From propagation to termination: exploring jet dynamics through numerical simulations

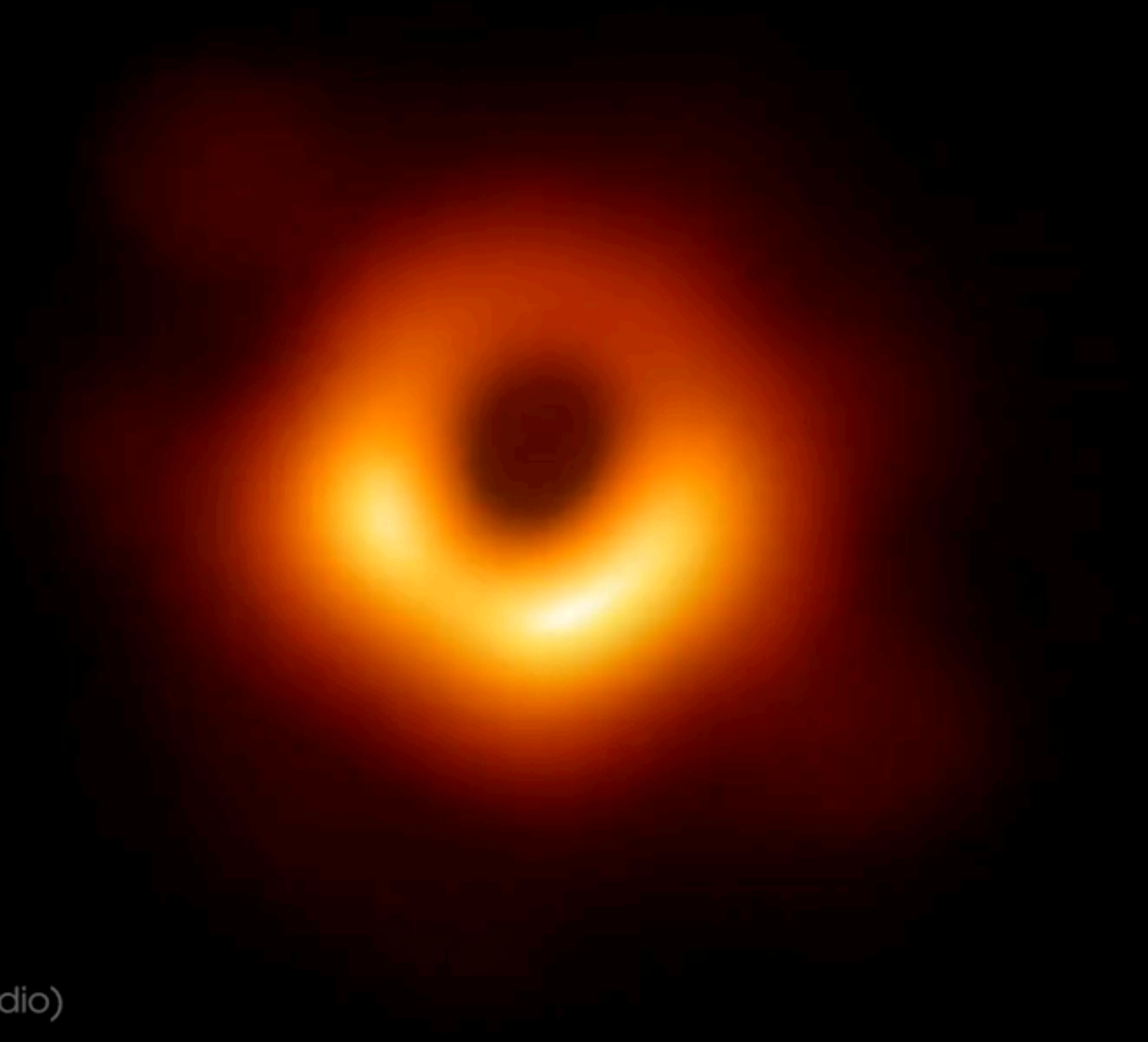
Fuentes et al. 2018

Gaëtan Fichet de Clairfontaine - Workshop on Numerical Multi-messenger Modeling - 22th February 2024

The selection of papers inevitably reflects subjective views and personal research interests. This review is not exhaustive!

Fuentes et al. 2018

What do we observe ?



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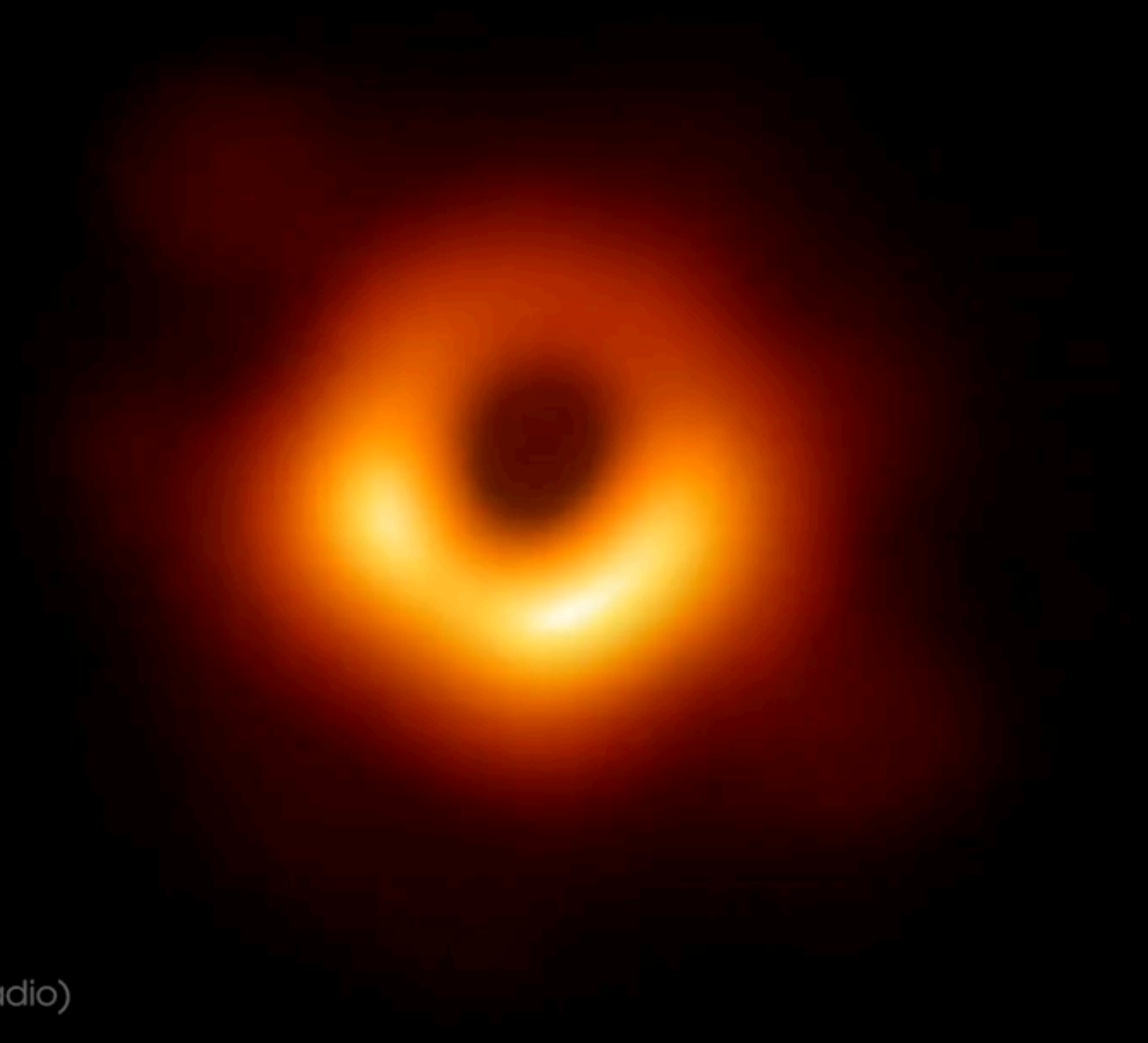

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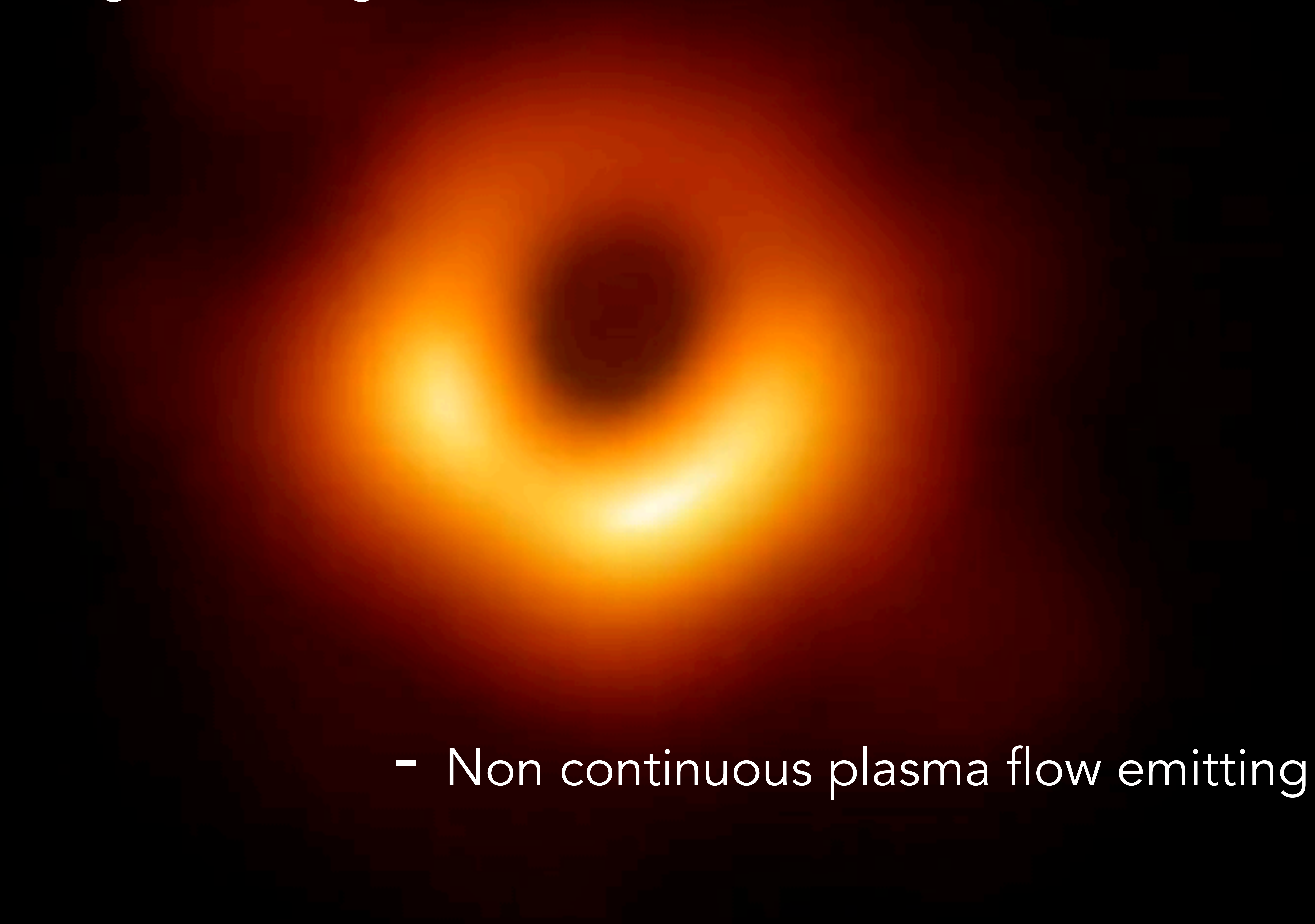

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We will mostly refer to radio observations, as they are a good tracer of the jet morphology.

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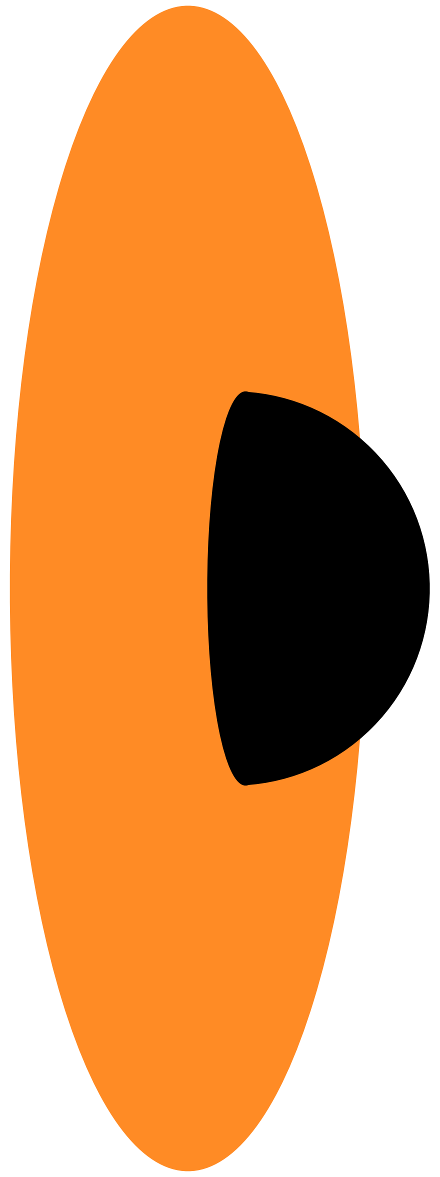

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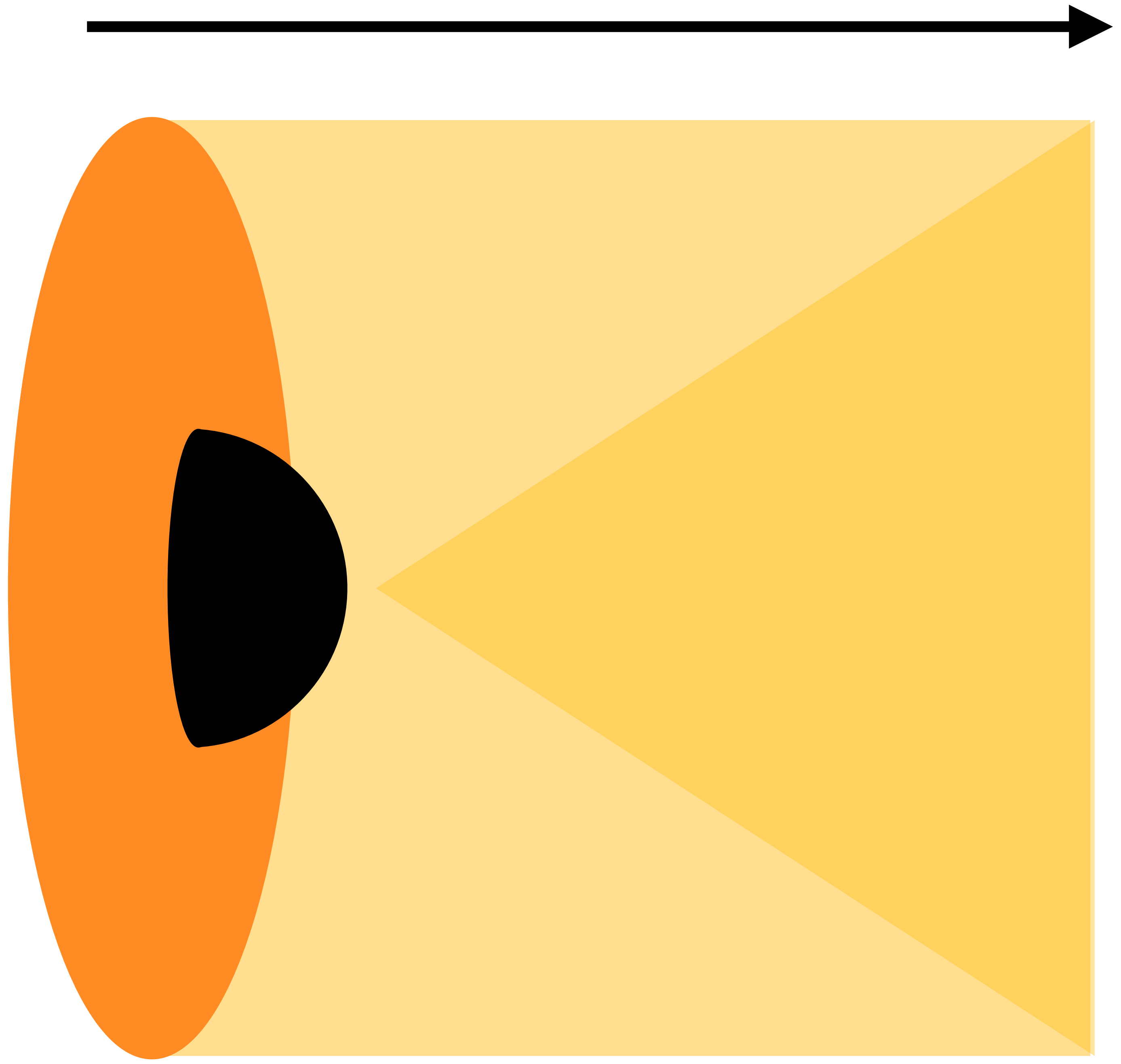

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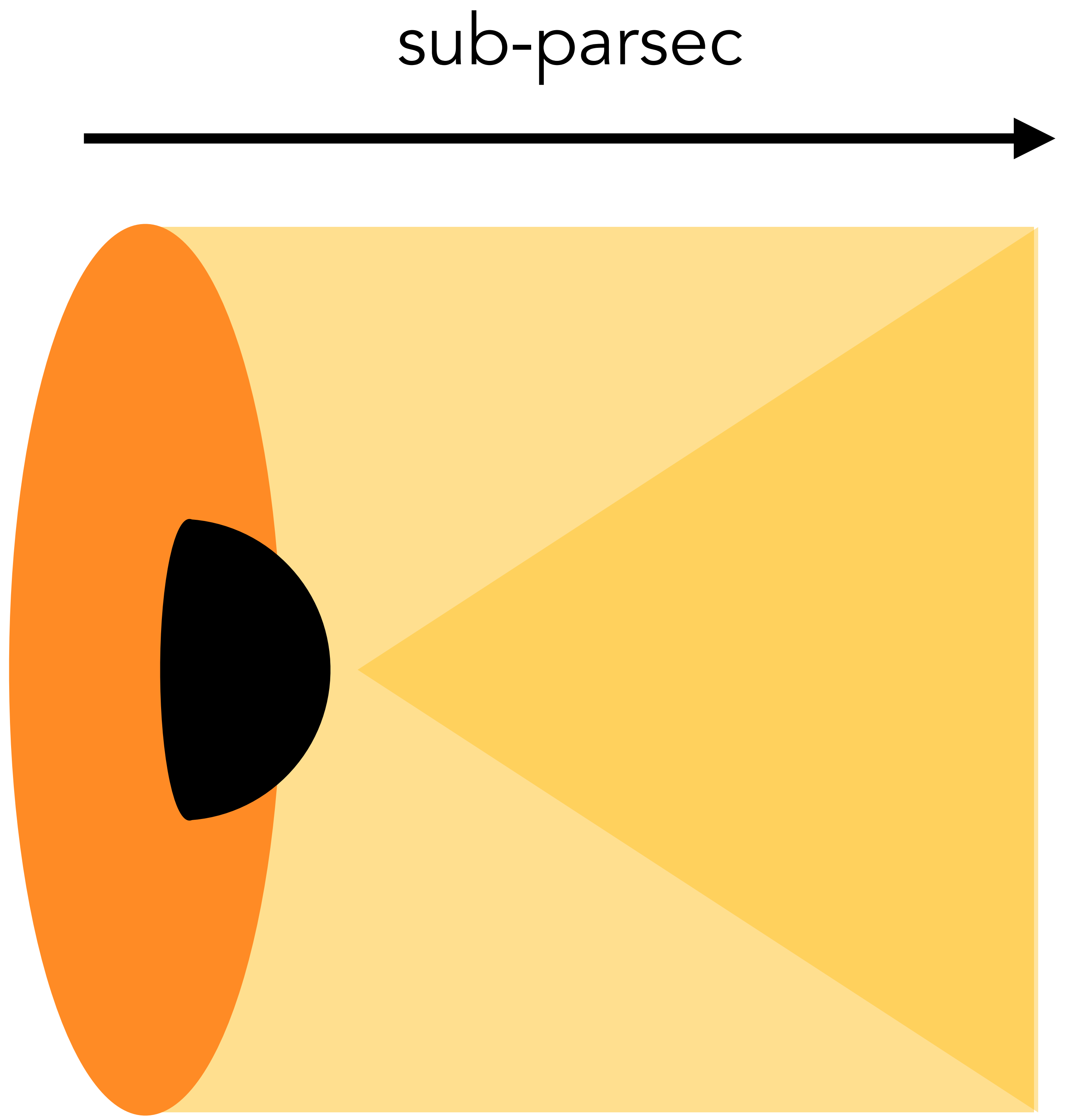

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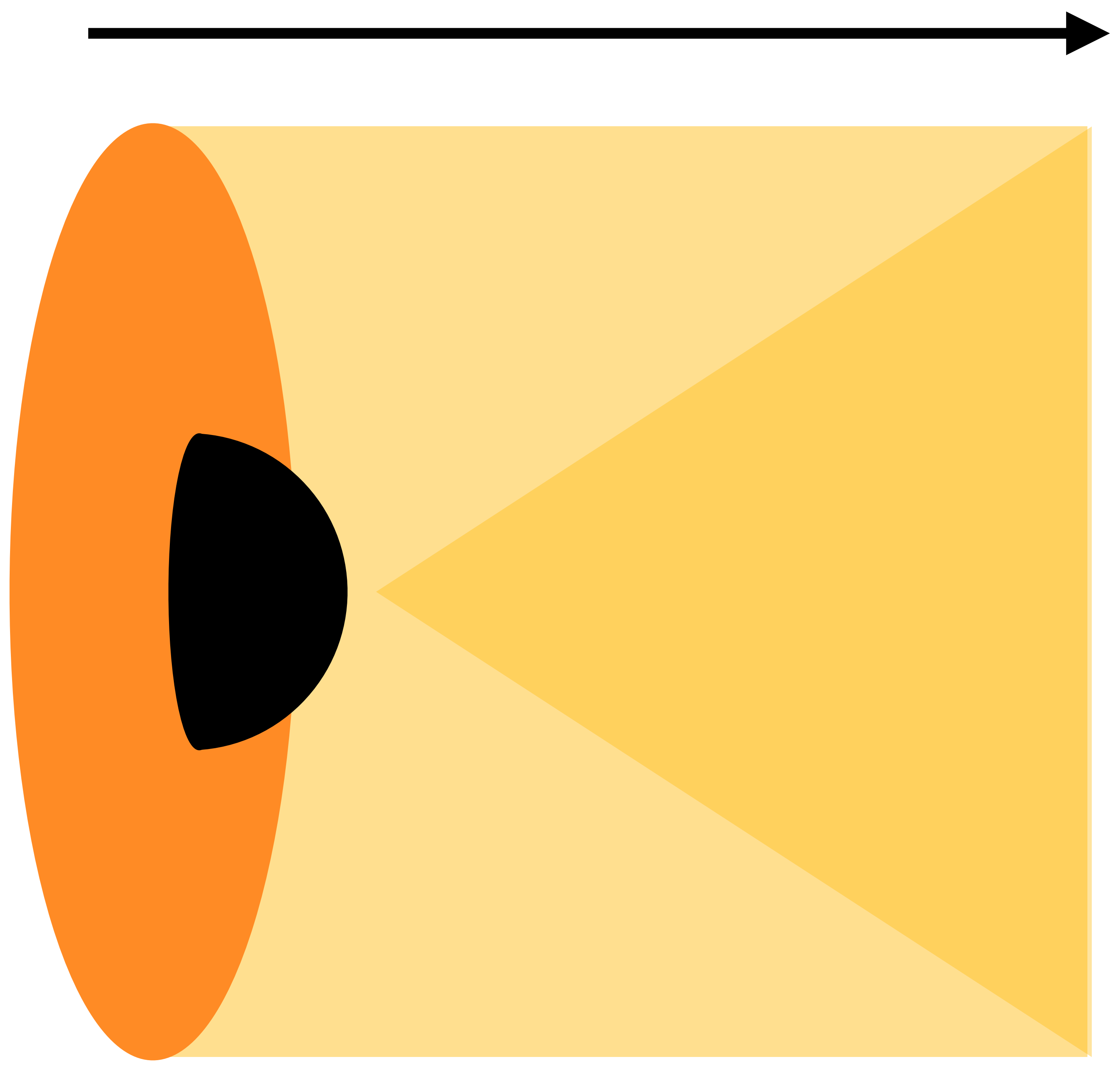
sub-parsec



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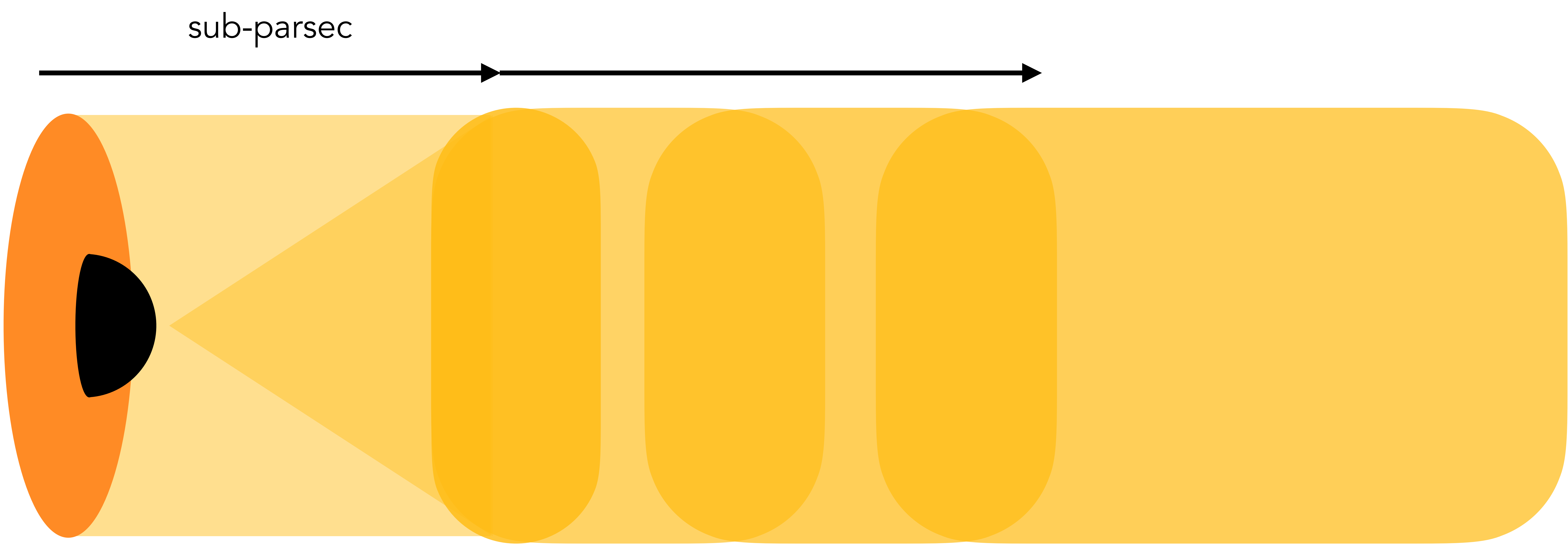

