Enhancing AGB Outflow Simulations: Implementing a Ray-Tracing Algorithm in PHANTOM for Efficient Radiation Field Computation

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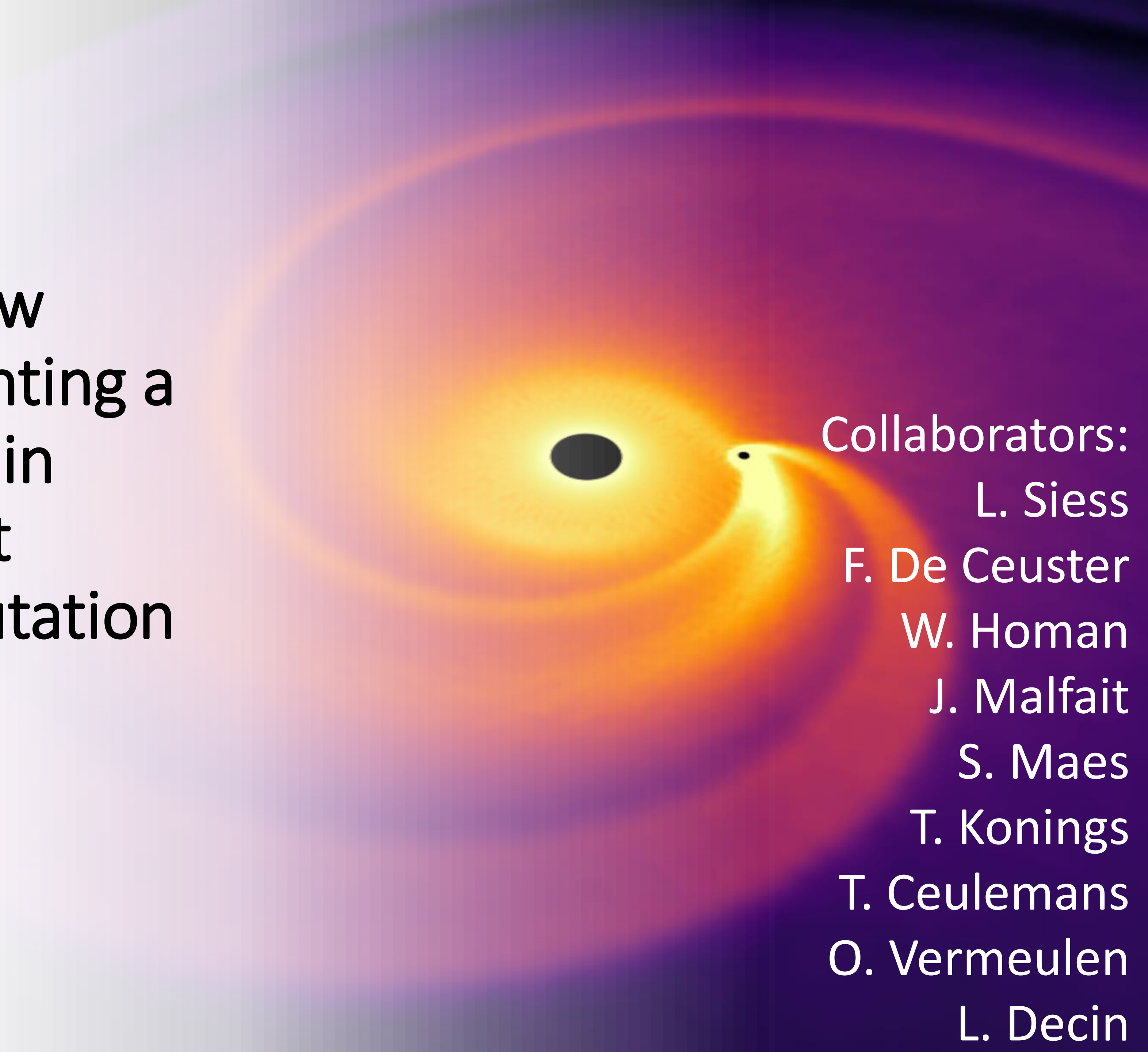
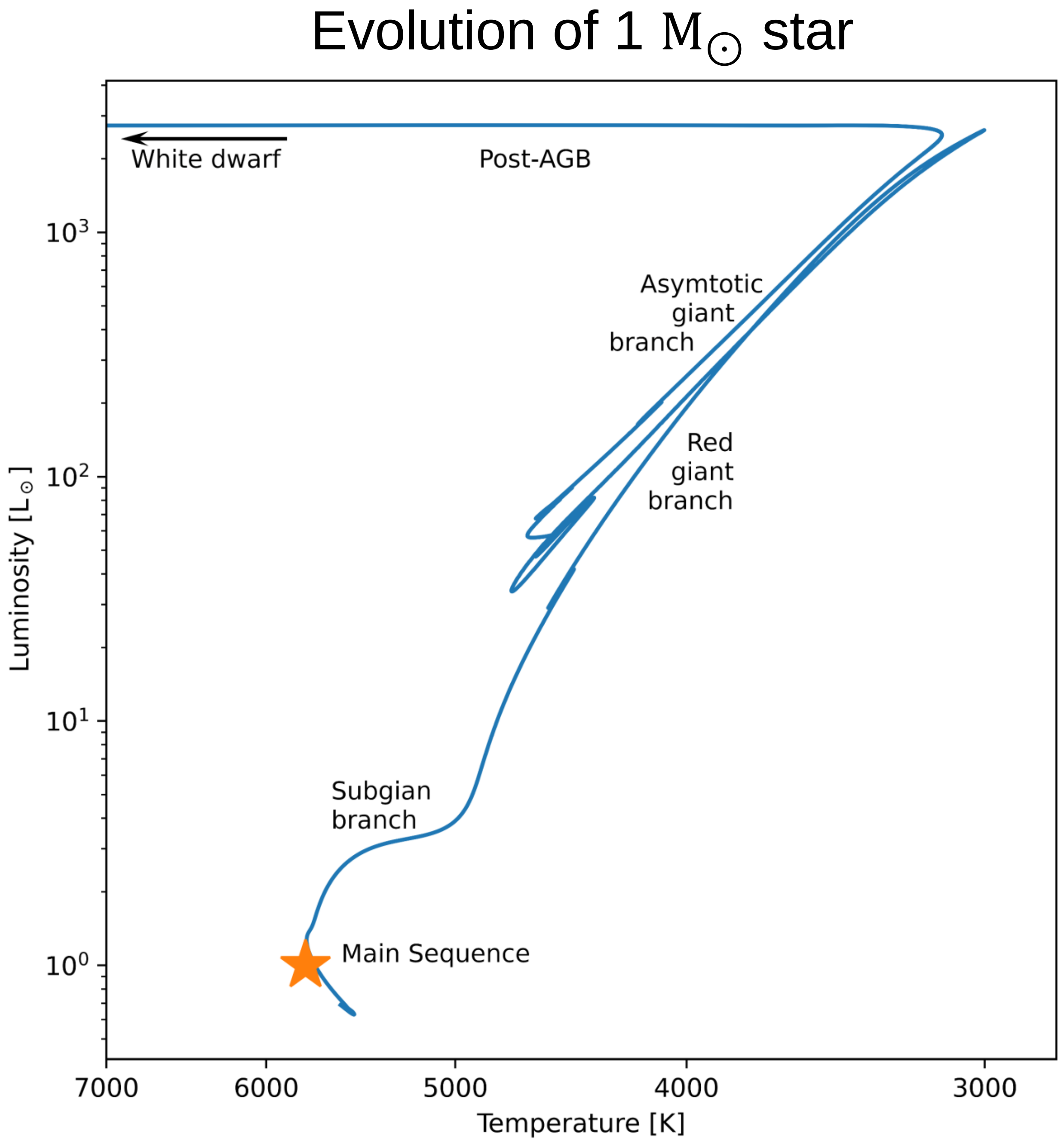


Collaborators:
L. Siess
F. De Ceuster
W. Homan
J. Malfait
S. Maes
T. Konings
T. Ceulemans
O. Vermeulen
L. Decin

AGB stars

- Low and intermediate mass
- $M_{ini} \in [0.8\ \mathrm{M}_\odot, 8\ \mathrm{M}_\odot]$



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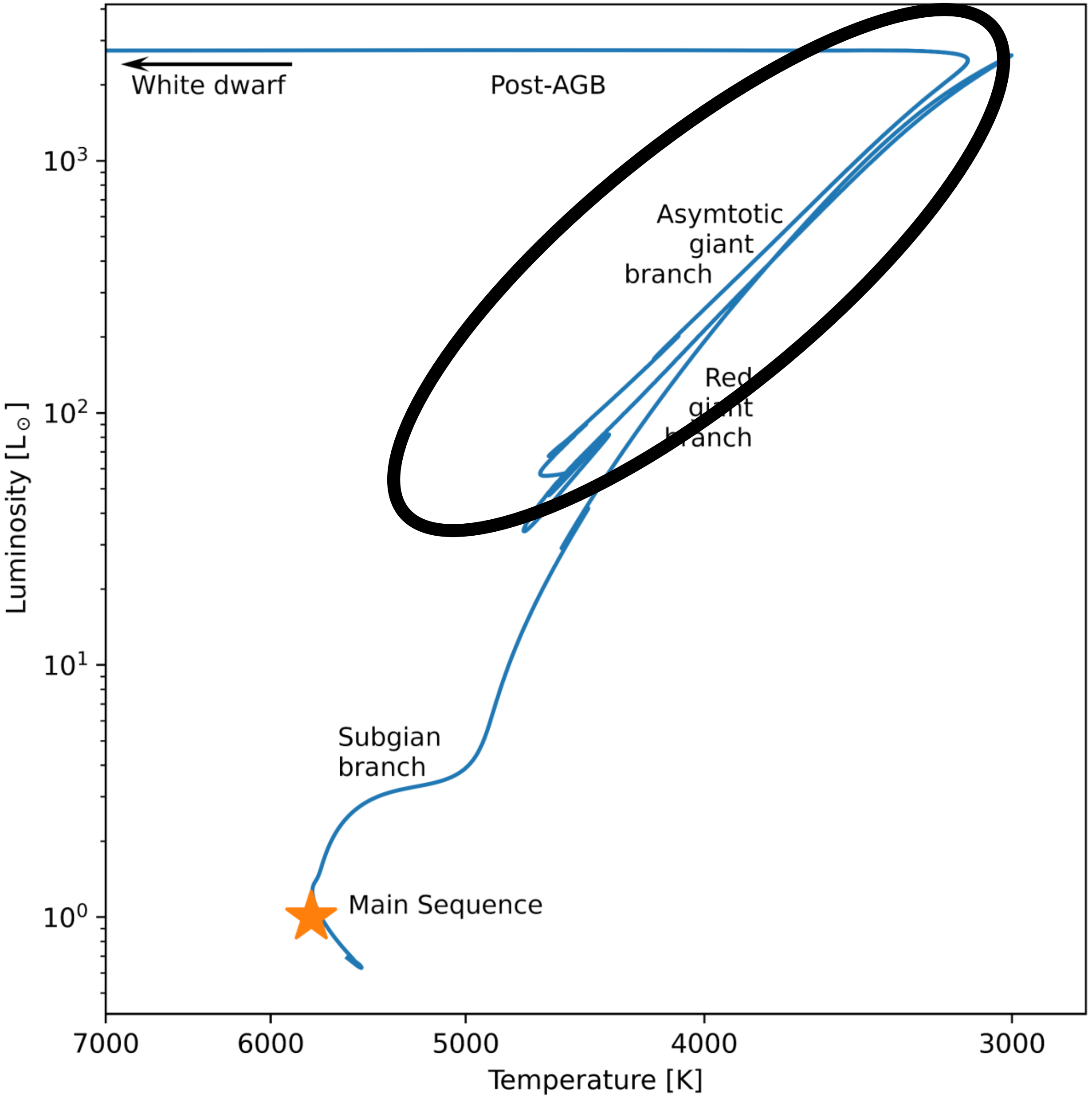
Evolution of 1 $\mathrm{M}_\odot$ star

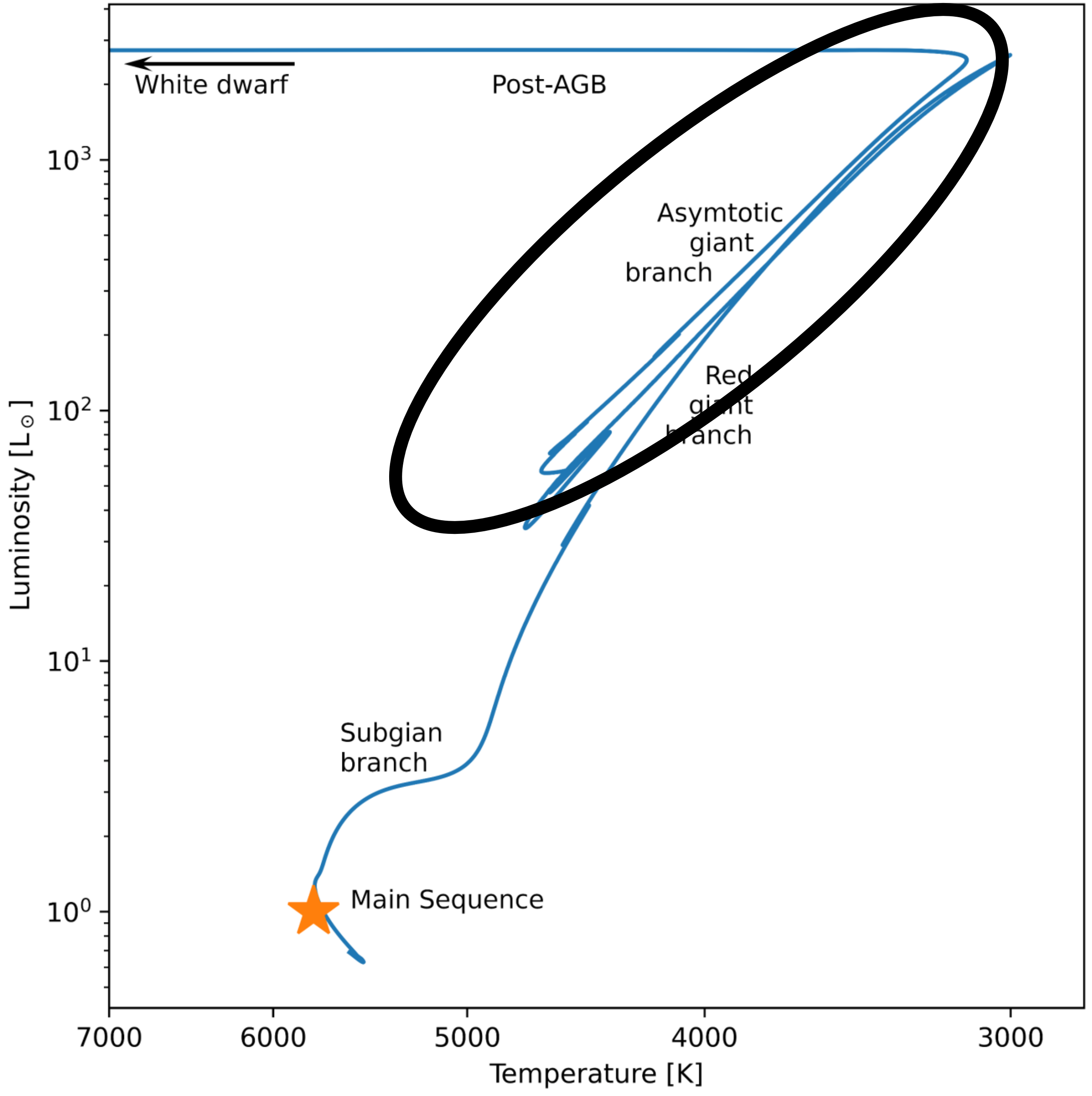


AGB stars

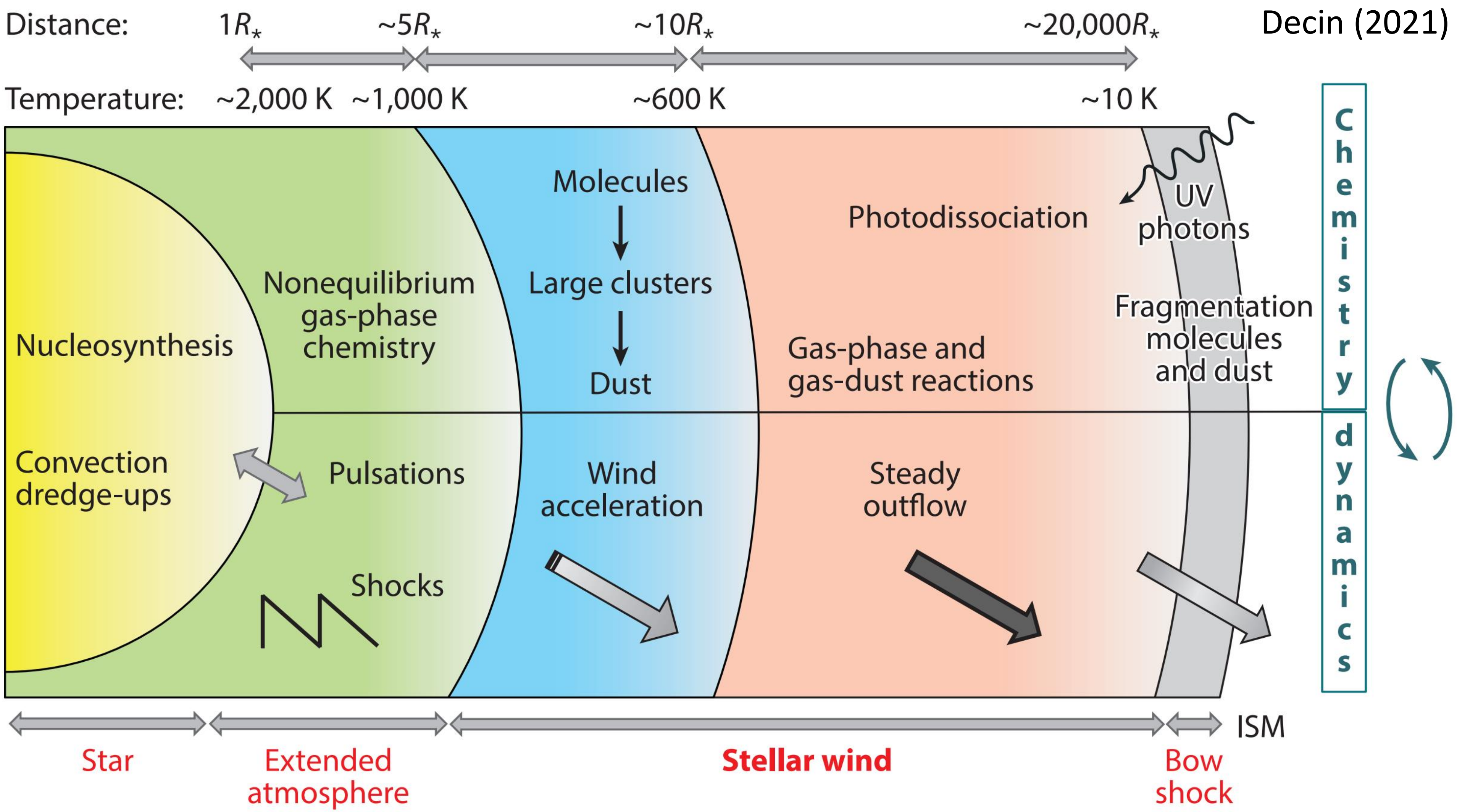
- Low and intermediate mass
- $M_{ini} \in [0.8\ \mathrm{M}_\odot, 8\ \mathrm{M}_\odot]$

- Significant mass loss
  - $\dot{M} = 10^{-8} - 10^{-4}\ \mathrm{M}_\odot/\mathrm{yr}$
  - $v_\infty = 5 - 25\ \mathrm{km/s}$
- Dust-driven wind

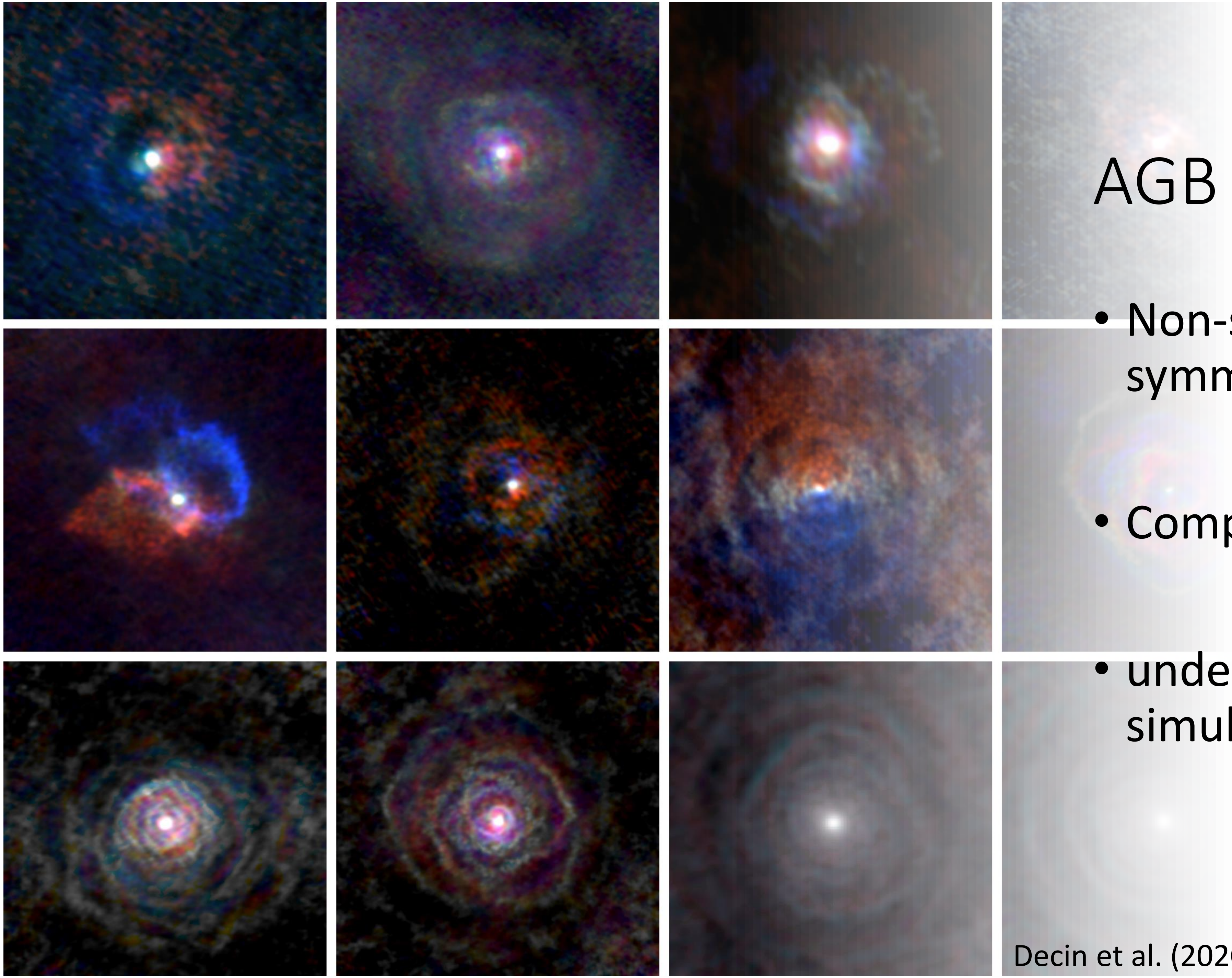
Evolution of 1 $\mathrm{M}_\odot$ star



AGB's dust-driven wind



Decin (2021)



