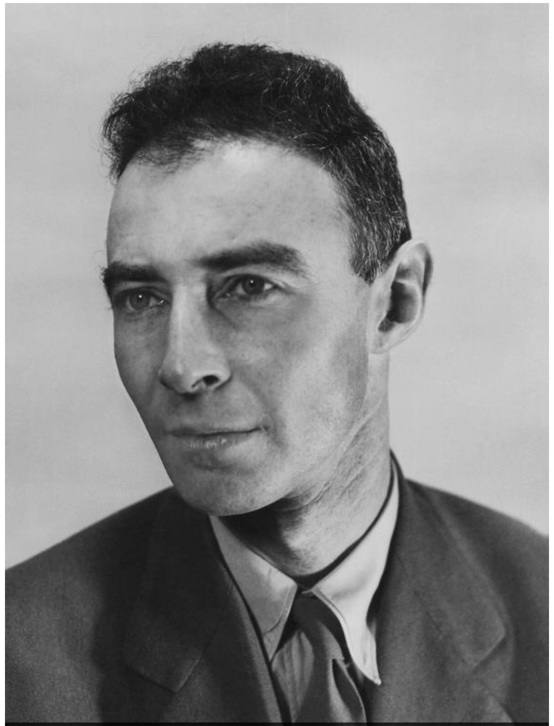
The Astro/Space and the Nuclear communities have been historically related through fundamental physics. Let's collaborate more often!

Lise Meitner

Explained fission, which explains synthesis of heavy elements in space.

Hans Bethe

Head of theory division in Los Alamos in WWII; developed the theory of stellar nucleosynthesis.



Robert Oppenheimer

Head of Manhattan project; helped determine the mass limit for a neutron star to turn into a black hole.

Lyman Spitzer

Inventor of the stellarator fusion concept; proposed telescopes operating in space (Hubble telescope).

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