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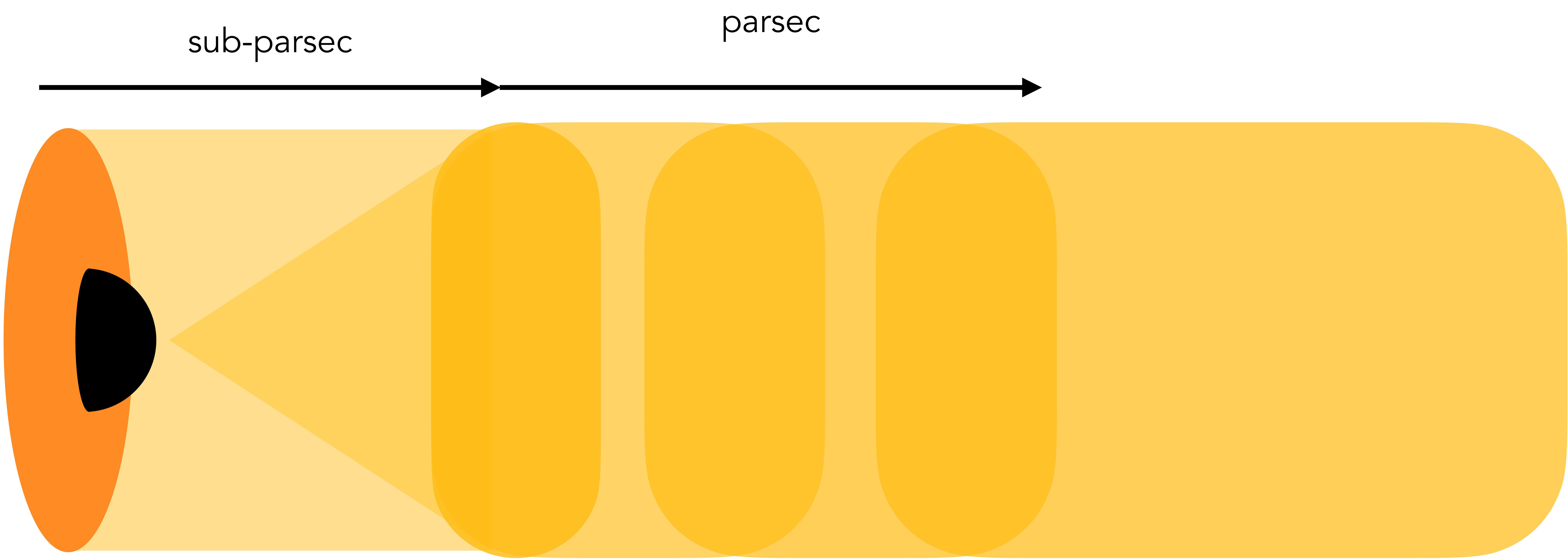

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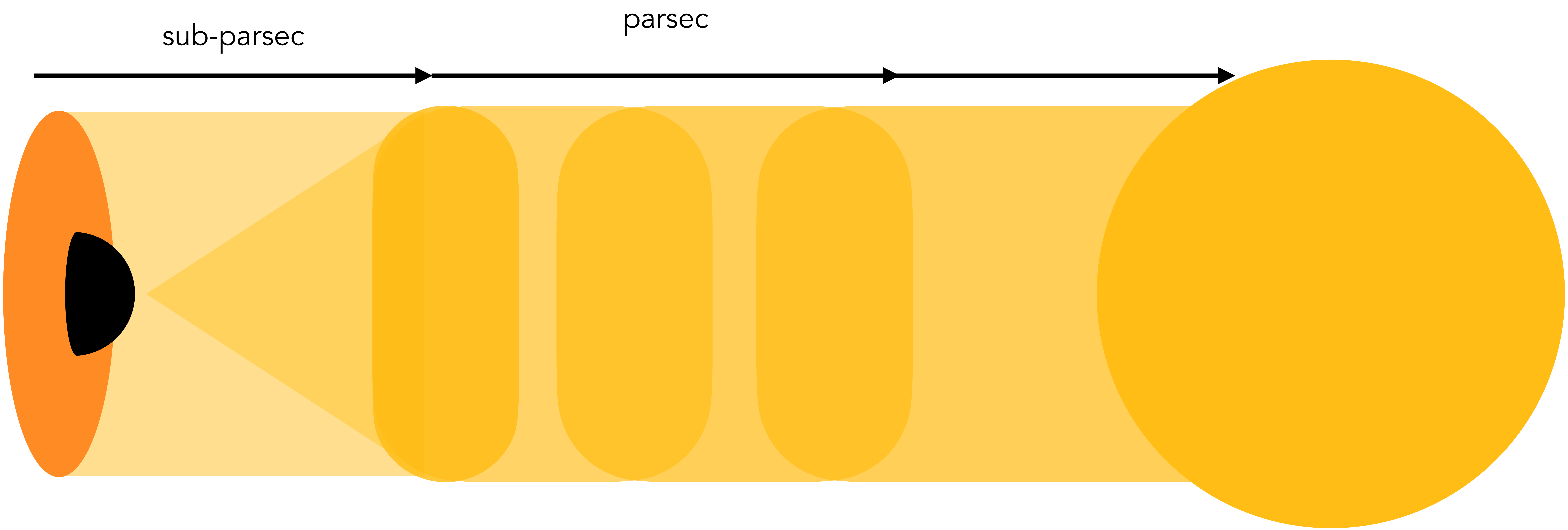

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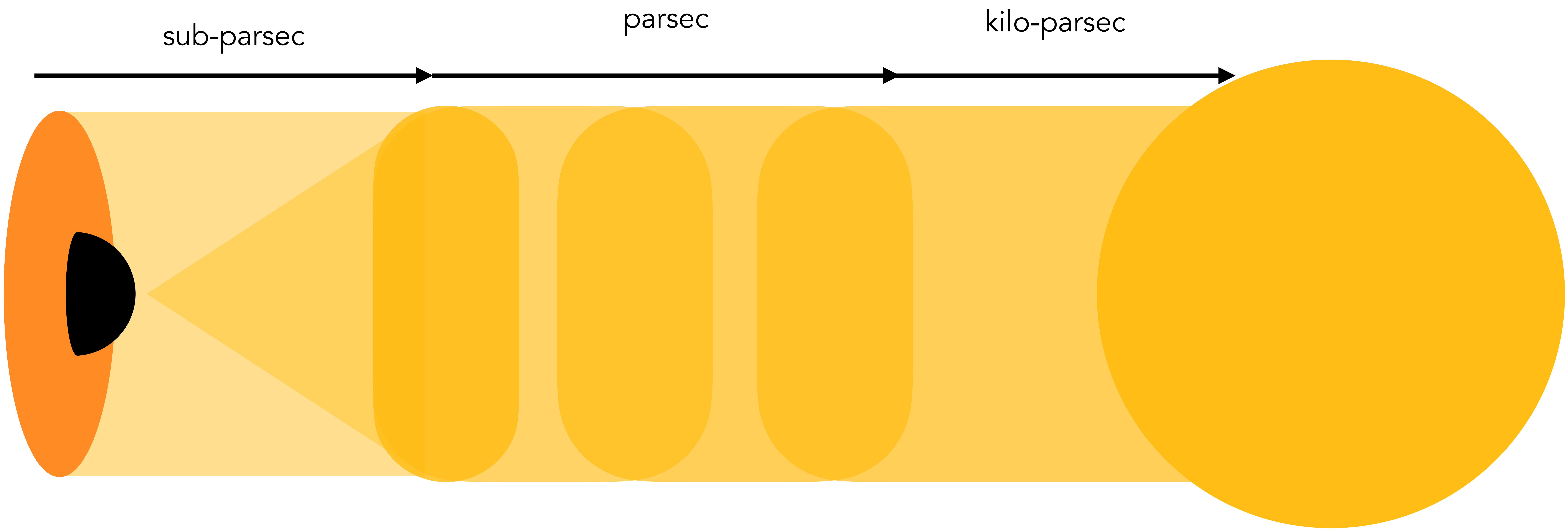

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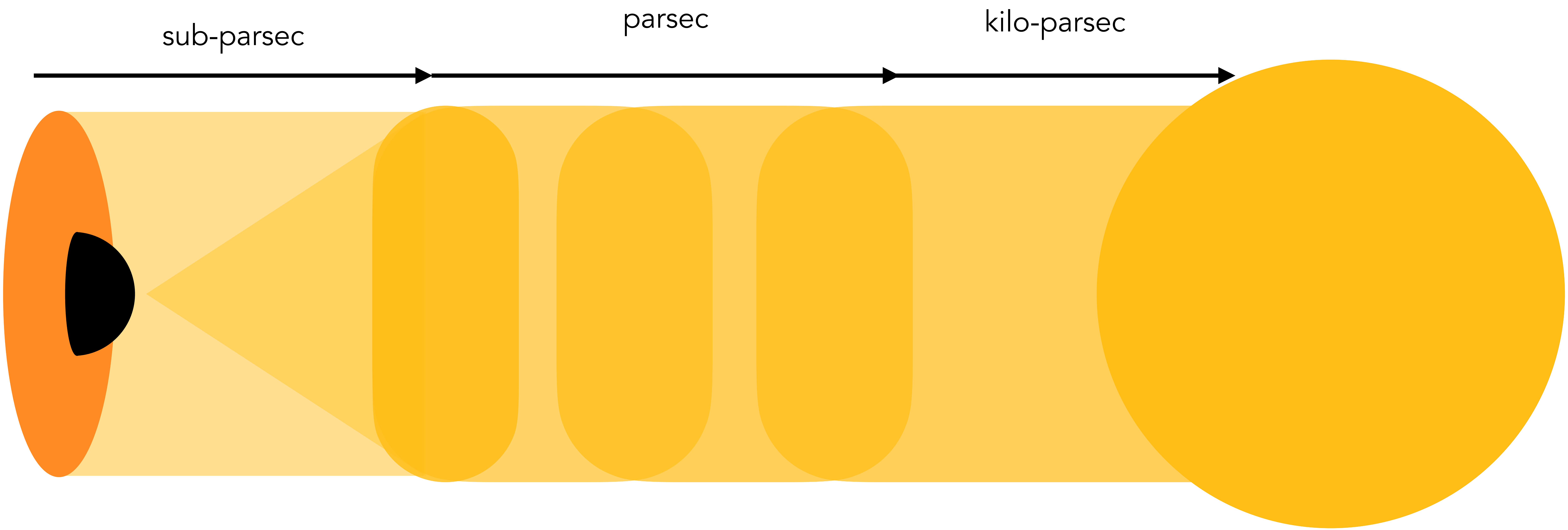

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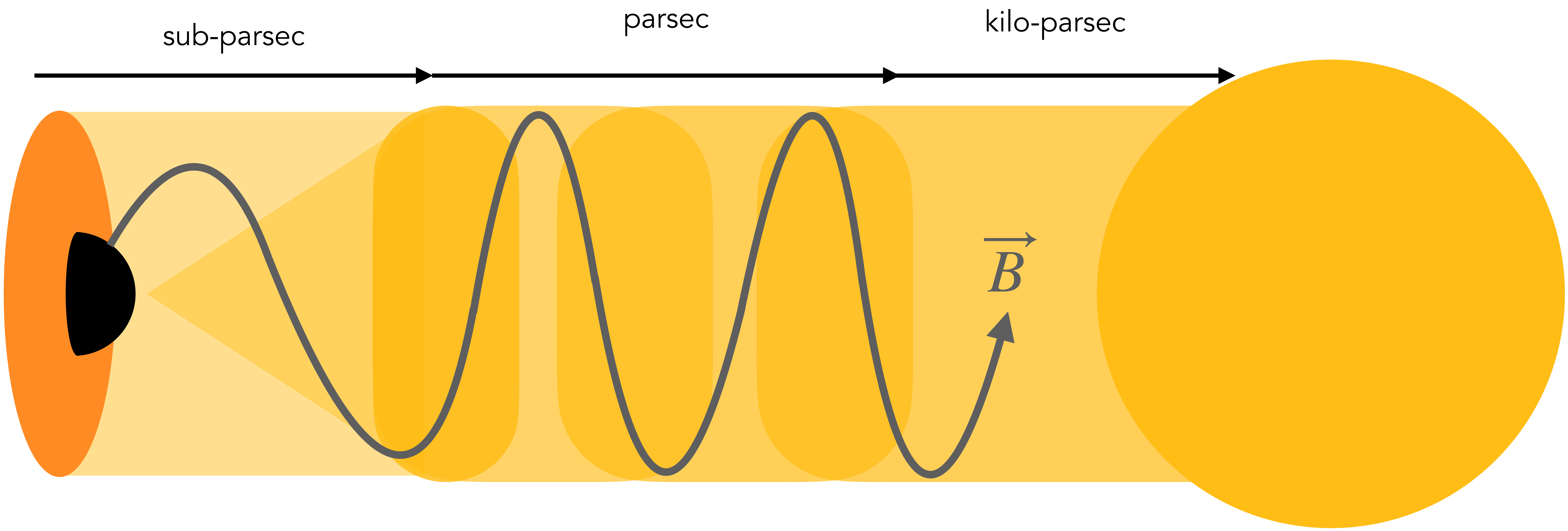

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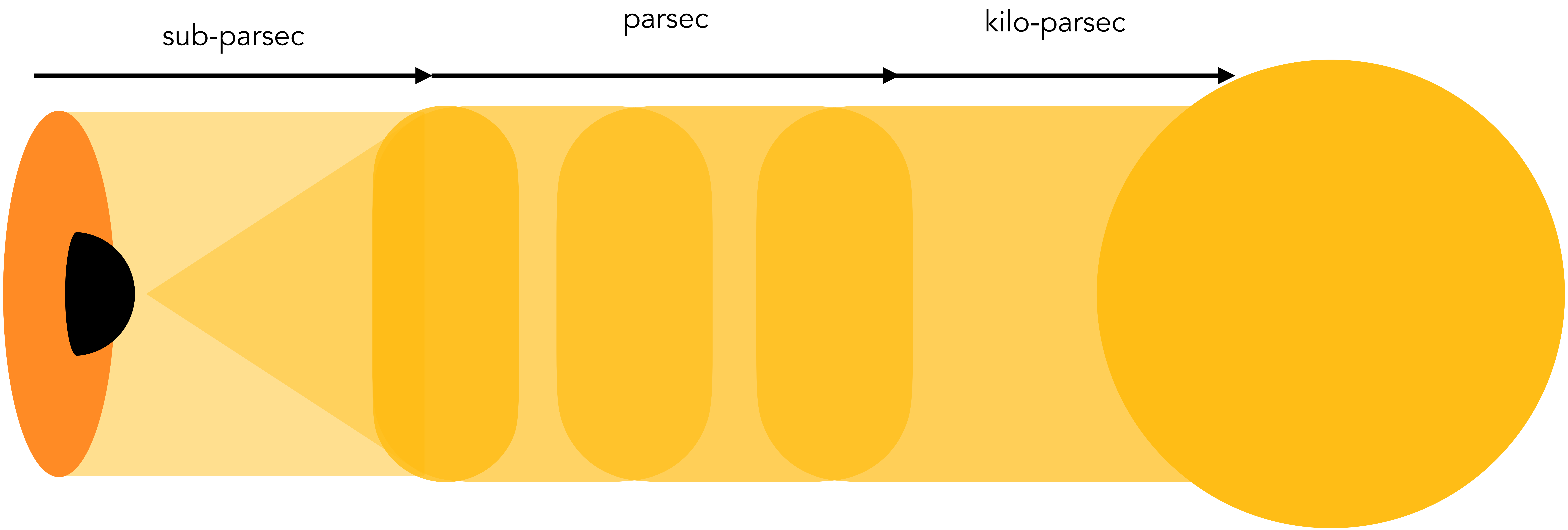

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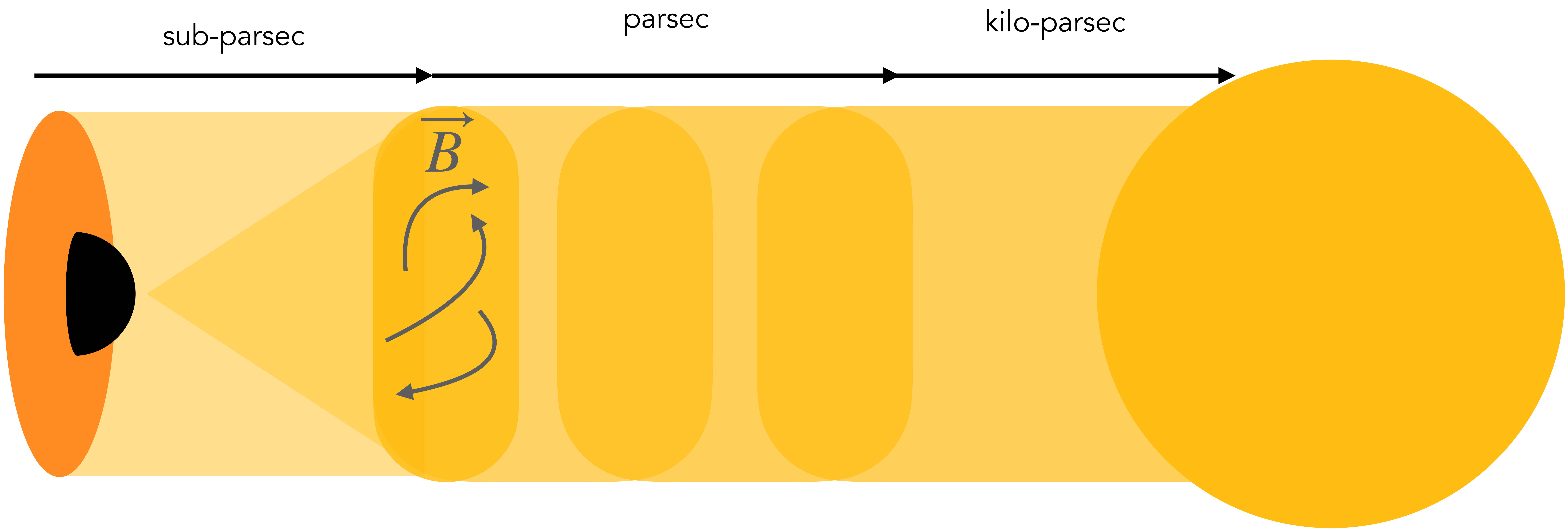

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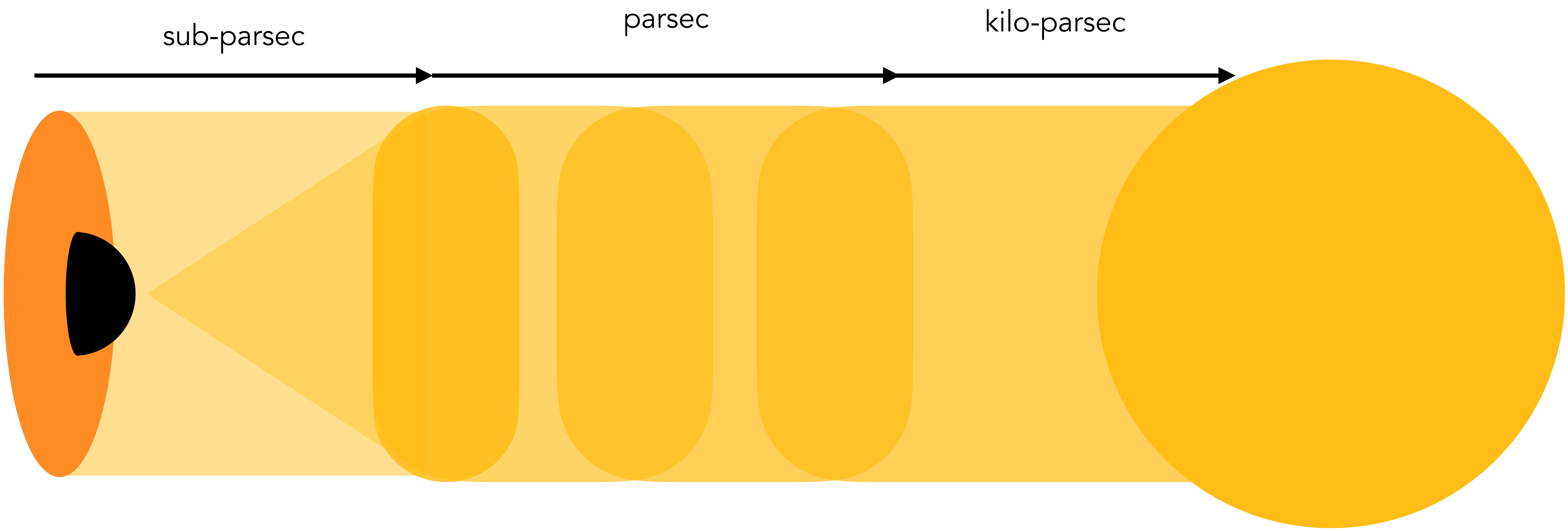

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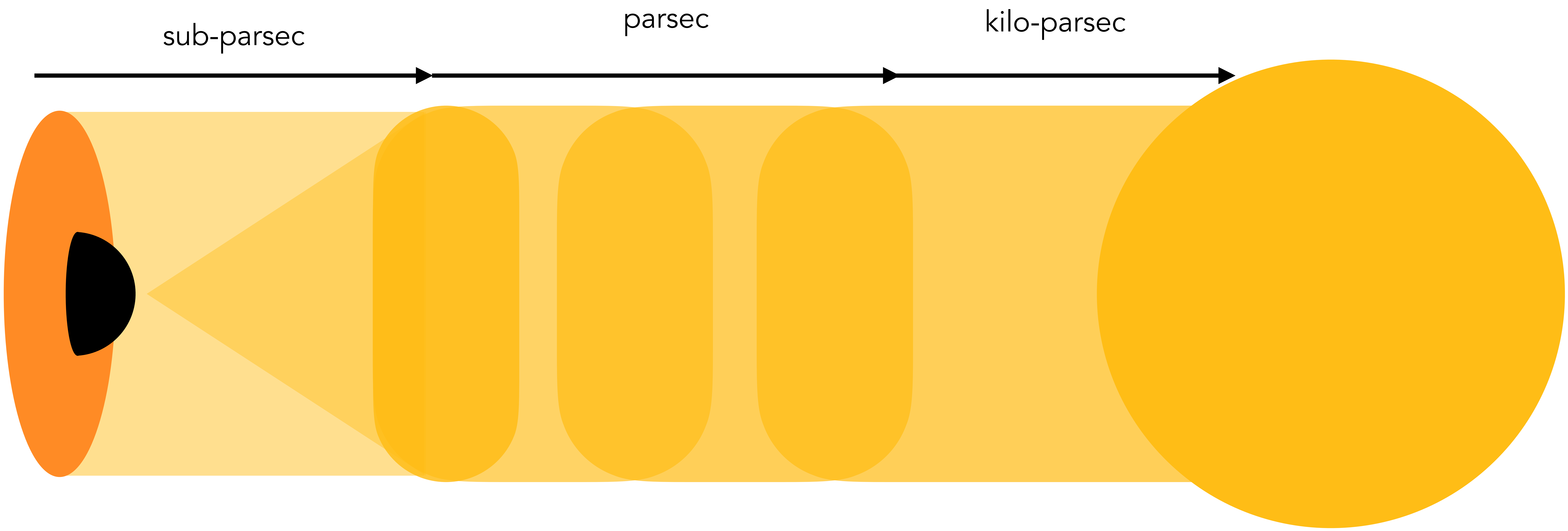

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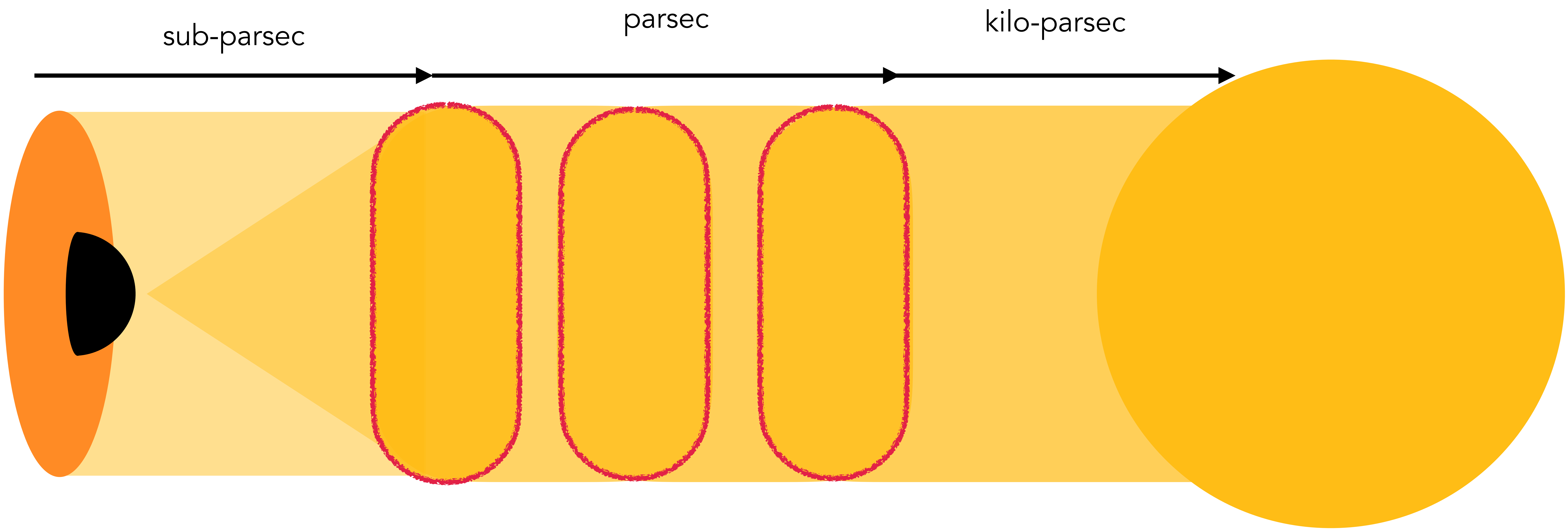

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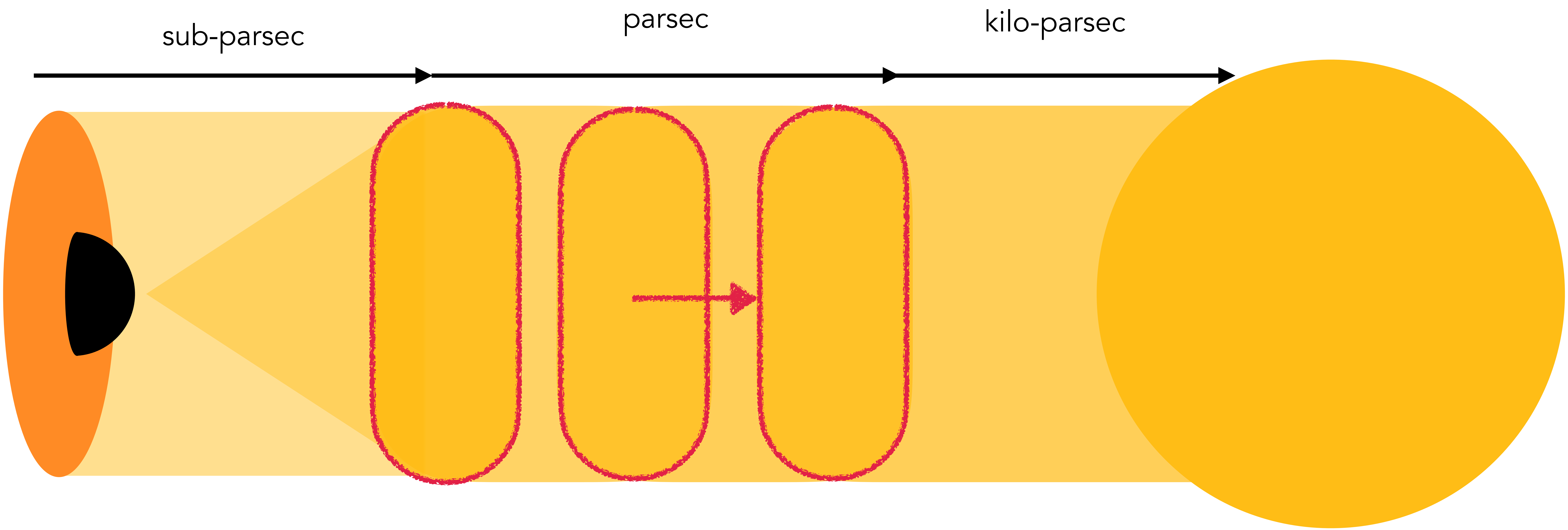

