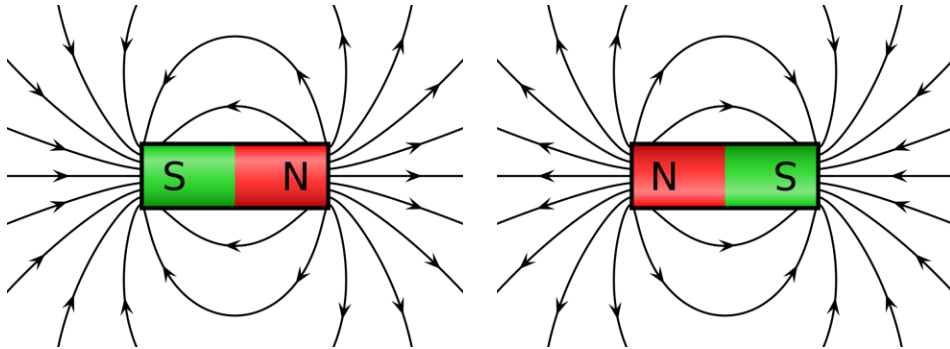


# Explorer les structures magnétiques à l'aide de l'intelligence artificielle

Prof. Dr. Bertrand Dupé  
Bertrand.dupe@uliege.be  
tom.uliege.be

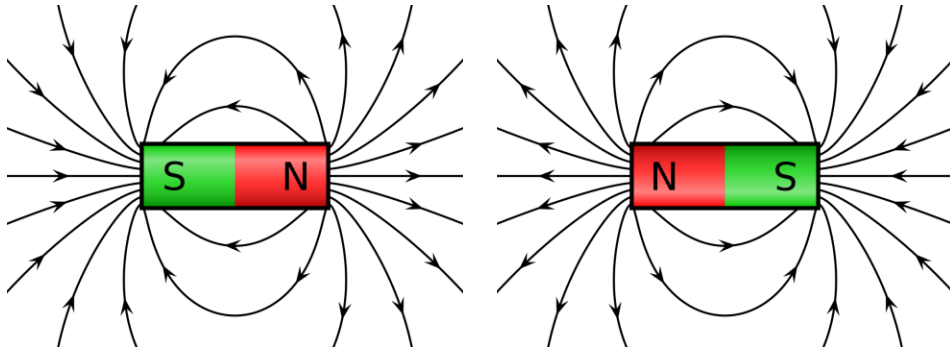
# Qu'est-ce qu'un aimant?

Aimant et ses lignes  
de champs

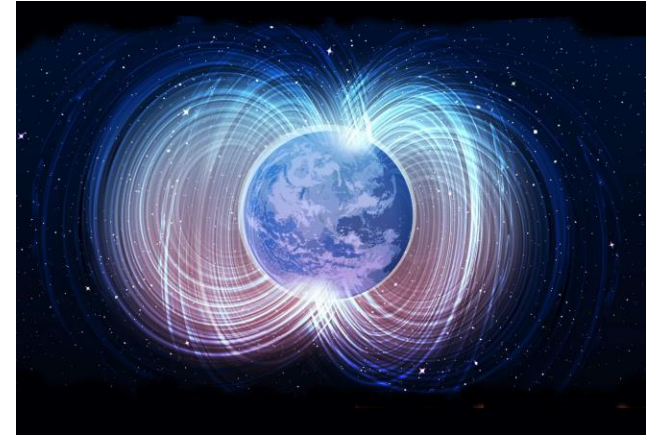


# Qu'est-ce qu'un aimant?

Aimant et ses lignes de champs

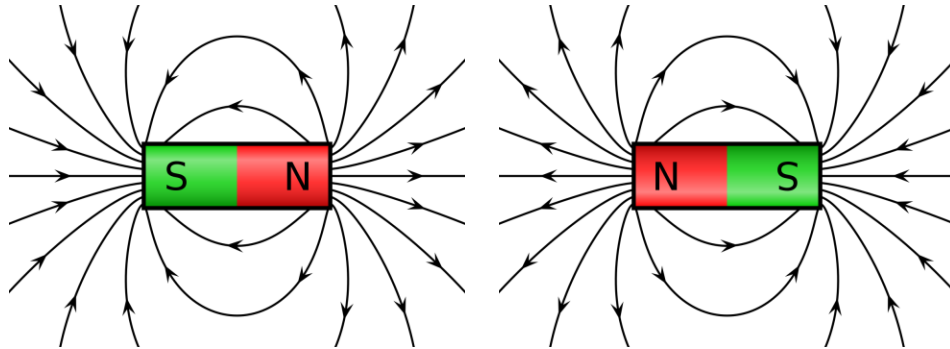


Champ magnétique terrestre

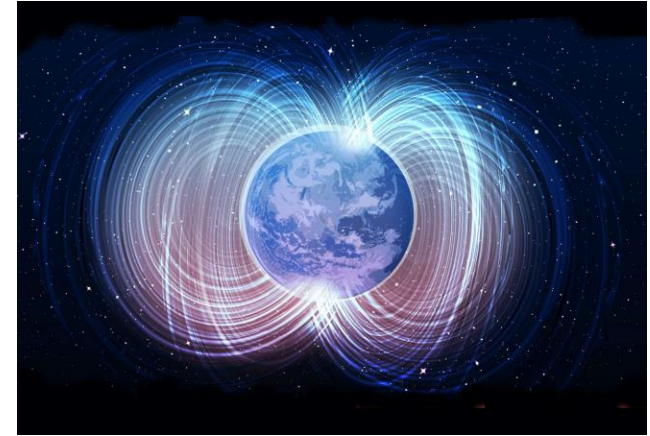


# Qu'est-ce qu'un aimant?

Aimant et ses lignes de champs de champs

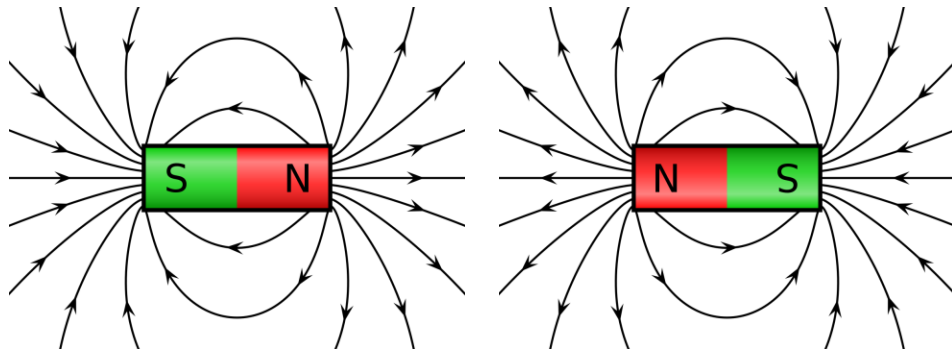


Champ magnétique terrestre

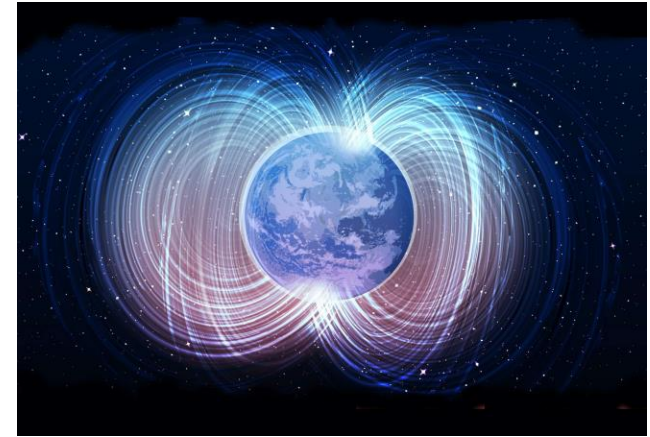


# Qu'est-ce qu'un aimant?

Aimant et ses lignes de champs



Champ magnétique terrestre



„Hello“:

