PINNs methods for the study of the magnetosphere of compact objects

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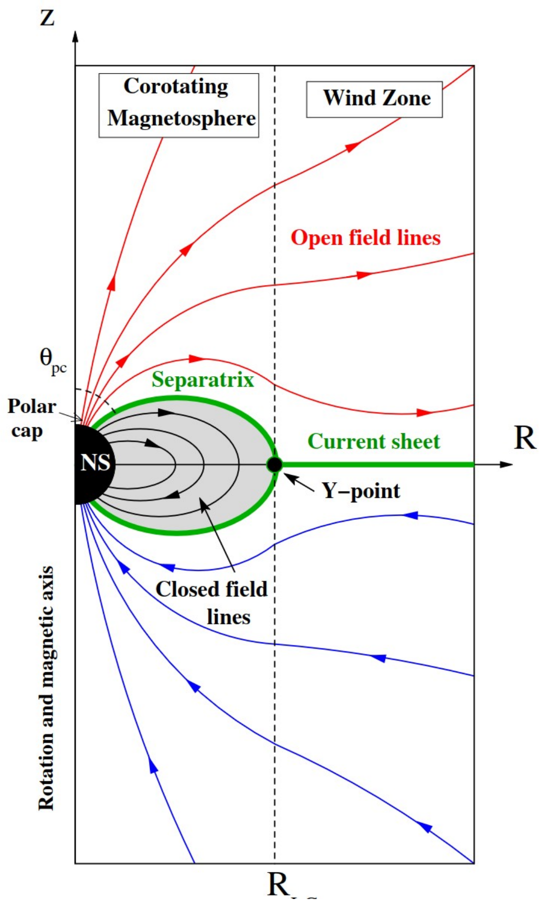
Magnetosphere of compact objects

- Important to understand the EM emission of compact objects, e.g. pulsars, magnetars, GRB, …

- To do so, multiple methods have been used → force free simulations, PIC, etc.



Cerutti and Beloborodov ‘16

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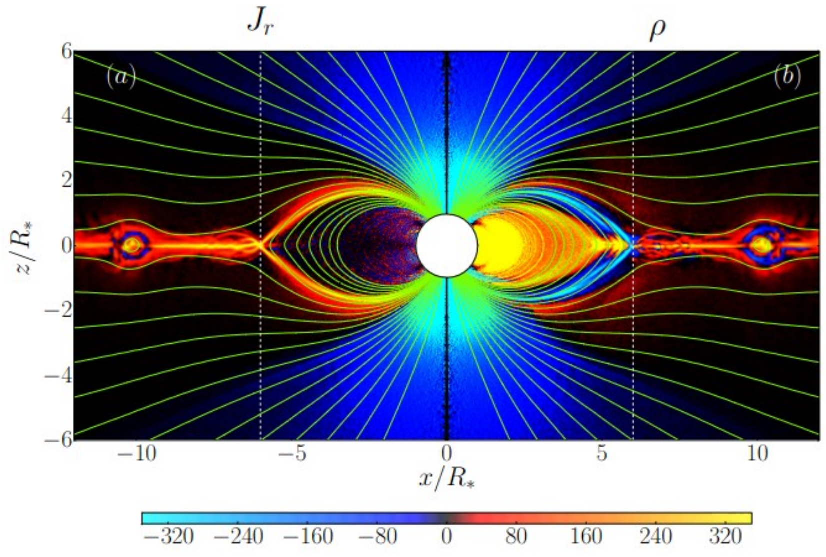

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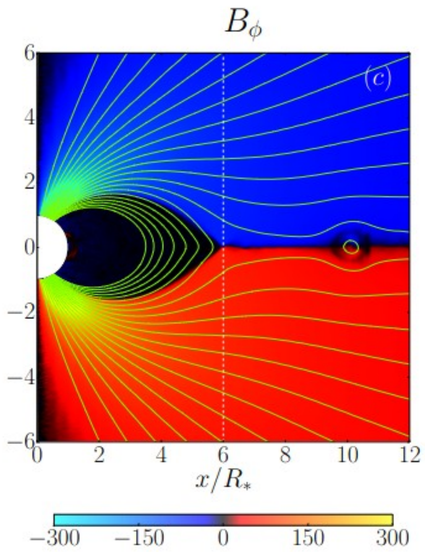