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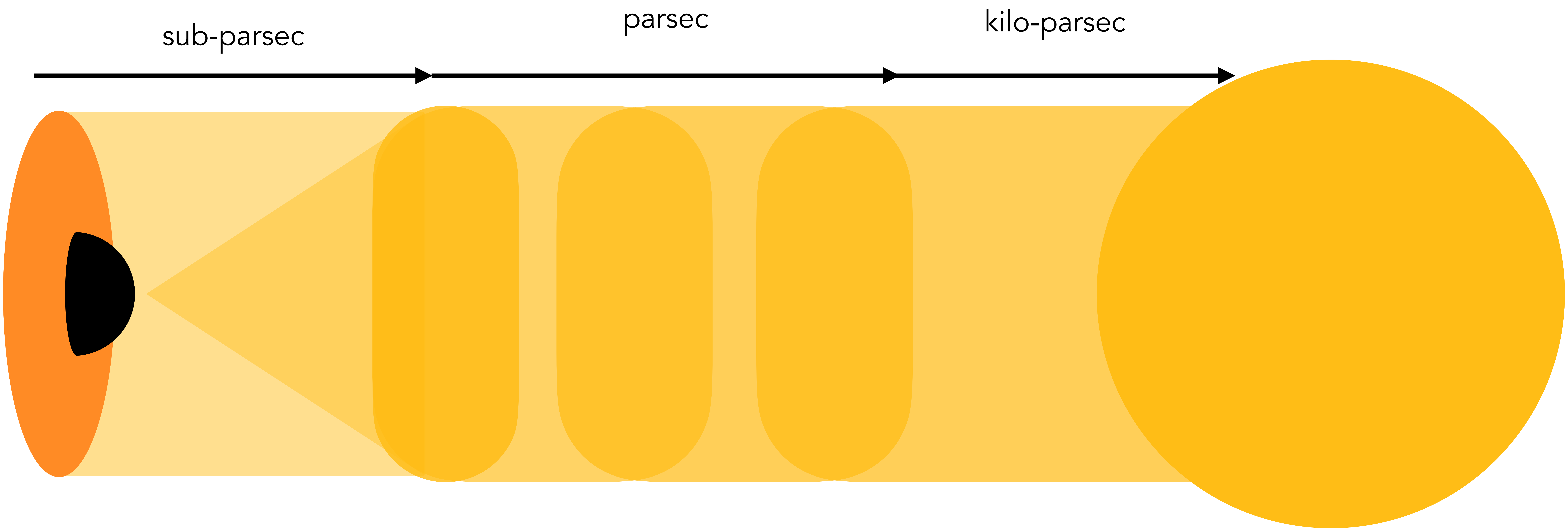

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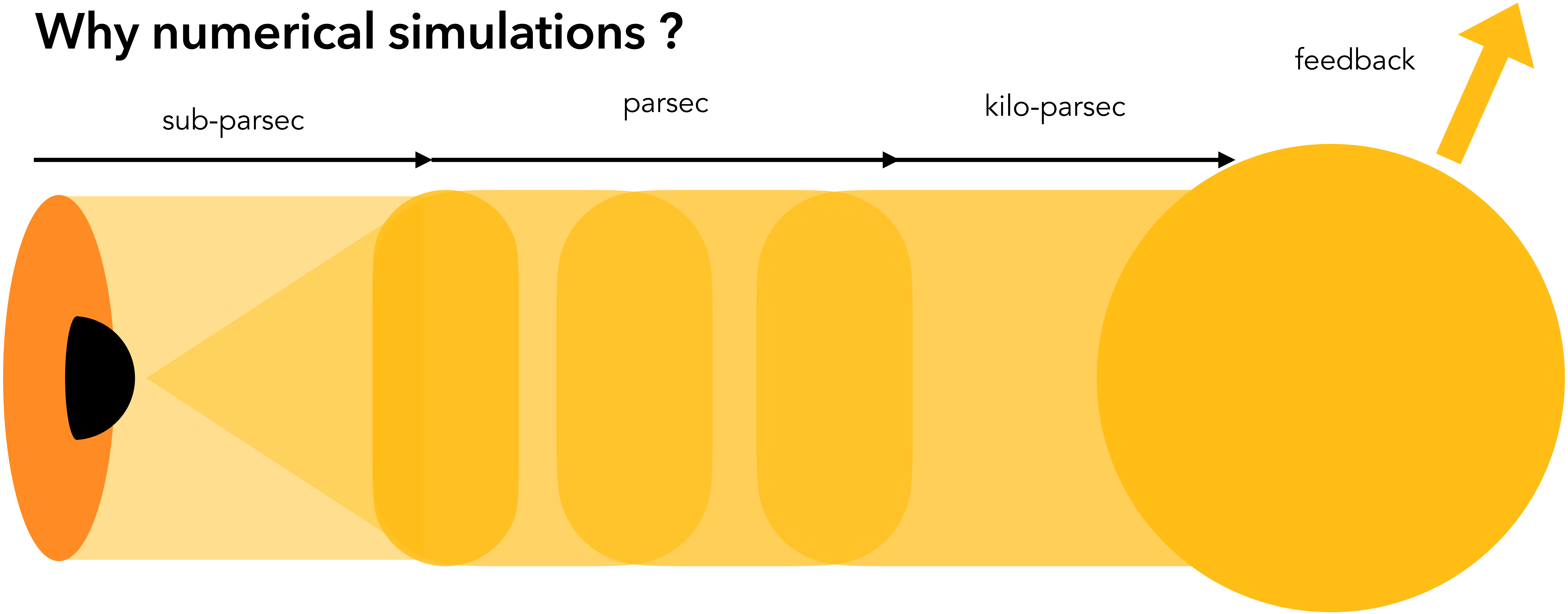

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  - Emission : acceleration of particles, emission processes, etc.

Basis of numerical simulations of jet

✓ Set of SR-MHD equations : conservation of

Marti & Muller, 2015

Basis of numerical simulations of jet

✓ Set of SR-MHD equations : conservation of mass

$$\partial_{\rm t}\rho\gamma + \nabla\cdot\left(\rho\gamma\mathbf{v}\right) = 0\,,$$

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where $p_\mathrm{m} = \left(B^2 + E^2\right)/8\pi$ the electromagnetic pressure, w the relativistic enthalpy, $\mathbf{S} = (\mathbf{E} \times \mathbf{B})\, c/4\pi$ the Poynting flux and $\mathbf{g}$ the metric tensor.

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$$\partial_t \mathbf{B} + \nabla \cdot (\mathbf{vB} - \mathbf{Bv}) = 0\,.$$

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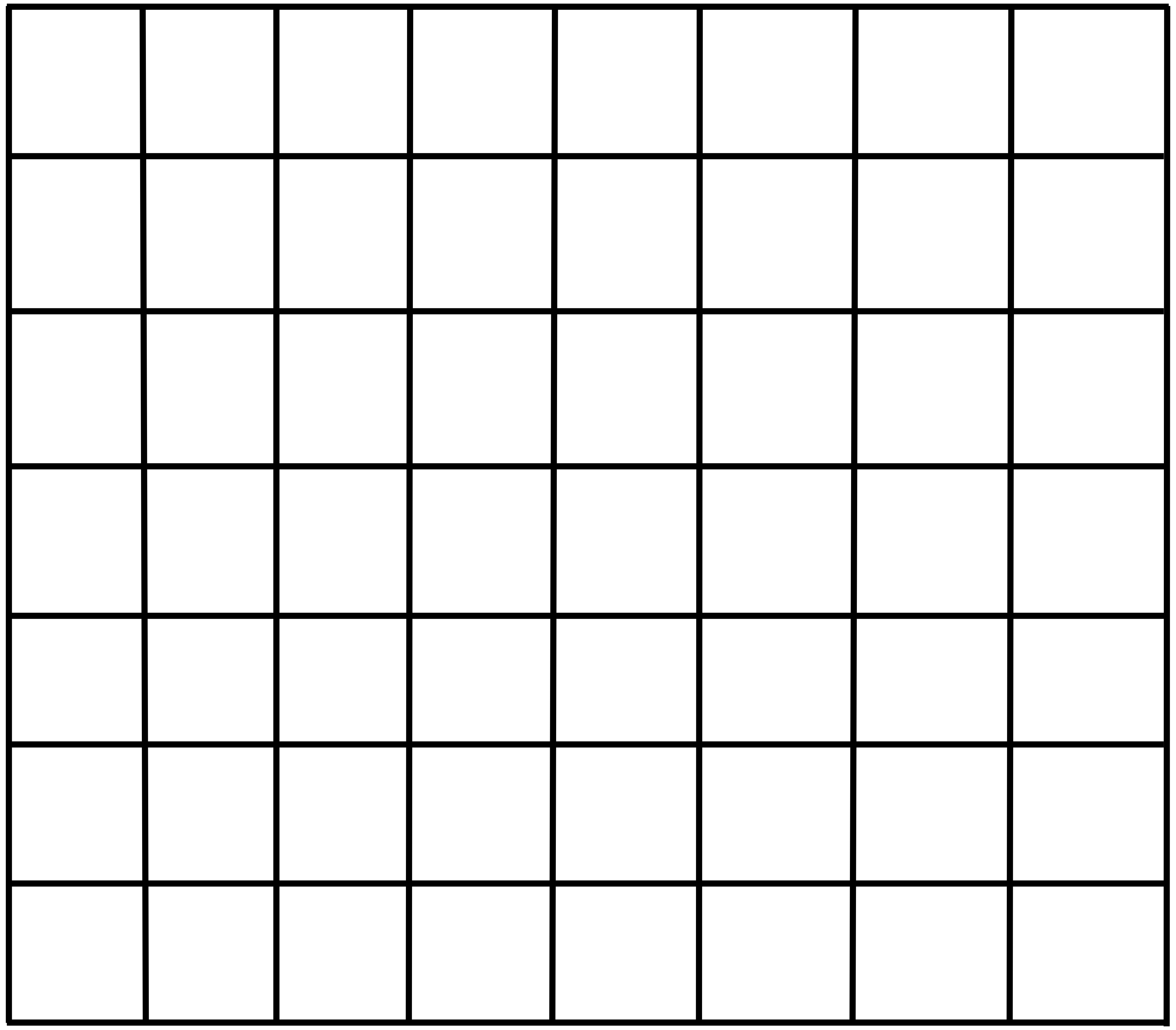

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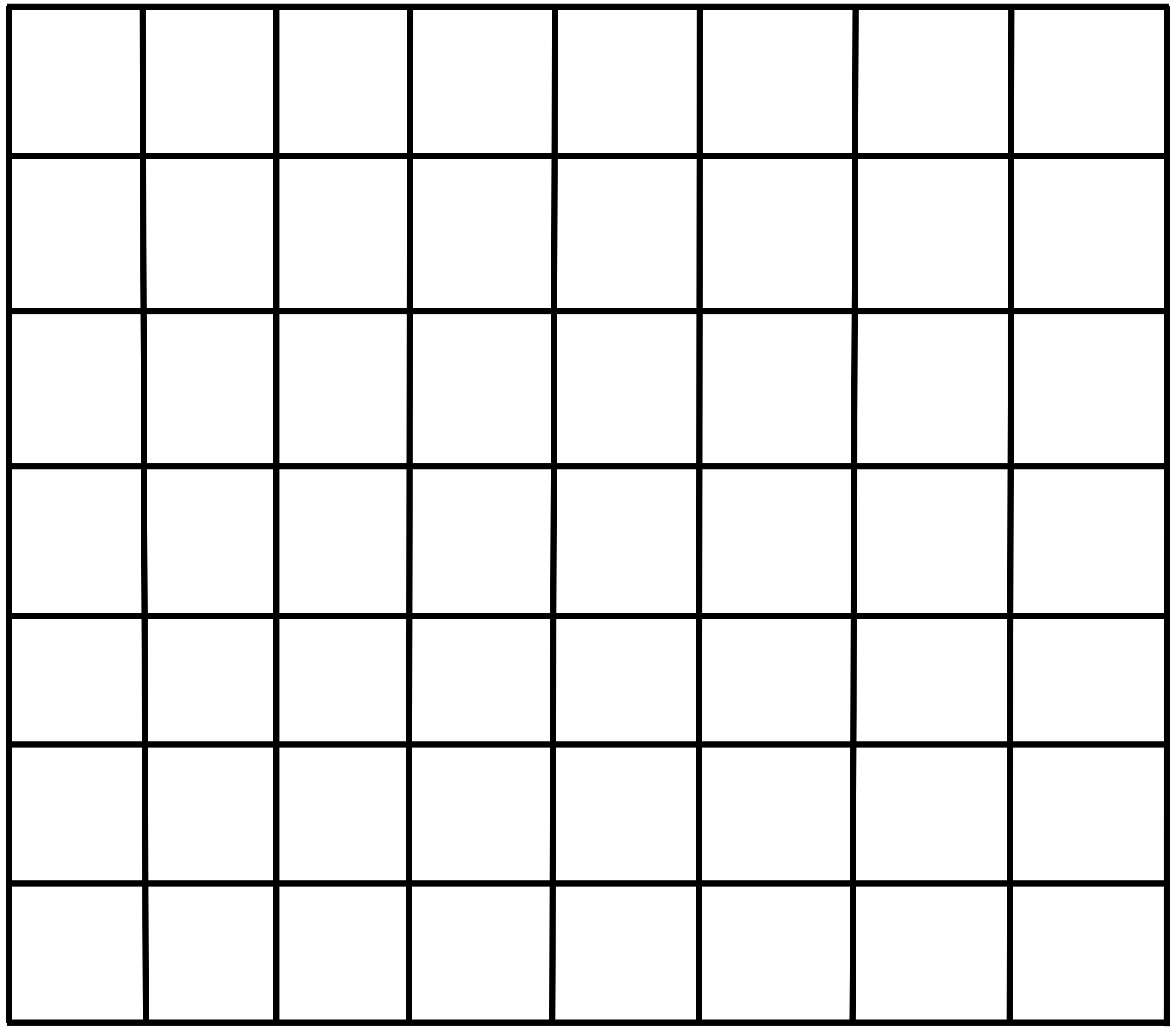

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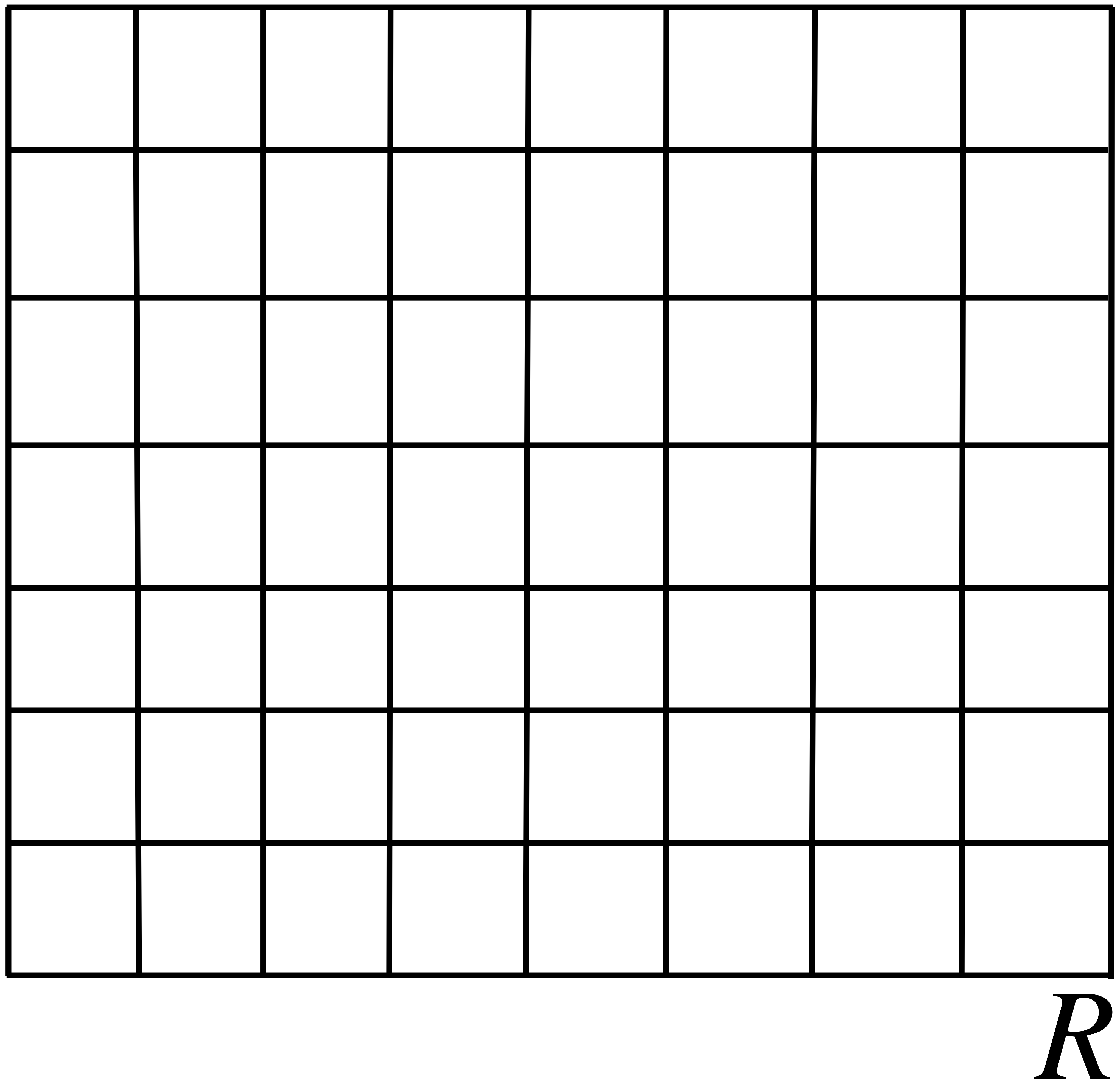

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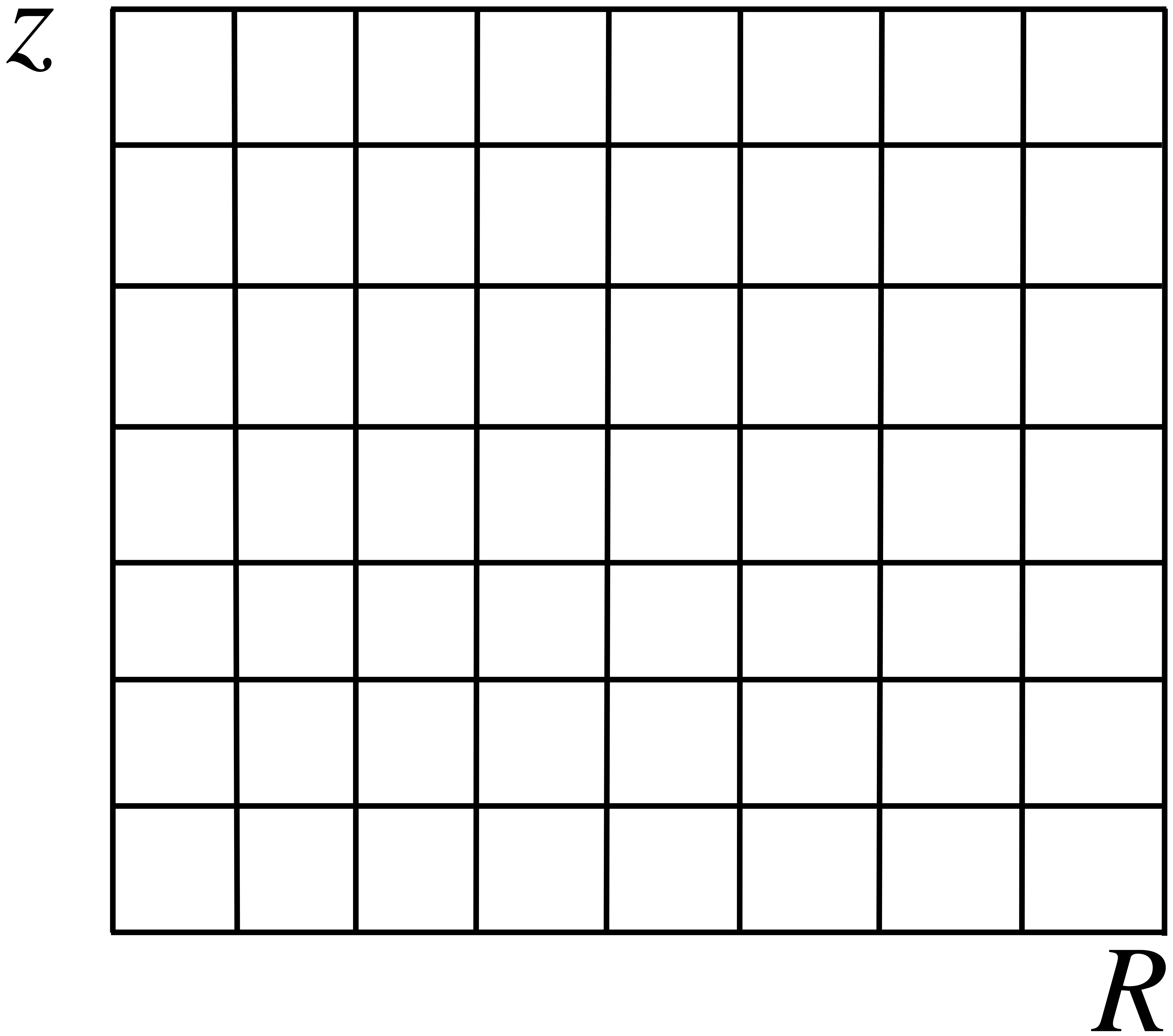

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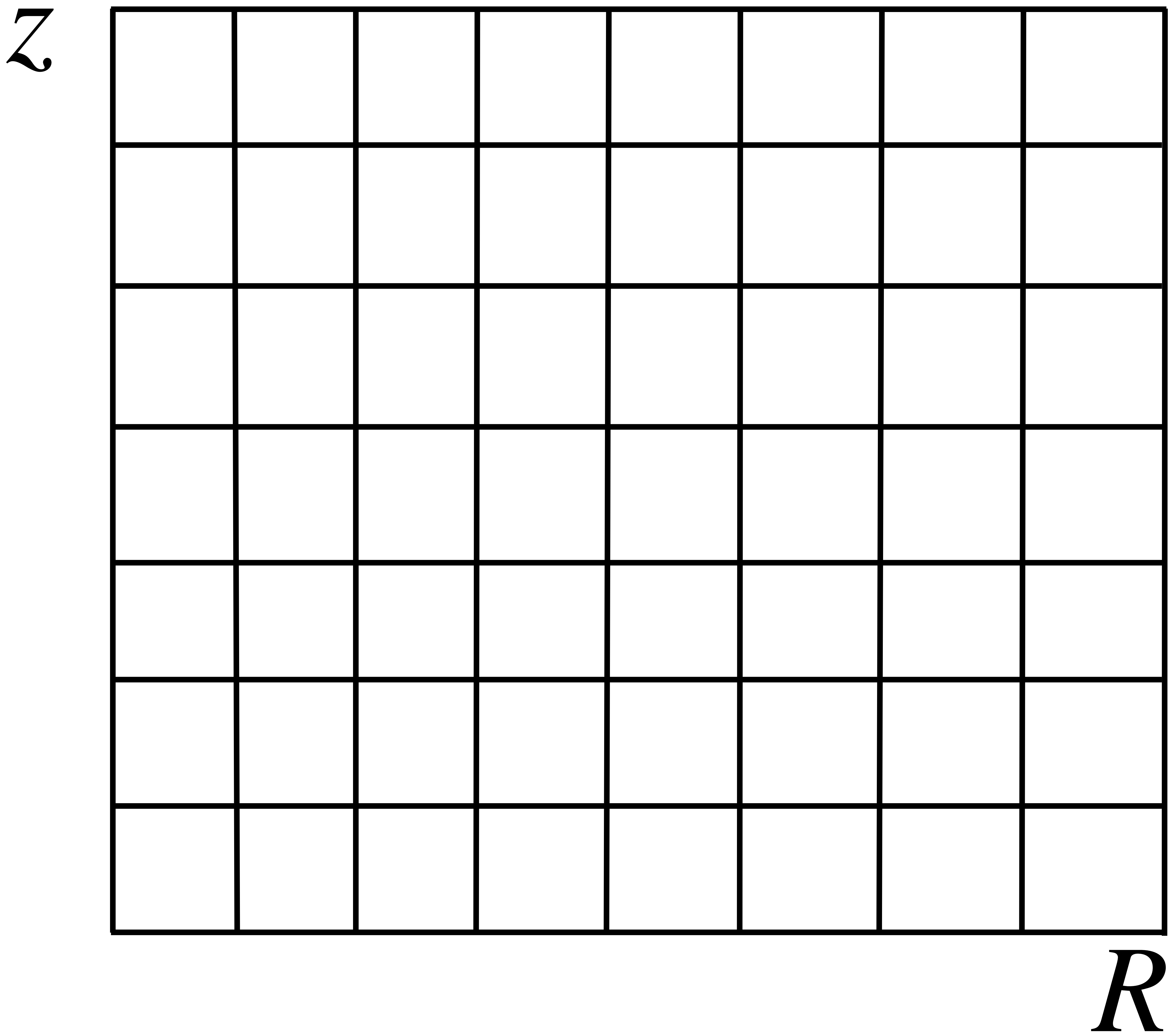

