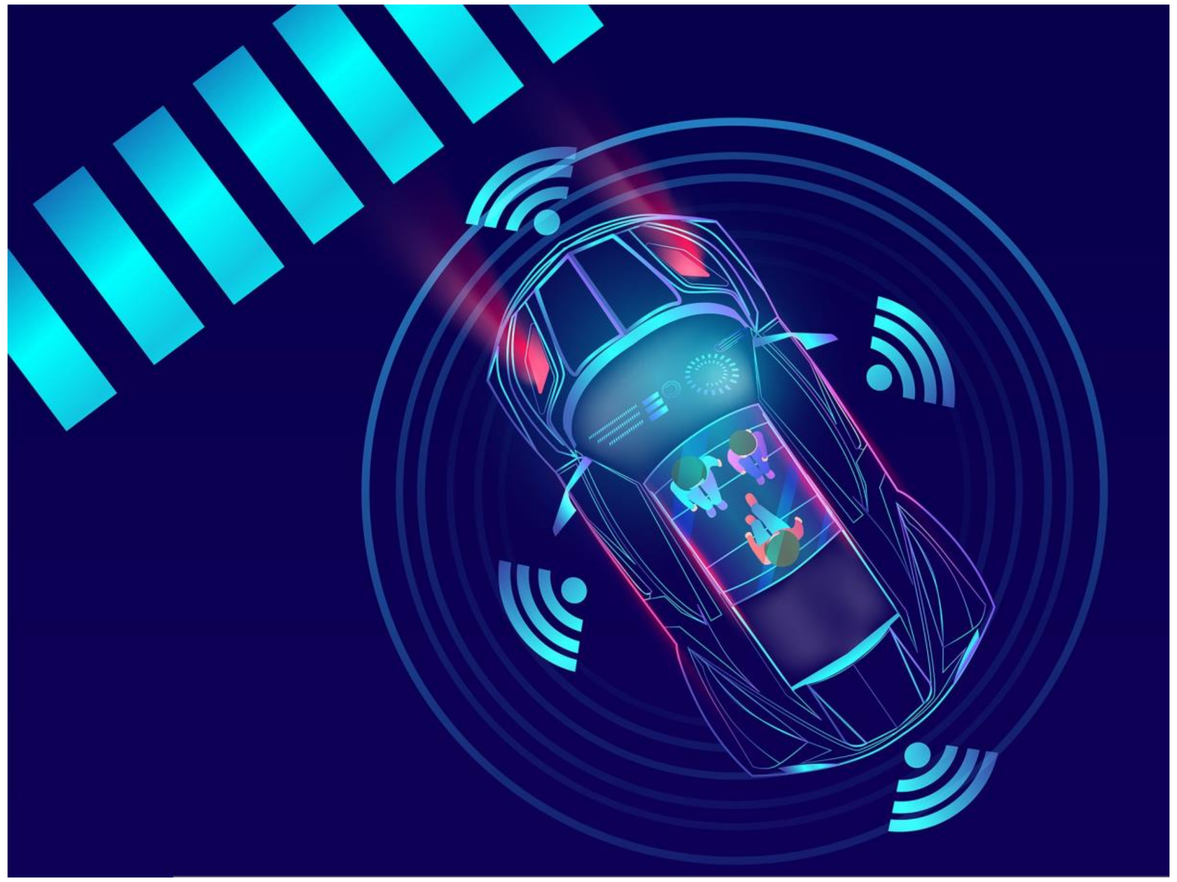
November 20th, 2025

MaxiMals: A Low-cost Hardening Technique for Large Vision Transformers

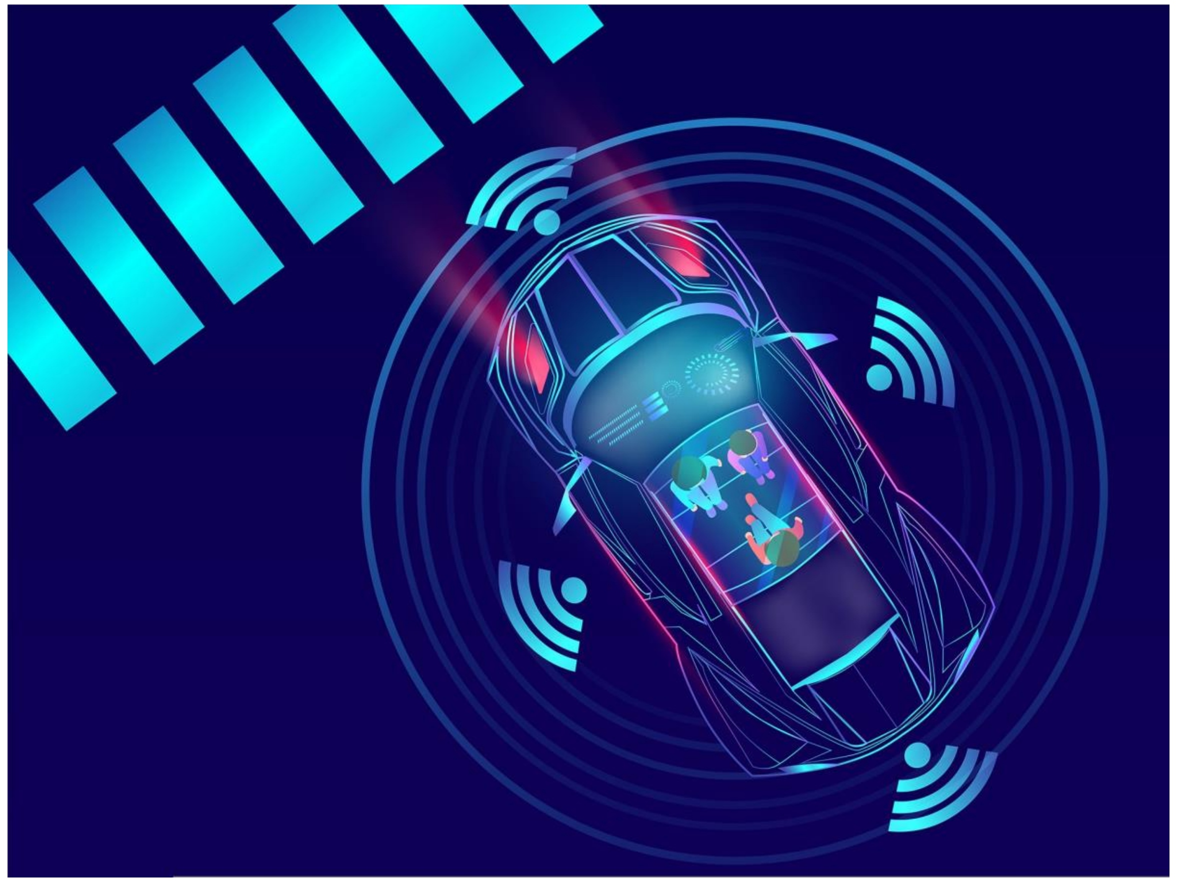
Lucas Roquet, Fernando Fernandes dos Santos, Paolo Rech, Marcello Traiola, Olivier Sentieys, and Angeliki Kritikakou

Machine Learning (ML) is Everywhere



- ML models are very **complex** and very **accurate**
- They can be applied to a wide range of applications

Machine Learning (ML) is Everywhere



ML models are included in Safety-critical Applications

Transformer Models

Transformer Models

- Transformers, state-of-the-art of ML

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  - Highly accurate

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Transformer Models

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  - … computer vision (ViTs)

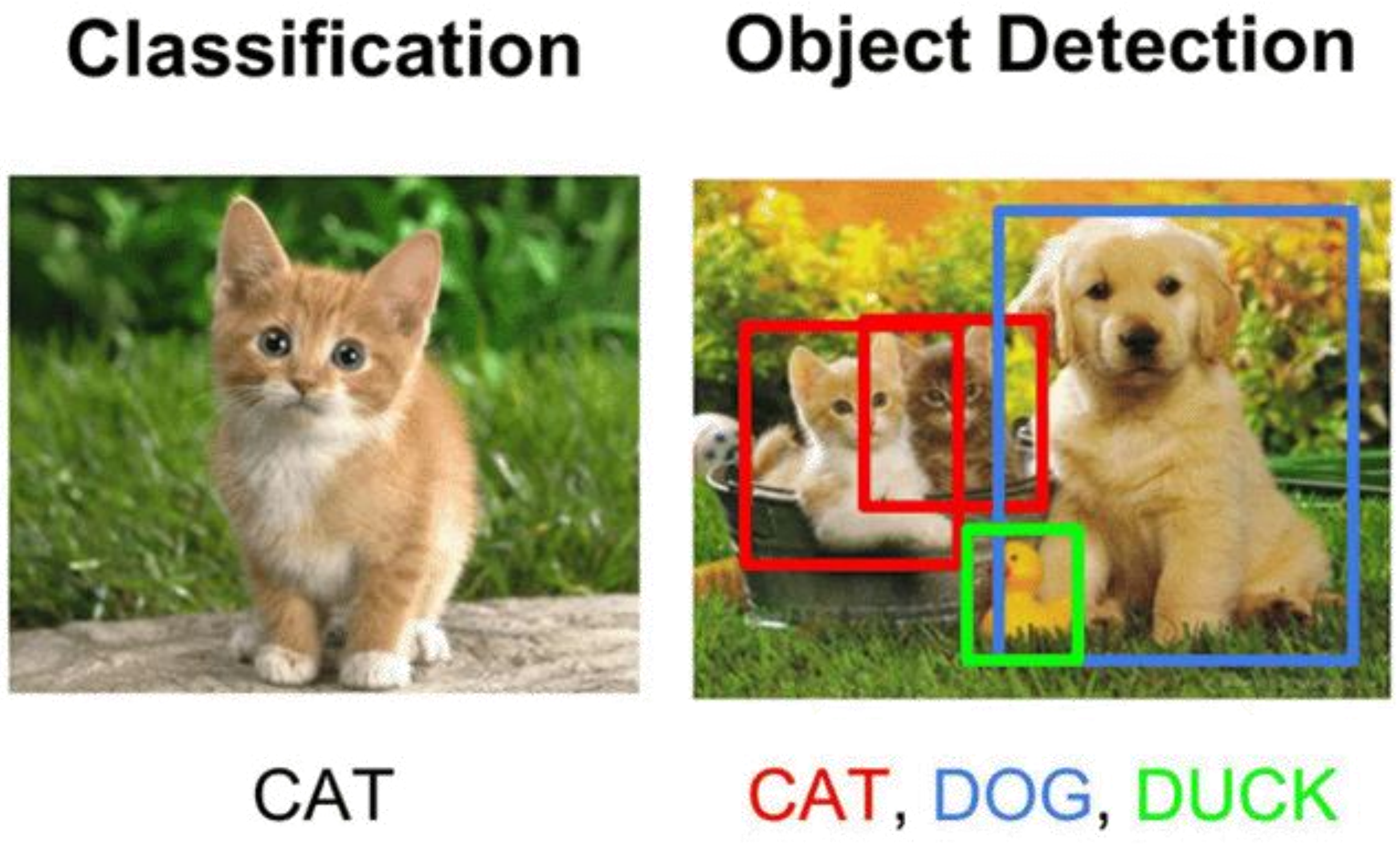
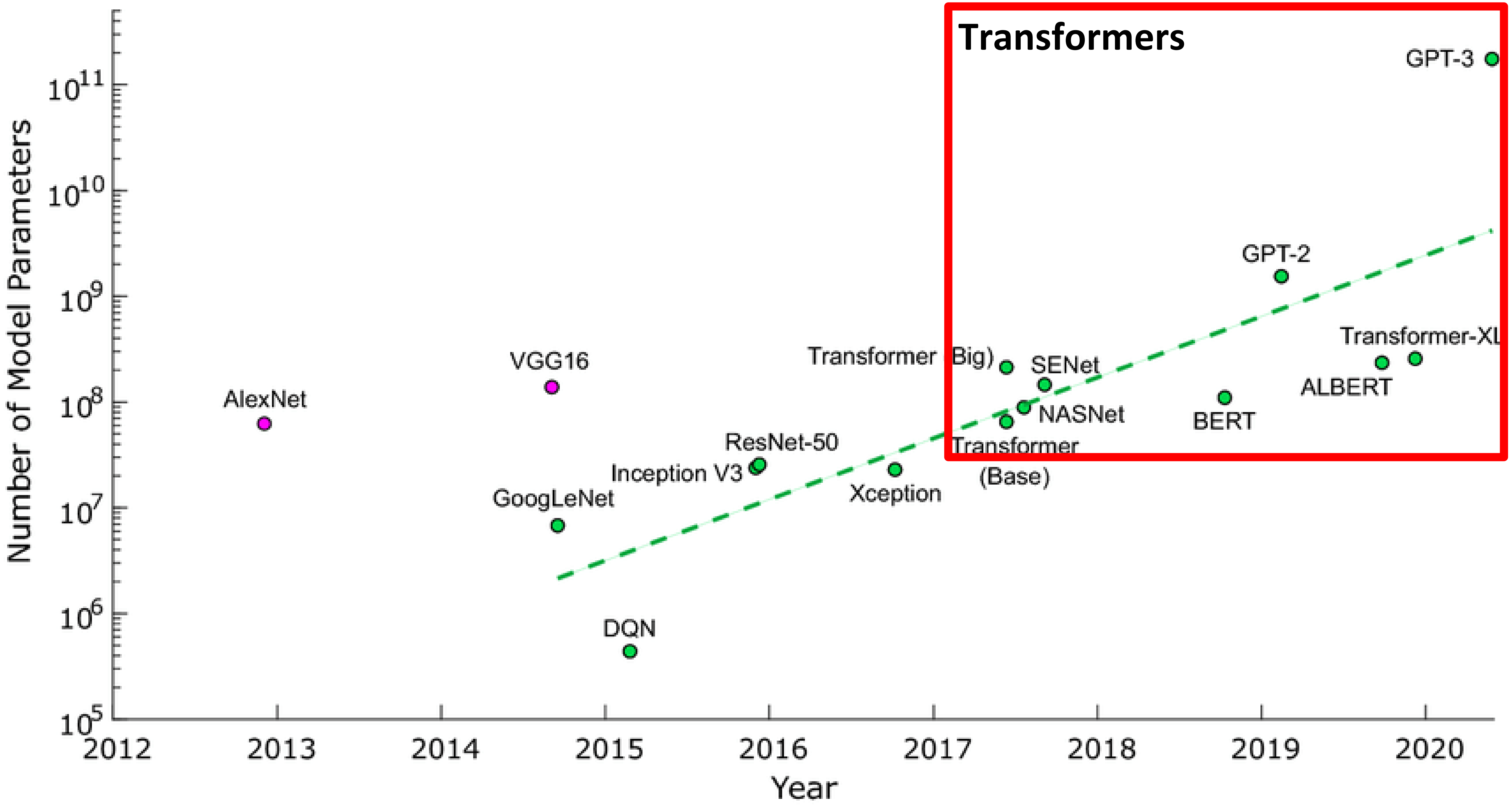


Image Segmentation

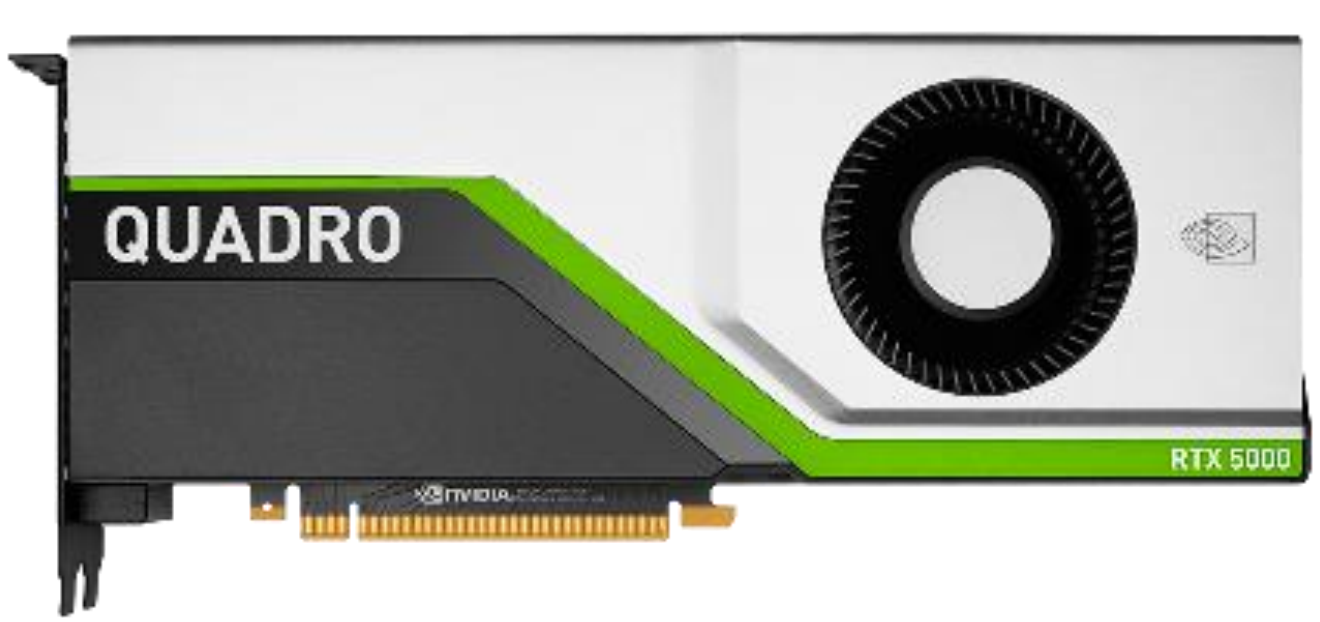
Transformer Models

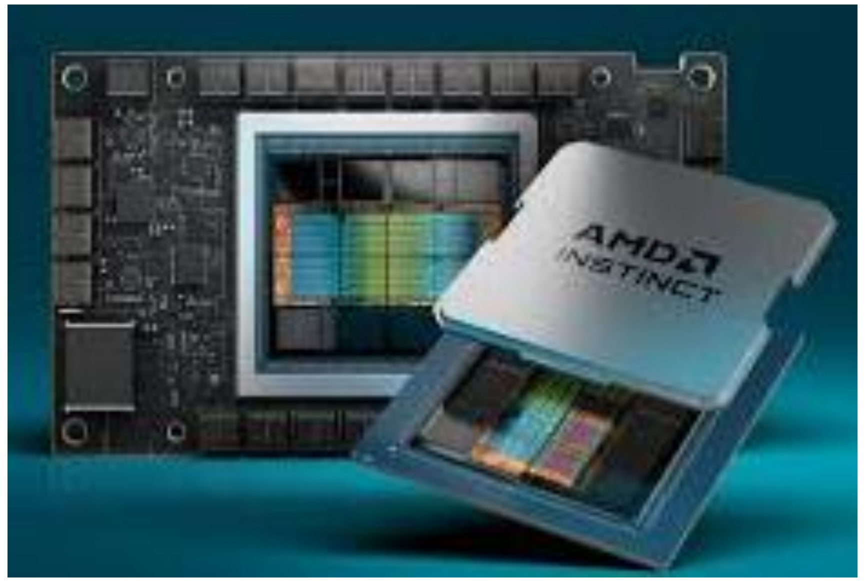


Evolution of the number of parameters of ML models[1]

[1] L. Bernstein *et al.* – Nature 2021

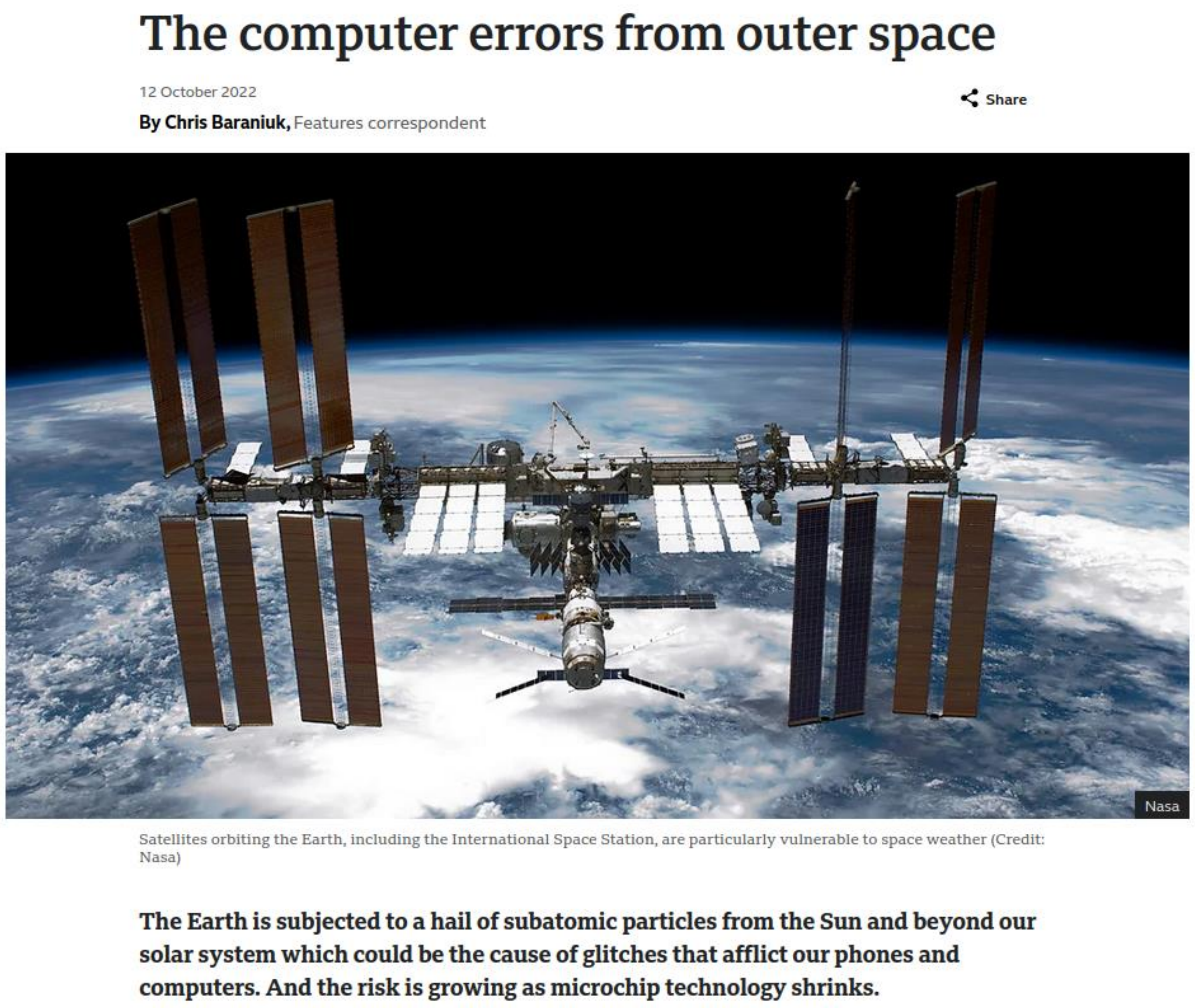
Transformer Models





They need large hardware accelerators

Vulnerability Sources



The computer errors from outer space

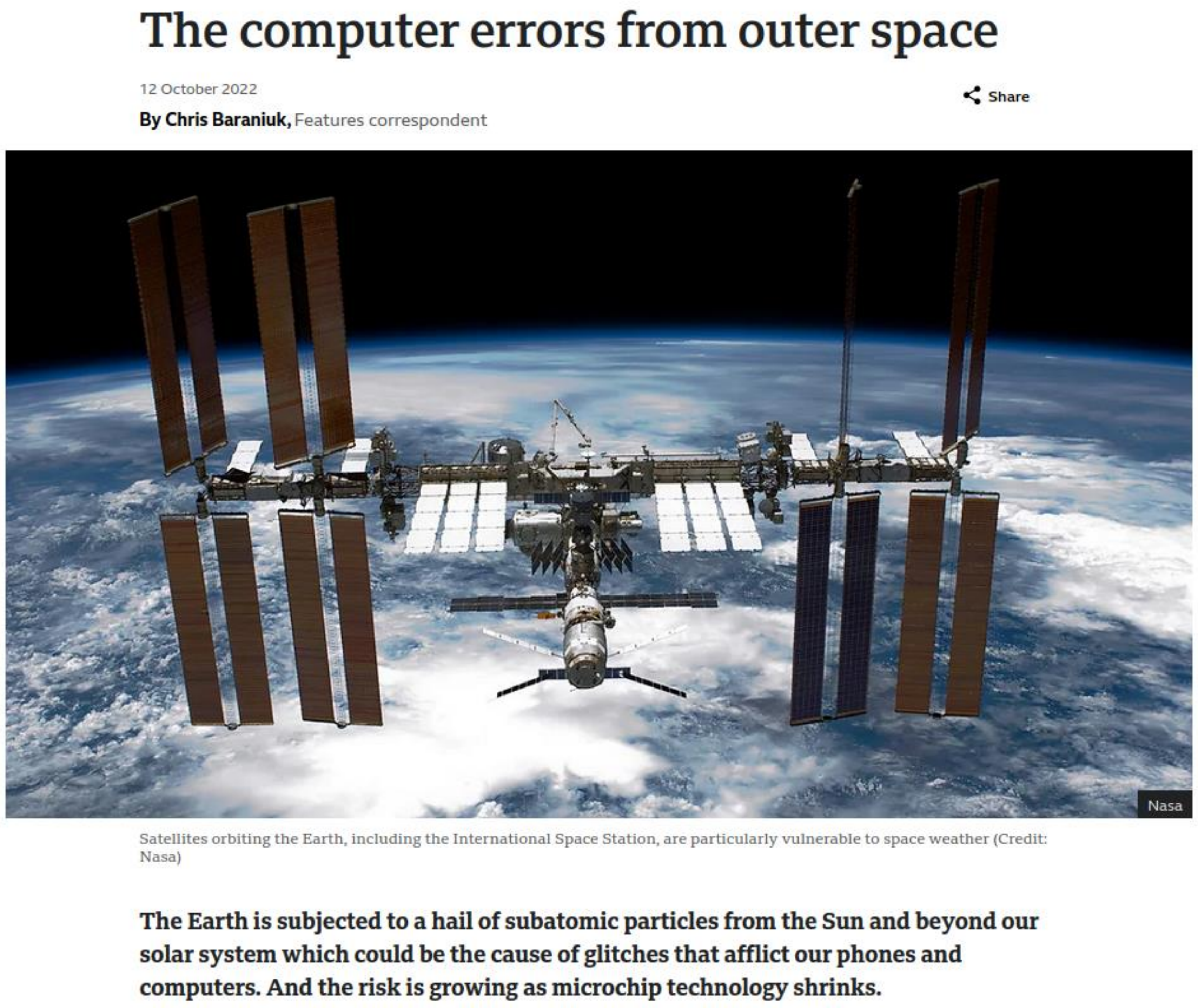
12 October 2022

By Chris Baraniuk, Features correspondent

Satellites orbiting the Earth, including the International Space Station, are particularly vulnerable to space weather (Credit: Nasa)

The Earth is subjected to a hail of subatomic particles from the Sun and beyond our solar system which could be the cause of glitches that afflict our phones and computers. And the risk is growing as microchip technology shrinks.

Vulnerability Sources



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☢ Neutrons, Protons, Heavy-ions, etc.

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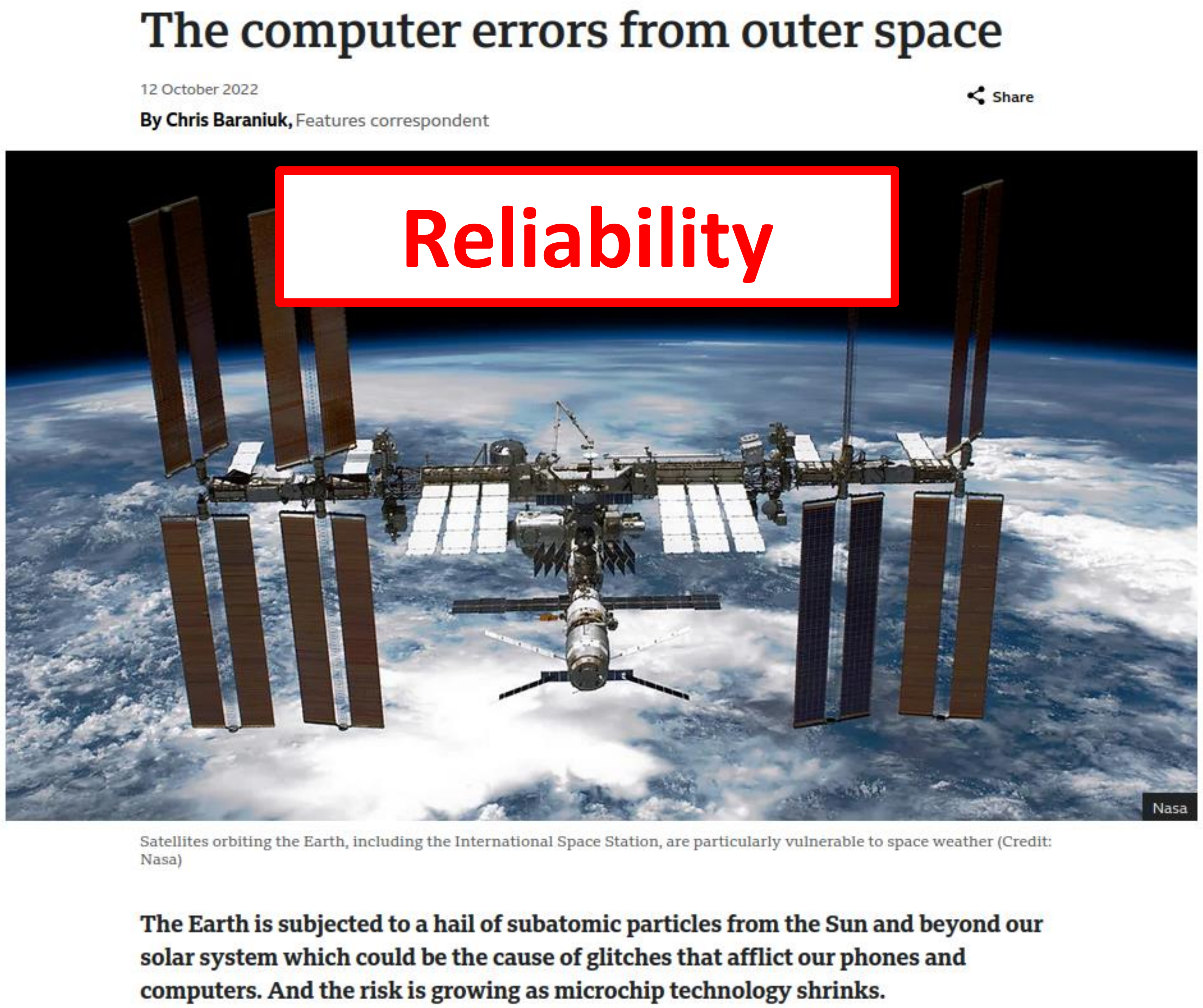