AGB outflows

- Non-spherically symmetric
- Companion perturbed
- understanding through simulations

Decin et al. (2020)

ATOMIUM

Hydrodynamic setup

- 3D Smoothed Particle Hydrodynamics (SPH)

- External acceleration
  - $\vec{a} = -\frac{GM_{AGB}}{r_1^2}(1-\Gamma)\hat{r}_1 \; - \; \frac{GM_{comp}}{r_2^2}\hat{r}_2$

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Gravity
AGB star

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- Eddington factor: radiative acceleration
  - $\Gamma = \frac{\kappa F/c}{GM_{AGB}/r_1^2}, \quad \kappa(T_{eq}) = \frac{\kappa_{max}}{1+exp[(T_{eq}-T_{cond})/\delta]} + \kappa_g$

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Approximations

Approximations	Γ	T_{eq}
Free-wind	$\Gamma = 1$	

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Geometrical	$\Gamma = \frac{\kappa L_{AGB}}{4\pi c G M_{AGB}}$	$T_{eq}^4 = \frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{R_\star}{r}\right)^2}\right) T_\star^4$

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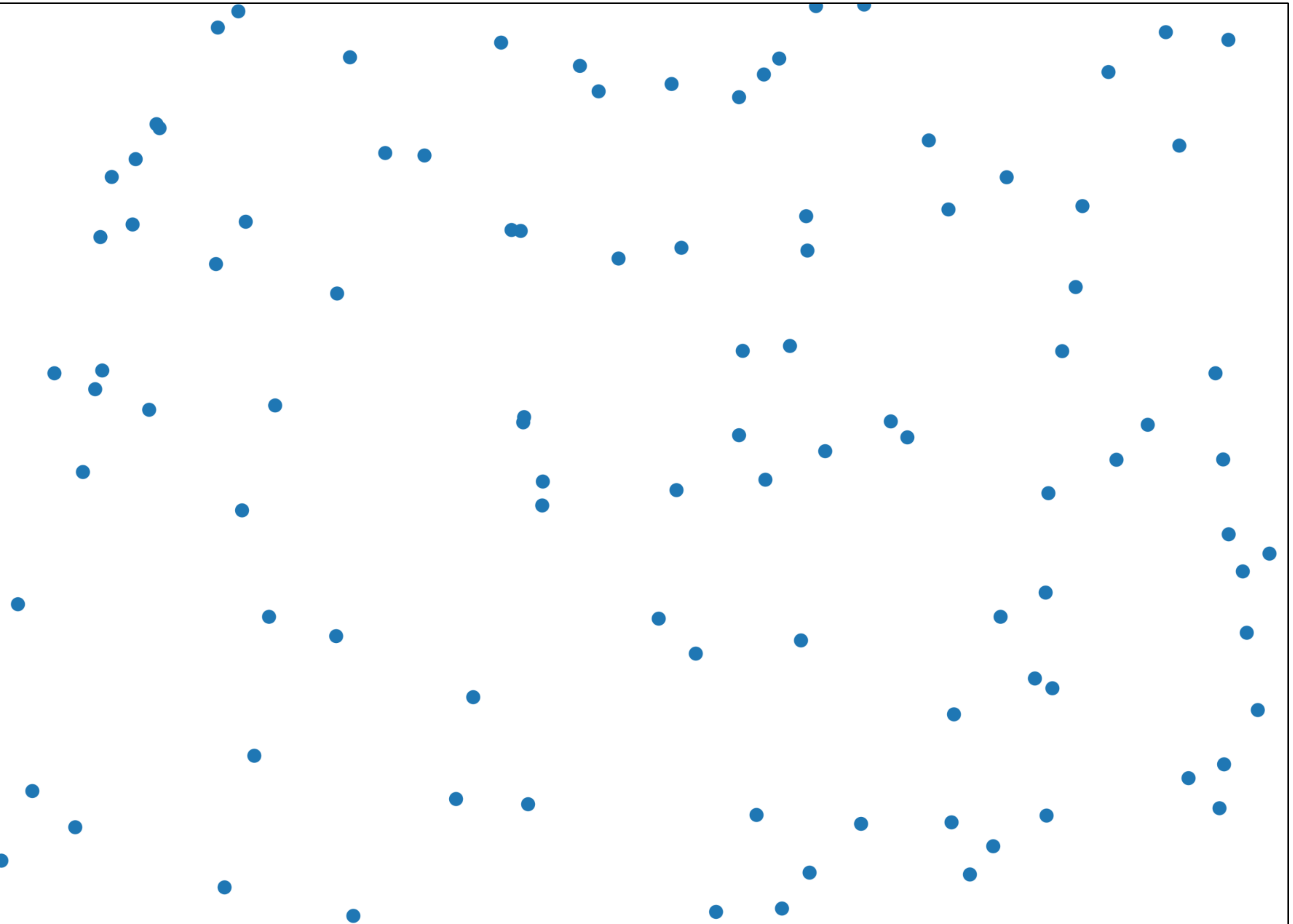
Attenuation	$\Gamma = \frac{\kappa L_{AGB}}{4\pi c G M_{AGB}} e^{-\tau}$	$T_{eq}^4 = \frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{R_\star}{r}\right)^2}\right) e^{-\tau} T_\star^4$

Ray-tracer



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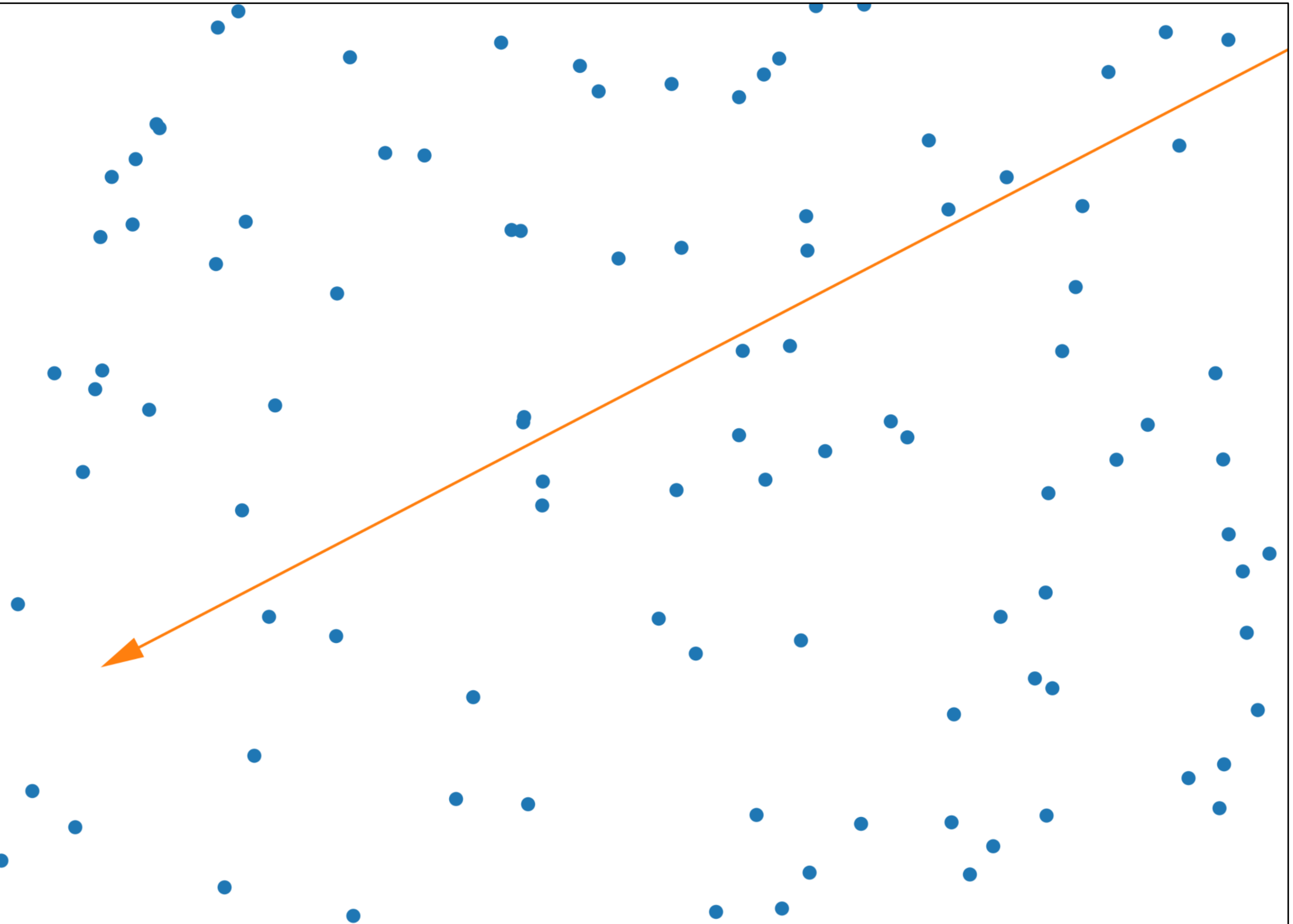
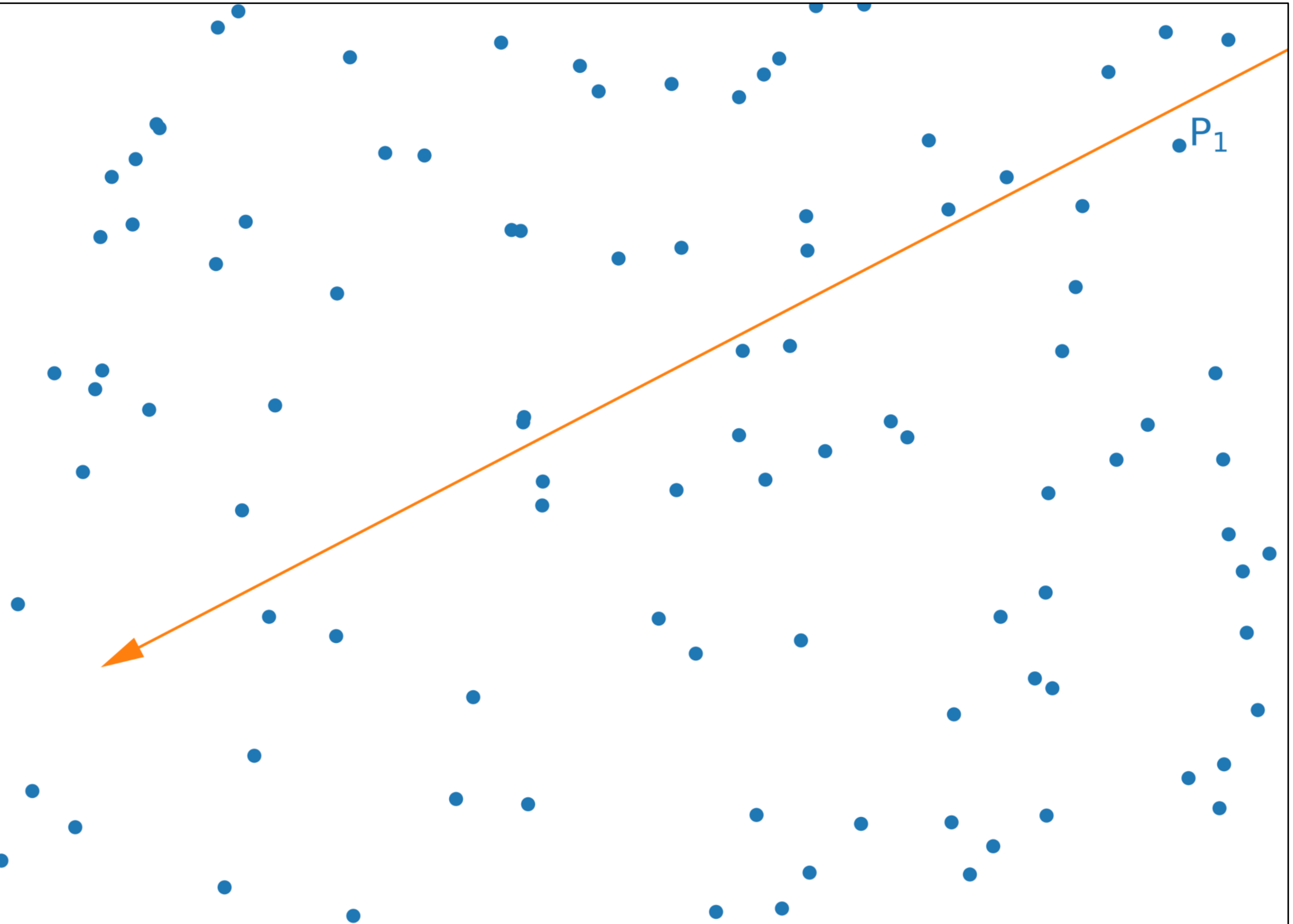


Ray-tracer

Magritte



Ray-tracer

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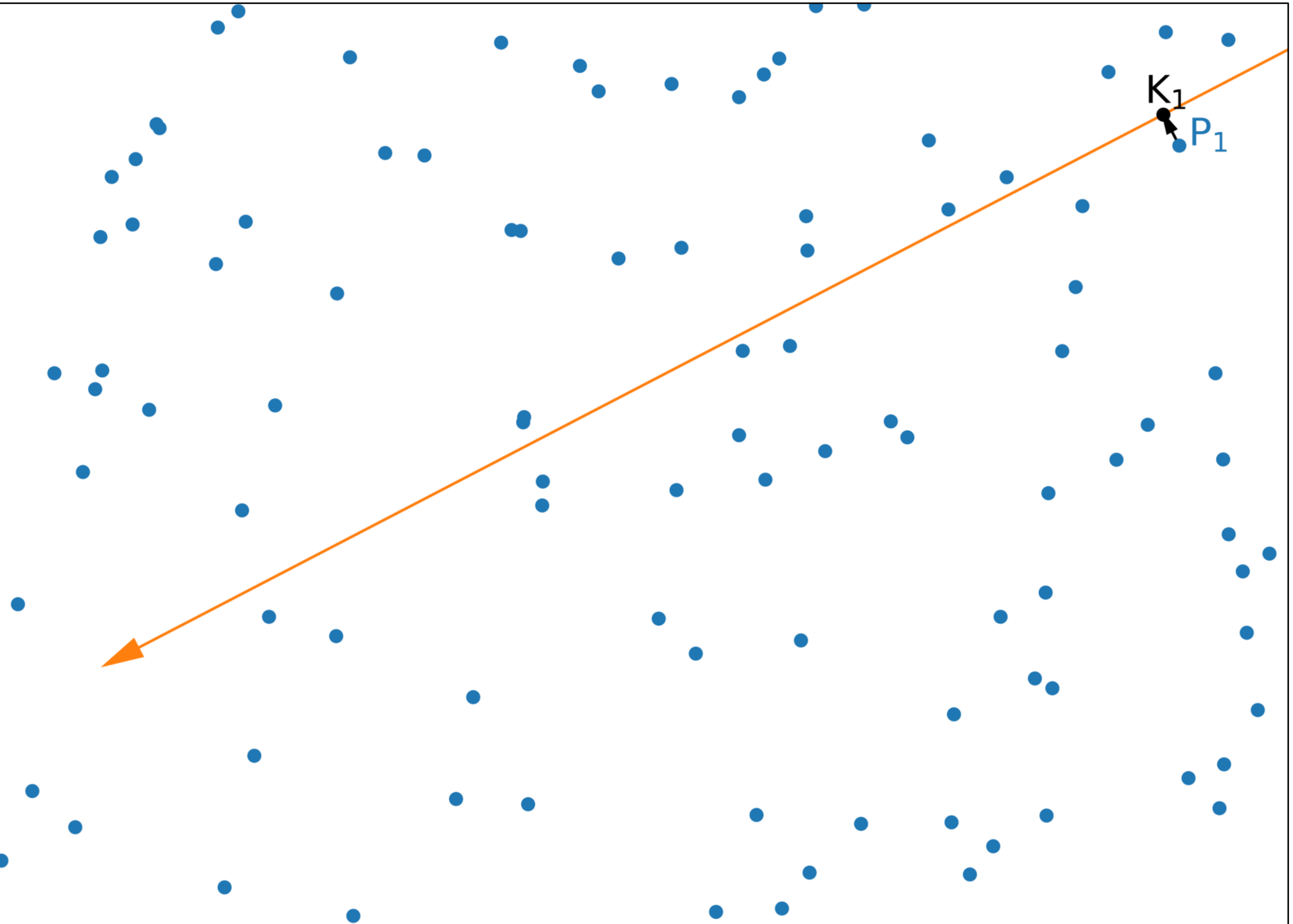

Ray-tracer

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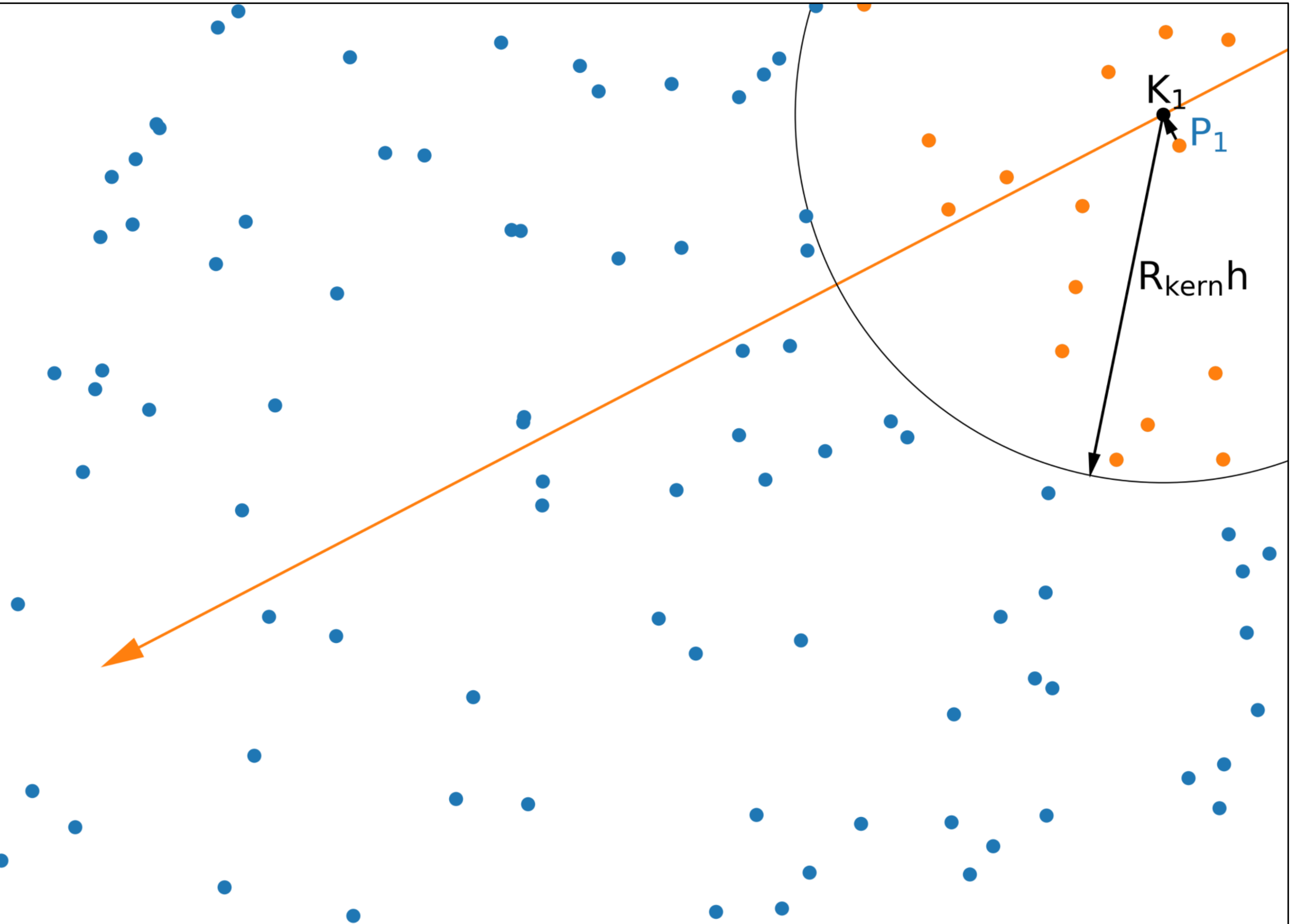
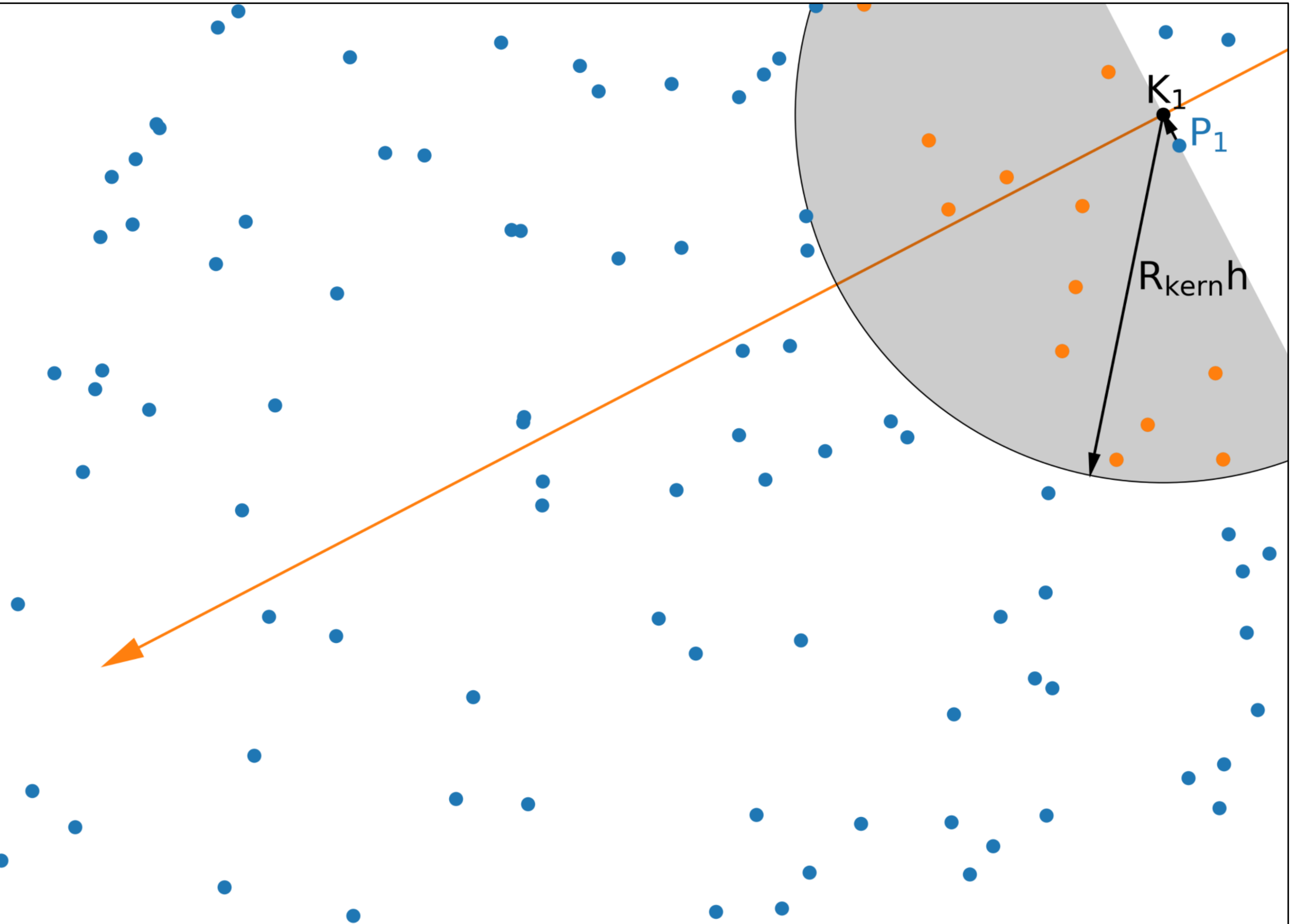