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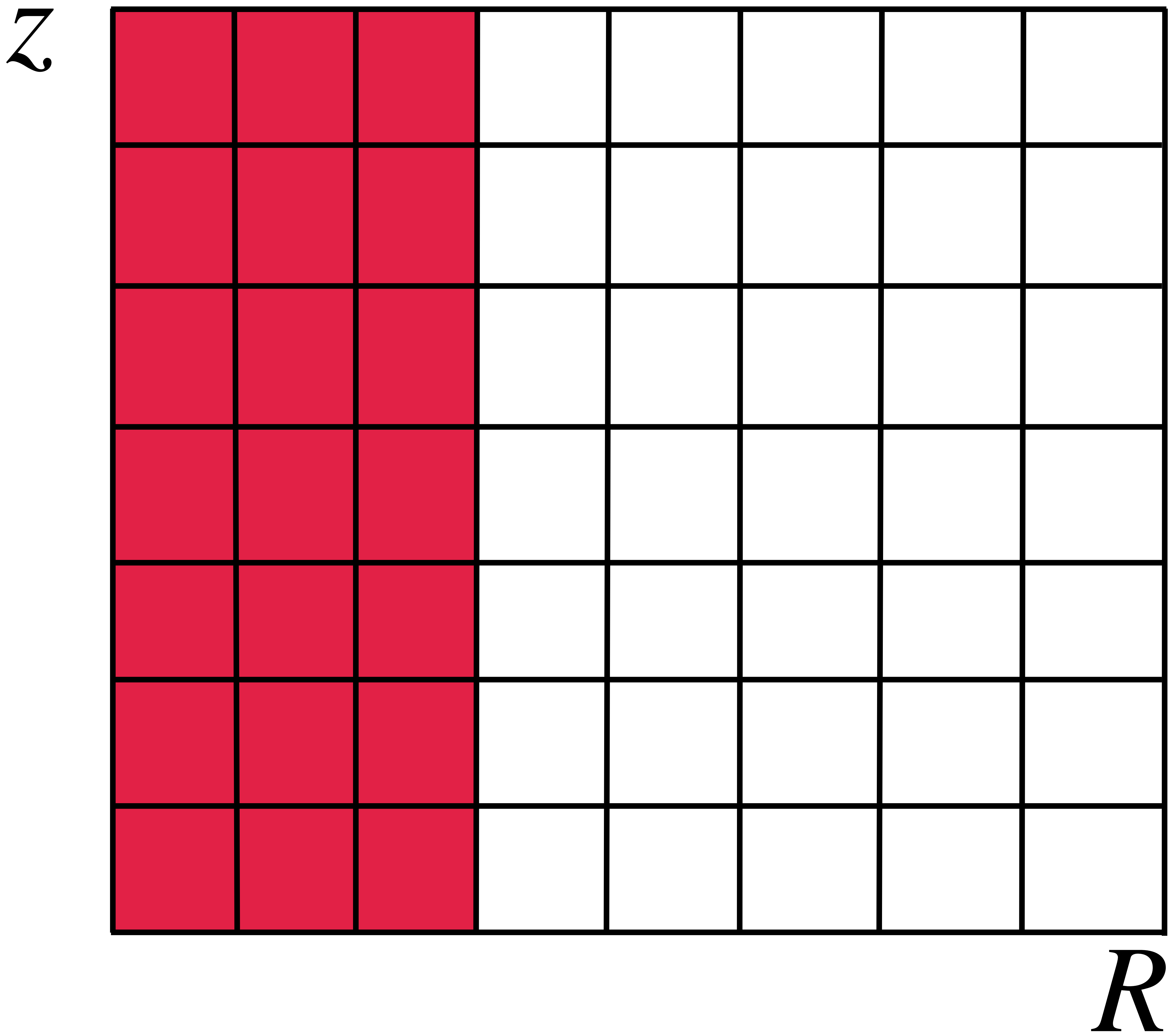

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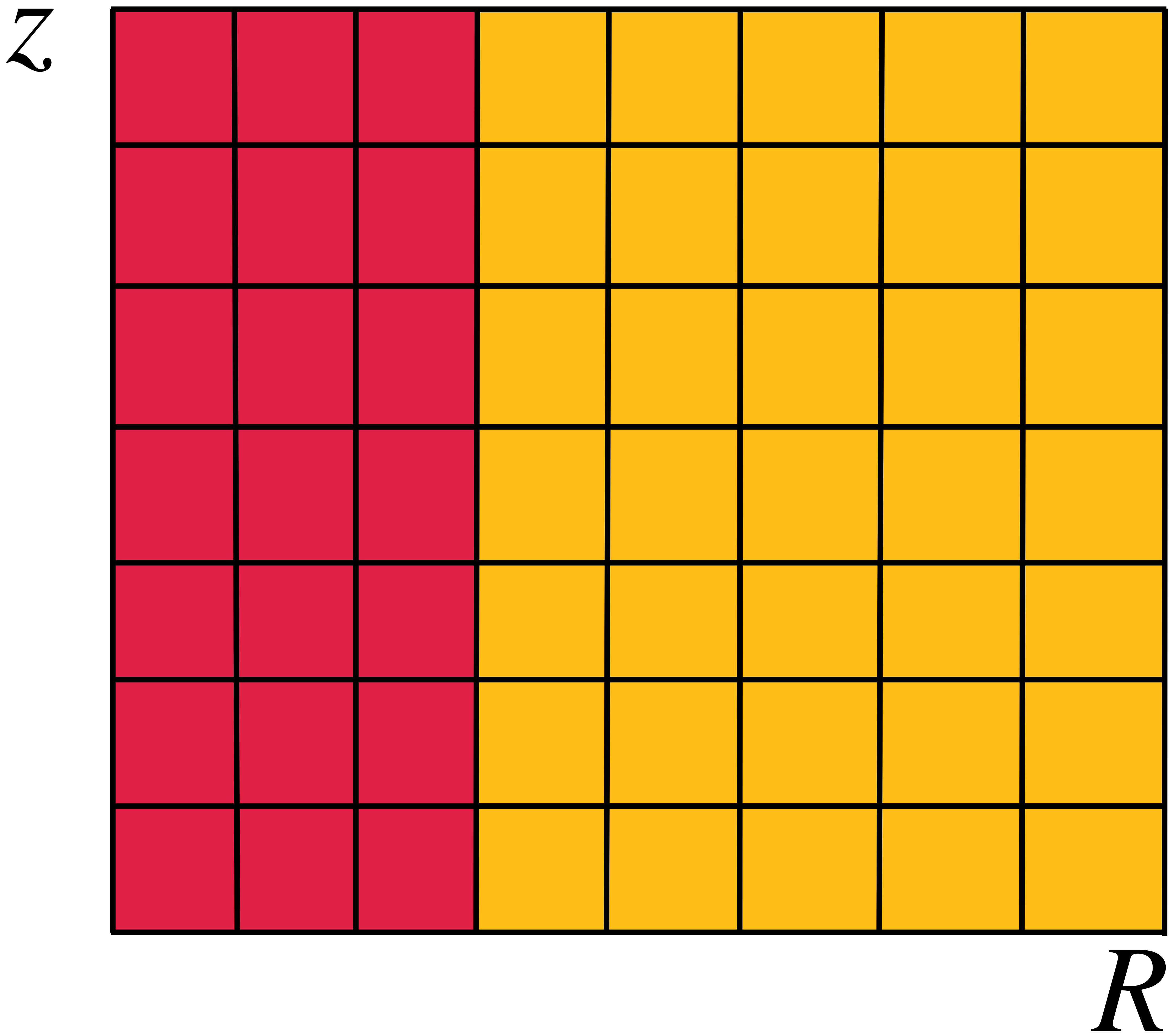

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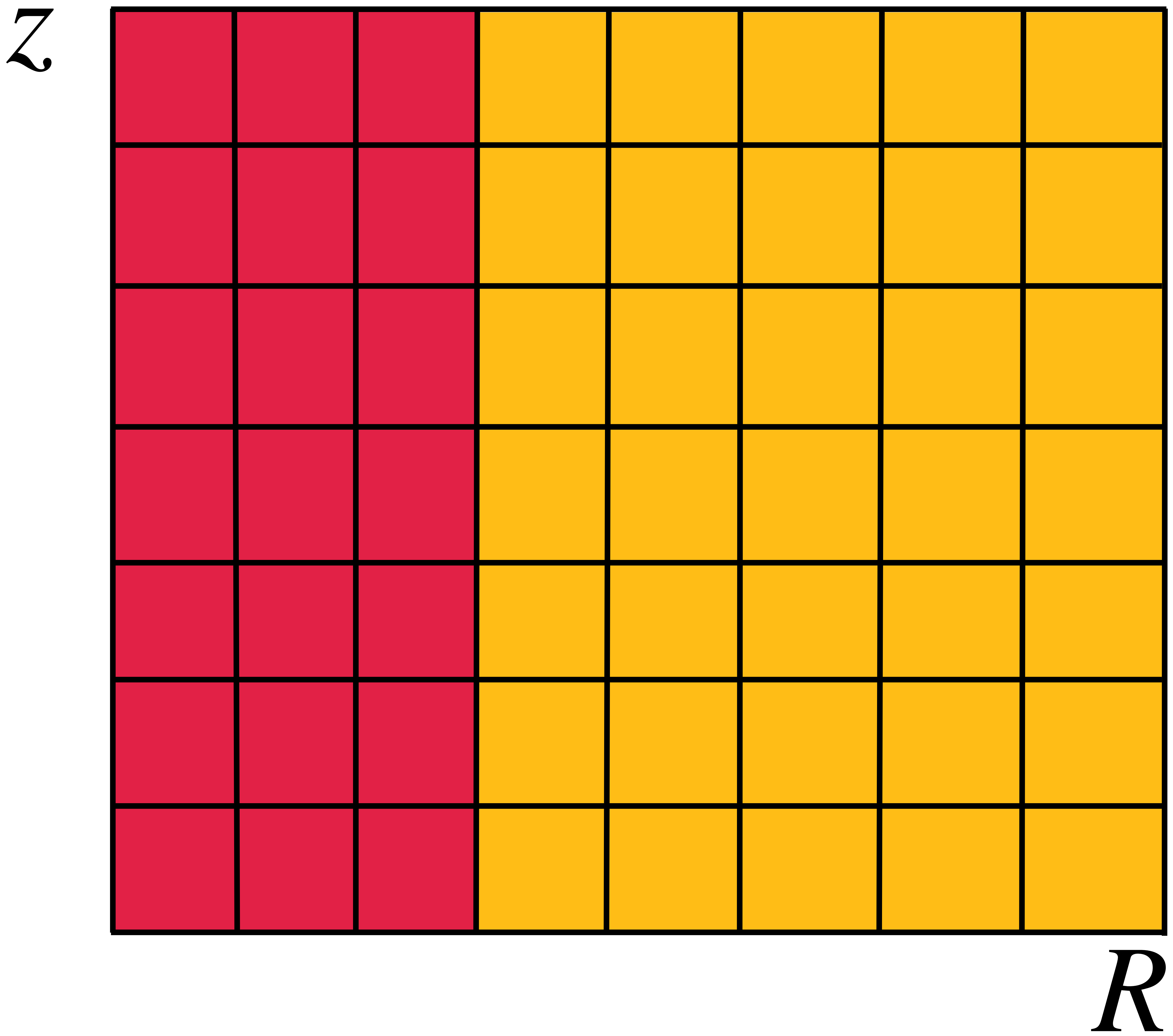

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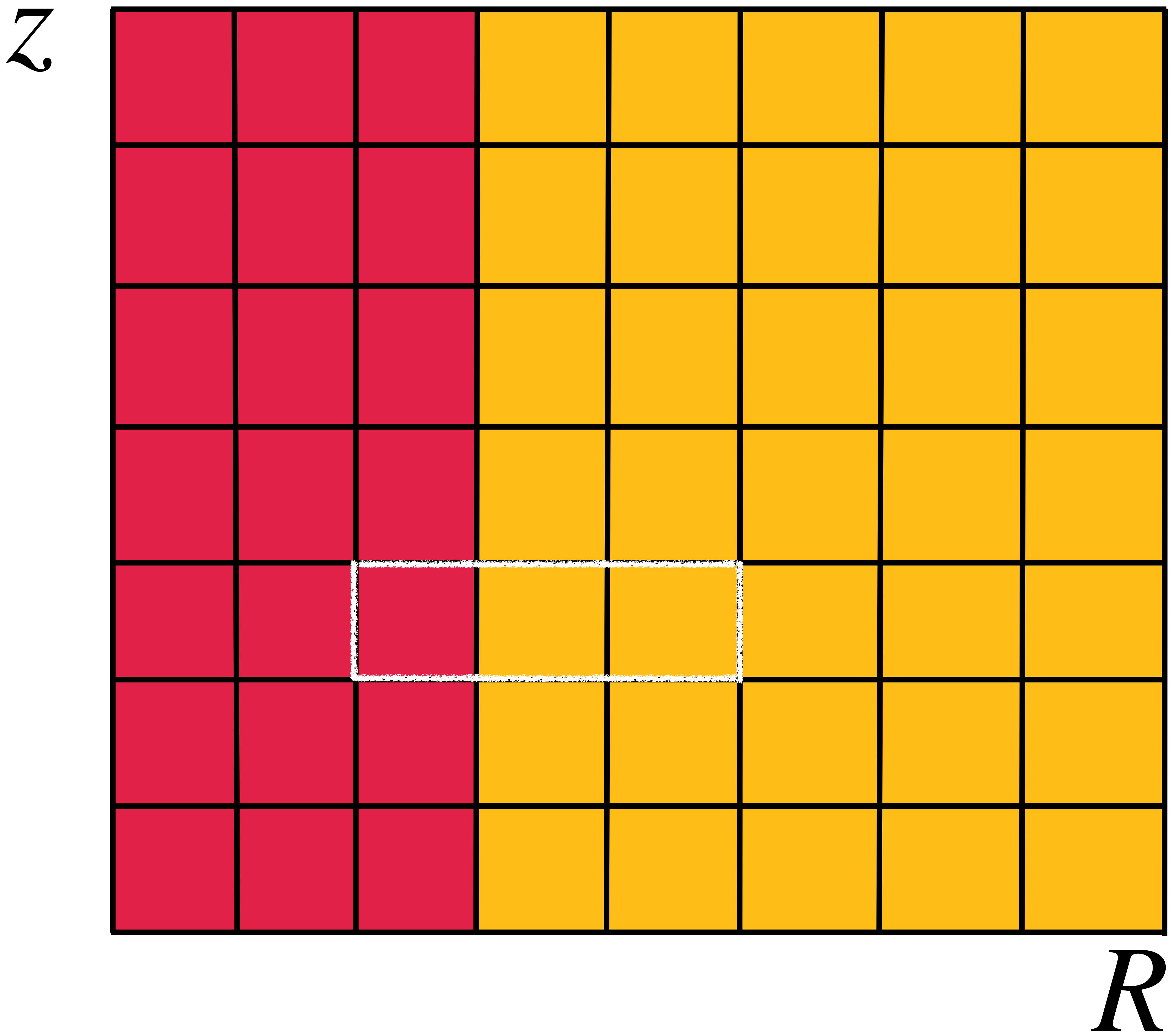

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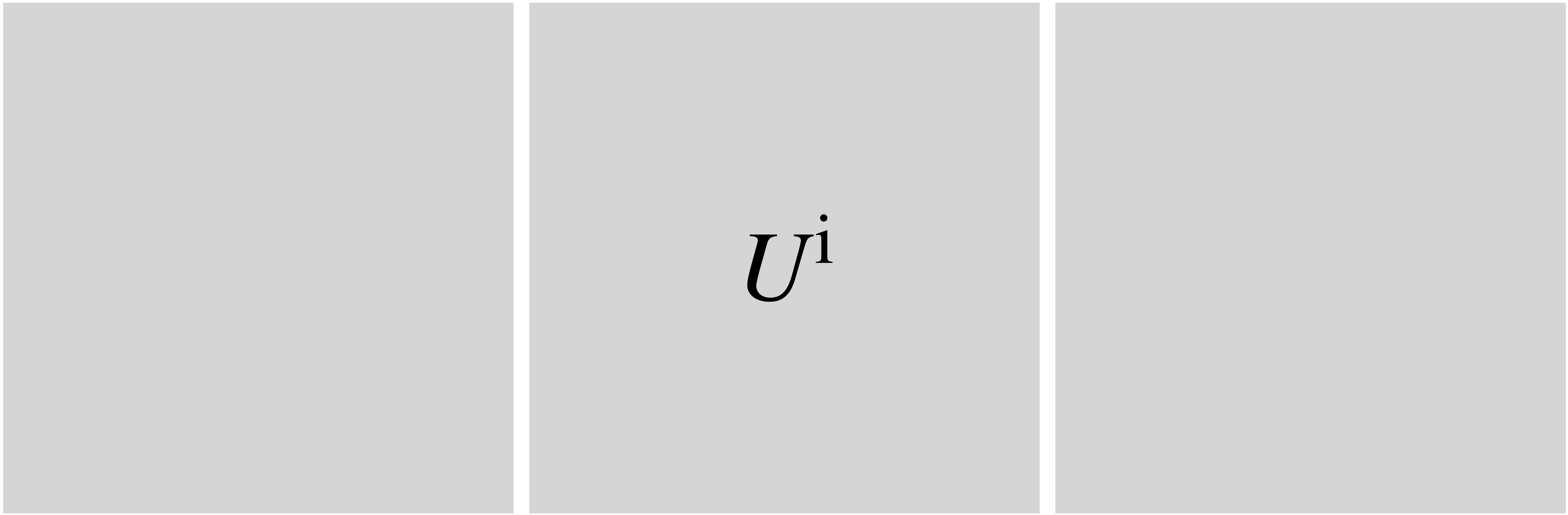

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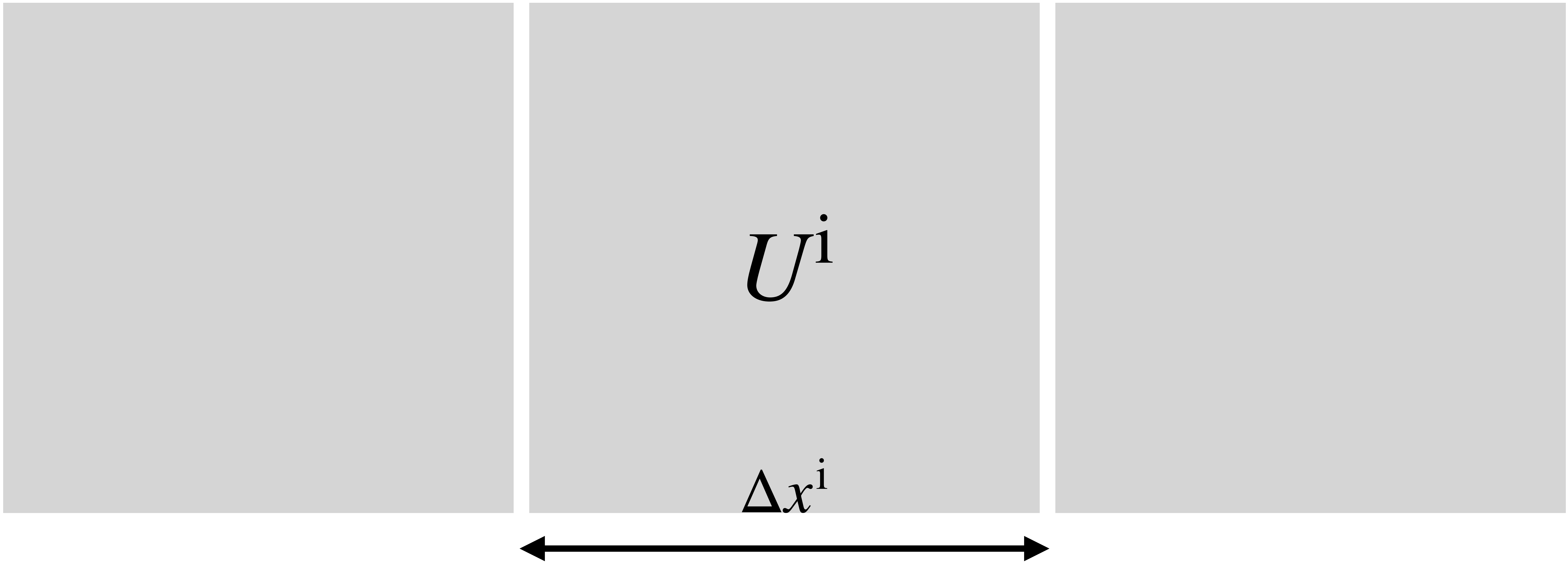

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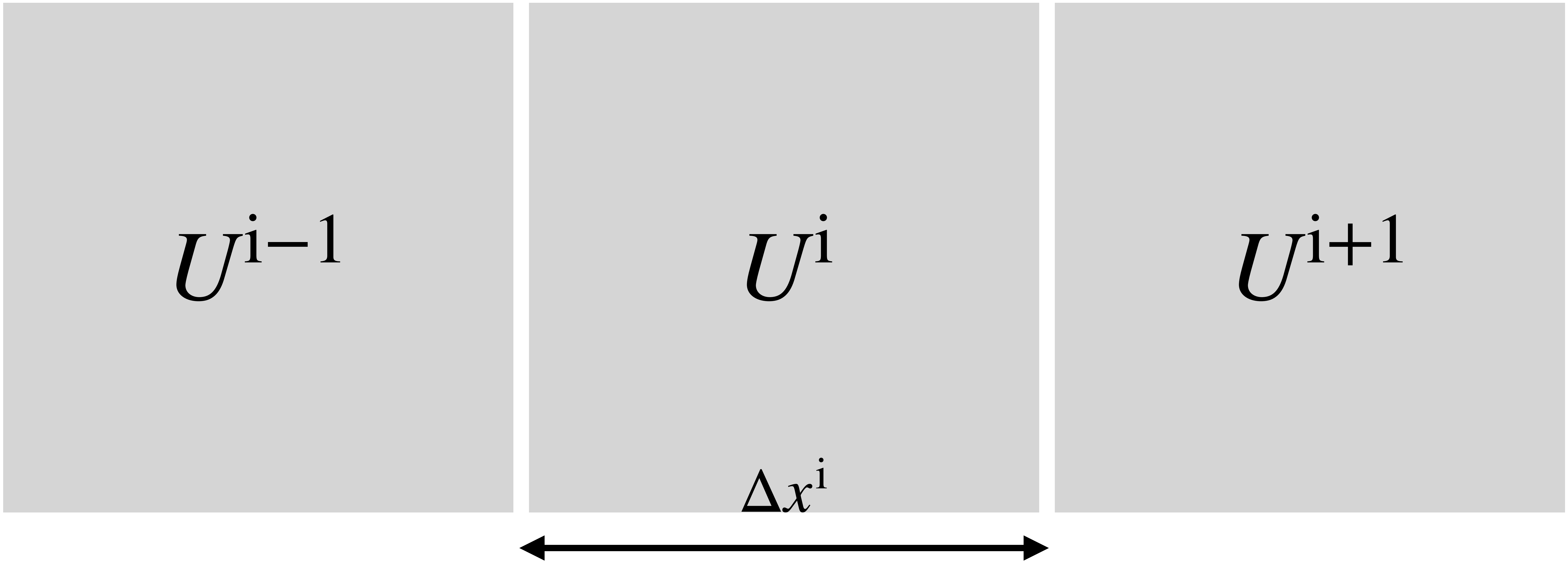

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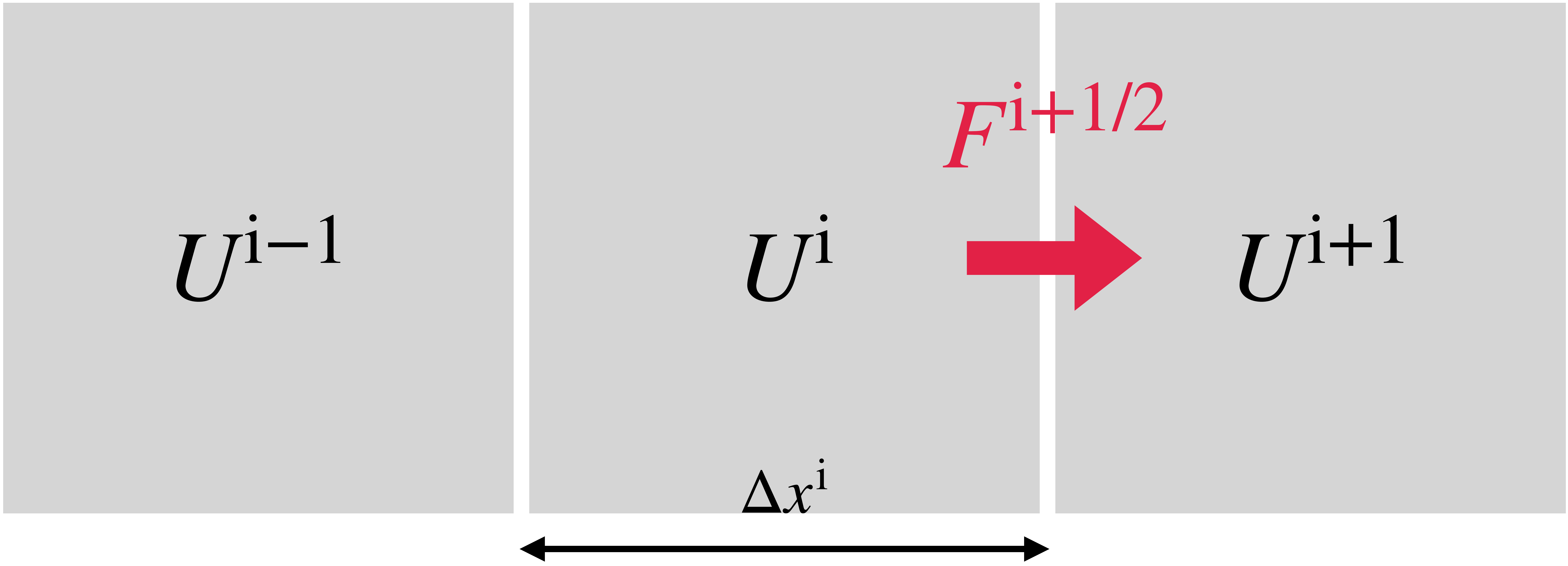

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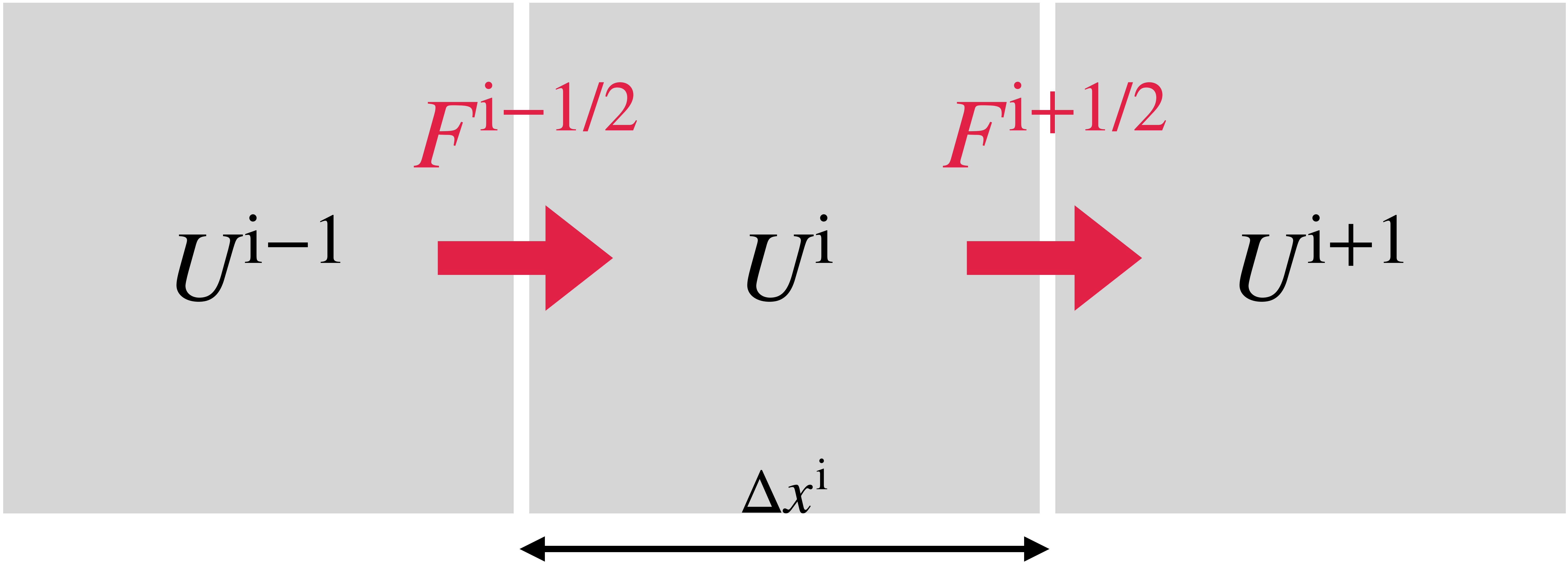