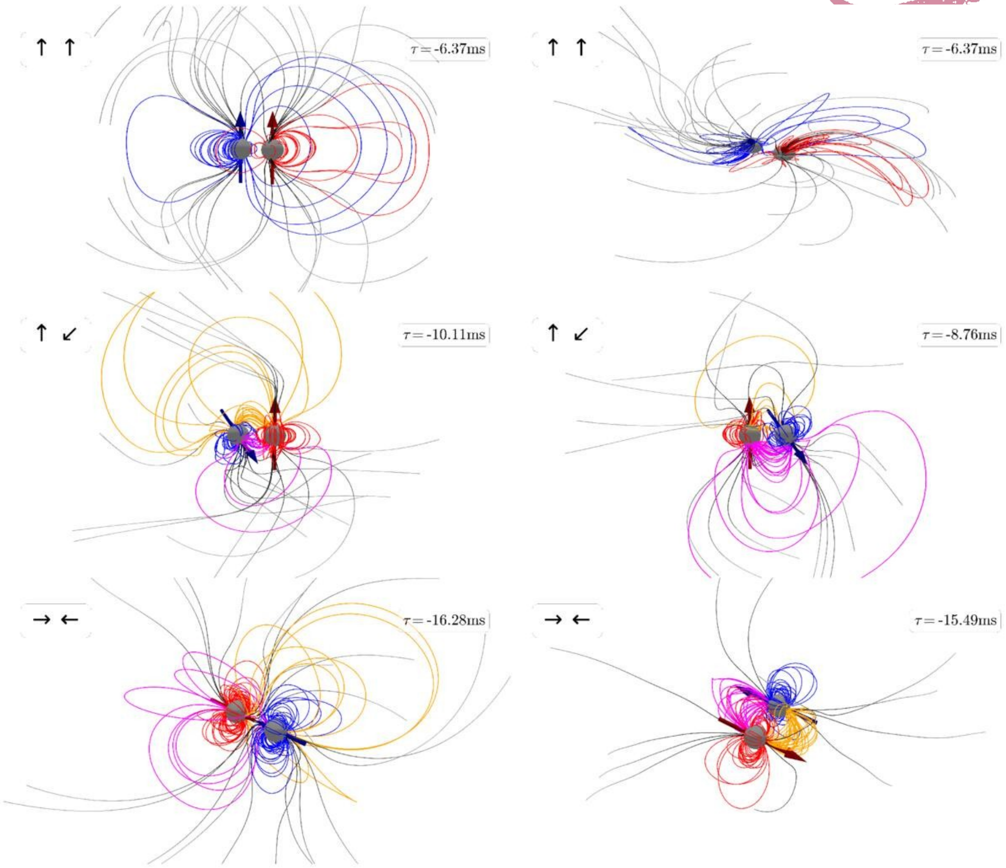
Chen and Beloborodov '14

Magnetosphere of compact objects

- Era of multimessenger astronomy will bring a lot of new phenomena to the front

- e.g. interaction of magspheres in BNS (c.f. Skiathas et al. ‘25, Parsons et al. ‘26)

- Large parameter space → big computational cost

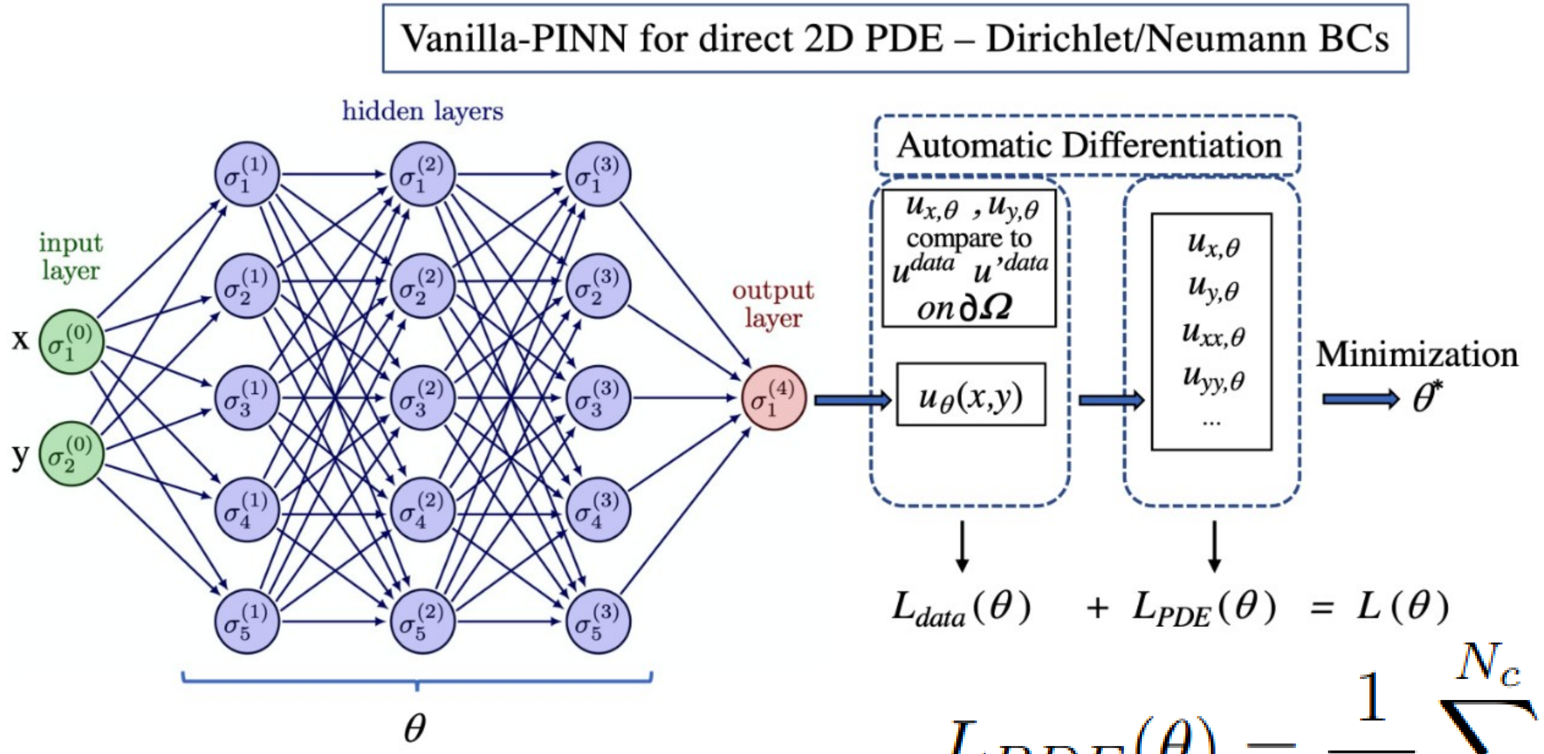


Skiathas et al., ‘25

Physics-informed Neural Networks (PINNs)

