Magnetic Reconnection in Magnetized Hot Plasmas

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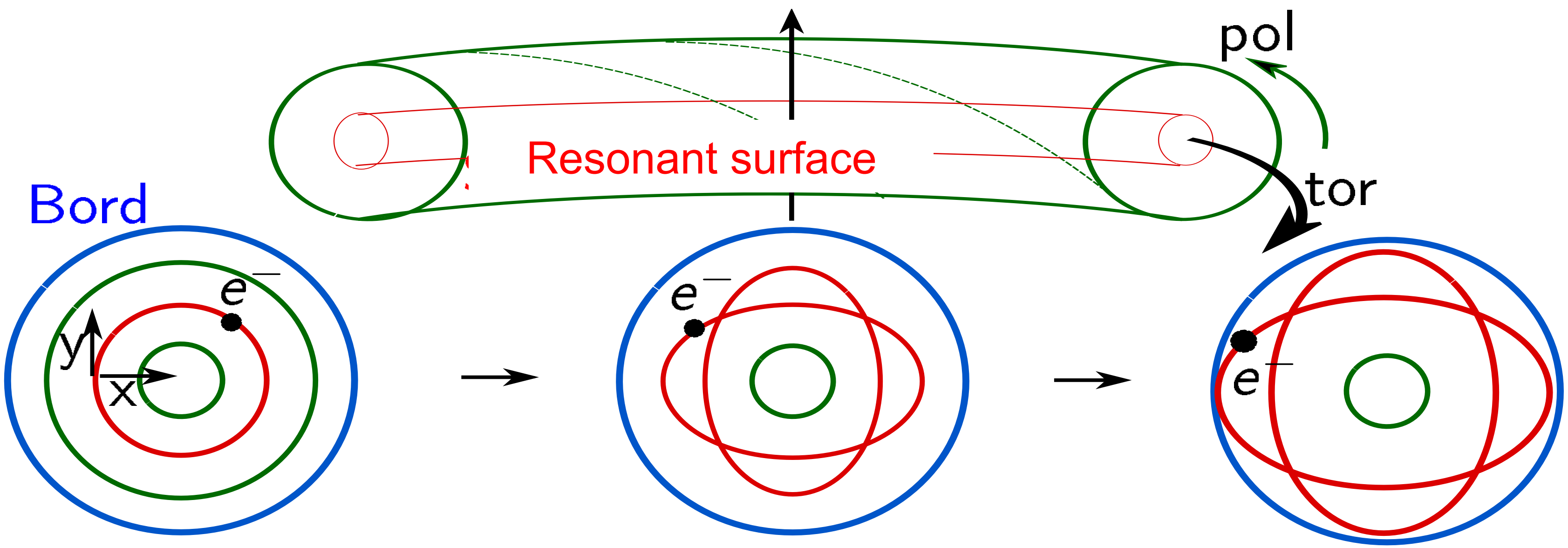
Magnetic Islands at various scales in tokamak

Magnetic reconnexion is ubiquitous in nature and it consists in a **modification** of magnetic field line **topology** between two moments.
In magnetized hot plasmas, **current driven instablity** leads to **magnetis island** formation at **various scales**.

Basic Mechanism leading to Large Magnetic Island :



- Equilibrium

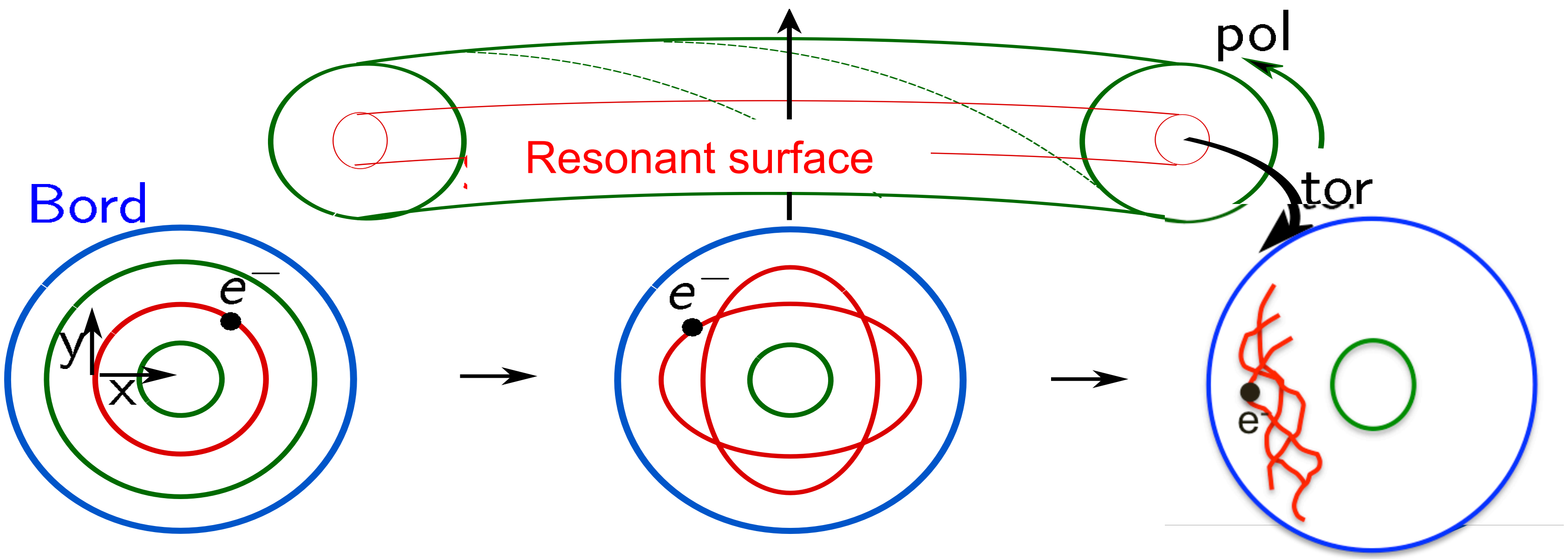
- Tearing instability
- Tearing and reconnection
of magnetic field lines
- Large (few cms) magnetic islands

- Disruption
- **Origin and
Control of large
magnetic islands ?**

Magnetic Islands at various scales in tokamak

Magnetic reconnexion is ubiquitous in nature and it consists in a **modification** of magnetic field line **topology** between two moments.
In magnetized hot plasmas, **current driven instablity** leads to **magnetis island** formation at **various scales**.

Basic Mechanism leading to Micro Magnetic Island :



- Equilibrium

- Micro-Tearing instability
- Tearing and reconnection of magnetic field lines
- Micro (mm) magnetic islands

- Stochaztisation
- **Impact on the electron heat transport**

Magnetic Island Formation Recipe's

Open questions in tokamaks context relative to magnetic reconnexion at small and large scales :

1. Non ideal phenomenom to violate the frozen flux condition locally ?

=> modification of the magnetic field line topology is allowed

resistivity and collisions, electron mass inertia, other mechanisms ?

2. Free energy to let the island grows ?

large island : **magnetic equilibrium**, resistivity, pressure gradient, **turbulent modes**, …

micro island : **electronic temperature gradient**, collisions, **curvature**, **electric potential fluctuations**, …

3. Saturation mechanisms ?

Size of large island at saturation .
Electron heat transport due to micro-reconnexion at plasma edge ?

Outline

I. Classical theory of the tearing instability

1. Resistivity at the origin of the reconnection
2. Equilibrium current for the growth and the saturation
3. Saturation ?