01101000 01100001 01101100 01101100 01101111



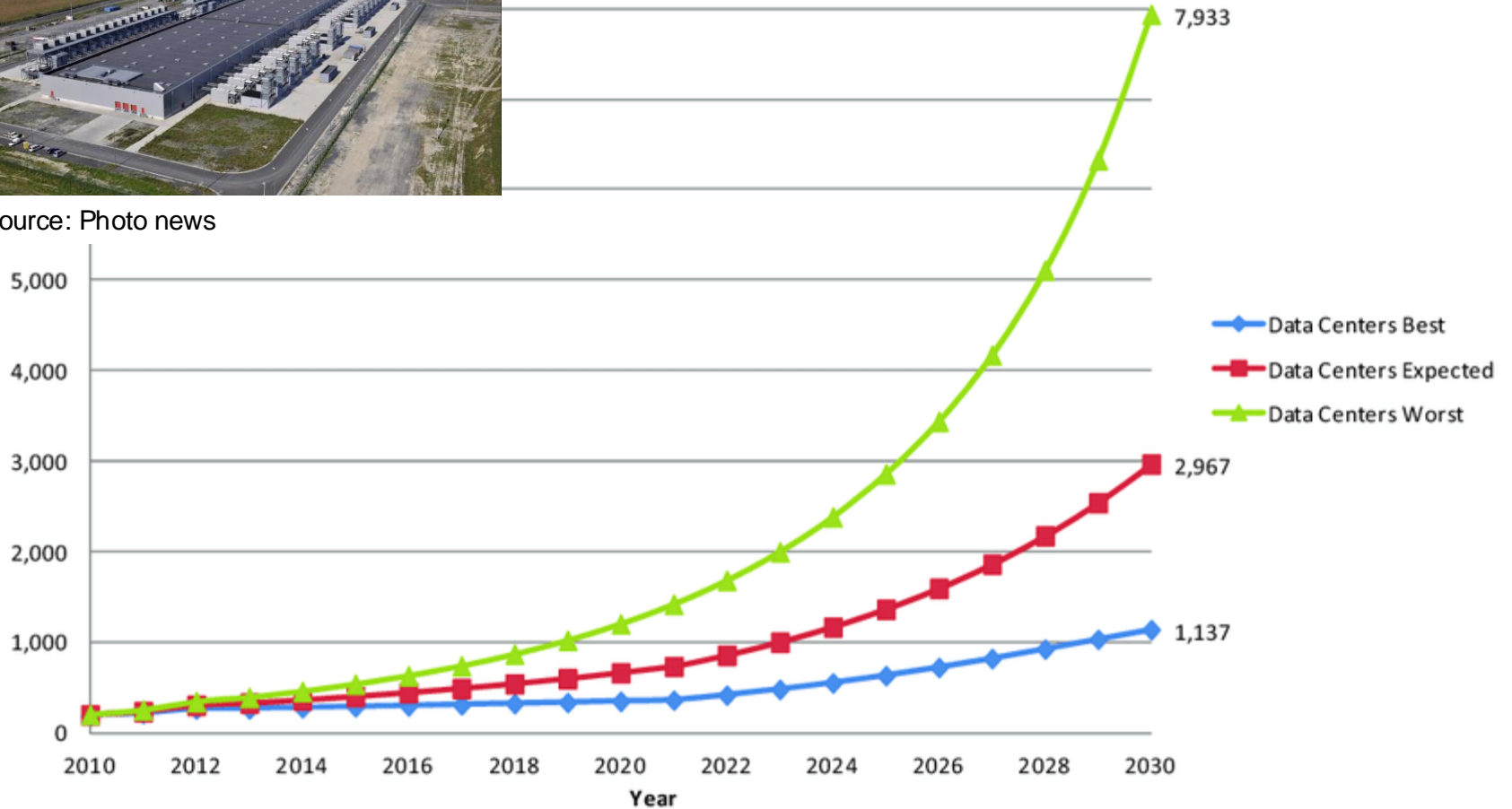
# Consommation électrique des centres de données

Data center St Ghislain (1.5G€)



Actuellement ~4% de l'électricité mondiale  
2% des émissions de CO<sub>2</sub>

Source: Photo news



Anders S. G. Andrae and Tomas Edler *Challenges* 6, 117-157 (2015)

Bertrand Dupé

# Les technologies de l'information

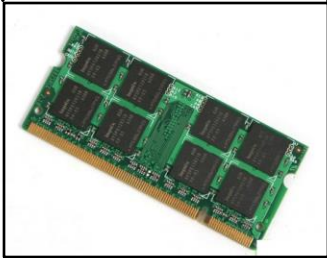
Data center St Ghislain (1.5G€)



Disque dur



Mémoire vive



# Les technologies de l'information

Data center St Ghislain (1.5G€)



Disque dur



Mémoire vive



Manipulation

- **Rapide** (électrique)
- **Volatile** (électrostatique)
- **Énergivore** (courant)

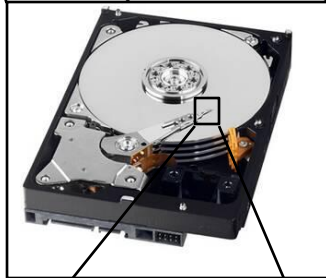


# Les technologies de l'information

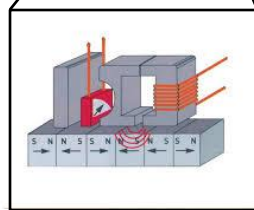
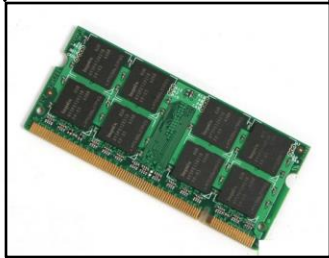
Data center St Ghislain (1.5G€)



Disque dur



Mémoire vive



Manipulation

- **Rapide** (électrique)
- **Volatile** (électrostatique)
- **Énergivore** (courant)

Stockage

- **Lent** (mécanique)
- **non volatile** (magnétique)
- **Énergivore** (courant)

# Les Nouvelles technologies de l'information

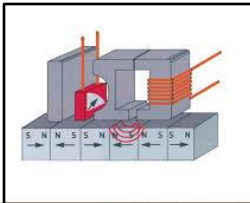
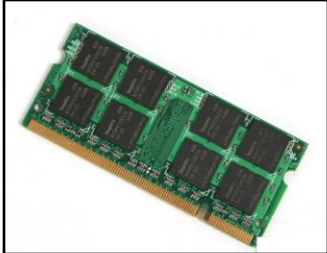
Data center St Ghislain (1.5G€)



Disque dur



Mémoire vive



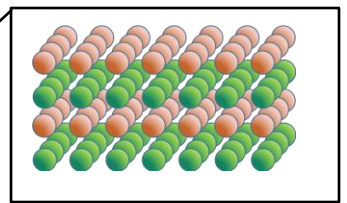
Manipulation

- **Rapide** (électrique)
- **Volatile** (électrostatique)
- **Énergivore** (courant)

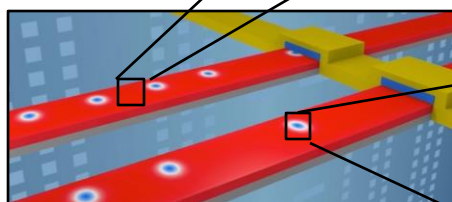
Stockage

- **Lent** (mécanique)
- **non volatile** (magnétique)
- **Énergivore** (courant)

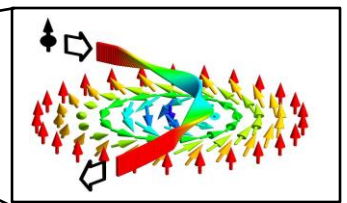
Nouveaux matériaux:  
Multiferroïques, supraconducteurs