- PDEs to solve

$$\mathcal{F}(u, x, \mu, u_x, \ldots) = 0, \quad x \in \Omega, \quad \mu \in \Omega_p,$$



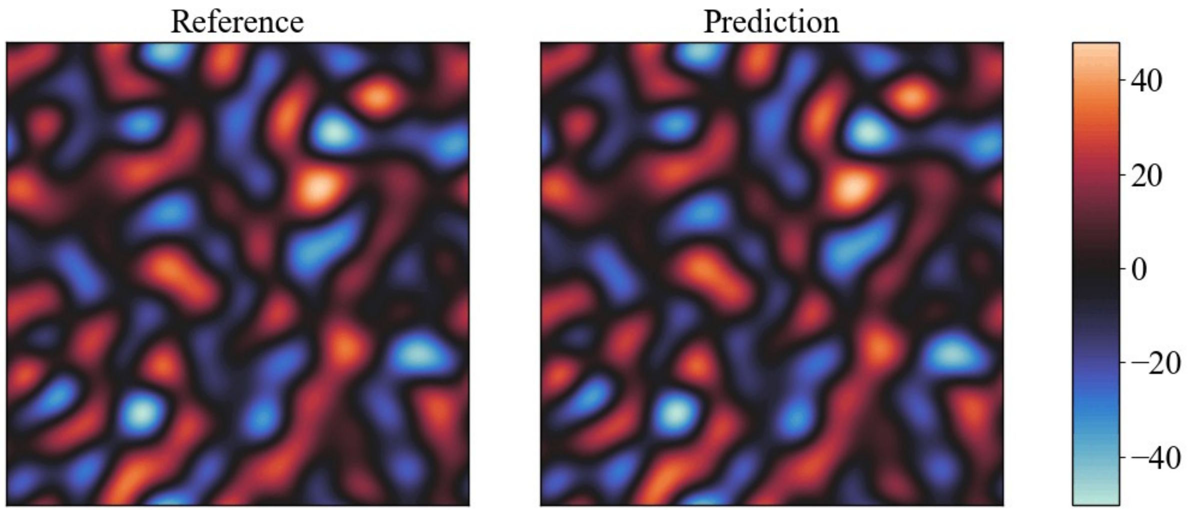
$$L_{PDE}(\theta) = \frac{1}{N_c} \sum_{i=1}^{N_c} \left|\mathcal{F}(u_\theta(\boldsymbol{x_i}))\right|^2 ,$$

Baty ‘24

PINNs current status

- Recent capabilities for fluid computations (e.g. Wang et al. ‘23)

Kolmogorov flow (S. Wang et al. ‘23)



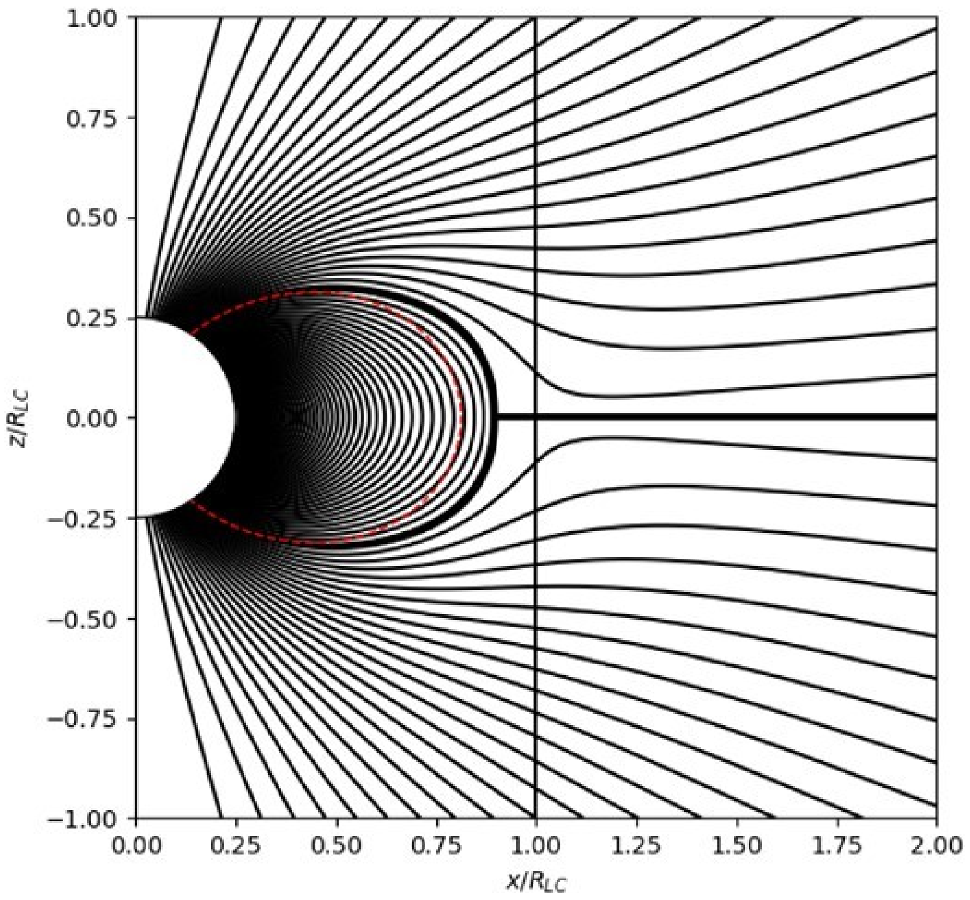
- Possibly interesting for high dimensional cases and with complex geometry (Hu et al. ‘24)

- Flexible, easy to code

PINNs for the study of magnetospheres

- Previous work on PINNs w/ magnetospheres of compact objects (Stefanou et al. ‘23, Dimitropoulos et al. ‘23,’24,’26)

- Found multiple degenerate solutions for the pulsar equation



How do we want to apply PINNs here ?