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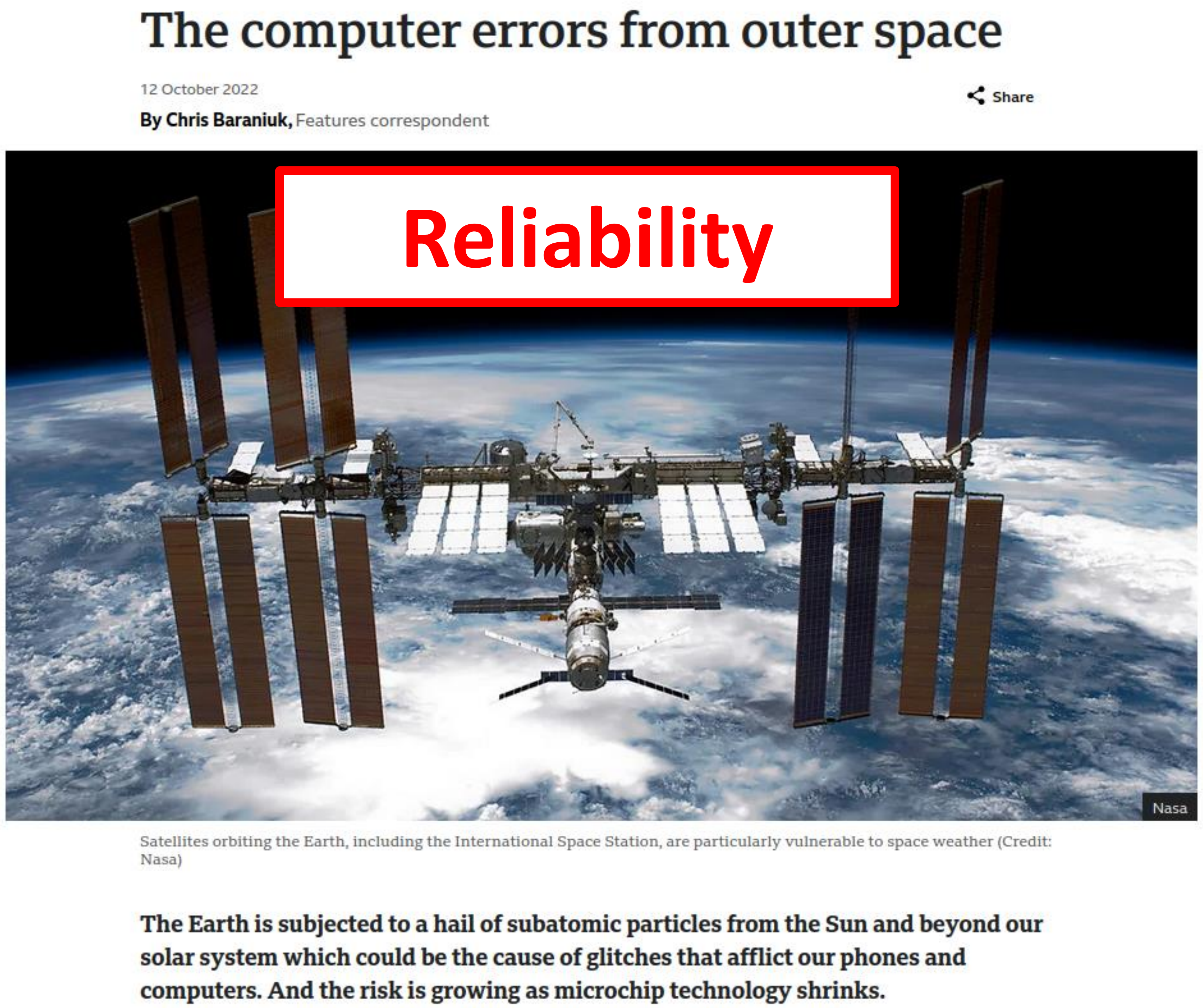

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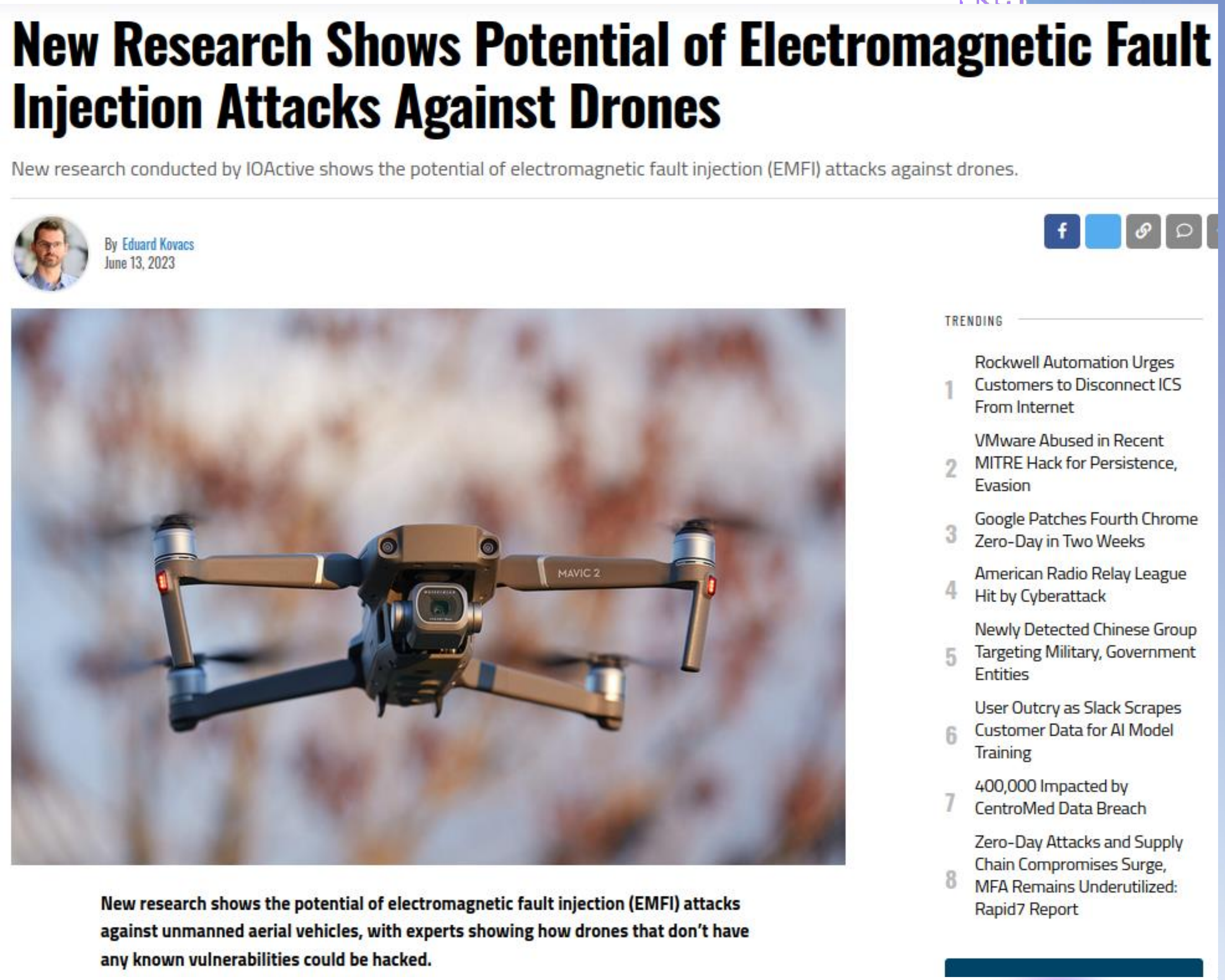

New Research Shows Potential of Electromagnetic Fault Injection Attacks Against Drones

New research conducted by IOActive shows the potential of electromagnetic fault injection (EMFI) attacks against drones.

By Eduard Kovacs
June 13, 2023

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European Cyber Week

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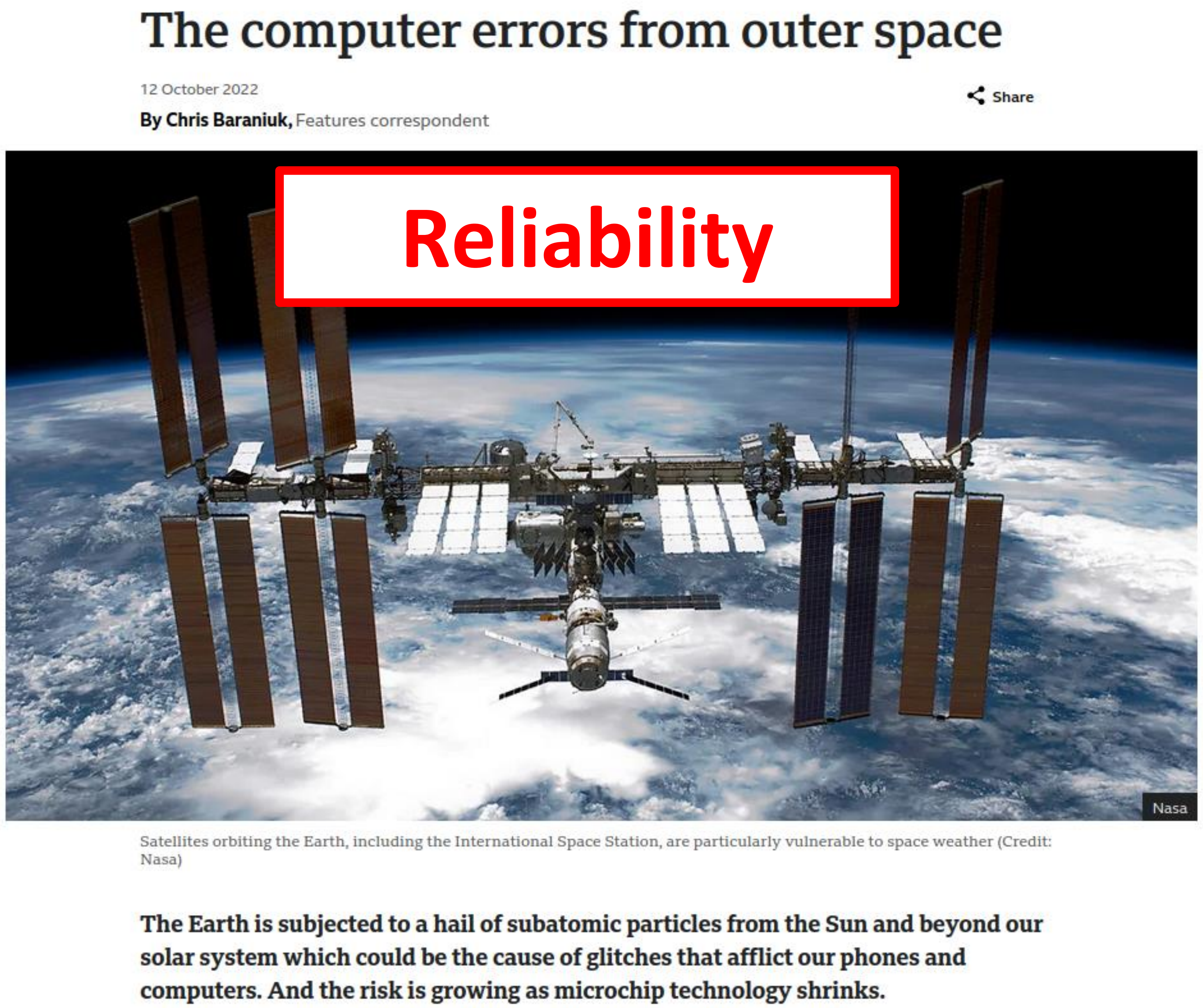

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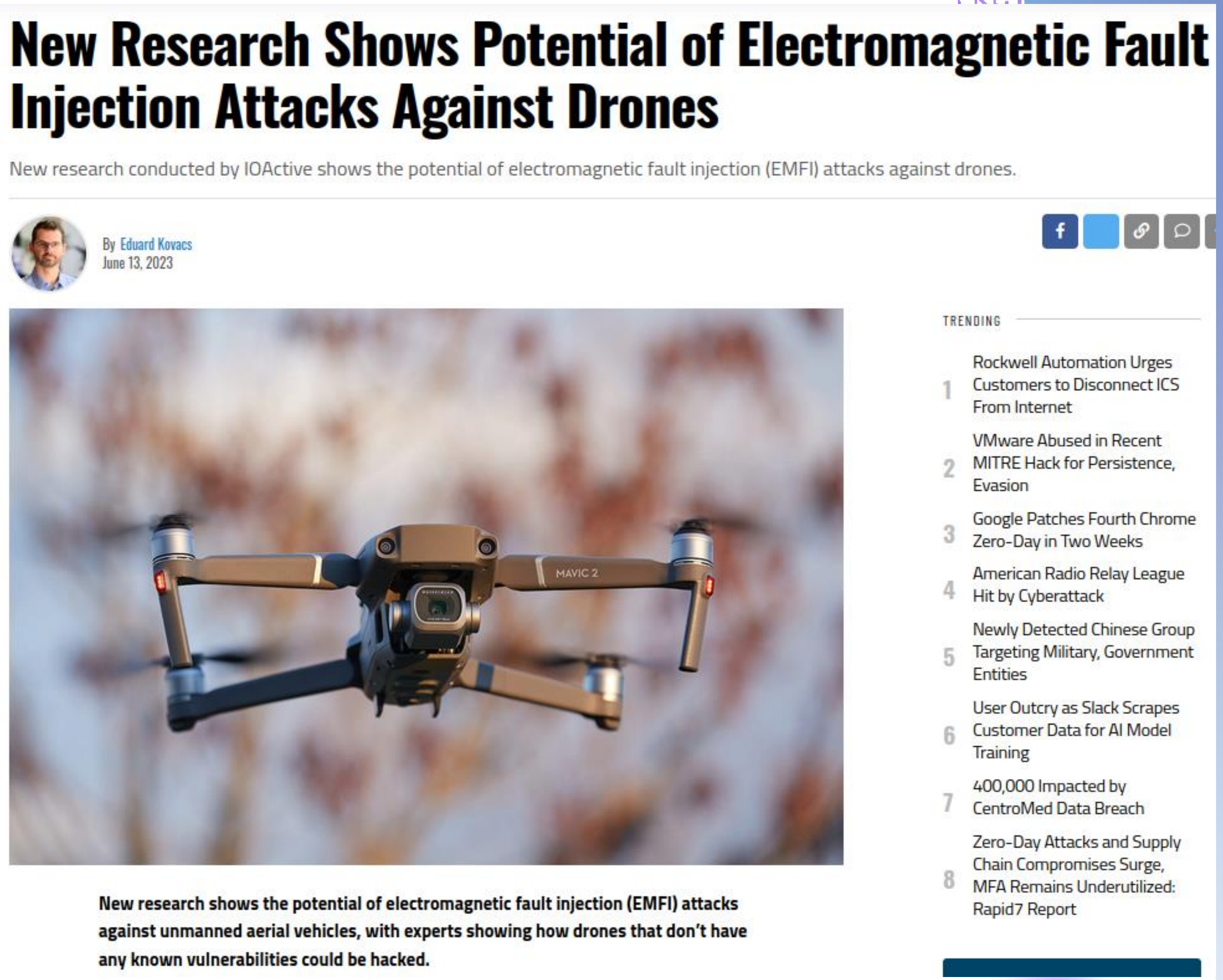

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Electromagnetic FI, laser FI, SCAs, etc.

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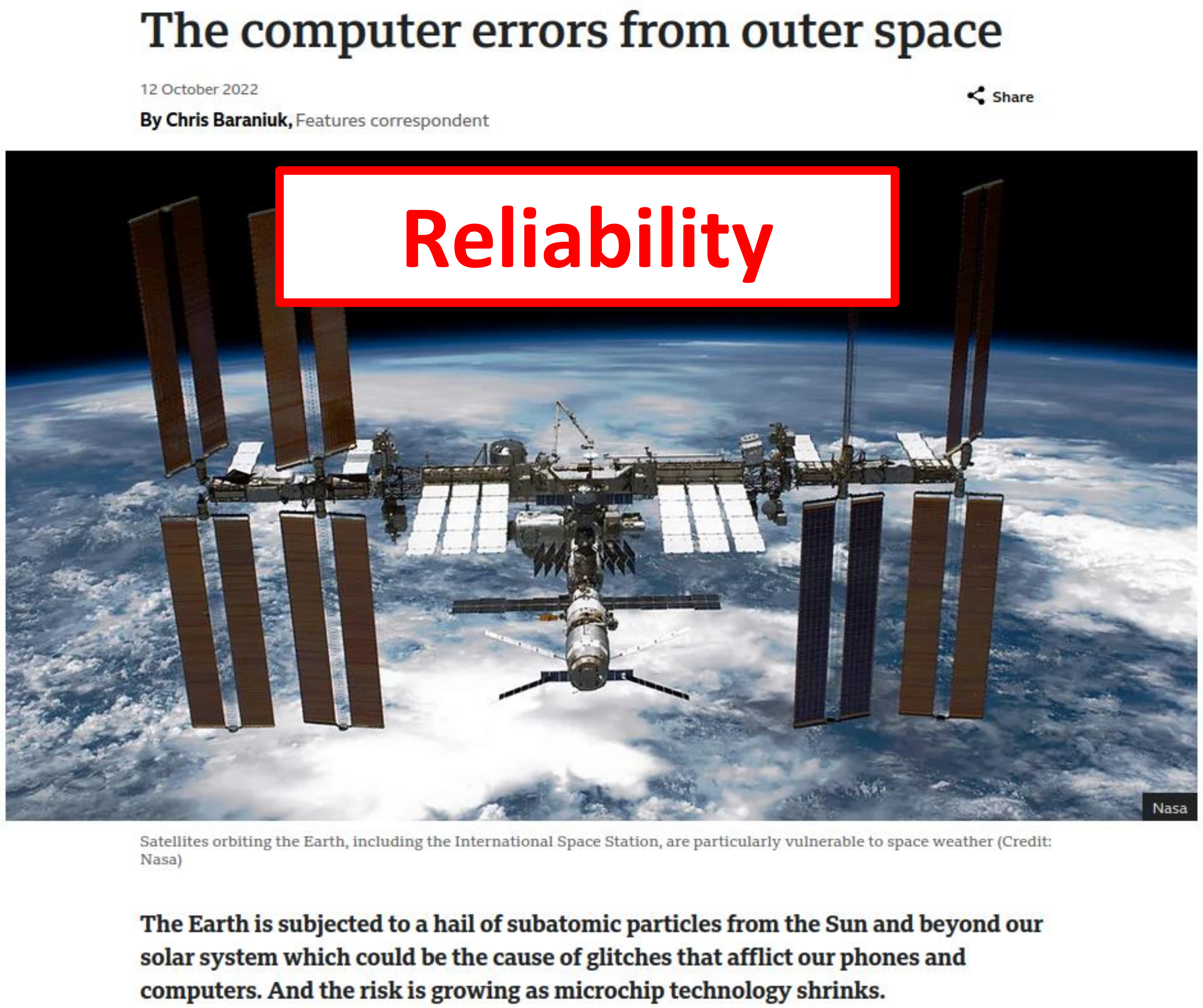

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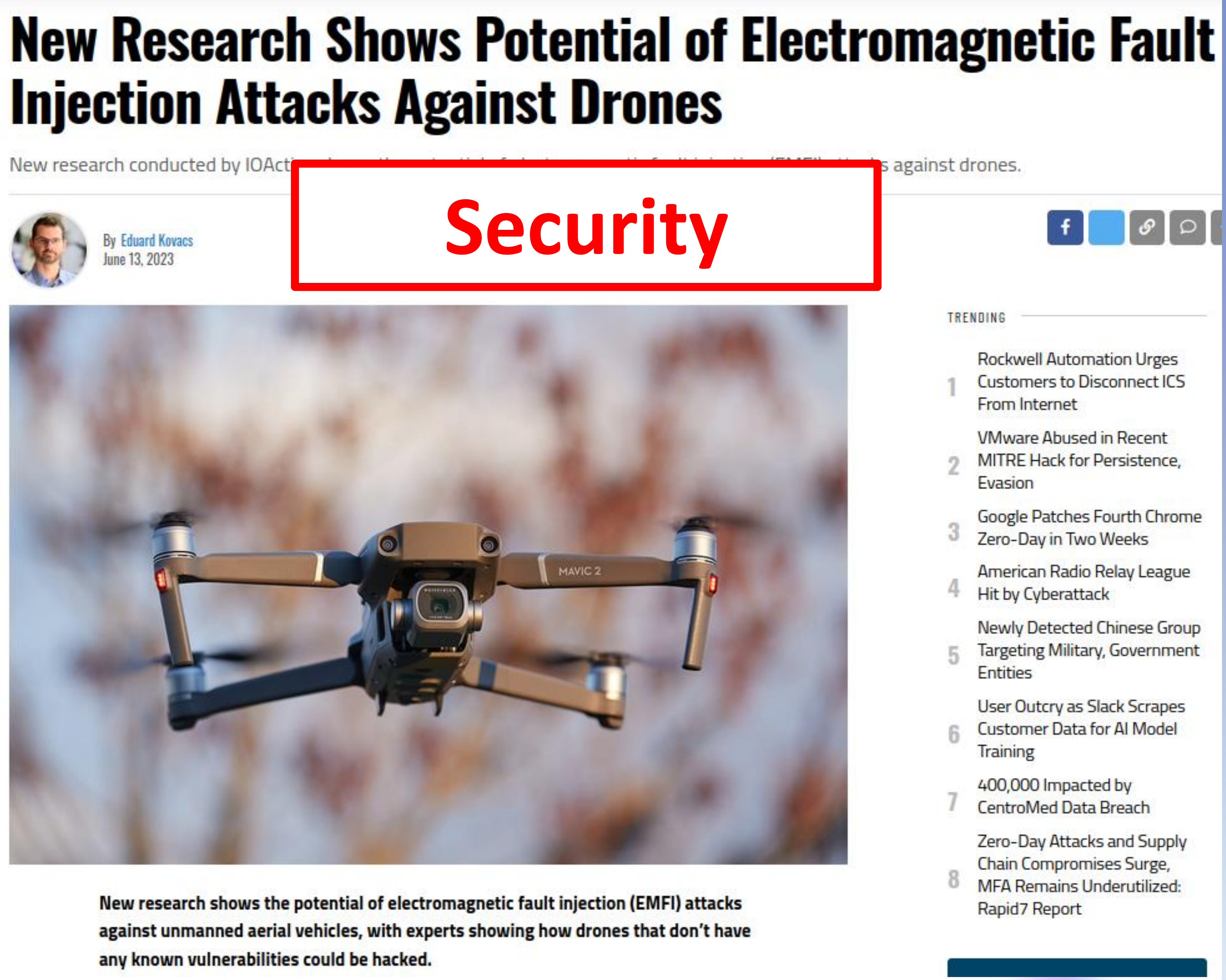

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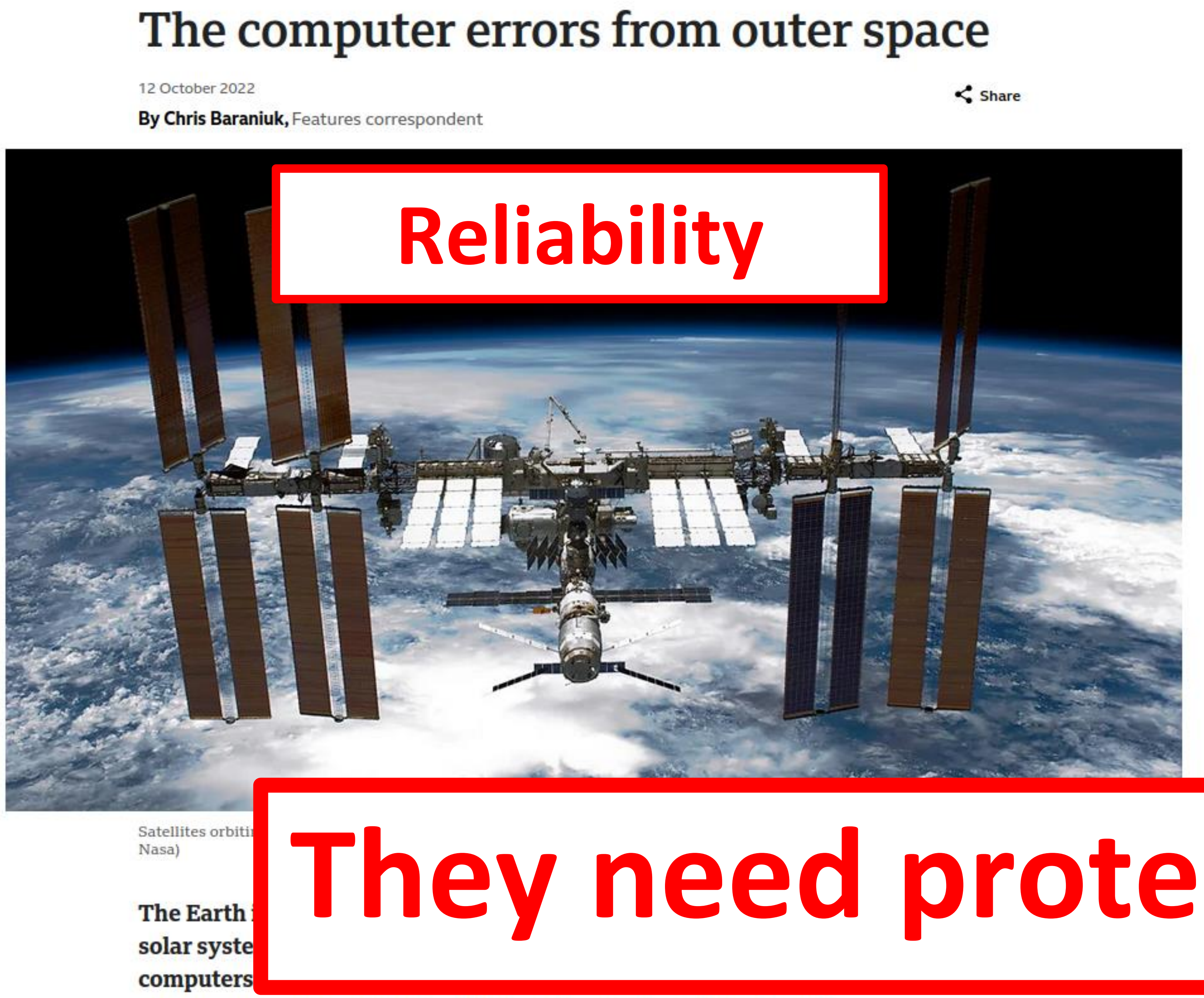

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The Earth i
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any known vulnerabilities could be hacked.

Security

They need protection mechanisms

Neutrons, Protons, Heavy-ions, etc.

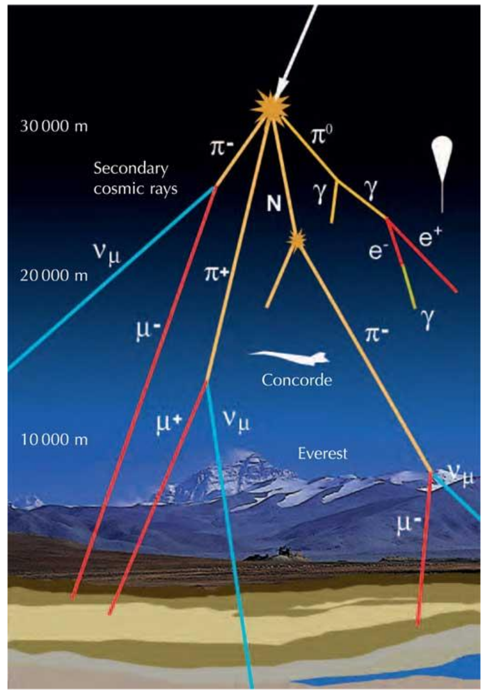
Electromagnetic FI, laser FI, SCAs, etc.

Agenda

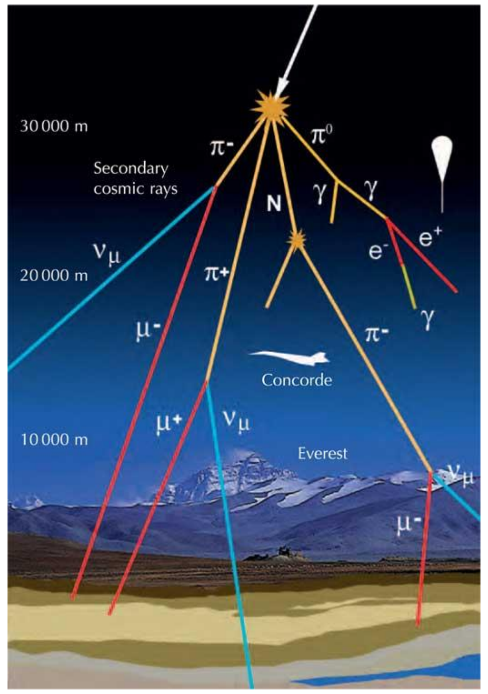
- Radiation Effects on ML
- ViT Reliability Characterization
- Efficient Fault Tolerance
- Conclusions and Future Directions

Radiation Effects on ML

Radiation Impact on GPUs



Radiation Impact on GPUs



Ionizing particle

Memories

0 1 0 0 0 1 0 0 1 0 1 0 0 0 1 1
0 1 1 1 0 1 0 0 1 0 1 0 1 0 0 0
1 0 0 1 1 0 1 0 1 0 1 0 0 0 1 1
0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 0

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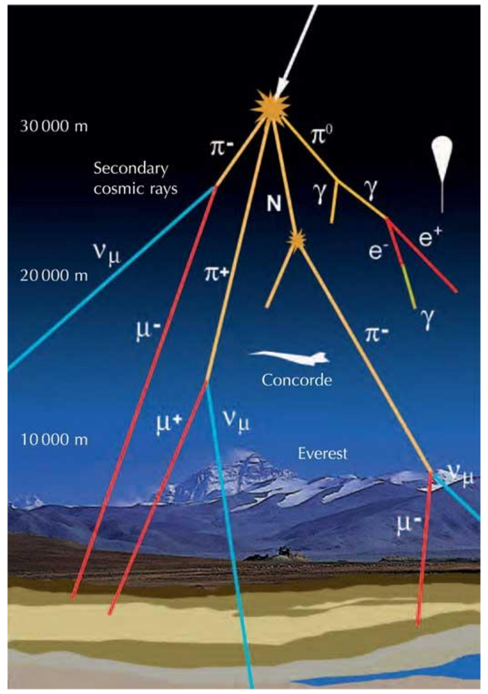

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0 1 1 1 0 1 0 0 1 0 1 0 1 0 0 0
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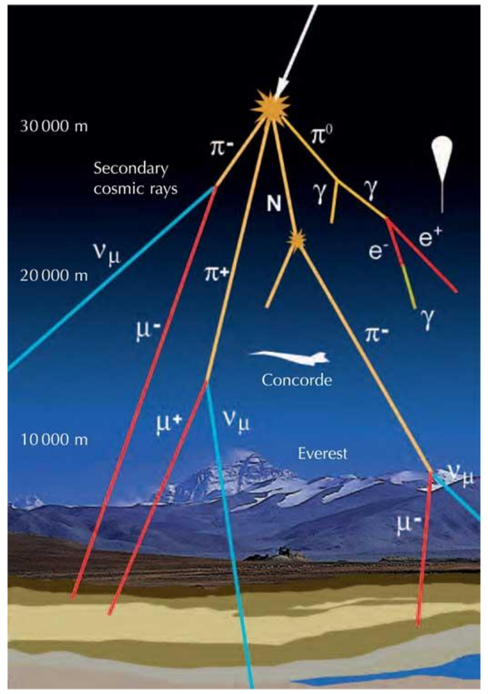
0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 0

Logic

1 + 1 = 3

Radiation Impact on GPUs



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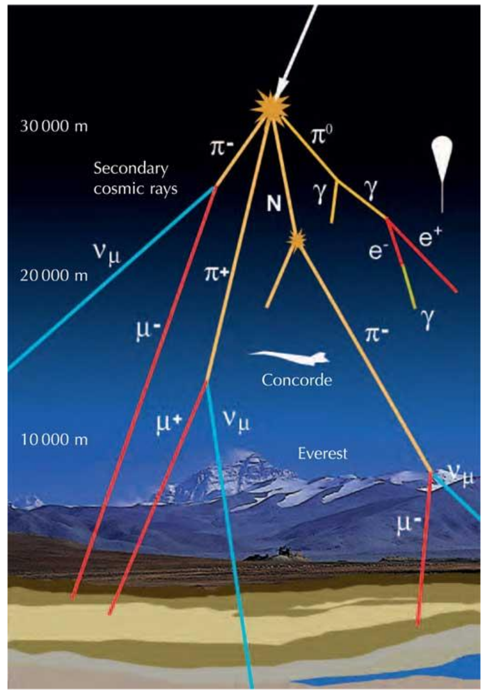

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0 1 1 1 0 1 0 0 1 0 1 0 1 0 0 0
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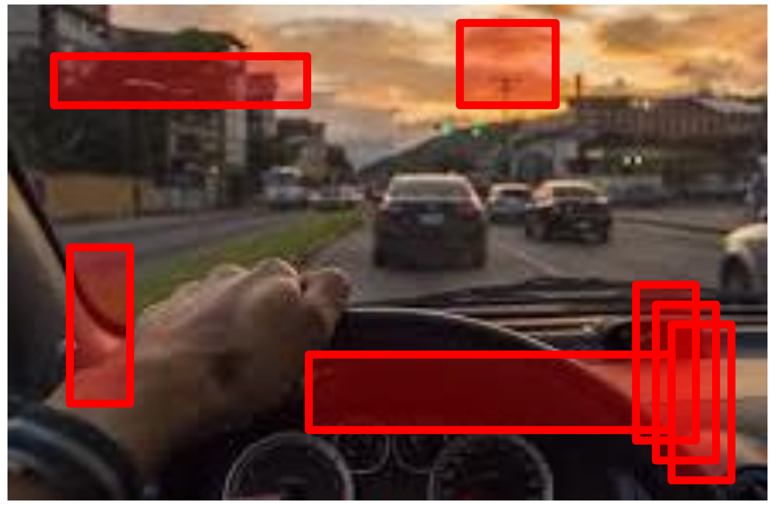
Silent Data Corruption (SDC)

