LENS PRIOR MATCHING WITH LATENT DIFFUSION MODELS

SKACH WINTER MEETING 2025

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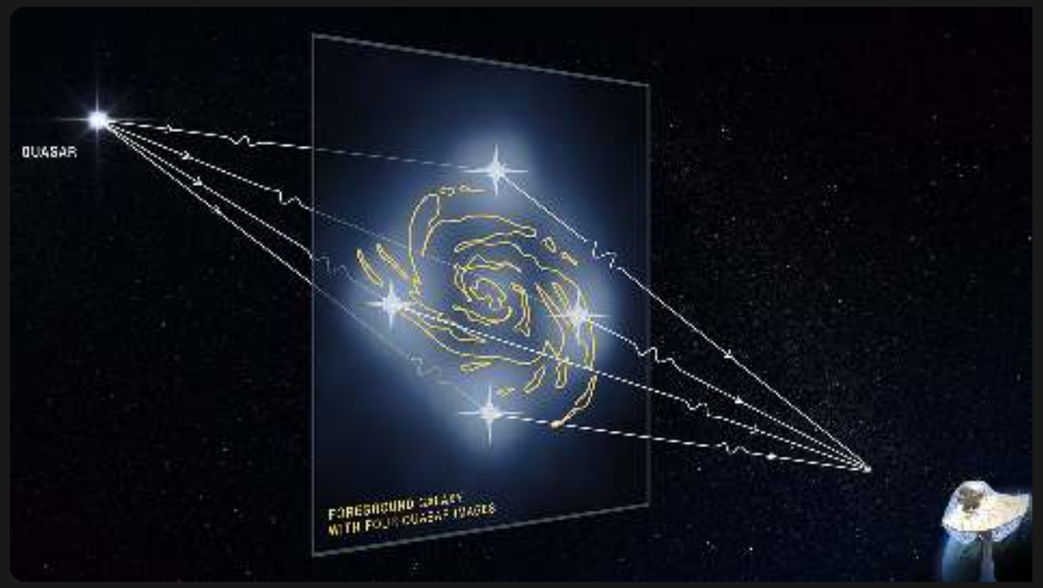
STRONG GRAVITATIONAL LENS PRIOR

- Let D be a lens observation



Credits: NASA/ESA

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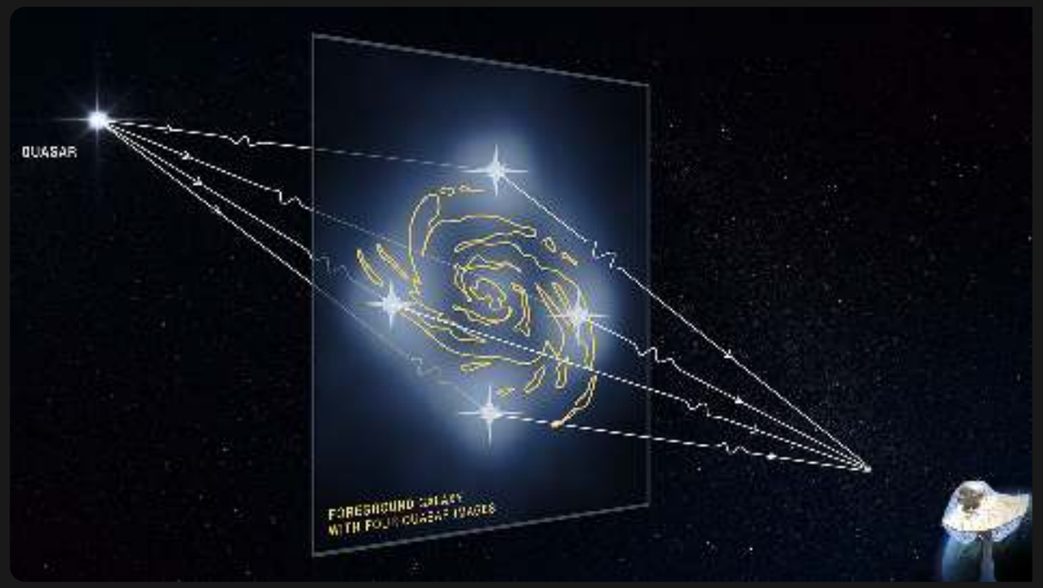