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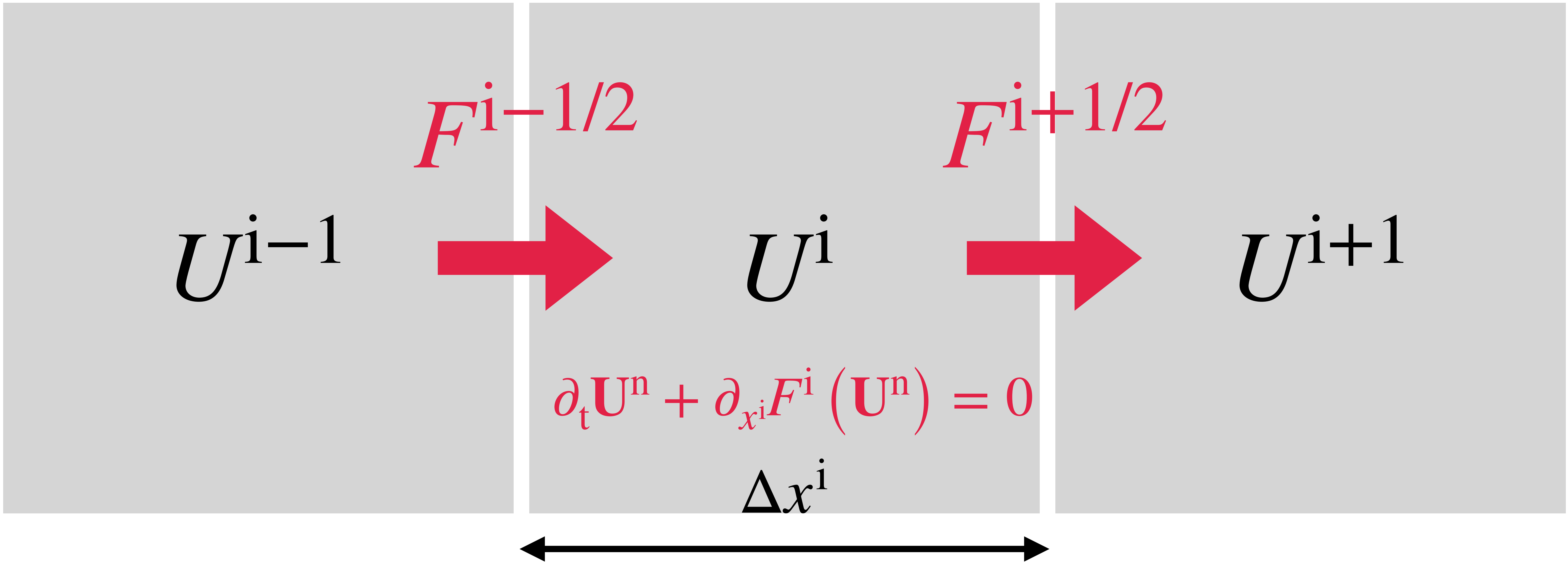

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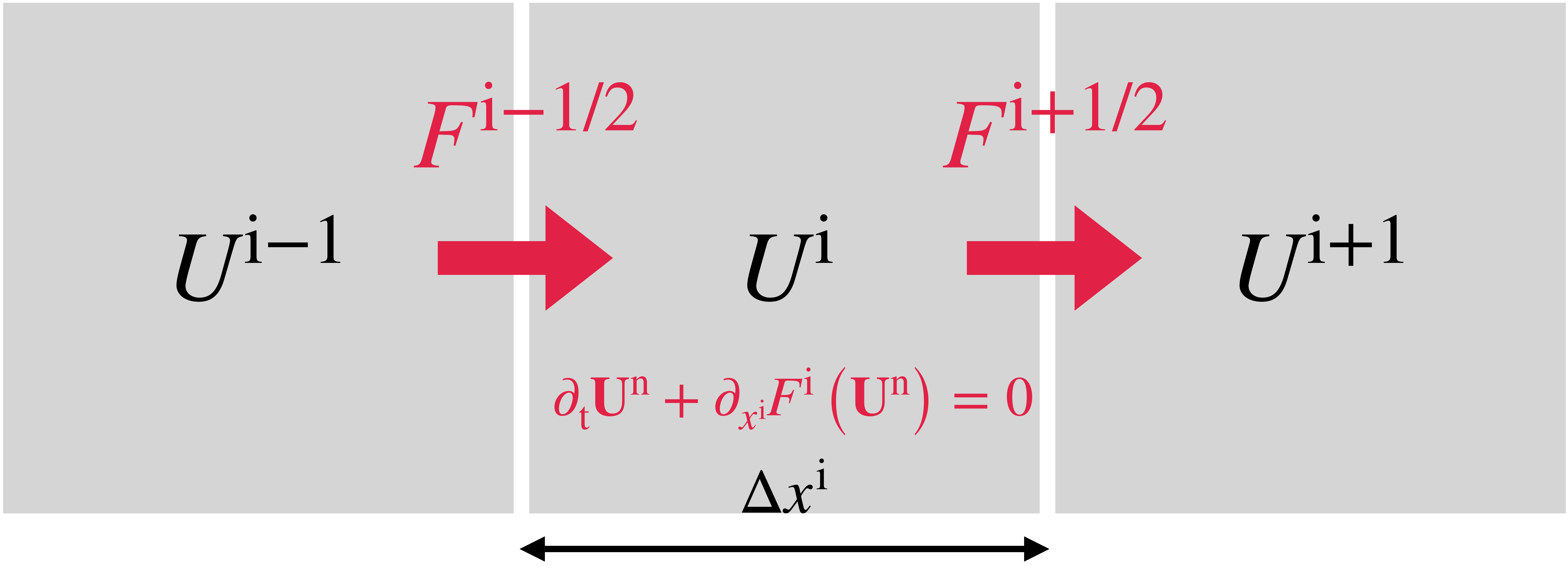

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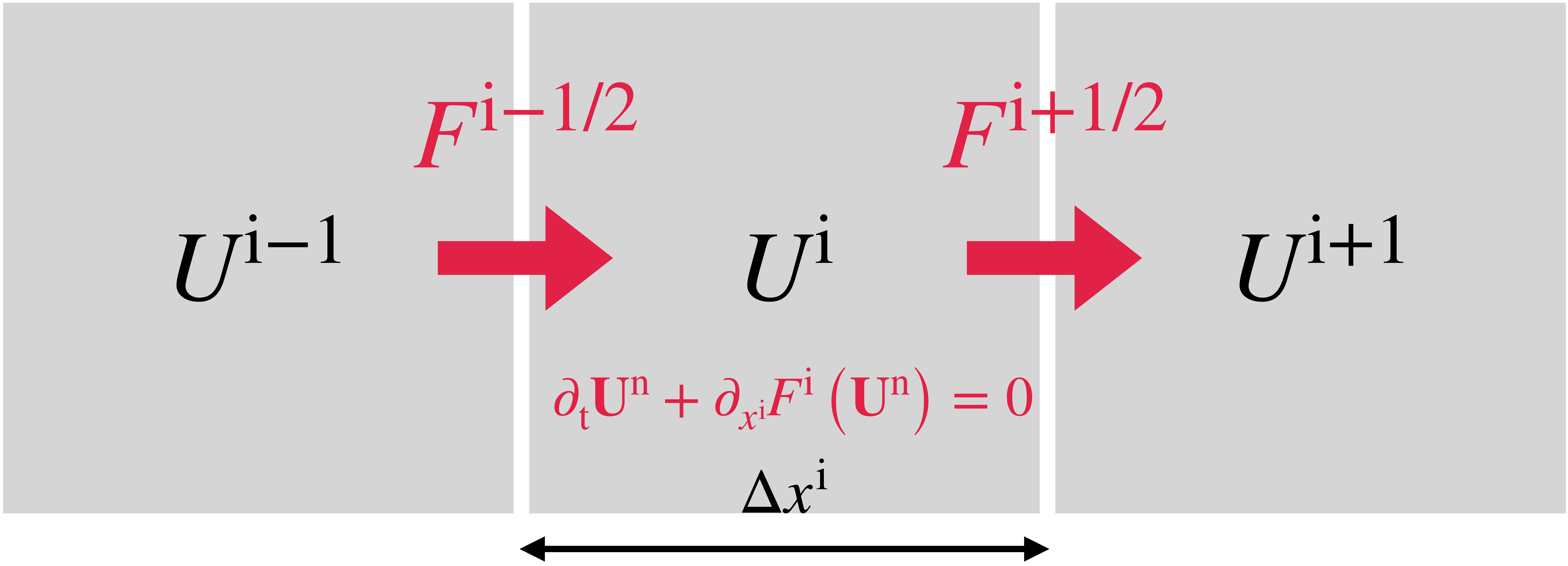

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2D MHD Alfvèn shock moving against Alfvèn face. MPI-AMRVAC (https://amrvac.org/md_doc_demo_movies.html).

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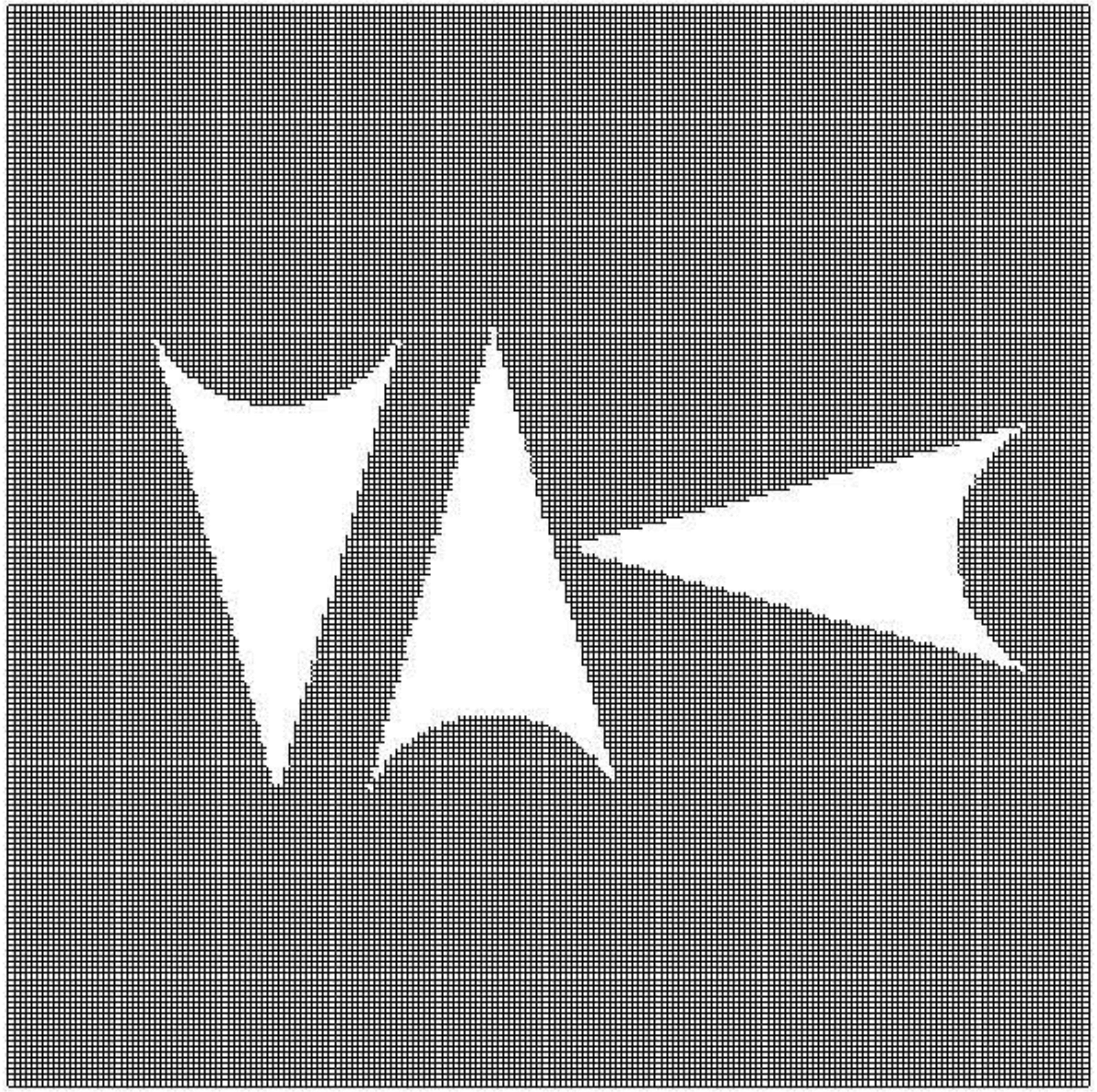
Basis of numerical simulations of jet

✔ Set of SR-MHD equations : conservation of mass, energy, momentum and Maxwell equations.

✔ 1D, 2D or 3D grid where to solve the coupled equations with a specific solver.

✔ Adaptive mesh refinement.

Refinement if : $$E^{\mathrm{n}}_{\mathrm{rel}} = \frac{\left|A^{\mathrm{n}-1} - A^{\mathrm{n}}\right|}{\left|A^{\mathrm{n}-1}\right|} > 1$$



https://amrvac.org/md_doc_examples.html

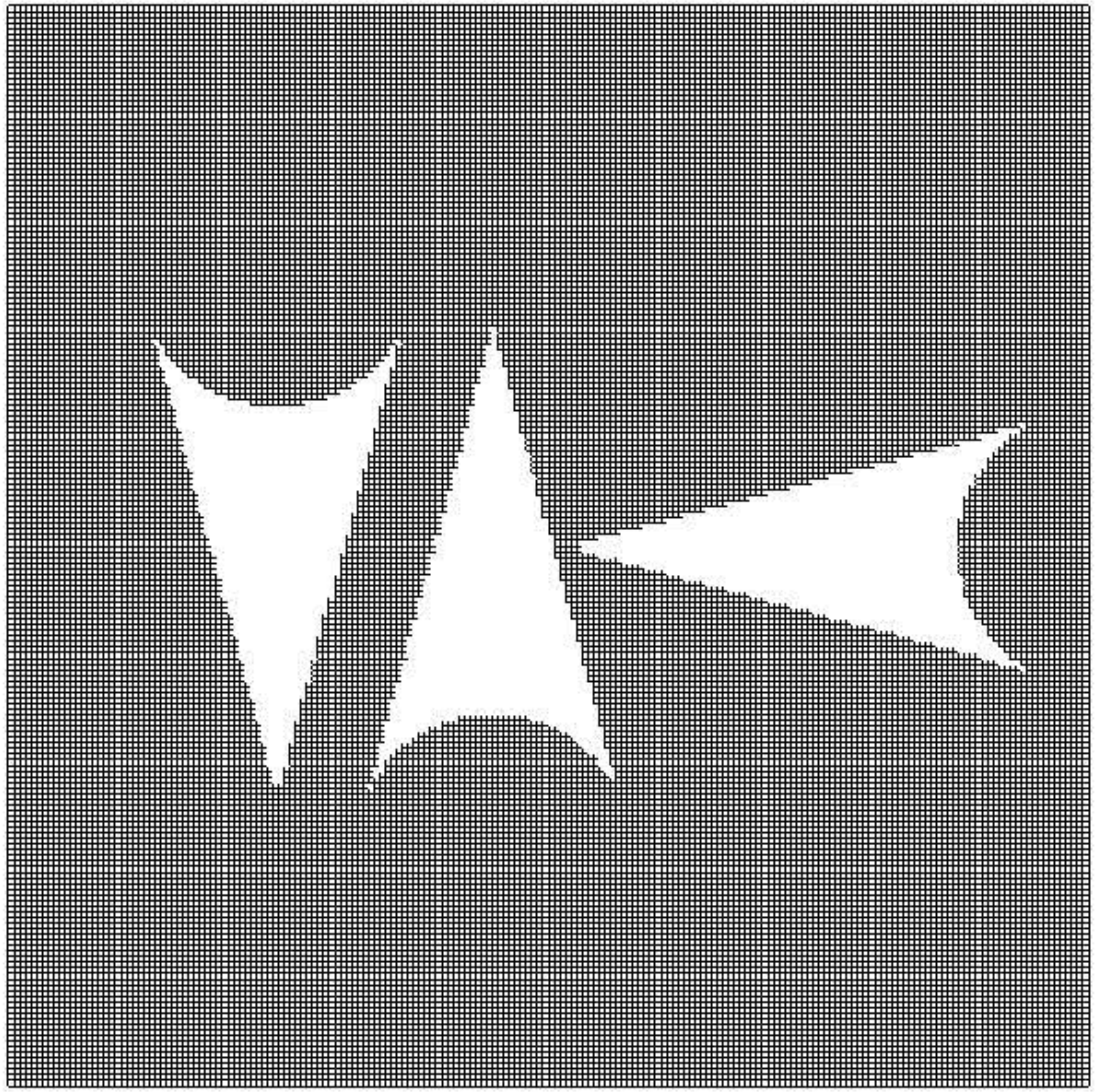
Basis of numerical simulations of jet

✓ Set of SR-MHD equations : conservation of mass, energy, momentum and Maxwell equations.

✓ 1D, 2D or 3D grid where to solve the coupled equations with a specific solver.

✓ Adaptive mesh refinement.

Refinement if : $$E_{\mathrm{rel}}^{\mathrm{n}} = \frac{\left|A^{\mathrm{n}-1} - A^{\mathrm{n}}\right|}{\left|A^{\mathrm{n}-1}\right|} > 1$$



https://amrvac.org/md_doc_examples.html

Special-relativistic MHD simulations : parsec scales

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- Reproduction of stationary components:
  - pressure mismatch in the jet,
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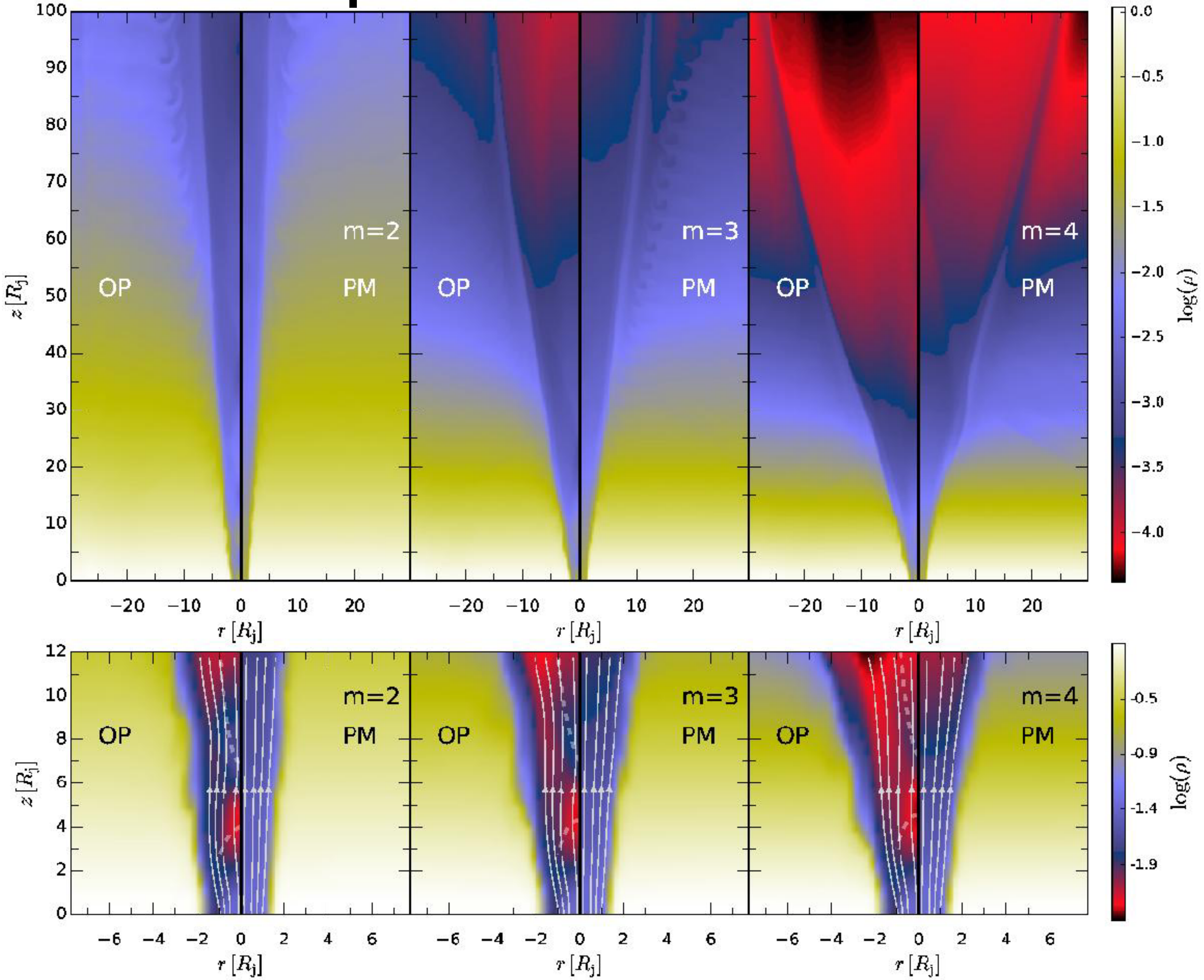

Fromm et al. 2018

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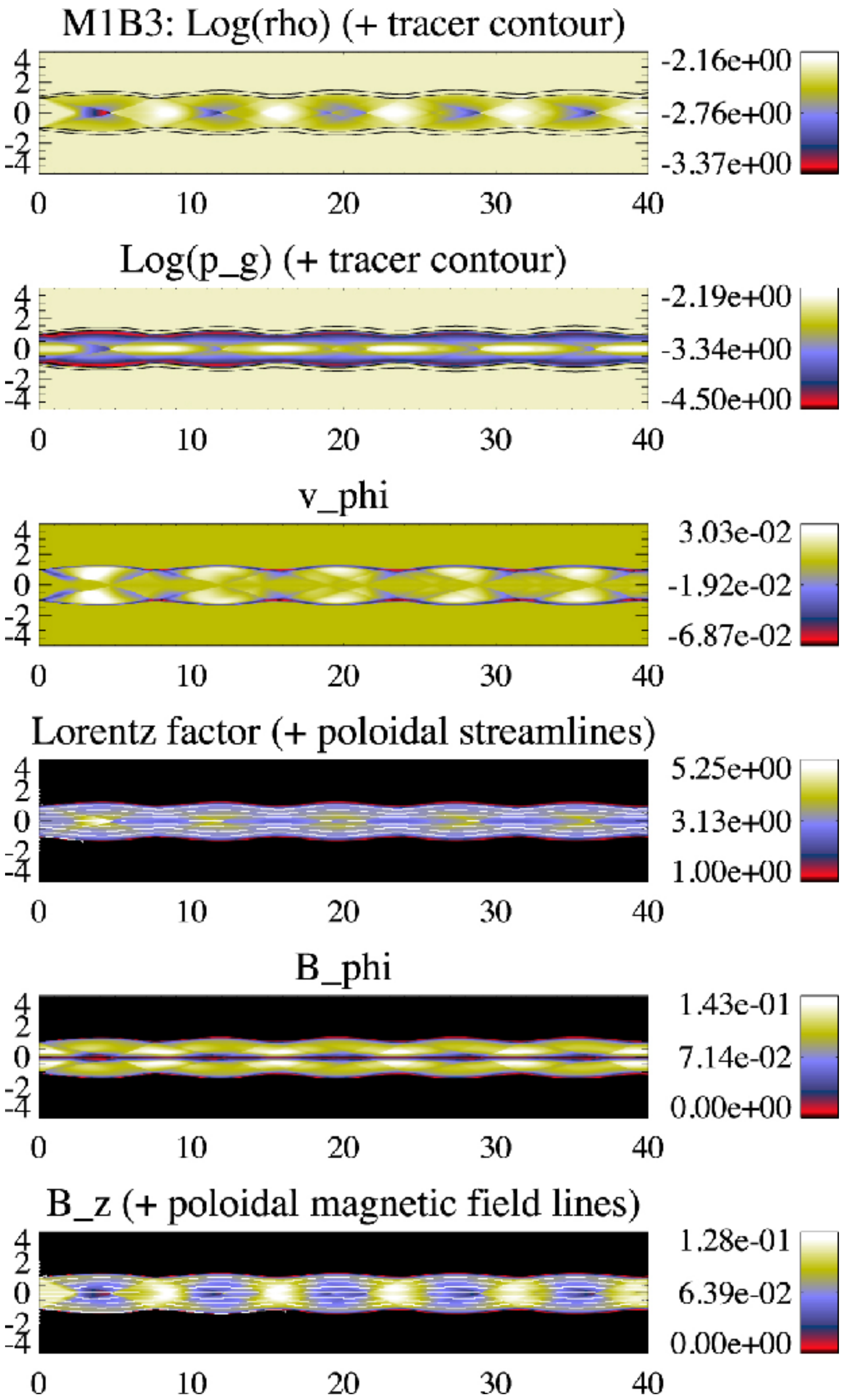

Fuentes et al. 2018

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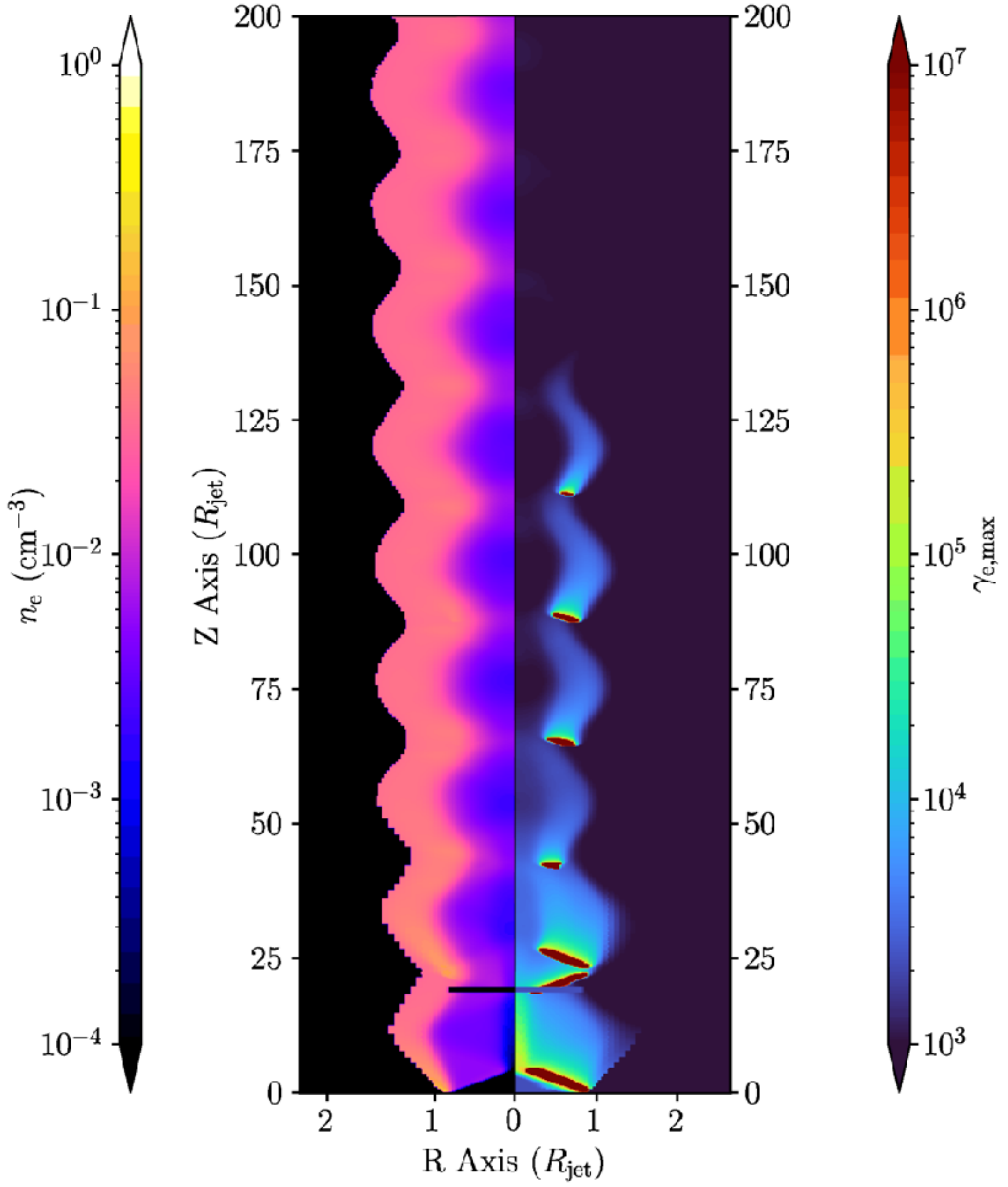