Nouveau disque dur



Nouveaux états magnétiques:  
skyrmions

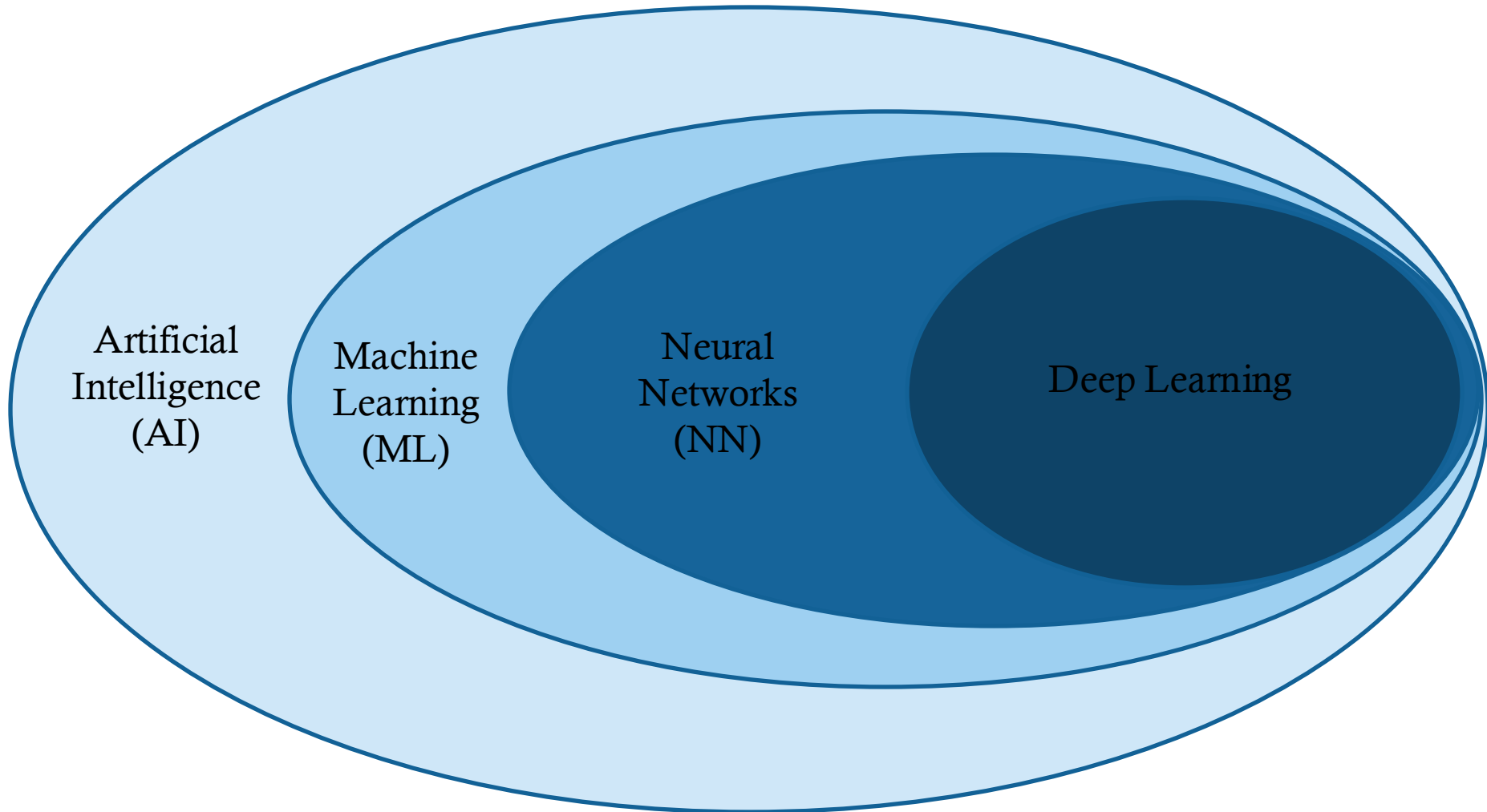


Stockage

- **rapide** (électrique)
- **non volatile** (magnétique)
- **économique** (pas de courant)



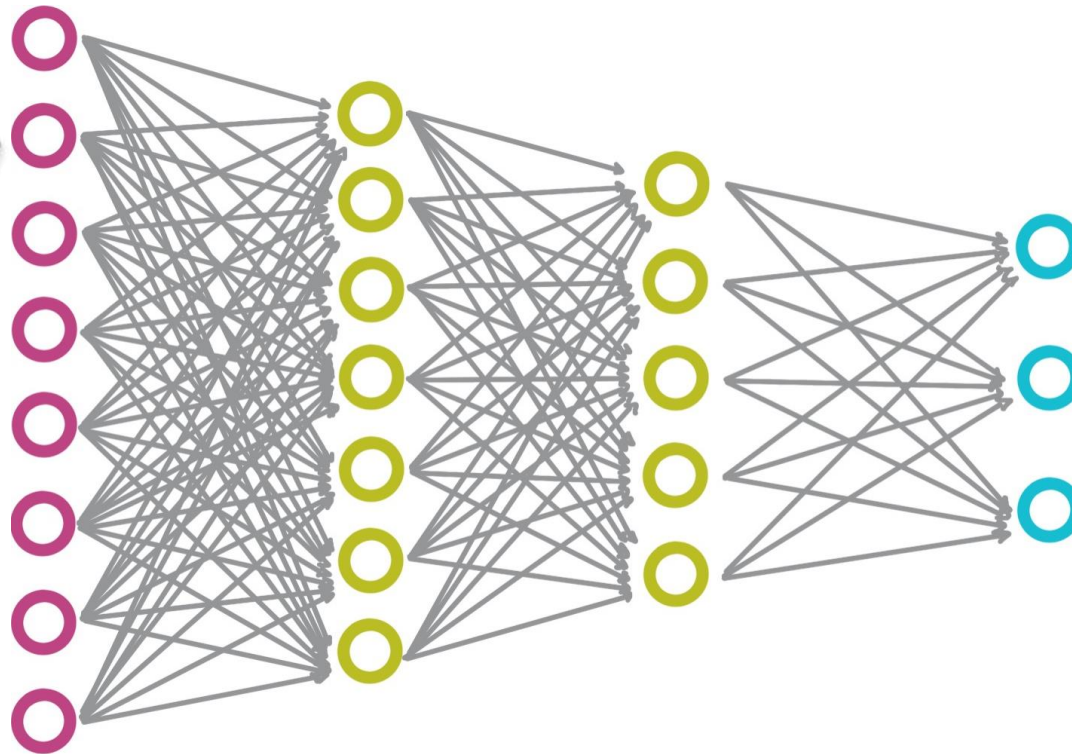
# Intelligence artificielle



Xavier Bosch *Master thesis*, dép. Physique, Université de Liège  
2024

Bertrand Dupé

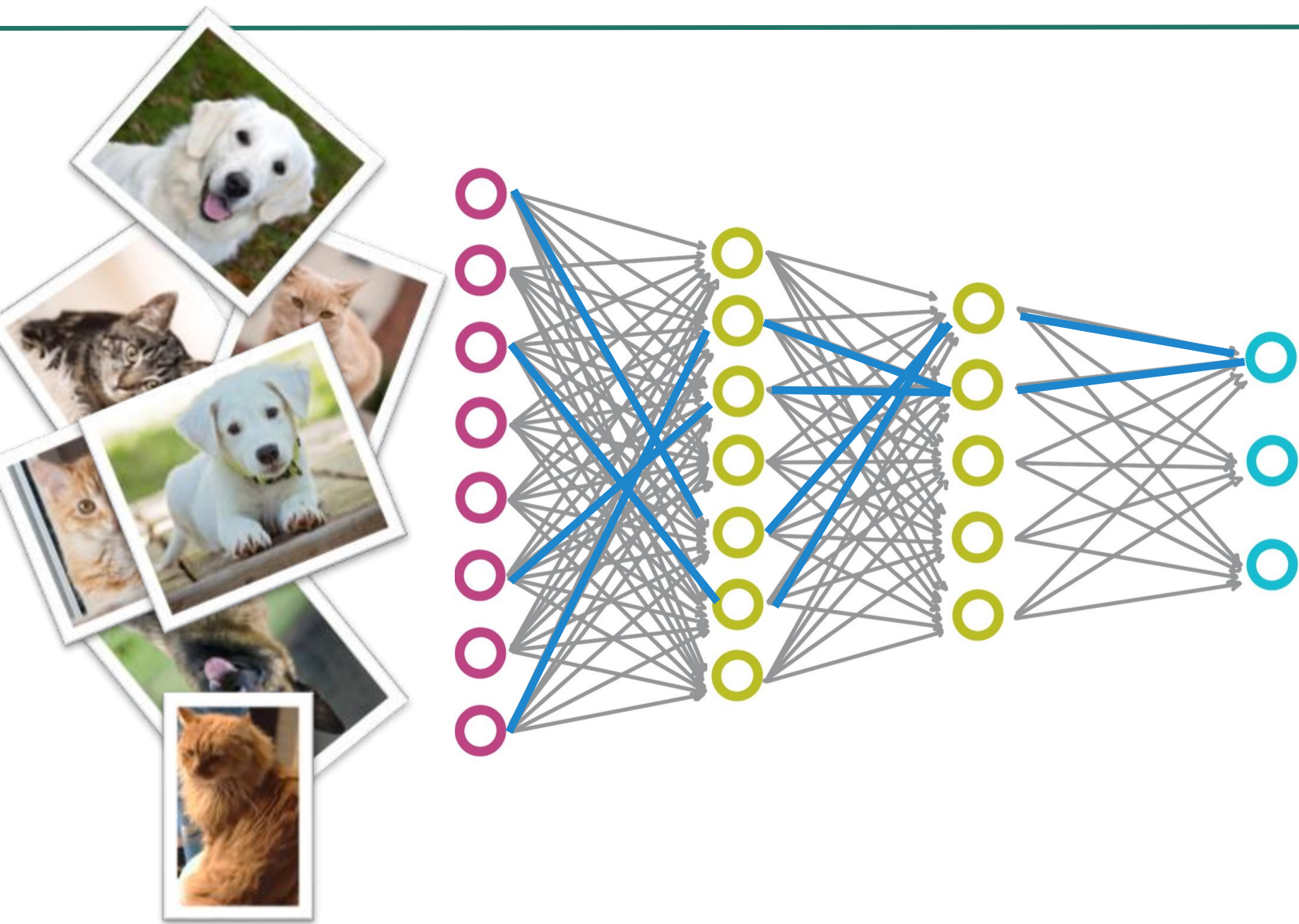
# Fonctionnement d'un réseau de neurones