II. Turbulence Driven Magnetic island

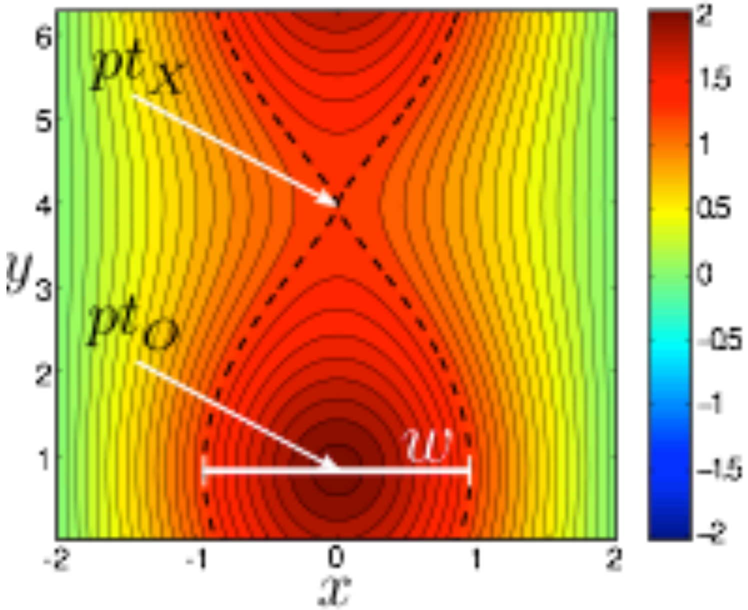
1. Resistivity at the origin of the reconnection
2. Turbulent modes drive the island growth
3. Saturation ?

III. Stability of Micro-Tearing Modes

1. Collisions at the origin of the reconnection
2. Instability growth : electron temperature gradient, curbature, electric potential fluctuations
3. Saturation ?

Conclusions

I. Classical Theory of the Tearing instability



2D Reduced MagnetoHydroDynamic Model

Large island => Minimal model RMHD
Fluctuations dynamics evolution of the electrostatic Potential Φ and of the magnetic flux Ψ

2D model => near a resonant surface in a (x, y) poloidal cross section

Fourier decomposition of Φ and Ψ in poloidal direction :

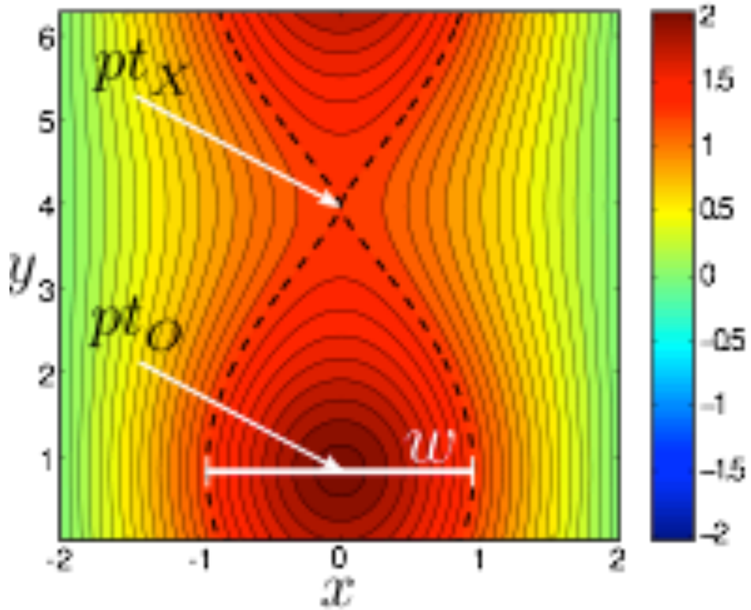
$$\psi(x,y,t) = \sum_{m\in\mathbb{Z}} \psi_m(x,t)\exp\left(i\frac{2\pi m}{L_y}y\right)$$

$$\begin{aligned} \partial_t \nabla_\perp^2 \phi + [\phi, \nabla_\perp^2 \phi] &= [\psi + \psi_{eq}, j + j_{eq}] + \nu \nabla_\perp^4 \phi \\ \partial_t \psi + [\phi, \psi + \psi_{eq}] &= \eta j \end{aligned}$$

$$j = \nabla_\perp^2 \psi \qquad B_{eq} = \psi'_{eq}(x)\,\mathbf{y}$$

The model is solved numerically using the semi-spectral code AMON in a 2D [Lx, Ly] box.

I. Classical Theory of the Tearing instability



◆ **Tearing instability of the mode m=1**

- Resistivity allows magnetic reconnection (step 1)
- Magnetic equilibrium B_0 induces an equilibrium current j_0 allowing the growth of a magnetic island (step 2)

=> An important parameter **Δ'**

Δ' is a measure of the magnetic energy avalaible in the equilibrium for the magnetic island growth

◆ **Linear prediction of instability**

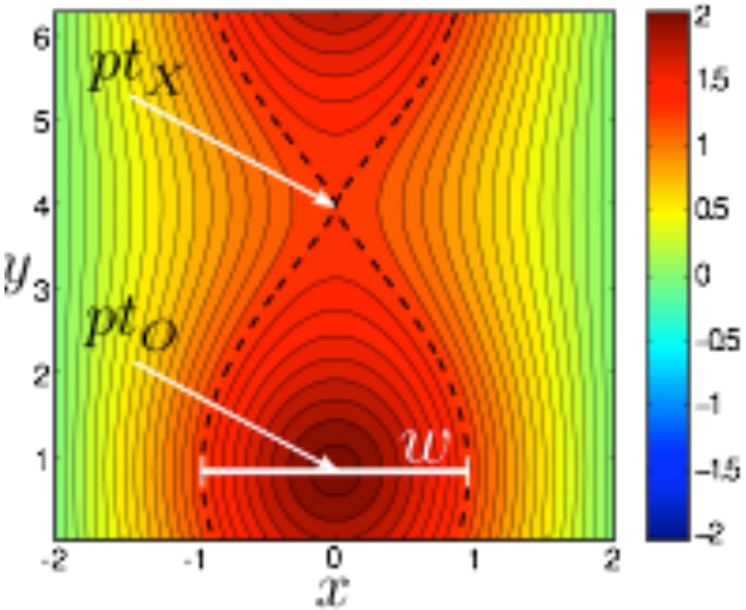
Δ' is an good index stability parameter
Δ' < 0 No island growth
Δ' > 0 Tearing instability
Island growth

◆ **Island size at saturation ? An open question**

Rutherford model **[R.J. La Haye, POP 13 (2006)]**

$$\partial_t w_{m=1} = \partial_t w_1 = \eta \Delta' + NL$$

I. Classical Theory of the Tearing instability



◆ Tearing instability of the mode m=1

- Resistivity allows magnetic reconnection

- Magnetic equilibrium B_0 induces an equilibrium current j_0 allowing the growth and the saturation of a magnetic island

=> An important parameter **Δ'**

Δ' = equilibrium current integral over the radial profile
Δ' is a measure of the magnetic energy avalaible in the equilibrium for the magnetic island growth

◆ Linear prediction of instability

Δ' is an good index stability parameter
Δ' < 0 No island growth
Δ' > 0 Tearing instability
Island growth