Fichet de Clairfontaine et al. 2022

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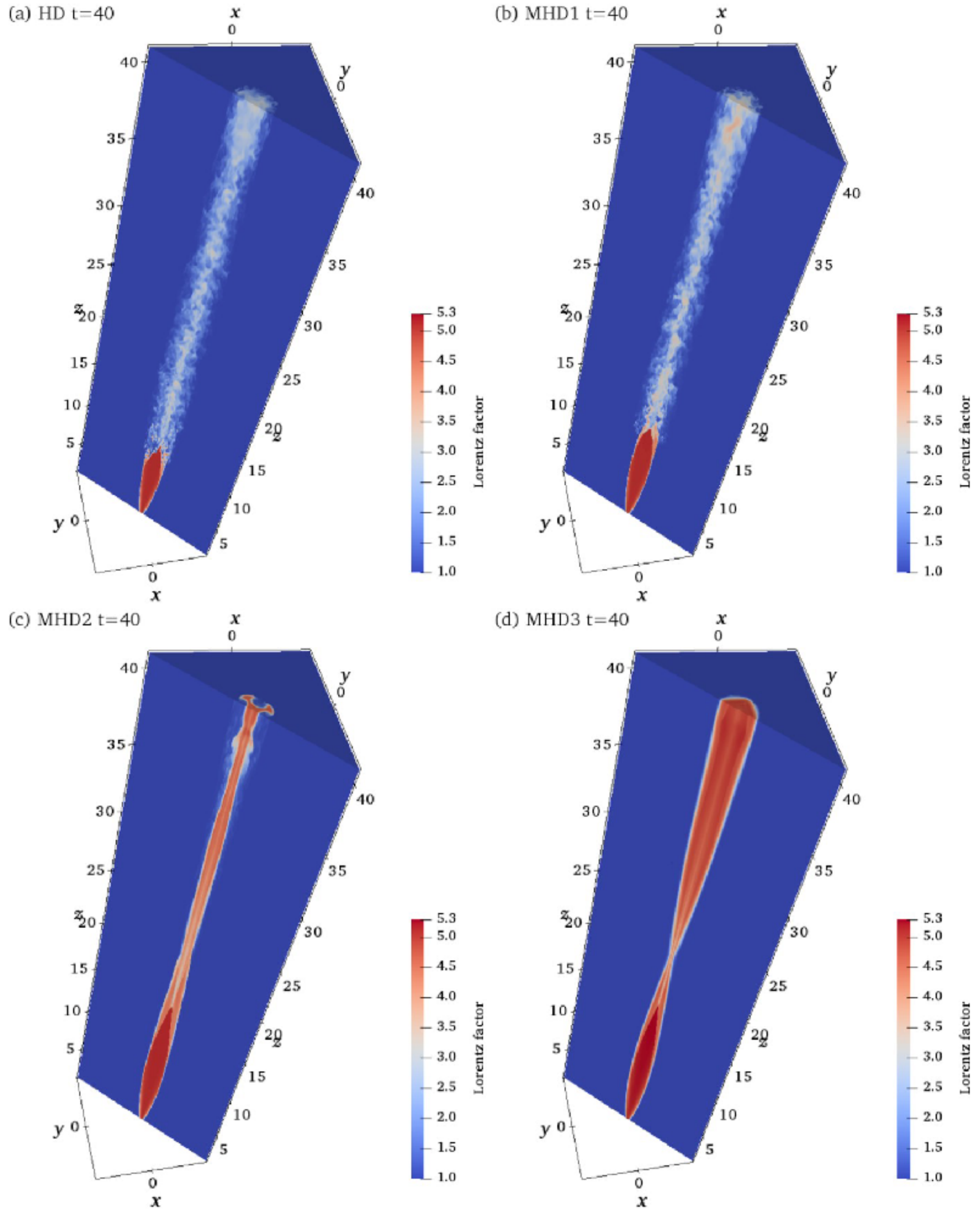

Matsumoto et al. 2021

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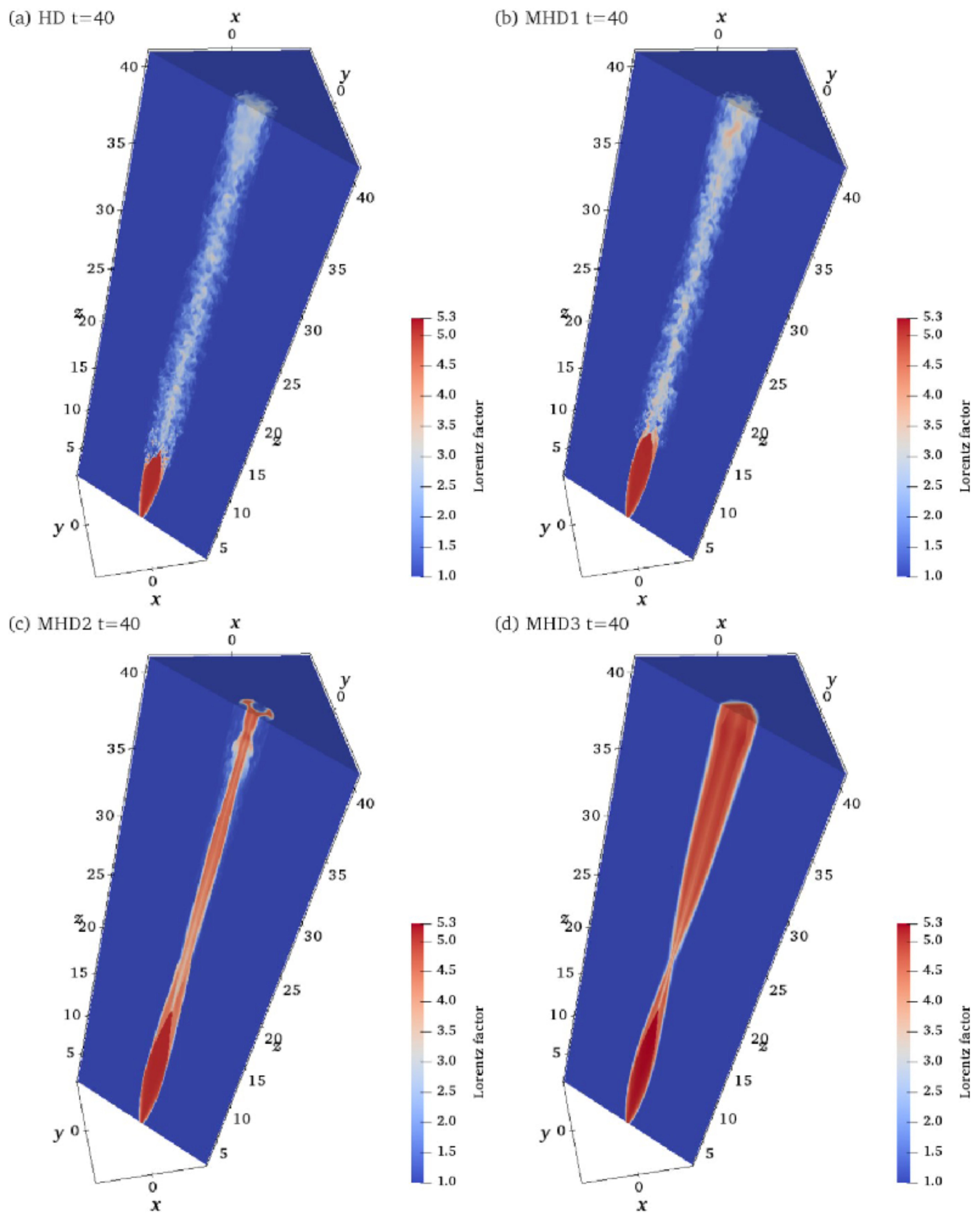
Usually 2D, focus on jet structure in sub/parsec scales and linked with radio features.



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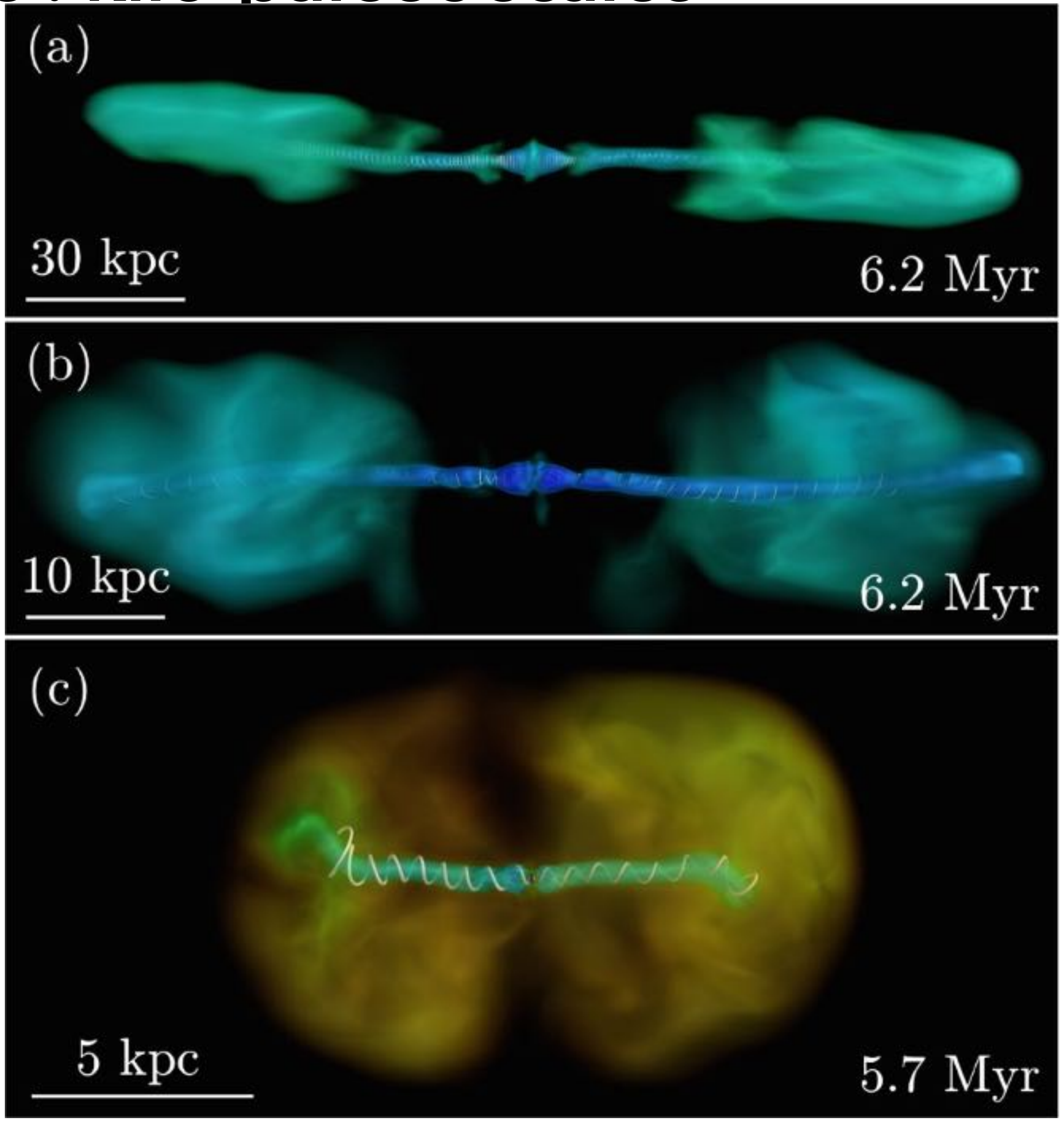

Tchekhovskoy & Bromberg, 2016

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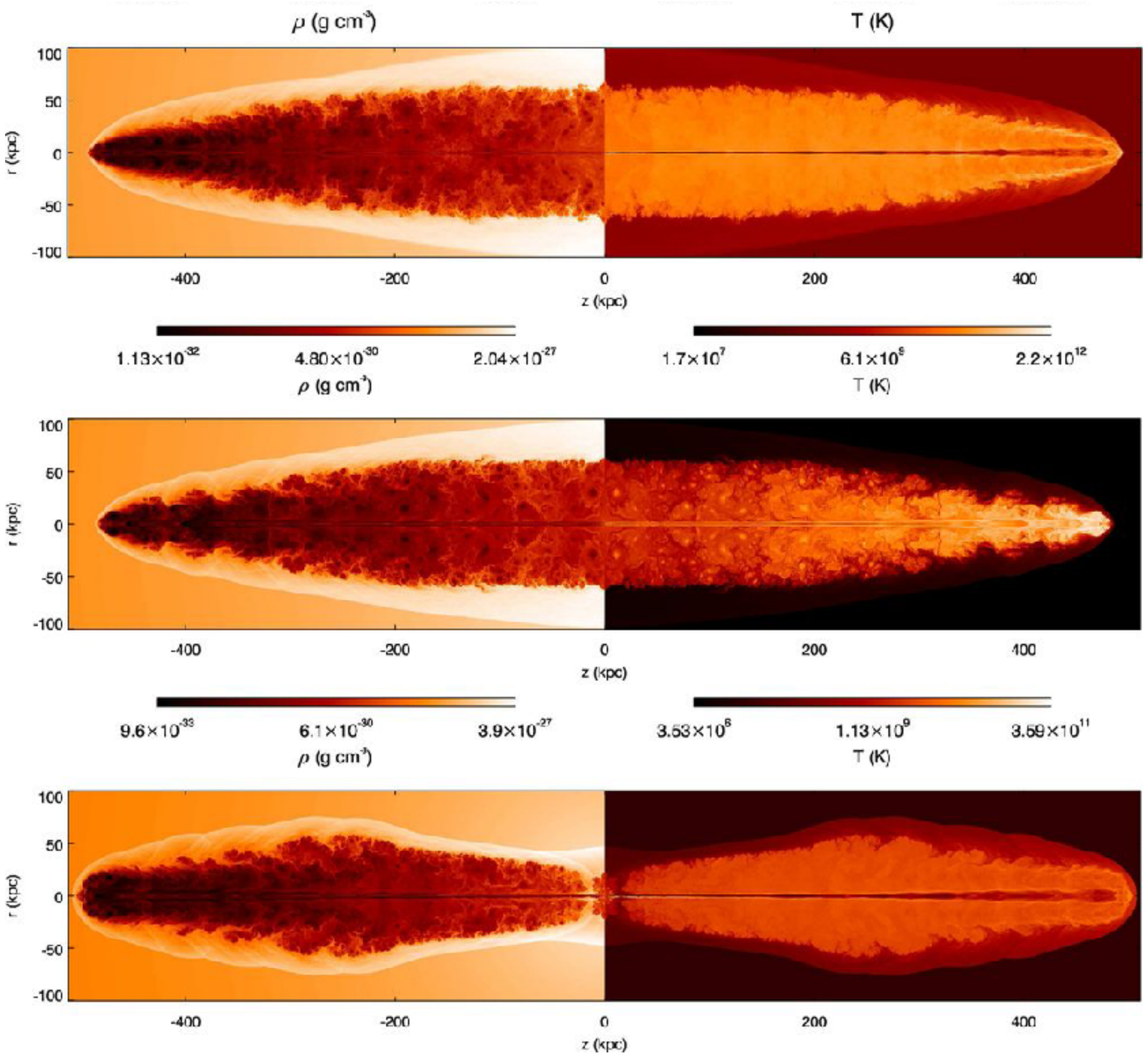

Perucho et al. 2014

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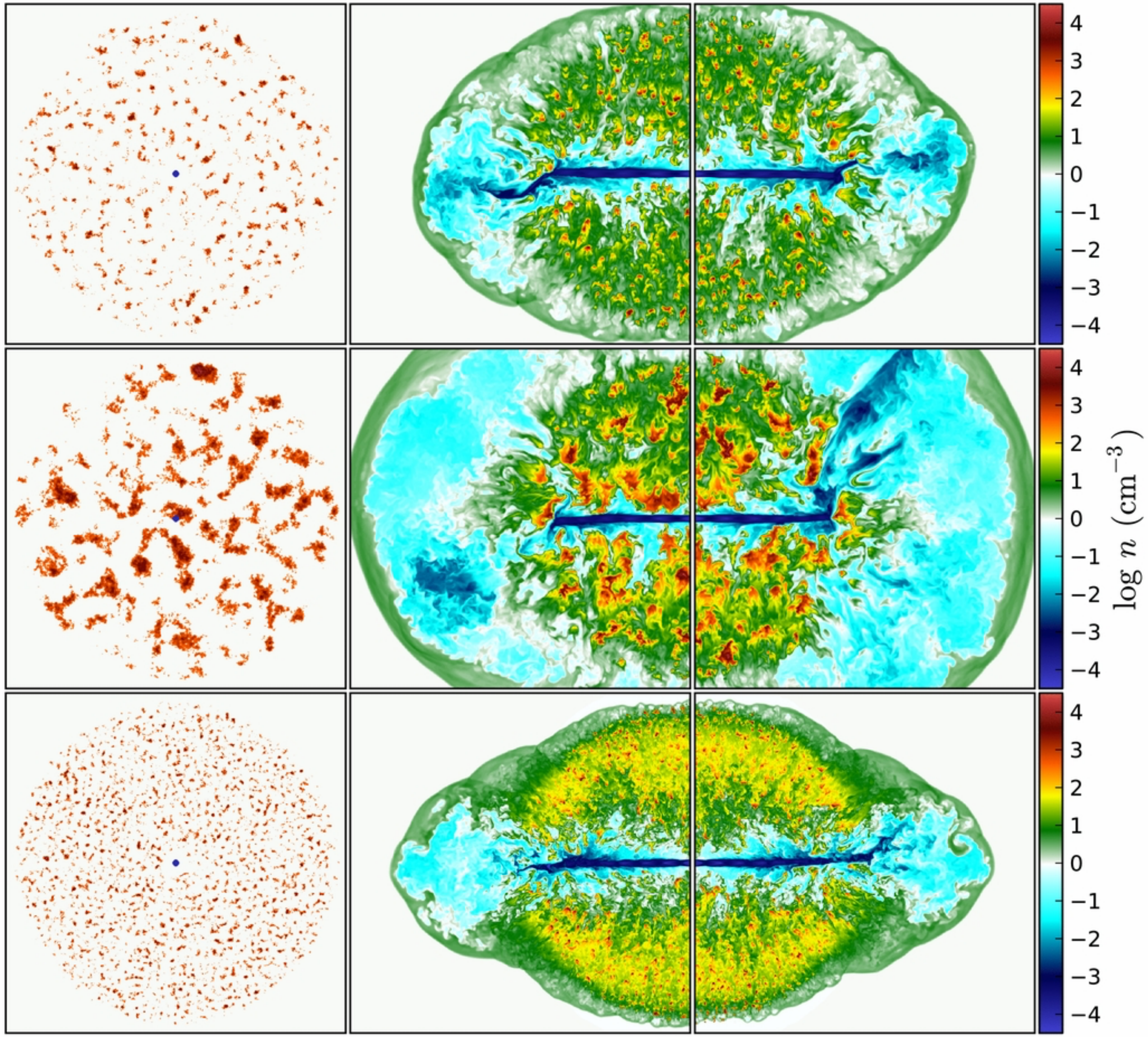

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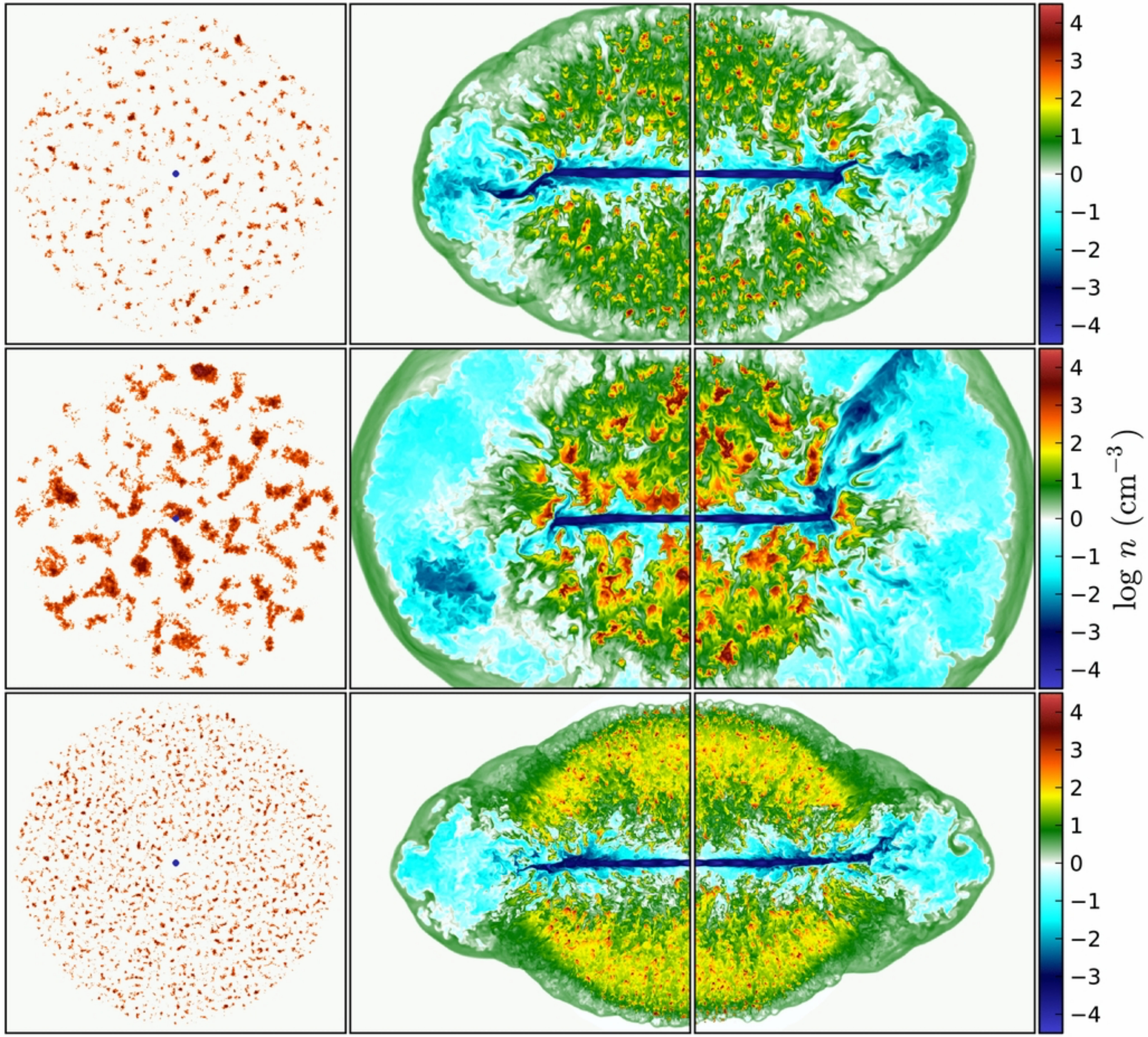
Usually in 3D, demanding large-scale simulations, and microphysics. Application on jet morphology, galaxy / cluster evolution.