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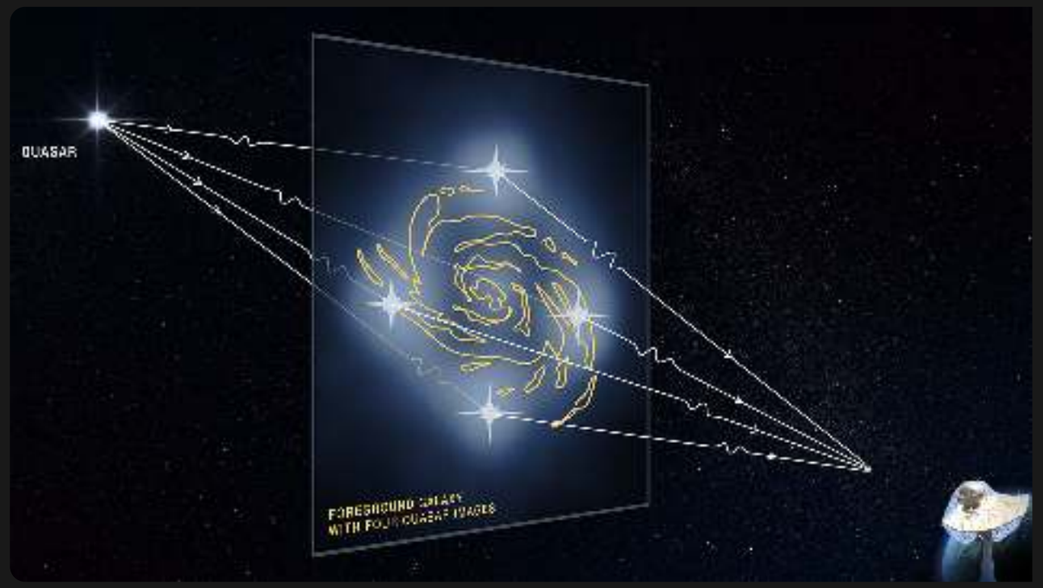
- In Bayesian terms: $p(\Gamma \mid D) \propto p(D \mid \Gamma)\, p(\Gamma)$
  - data likelihood $p(D \mid \Gamma)$ contains the physics
    $p(\Gamma)$ is our **prior** knowledge about galaxies



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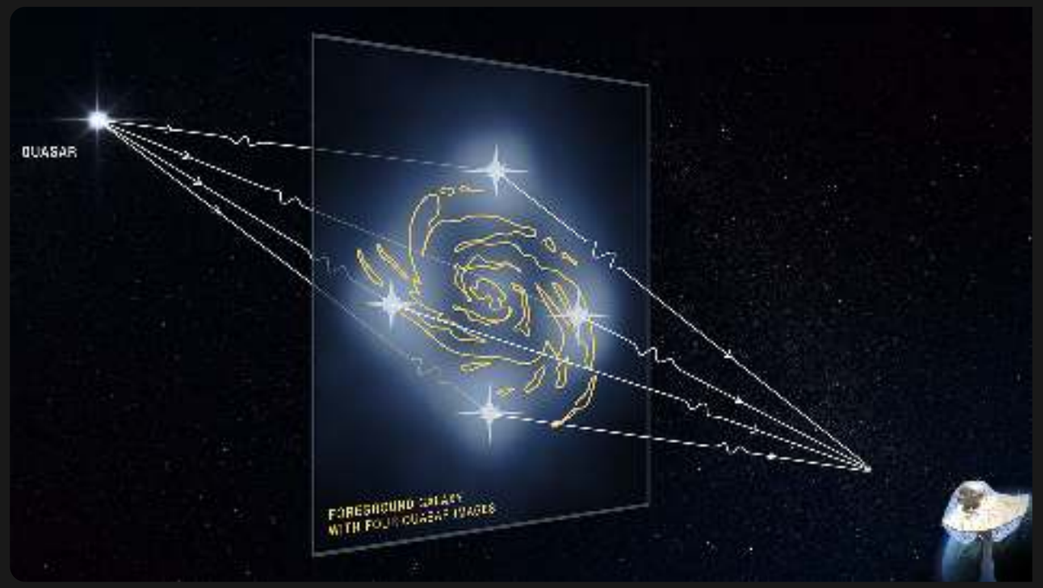
- This means finding a galaxy s.t.