At each point K:

- $\kappa_i \ \rho_i$
- d_i

Ray-tracer



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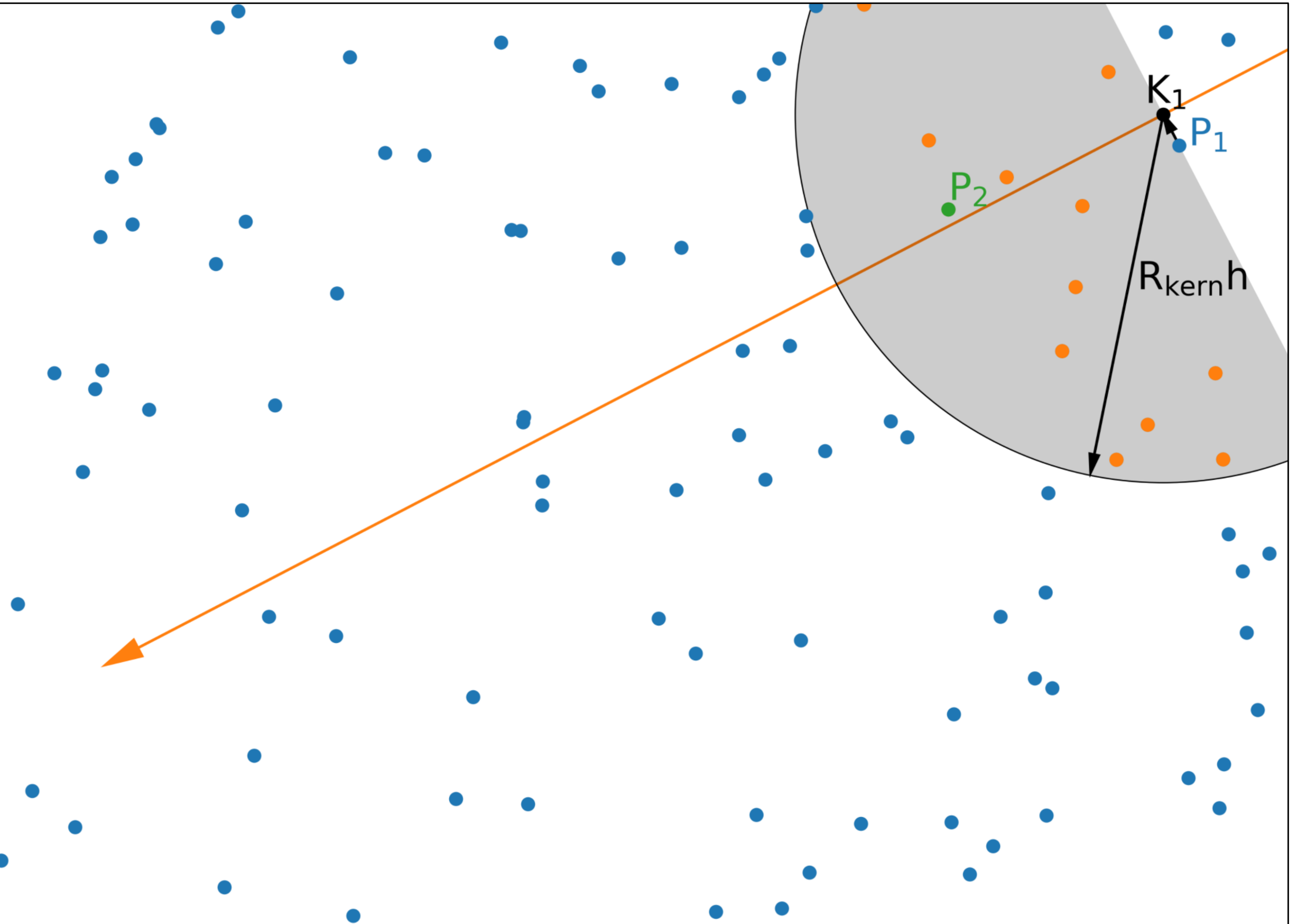

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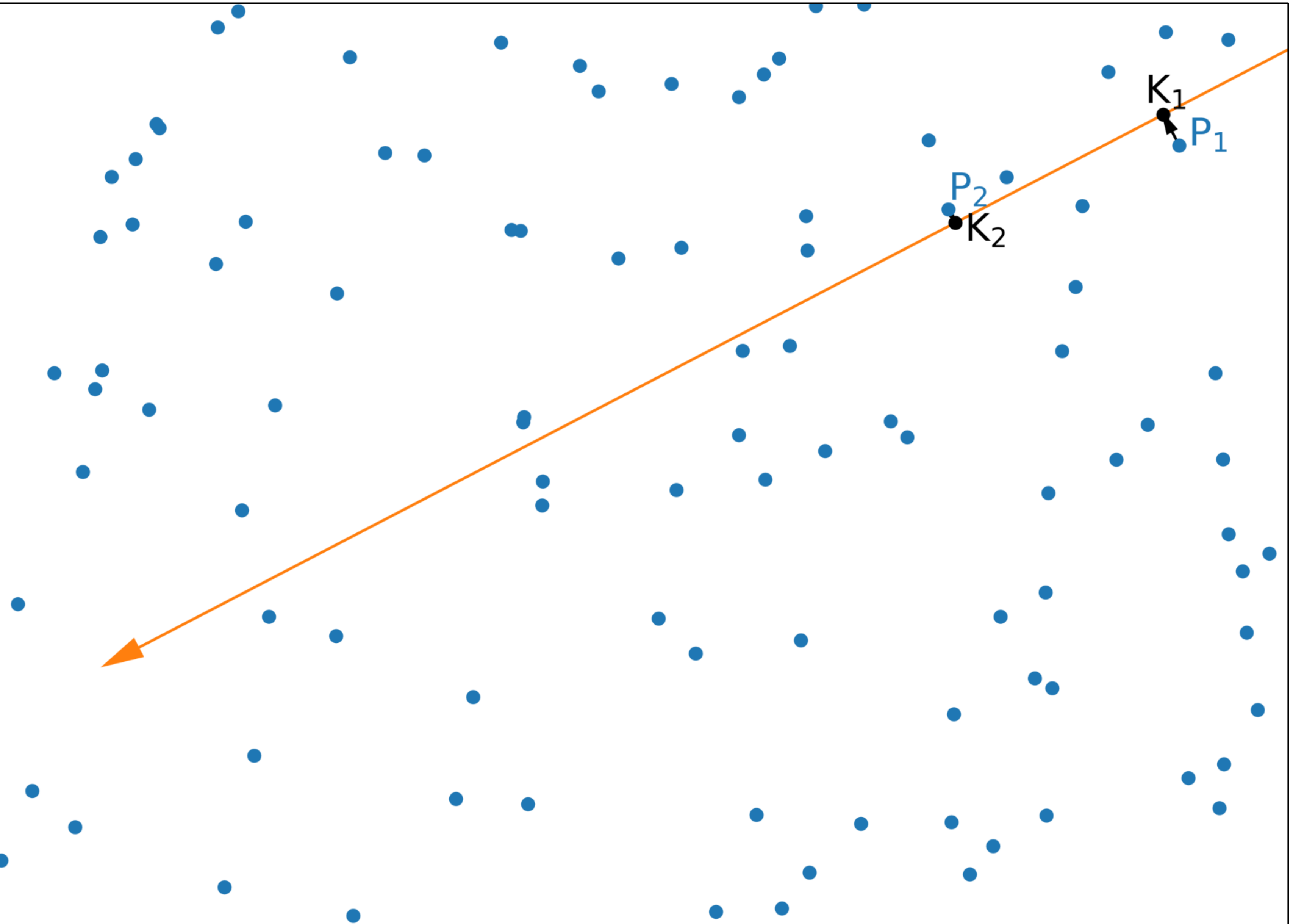

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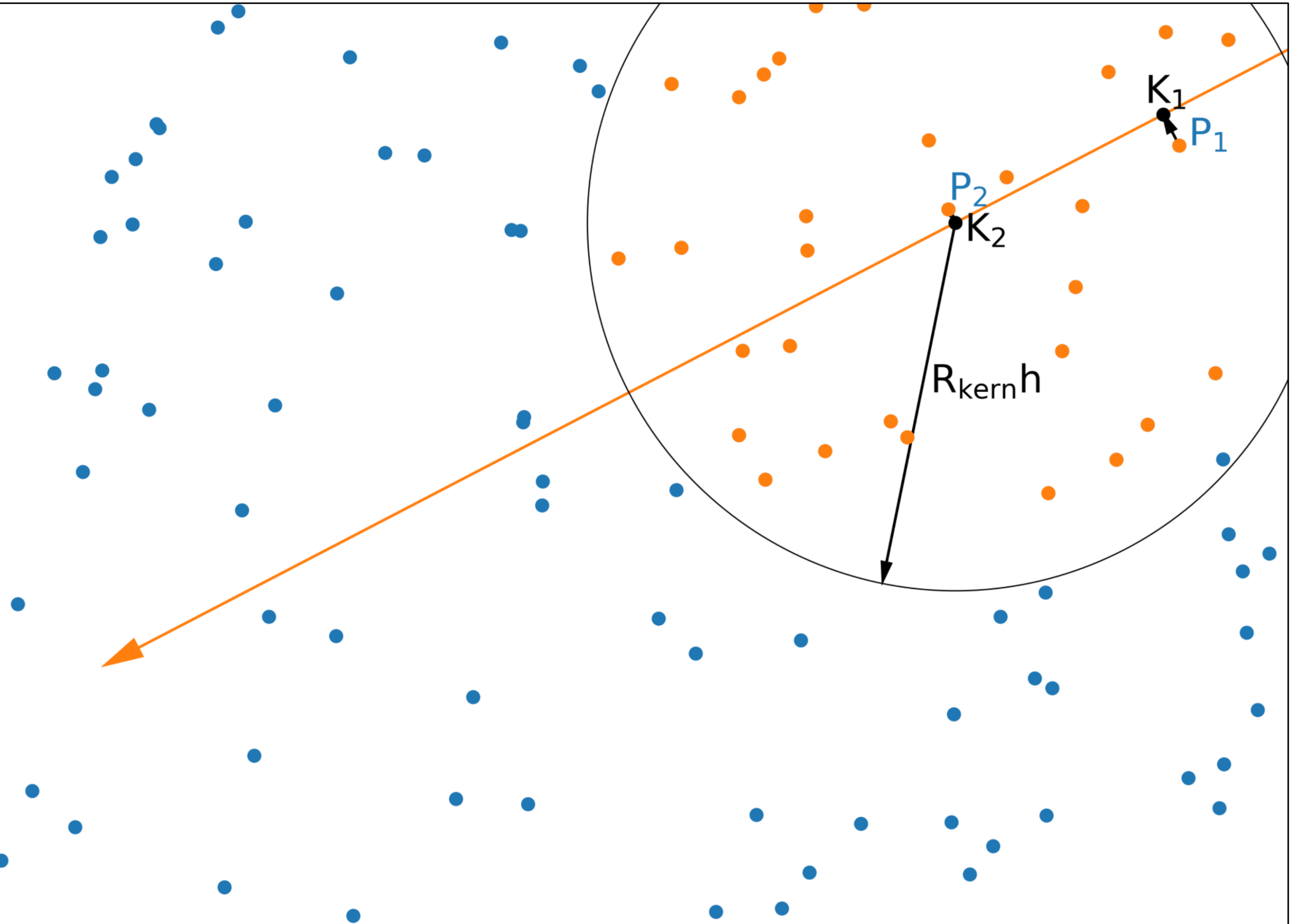

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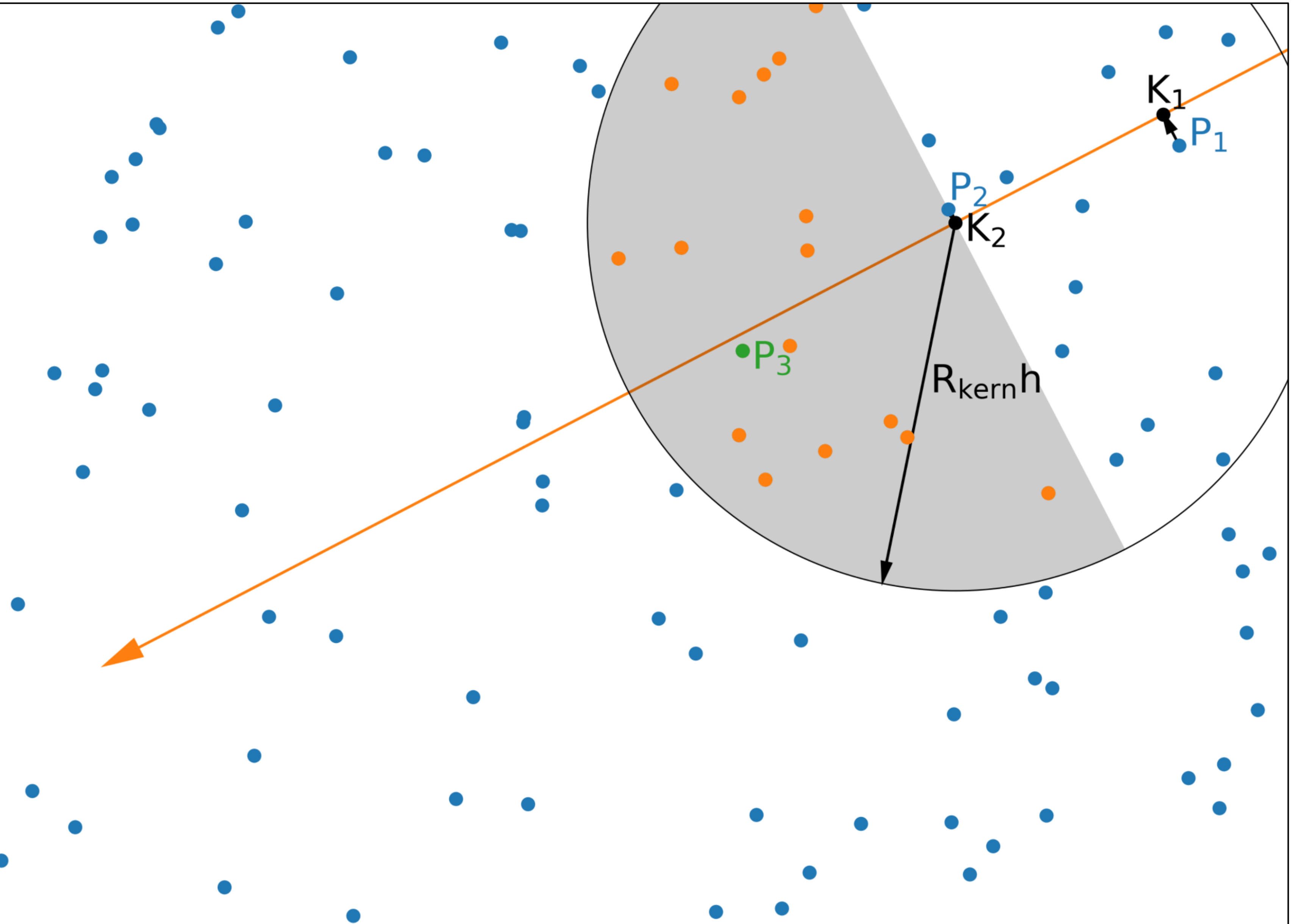

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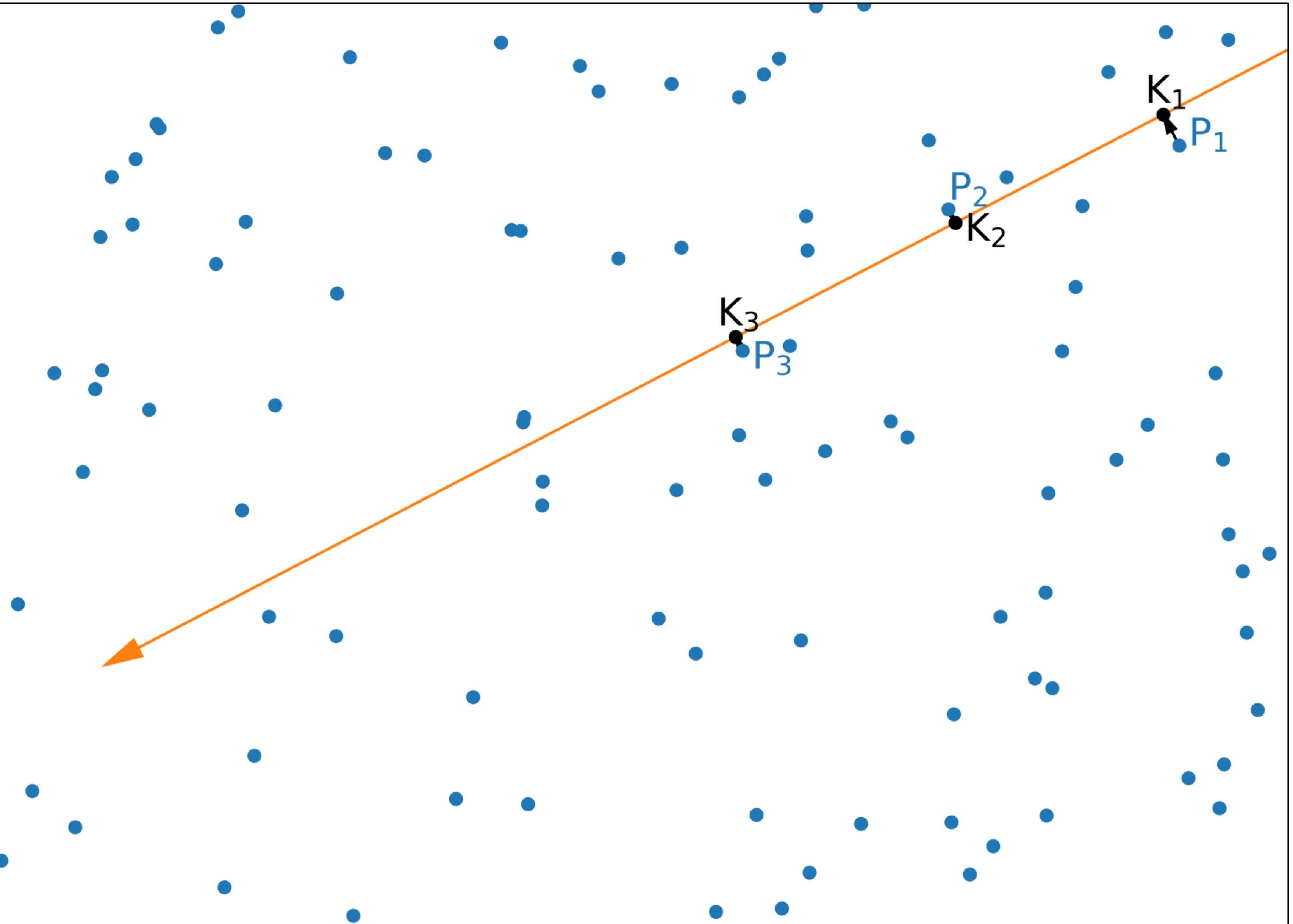

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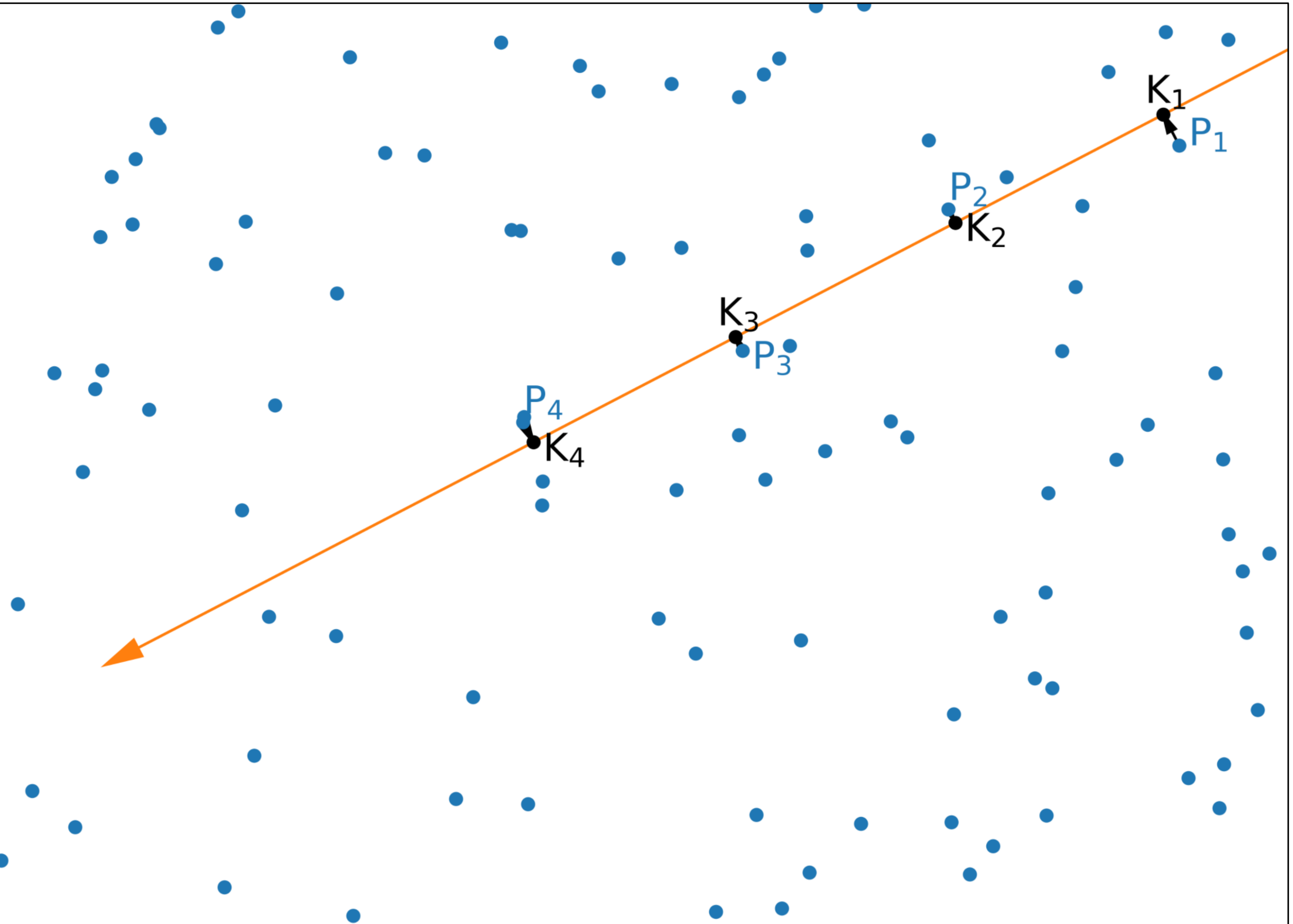