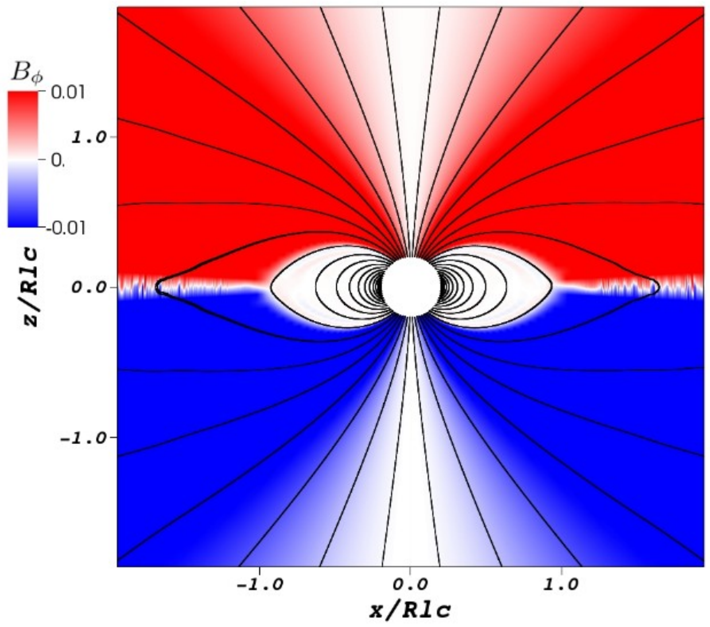
- Objective : do time dependent simulations (allow for more physically interesting scenarios)

- Try and not help the PINNs as much as possible to see if the NN can figure out the structure of the magnetosphere by itself

How do we want to apply PINNs here ?

- First test : aligned rotator

- Comparison w/ force free simulations, e.g. onion code



“onion” code
F. Carroso et al. ‘18

How do we want to apply PINNs here ?

- So we solve the Maxwell eq. w/ force free condition

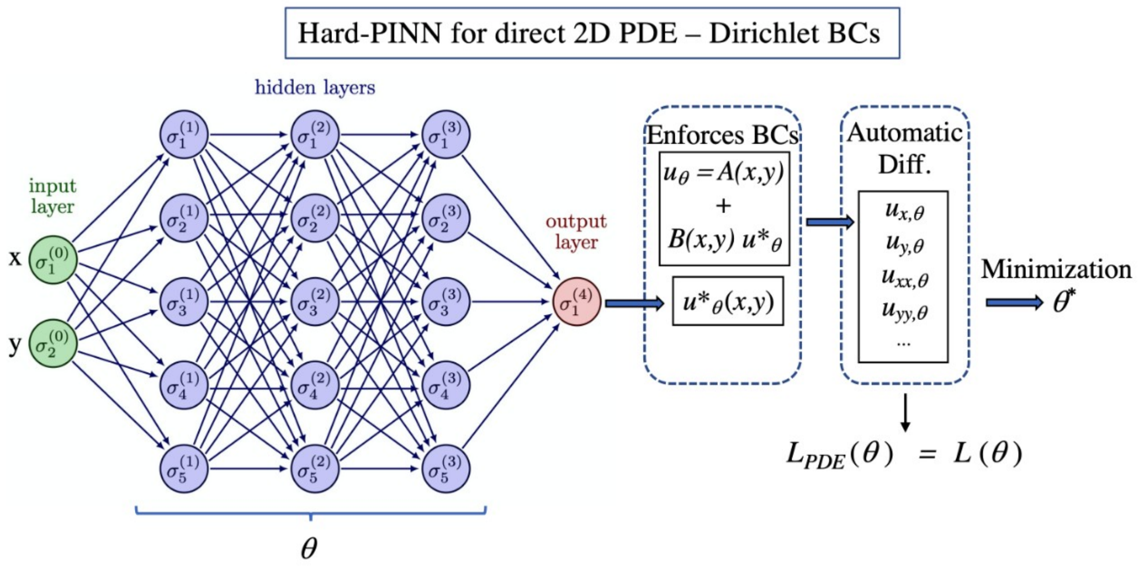
$$\begin{aligned} \partial_t \vec{E} &= \vec{\nabla} \times \vec{B} - \vec{j}, \\ \partial_t \vec{B} &= -\vec{\nabla} \times E, \\ \vec{E} \cdot \vec{B} &= 0, \\ \vec{\nabla} \cdot B &= 0, \end{aligned}$$

$$\begin{aligned} \vec{j} &= \frac{\vec{B}}{B^2}\left[\vec{B} \cdot (\vec{\nabla} \times \vec{B}) - \vec{E} \cdot (\vec{\nabla} \times \vec{E})\right] \\ &+ \frac{\vec{E} \times \vec{B}}{B^2} \vec{\nabla} \cdot \vec{E} \end{aligned}$$

- Potential hurdles → discontinuities, more dimensions, scale separation

Adaptation of the architecture

- Problem of BC → competing losses
- More suitable to «hard»-enforce them
- Can help spectral bias (Cooley et al. '25)