Xavier Bosch *Master thesis*, dép. Physique, Université de Liège  
2024

Bertrand Dupé

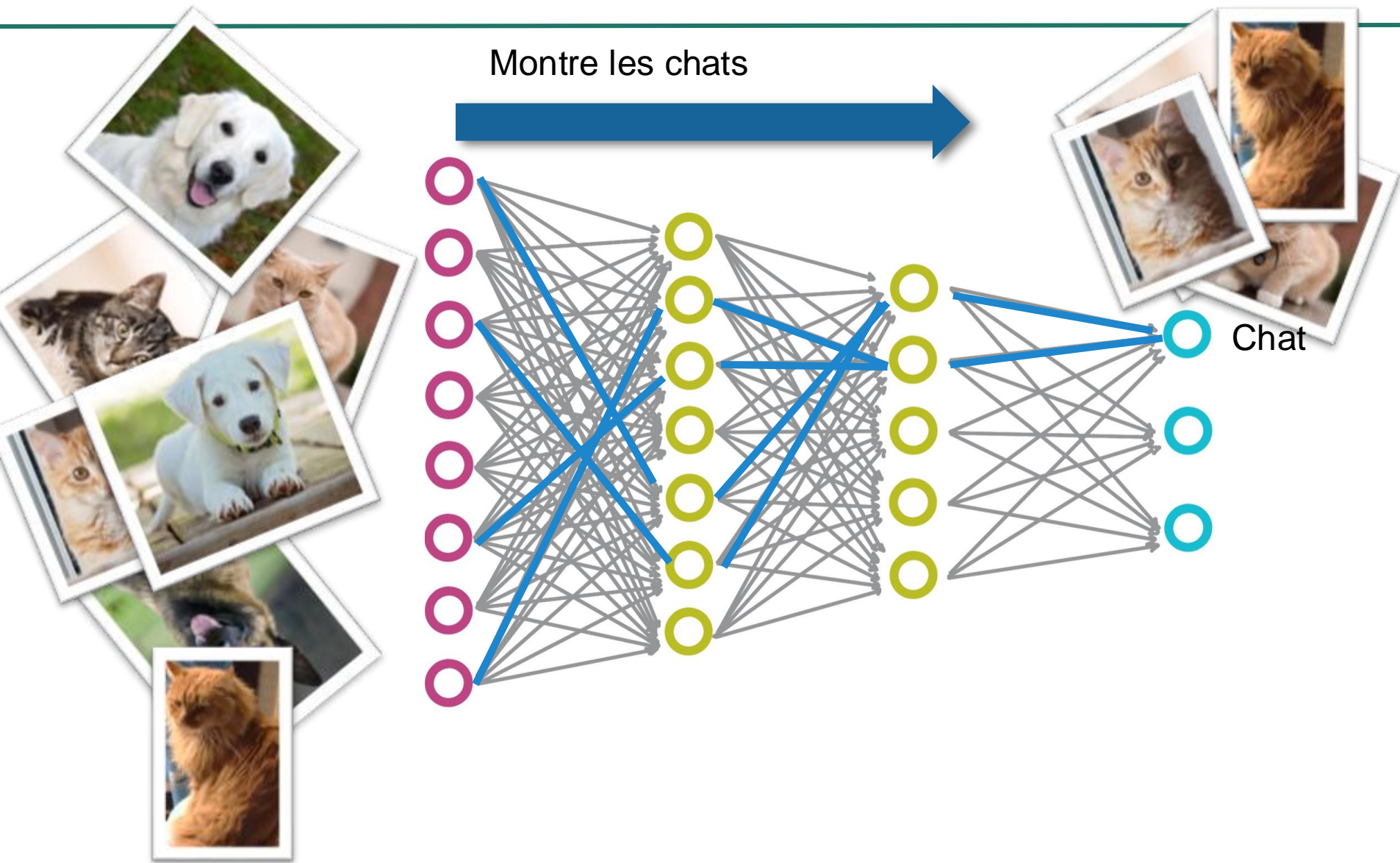
# Fonctionnement d'un réseau de neurones



Xavier Bosch *Master thesis*, dép. Physique, Université de Liège  
2024

Bertrand Dupé

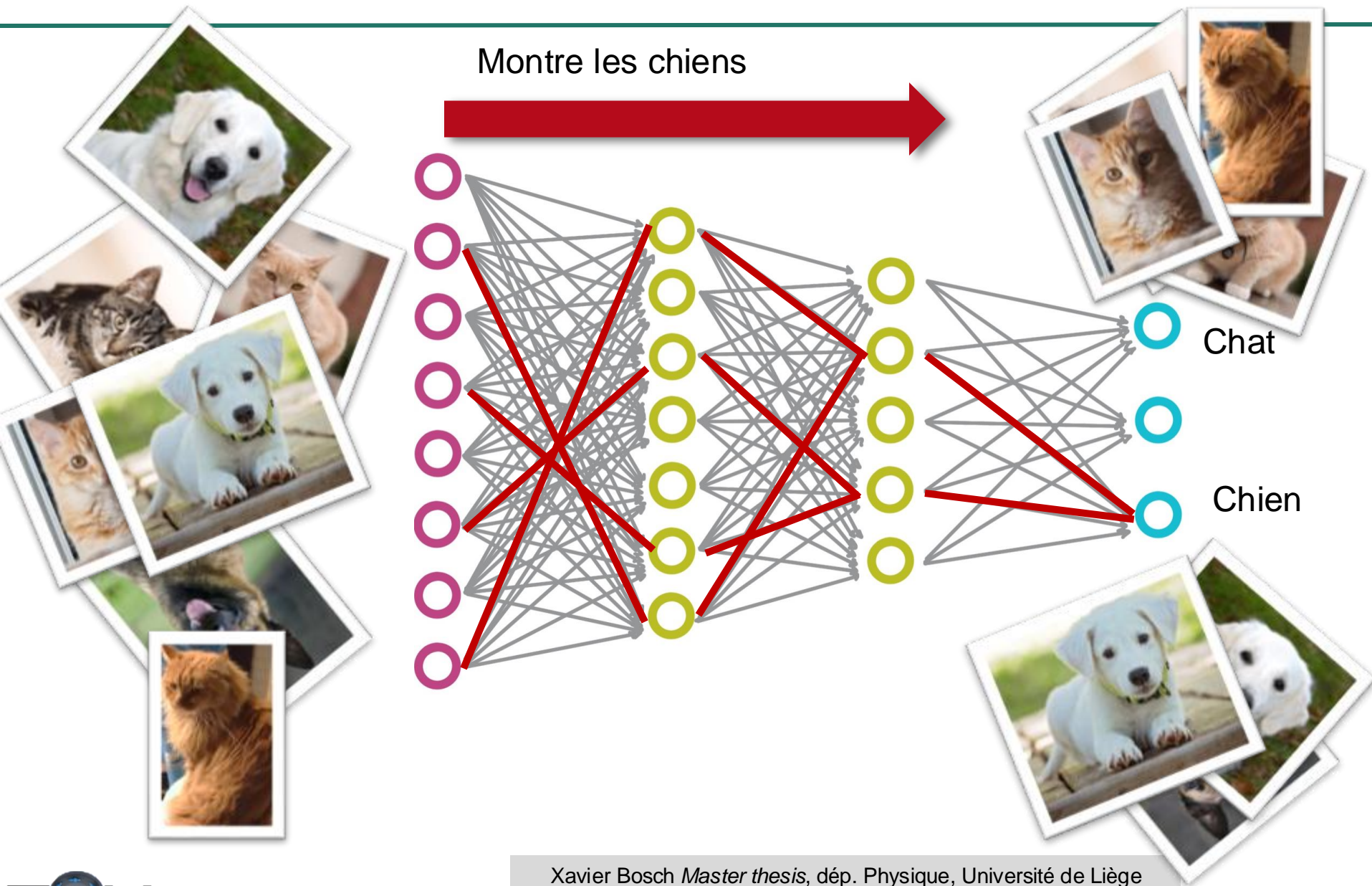
# Fonctionnement d'un réseau de neurones