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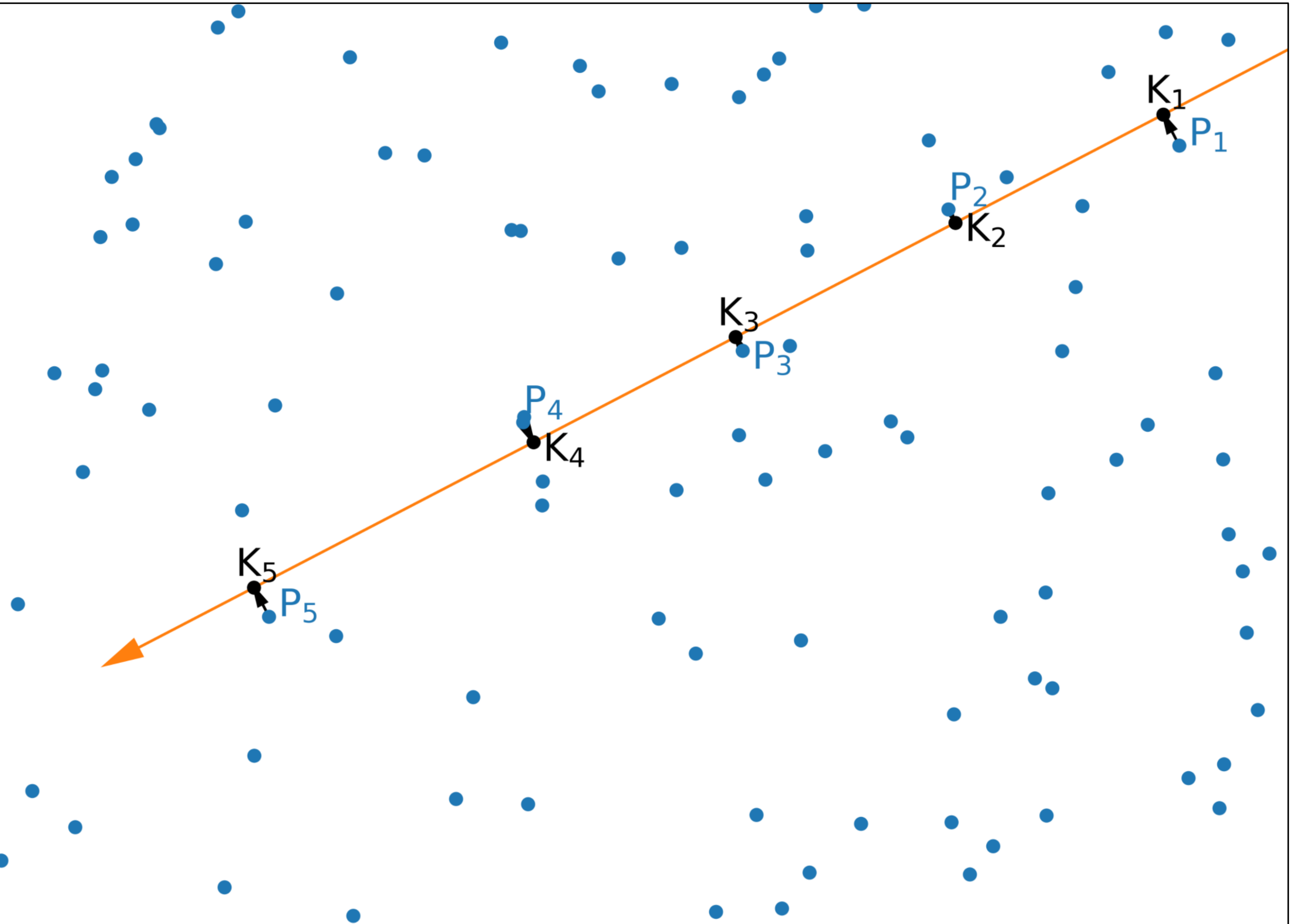

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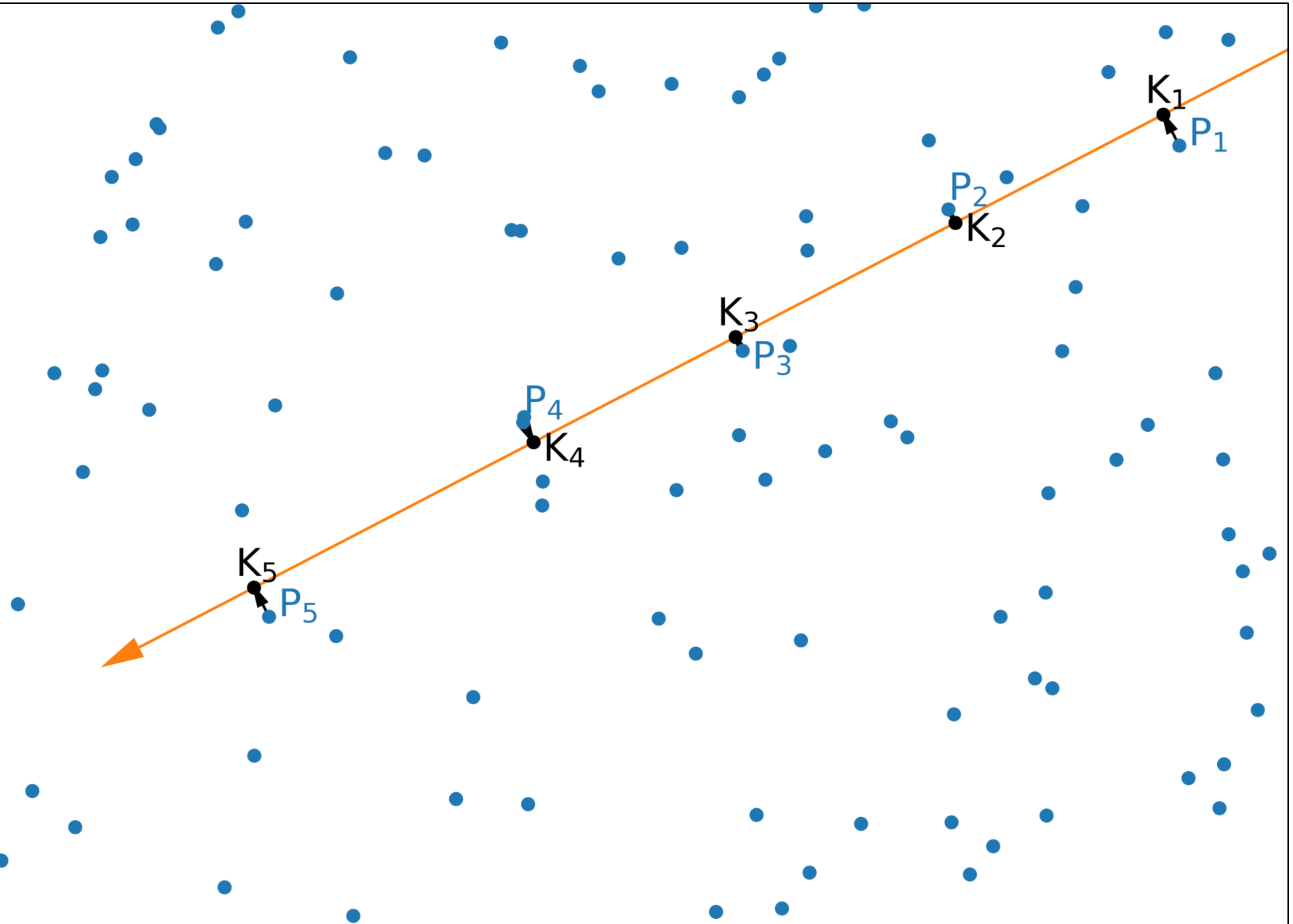

At each point K:

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$$\tau = \int_{R_\star}^{r} \mathrm{d}\tau \approx \sum_i \Delta\tau_i$$

$$= \sum_i \left(\frac{\kappa_i \; \rho_i + \kappa_{i+1} \; \rho_{i+1}}{2} \right) \Delta s_i$$

Ray-tracer

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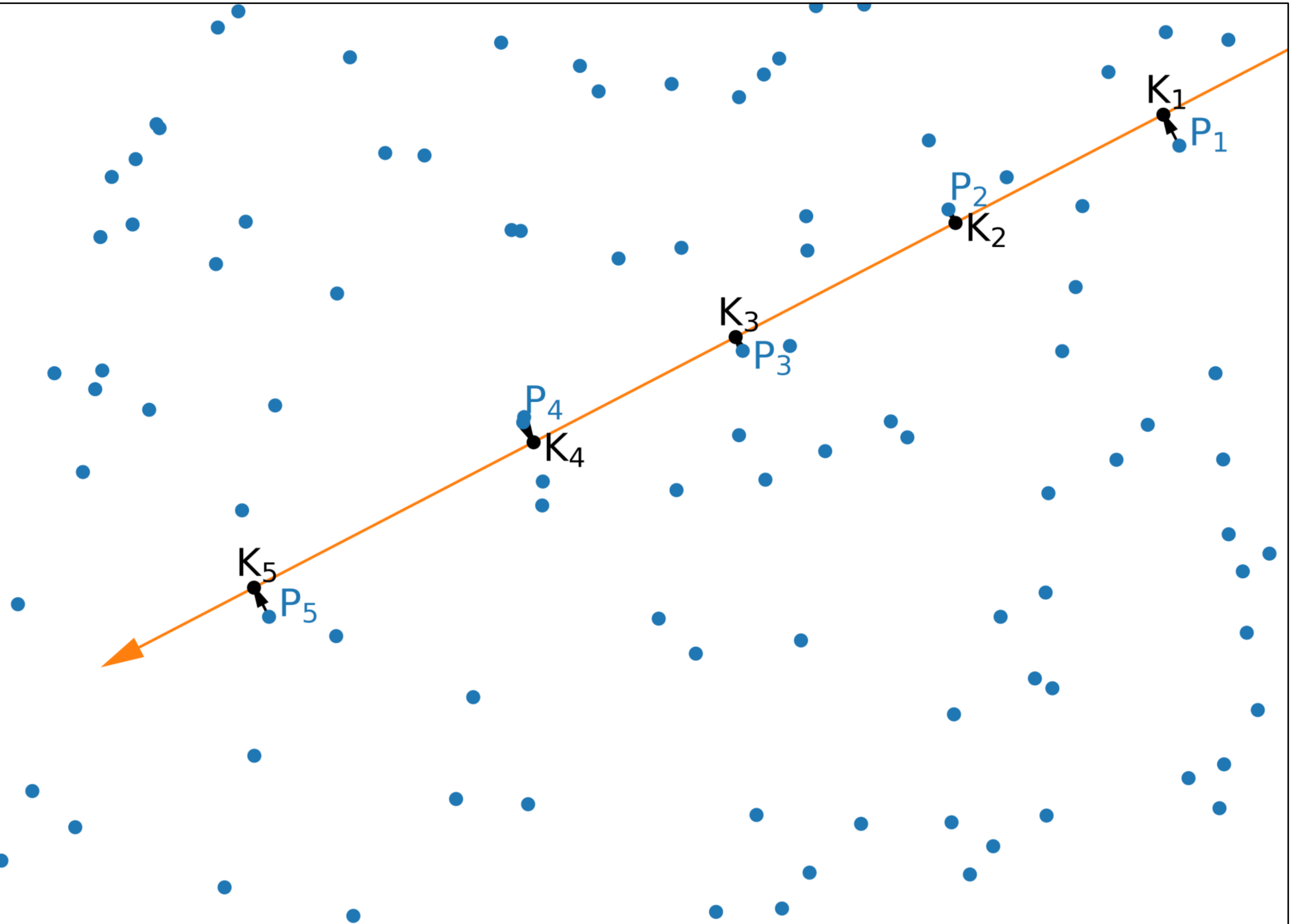

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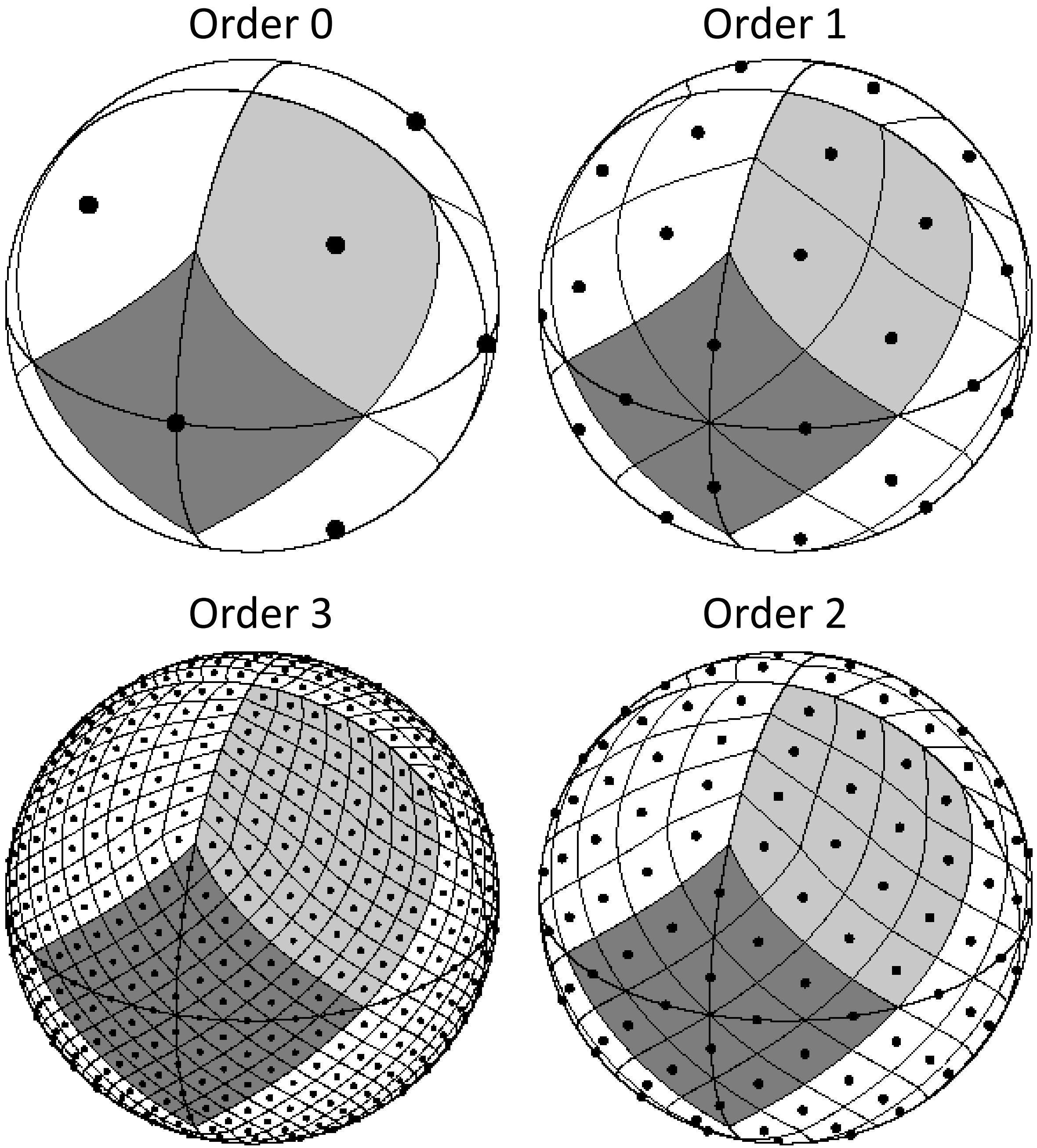
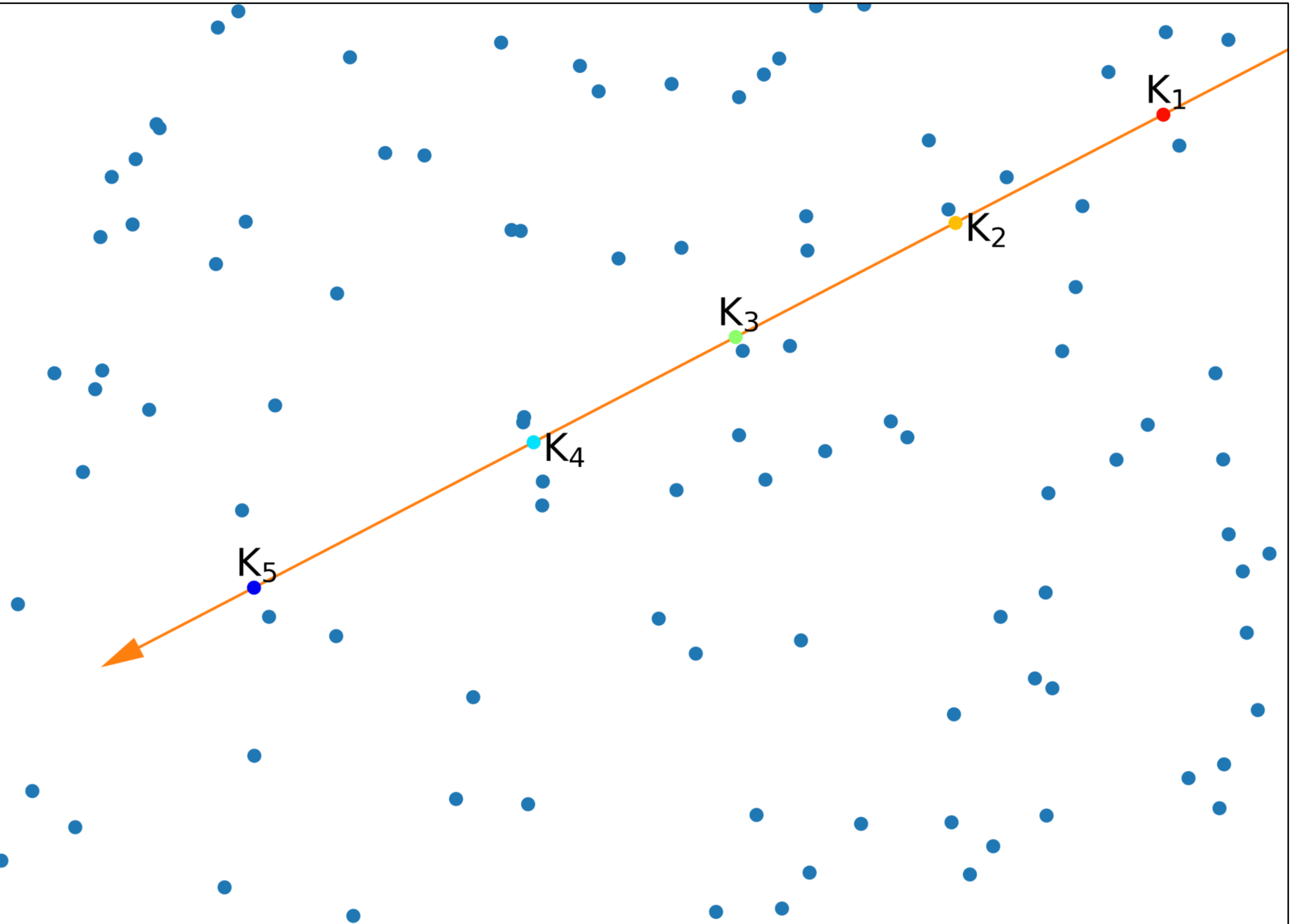
3D → Healpix



Interpolation along a ray



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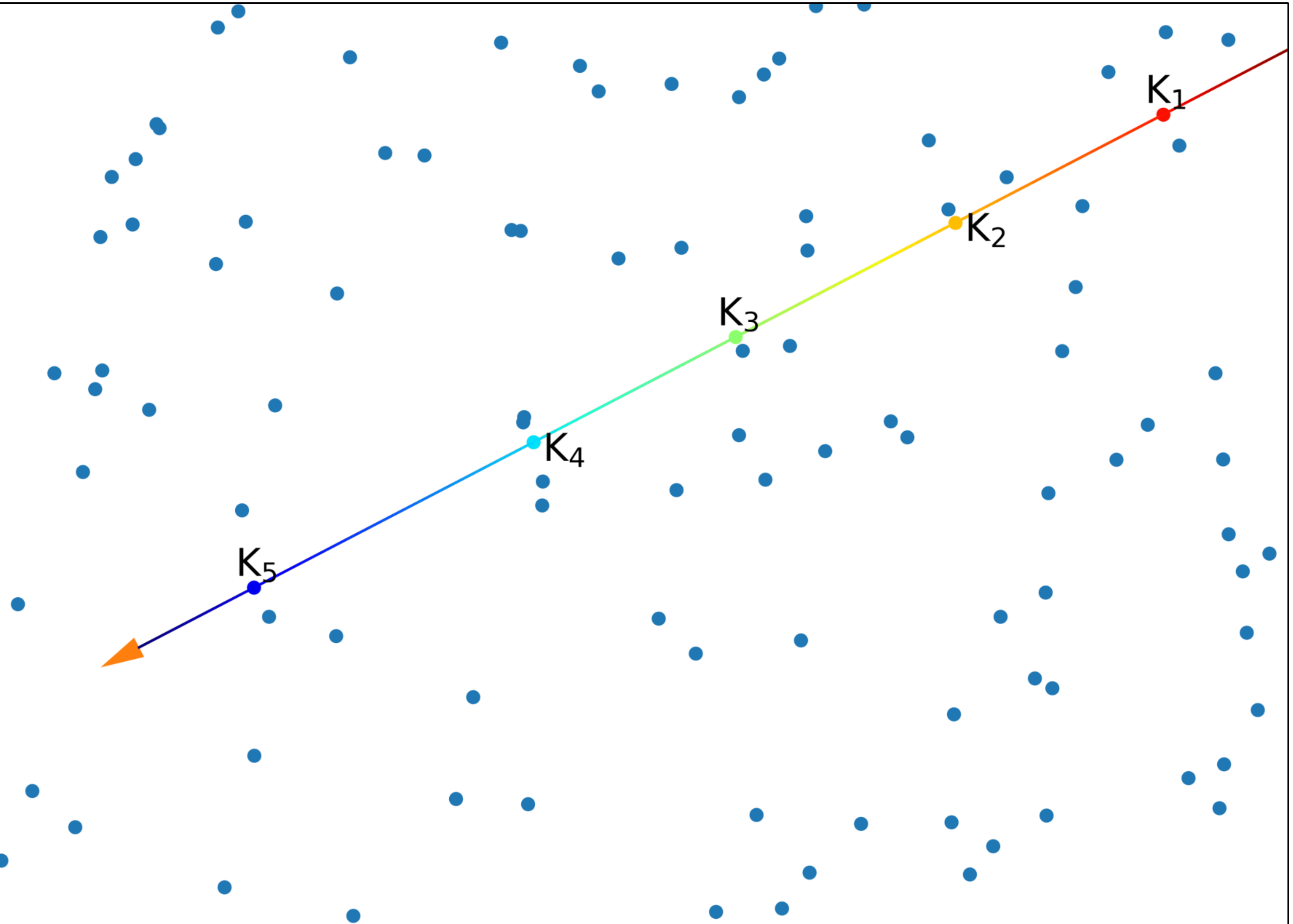