- Computation is done but result is altered



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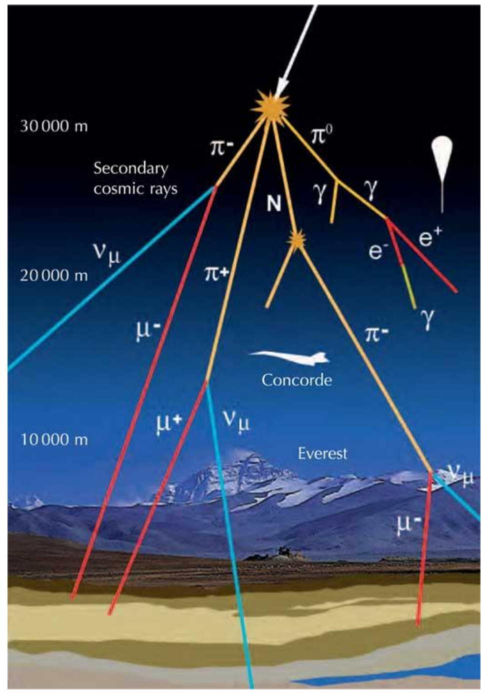

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0 1 0 0 0 1 0 0 1 0 1 0 0 0 1 1
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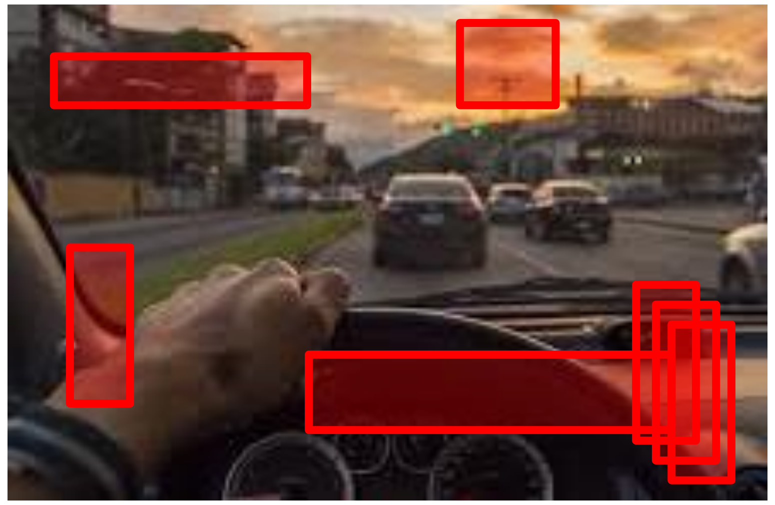
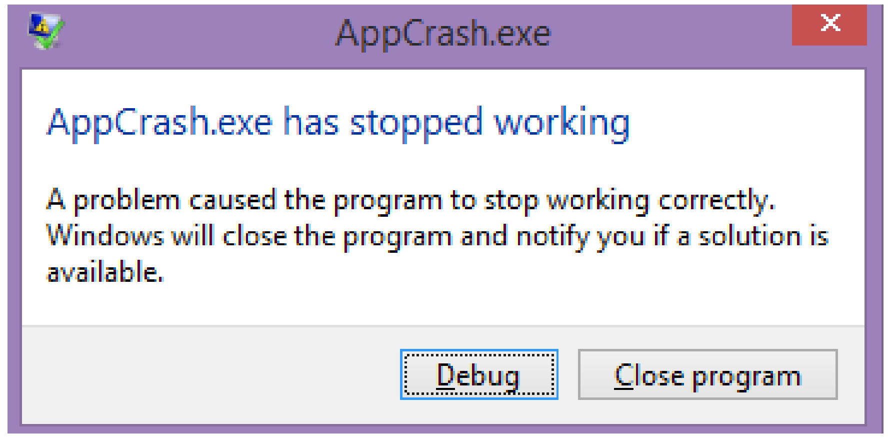


Data Unrecoverable Error (DUE)

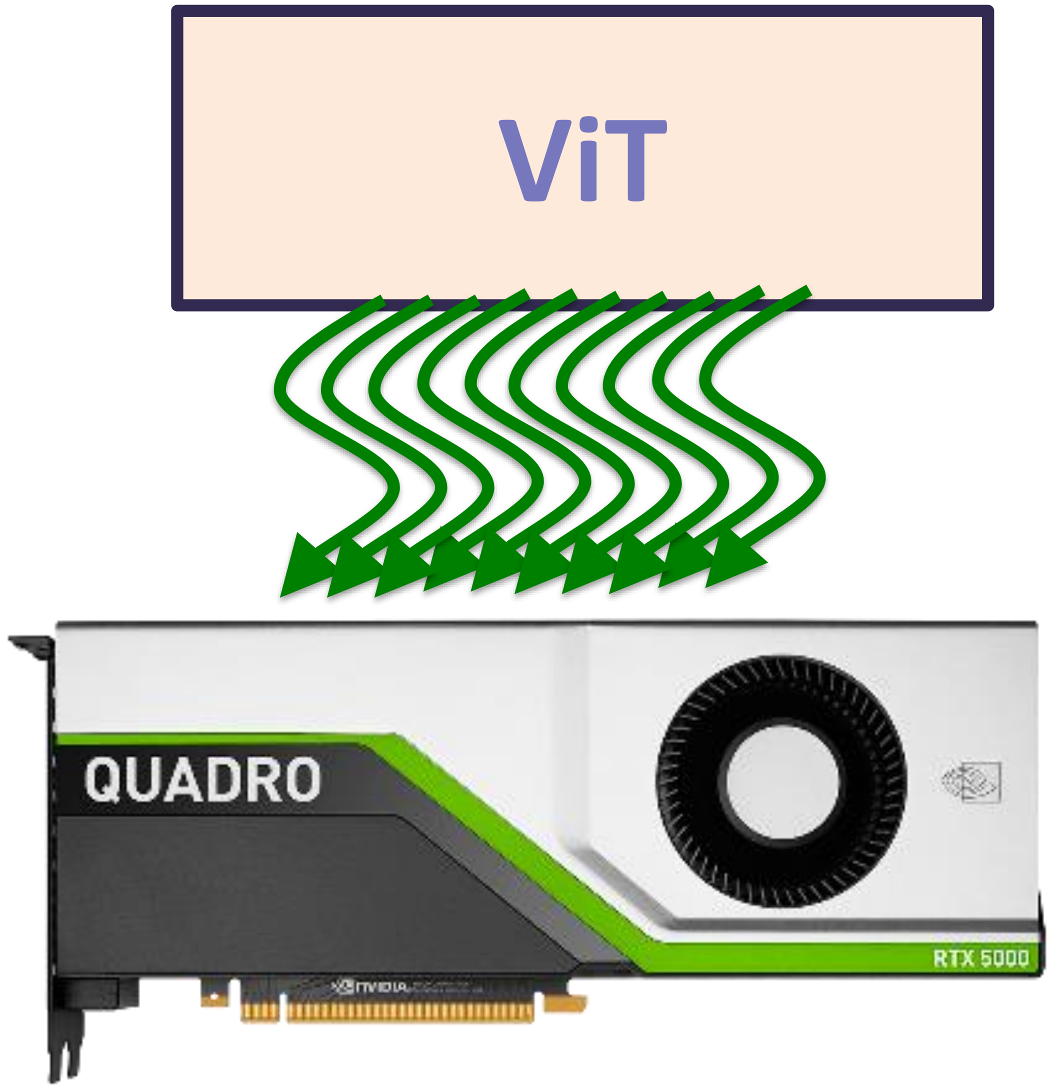
- Crash and OS hangs



AppCrash.exe has stopped working

A problem caused the program to stop working correctly. Windows will close the program and notify you if a solution is available.

ViT SDC Types



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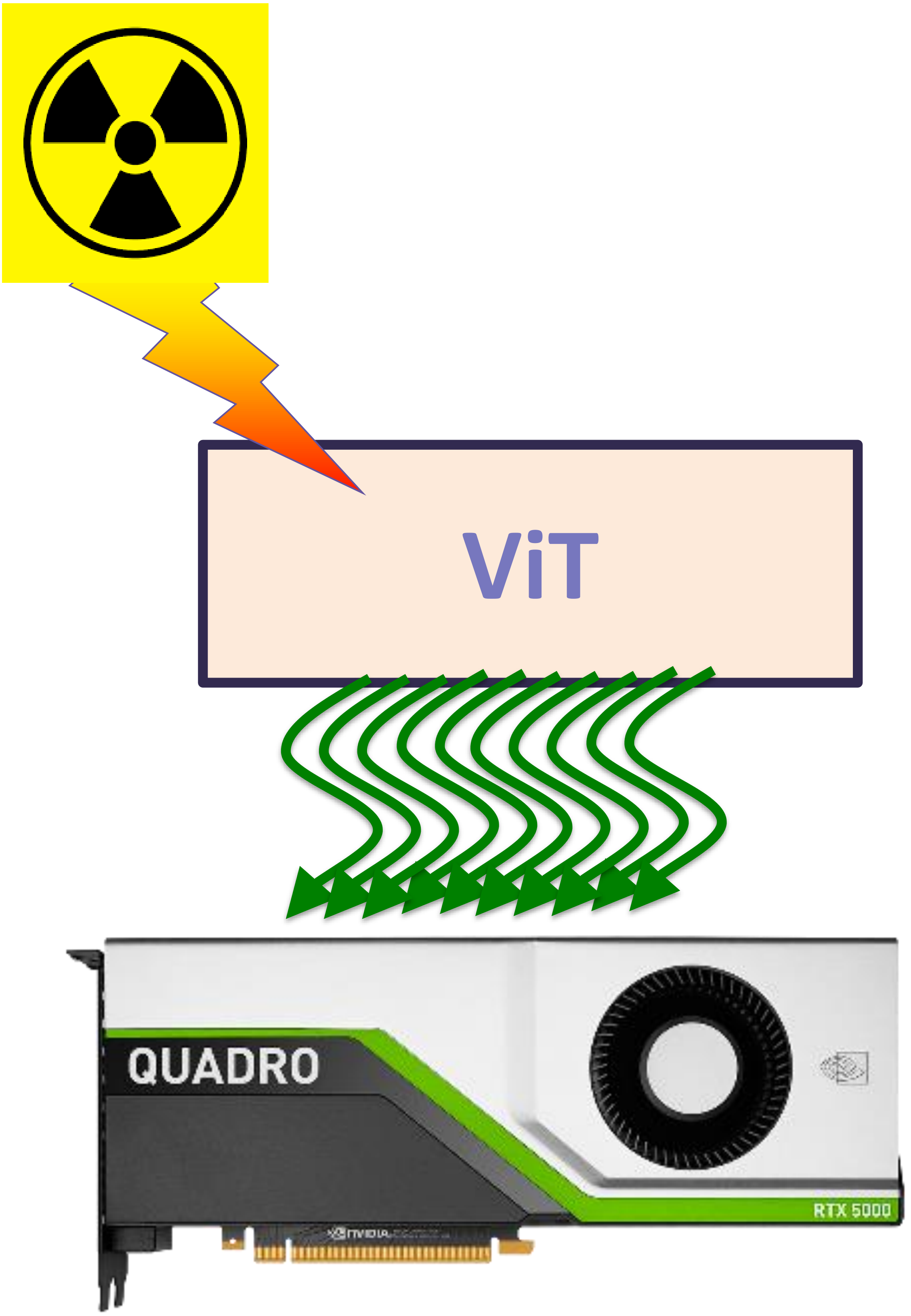

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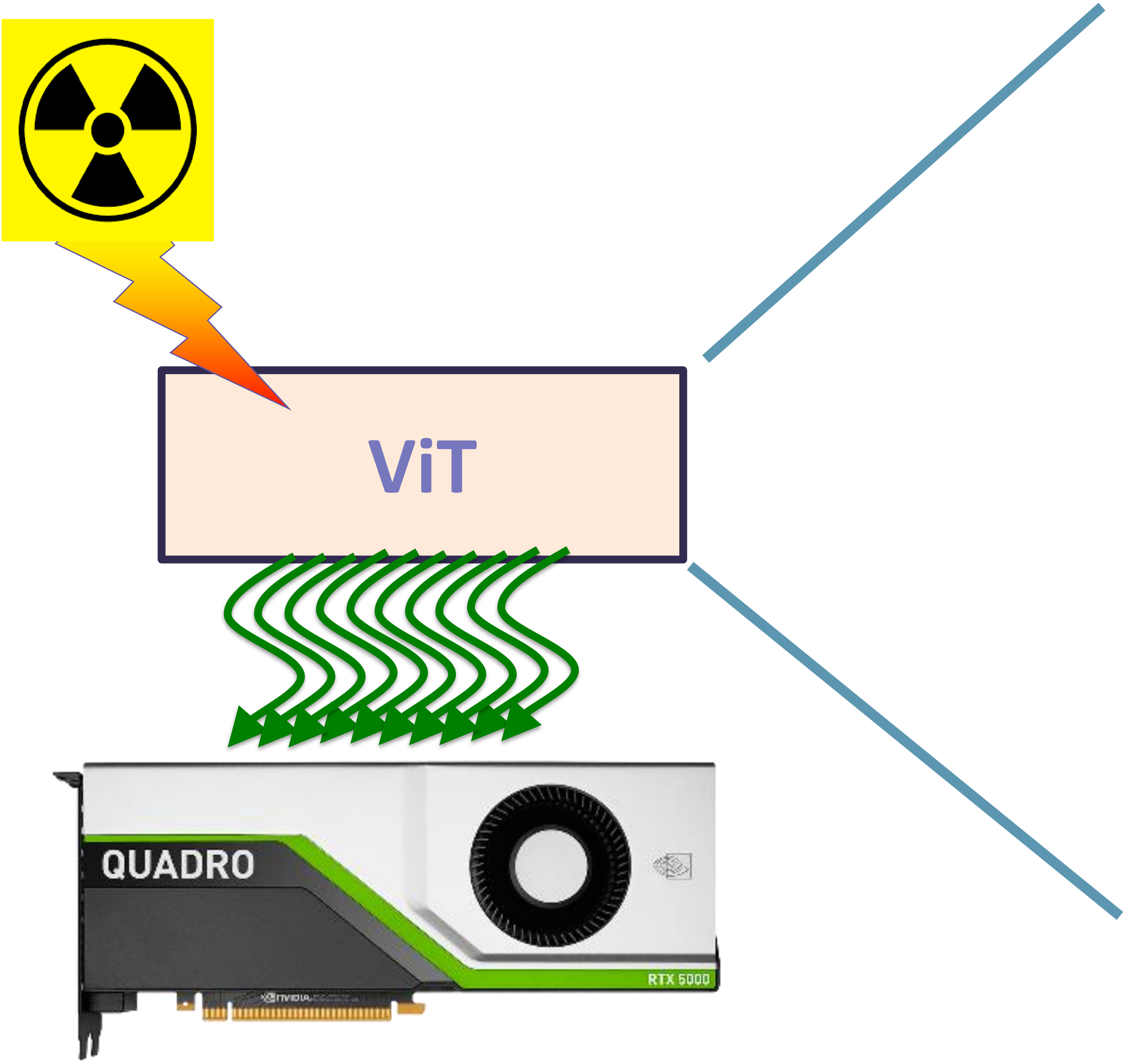

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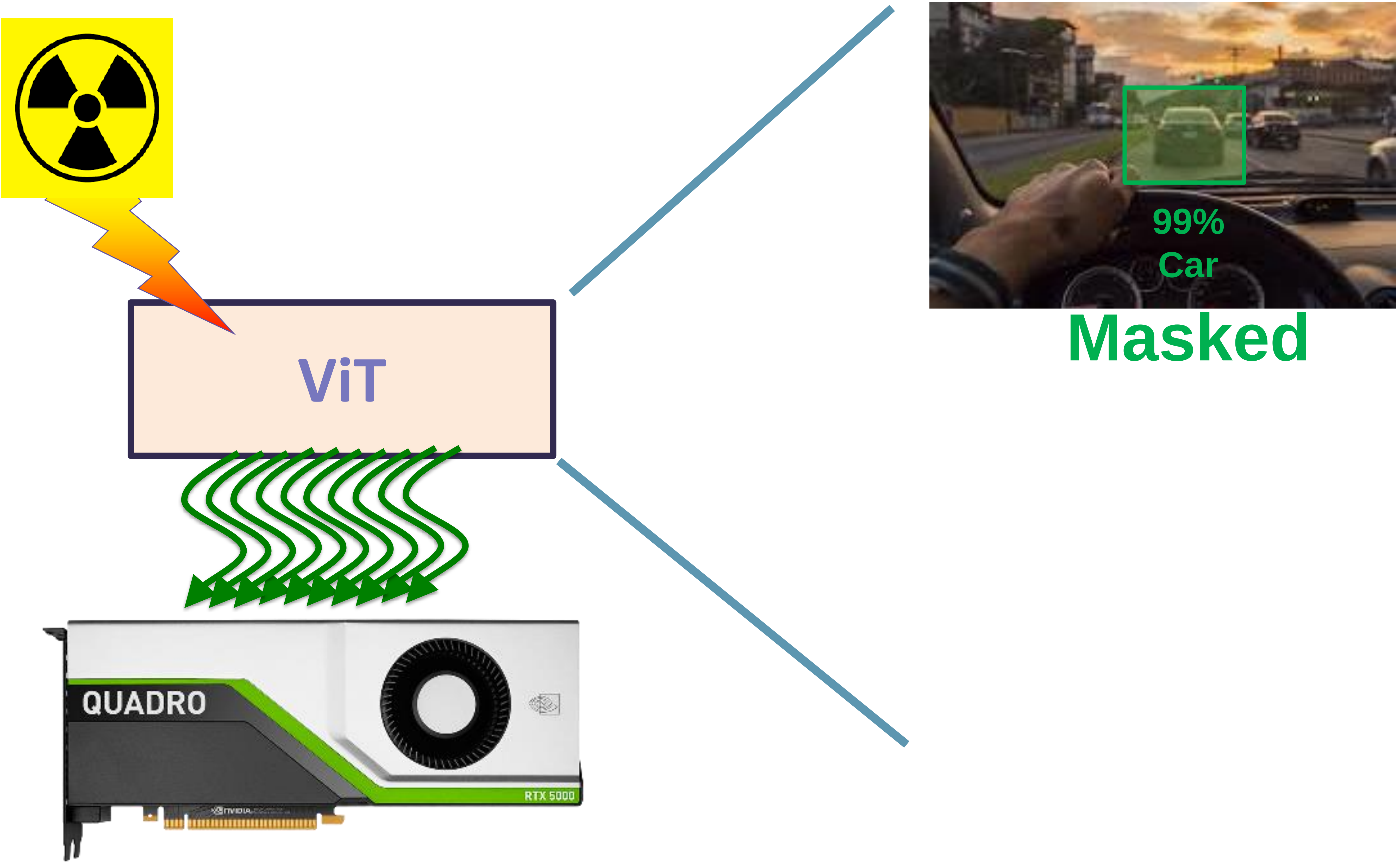
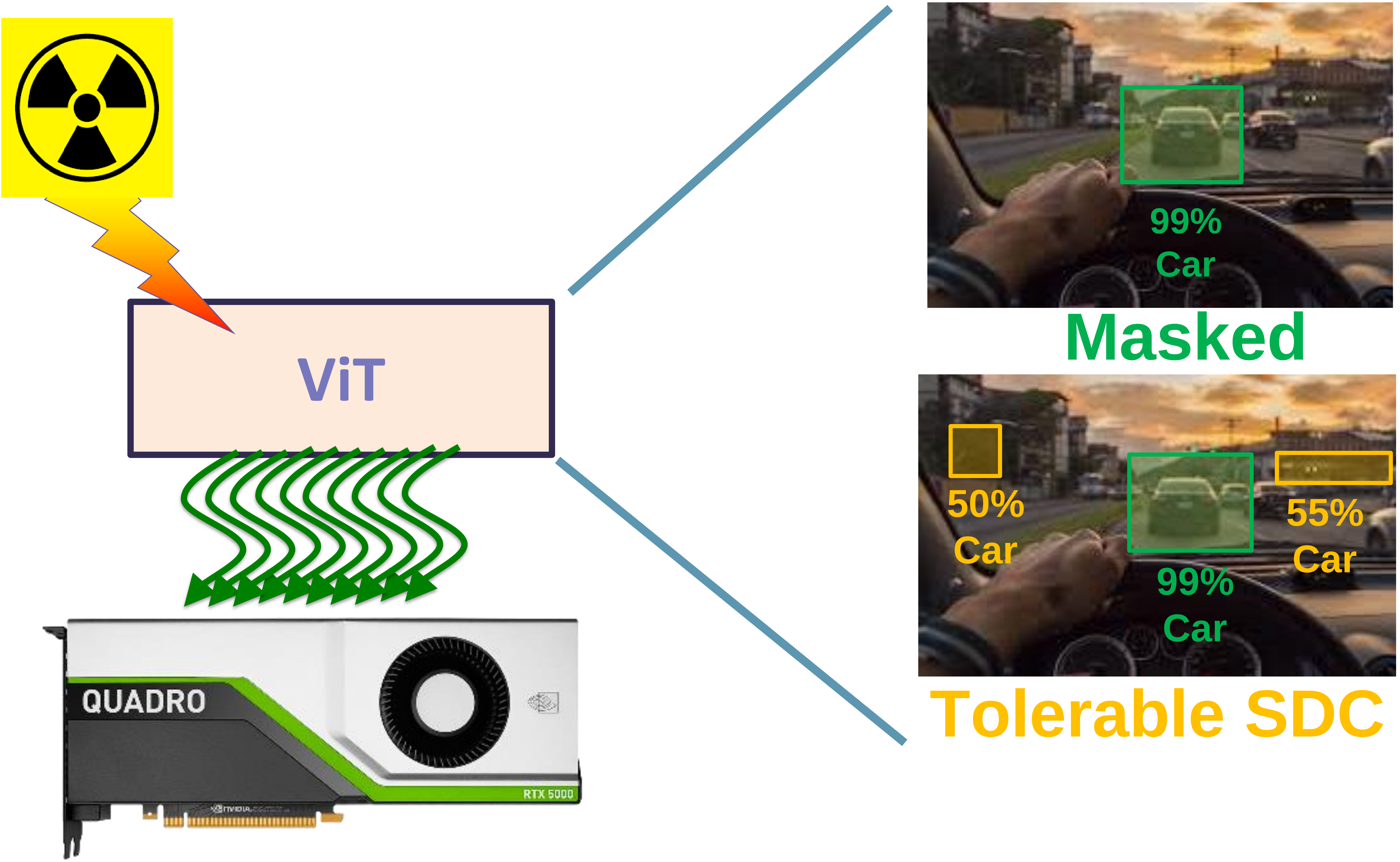