◆ Island size at saturation ? An open question

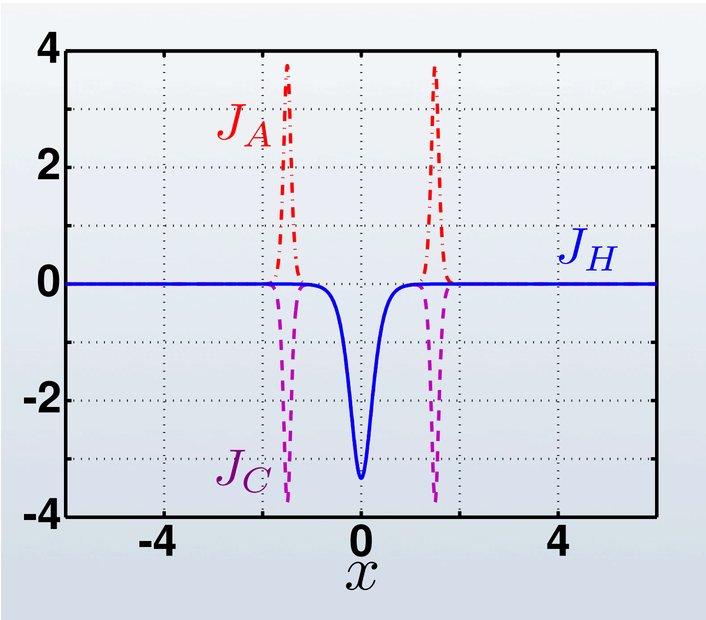
Rutherford model **[R.J. La Haye, POP 13 (2006)]**

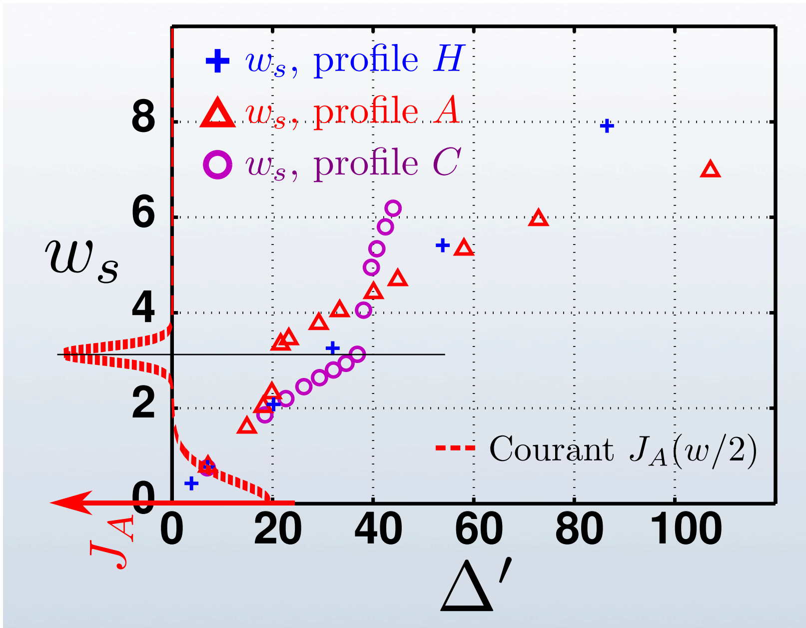
$$\partial_t w_{m=1} = \partial_t w_1 = \eta \Delta' + NL$$

Does not work for large island. Δ' is not the good parameter.

I. Current sheets **attract/repulse** islands

- w_1 in the Rutherford model measures the m=1 mode width and not the full island size is given by taking into account all the mode => a good measure of the island width w_s can be done directly using the simulations. **[A. Poyé et al., POP 21 (2014)]** **[A. I. Smolyakov et al., PPCF 56 (2014)]**
- Different saturation widths w_s if **current sheets** are crossed





[A. Poyé et al., POP 20 (2013)]
[A. I. Smolyakov et al., POP 20 (2013)]

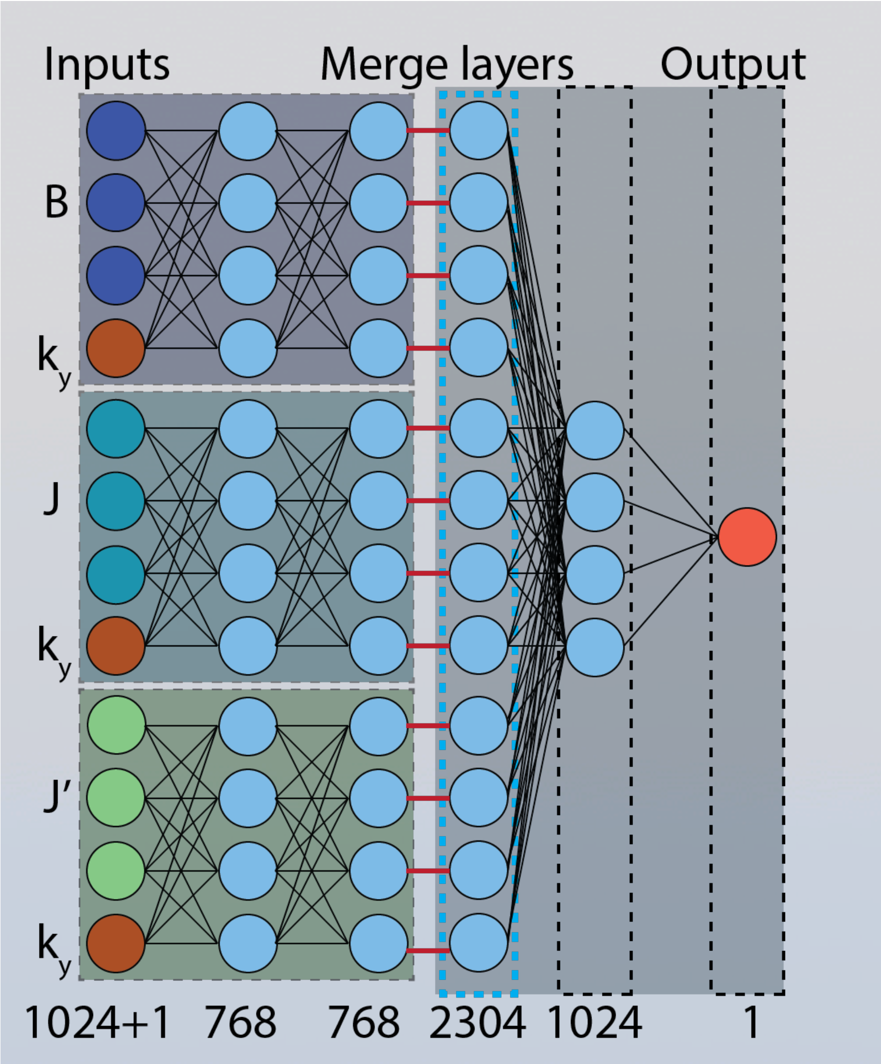
=> External current sheets do modify island size at saturation

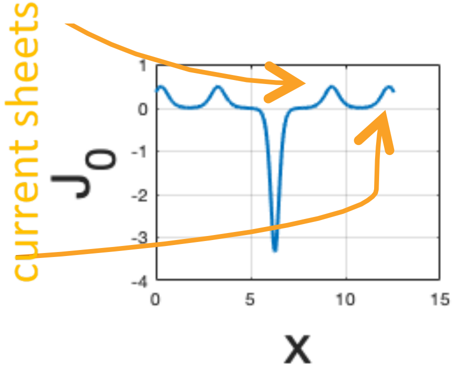
=> Physics far from the resonance can not be casted into Δ' parameter

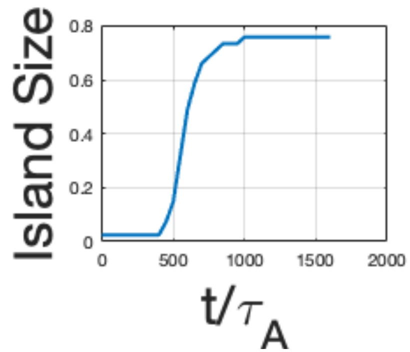
What is the missing ingredient to predict the saturated island size ?