At each point K:

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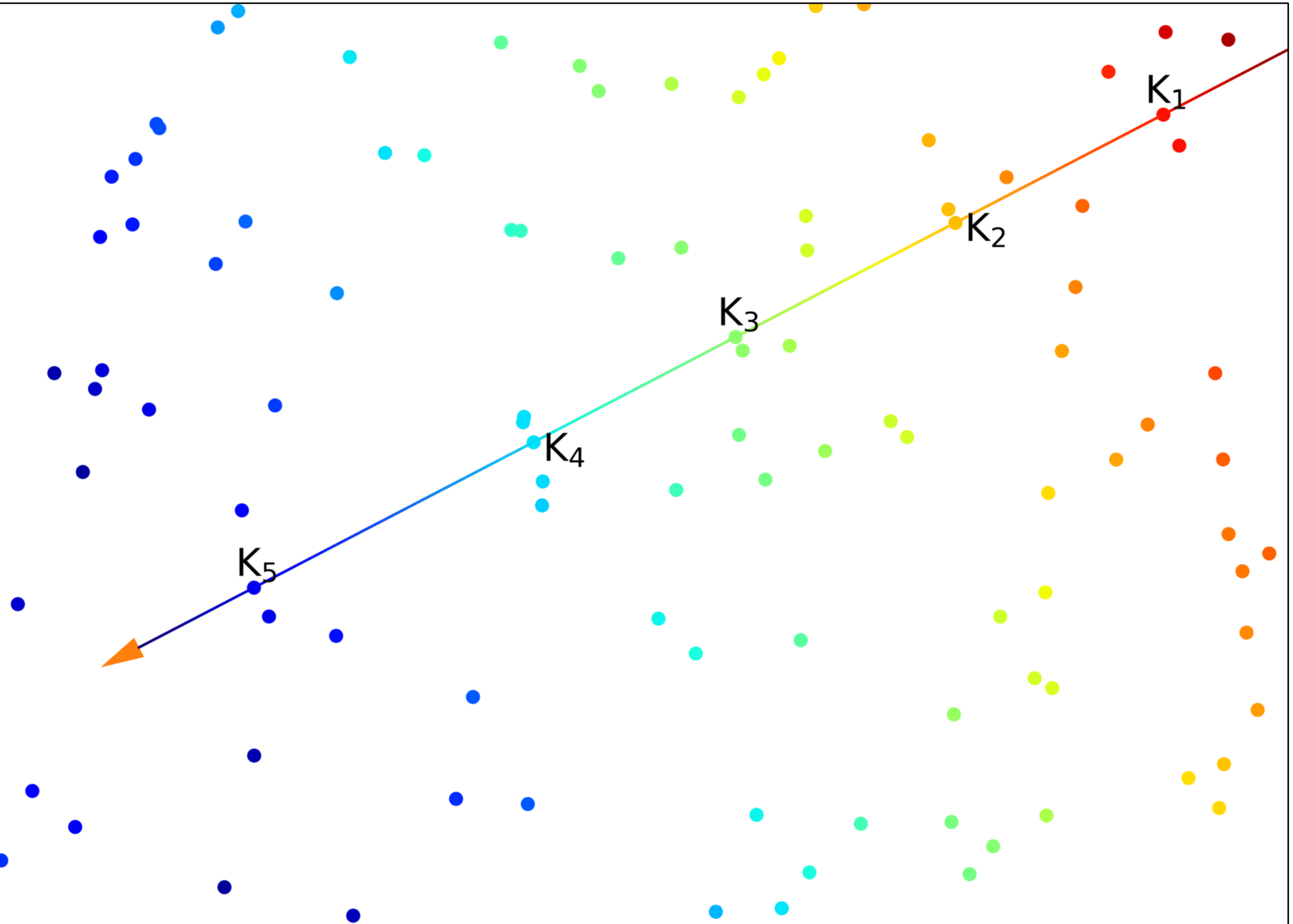
Linear interpolations between points

Interpolation along a ray



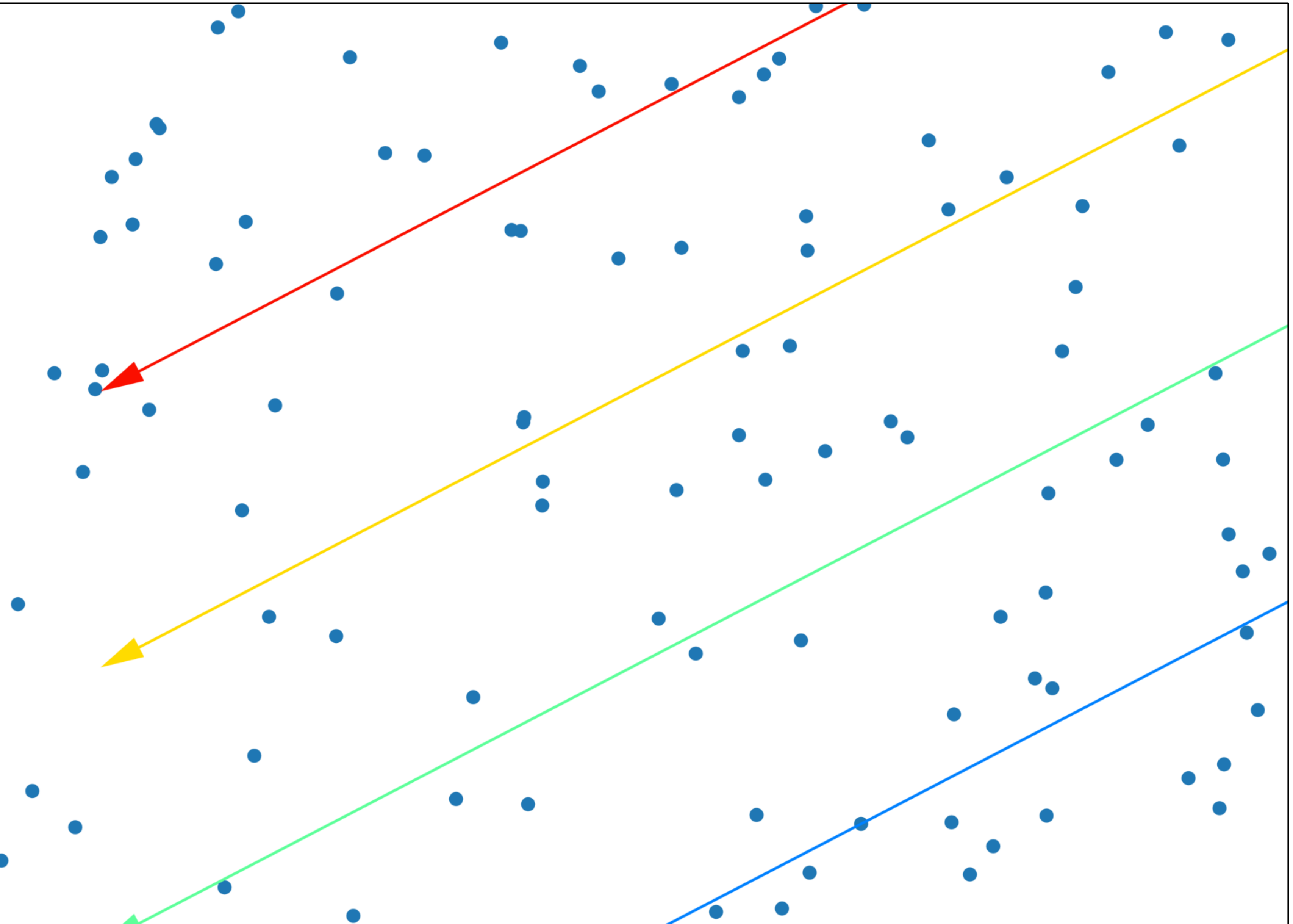
At each point K:

- τ_i

Linear interpolations between points

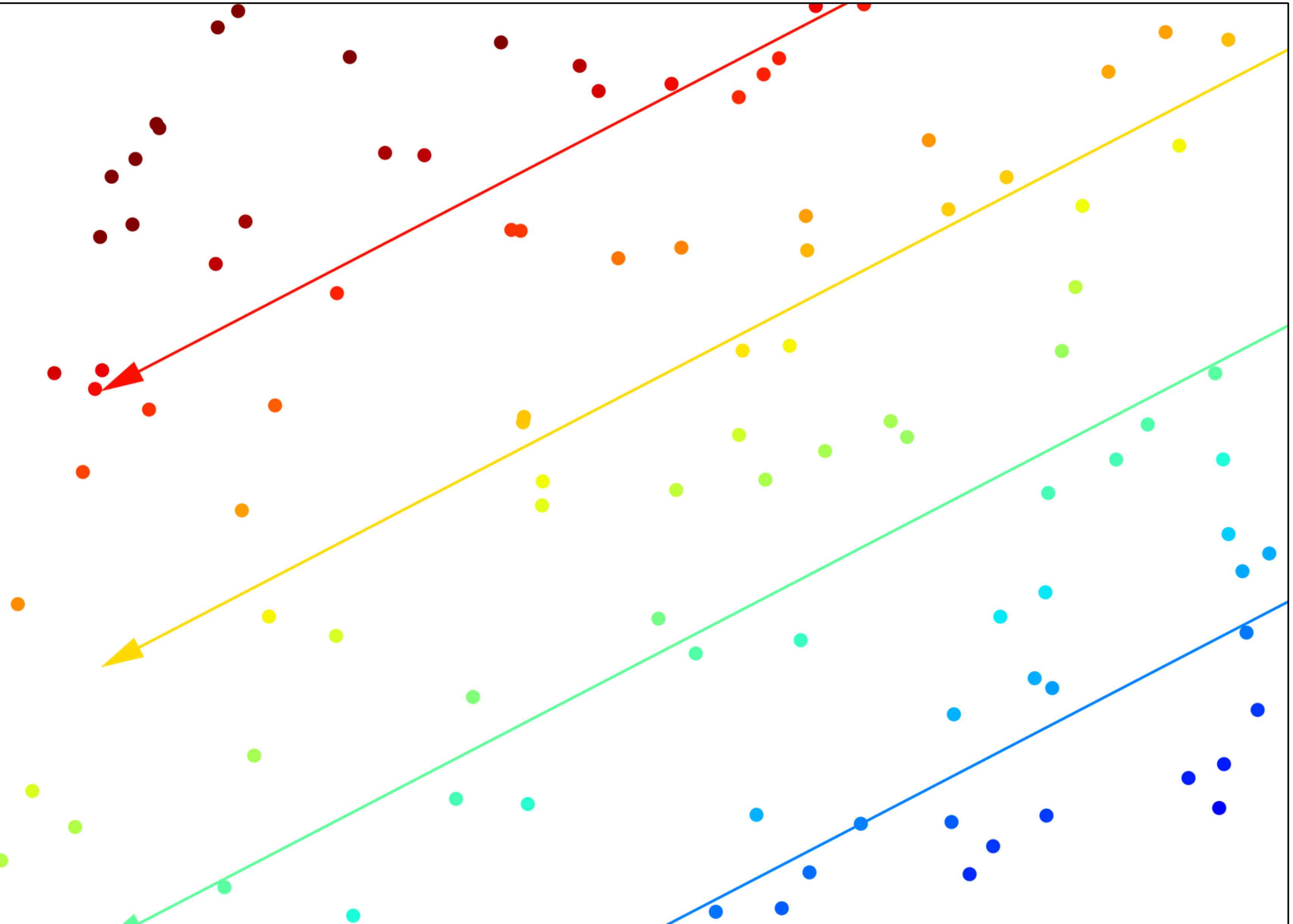
τ at closest point along the ray

Interpolation in between rays



Trace more rays

Interpolation in between rays

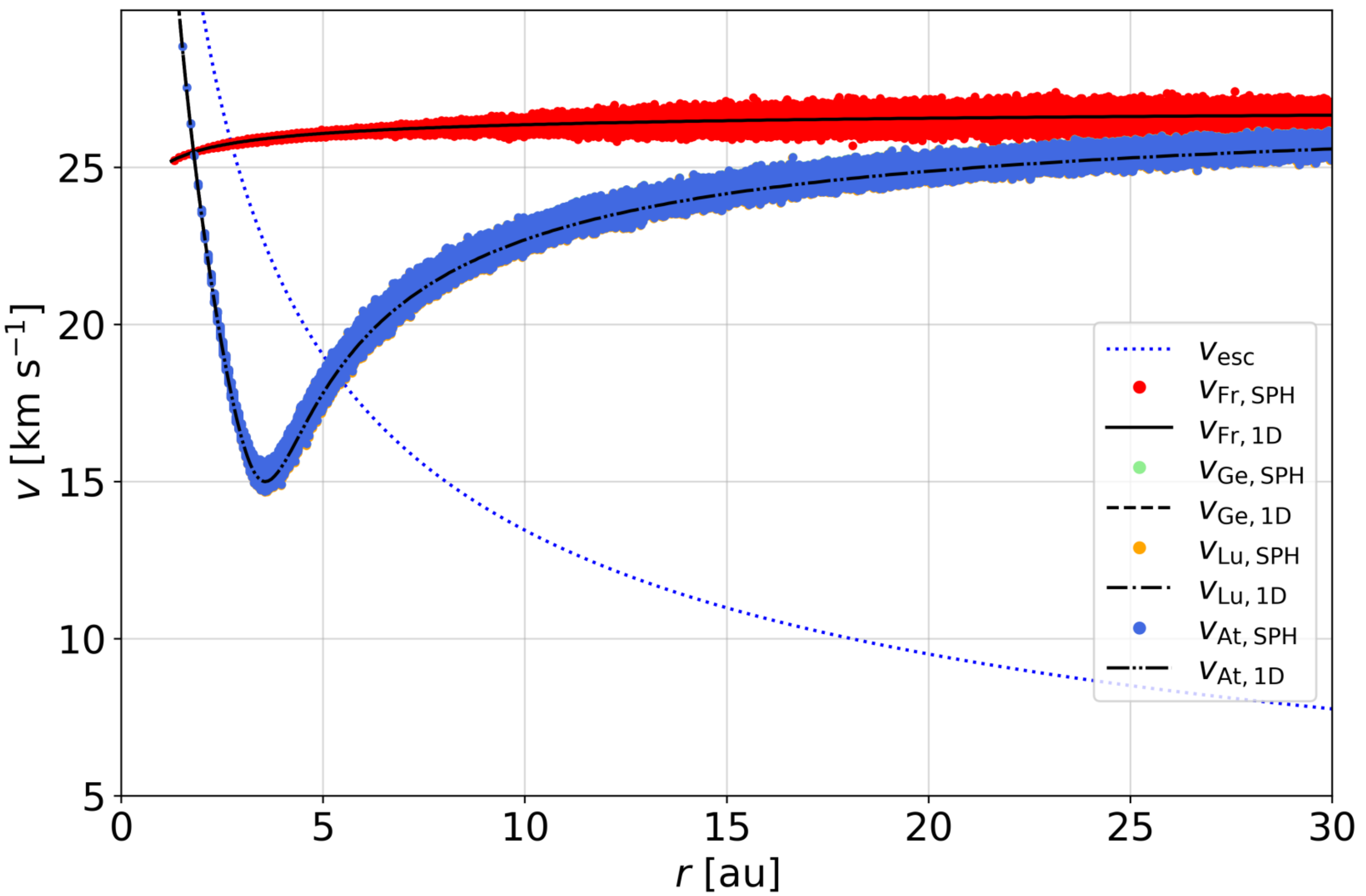


Trace more rays

Interpolate τ between closest rays

Velocity profile

Parameter	Value	Unit
$\dot{M}_{\mathrm{AGB}}$	10^{-8} or 3×10^{-6}	$\mathrm{M}_\odot\ \mathrm{yr}^{-1}$
M_{AGB}	1.02	$\mathrm{M}_\odot$
L_{AGB}	4384	$\mathrm{L}_\odot$
$T_{\mathrm{eff,AGB}}$	2874	K
R_{AGB}	1.24	au



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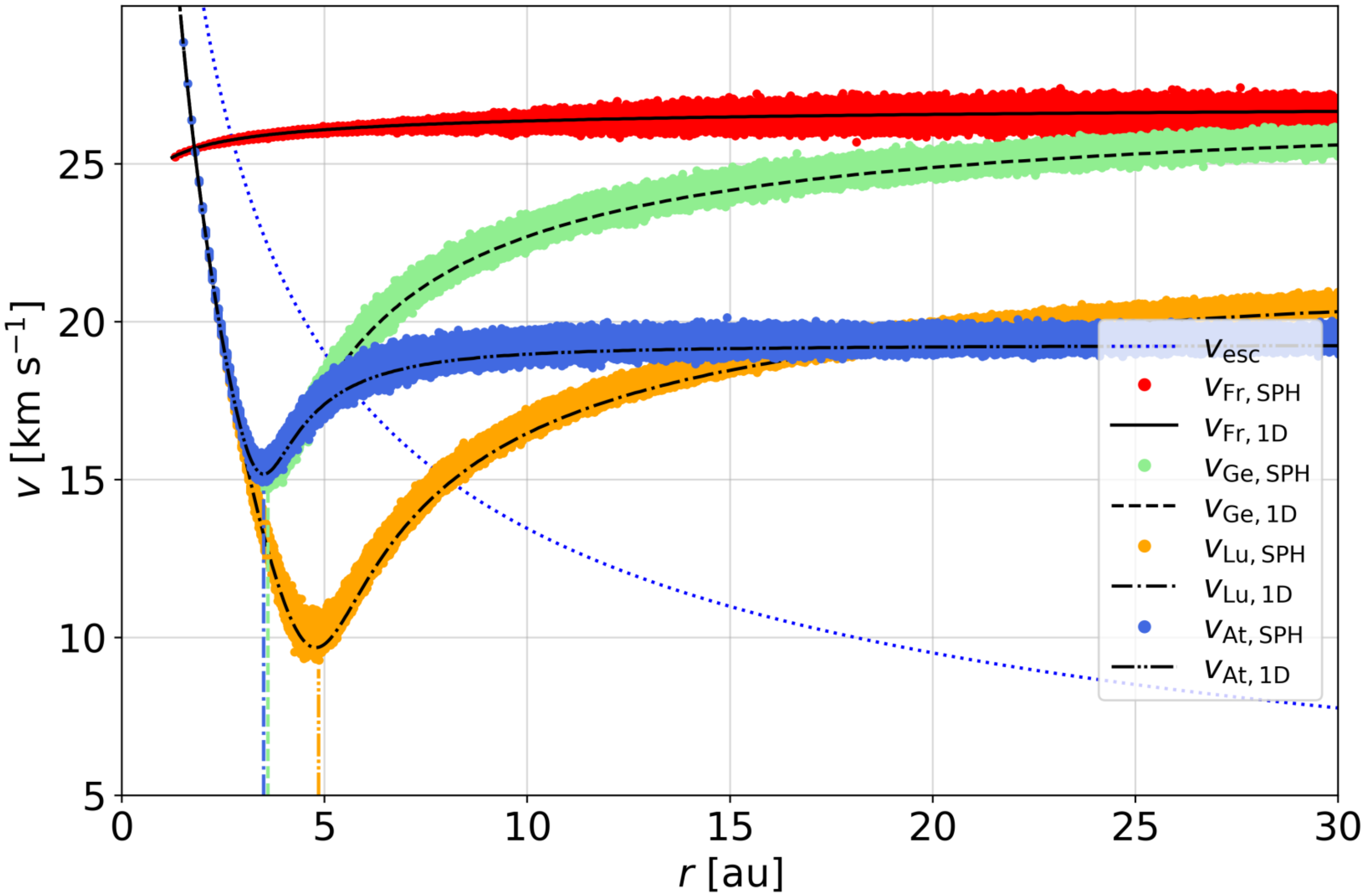