Baty '24

Adaptation of the architecture

- IC → t=0 : magnetic dipole

$$B_r(r,\theta,\phi) = \frac{2\mu\cos\theta}{r^3}$$

$$B_\theta(r,\theta,\phi) = \frac{\mu\sin\theta}{r^3}$$

- At surface of star (r=r*) → perfect conductor

$$\vec{n}\cdot\vec{b} = f(r_*,\theta,\phi),$$

$$\vec{e} = 0,$$

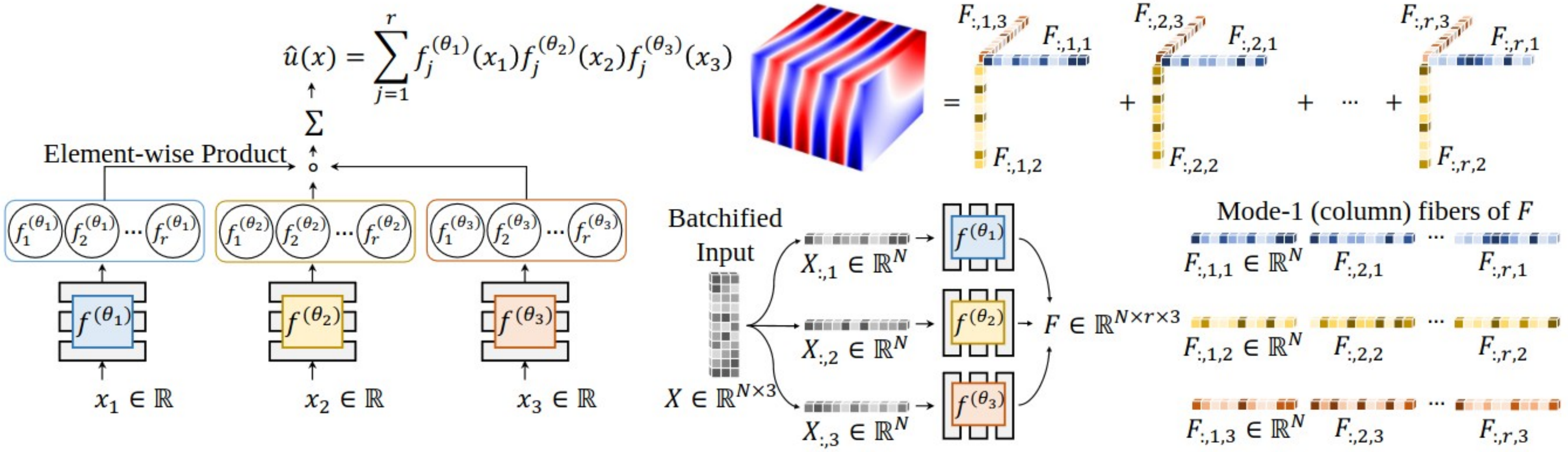
for the aligned rotator

$$f(r_*,\theta,\phi) = \frac{2\mu\cos\theta}{r_*^3}$$

- We do not enforce anything at the outside of the box

Adaptation of the architecture

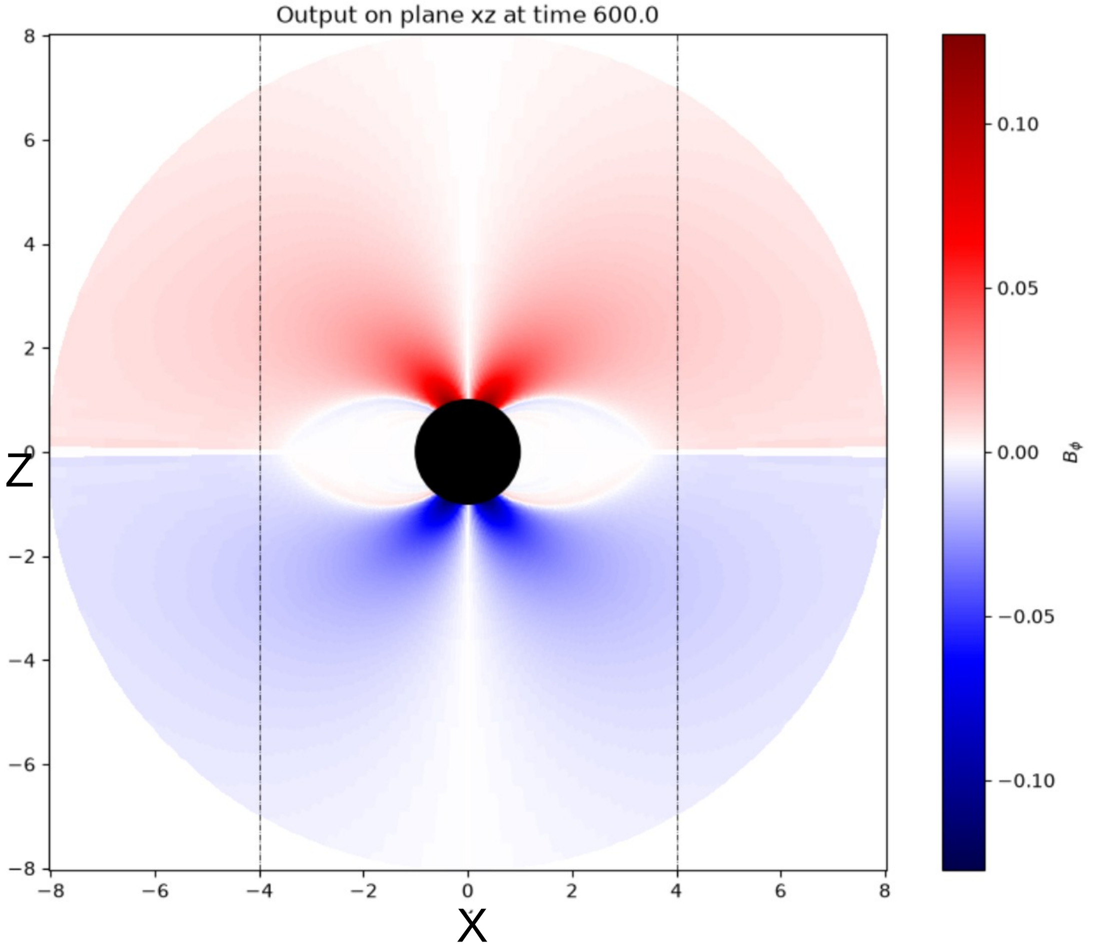
- Separable PINN (Cho et al.’23 SPINN)
- Allows larger batch of points