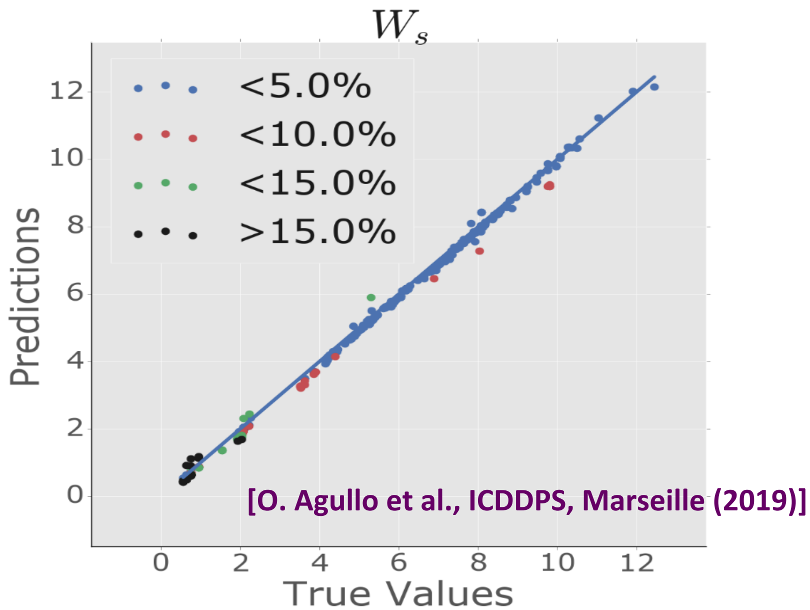
I. Island size prediction using Neural Network

- Neural Network training using MDH simulation of magnetic island w_s with different equilibrium current profiles composed of various external current sheets





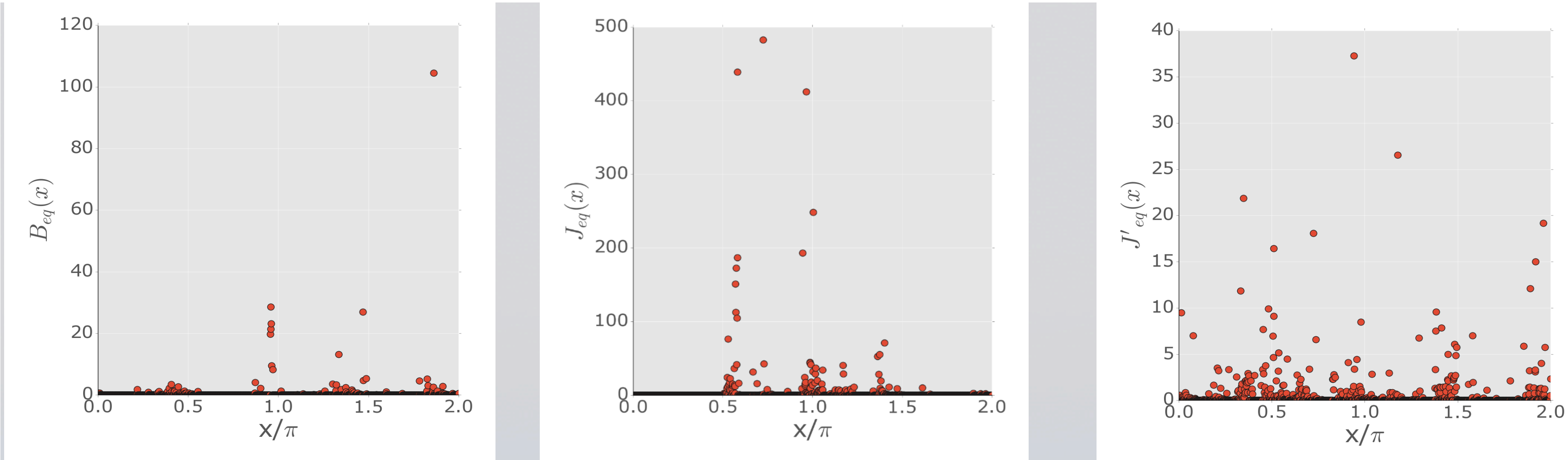




5% correct predictions 623/870

I. Island size prediction : Importance of J_{eq}

◆ Which radial points are important for w_s predictions ? [O. Agullo et al, ICDDPS 2019]



◆ The forest of decision tree has scored points where current sheets are loacted (in the dataset they were at x/π = 0.5, 1, 1.5)

◆ No scoring at the resonance! (lack of profile diversity at the resonance x=0 ?)

◆ Scoring is concentrated on J_{eq} dataset

=> Δ' is insufficient to predict saturated island size

=> Indeed, the radial structure and the amplitude of the equilibrium current profile affect also the saturated island size ws [O. Agullo et al., ICDDPS, Marseille (2019)]

I. Classical Tearing Mode – Conclusion

◆ In the classical theory, magnetic reconnection is allowed thanks to resistivity (step 1)

◆ The growth of the island is due to free energy avalaible in the equilibrium magnetic field (and in the equilibrium current profile) (step 2)

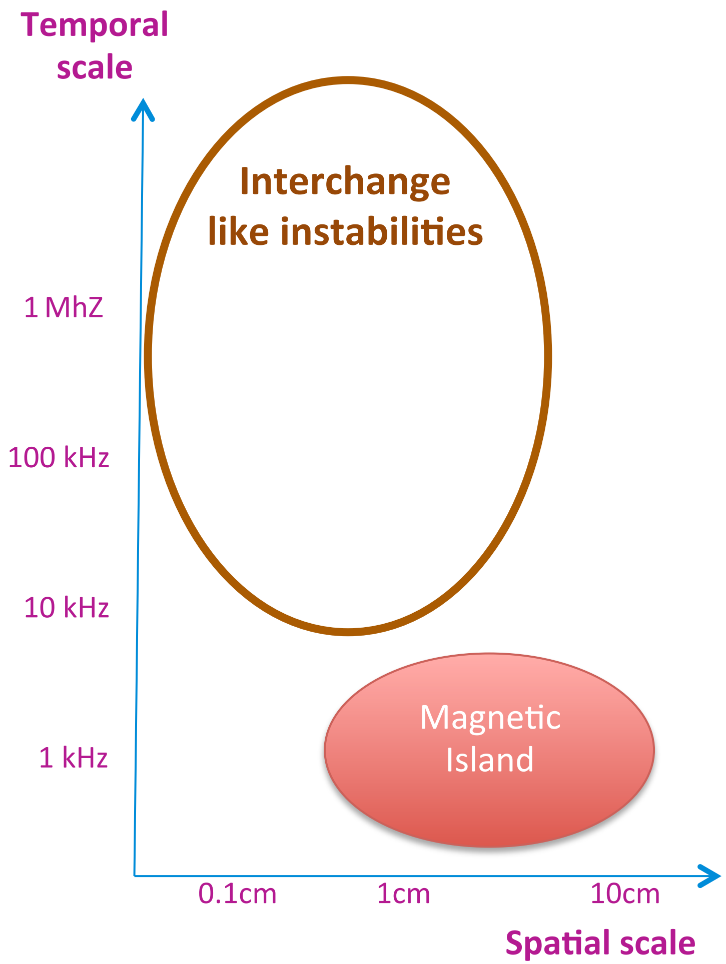
◆ **Open question : prediction of the saturated island size (step 3) ?**

However :

Tearing instabiliy <u>is stable</u> in tokamaks although a seed magnetic island (?) can be amplified by neoclassical effects and lead to a nonlinear growth of a Neoclassical Tearing Mode (NTM) which can damage the device.

=> Since tearing is stable, what is the origin of a such seed island in tokamak?
=> Can there be other physical mechanisms to explain seed magnetic island growth in tokamaks ?

II. MHD-Turbulence Interaction, a Multi-Scales Problem



- Interchange like instabilities coexist with macro
MHD instabilities and lead to micro-turbulence in fusion devices.