Morphological structures

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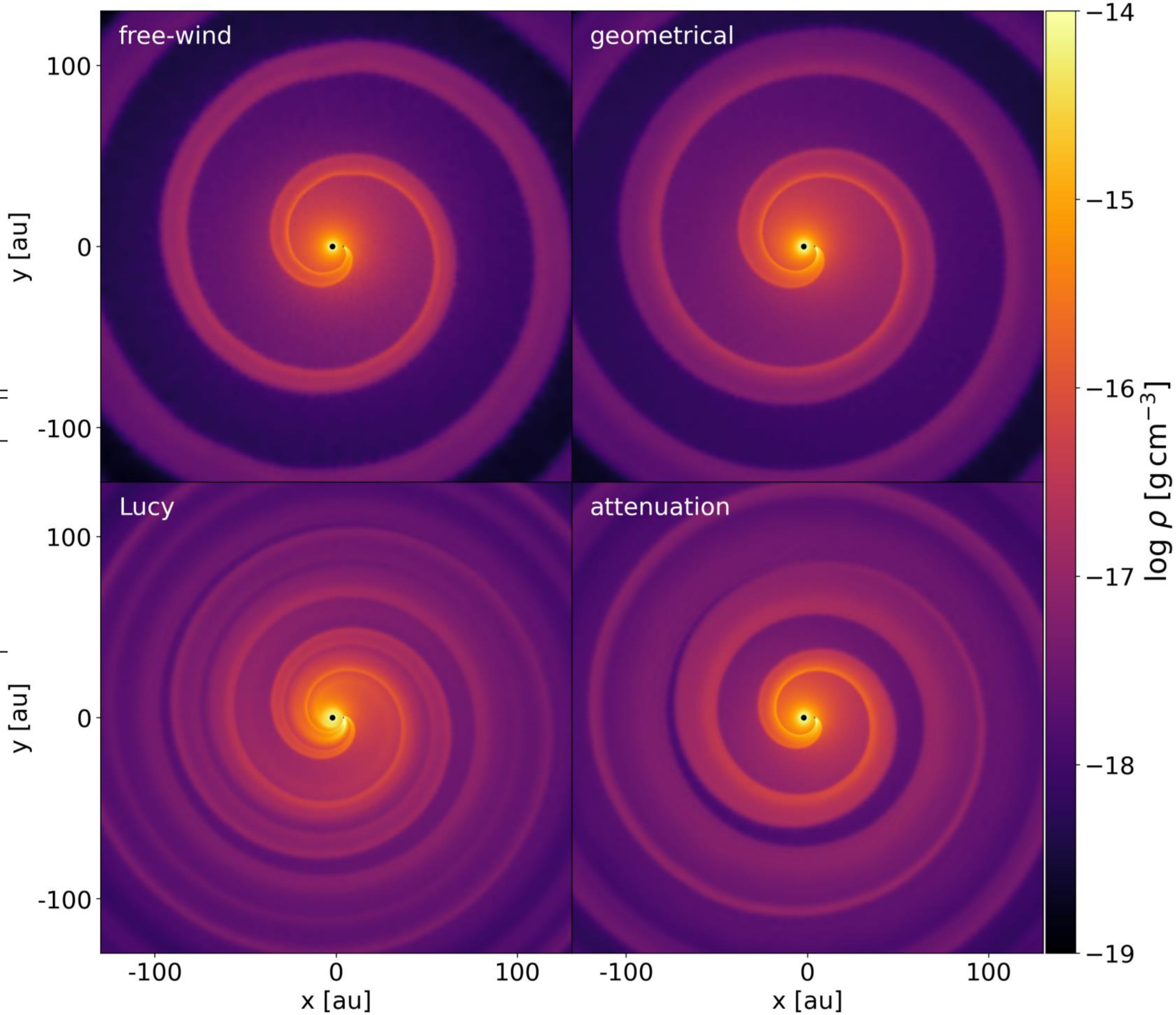

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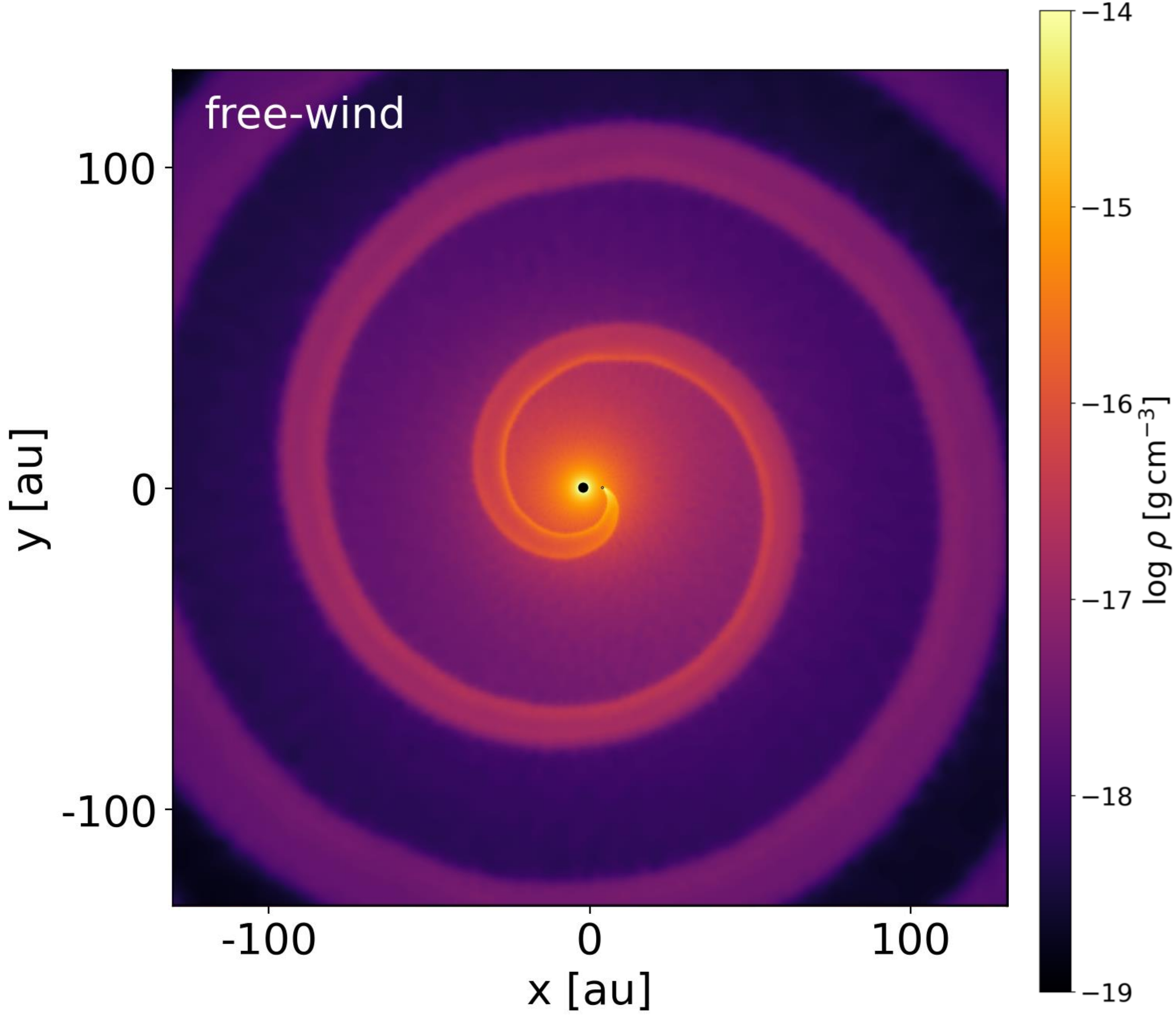

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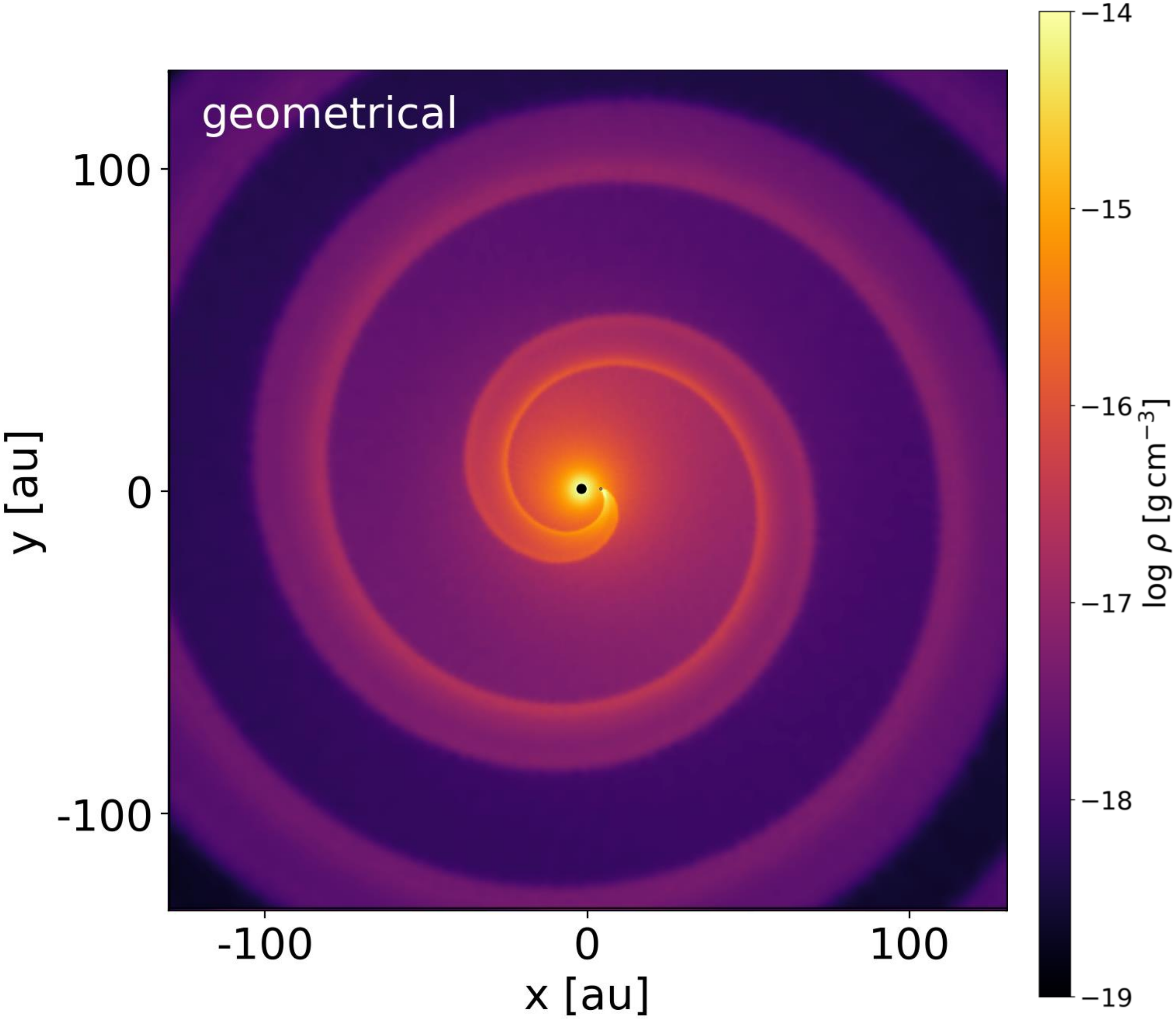

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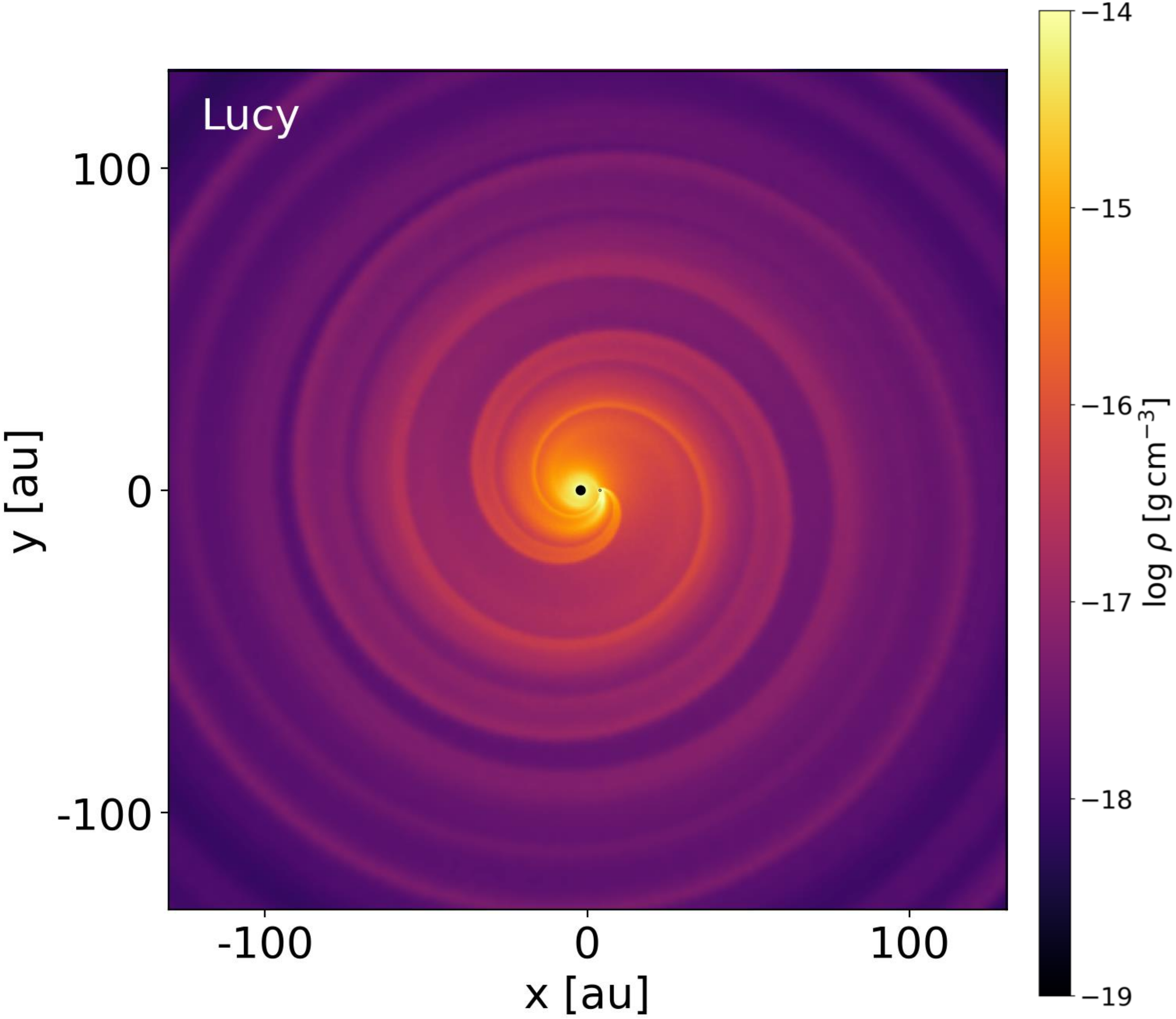

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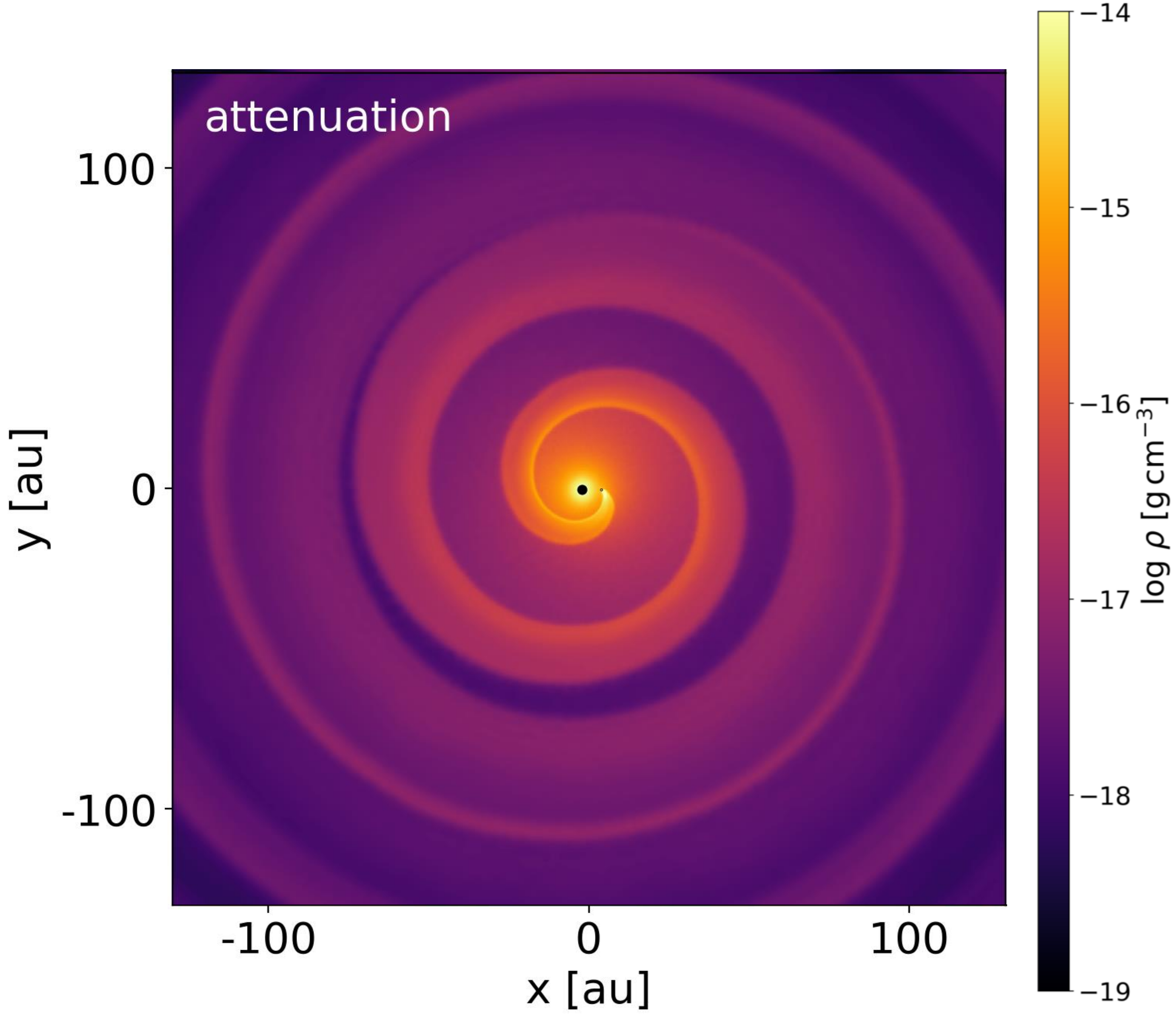

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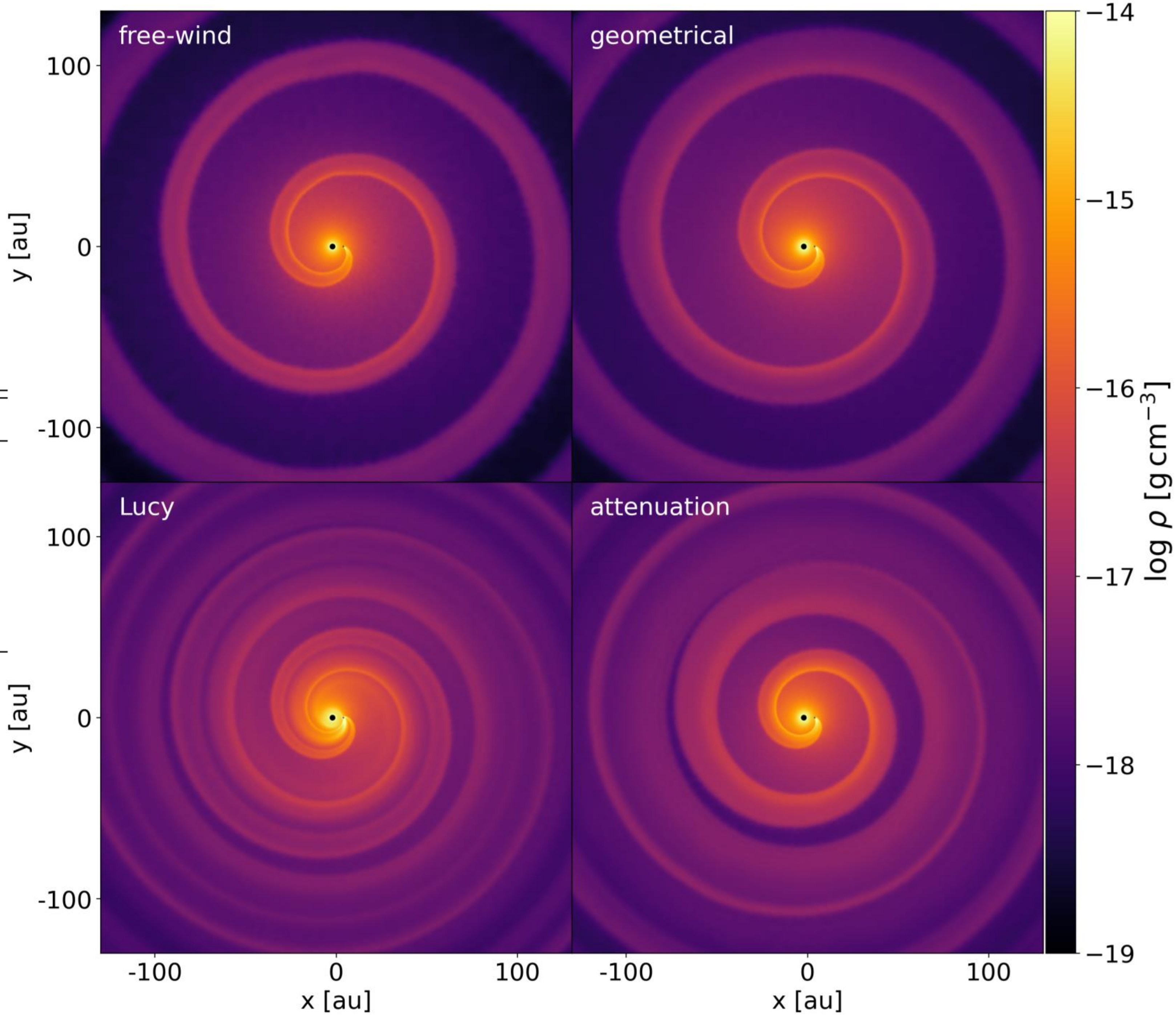
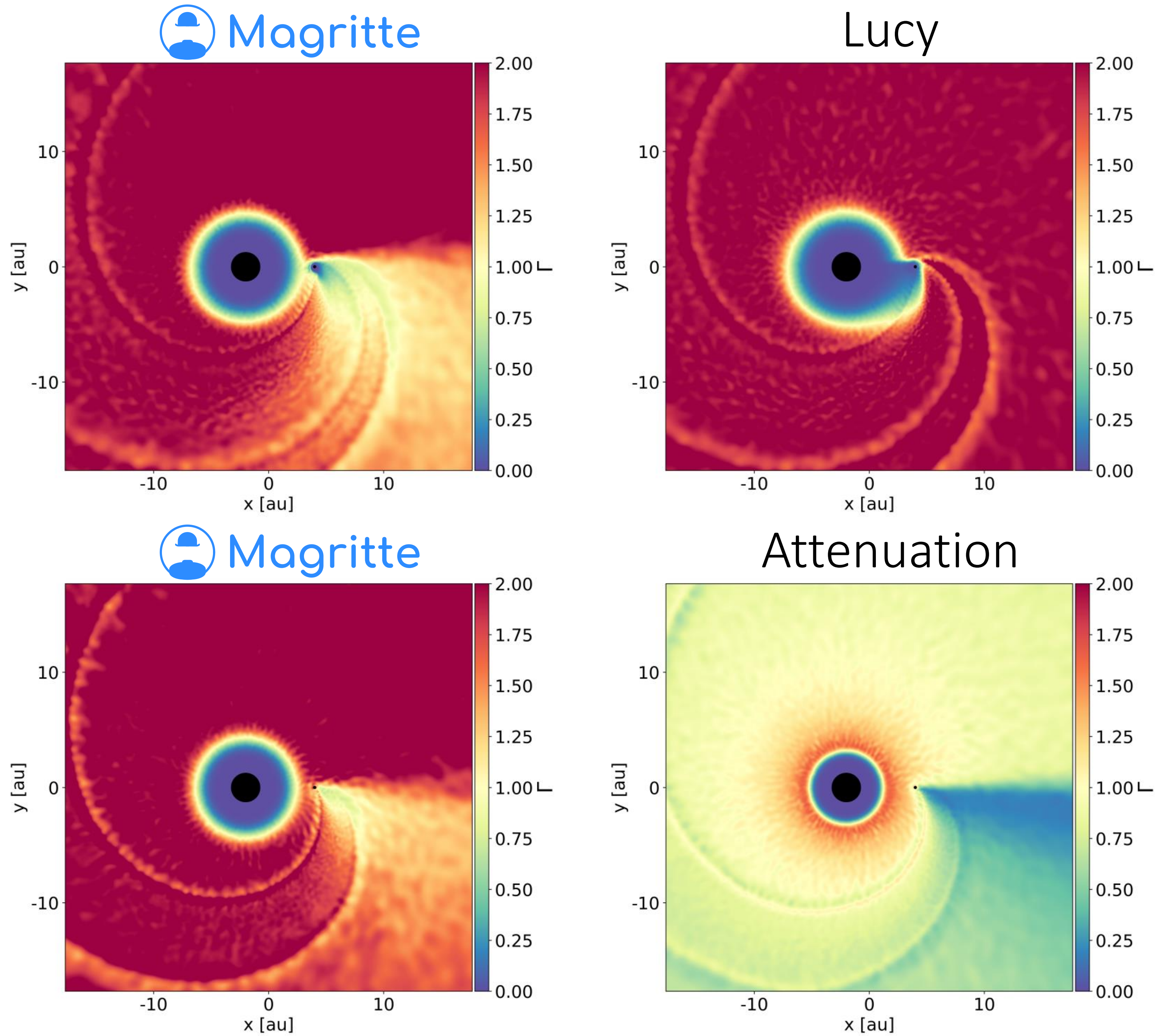