ViT

99%
Car

Masked

ViT SDC Types

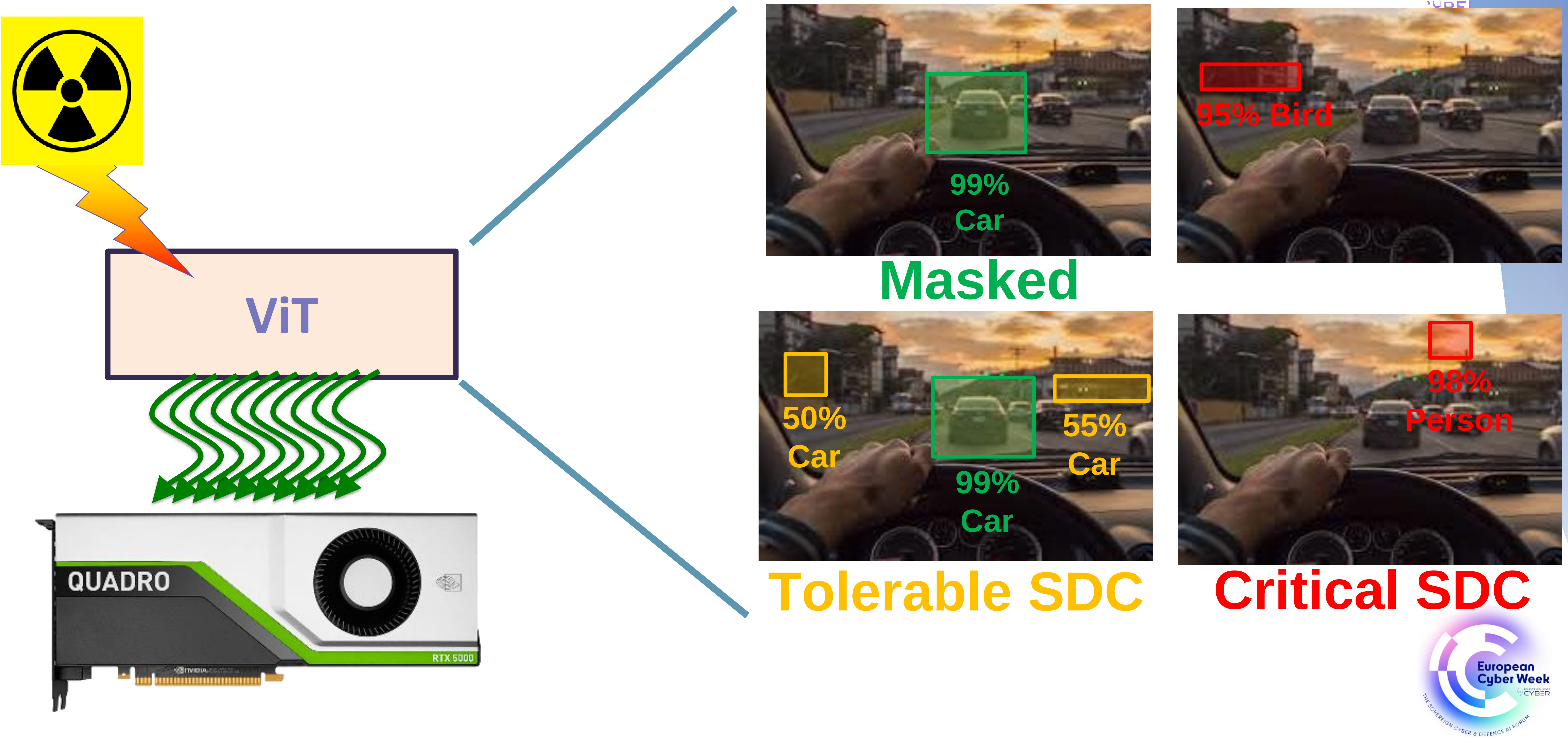


ViT

Masked

Tolerable SDC

ViT SDC Types



ViT

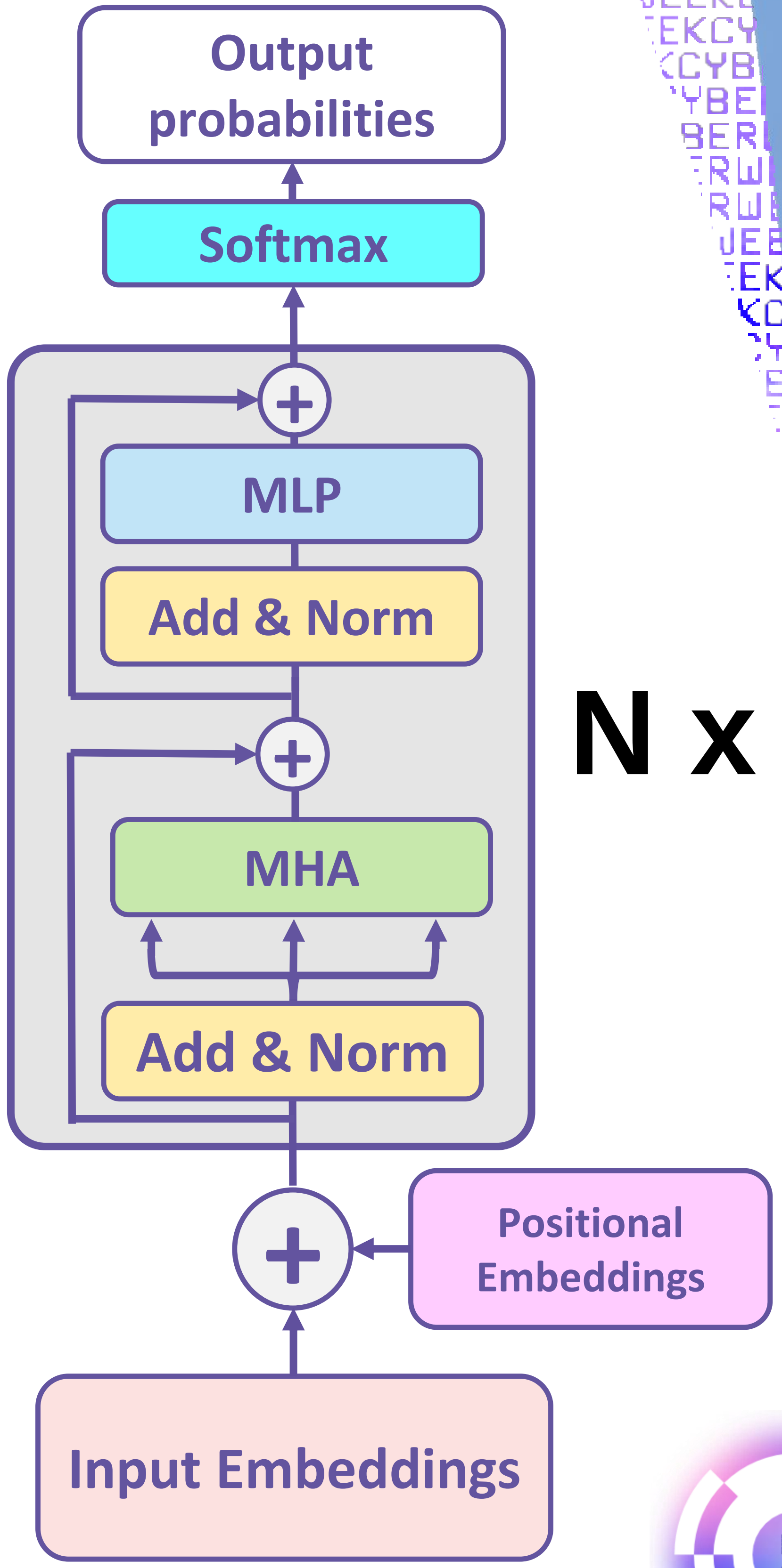
Masked

Tolerable SDC

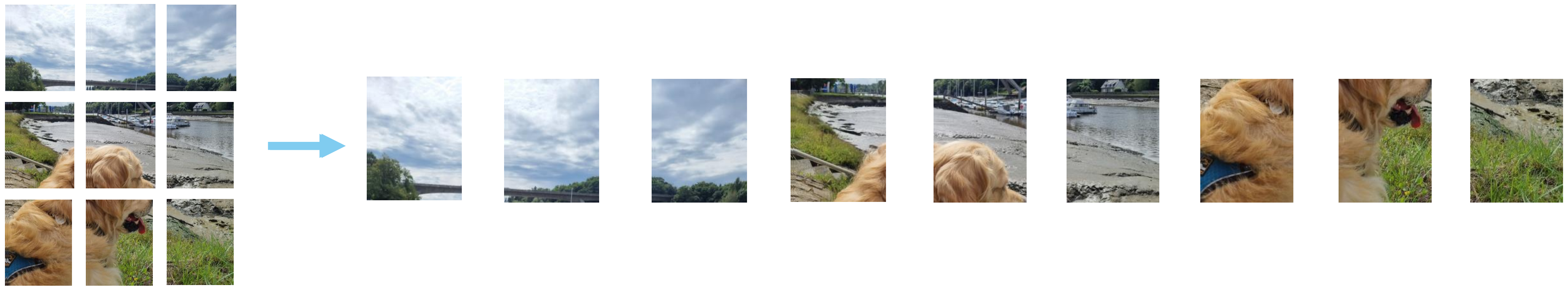
Critical SDC

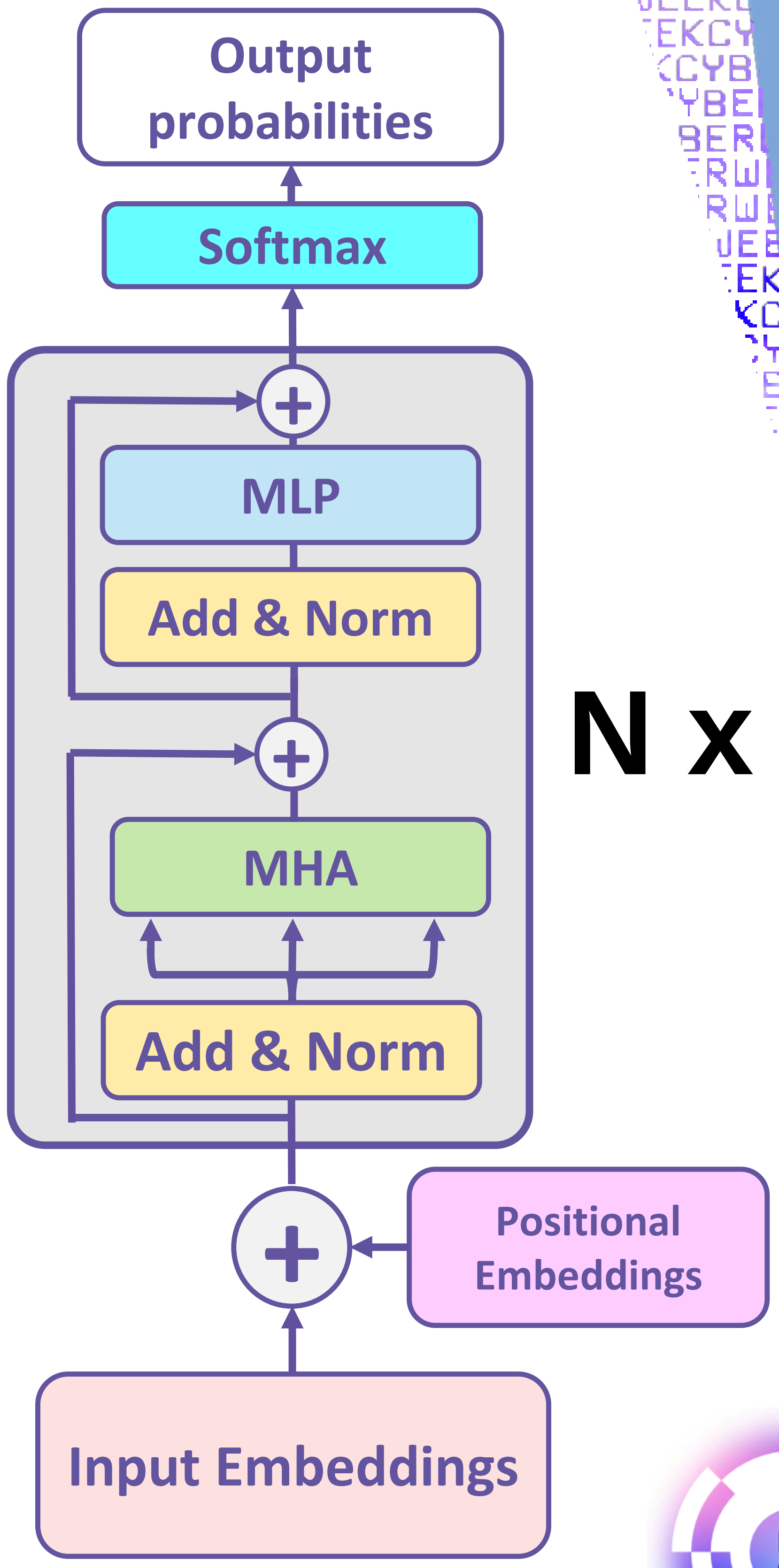
ViT Relibility Characterization

ViT Architecture



ViT Architecture





Output probabilities

Softmax

MLP

Add & Norm

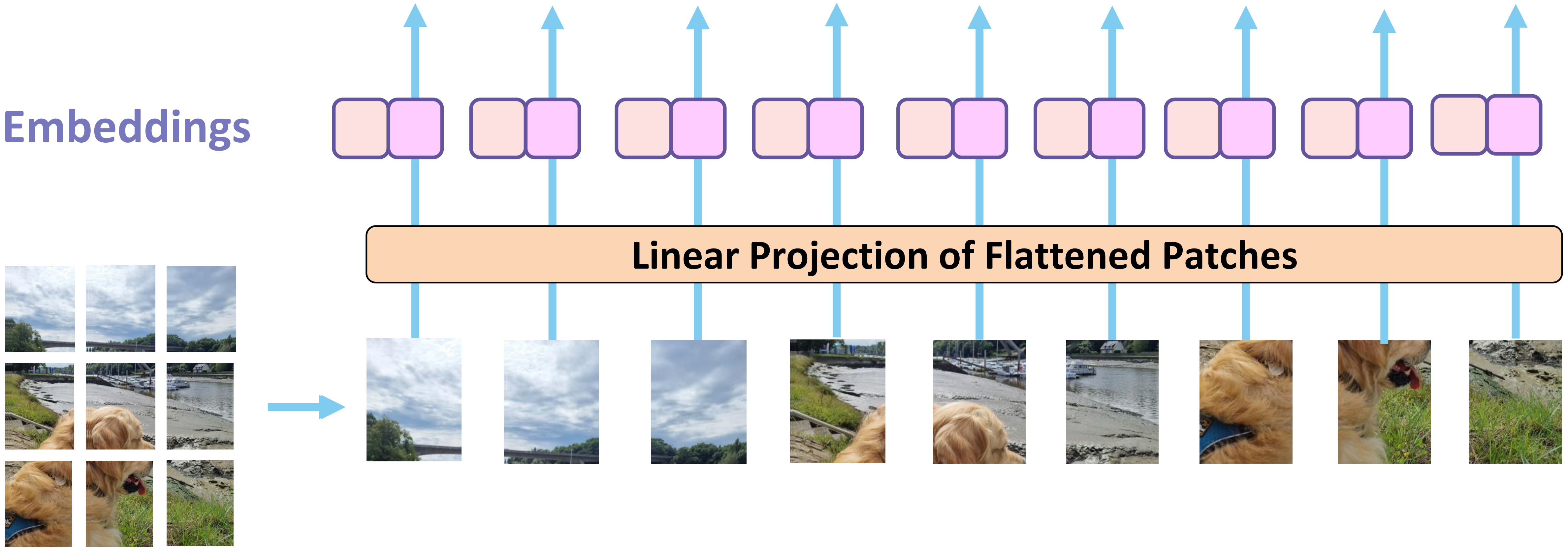
MHA

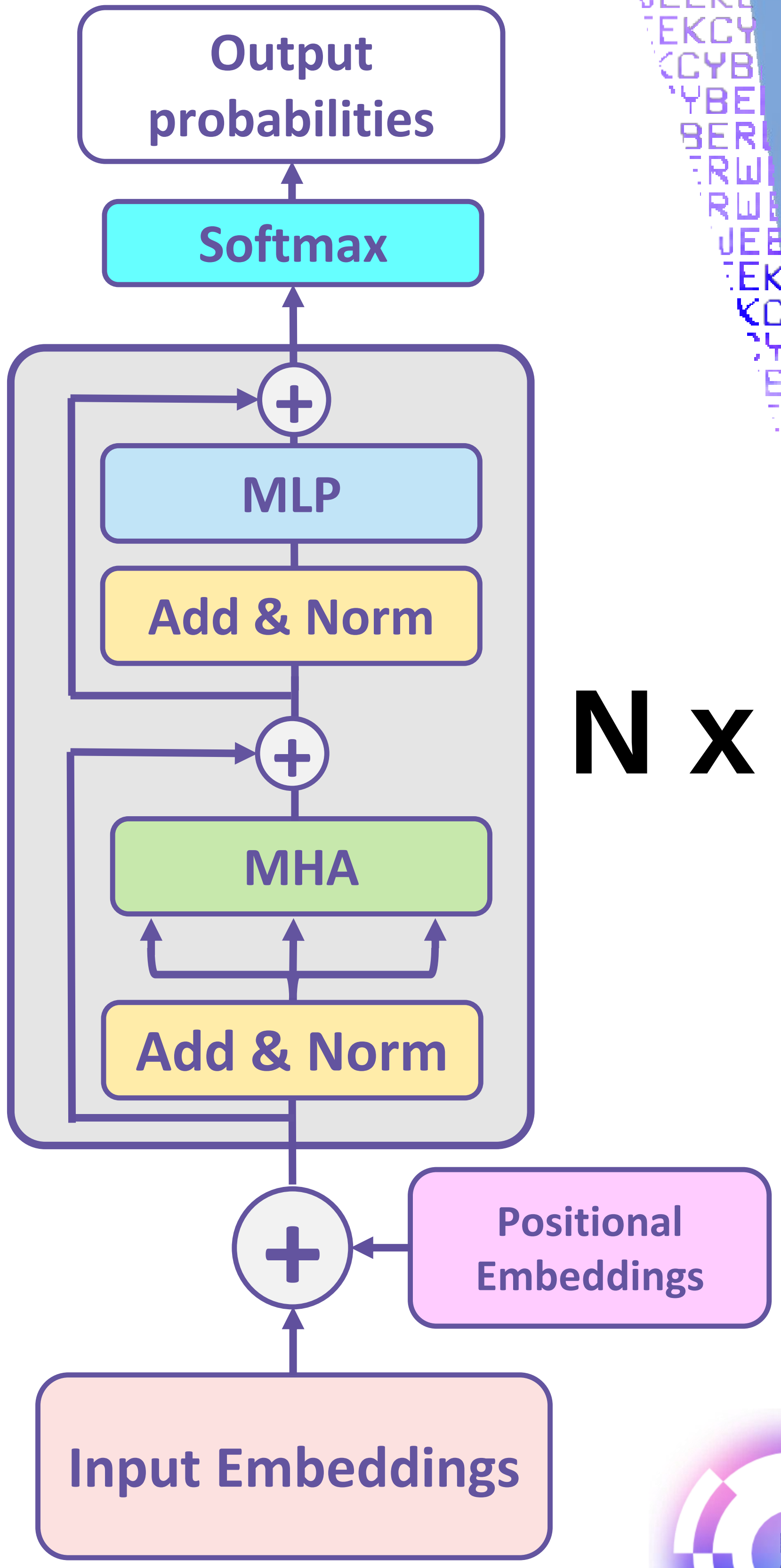
Add & Norm

Positional Embeddings

Input Embeddings

ViT Architecture





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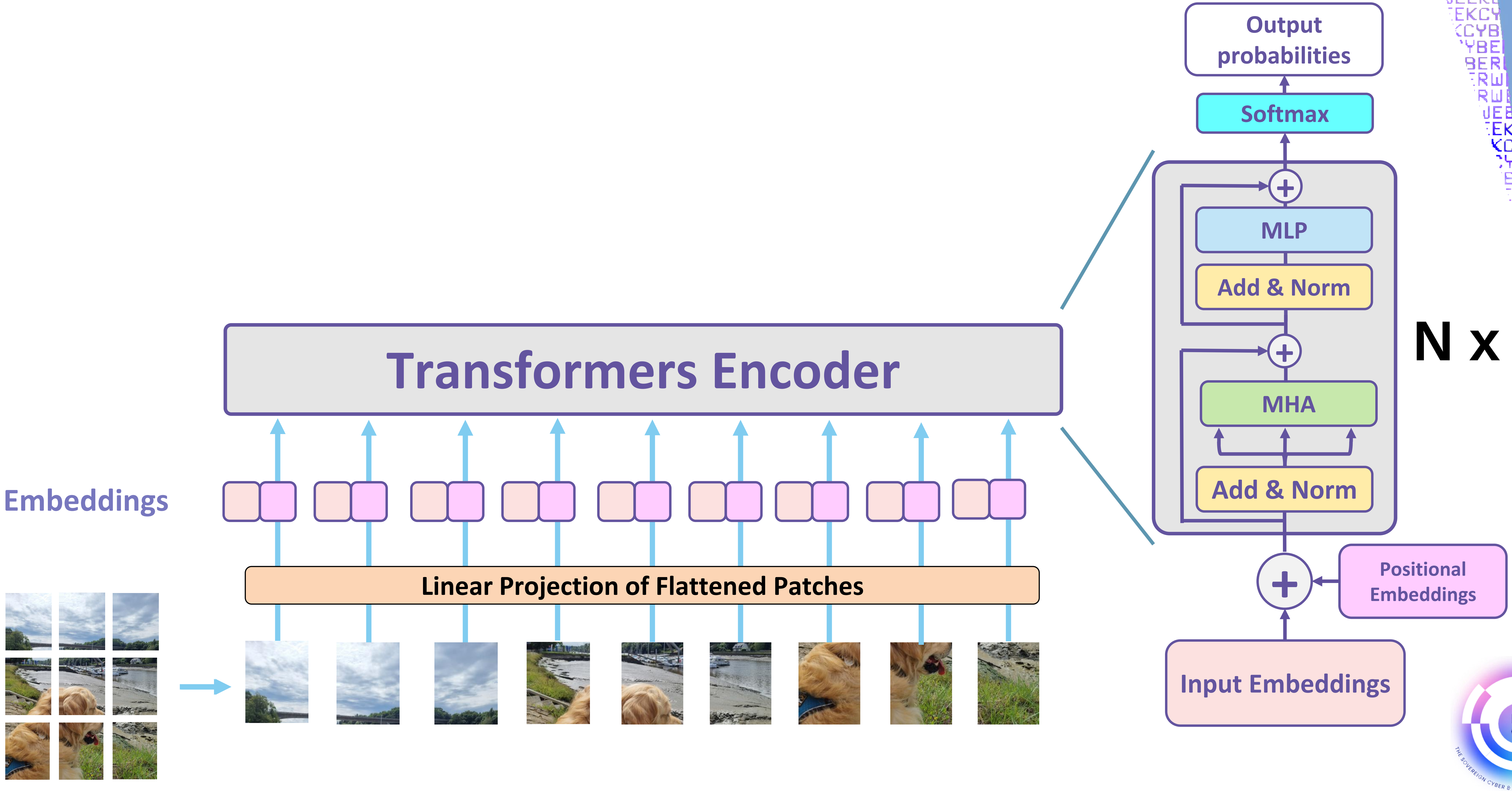

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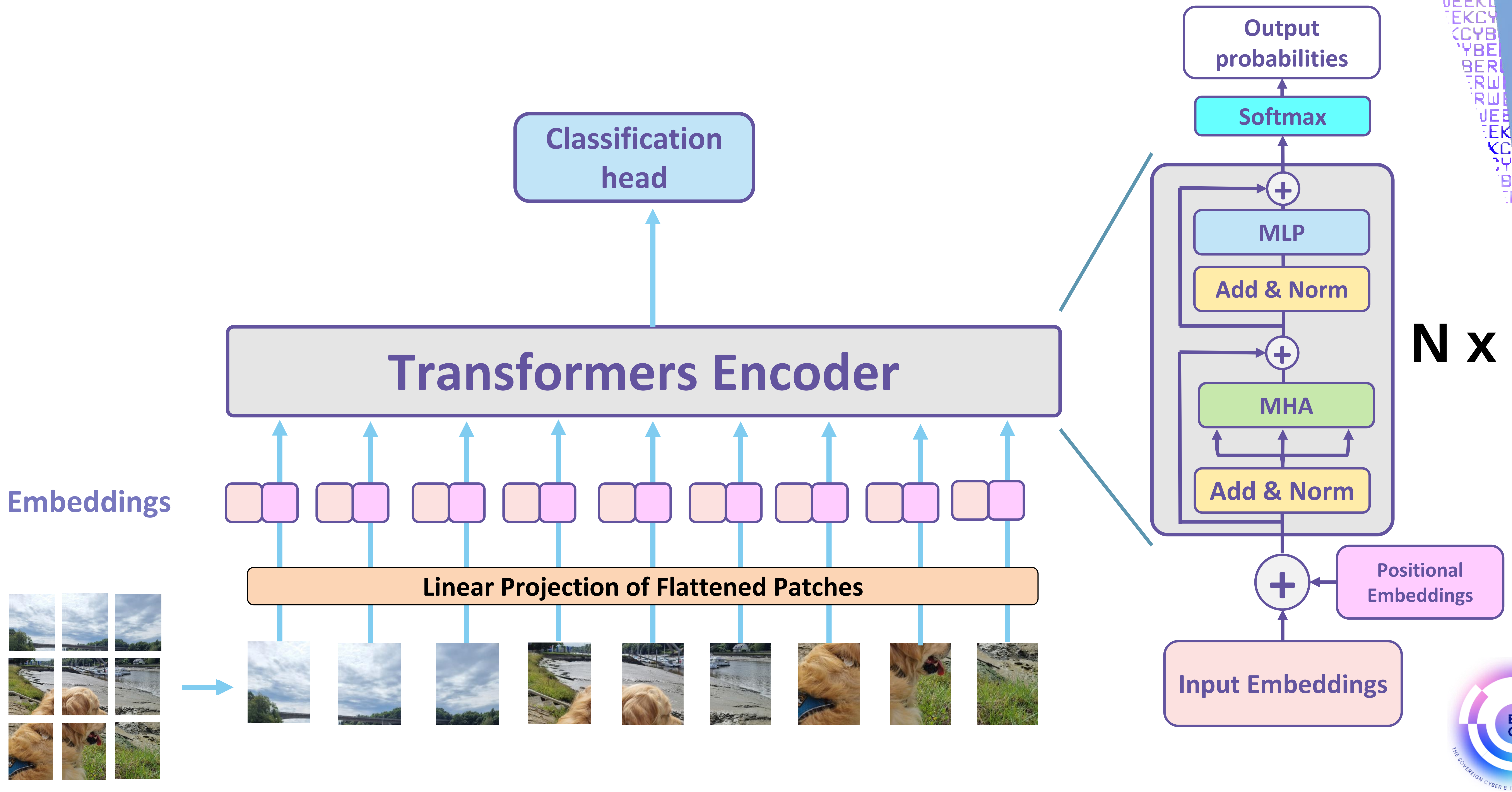

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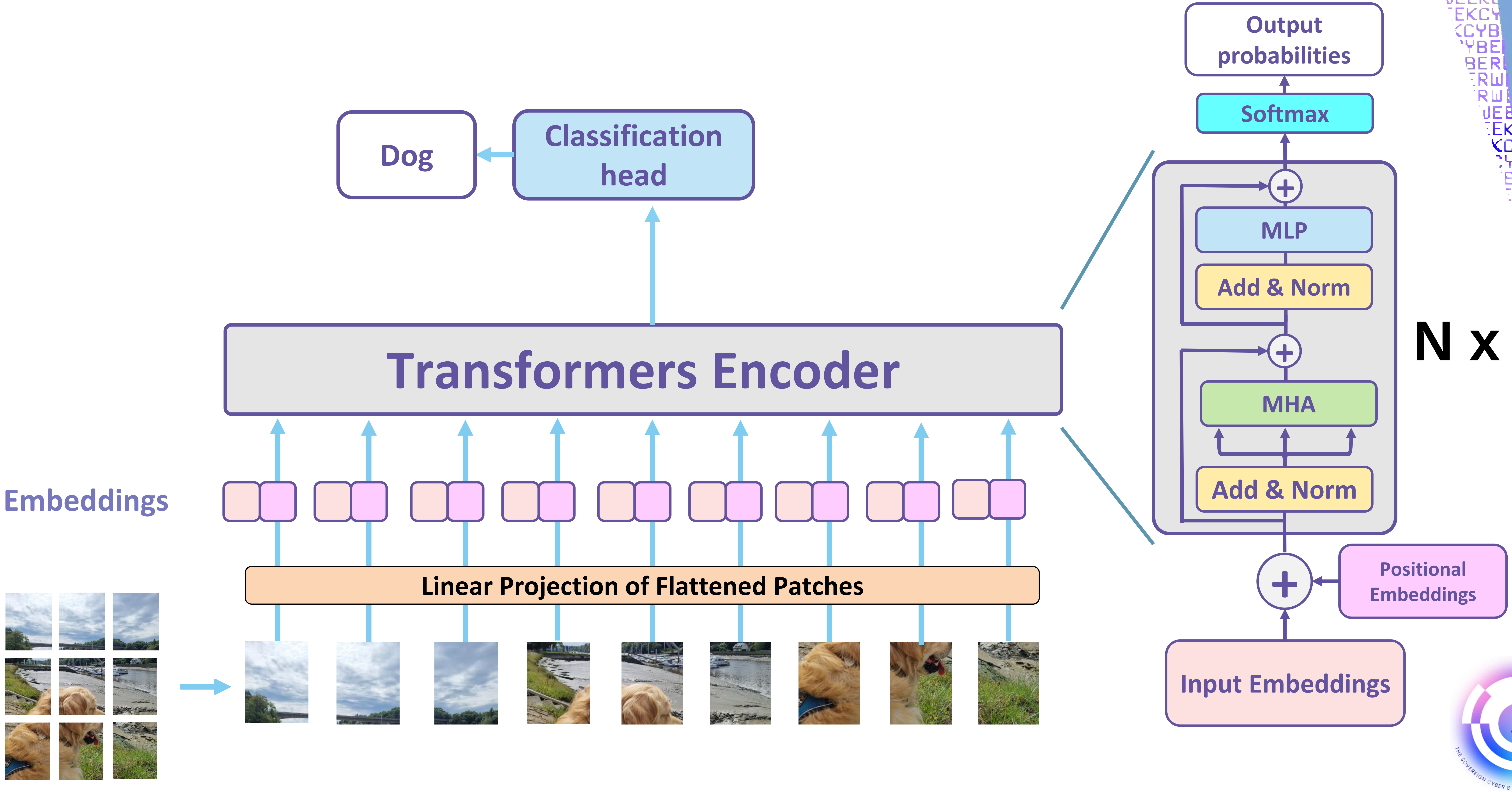
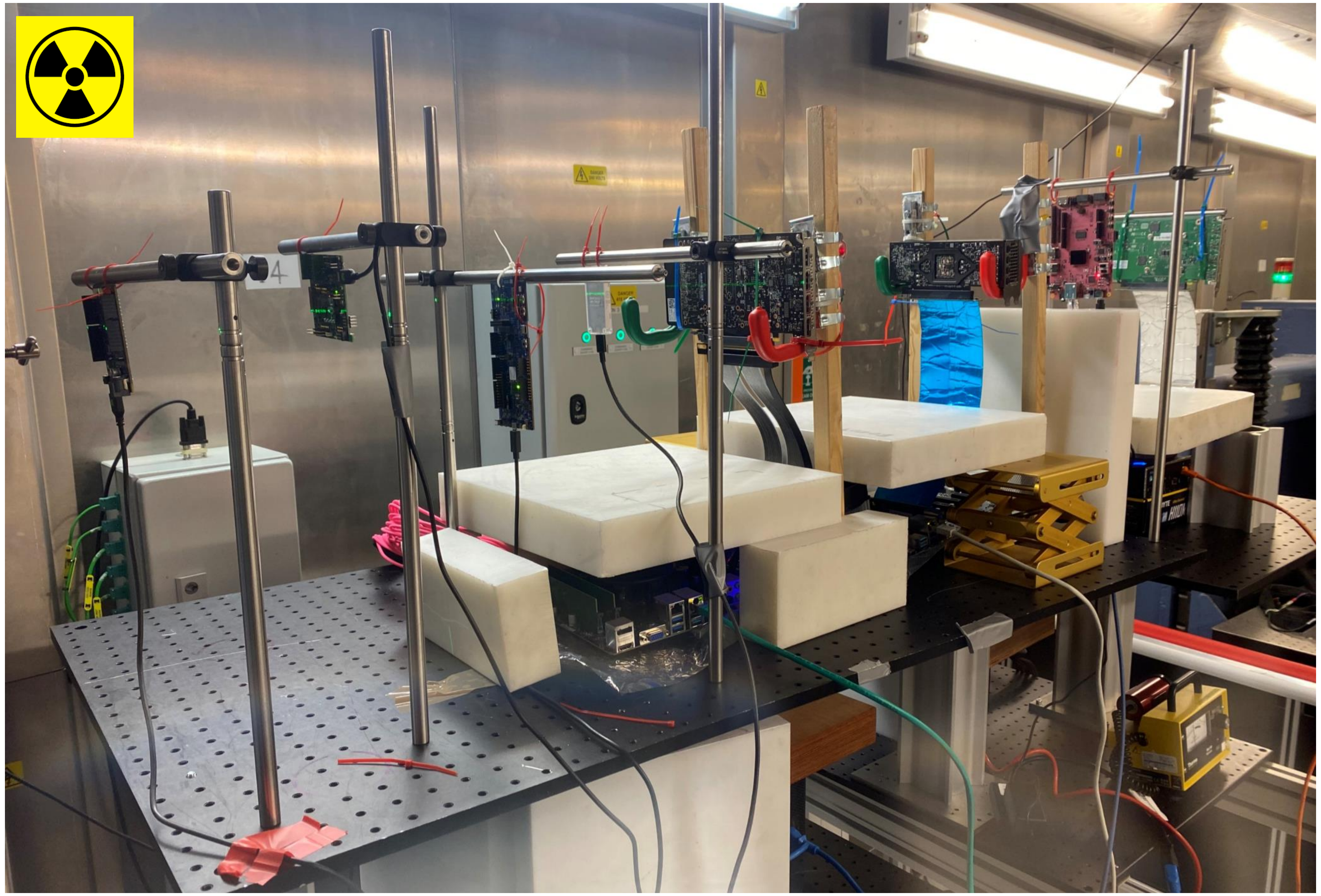
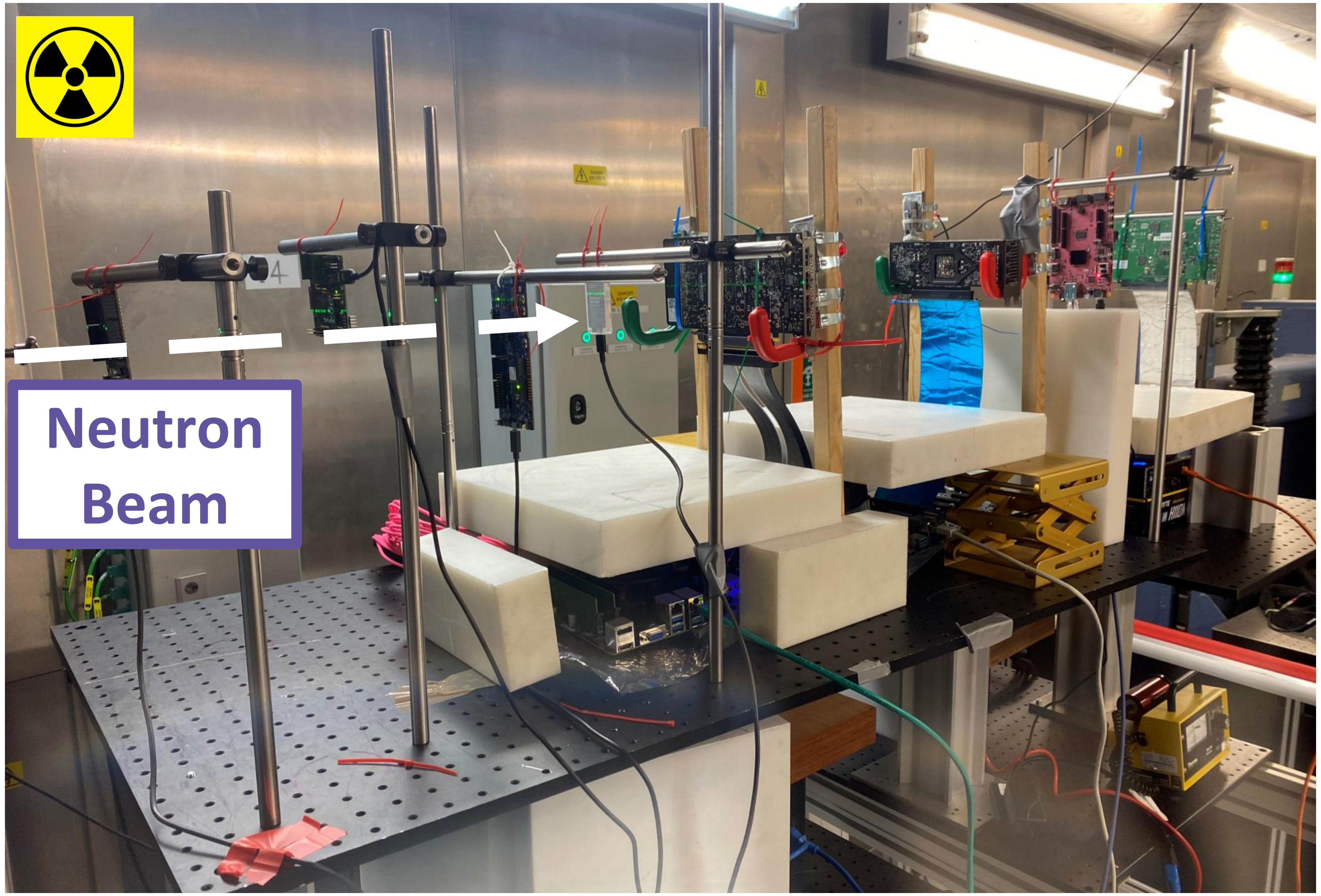


Neutron Beam Setup



Setup at ChipIR Facility, RAL, UK

Neutron Beam Setup



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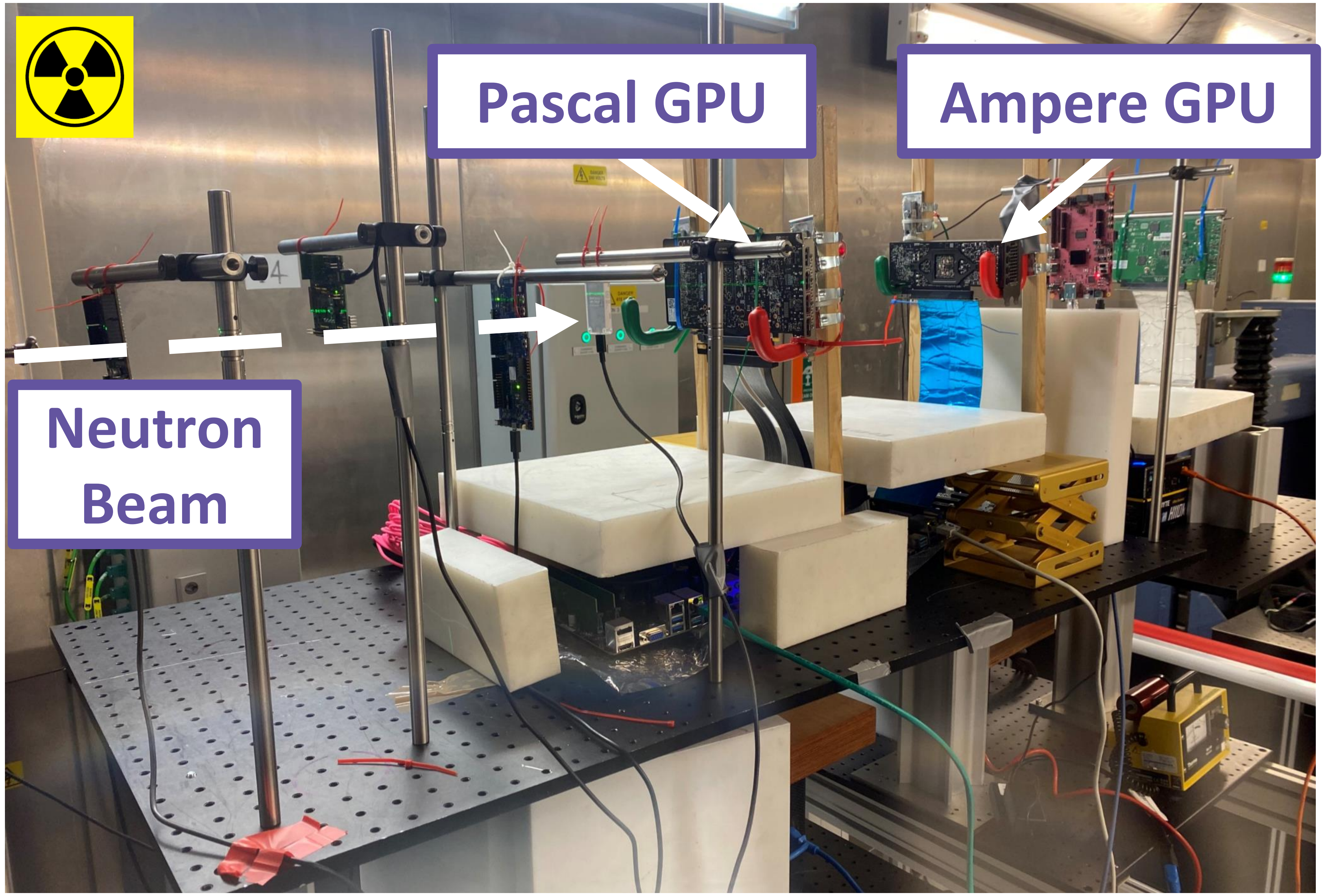