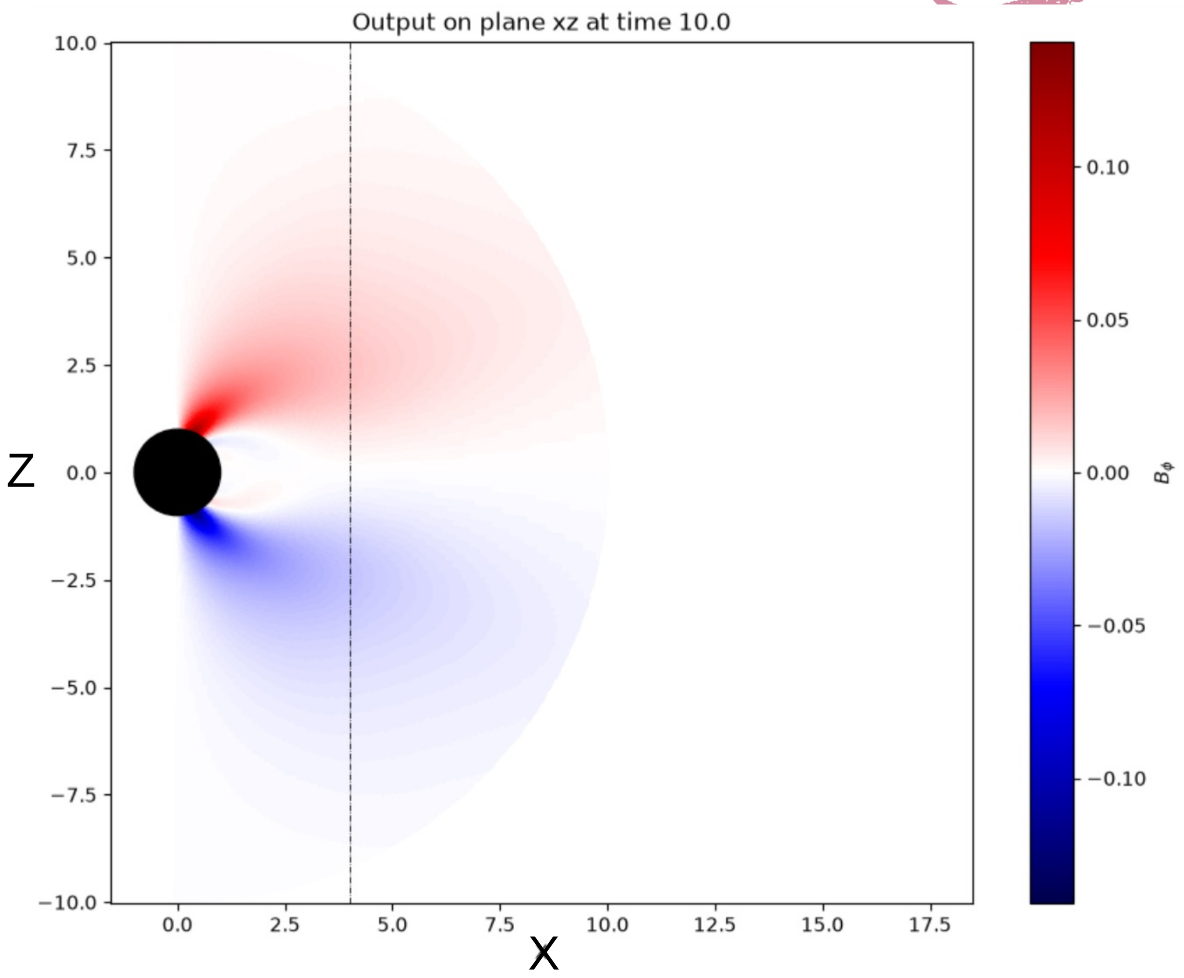
(a) Architecture (single input) (b) Low-rank tensor decomposition (batchified input)