Validation Study

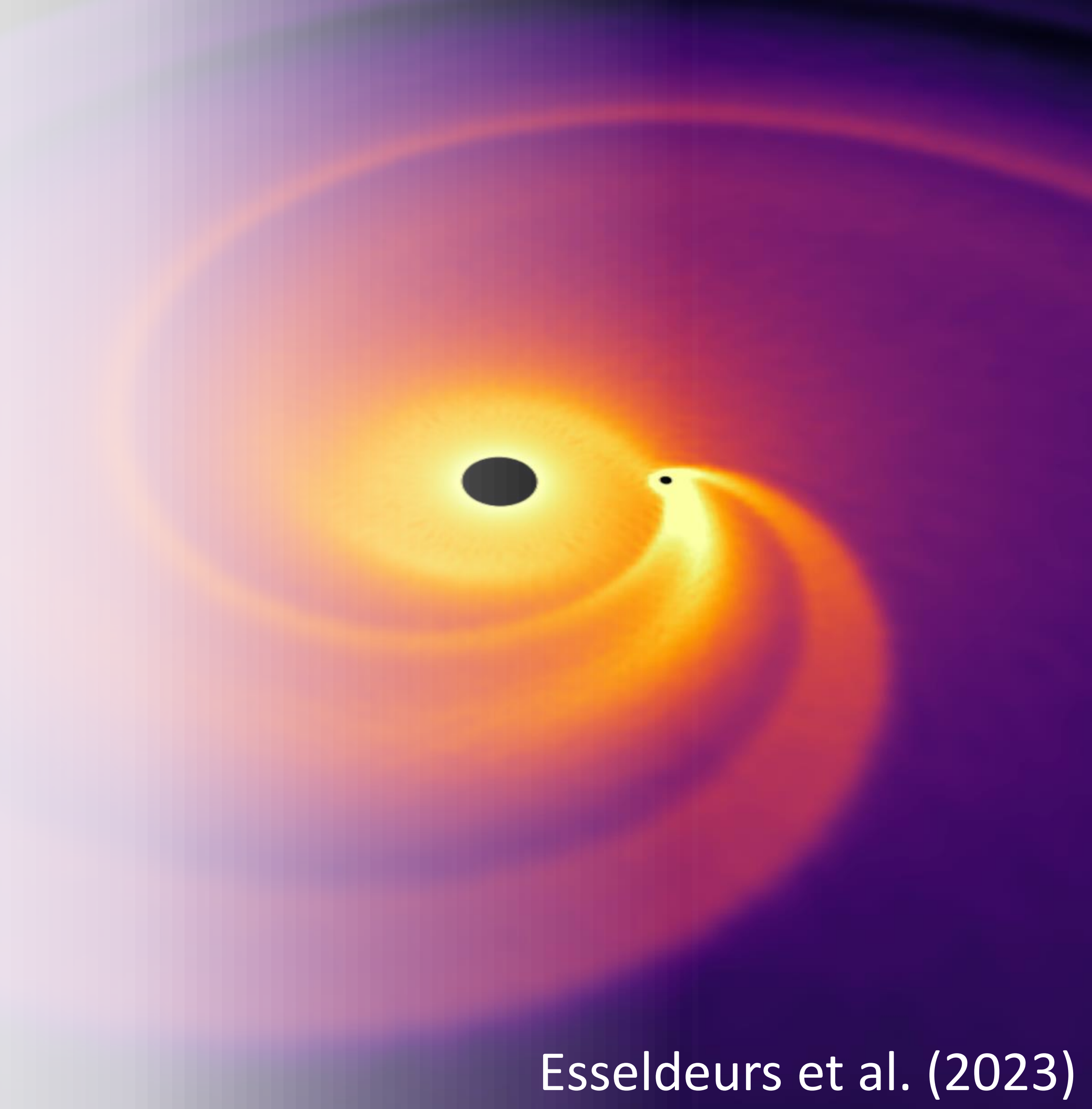
- Full 3D radiation transfer code Magritte

- Lucy approximation most accurate



Conclusions

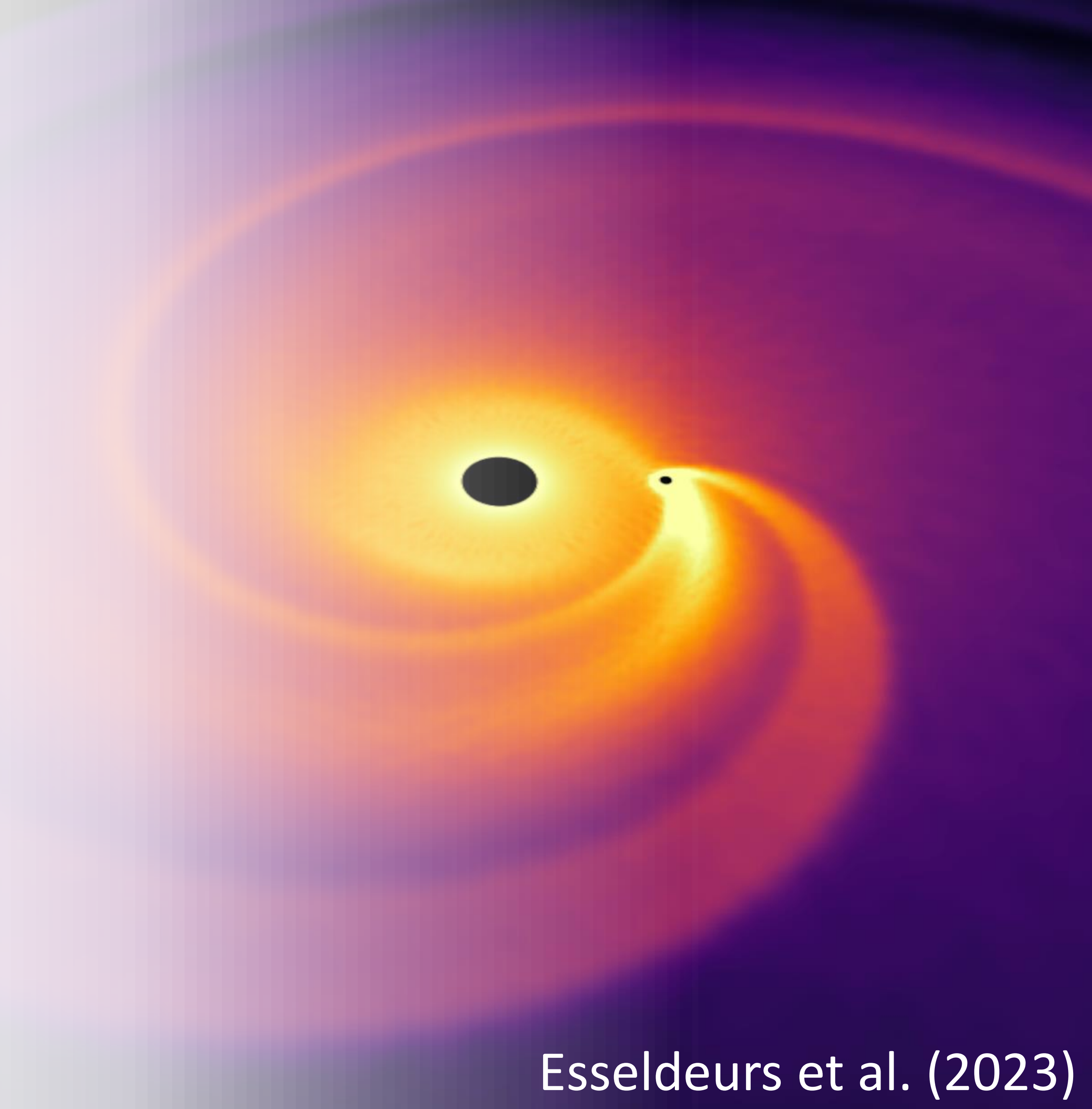
- Dust formation and radiative transfer is crucial
- Different approximations can make significant changes
- Lucy approximation most accurate



Esseldeurs et al. (2023)

Future work

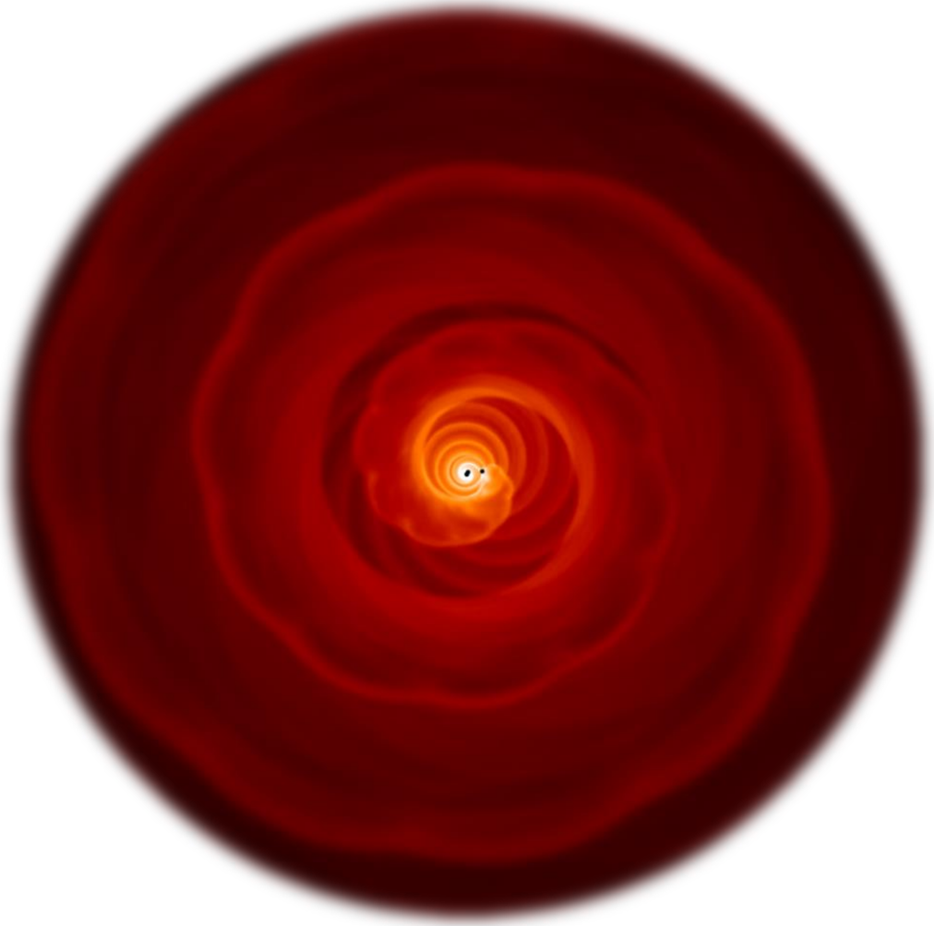
- Combination of Lucy and attenuation approximation
- Couple Phantom to MCFOST for full radiation transfer calculation

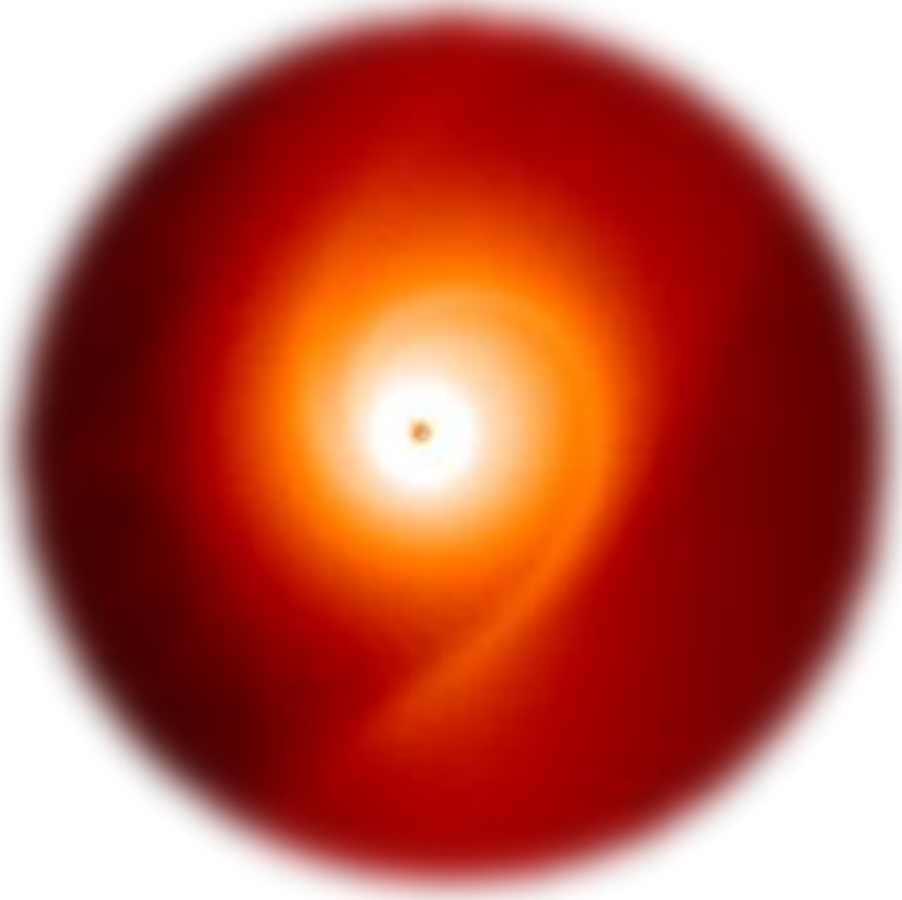


Esseldeurs et al. (2023)

Tripple simulations and disk formation

Jolien Malfait

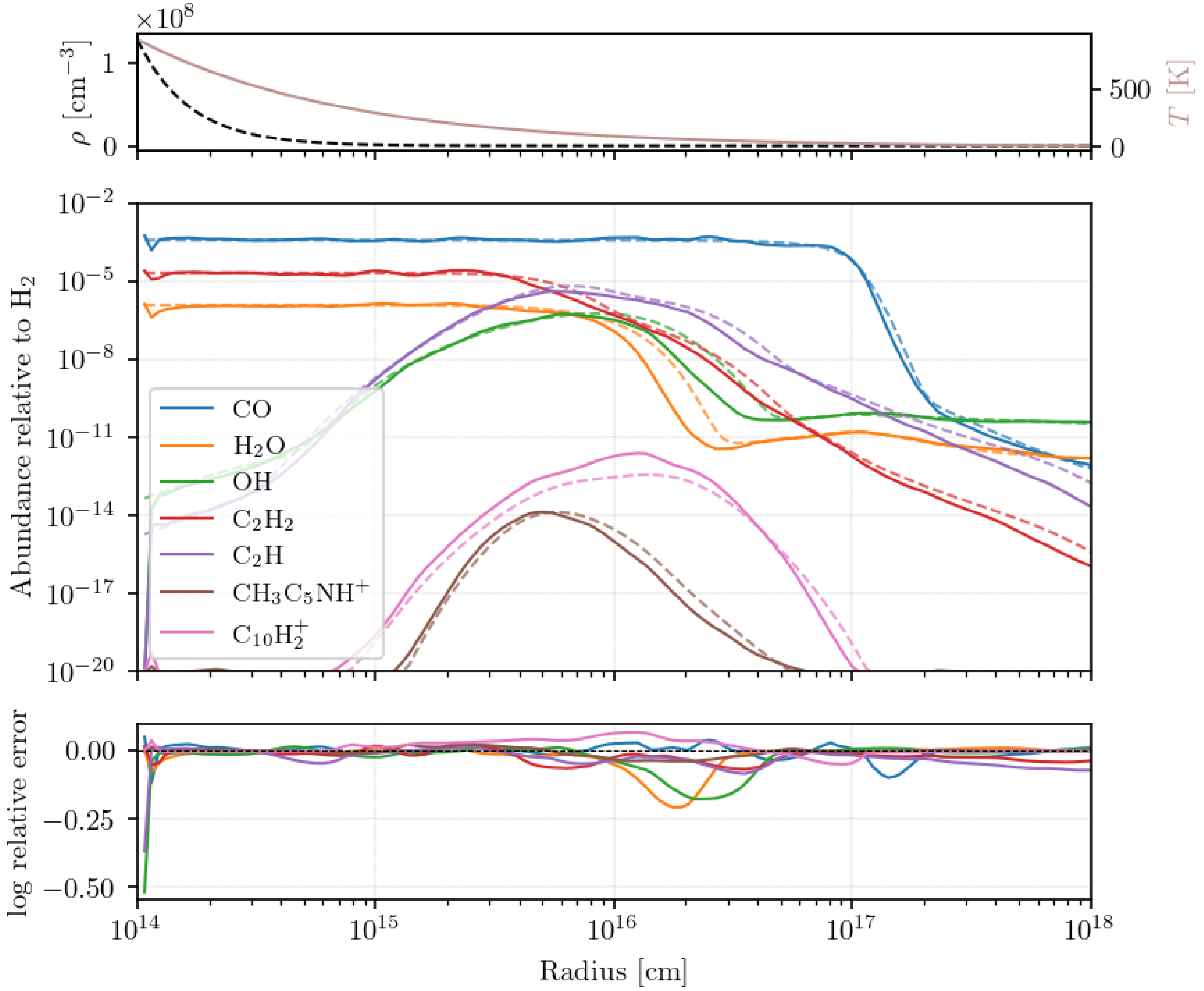




Malfait+ (in prep. a,b)

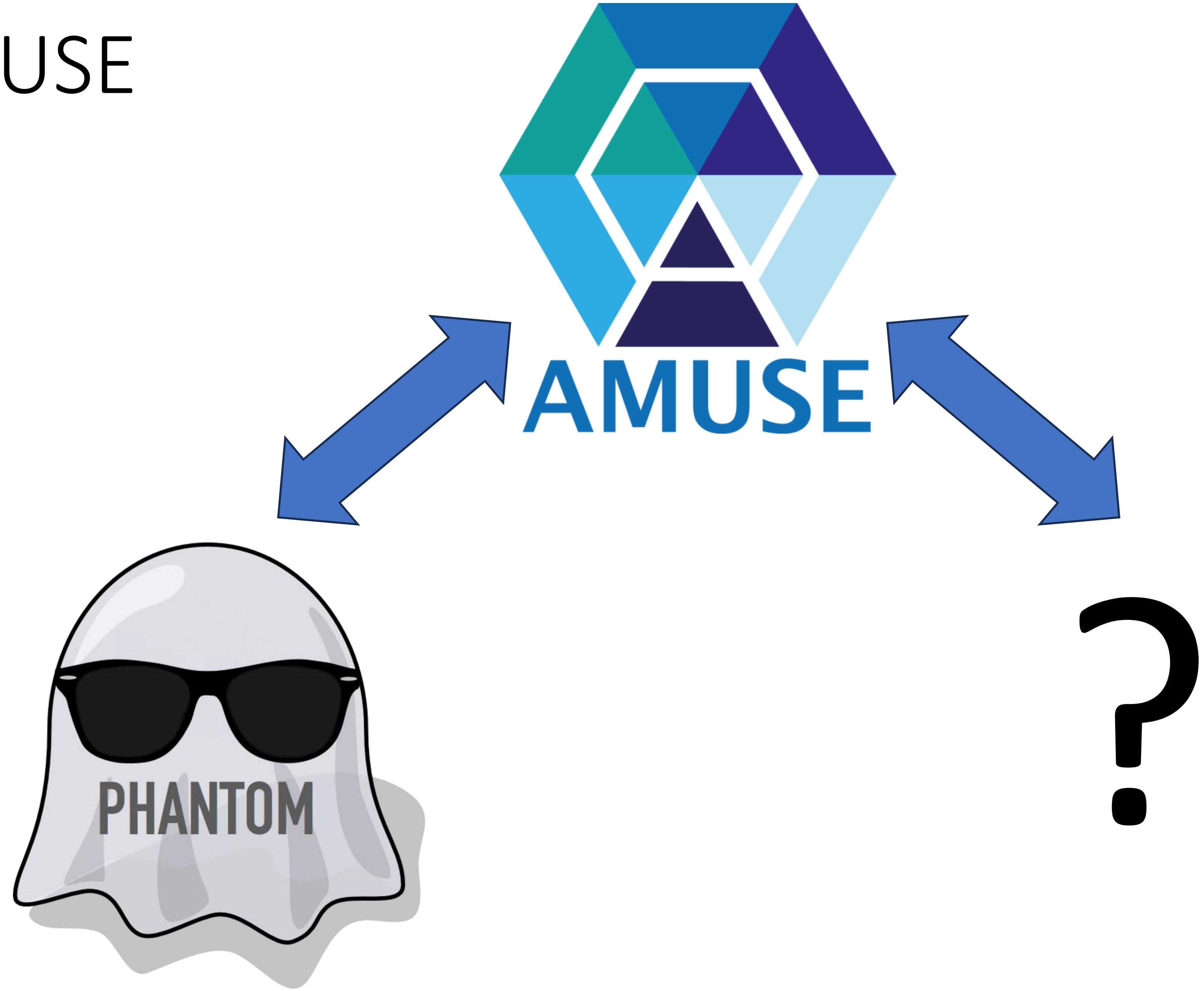
Machine learning Approach to Chemistry Emulation (MACE)

Silke Maes



Maes+ (in prep.)