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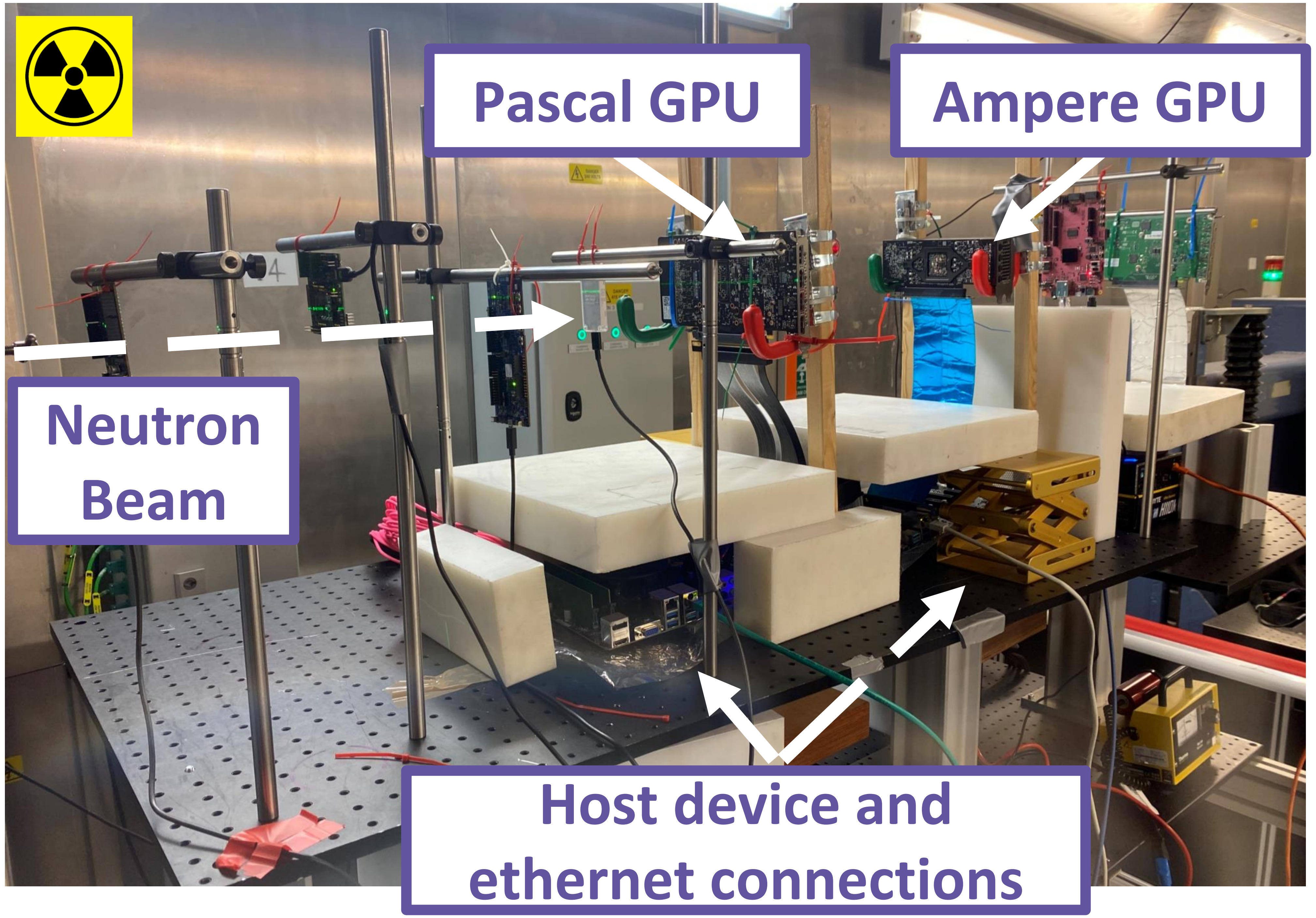

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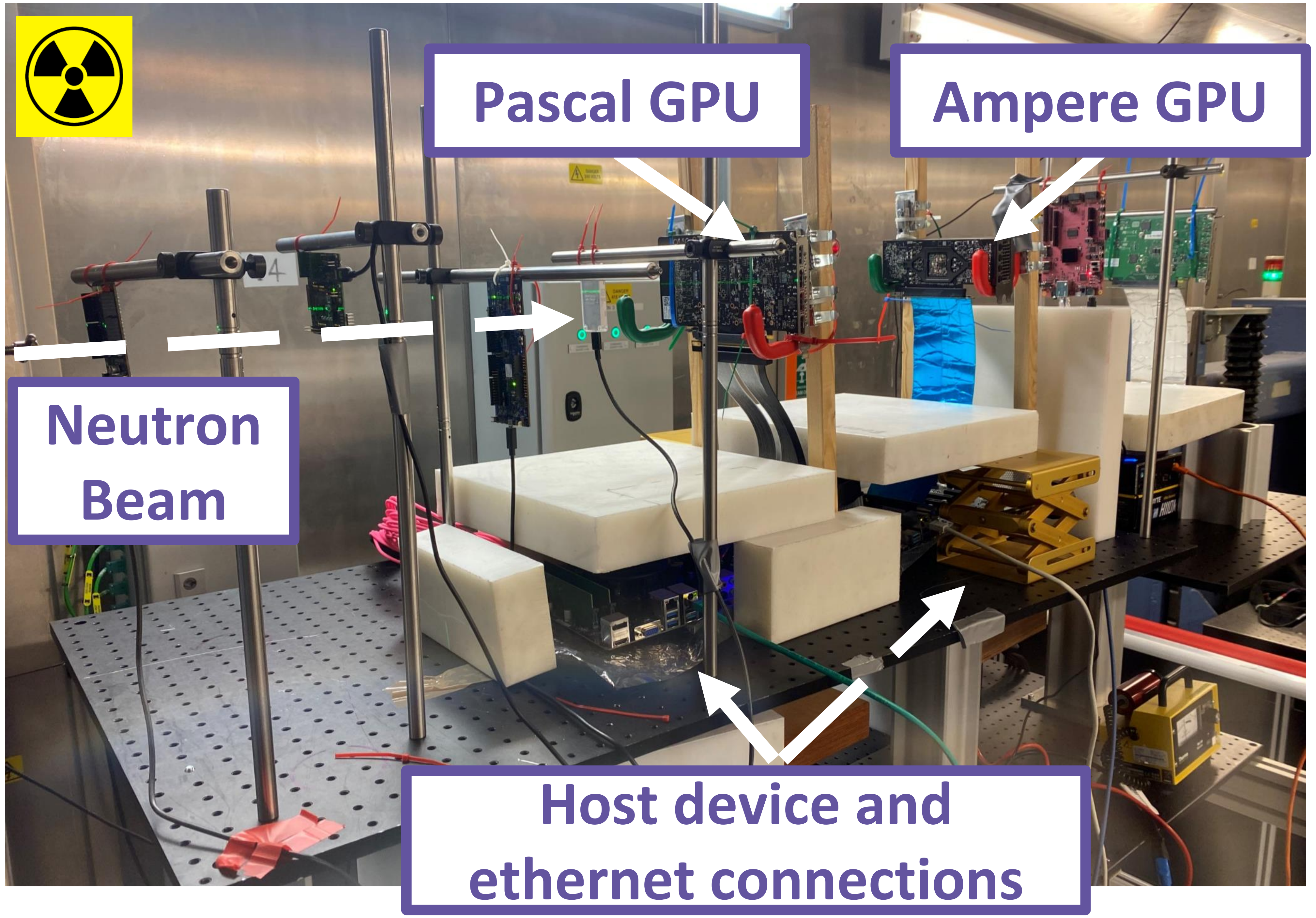


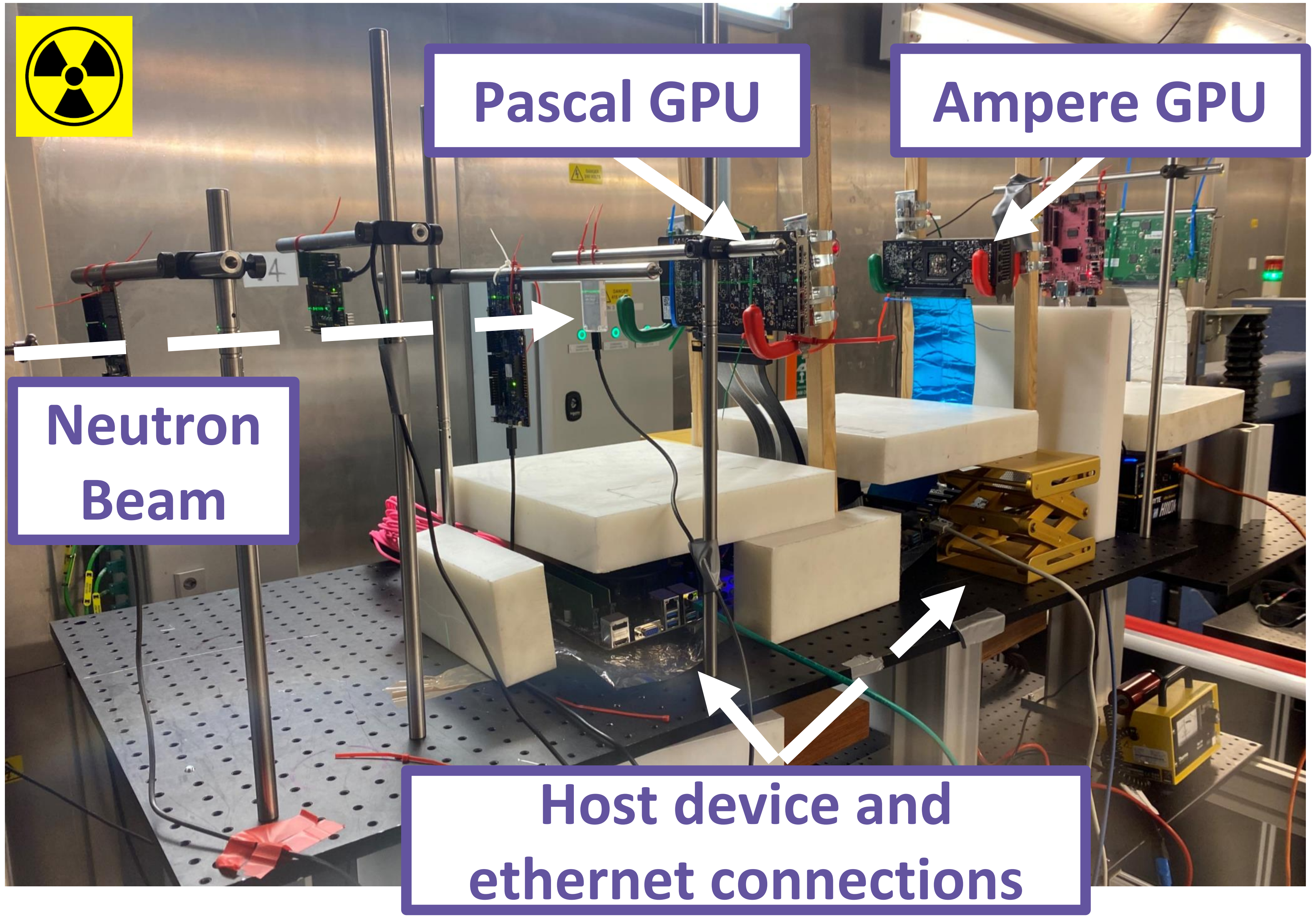
Setup at ChipIR Facility, RAL, UK

Failure Classification

- SDC: Tolerable and Critical
- DUE: ViT crashes, OS hangs

A server outside controls the experiments

Neutron Beam Setup



Setup at ChipIR Facility, RAL, UK

Failure Classification

- SDC: Tolerable and Critical
- DUE: ViT crashes, OS hangs

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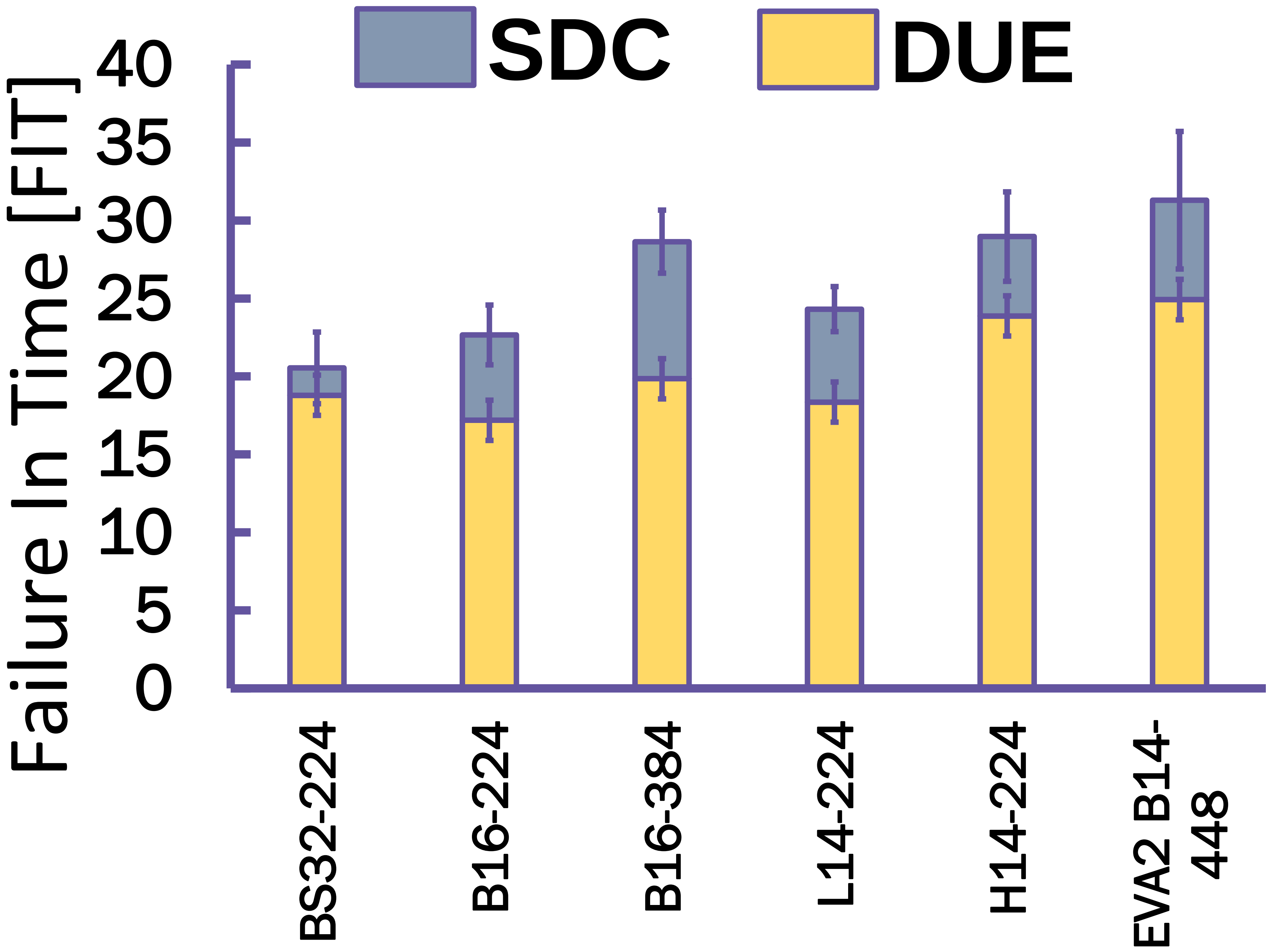
Configurations

- Dataset: ImageNet (classification)
- 12 ViTs, 4 families: ViT, EVA2, SwinV2 and MaxViT
- 2 NVIDIA GPUs: Quadro P2000 (Pascal) and RTX A2000 (Ampere)

ViT’s Failure in Time (FIT)



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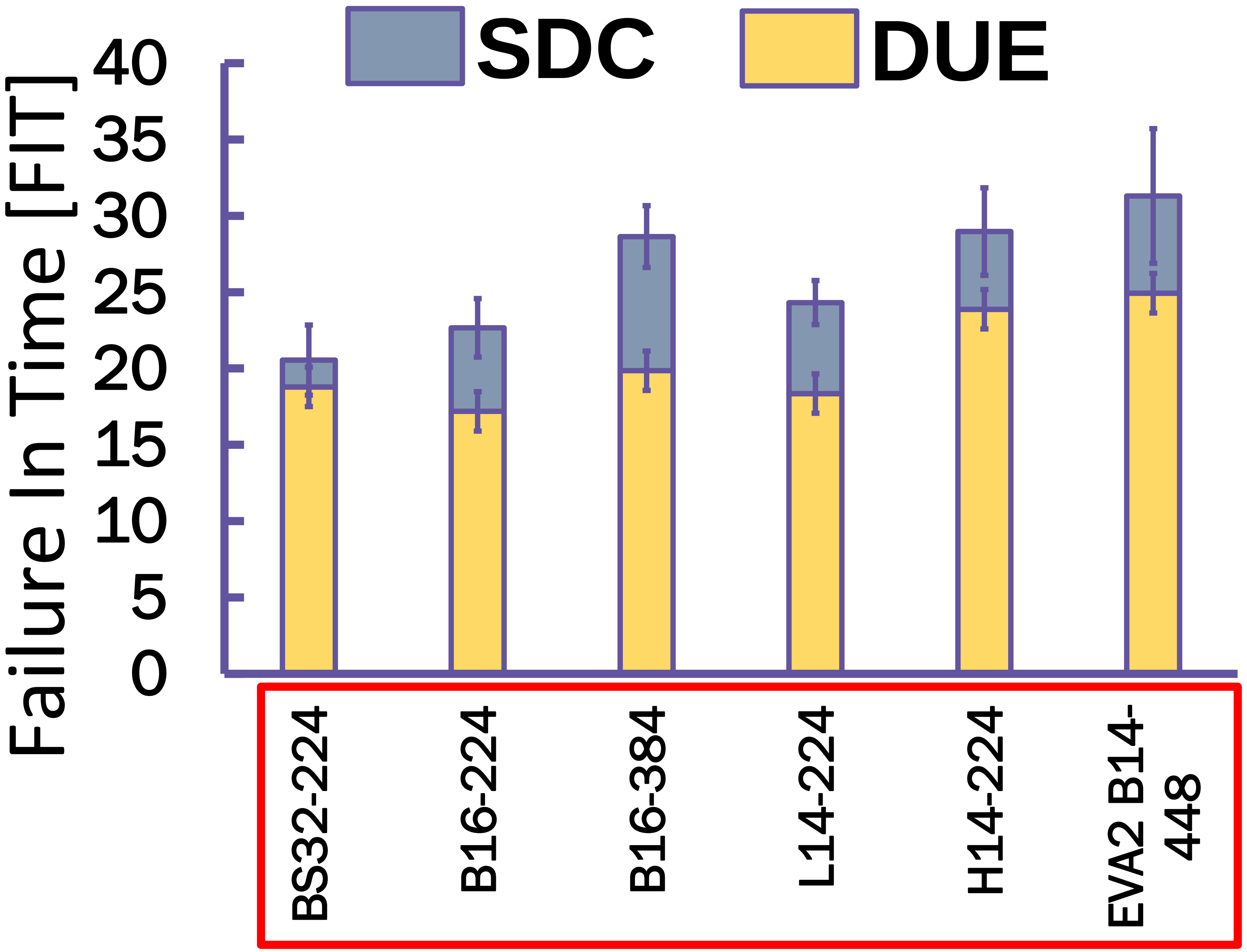
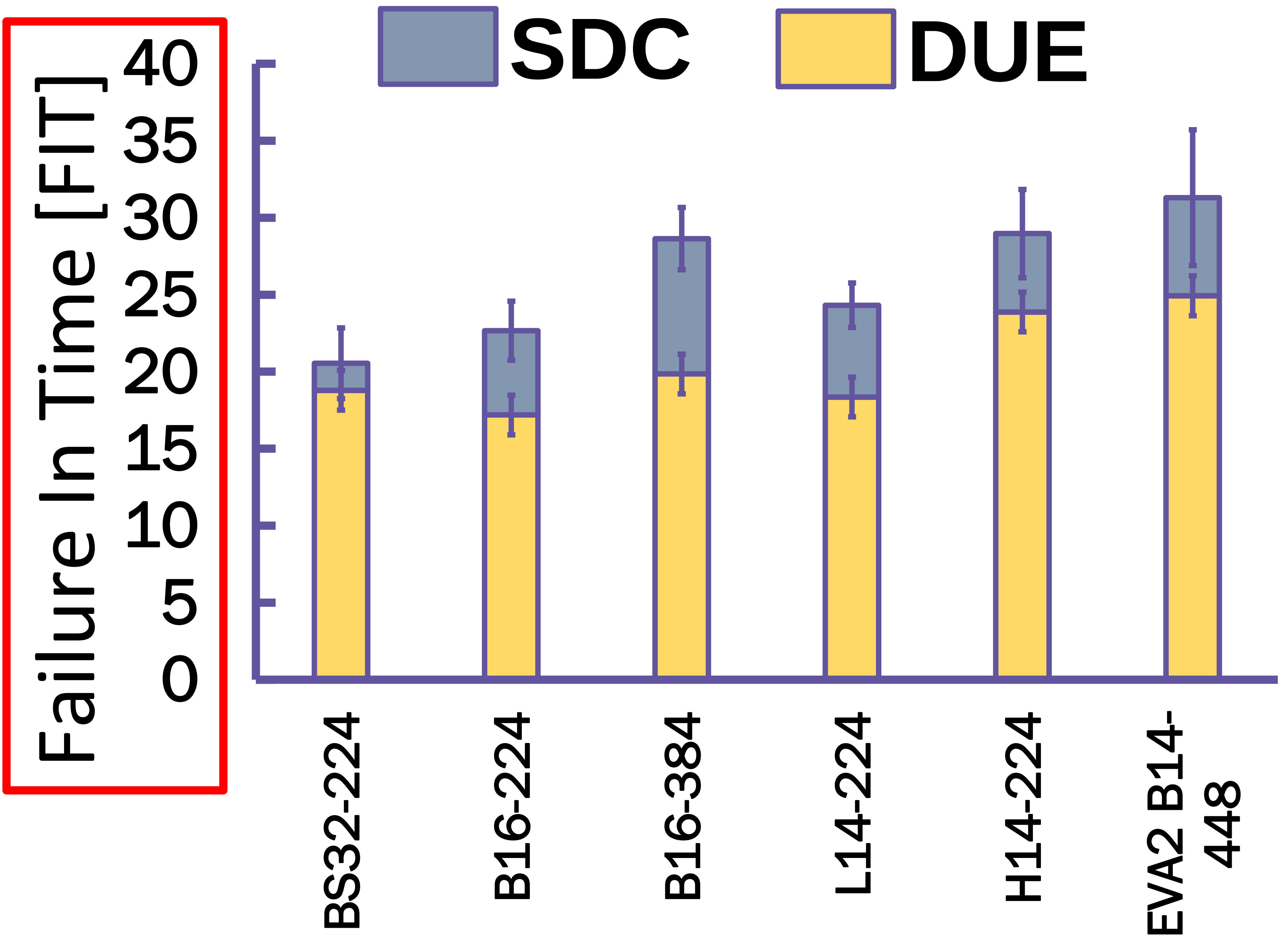


Configuration for Pascal GPU

ViT’s Failure in Time (FIT)



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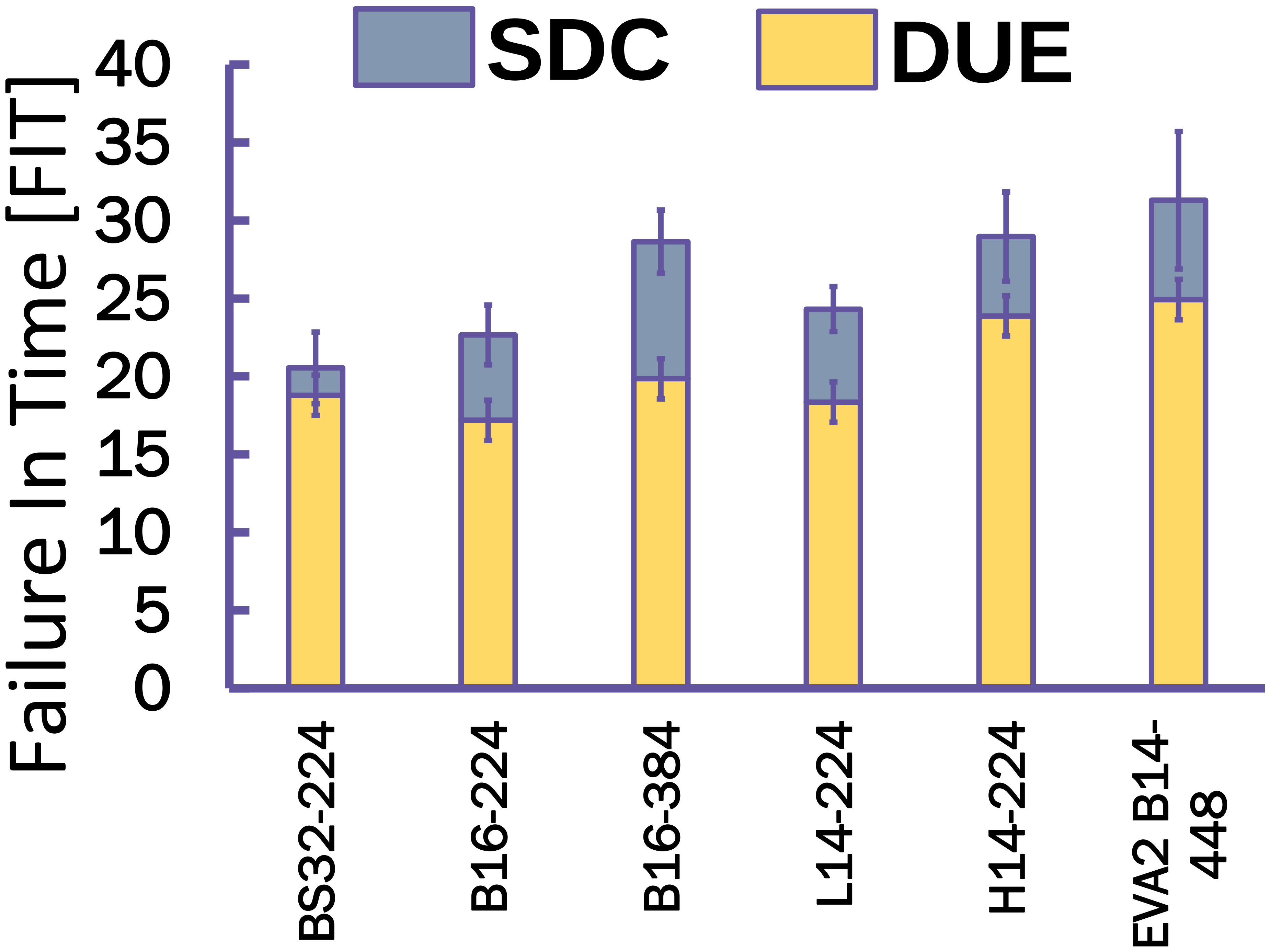

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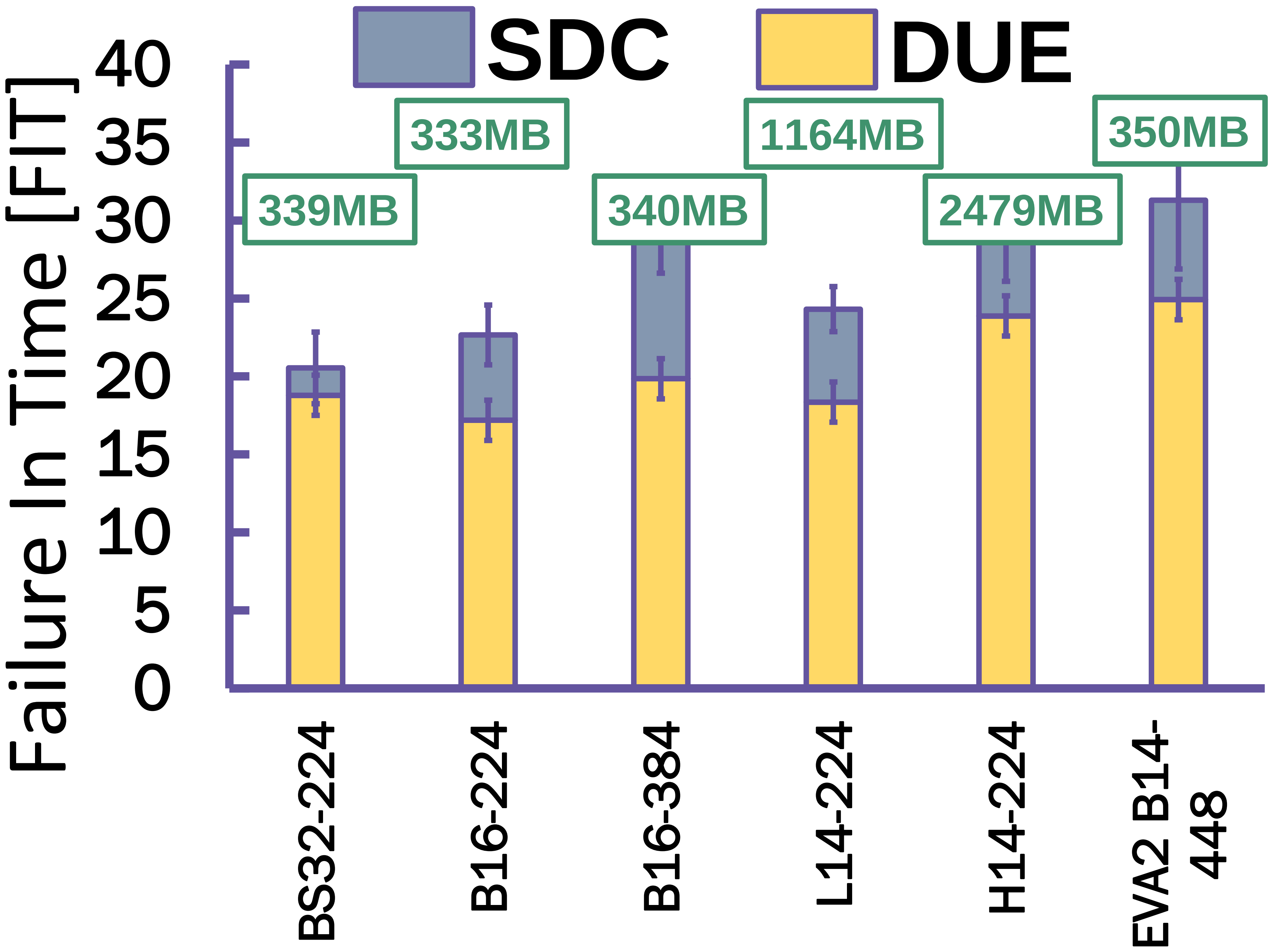