Comparison in case of aligned rotator

onion result



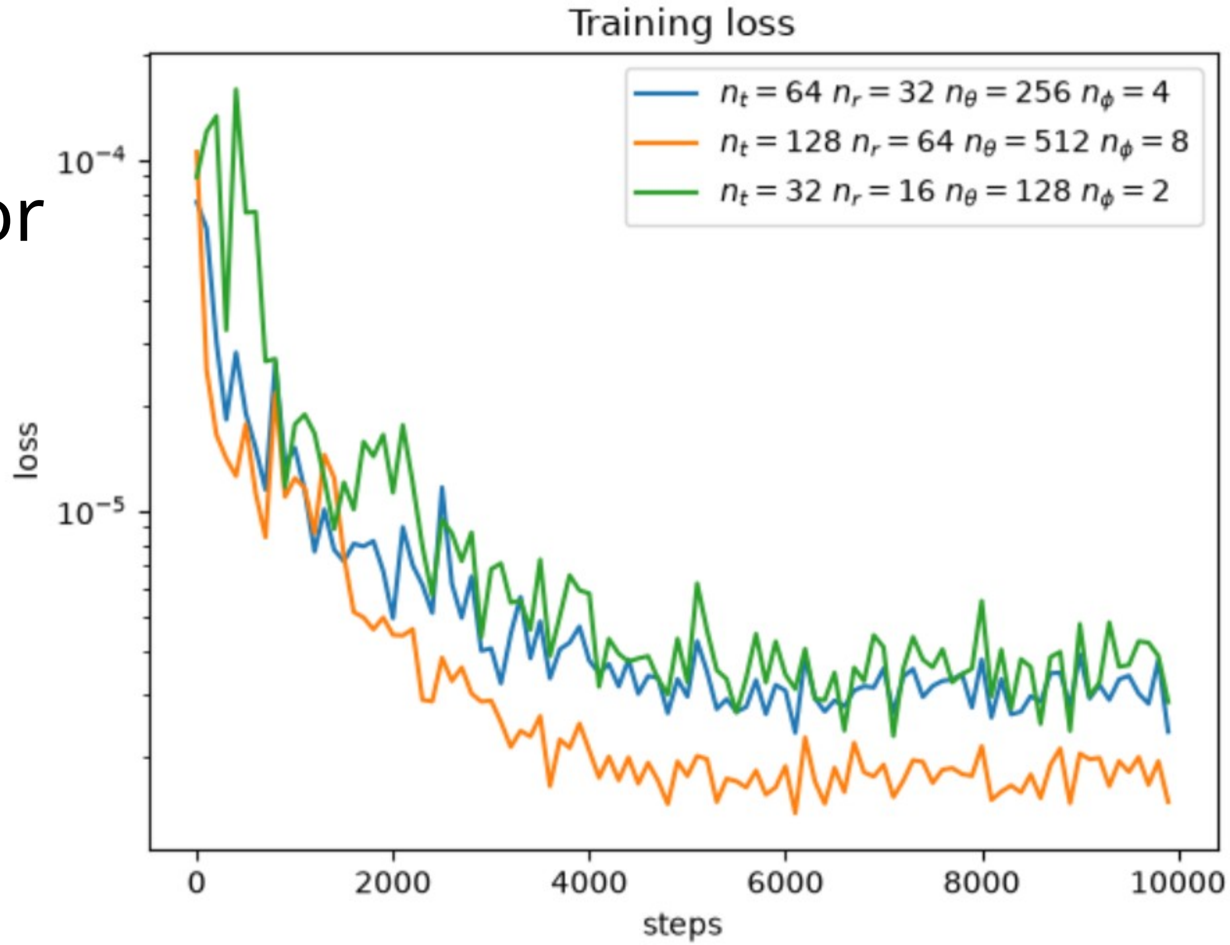
PINN result



Most important hyperparameter

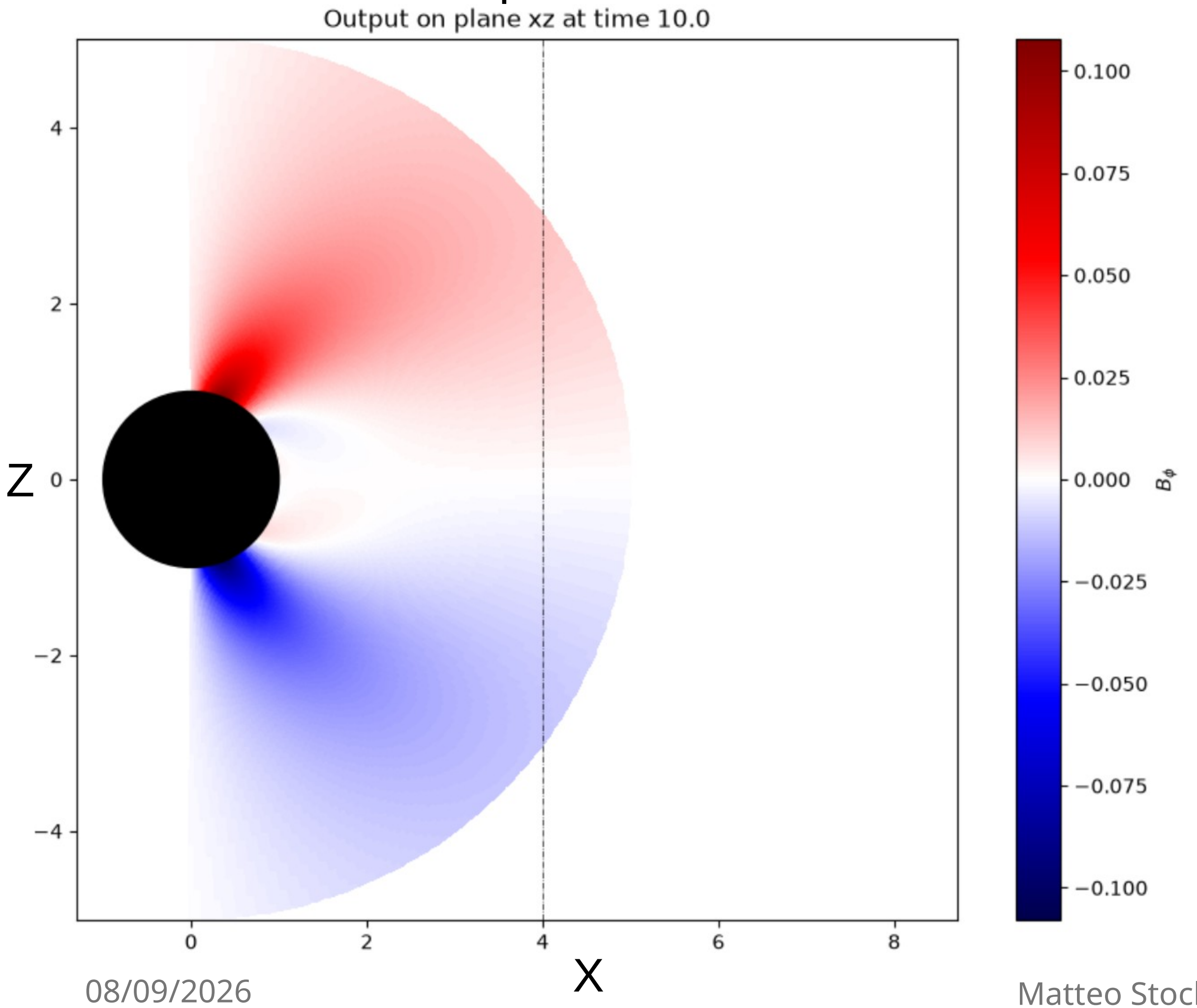
- Where those points are situated → more points inside the light cylinder for better performance