AMUSE



Steven Rieder

Magritte

Thomas Ceulemans

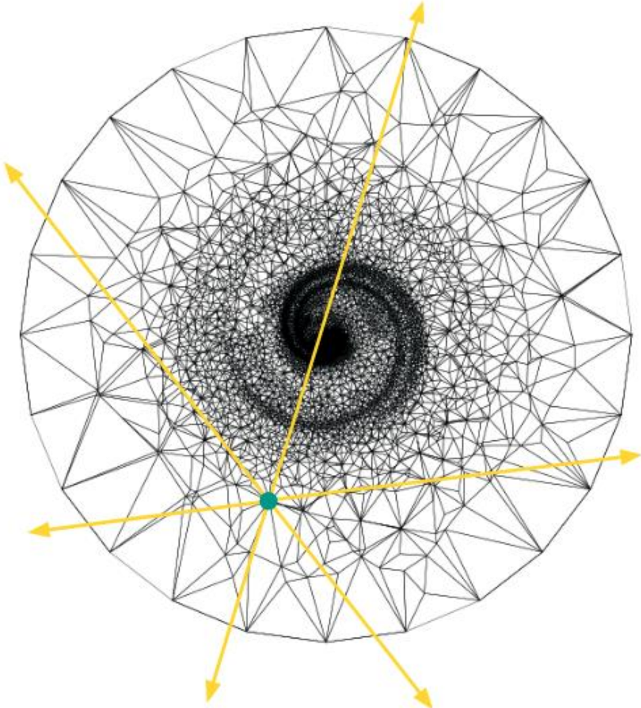
Frederik De Ceuster

- Open-source software library for **3D non-LTE line radiative transfer**

  De Ceuster+ (2020a,b; 2022), Ceulemans+ (in prep.), github.com/Magritte-code/Magritte

- **Optimize discretization** for RT through remeshing
  (De Ceuster+ 2020b & accelerated by Ceulemans+ in prep.)
- **Traces rays** and **solves RT equation** along each ray
- **GPU version** in progress

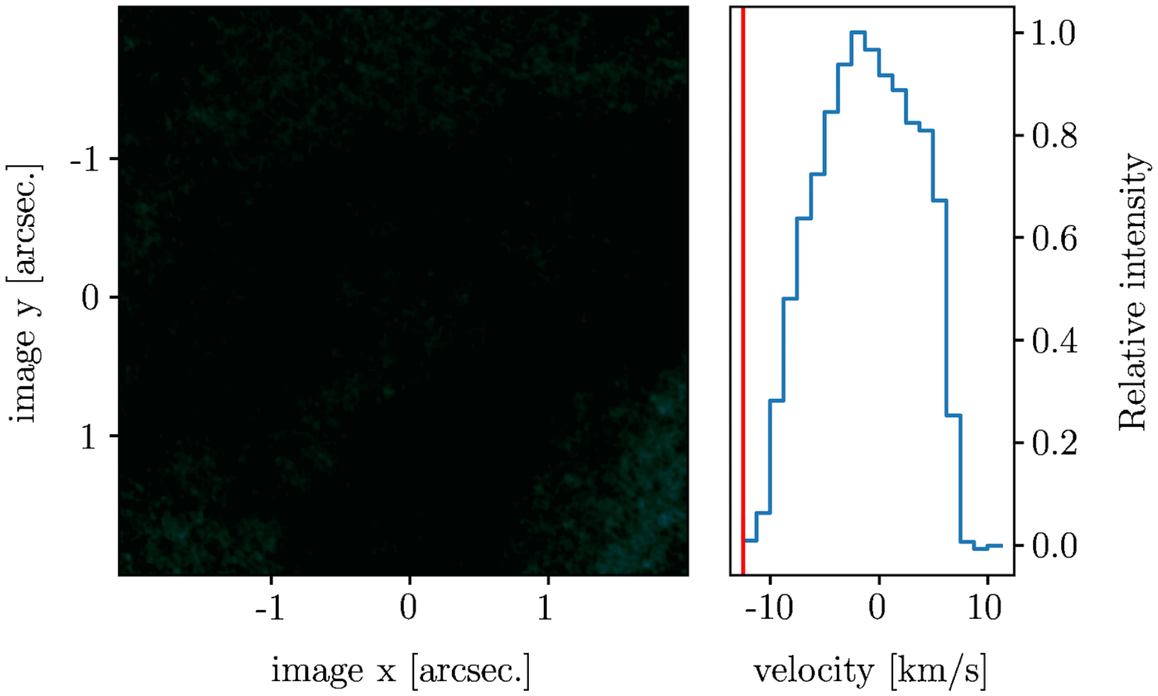
Magrittetorch



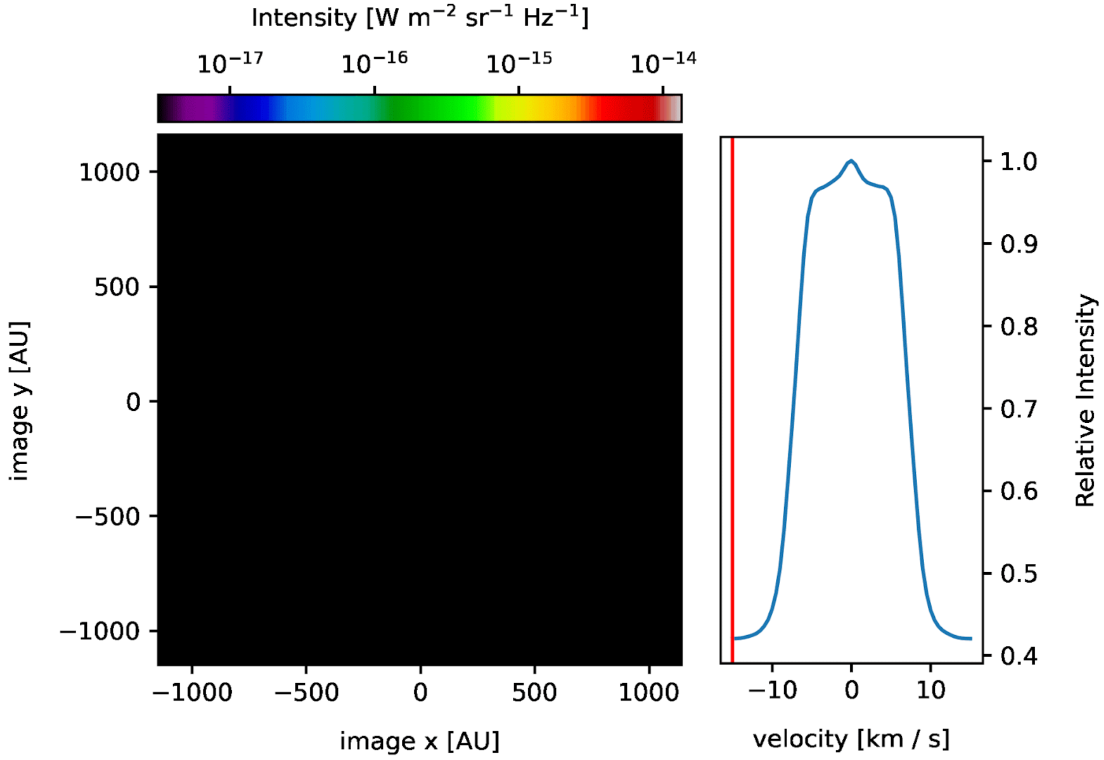
Magritte

Jolien Malfait

R Aql observation



Triple system synthetic observations



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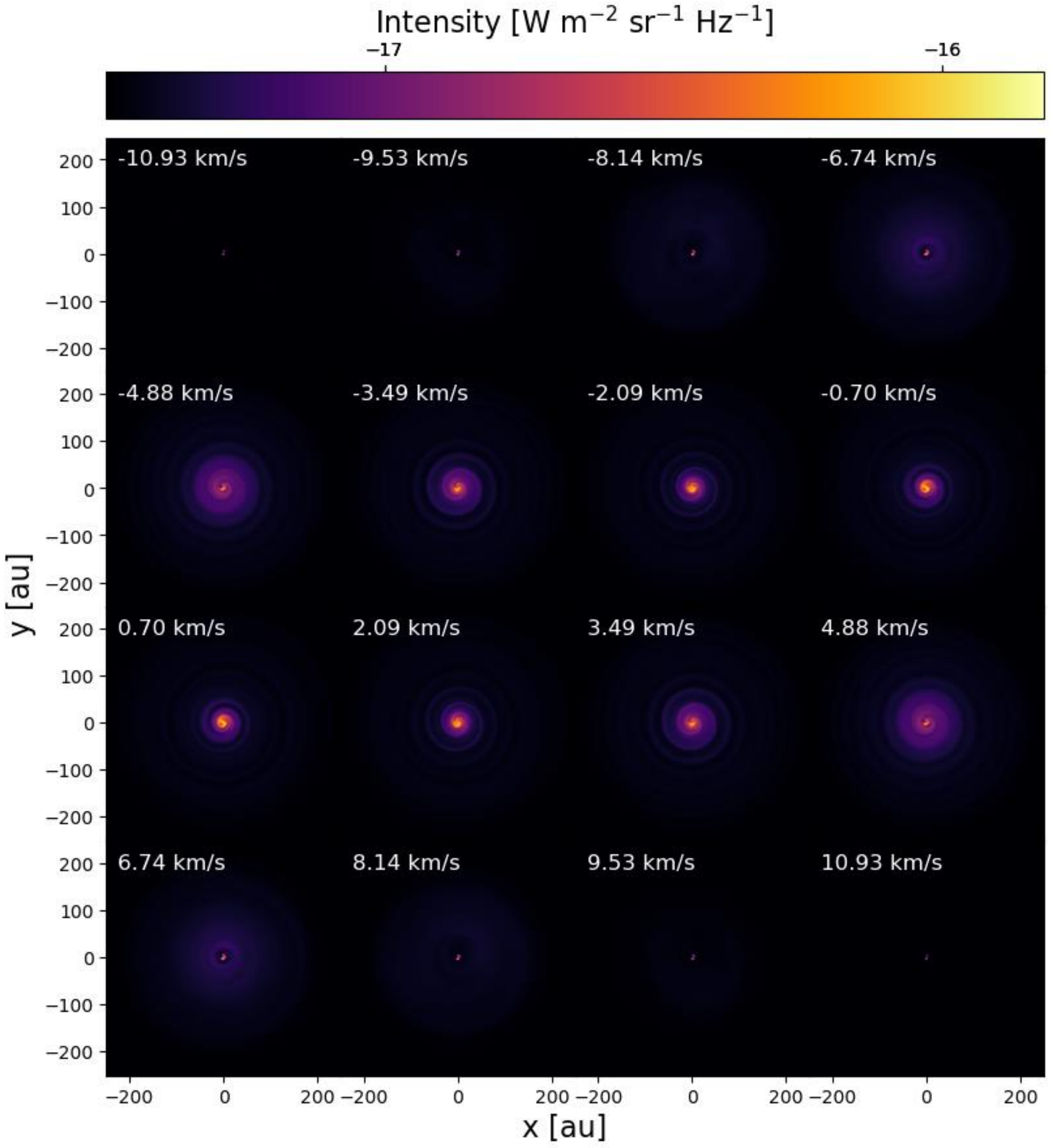

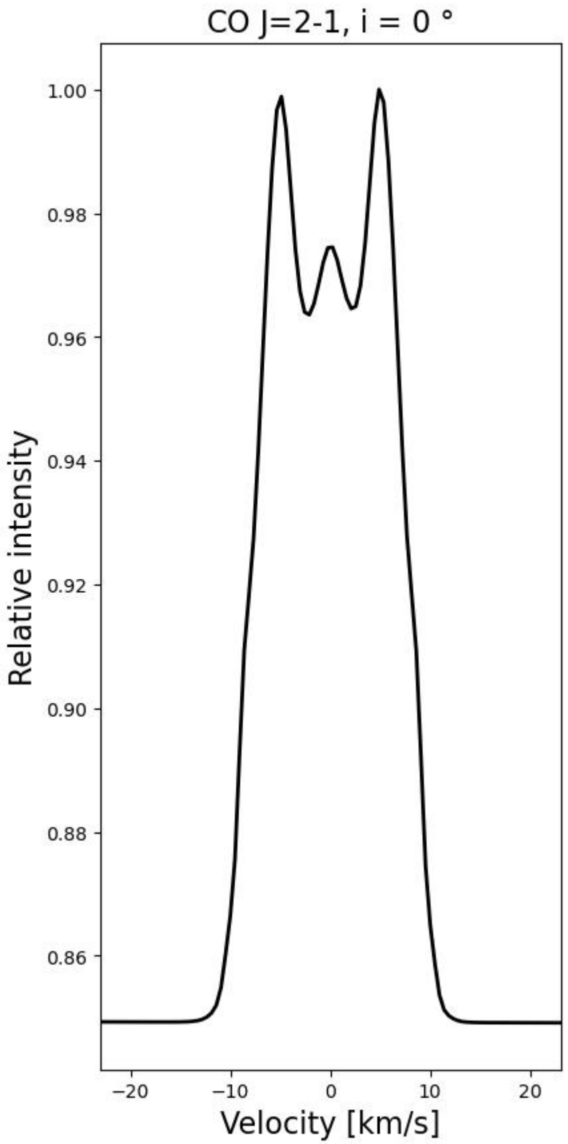

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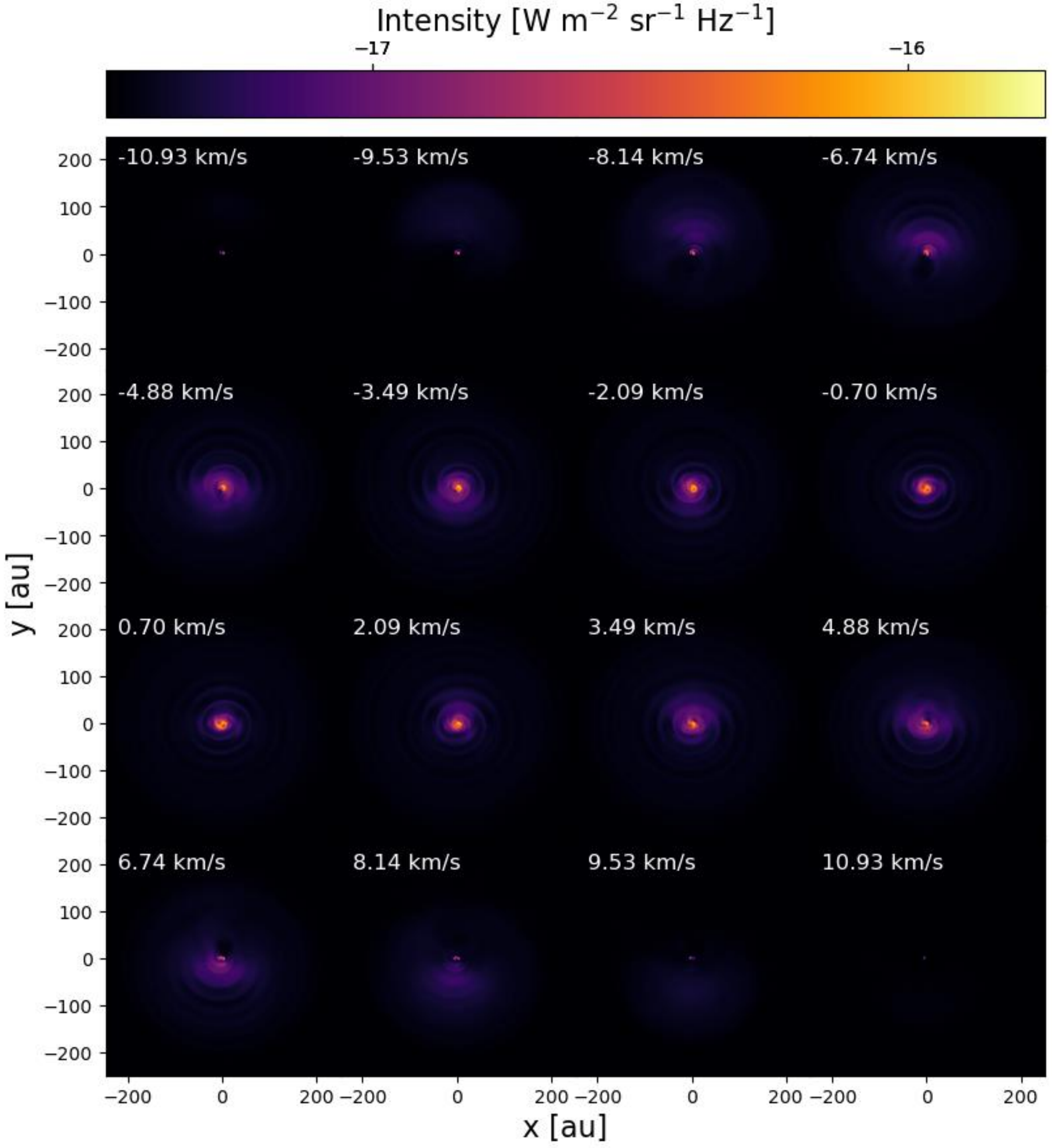
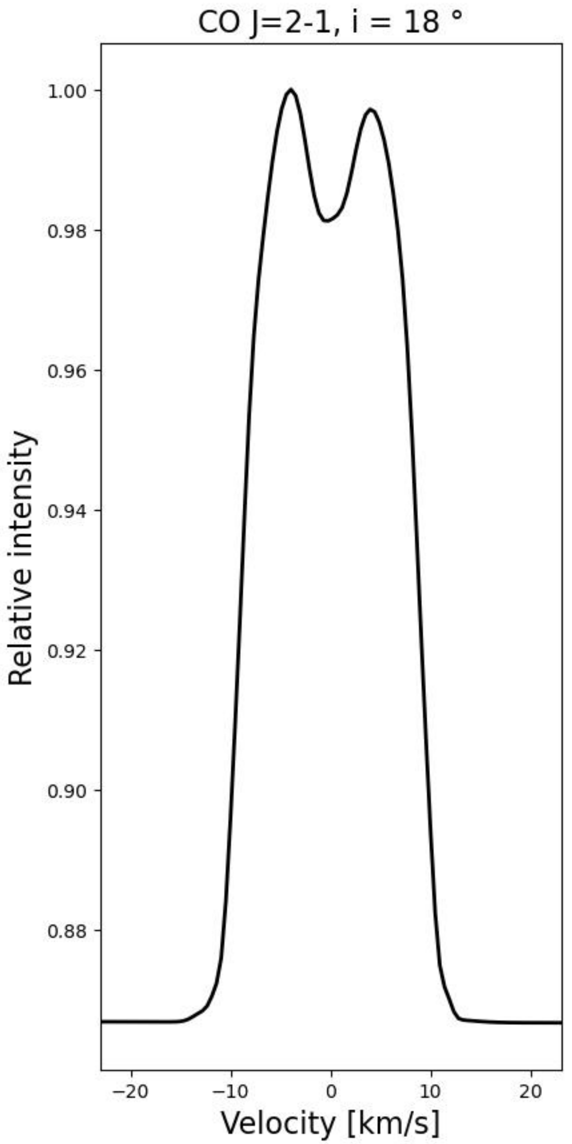
Magritte





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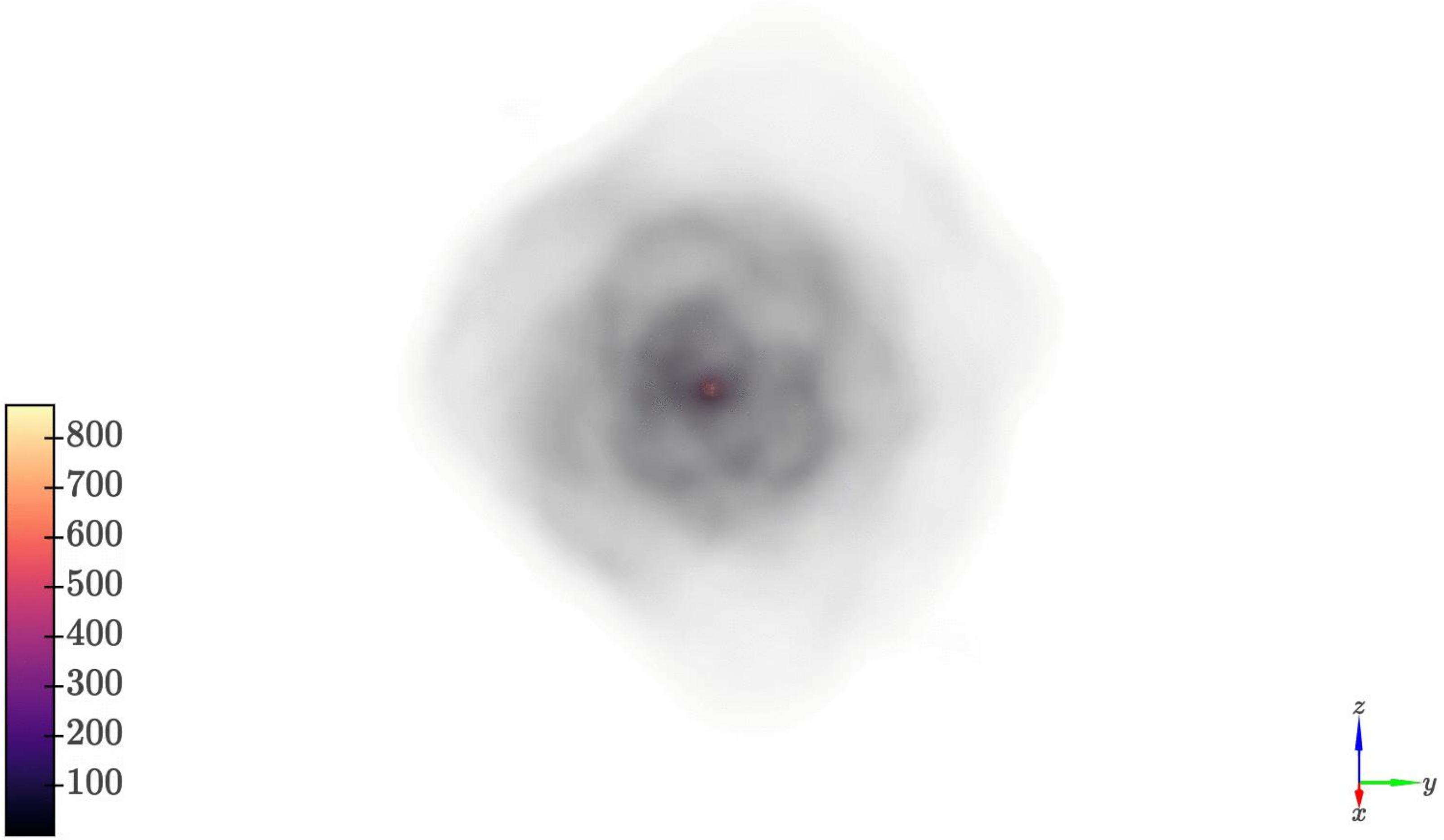
p3droslo

Frederik De Ceuster



De Ceuster+ (in prep.)