- The ViT FIT grows along its resource usage and family

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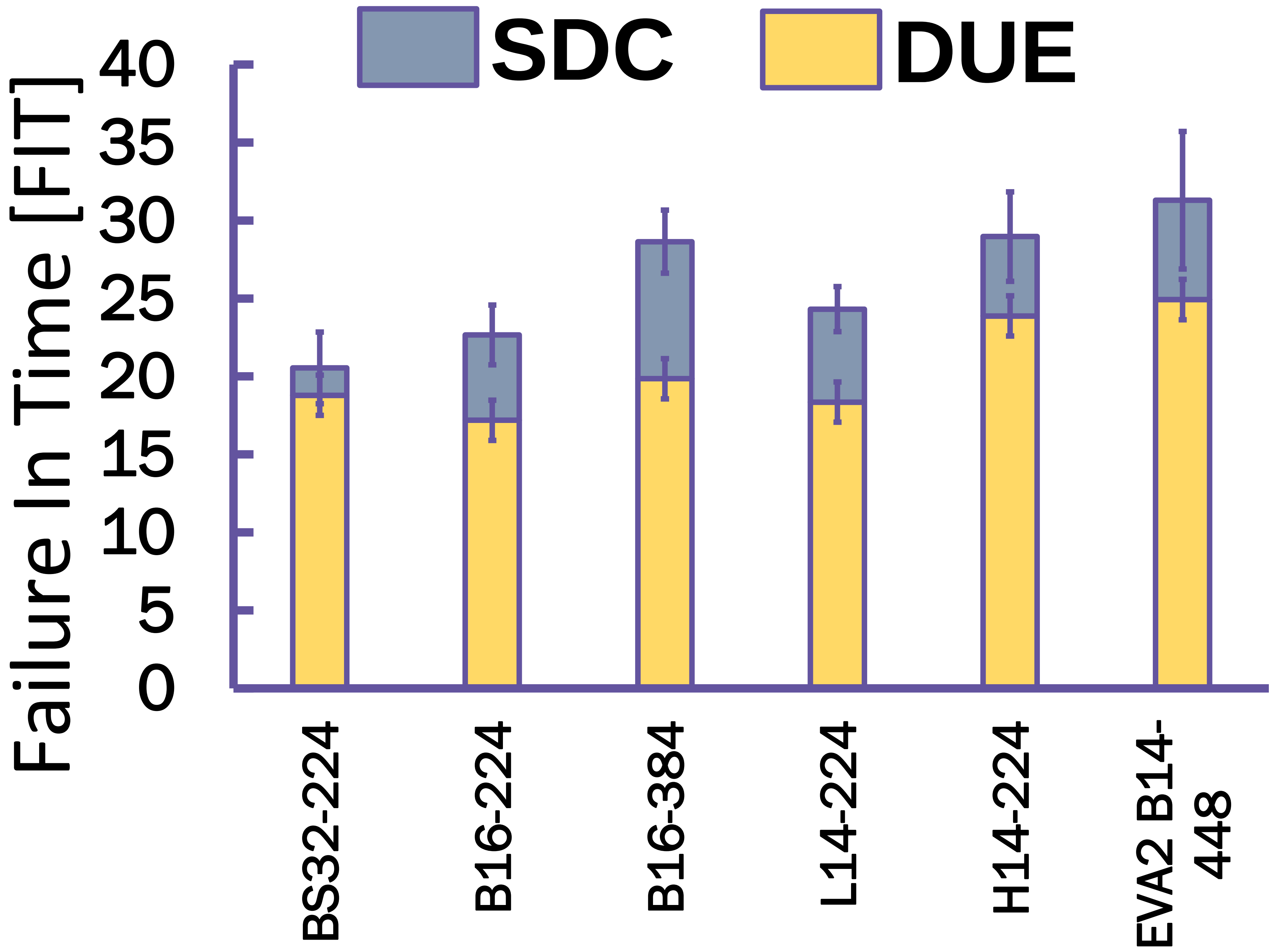

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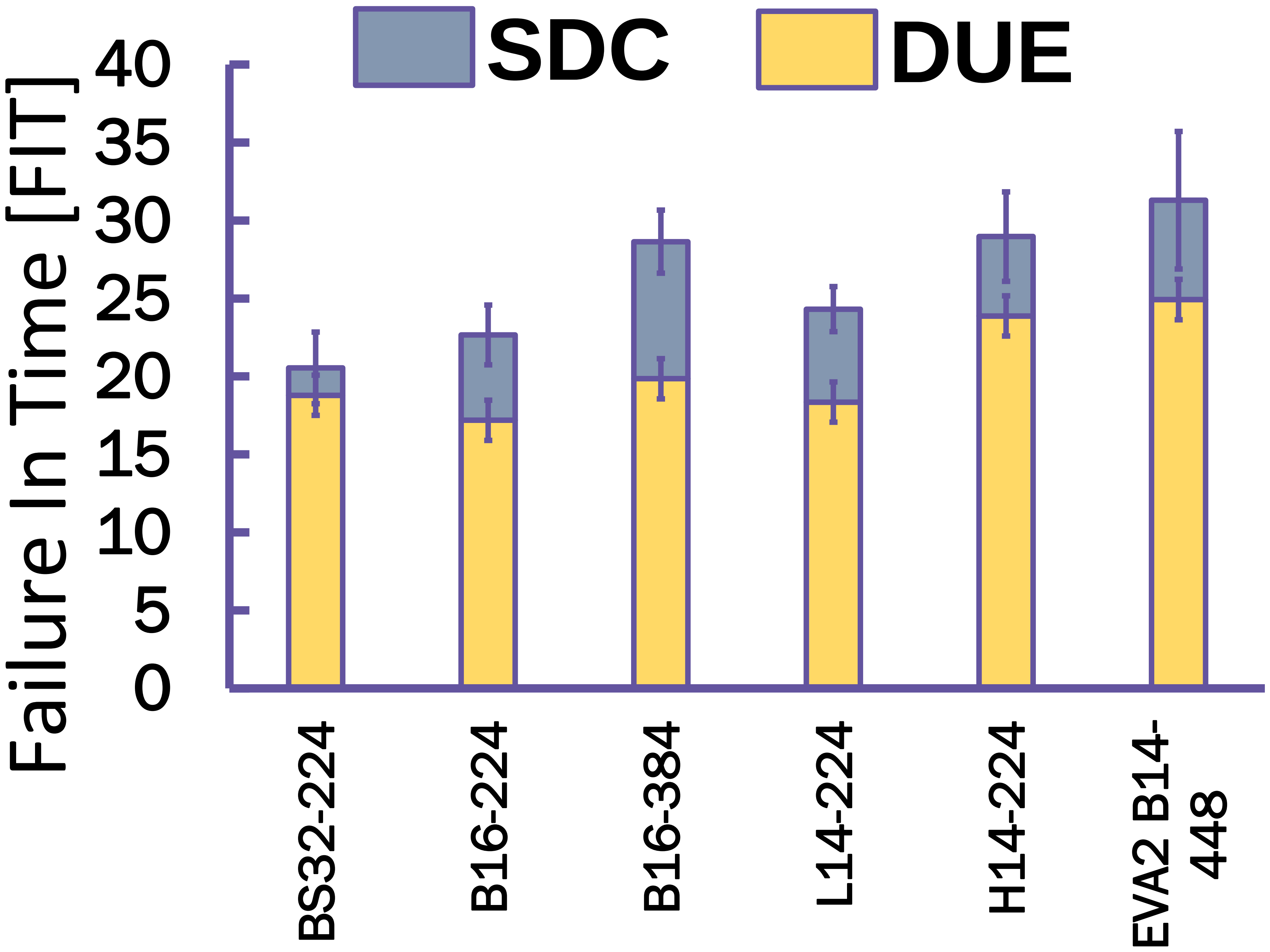

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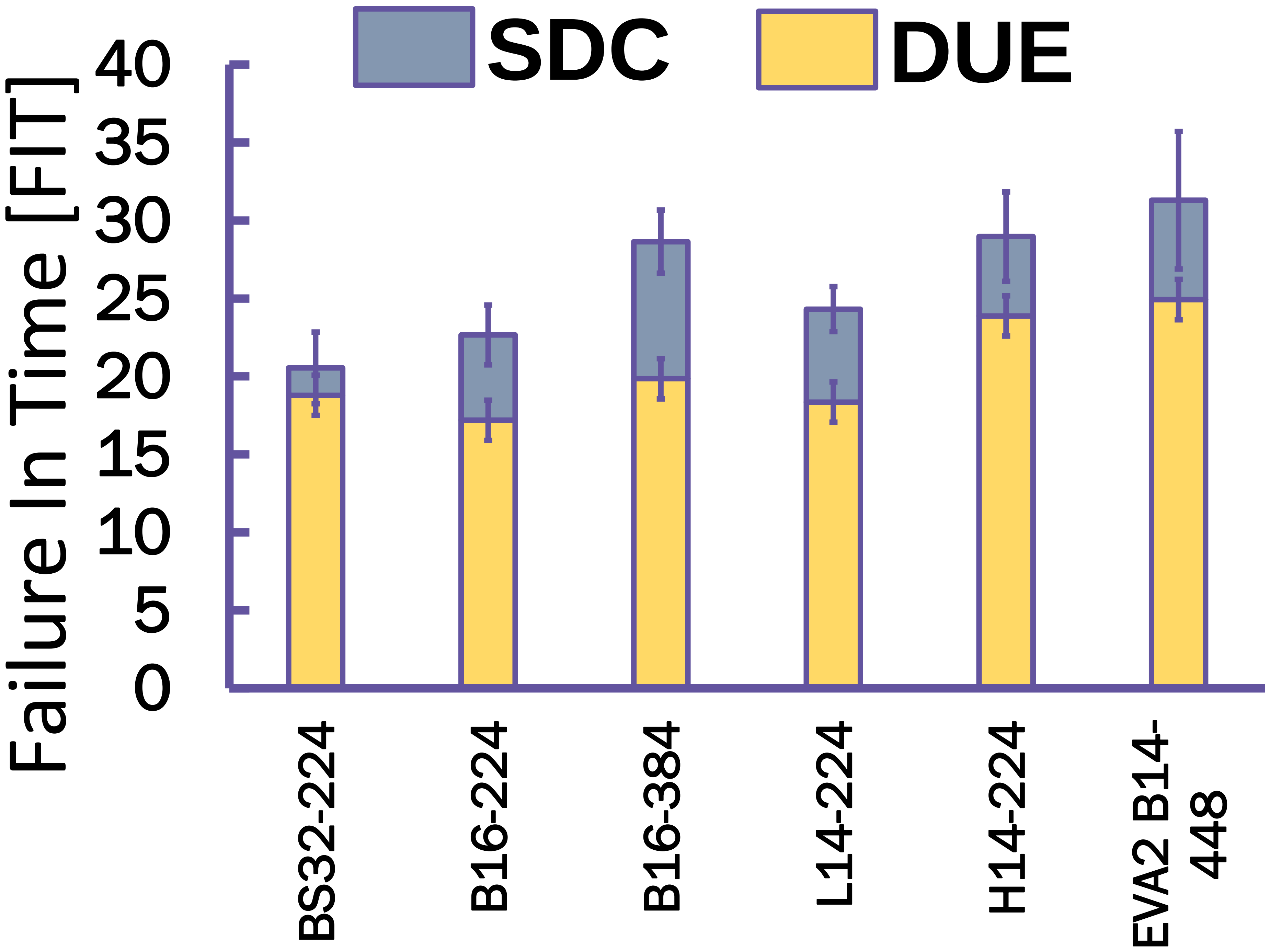

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  - 16.3% of Critical SDCs on average (max. 37.3%)

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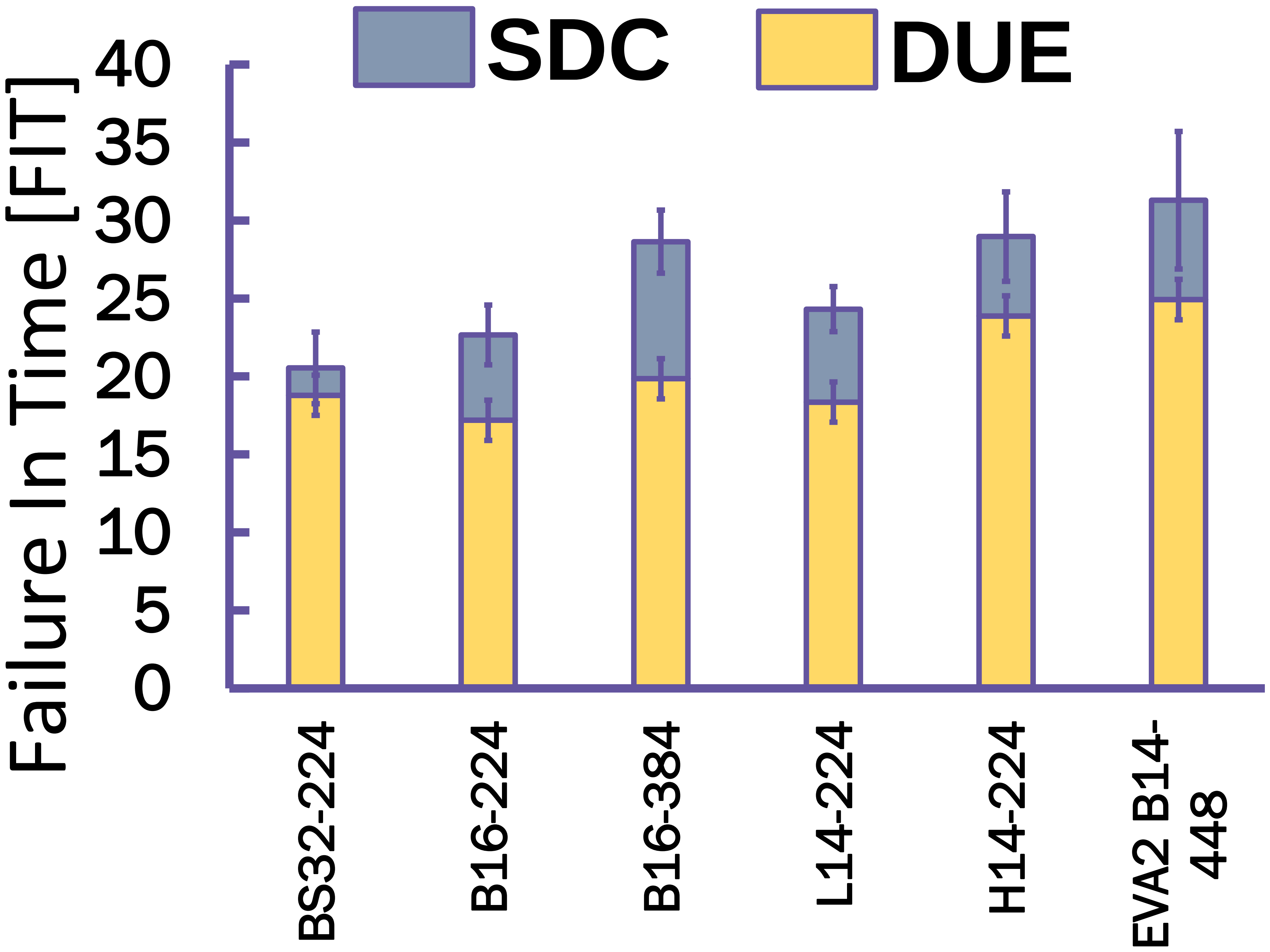

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- Same observations for Ampere GPU
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  - with ECC ON: up to 10.0% of Crititical SDCs

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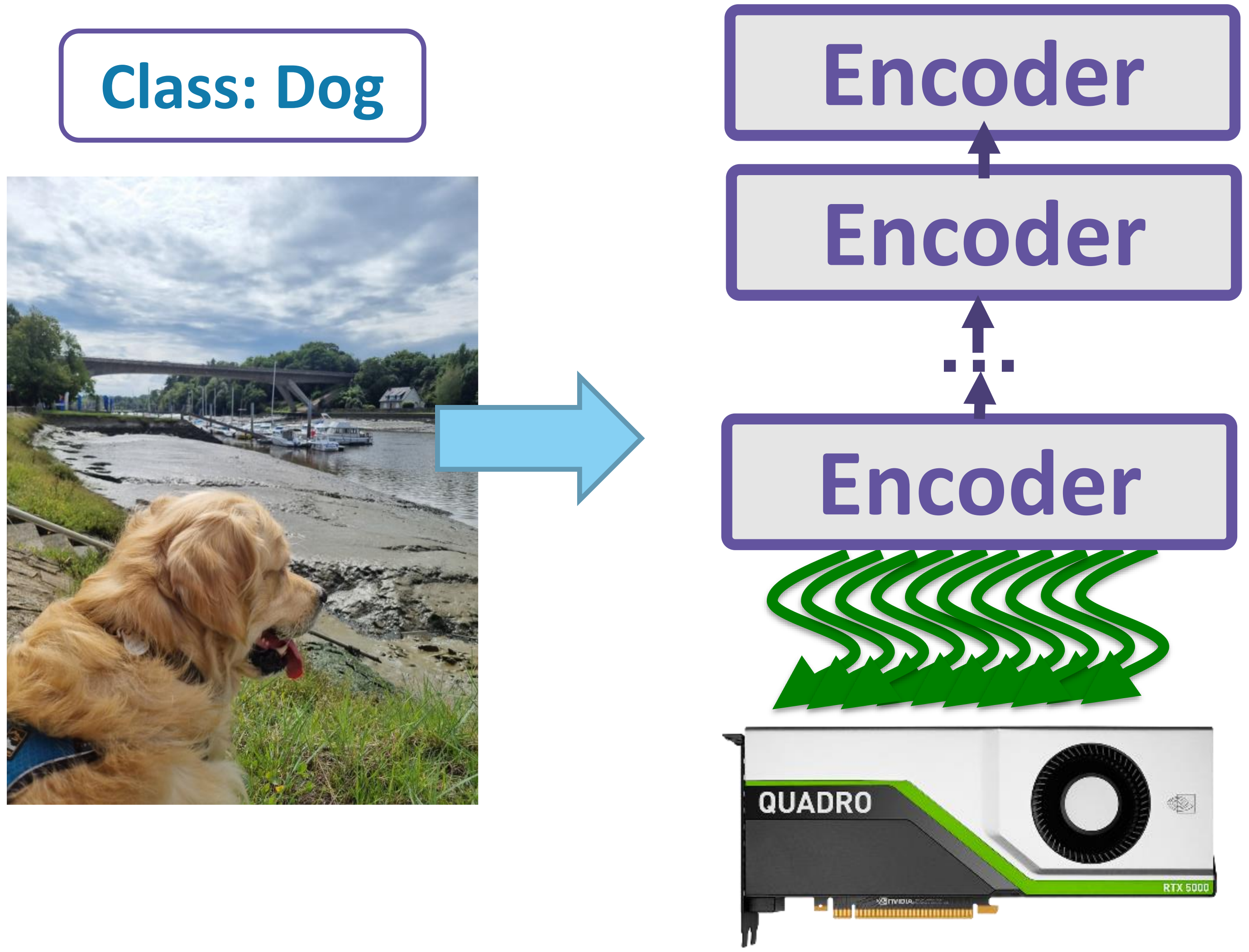
Efficient Fault Tolerance

Fault Impact on ViTs



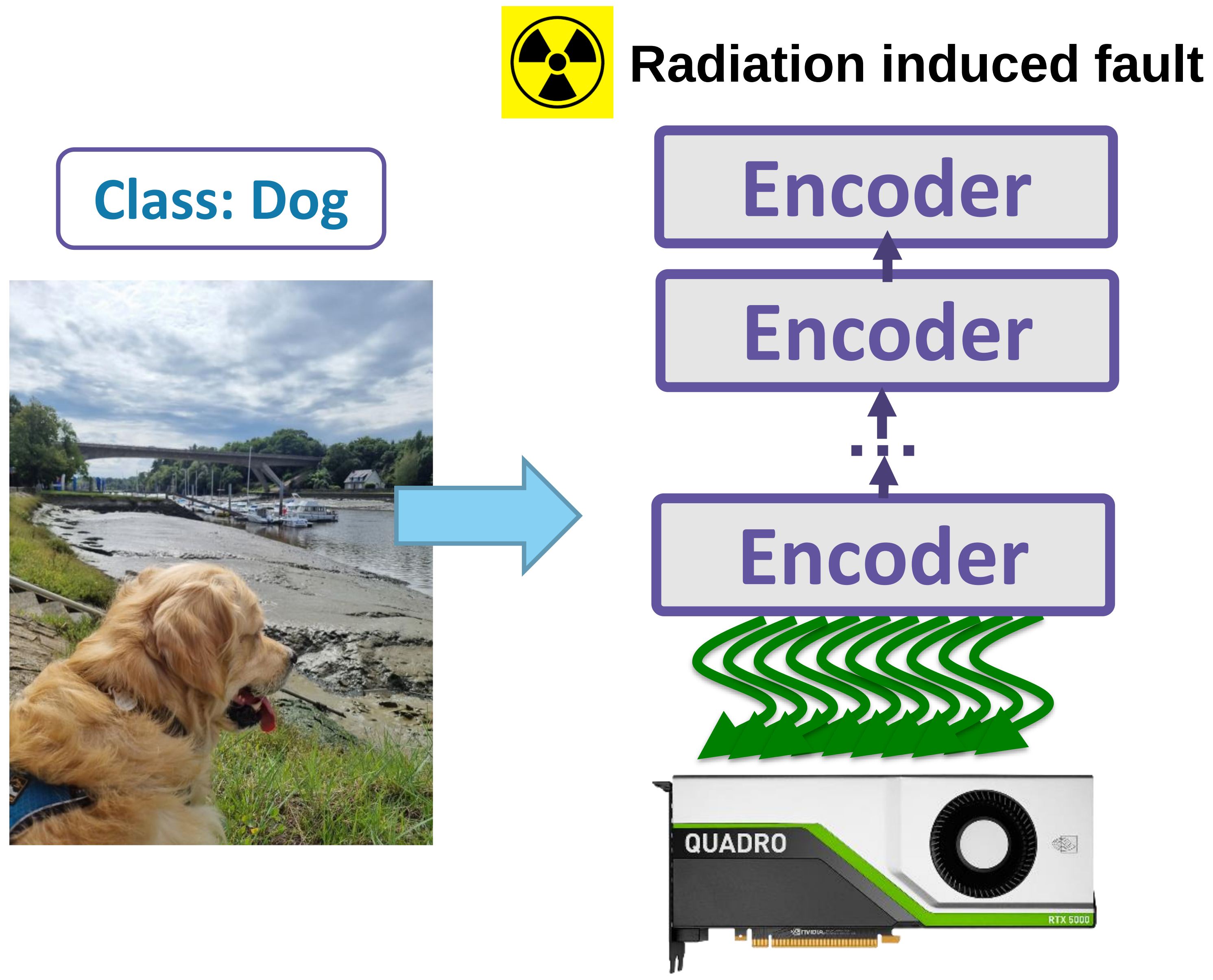
Class: Dog

Encoder

Encoder

Encoder

Fault Impact on ViTs



Radiation induced fault

Class: Dog

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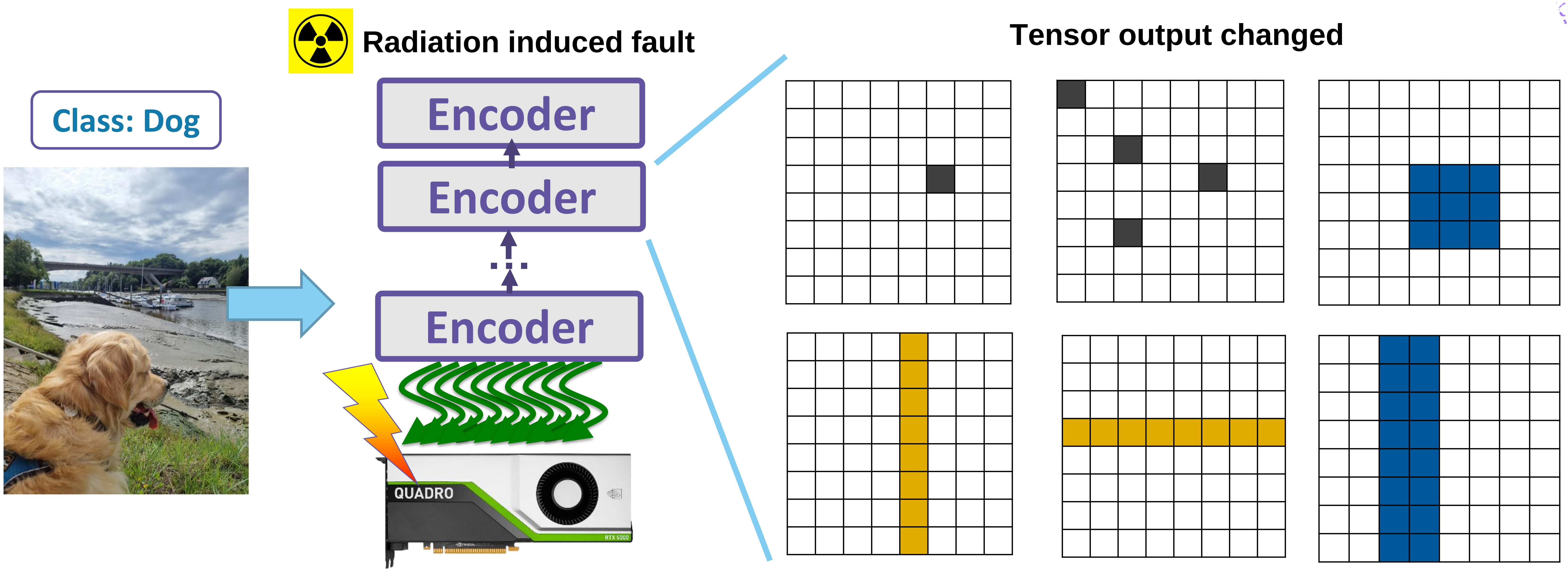
Encoder

Fault Impact on ViTs



Radiation induced fault

Tensor output changed

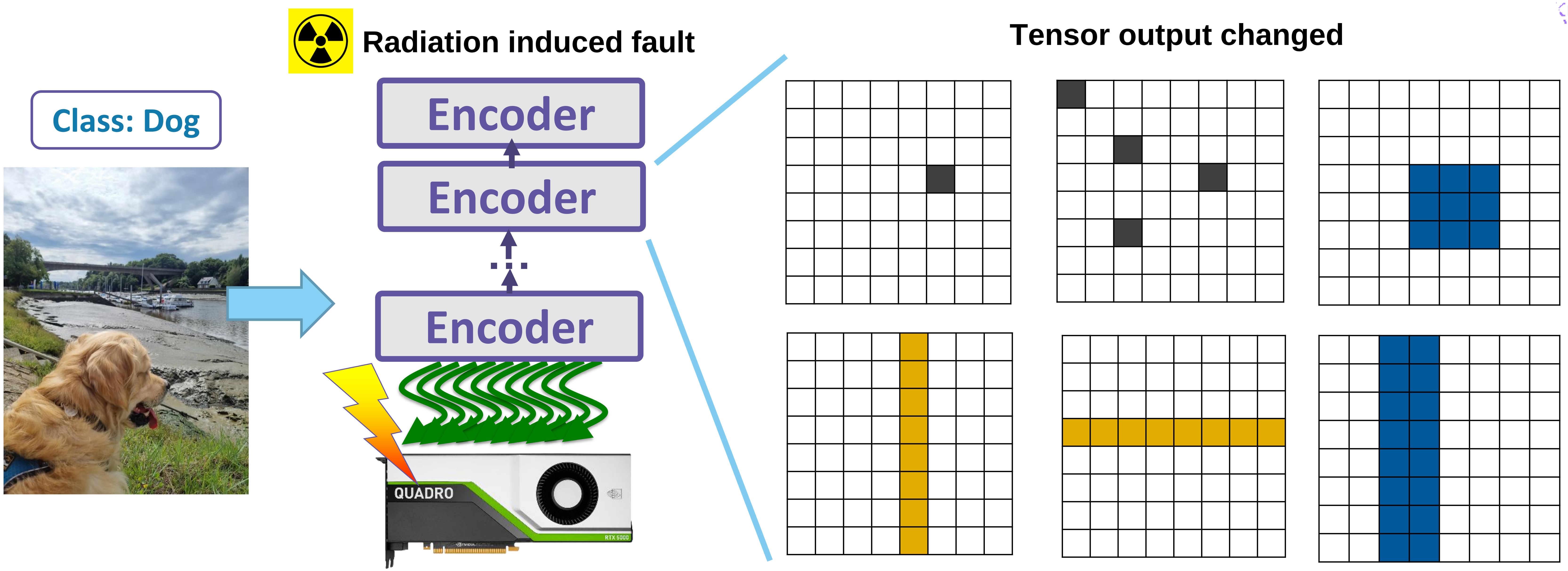
Class: Dog

Encoder

Encoder

Encoder

Fault Impact on ViTs



Fault assessement

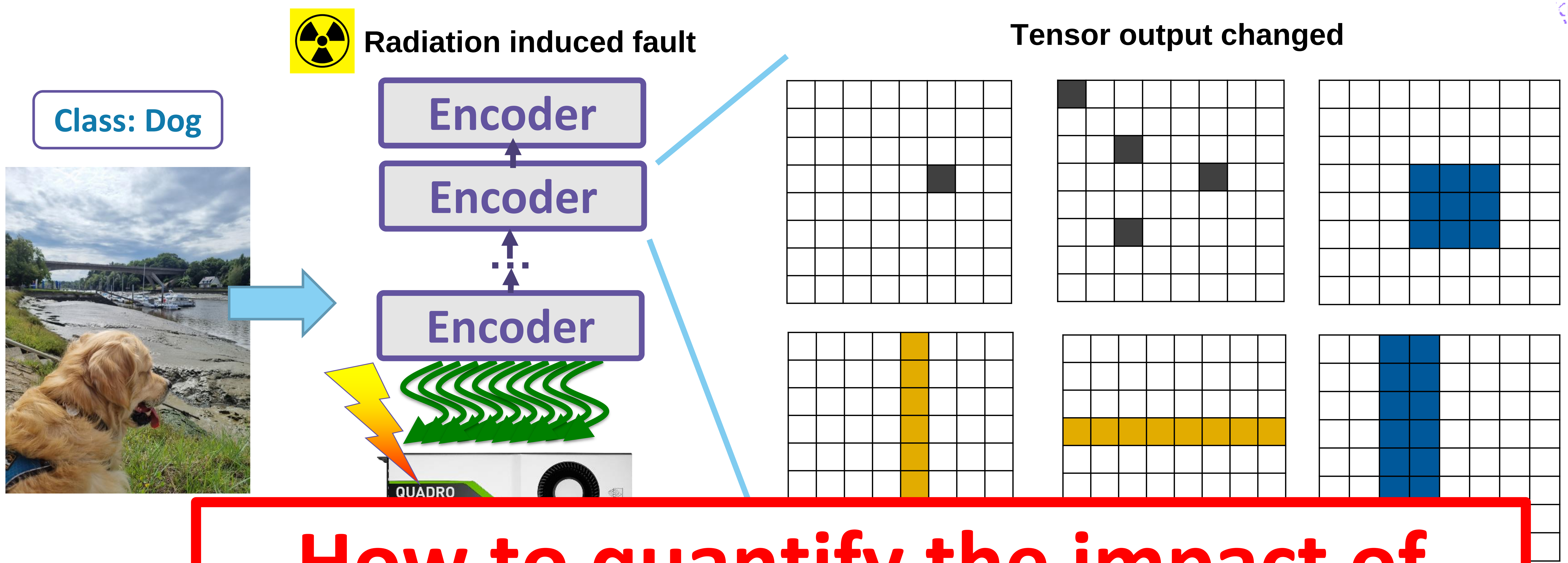
- Physical fault injection
- Software fault simulation

NVIDIA.

```
int foo(S,P){
  int r;
  if (S==P)
    r=1;
  else
    r=0;
  return r;
}
```

European Cyber Week

Fault Impact on ViTs



How to quantify the impact of faults ?