- The interaction of magnetic island with interchange is a multi-scales problem.

[F. Militello et al, POP 15 (2008)]
[F.L. Waelbroeck et al, PPCF 51 (2009)]
[M. Muraglia et al, PRL 103 (2009)]
[A. Ishizawa et al, POP 17 (2010)]
[F. Hariri et al, PPCF 57 (2015)]
[L. Bardoczi et al, POP 24 (2017)]

- **Turbulence Driven Magnetic Island (TDMI)**

[M. Muraglia et al, PRL 107 (2011)]
[A. Poyé et al, POP 22 (2015)]
[W. Hornsby et al, PPCF 58 (2015)]
[O. Agullo et al, POP 24 (2017)]
[A. Ishizawa et al, PPCF 61 (2019)]

- **TDMI amplified and at the origin of a NTM**

[M. Muraglia et al, NF (2017)]
J. Frank, PhD thesis, CEA and PIIM Lab

II. Model: 2D Reduced MHD

- Model includes both resistive **Interchange** and **Tearing Mode** :

[M. Muraglia et al, NF 49, 055016 (2009)]

$$\partial_t \nabla_\perp^2 \phi + [\phi, \nabla_\perp^2 \phi] = [\psi + \psi_0, \nabla_\perp^2 \psi] - \kappa_1 \partial_y P + \nu \nabla_\perp^4 \phi$$

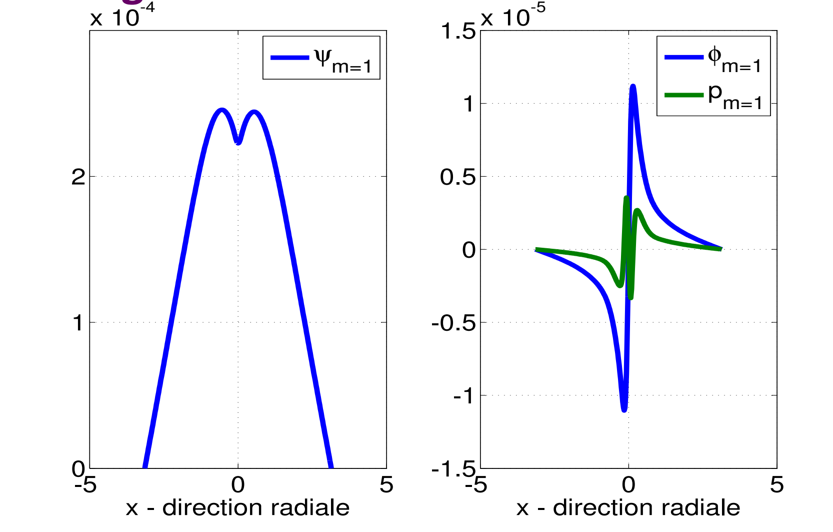
$$\partial_t P + [\phi, P] = -\partial_x P_0((1-\kappa_2)\partial_y \phi + \kappa_2 \partial_y P) + \rho_\star^2 [\psi + \psi_0, \nabla_\perp^2 \psi] + \chi_\perp \nabla_\perp^2 P$$

$$\partial_t \psi = [\psi + \psi_0, \phi - P] - \partial_x P_0 \partial_y \psi + \eta \nabla_\perp^2 \psi$$

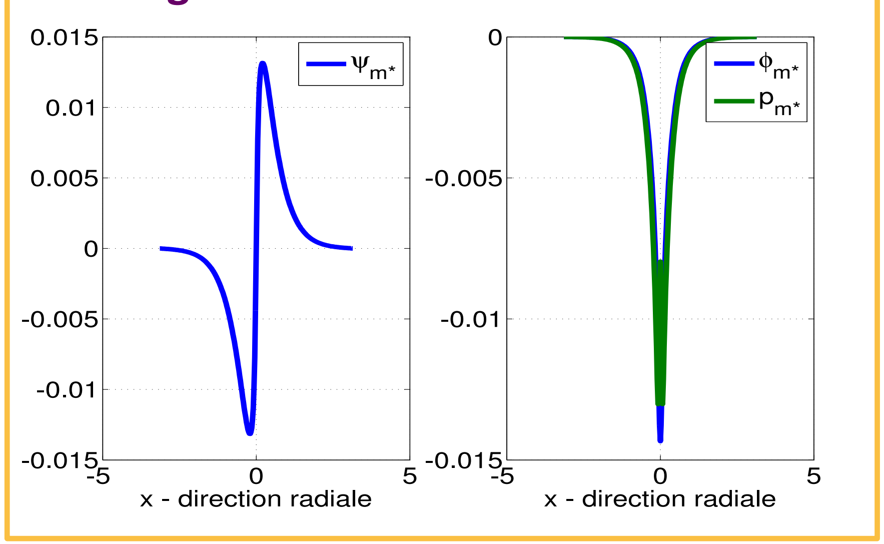
- Instability characterization : **THE PARITY** of the eigenfunctions ψ_m, ϕ_m, P_m

$$\psi(x, y, t) = \sum_{m \in \mathbb{Z}} \psi_m(x, t)\, exp^{i\frac{2\pi m}{Ly} y}$$