Xavier Bosch *Master thesis*, dép. Physique, Université de Liège  
2024

Bertrand Dupé

# Fonctionnement d'un réseau de neurones

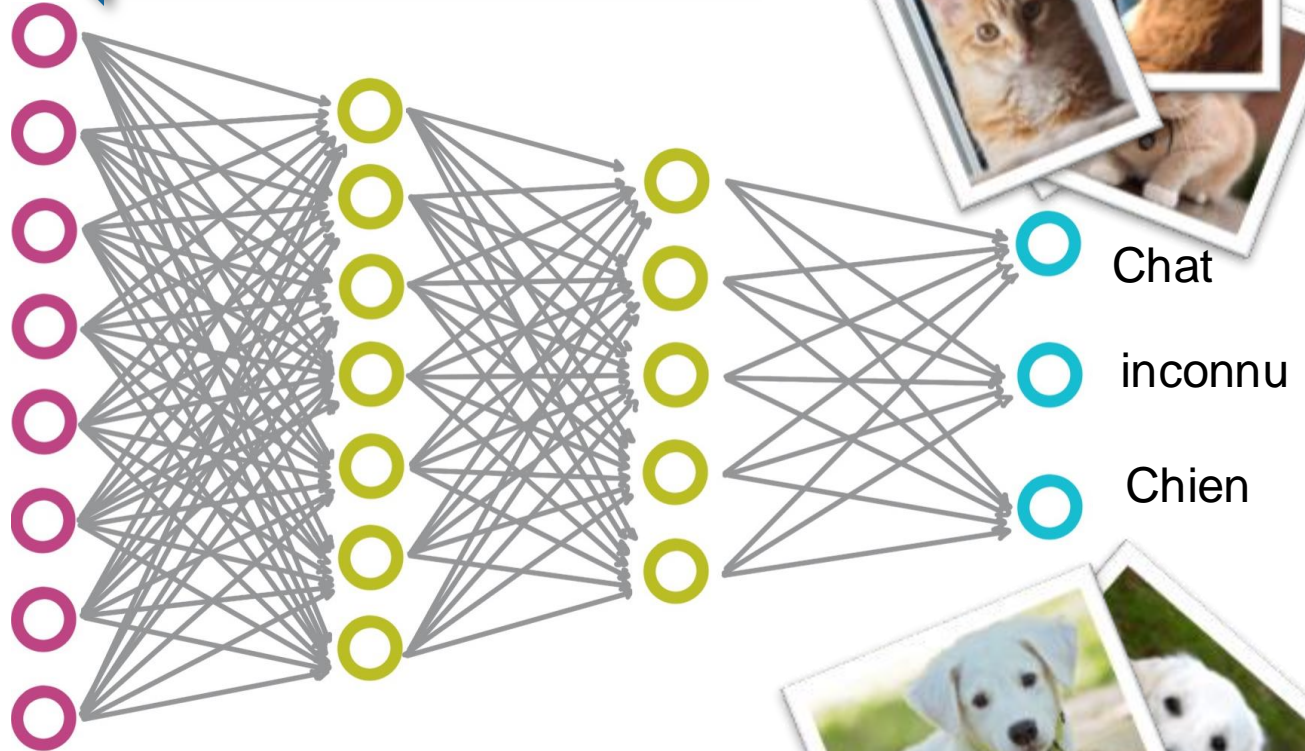


Xavier Bosch *Master thesis*, dép. Physique, Université de Liège  
2024

Bertrand Dupé

# IA générative

Dessine un chat



Xavier Bosch *Master thesis*, dép. Physique, Université de Liège  
2024

Bertrand Dupé

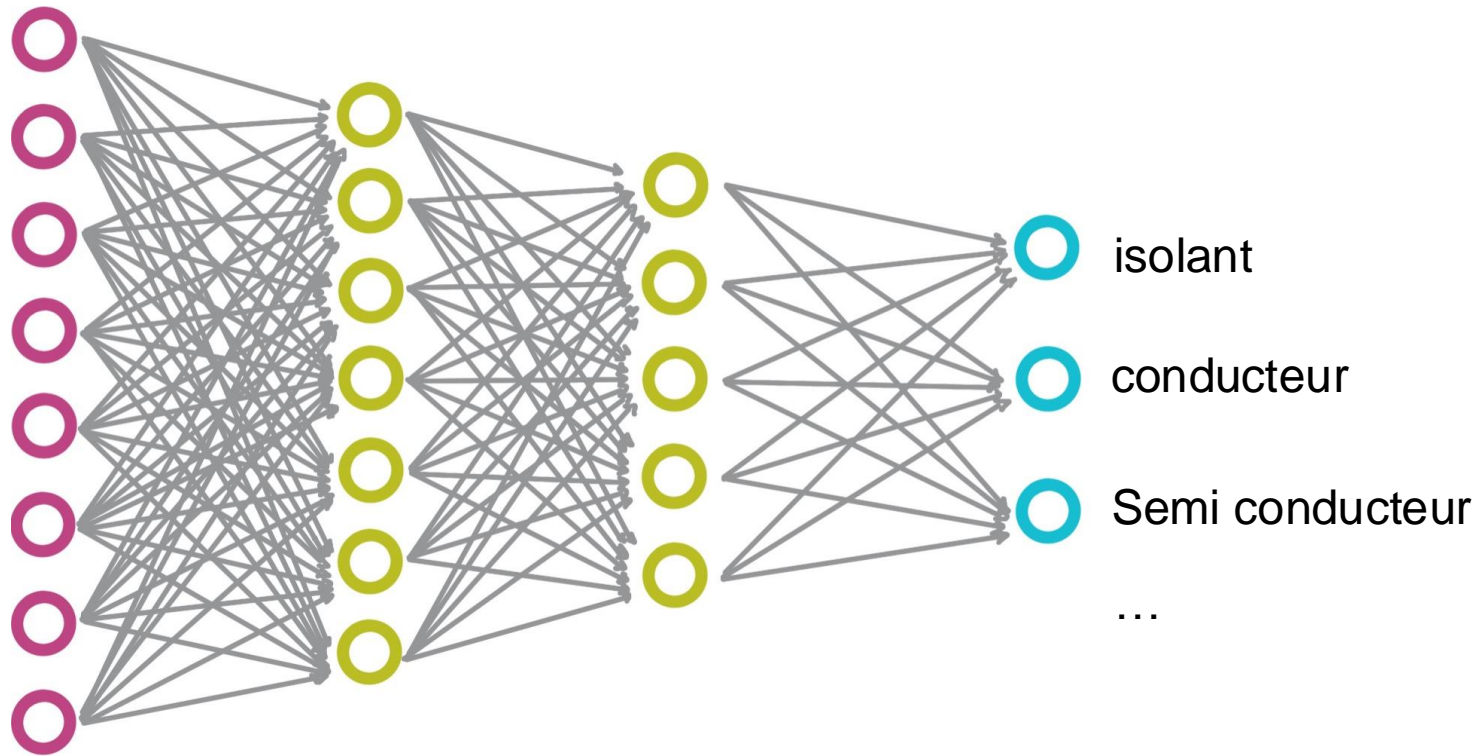


# L'IA pour la science des matériaux

Éléments (Co,  
Fe, Ni, O...)

Symétrie  
(cubique,  
hexagonale...)

Energie de  
formation,  
stabilité...