Fault

- Phys
- Software fault simulation

```
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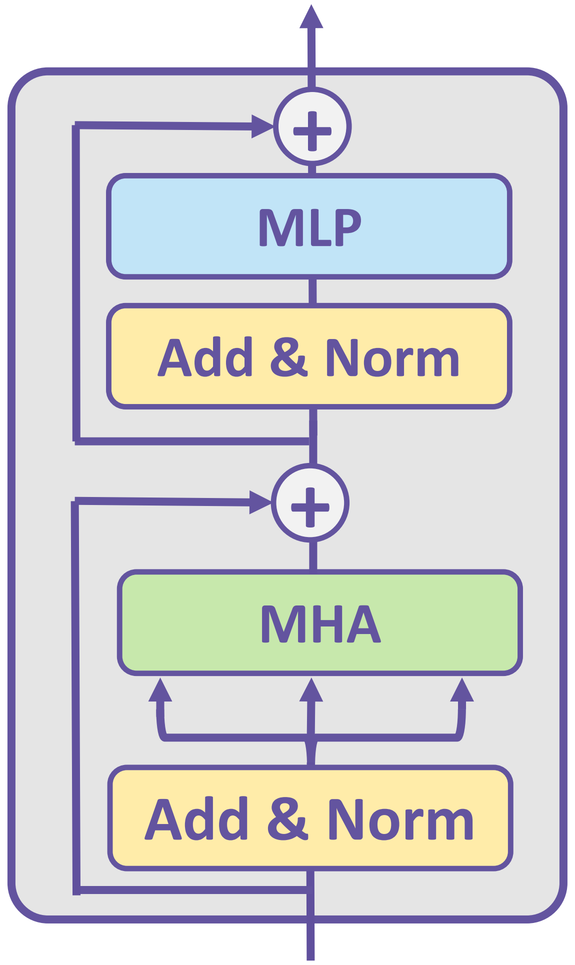
Fault Impact on ViT Operations

- We split the ViT into its essential operations
- We measure the FIT rate of each operation



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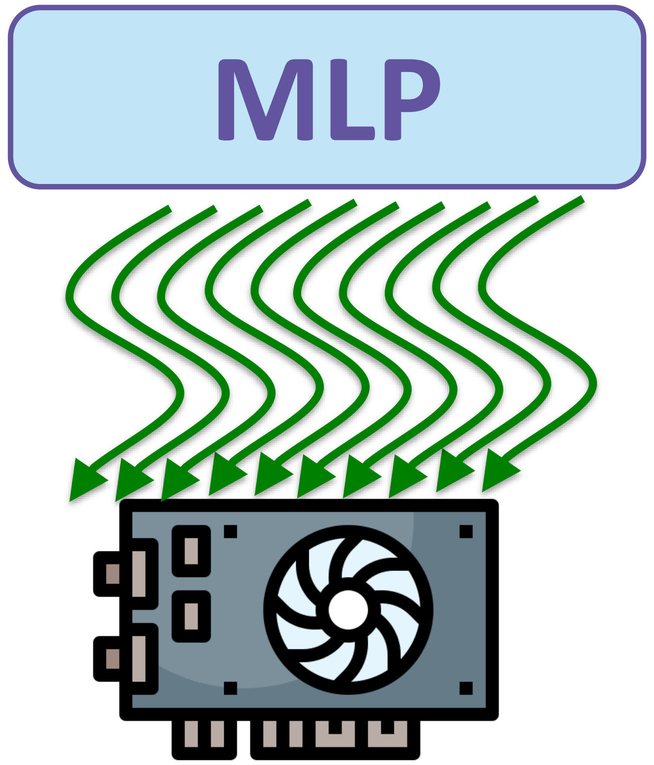

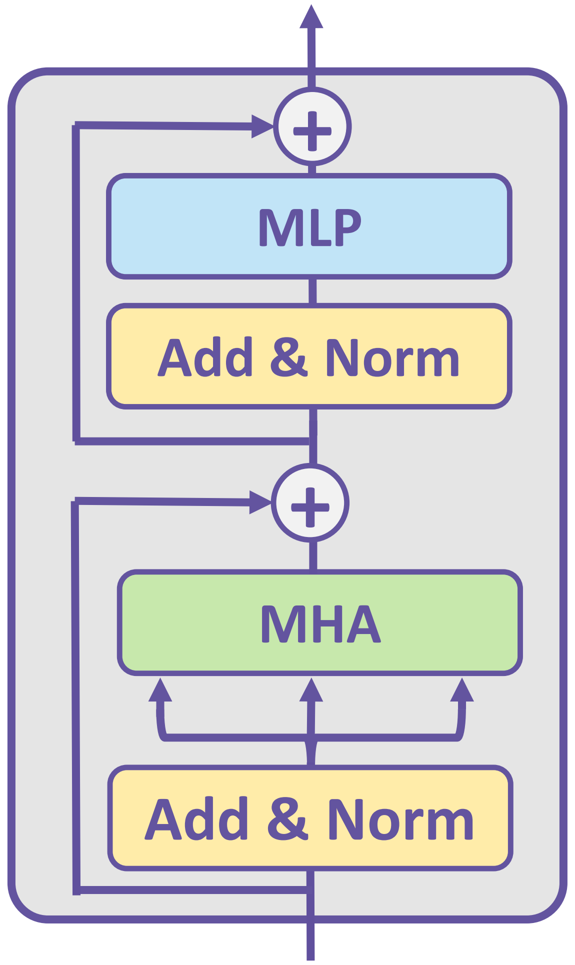

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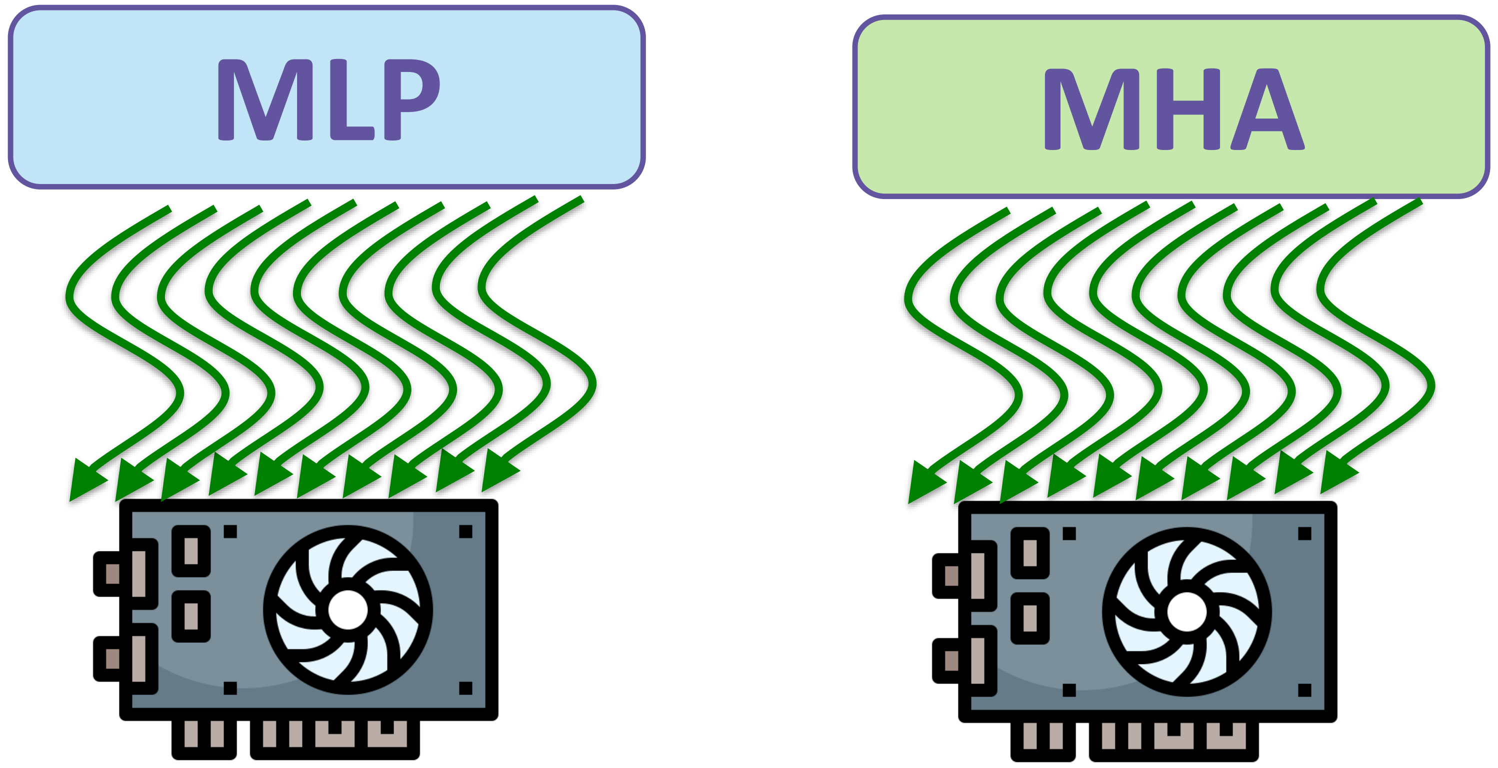

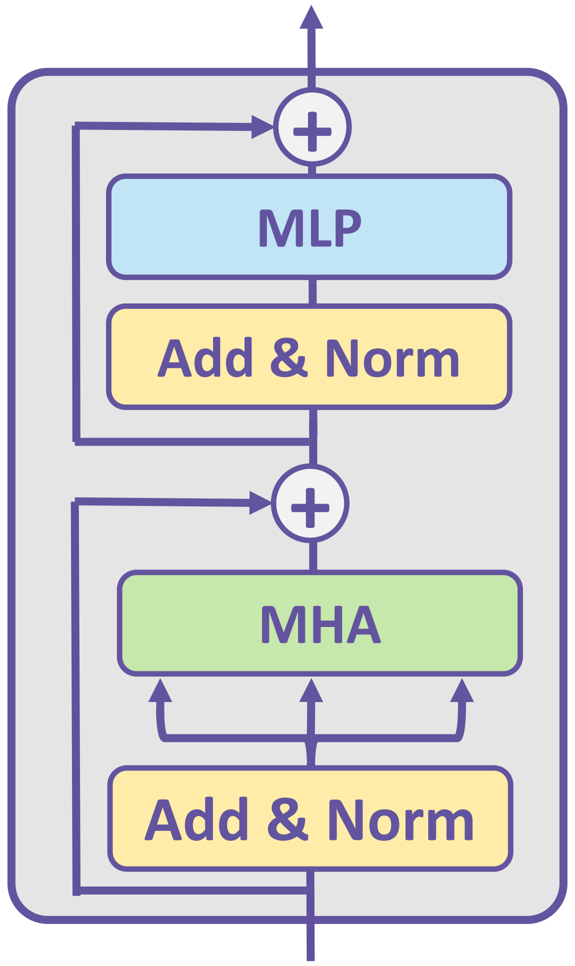

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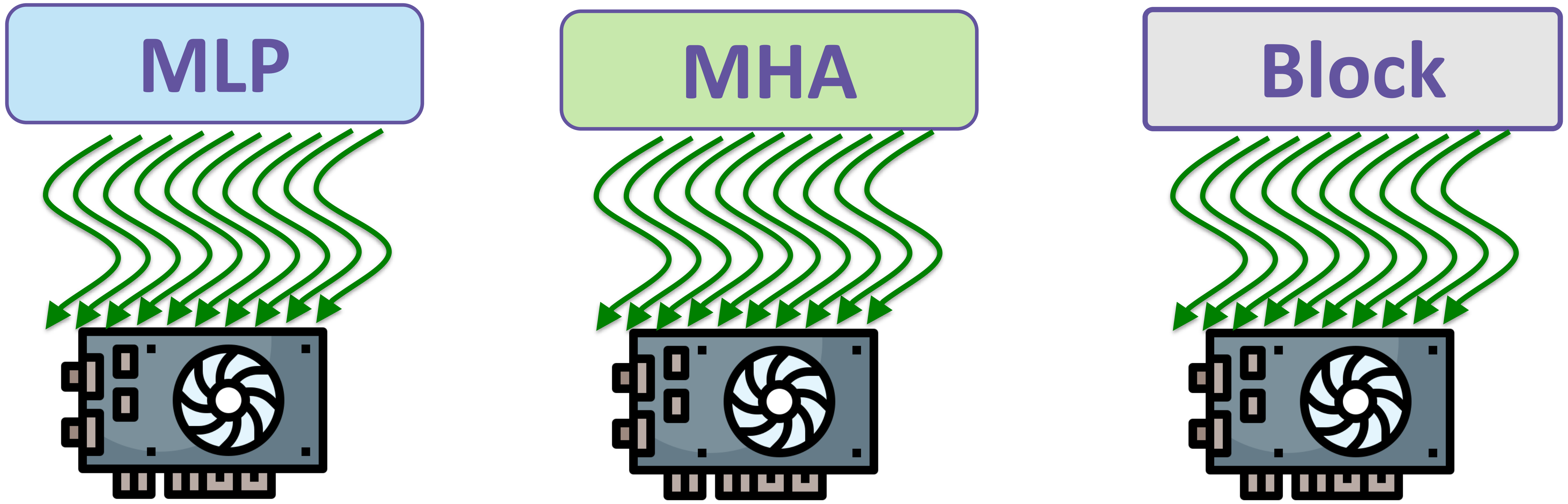

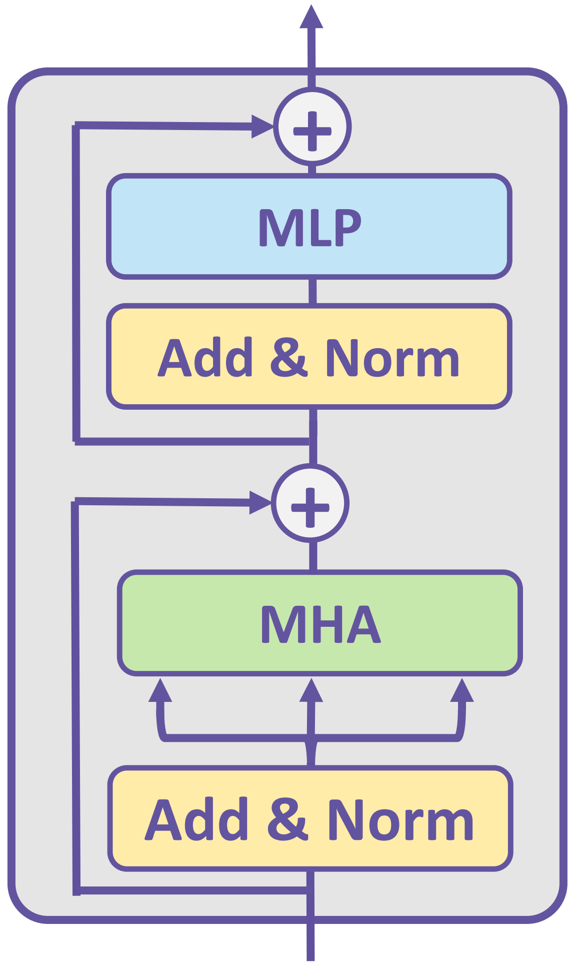

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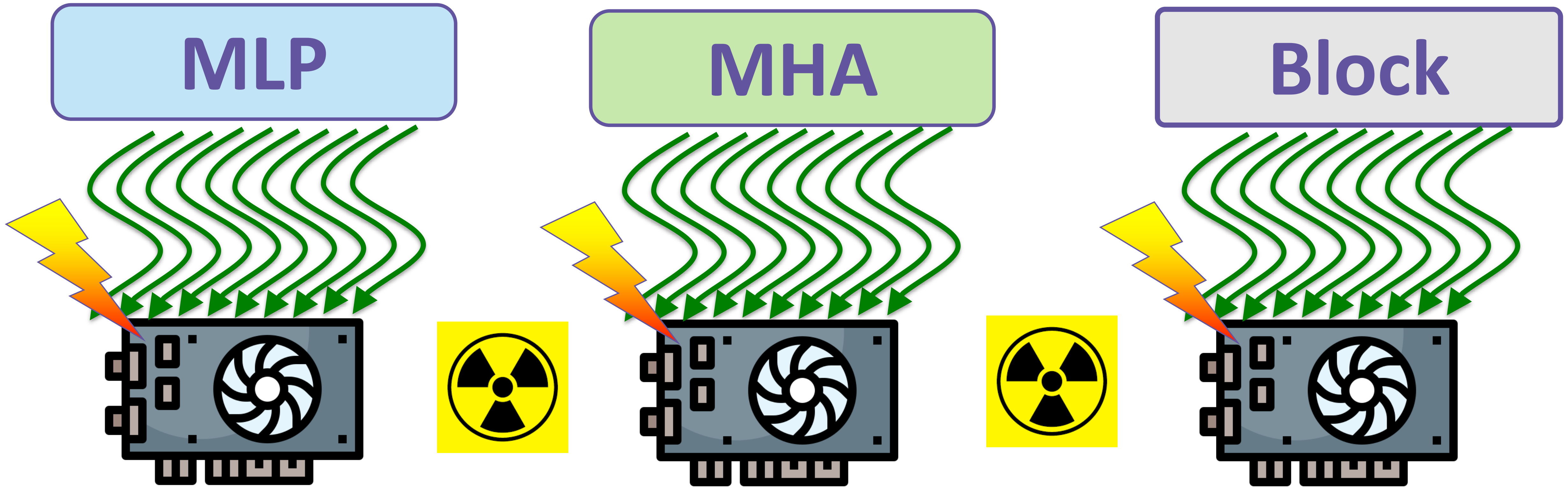

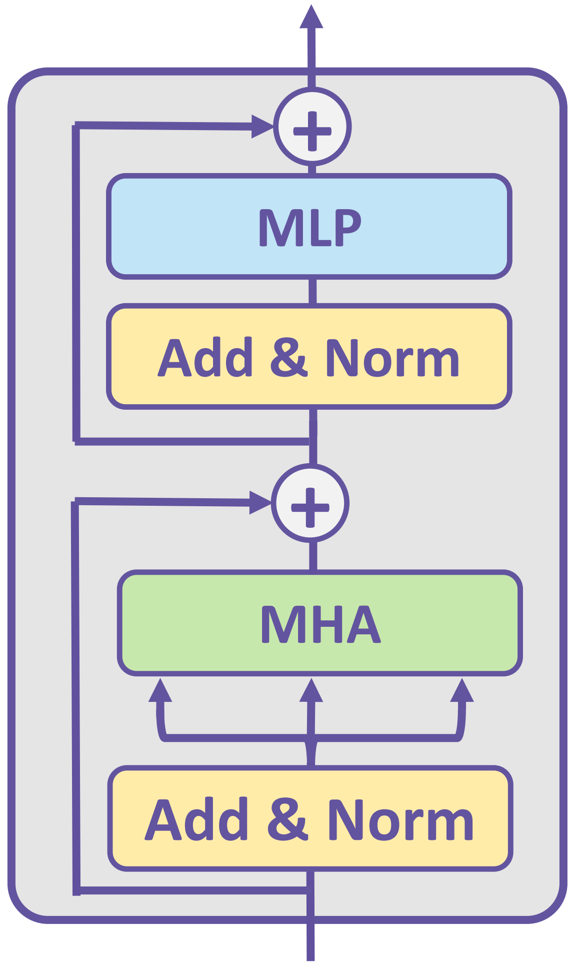

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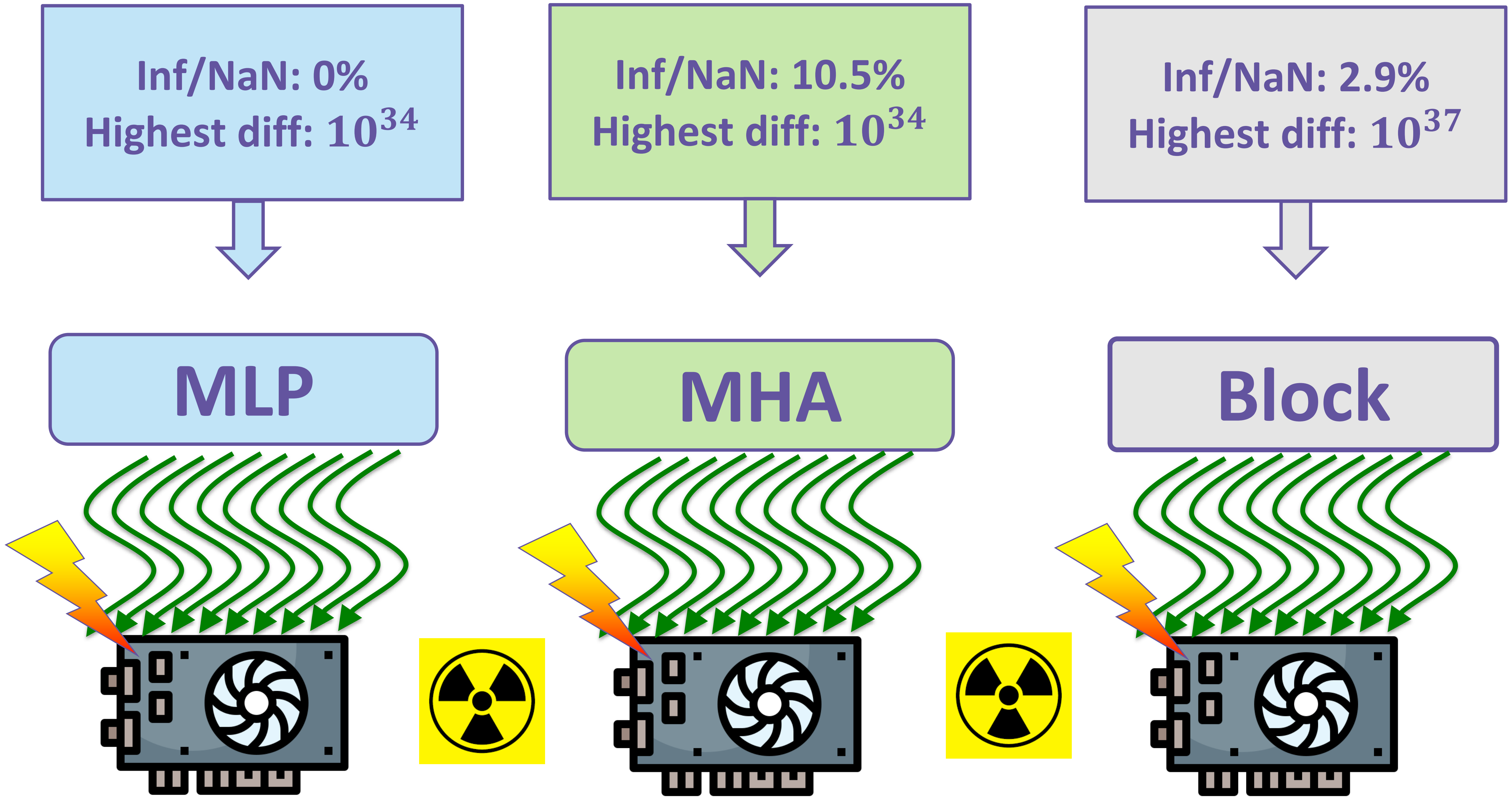
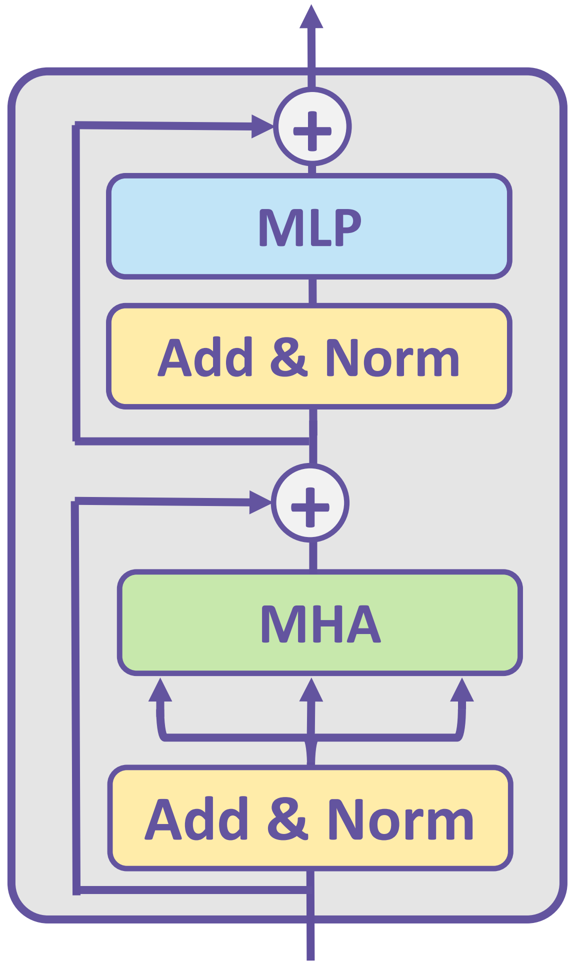
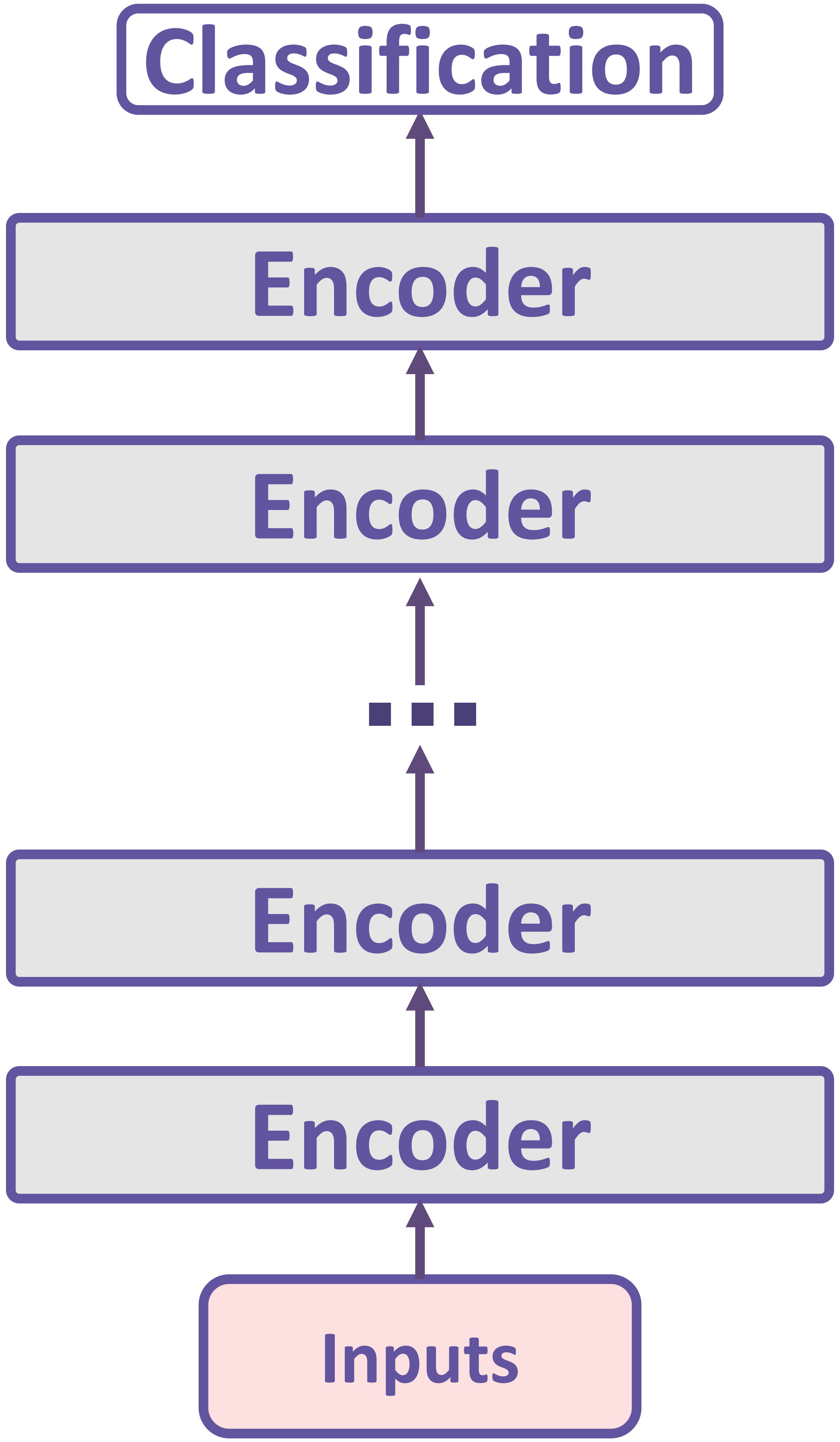




MaxiMals Idea



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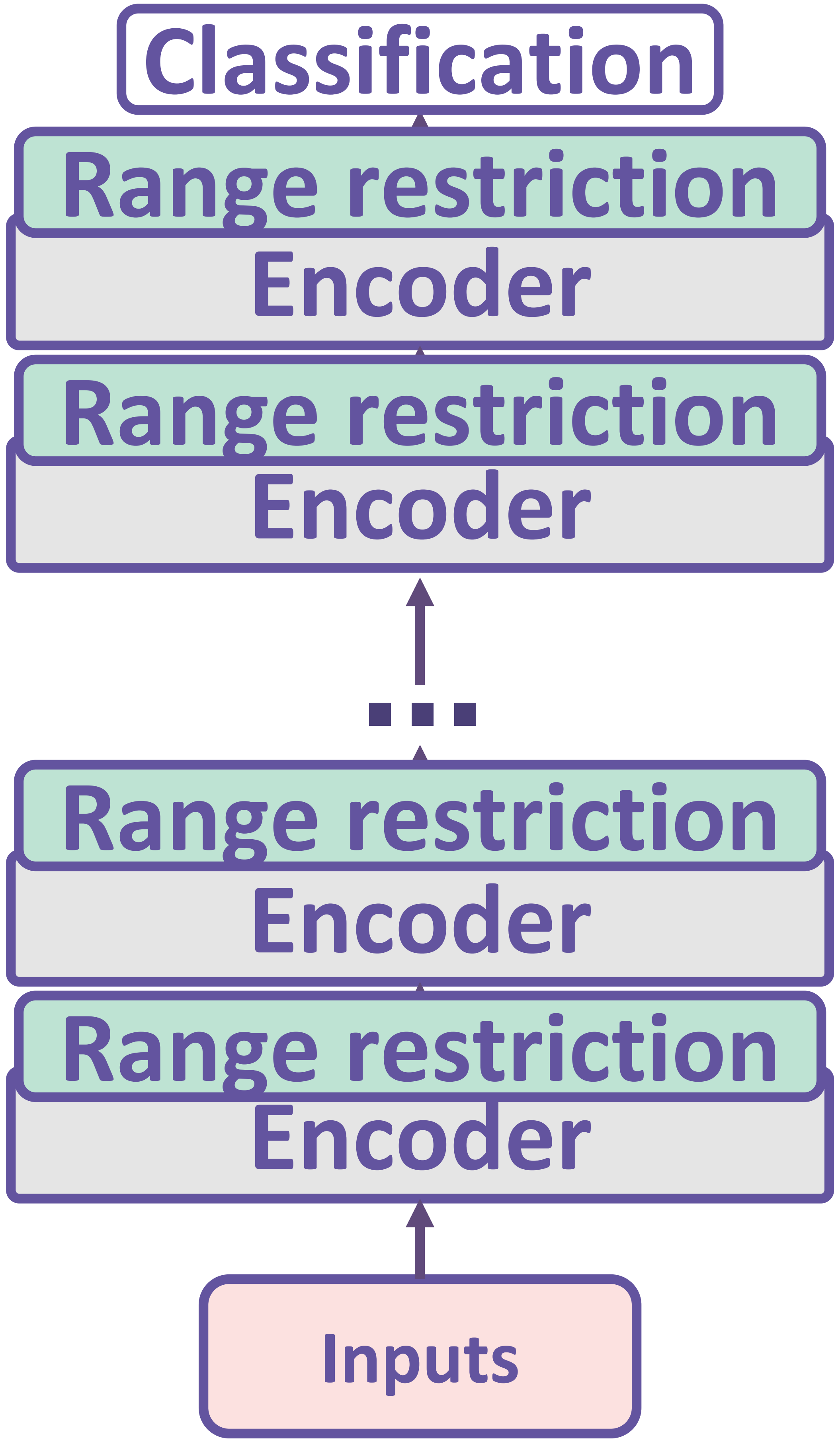

Classification

Range restriction

Encoder

Range restriction

Encoder

...

Range restriction

Encoder

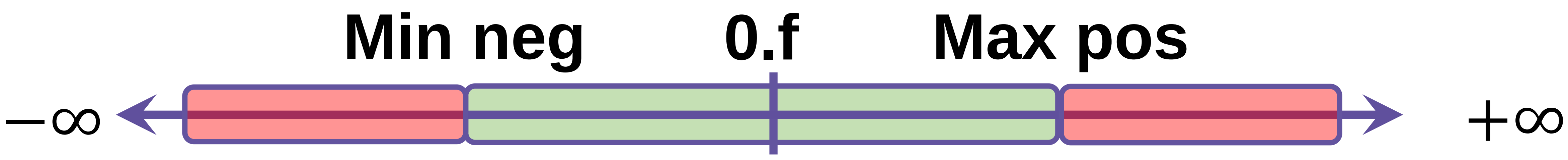
Range restriction

Encoder

Inputs

Range Restriction is a common hardening technique

🟩 Safe values 🟥 Values that may change the classification



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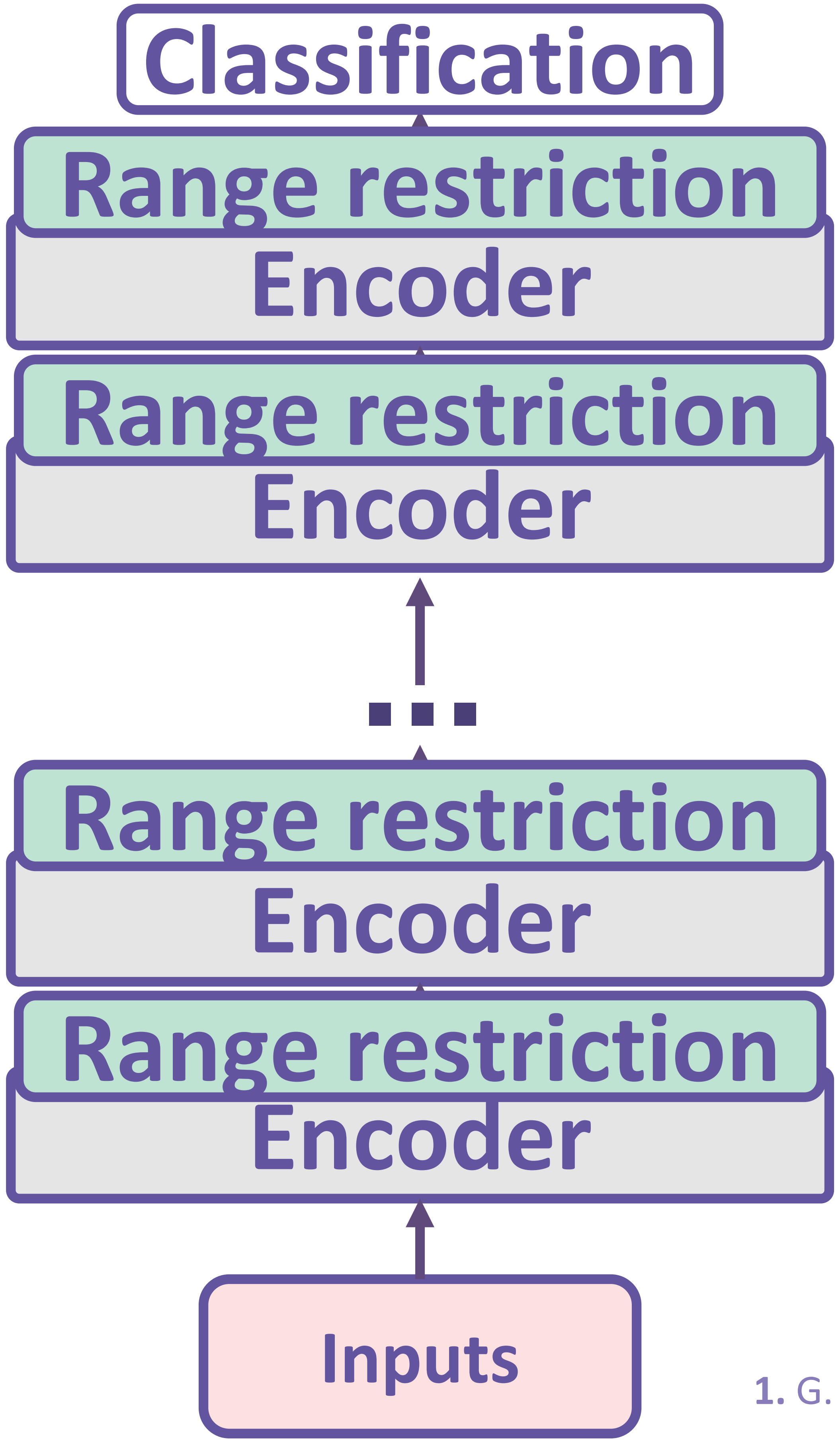

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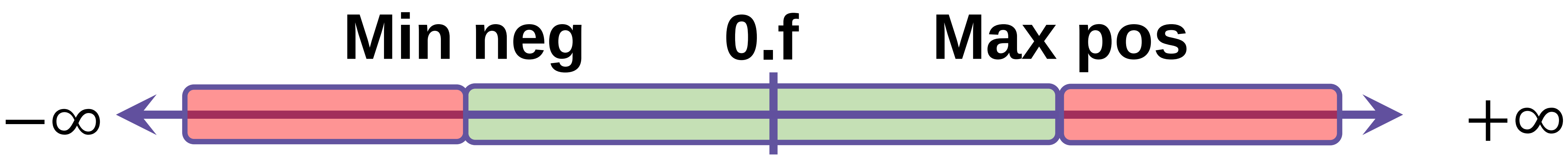
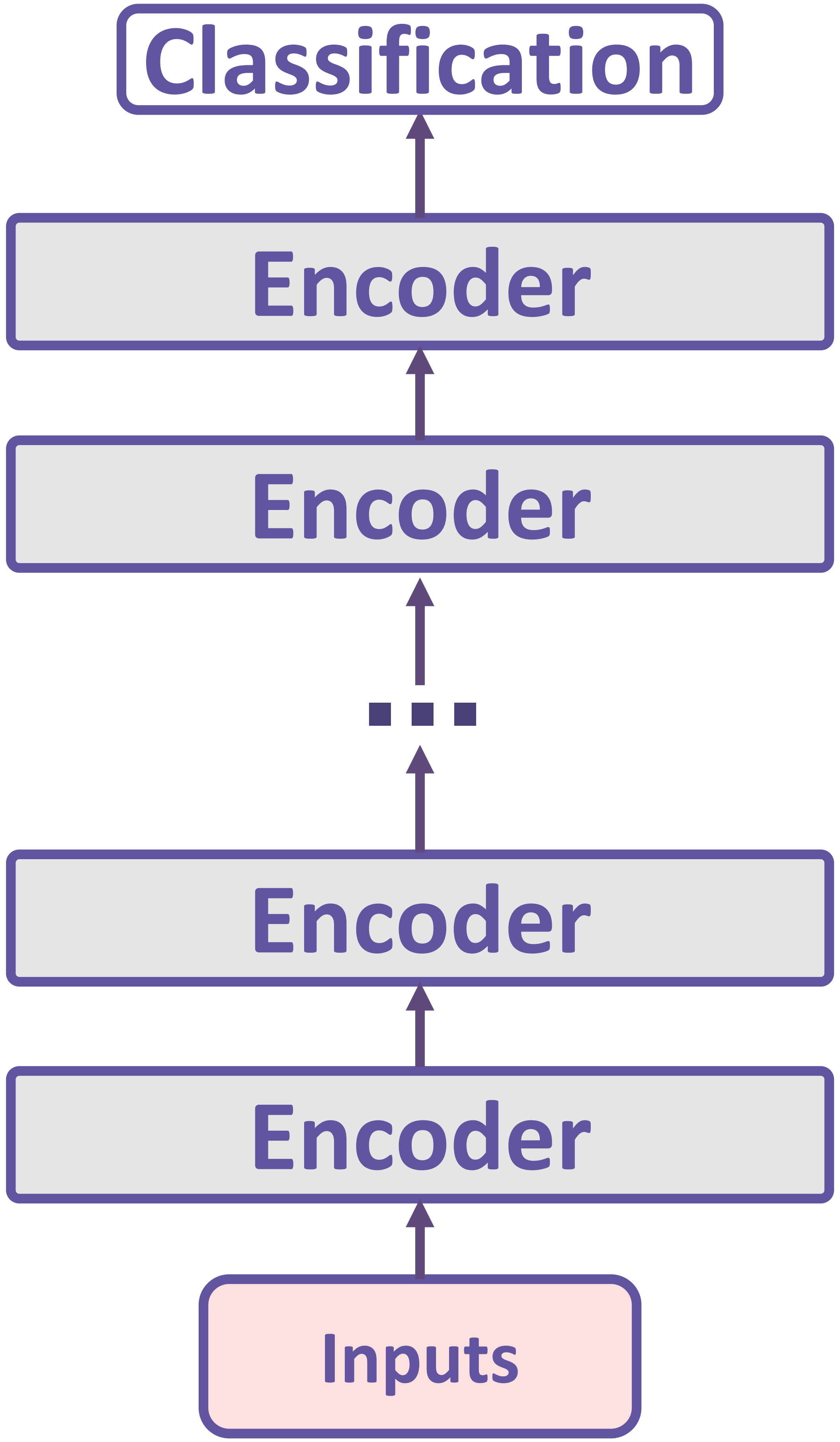


68% time overhead if applied on every block of a ViT[1]

[1] G. Gavarini *et al.* "**Evaluation and mitigation of faults affecting swin transformers**" – IEEE IOLTS 2023

MaxiMals Idea



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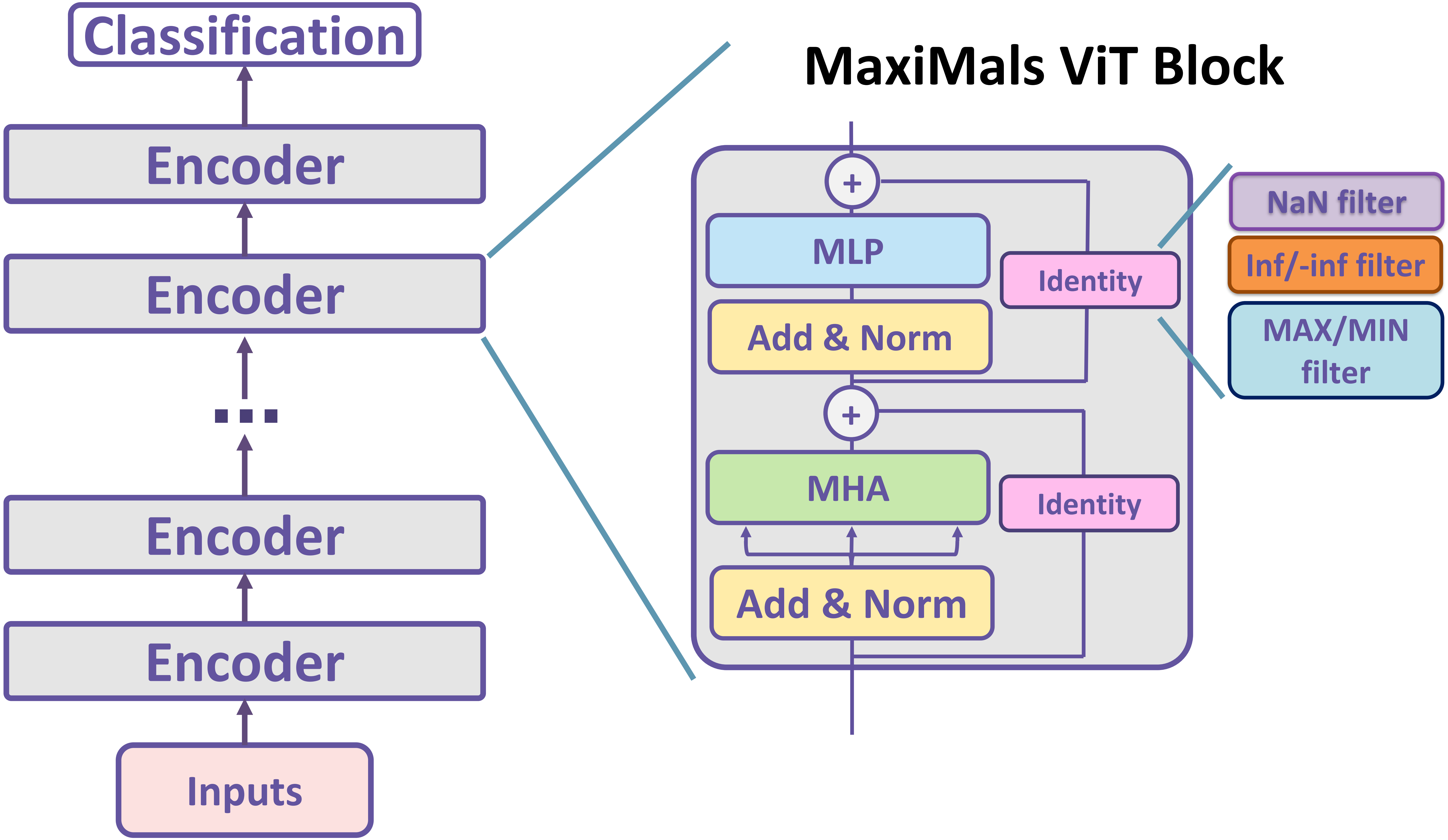
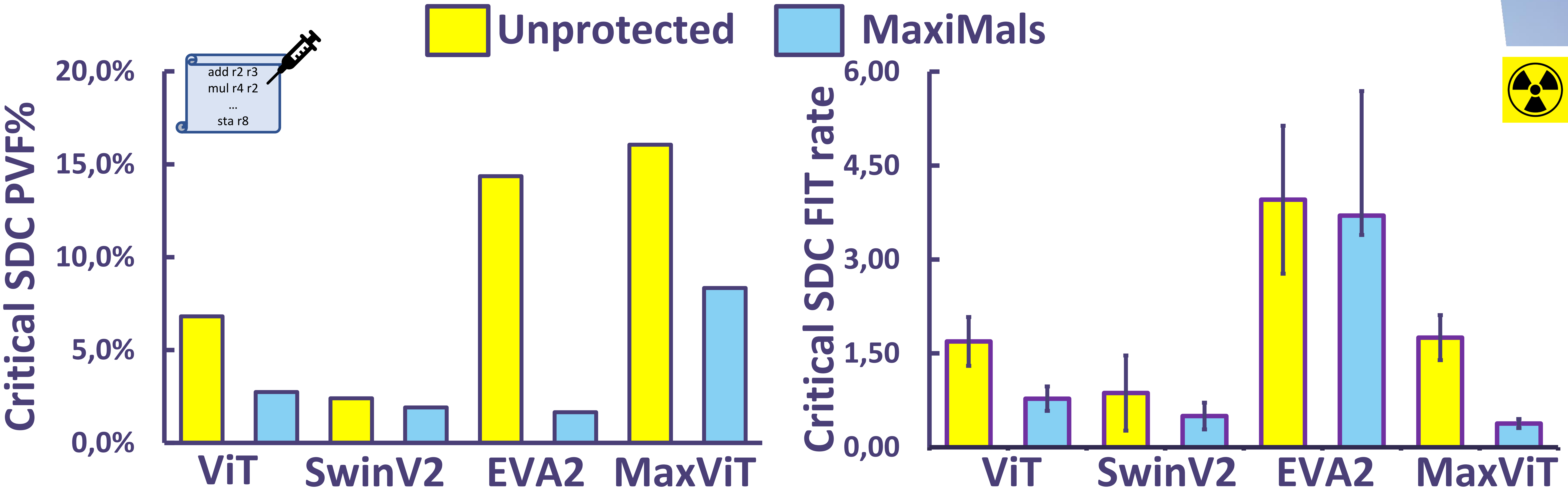
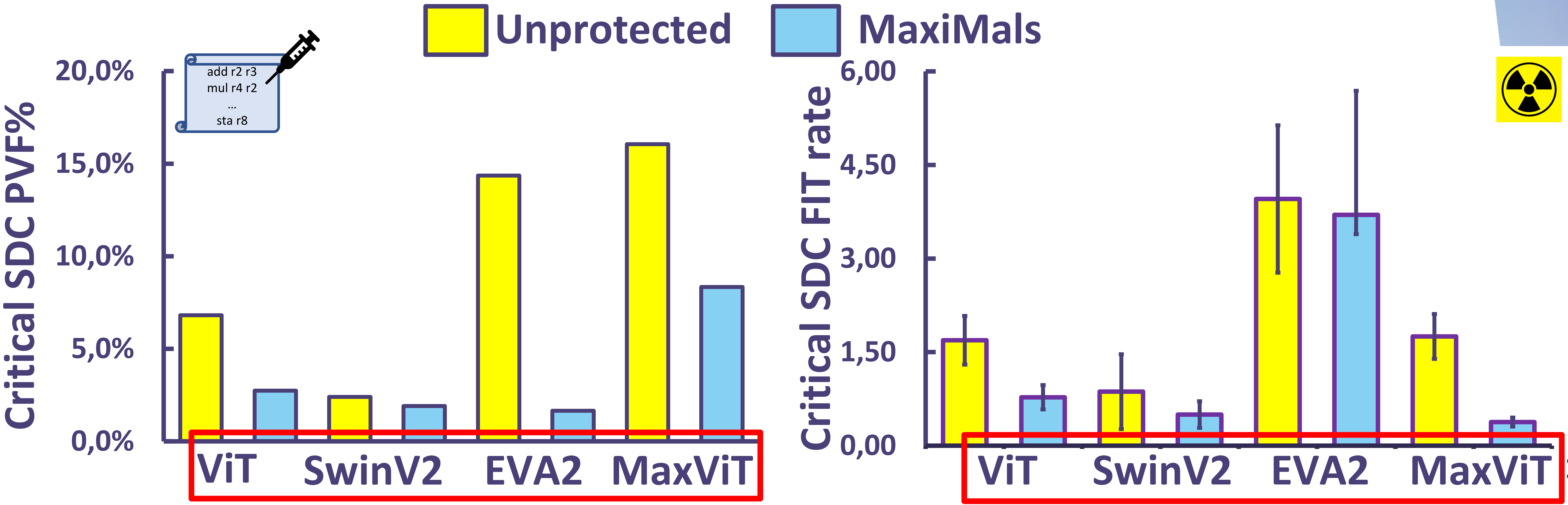


MaxiMals Efficiency