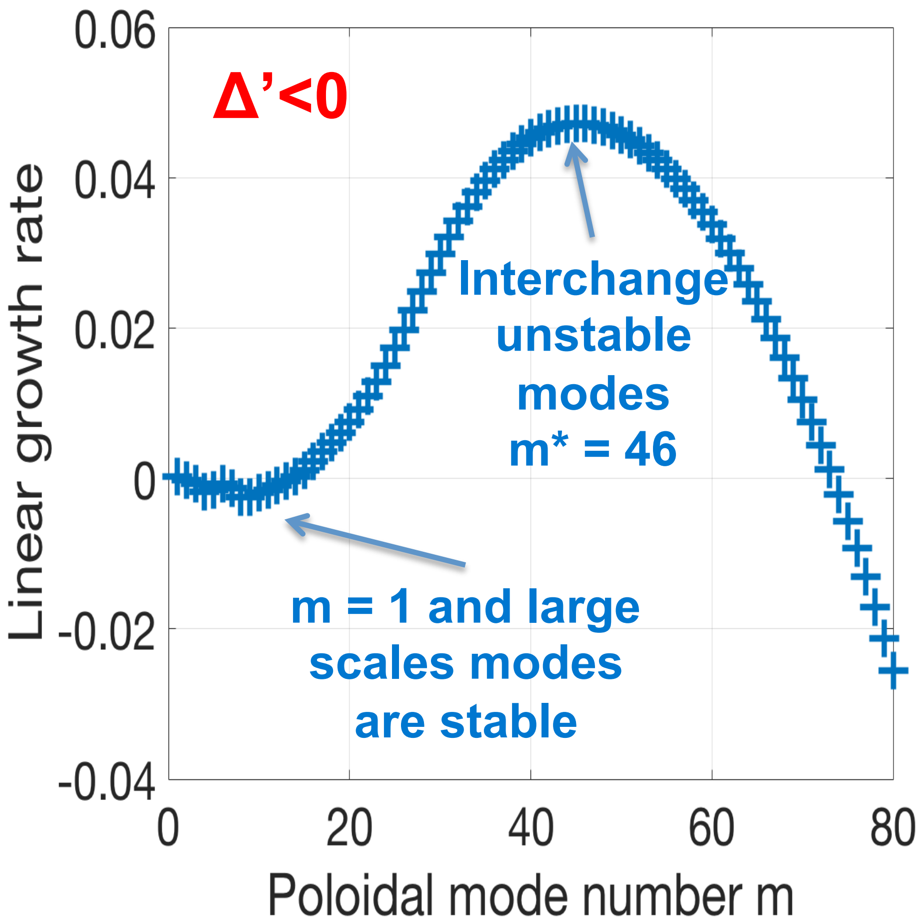
Tearing mode



Interchange mode



II. Linear Turbulent spectrum



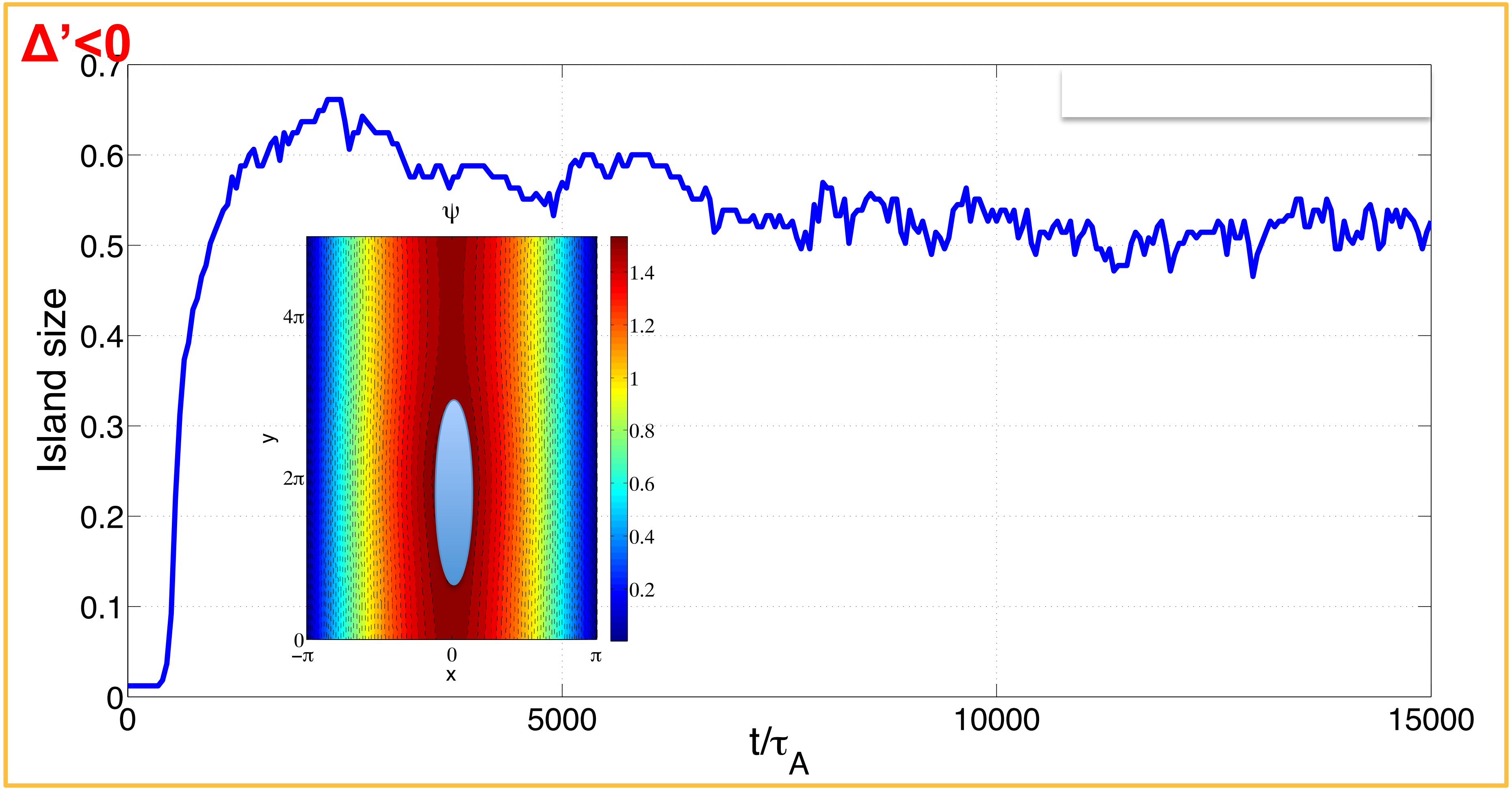
- Δ'<0 Linear spectrum is stable with respect with tearing instability

  => **No island**

- Stable large scales modes
- Small scales turbulence driven by interchange instability

=> **What 's about non-linear dynamics ?**

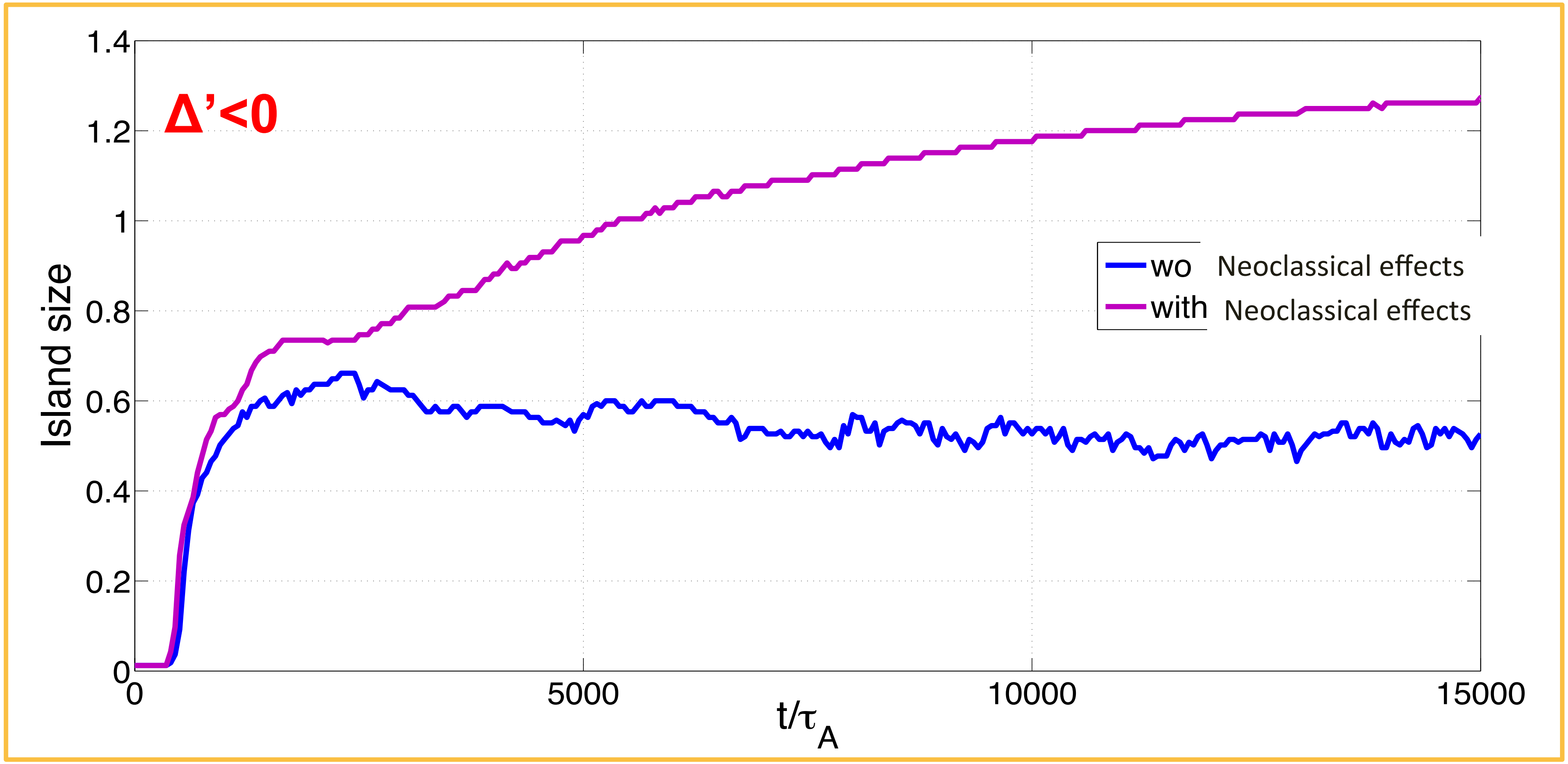
II. NL generation of TDMI



◆ NL generation of TDMI by a beating of interchange modes

[M. Muraglia et al, PRL 107 (2011)] & [A. Poyé et al, POP 22 (2015)]
[W. Hornsby et al, PPCF 58 (2015)]