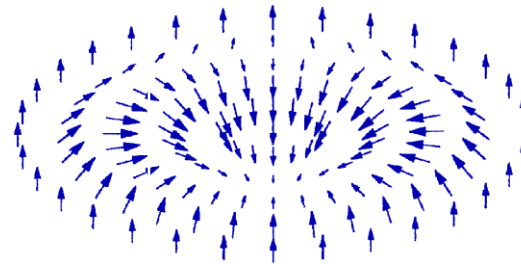


Y. Liu *et al.* *Journal of Materiomics* **9**, 798 – 816 (2023)  
Z. Wang *et al.* *J. Am. Chem. Soc.* **145**, 48, 26412 (2023)  
K. Litzius *et al.* *Nat. Phys.* **13**, 170 – 175 (2016)  
U. Ritzmann, BD *et al.*, *Nature Electronics* **1**, 451-457 (2018)

# L'origine des skyrmions dans la matière condensée

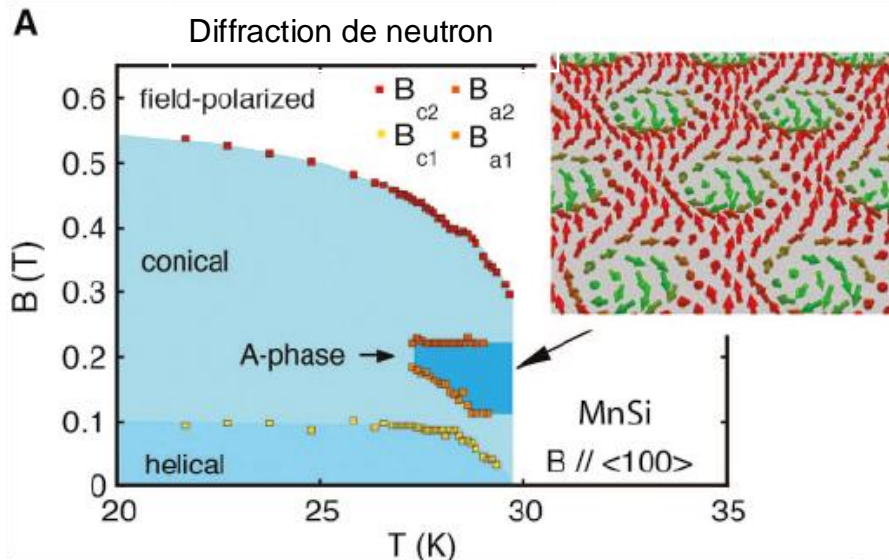
## Prédiction théorique des skyrmions

Existence de skyrmion de taille micrométrique



A. N. Bogdanov & D. A. Yablonskii *Sov. Phys. JETP* **68**, 101 (1989)

## Découverte expérimentale



P. Milde *et al.*, *Science* **340**, 1076 (2013)

S. Mühlbauer *et al.*, *Science* **323**, 915 (2009)

A. Neubauer *et al.*, *PRL* **102**, 186602 (2009)

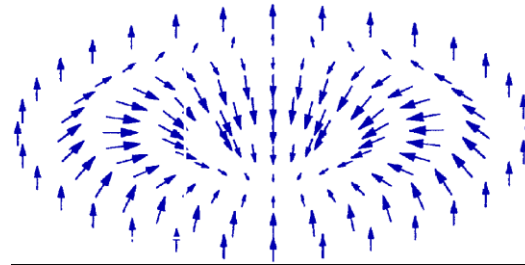
X. Z. Yu *et al.*, *Nature* **465**, 901 (2010)

M. Lee *et al.*, *PRL* **102**, 186601 (2009)

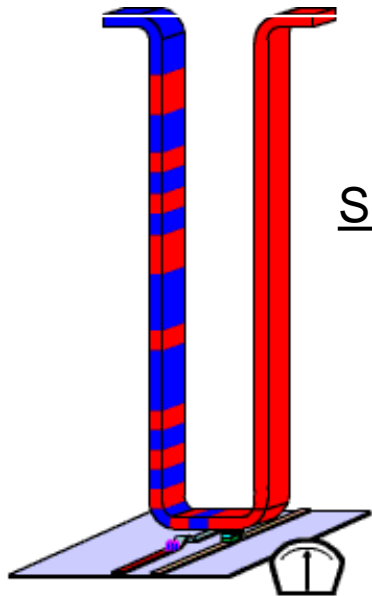
# Skymions dans la technologie

## Prédiction théorique des skymions

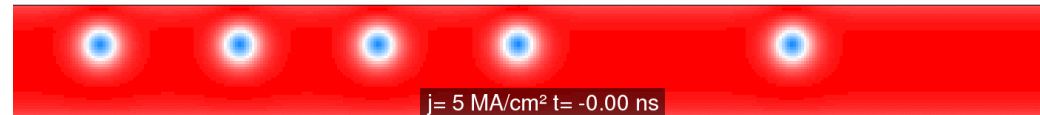
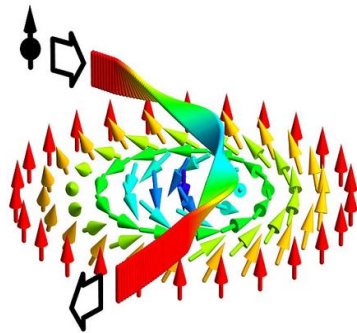
Existence de skymion de taille micrométrique



A. N. Bogdanov & D. A. Yablonskii *Sov. Phys. JETP* **68**, 101 (1989)



## Skyrmion race-track



S. Parkin *et al.*, *Science* **320**, 190 (2008)  
 N. S. Kiselev *et al.*, *J. Phys. D* **44**, 392001 (2011)  
 A. Fert *et al.*, *Nature Nanotech.* **8**, 152 (2013)  
 W. Jiang *et al.*, *Science* **349**, 283 (2015)  
 K. Litzius *et al.*, *Nature Phys.* **13**, 170 (2016)

$$\mathbf{F}_{\sigma k} = e\mathbf{E} + \mathbf{F}_H + q_{\sigma}^e \cdot \mathbf{v}_k \times \mathbf{B}^e$$

$$\mathbf{B}_i^e = \frac{\hbar}{2} \epsilon_{ijk} \mathbf{n} \cdot \left( \frac{\partial \mathbf{n}}{\partial x_j} \times \frac{\partial \mathbf{n}}{\partial x_k} \right)$$

$$\mathbf{E}_i = \hbar \mathbf{n} \cdot \left( \frac{\partial \mathbf{n}}{\partial x_i} \times \frac{\partial \mathbf{n}}{\partial t} \right)$$

T. Schulz *et al.*, *Nature Physics* **8**, 301 (2012)

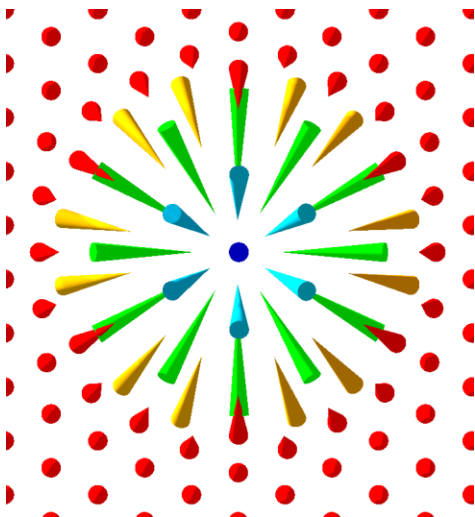
# Définition skyrmion et antiskyrmion

Charge topologique d'un champ de vecteur  $\mathbf{n}(x,y)$ :

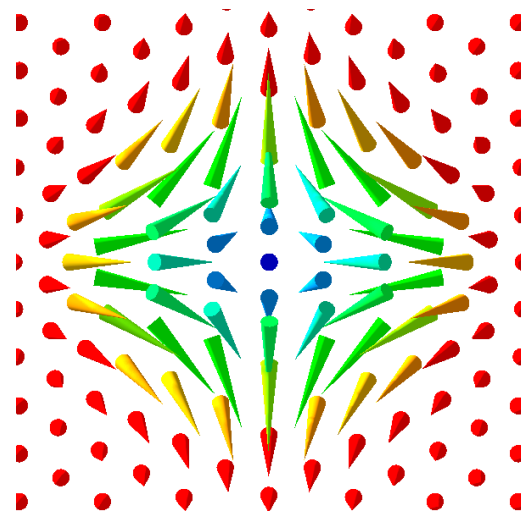
$$S = \frac{1}{4\pi} \int \mathbf{n} \cdot \left( \frac{\partial \mathbf{n}}{\partial x} \times \frac{\partial \mathbf{n}}{\partial y} \right) dx dy$$

État magnétique trivial ( $S=0$ ): Etat collinéaire

Skyrmion ( $S=+1$ )



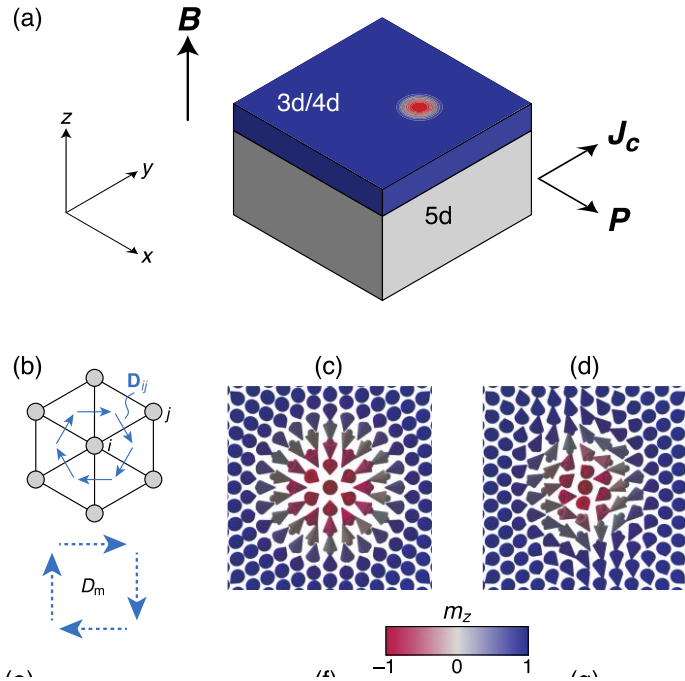
Antiskyrmion ( $S=-1$ )