- Number of points in the training

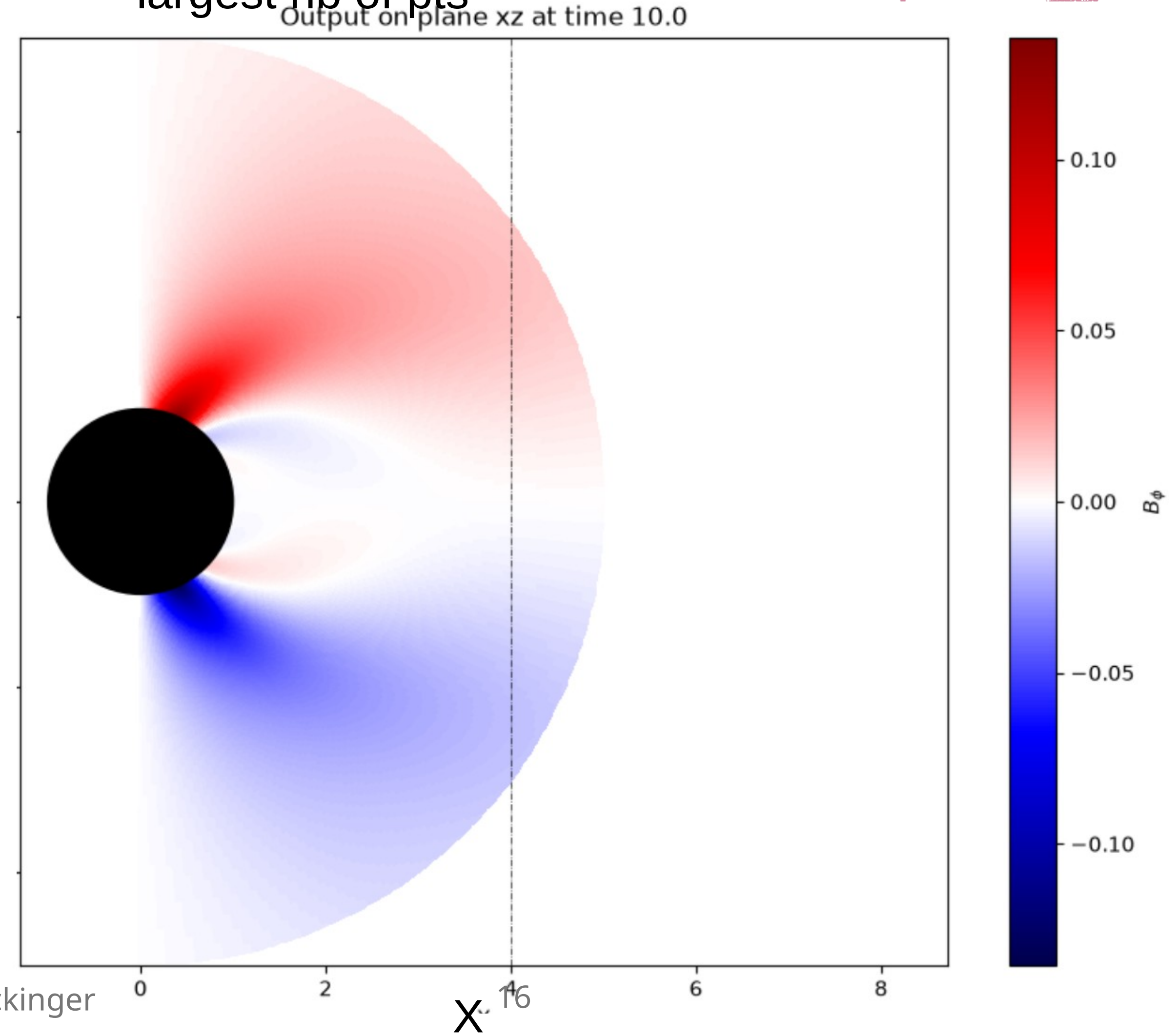


Most important hyperparameter

smallest nb of pts



largest nb of pts



Follow-up

- Try to make the algorithm more memory-efficient to handle more points in the training → main obstacle for PINNs ?
- Immediate follow-up:misaligned rotator + BH magnetosphere study
- Other scenarios e.g. BNS

Conclusion

- PINNs are quite new → no perfect recipe for how to use them

- Still they have a great potential in computational physics

Thank you for your attention !