II. NTM growth from a TDMI



◆ Self-consistent generation of NTM from TDMI

1. TDMI formation => **Seeding regime**

2. NL growth of NTM => **Amplification (by neoclassical effects) regime**

[M. Muraglia et al, NF (2017)]

II. TDMI - Conclusions

◆ The tearing instability is stable in tokamaks ($\Delta'<0$).

◆ However, it has been shown that, in presence of resistivity (even weak), turbulent modes at small scales can drive at large scales a seed magnetic island (step 2).

◆ Such seed island can be amplified by neoclassical effects and a large magnetic island can damage the device.

◆ **Open questions** :

1. Prediction of the saturated island size in presence of turbulence (step 3)?

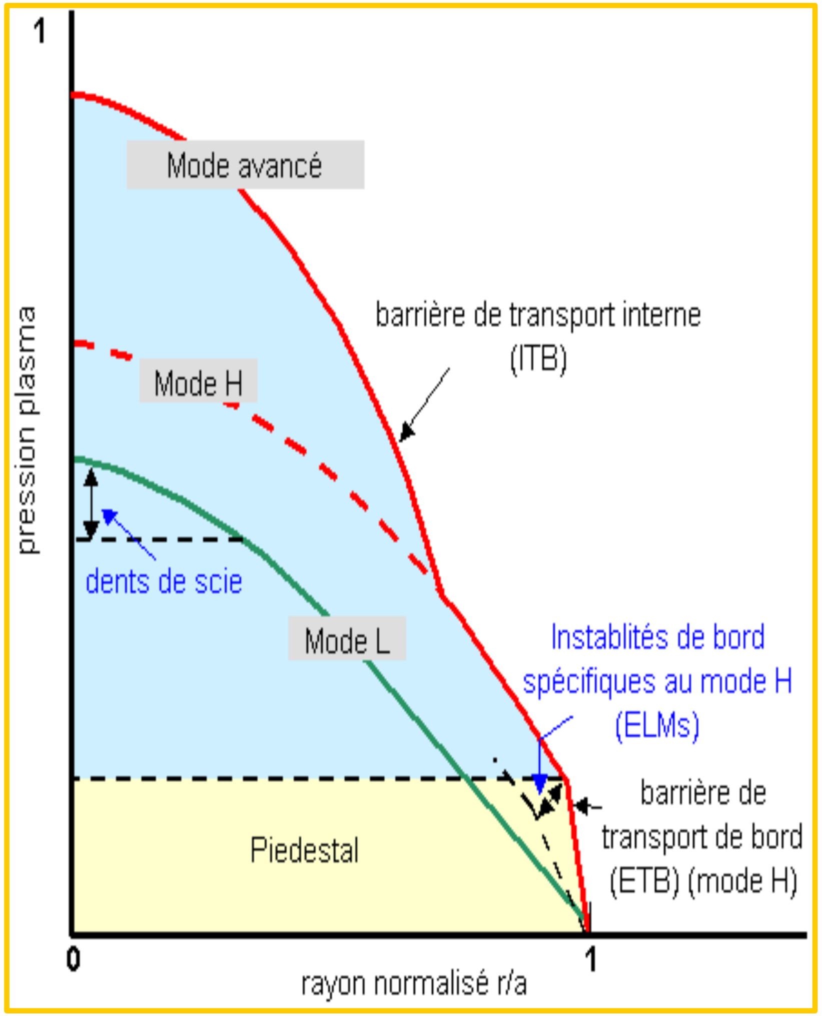
2. Experimental signature of such mechanisms

At small scales, $\Delta'<0$ and resistivity in tokamak is considered too weak for Micro-reconnection. However...

III. Contexte for micro-reconnection

◆ Challenge :

control of the confinement



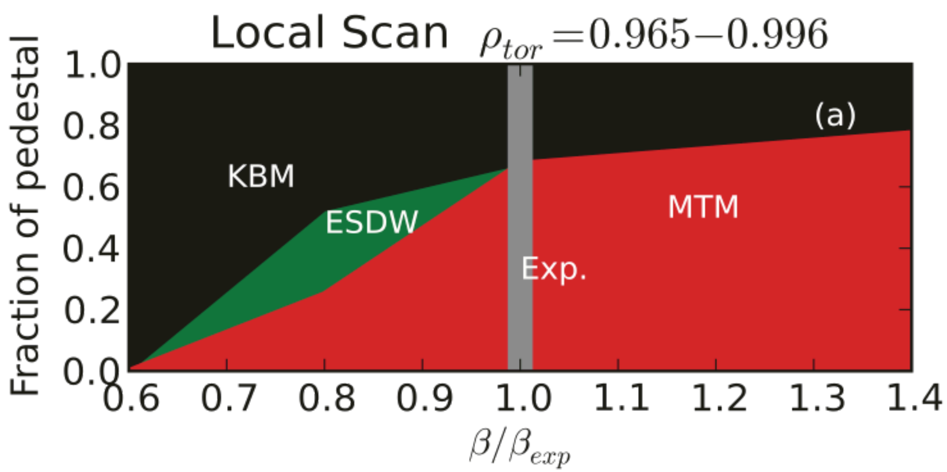
◆ Open questions :

- Mechanisms leading to H-mode ? Pedestal Physics?

- Origin of electronic turbulence ? Origin of **heat electron transport** ?

◆ Possible candidate :

Microtearing turbulence limiting the JET-ILW pedestal [Hatch et al, NF 56 (2016)]



=> Micro-TearingMode (MTM) instability ?

III. Origin of Micro-Tearing Mode (MTM) ?

- Disagreement between
  analytical theory and **gyrokinetic simulations**

Stable MTM in weak collisional regime

=> No MTM in tokamaks

[Hazeltine et al (1975)]
[Drake and Lee (1977)]
[Garbet (1990)]
[Smolyakov (1990)]

Unstable MTM in weak collisional regime

[Applegate et al (2007)]
[Doerk et al, Guttenfelder et al (2012)]
[Dickinson et al, Predebon et al (2013)]
[Swamy et al (2014)]
[Hatch (2017)]

- Possible physical mechanisms at the origin of MTM destabilization

  - Collisions ?
  - Magnetic curvature?
  - Electric potential fluctuations?