B. Dupé *et al.*, New J. Phys **18**, 055015 (2016)

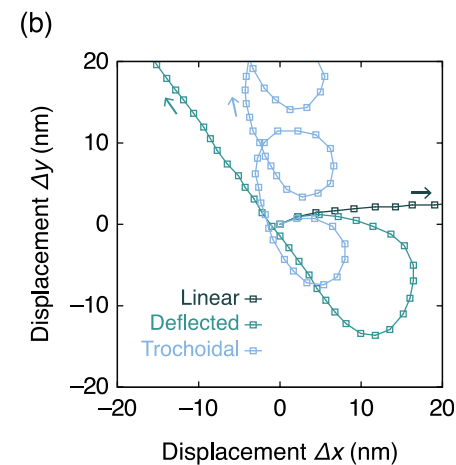
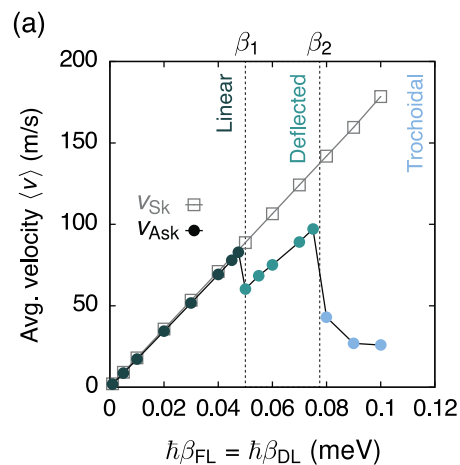
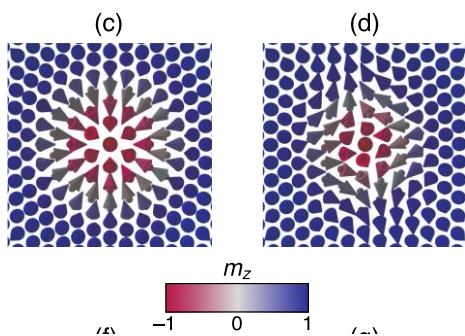
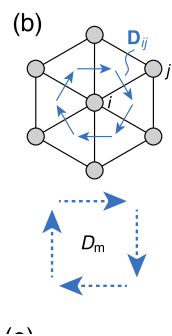
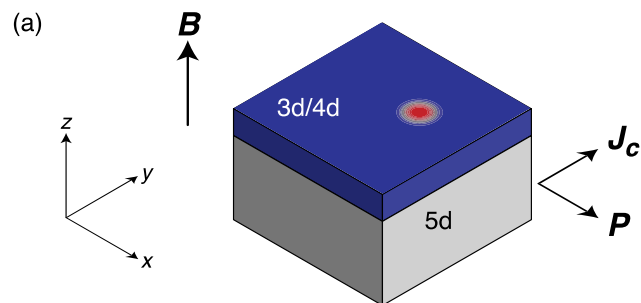
# prédiction de skyrmions en antiskyrmions

U. Ritzmann, BD *et al.*, Nature Electronics 1, 451-457 (2018)



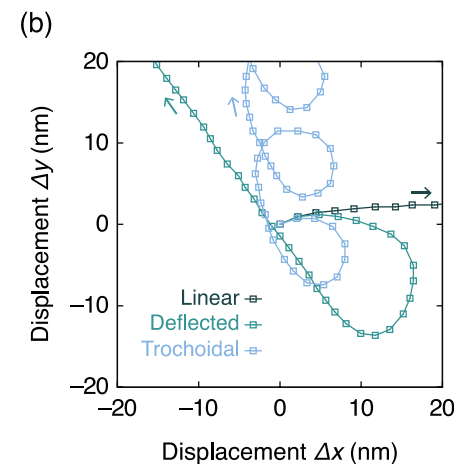
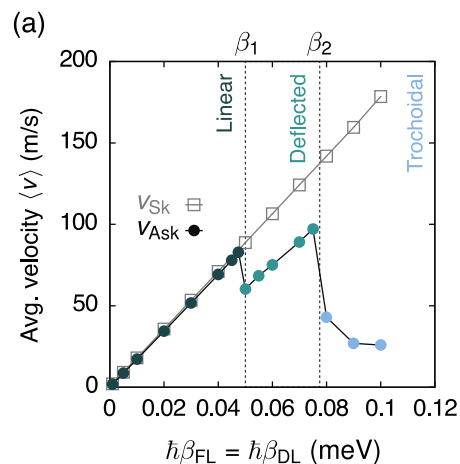
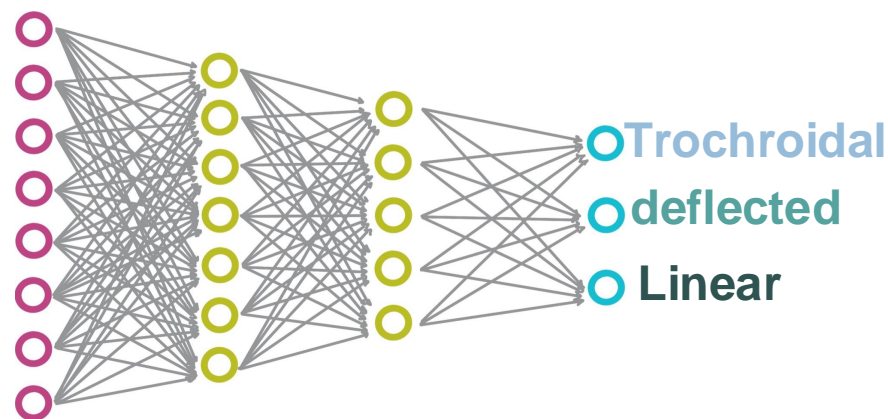
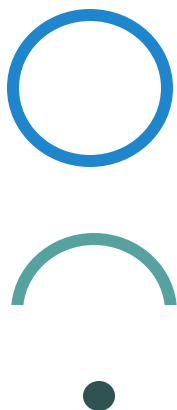
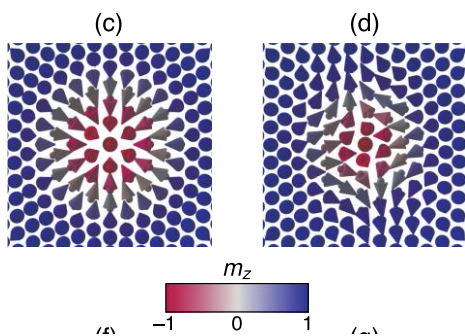
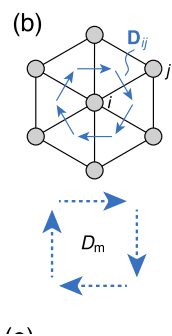
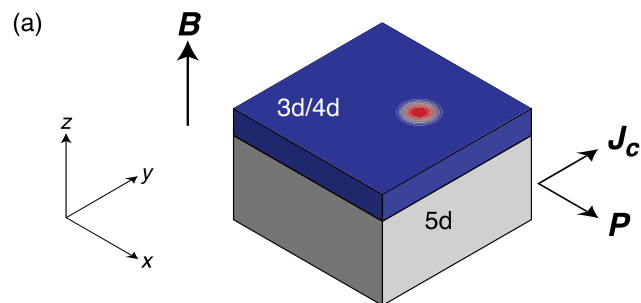
# Dynamique des skyrmions