```
add r2 r3
mul r4 r2
...
sta r8
```

MaxiMals Efficiency



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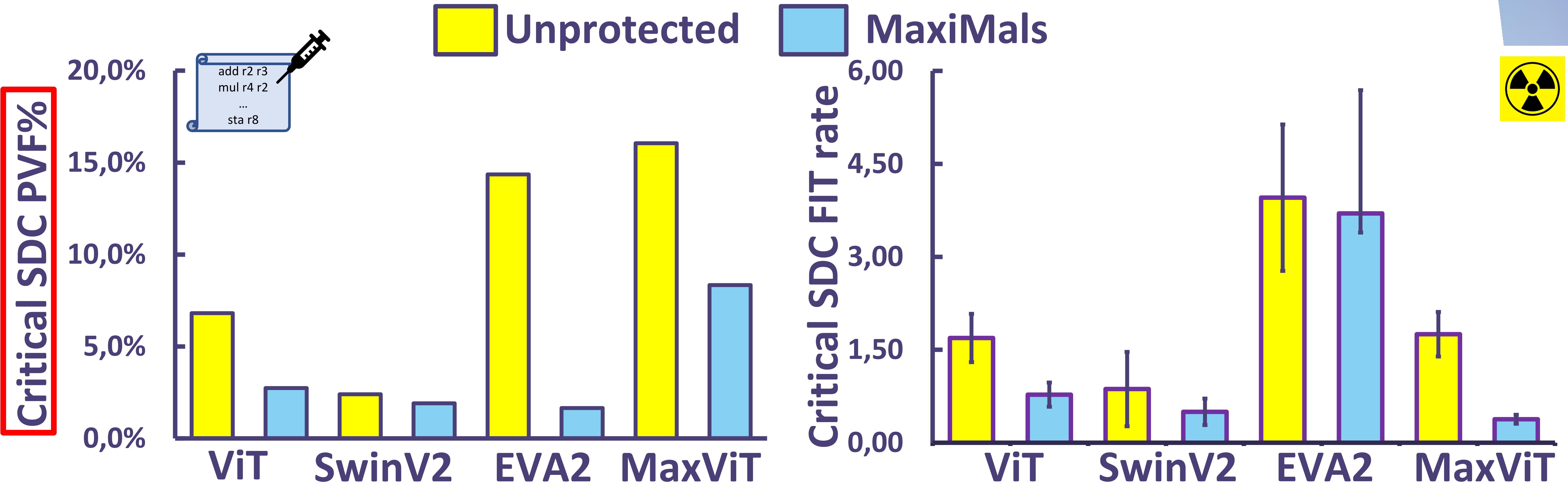

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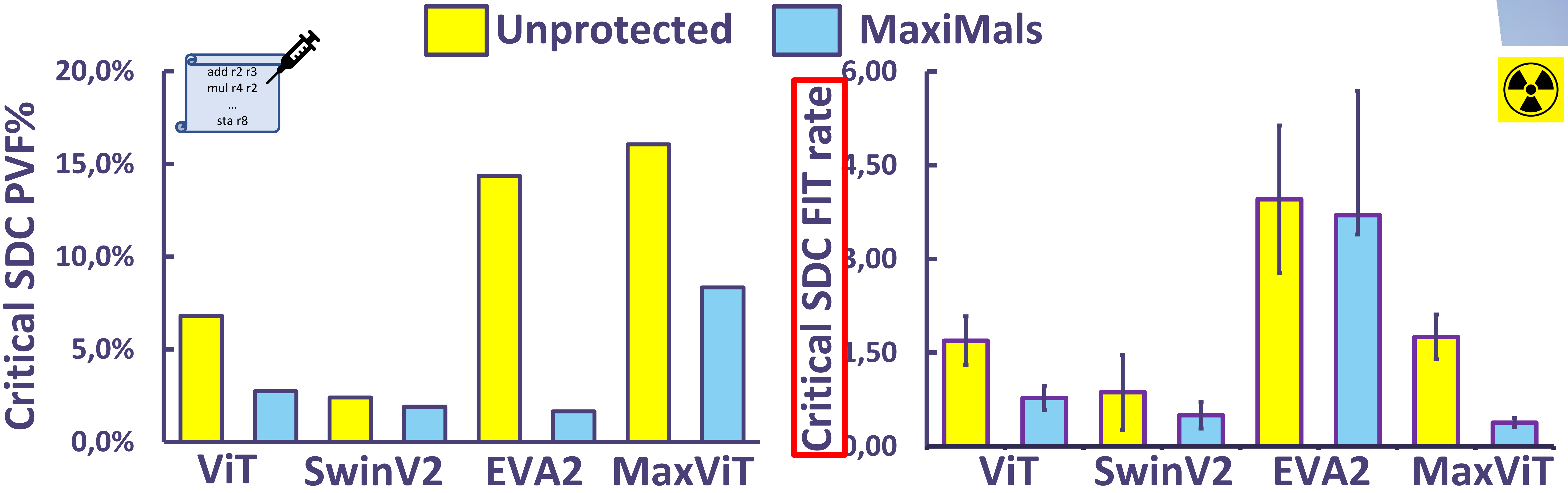

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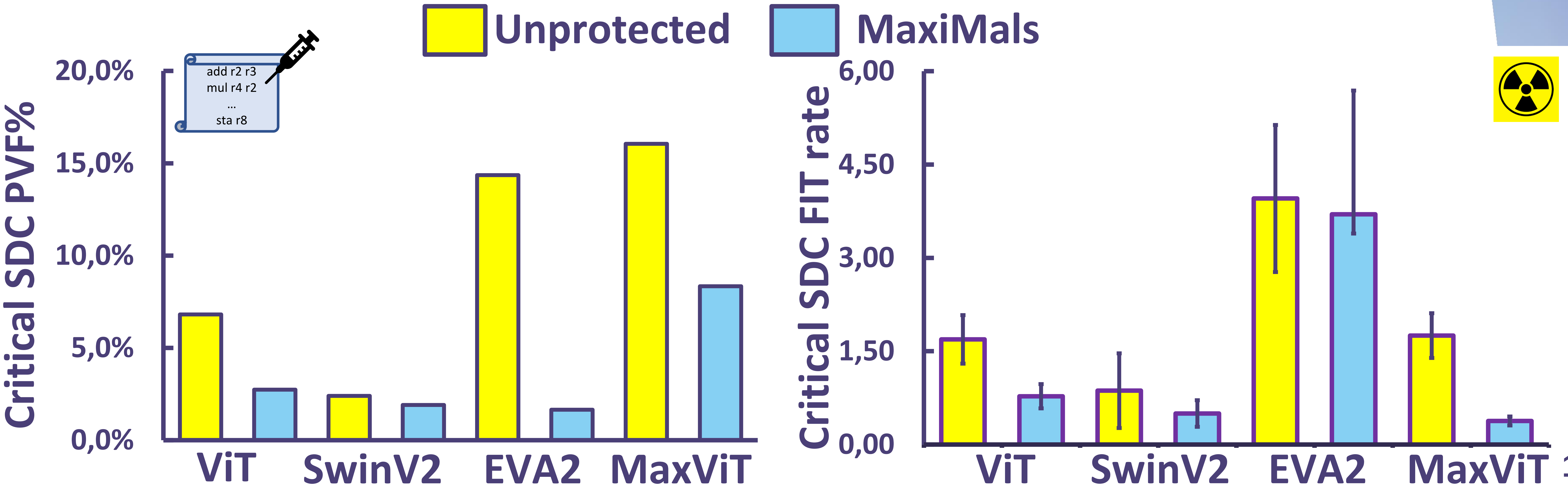

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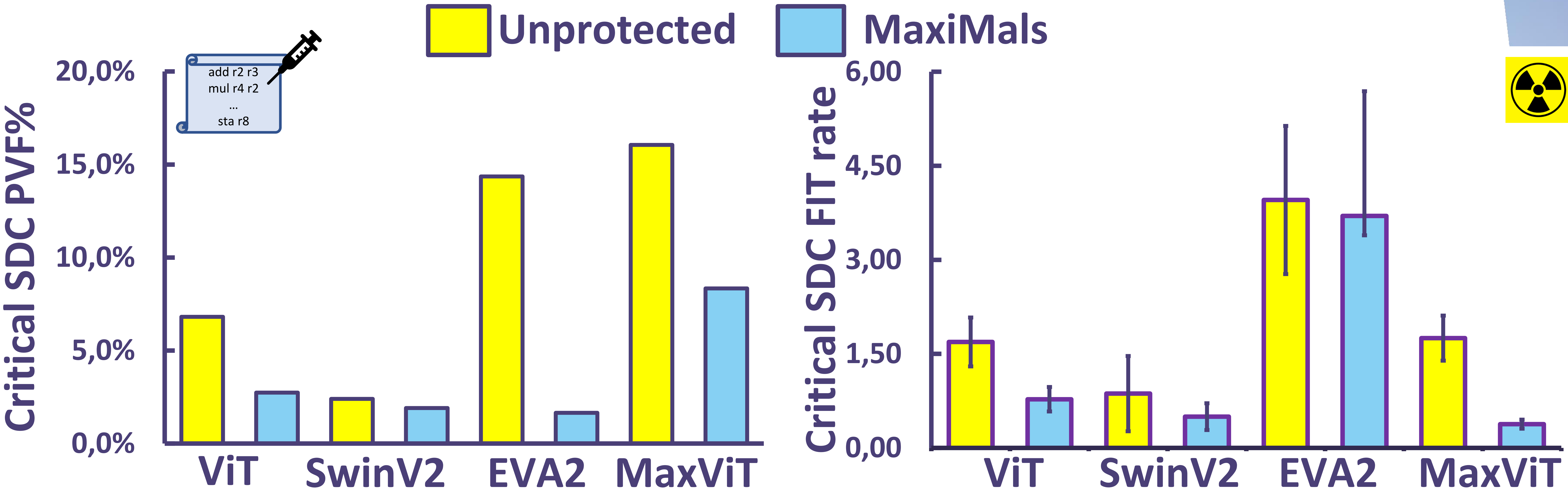
MaxiMals Efficiency

Fault Simulation:

- Injections with NVBitFI
- Critical SDCs are reduces by half on average



MaxiMals Efficiency

Fault Simulation:

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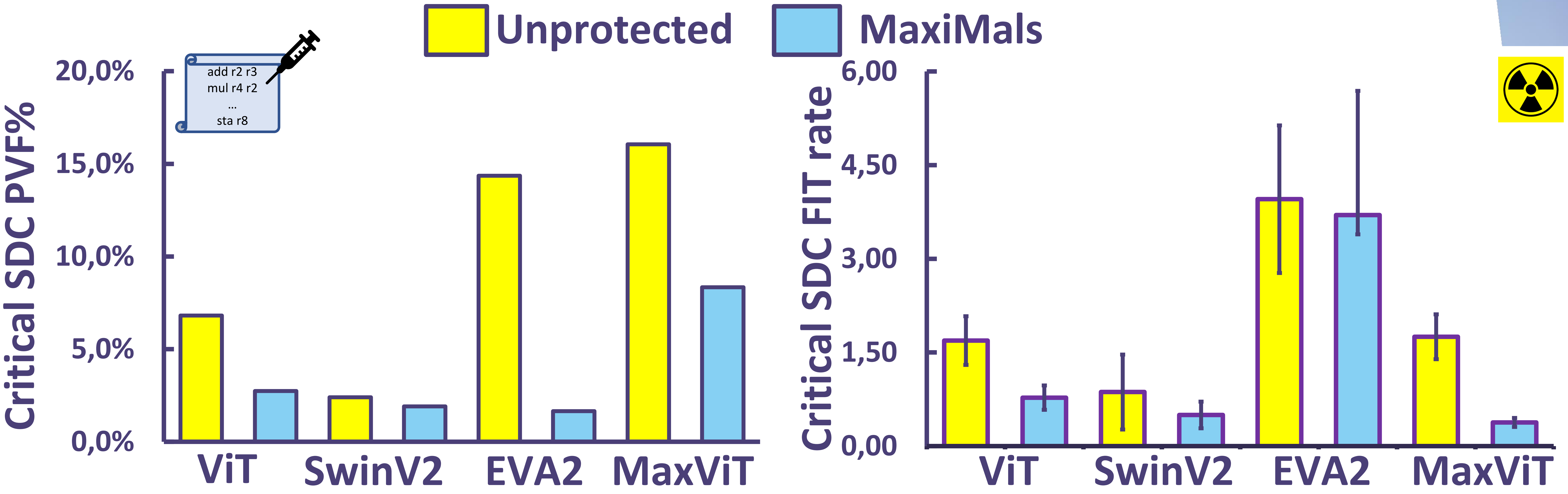
Beam injection:

- Similar reduction for beam
- Similar trend on FP16



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```
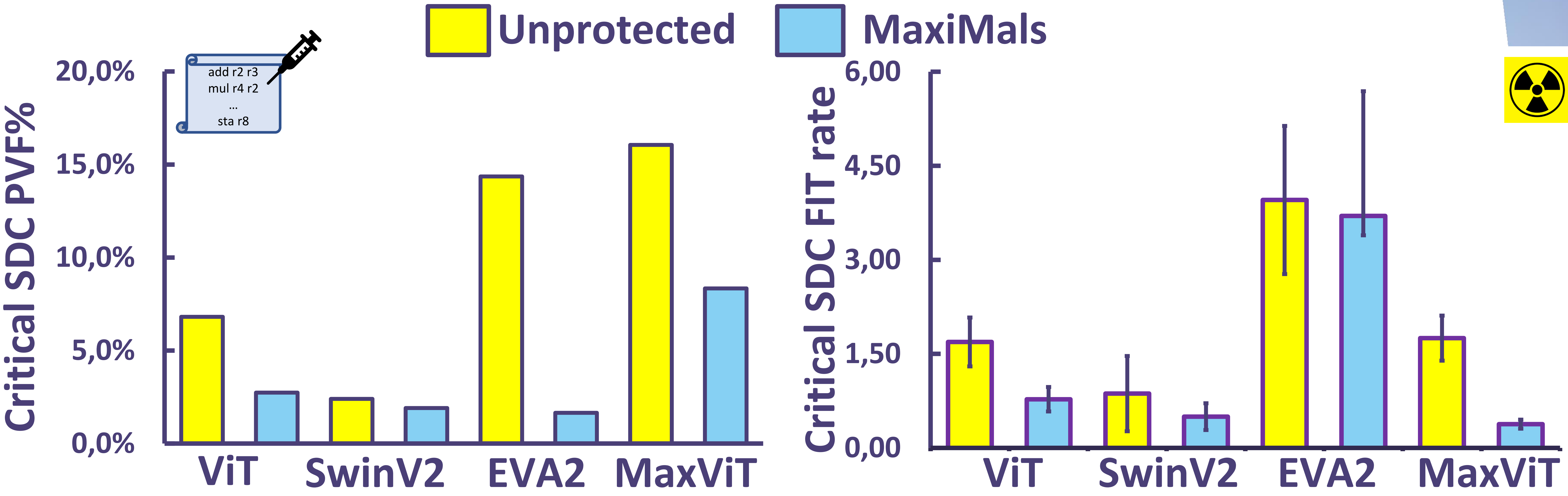

MaxiMals Efficiency

Average overhead:

- **Time: 7.1% (max. 16.1%)**
- **1.6% of additionnal instructions**



Conclusions and Future Directions

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- ViT are vulnerable even if ECC is enabled (up to 10%)

MaxiMals

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- Low overhead compared to similar techniques (max. 16%)

Future works

- Impact on INT8 precision
- Dependency between inputs and Critical SDC rates
- Other fault models:
  - different particles
  - HW attacks (RowHammer)

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Thank you ！

Questions ?

Contact: lucas.roquet@inria.fr