III. Reconciliation between theory and simulations

- After a lot of theory …

  Reduced Kinetic Model equivalent to the RMHD model in fluide theory

$$d_e^2 \nabla_\perp^2 \tilde{A}_\parallel = \sigma(\omega,\omega_d)\left(\tilde{A}_\parallel - \frac{k_\parallel v_{Te}}{\omega}\ \tilde{\phi}\right)$$

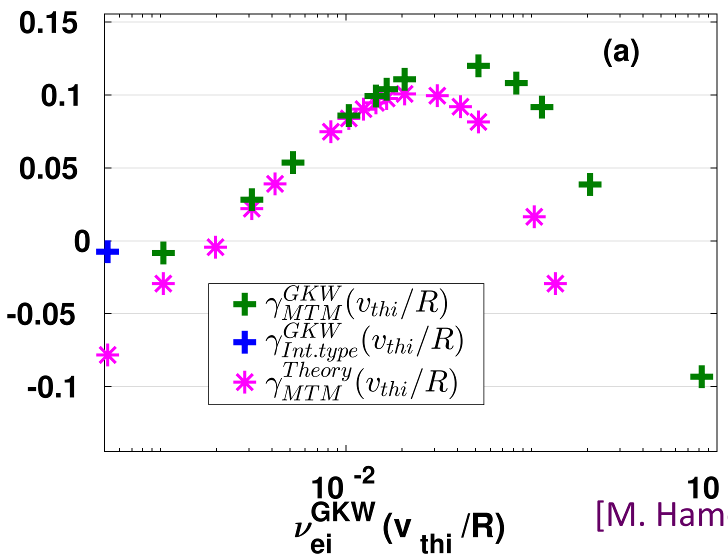
→ Ampère's law

$$\frac{\omega+\omega_T^*}{\omega}\rho_i^2\nabla_\perp^2\ \tilde{\phi} = \frac{k_\parallel v_{Te}}{\omega}\sigma(\omega,\omega_d)\left(\tilde{A}_\parallel - \frac{k_\parallel v_T}{\omega}\ \tilde{\phi}\right)$$

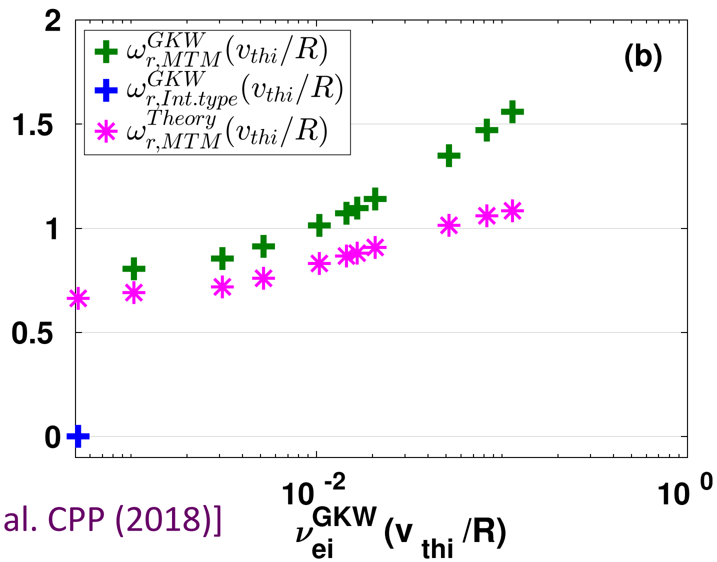
→ Poisson's equation

- Successful comparition between theory and gyrokinetic simulations

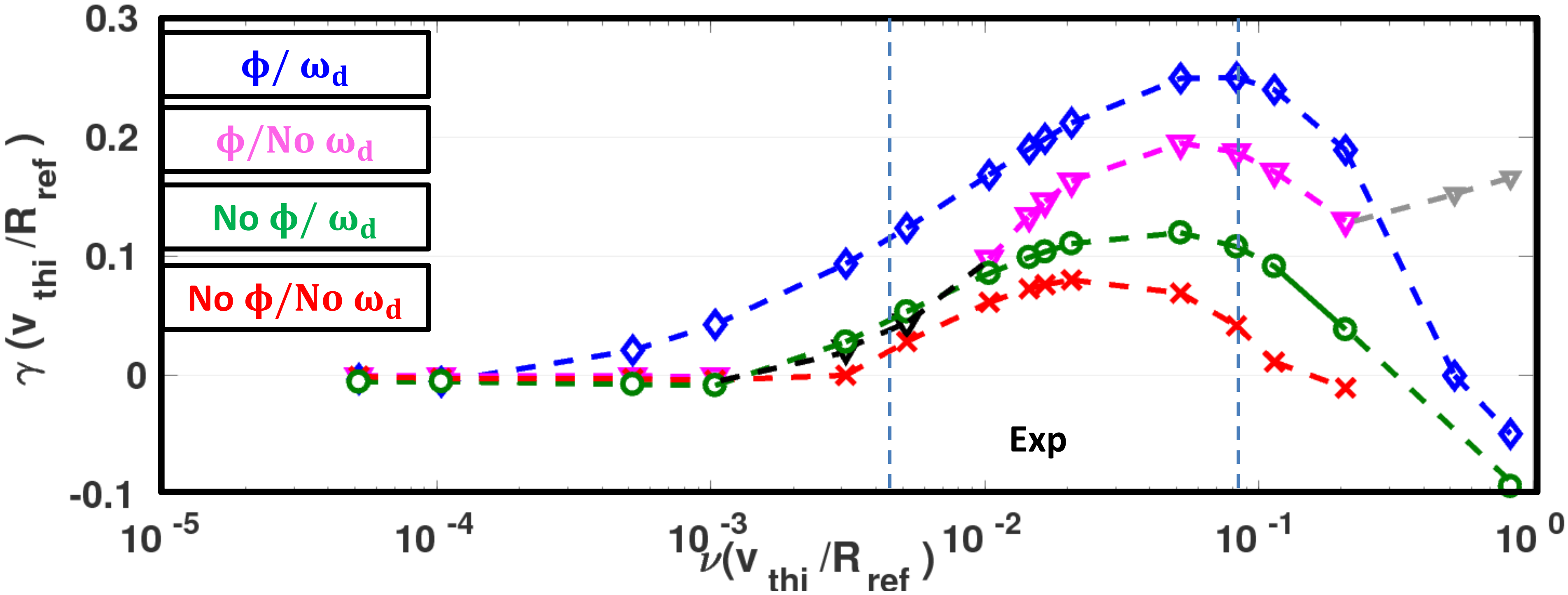
  In particular, MTM is stable in weak collisions regime



[M. Hamed et al. CPP (2018)]



III. Destabilization of a MTM



◆No instability without collisions => Magnetic reconnection is not allowed

◆Unstable MTM in the pedestal region even if collisions are weak (step 1)

◆Magnetic curvature and electric potential fluctuations can not destabilize MTM without collisions. However, in presence of collisions, they enhance the MTM growth rate (step 2) [M. Hamed et al. POP 26 (2019)]

III. MTM - Conclusions

- Derivation of a reduced kinetic model for the MTM stability
- Reconciliation between theory and gyrokinetic simulations
- In particular, without collisions, MTM is stable
- However, collisions are sufficient in tokamaks to let MTM unstable in the pedestal (step 1)
- Electron temperature gradient drive MTM. Magnetic curvature and electric potential fluctuations enhance the growth of unstable modes. (step 2)
- **Open question on saturation mechanisms : impact of MTMs on heat electron transport (step 3)**

General conclusion

- In hot magnetized plasmas of tokamaks, magnetic equilibrium is such as the tearing instability is stable ($\Delta' < 0$).

- However, magnetic reconnection can occur :

  - at large scales : nonlinear growth of Neoclassical Tearing Mode can lead to disruption and can damage the device

  - at small scales : micro-tearing instability can lead to magnetic field stochastisation and enhance the heat electron transport in the pedestal region

- Although resistivity and collisions are weak in such device, they are sufficient to allow magnetic reconnection

- It exist various mechanisms leading to an island growth :

  - Small-scales turbulent modes can drive nonlinearly a large magnetic island
  - Electron temperature gradient can drive micro-tearing mode in the pedestal

- Open question : Saturation mechanisms ?
  - Saturated size of large island ?
  - Electron heat transport due to MTM ?