U. Ritzmann, BD *et al.*, Nature Electronics 1, 451-457 (2018)



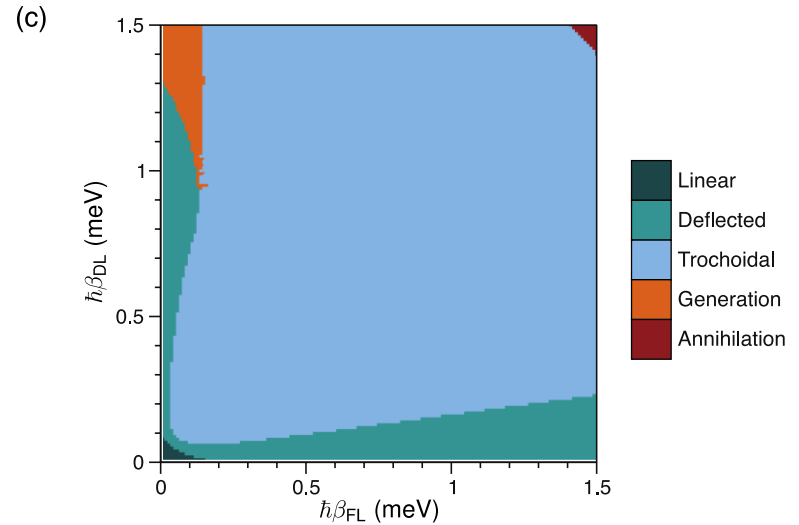
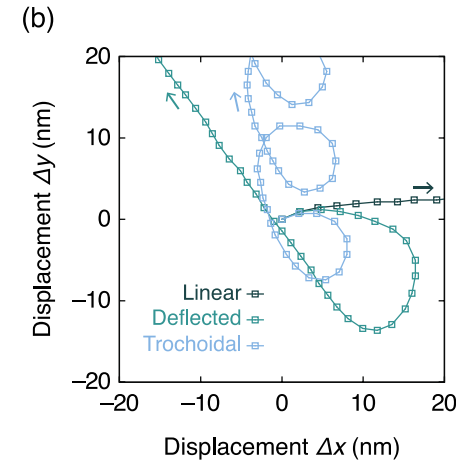
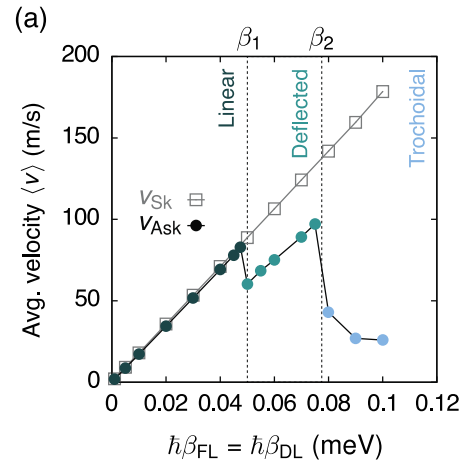
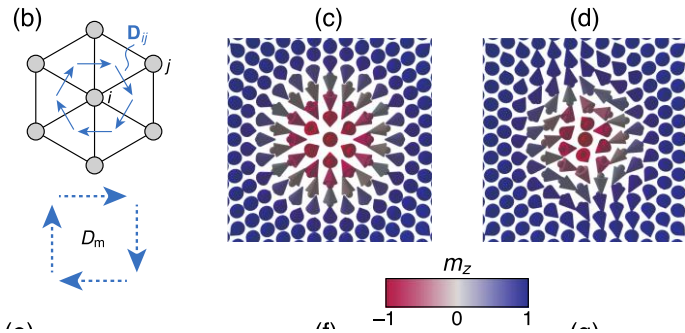
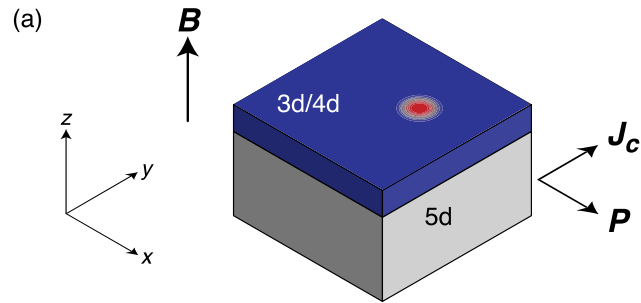
# Dynamique des skyrmions

U. Ritzmann, BD *et al.*, Nature Electronics 1, 451-457 (2018)



# Digramme de phase

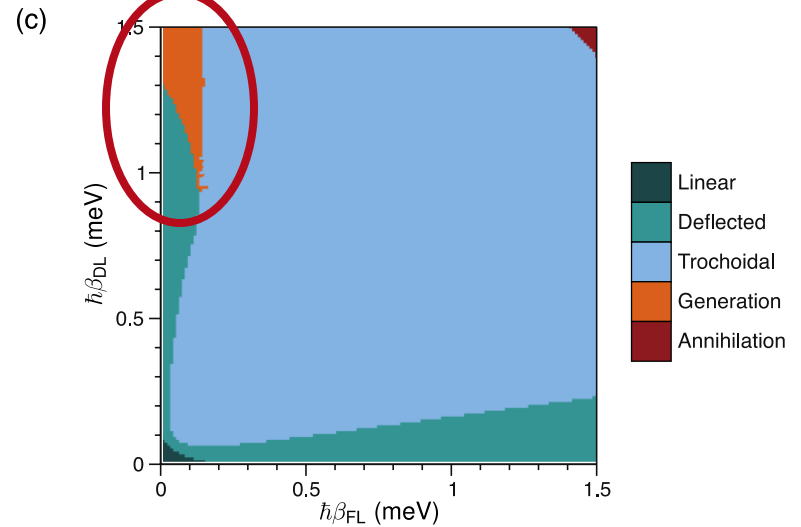
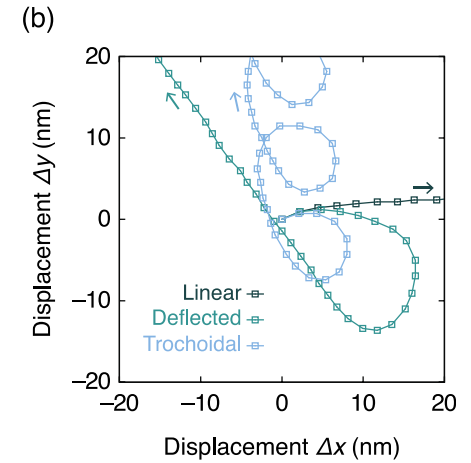
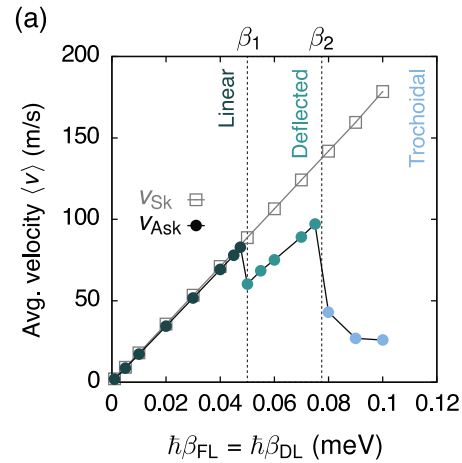
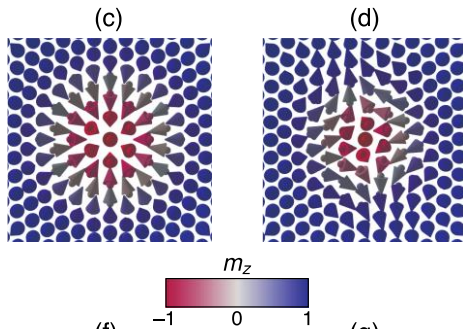
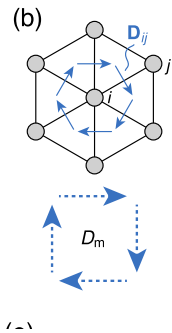
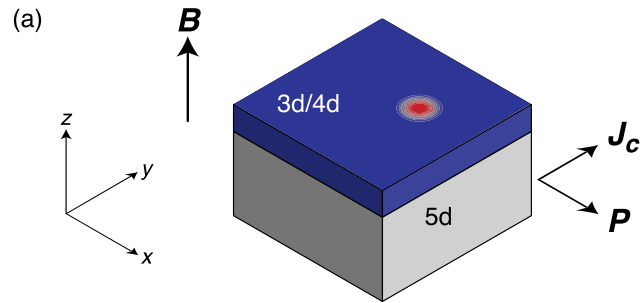
U. Ritzmann, BD *et al.*, Nature Electronics 1, 451-457 (2018)





# Digramme de phase

U. Ritzmann, BD *et al.*, Nature Electronics 1, 451-457 (2018)



# Auto-génération de skyrmions

U. Ritzmann, BD *et al.*, Nature Electronics **1**, 451-457 (2018)



Analogie avec la Bariogénèse: brisure de symétrie entre skyrmion and antiskyrmion

U. Ritzmann, BD *et al.*, Phys. Rev. B **102**, 174409 (2020)

# Conclusion

- L'AI et les NNs sont un outil pour l'analyse de données
- Les NNs sont paramétrables et versatiles
- L'AI consomme beaucoup d'électricité – à utiliser avec parcimonie