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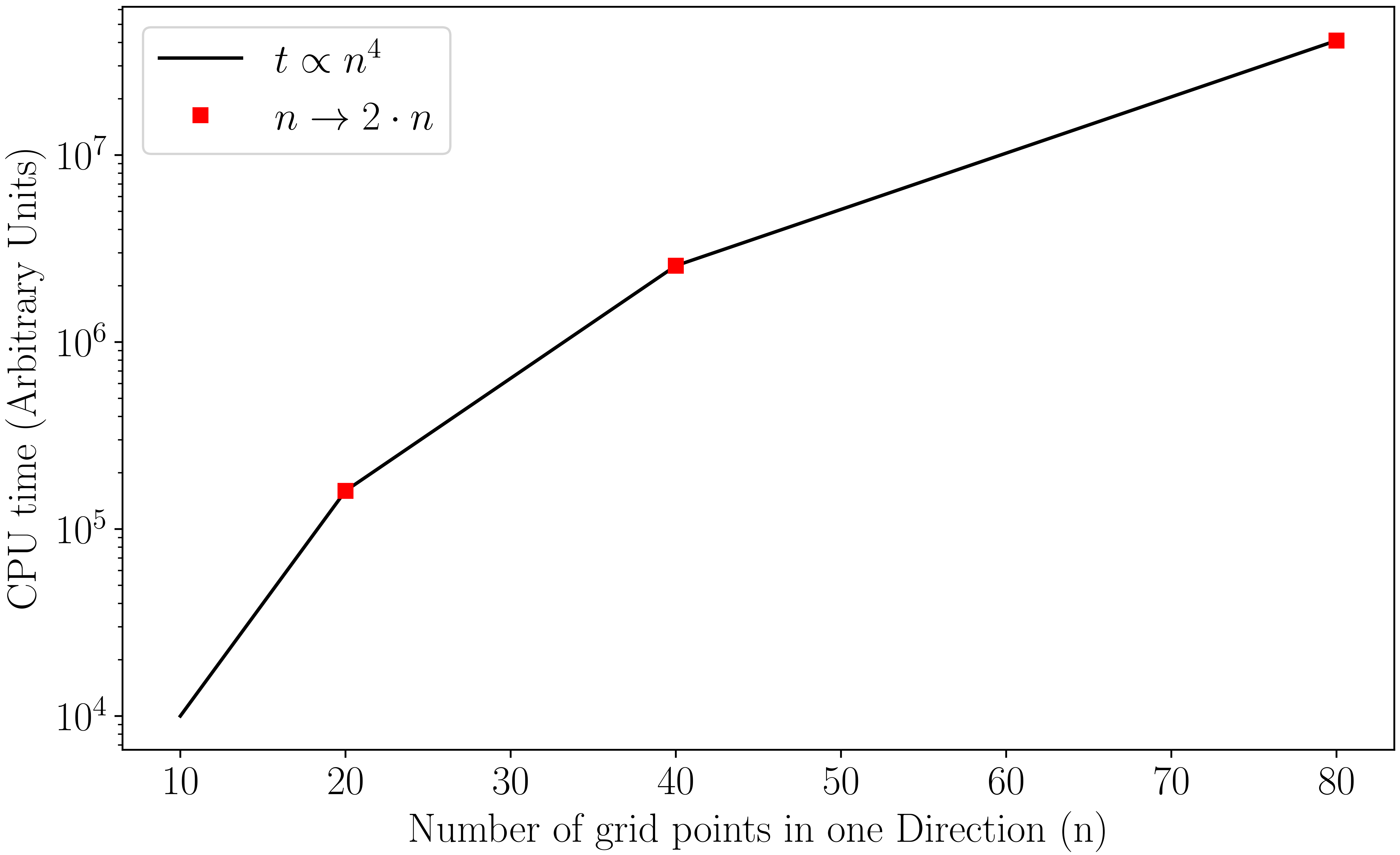

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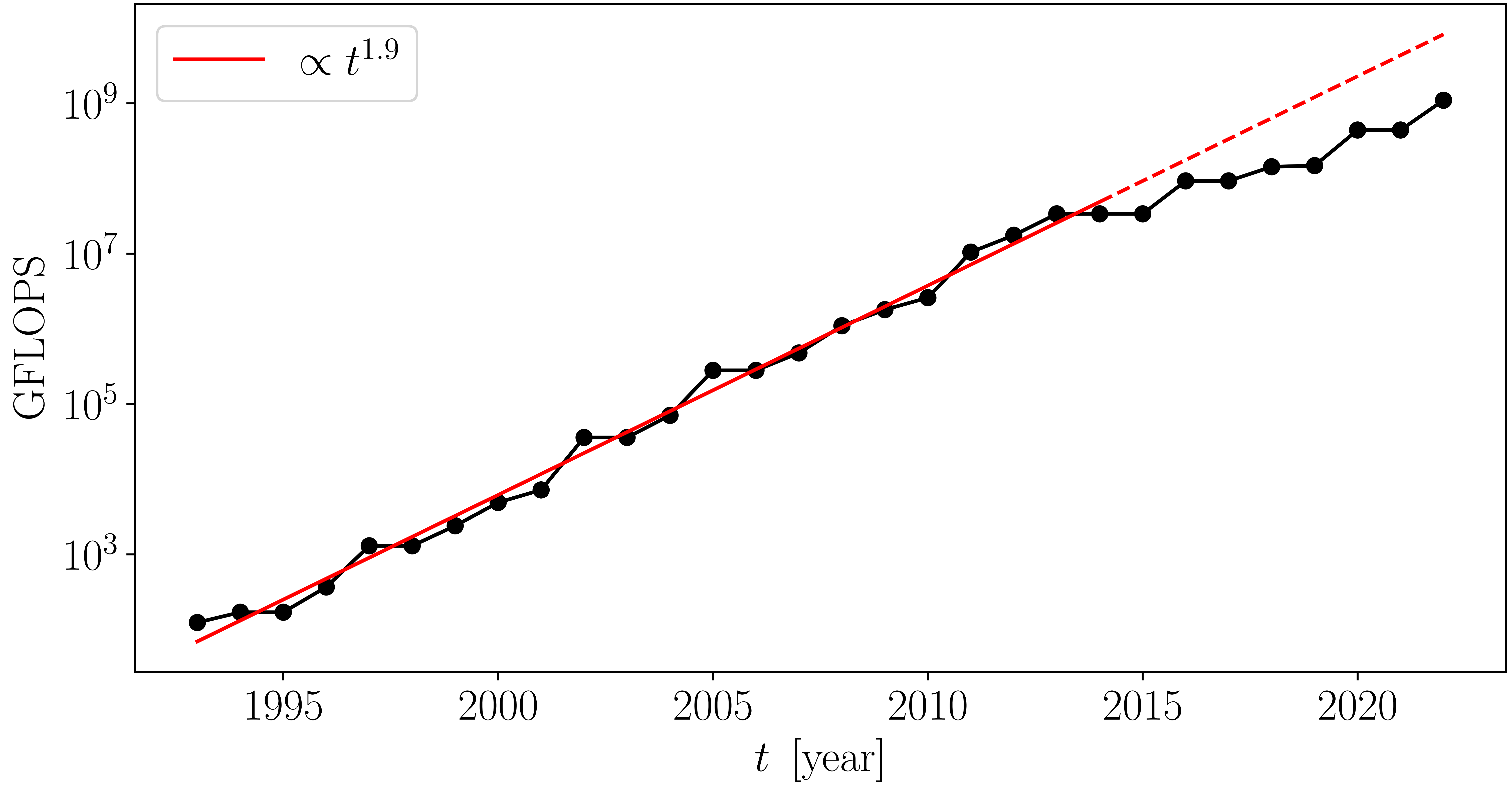

Max Roser, Hannah Ritchie and Edouard Mathieu (2023) - "What is Moore's Law?" Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/moores-law'

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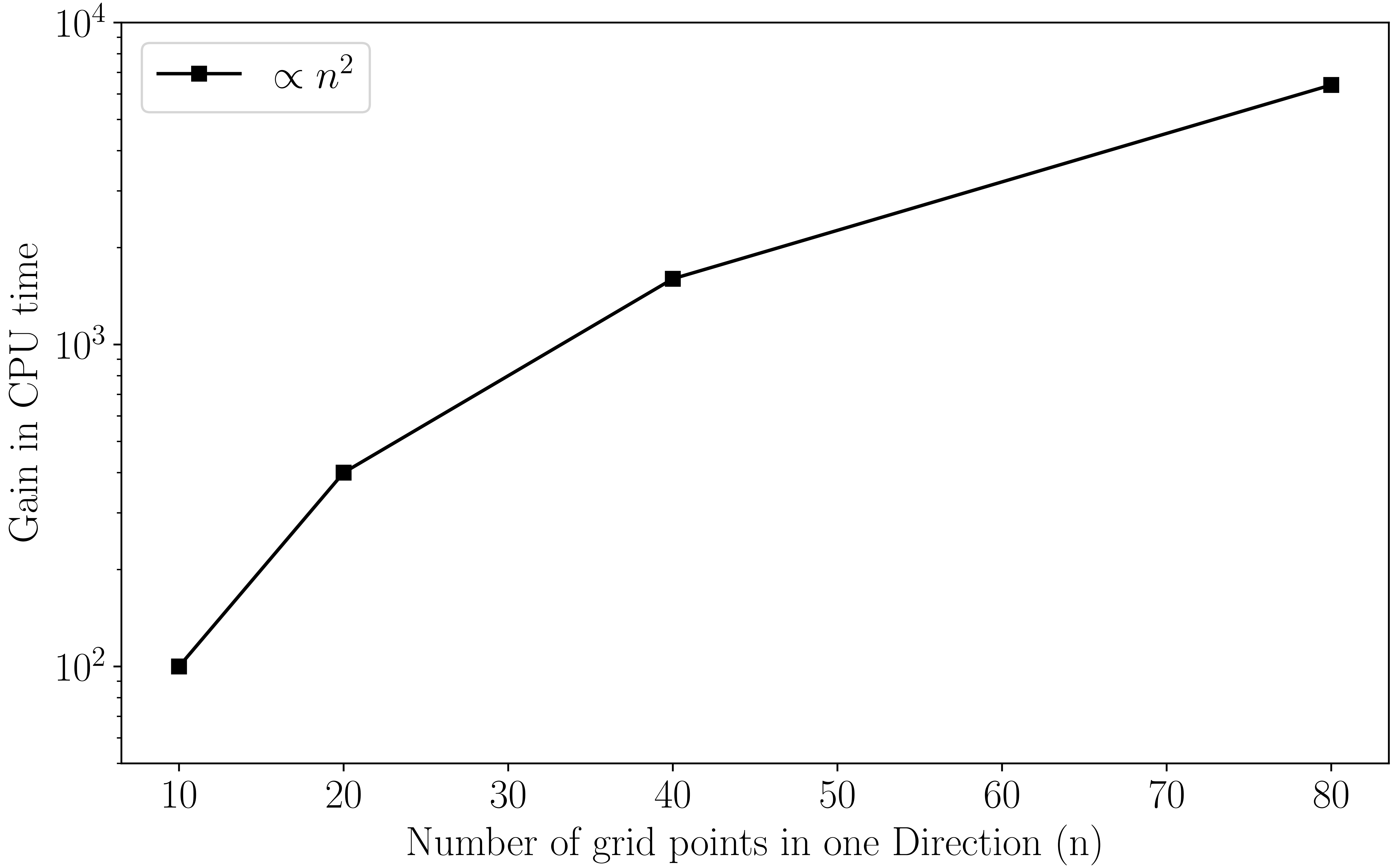

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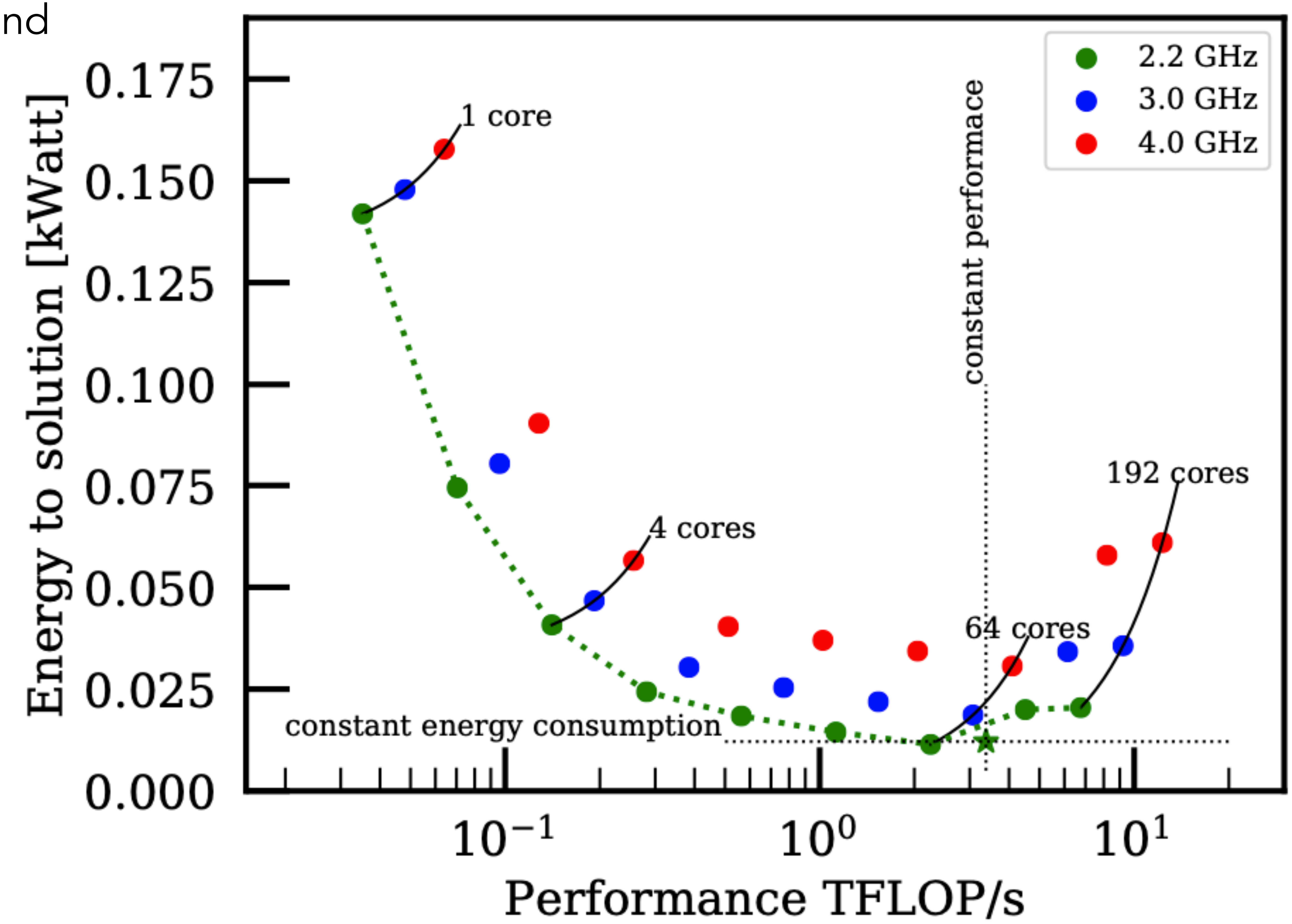
Zwart 2020



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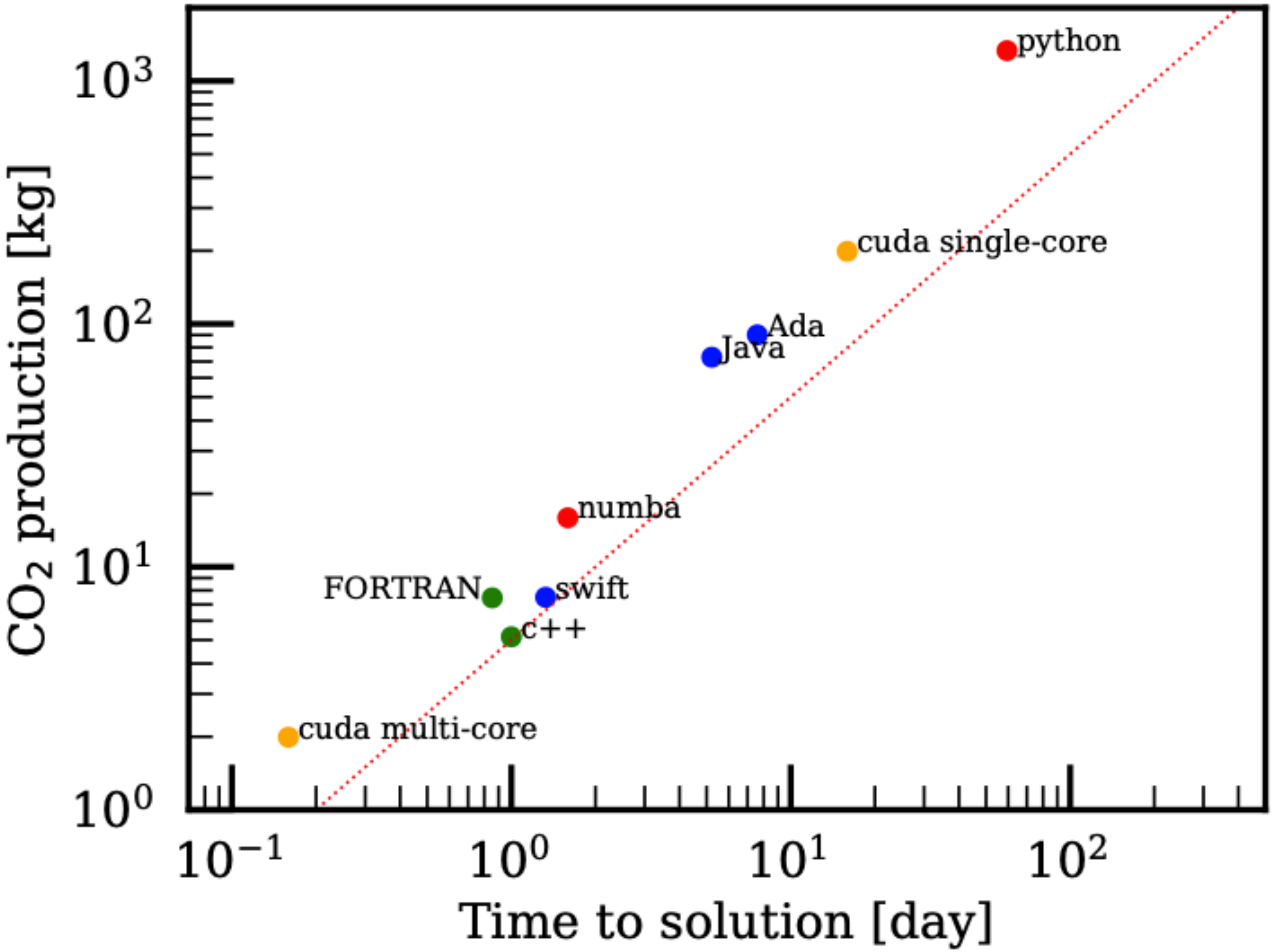

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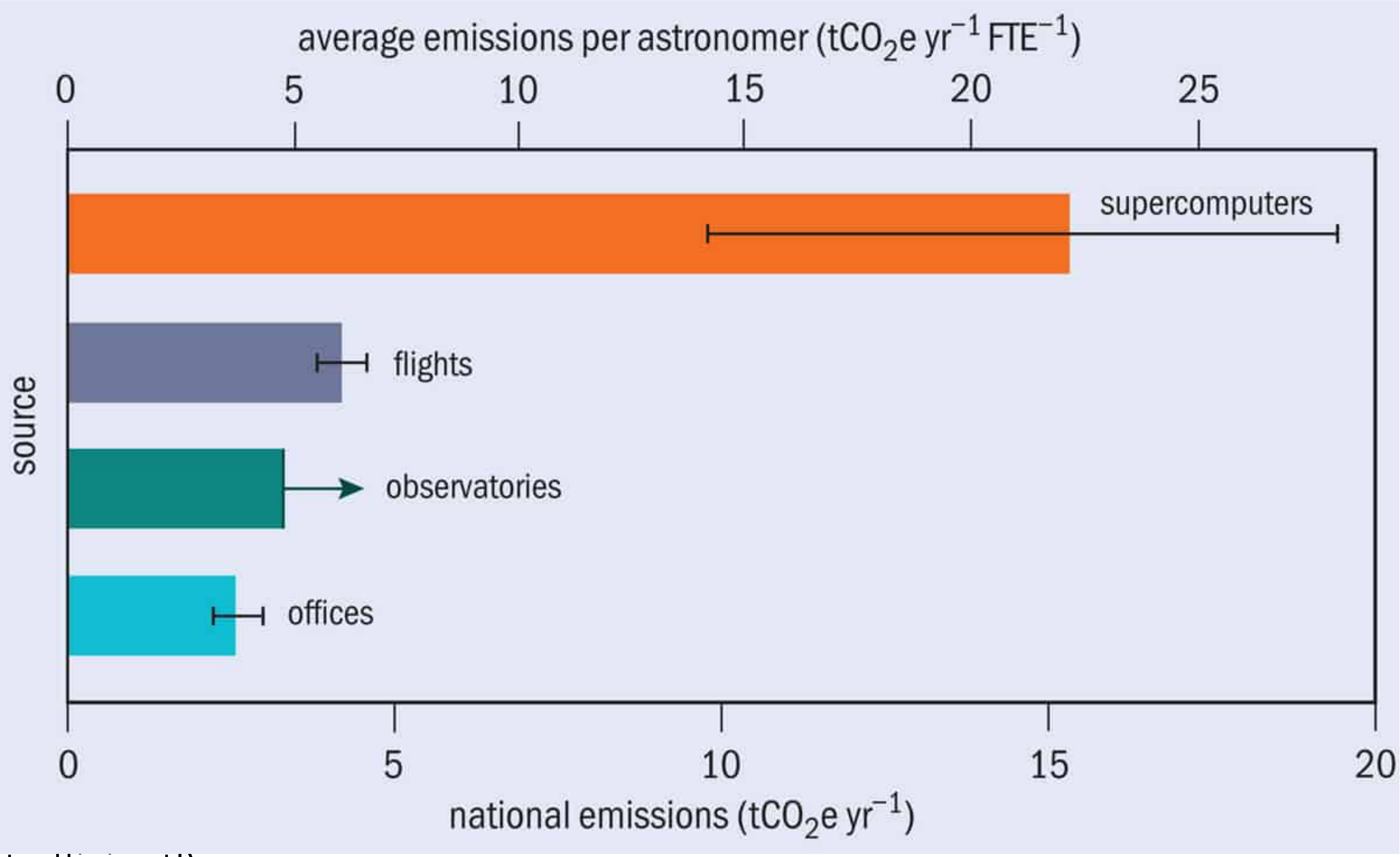

Stevens et al. 2020

Open-science status : *parsec simulations*

Keppens et al. 2023 / Gourgouliatos & Komissarov 2018 / PLUTO official website.

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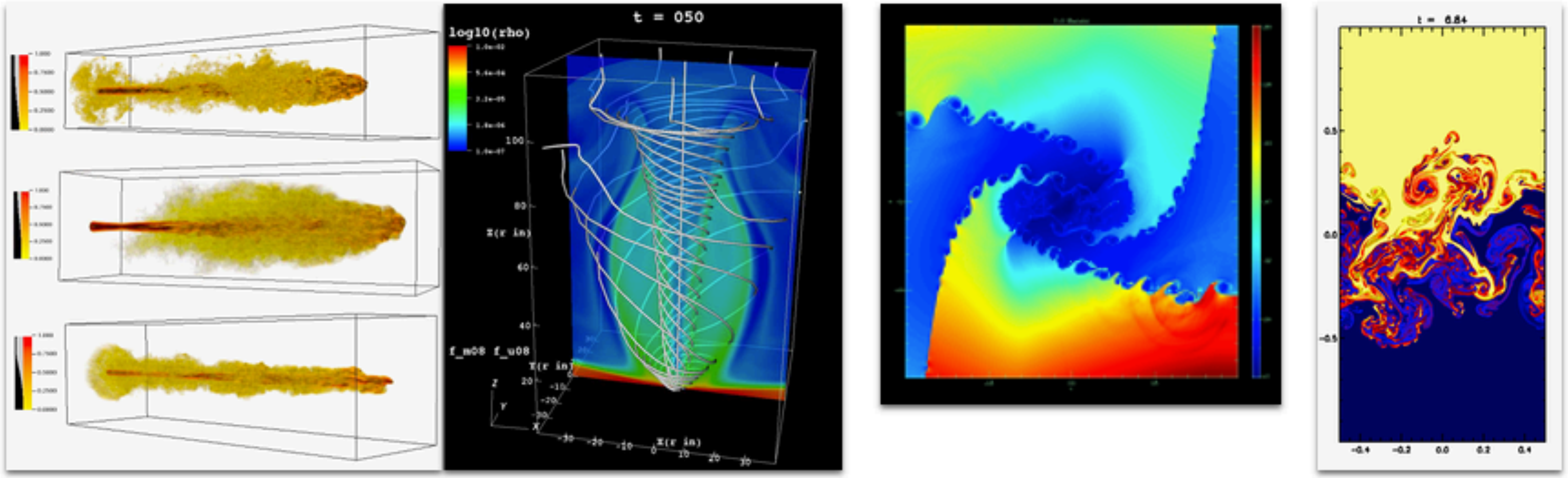

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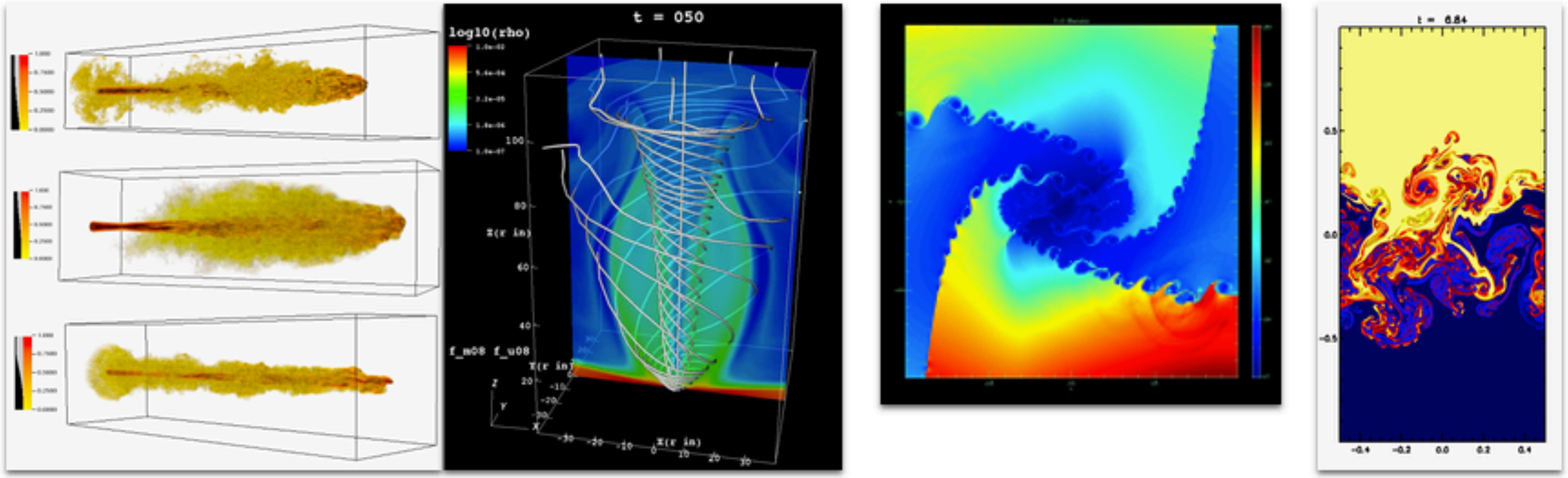

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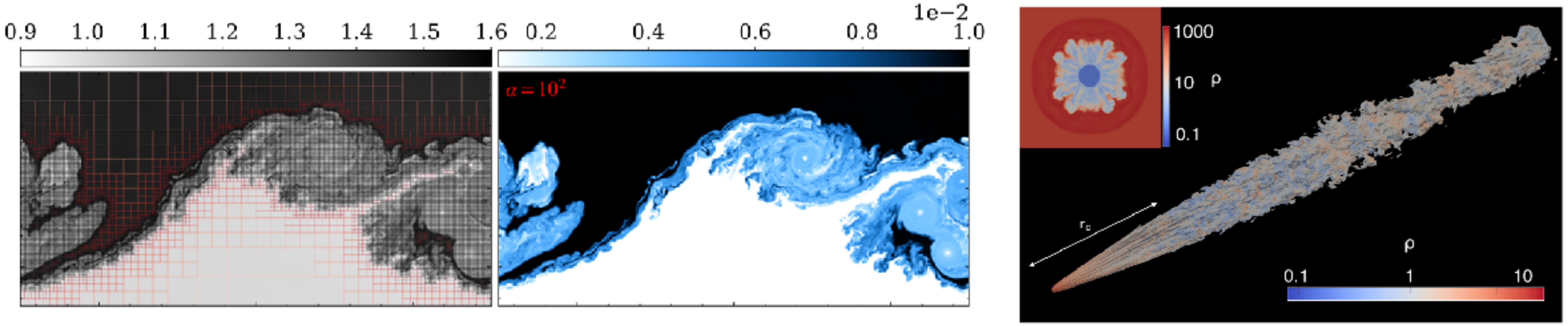

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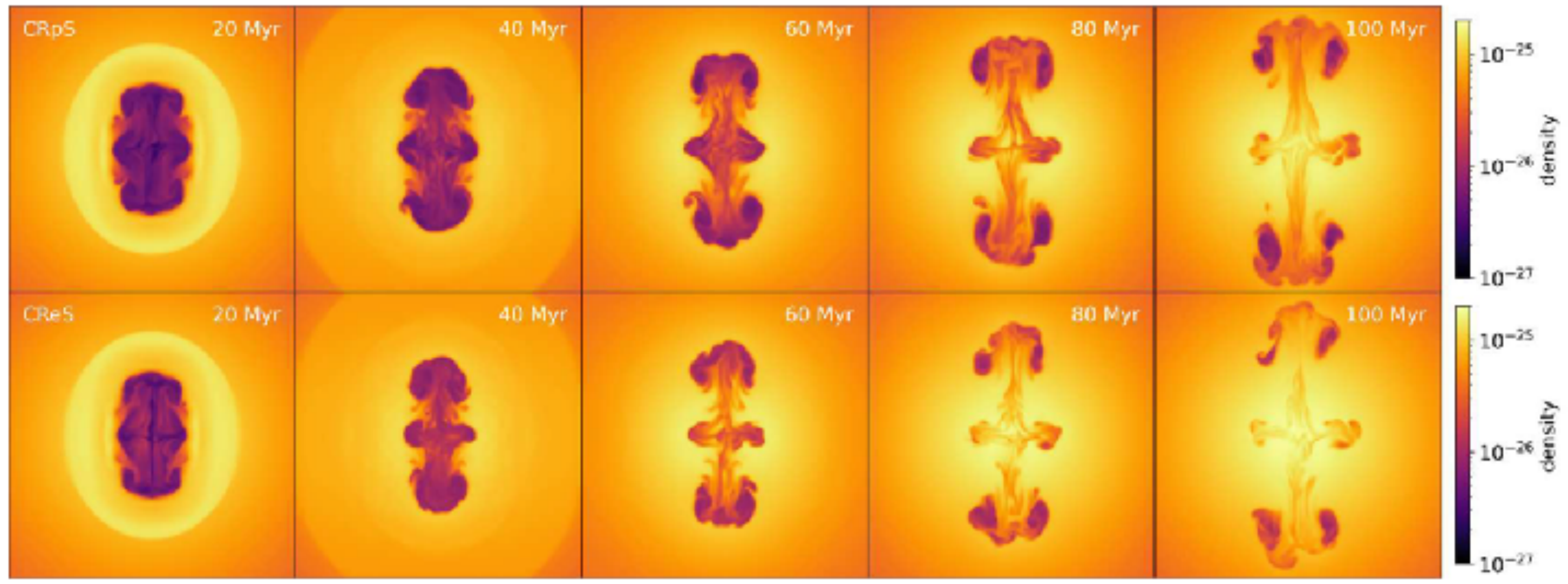

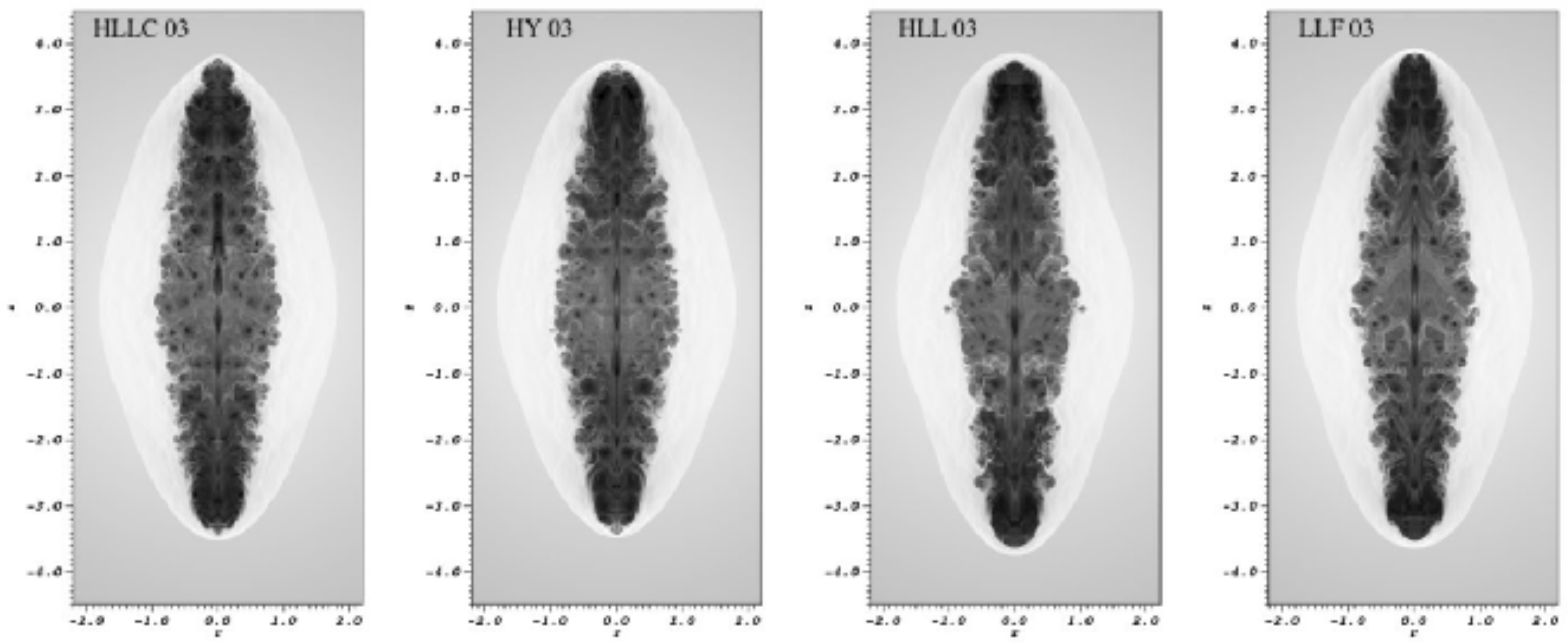

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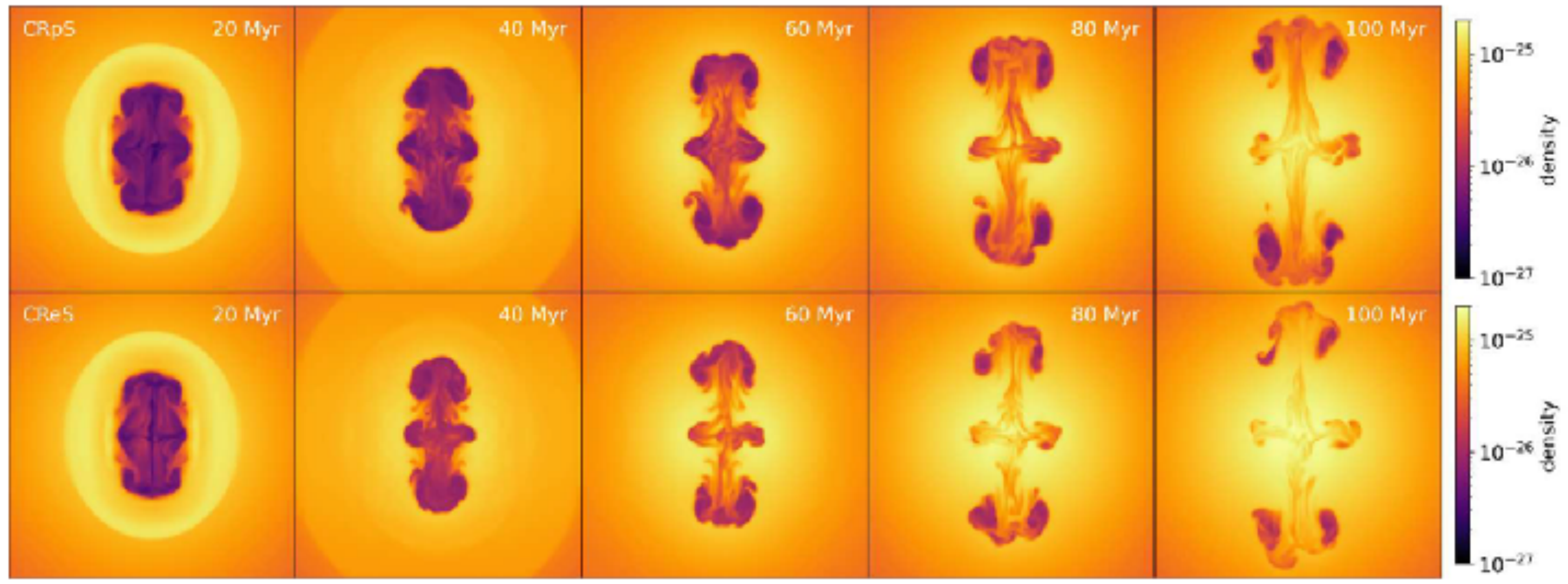
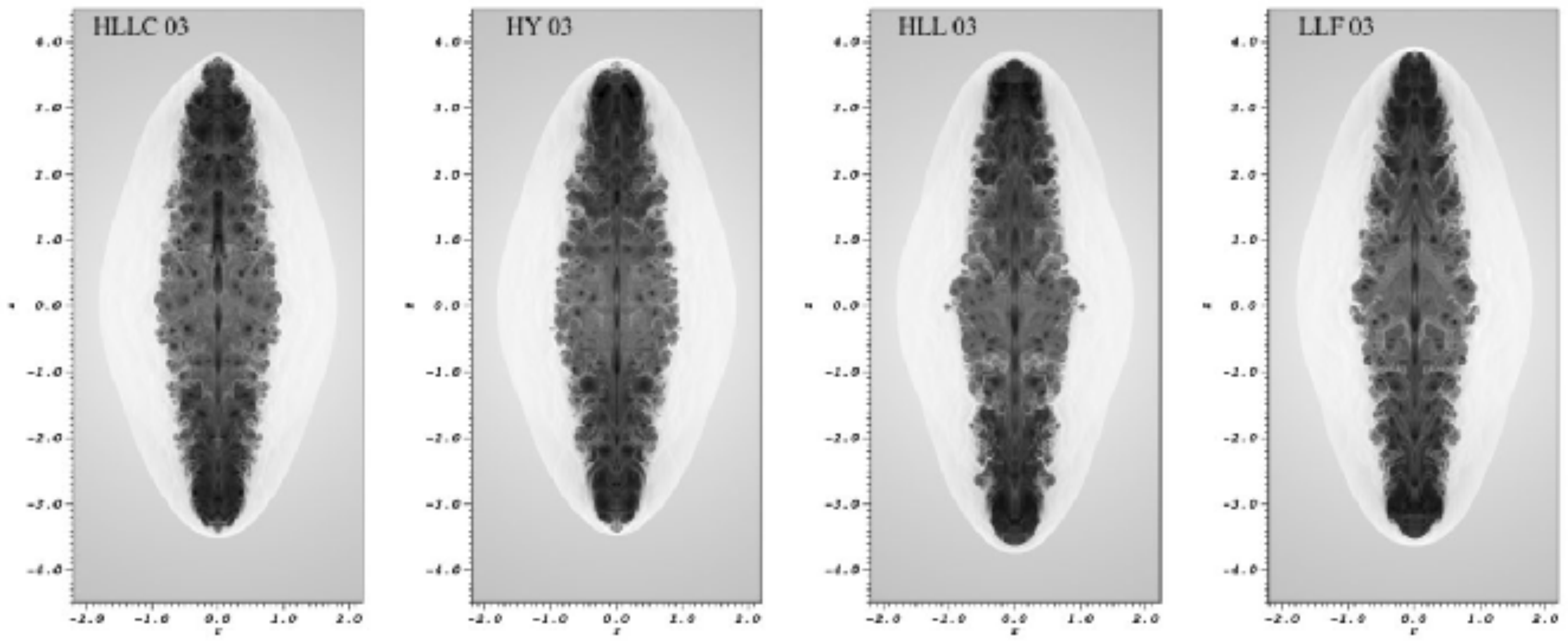

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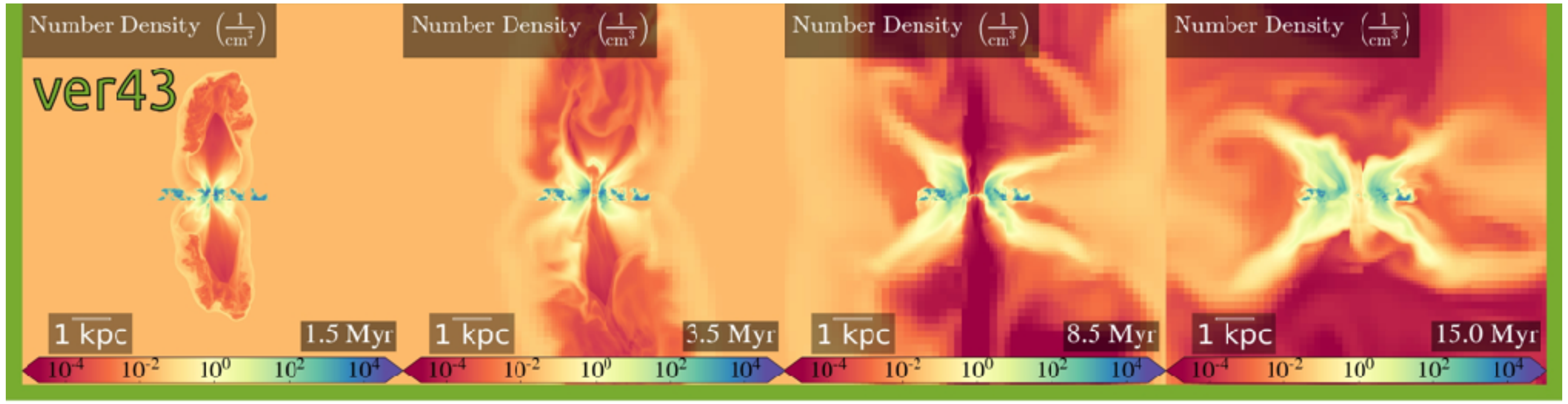

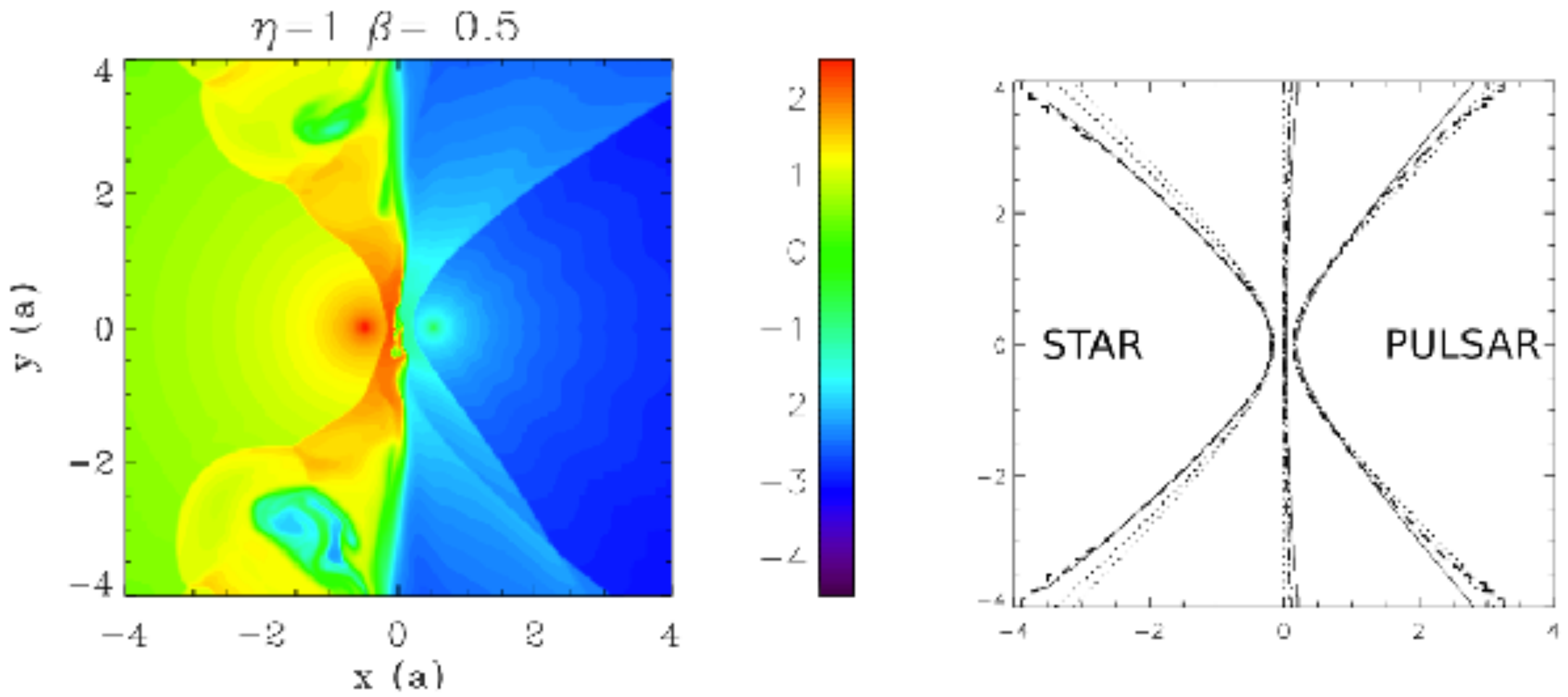

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- **Limited pre- and post-processing tools:** need to rely on external tools for data visualization and analysis, adding complexity to the workflow.
- **Documentation:** can be overwhelming and might not cover all practical use cases or troubleshooting scenarios.

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  - ▸ Parsec scale: jet acceleration, collimation, structures, etc.
  - ▸ Large-scale kpc: understanding the ISM/ICM interplay, jet morphology, galaxy / cluster evolution.
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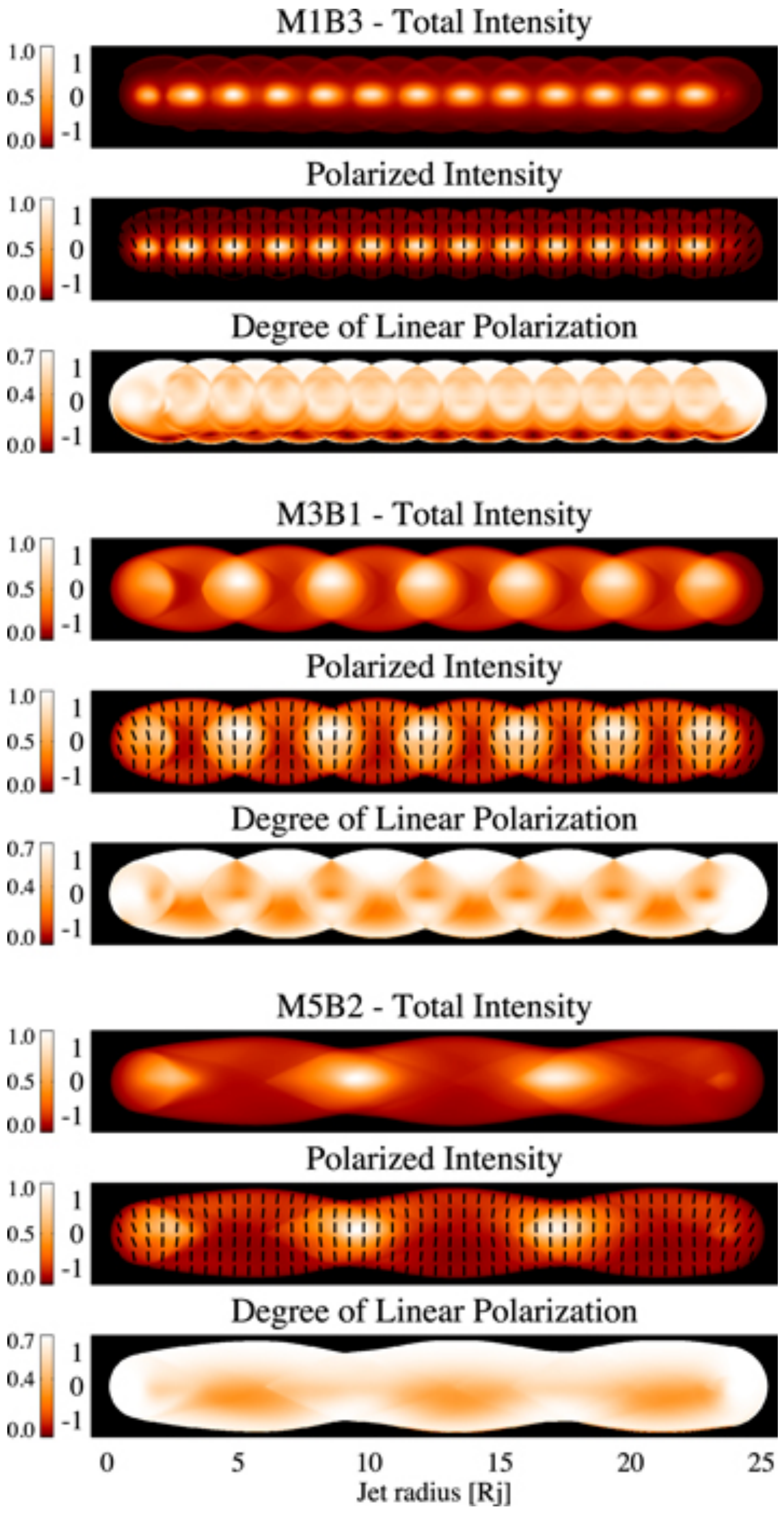

Fuentes et al. 2018

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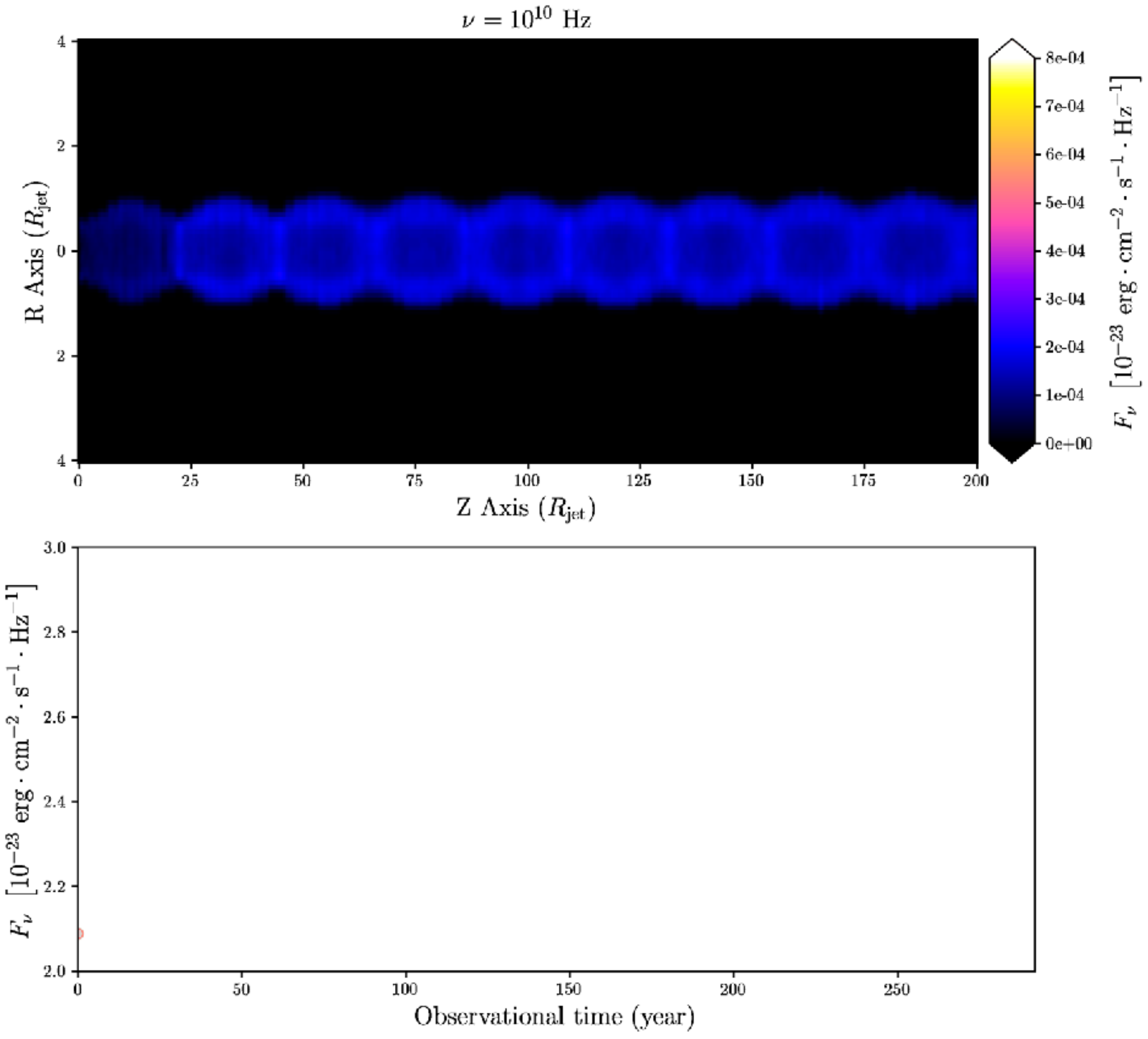

Fichet de Clairfontaine et al. 2021, 2022

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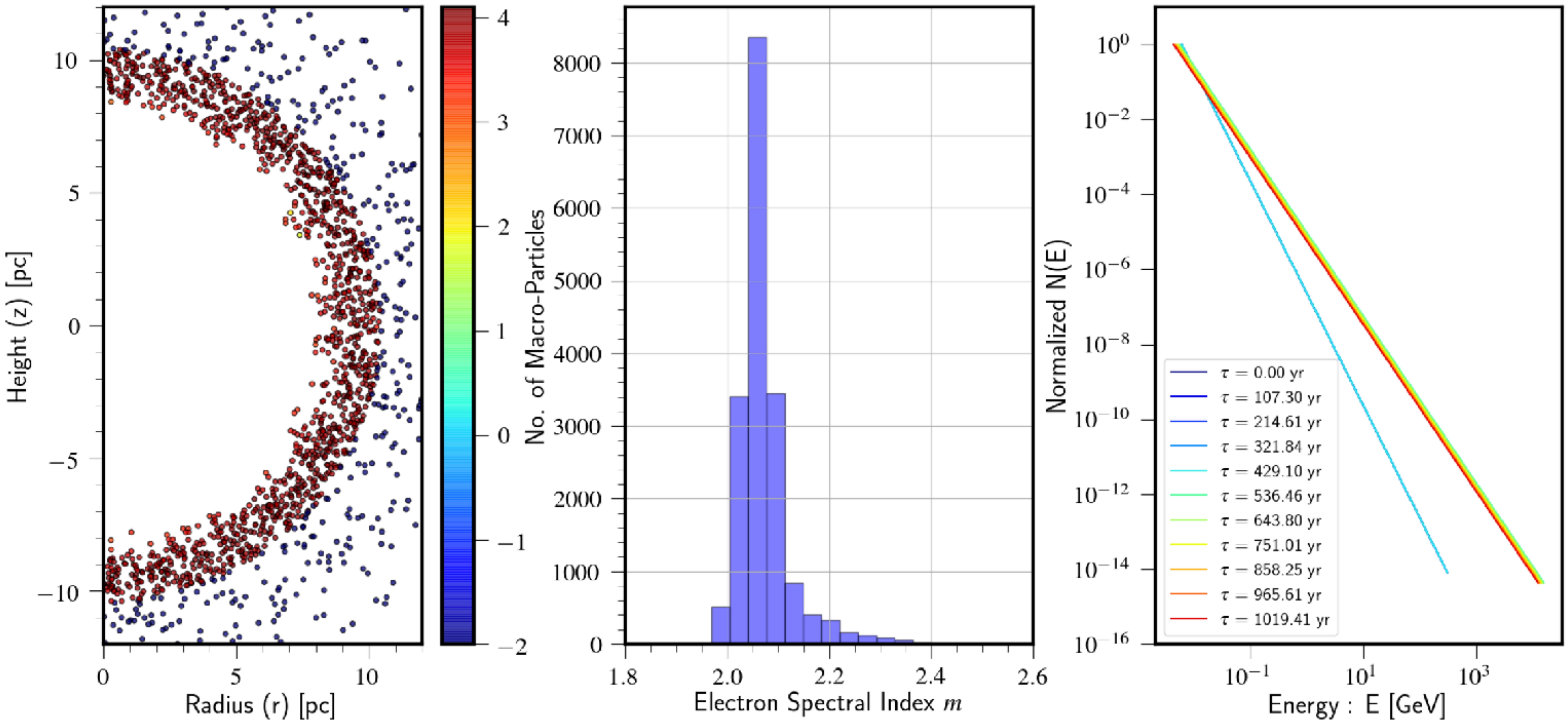

Vaidya et al. 2018

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