$$\Gamma_i = \arg\max_{\Gamma} \; p(D \mid \Gamma) + p(\Gamma)$$



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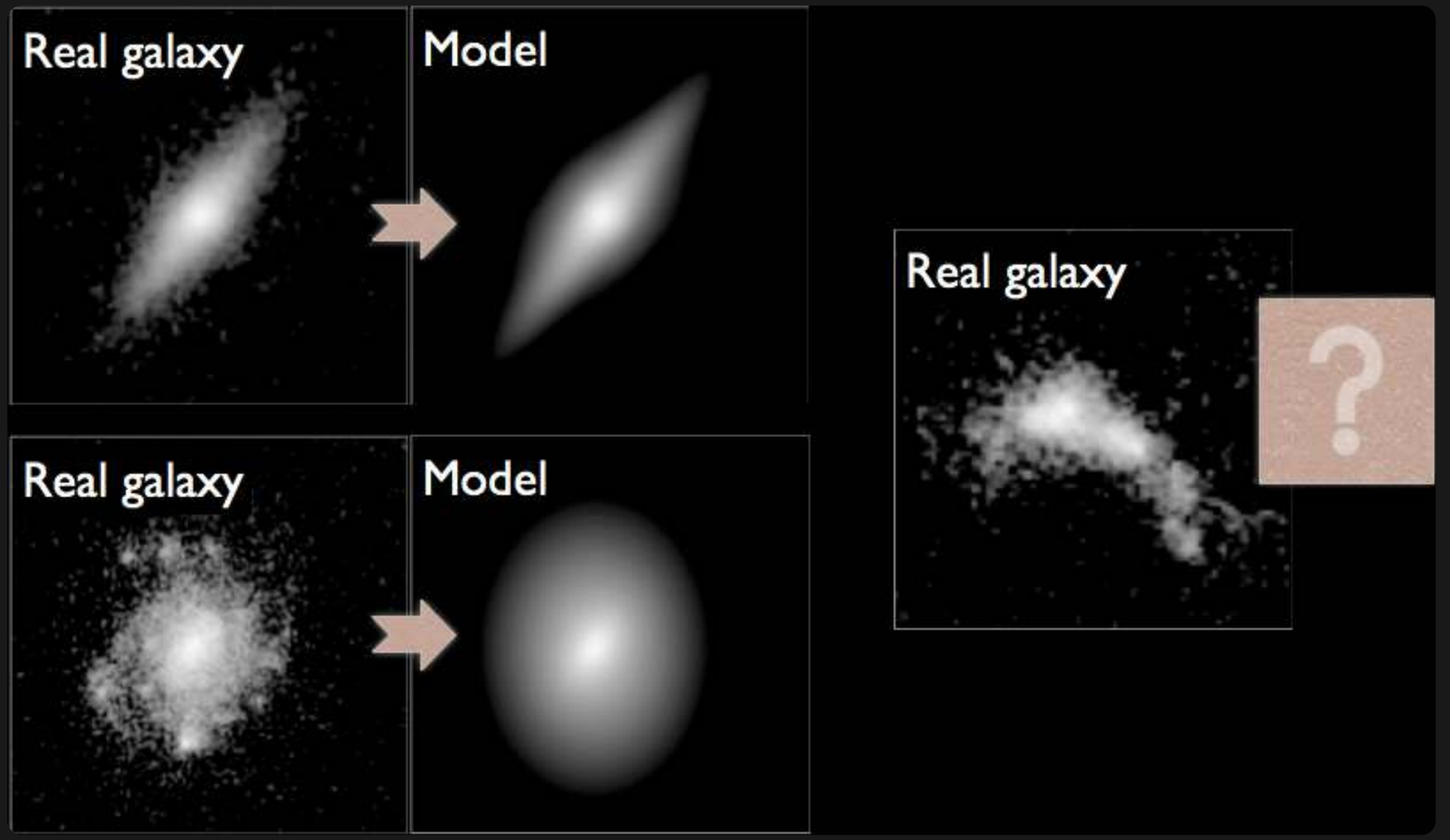
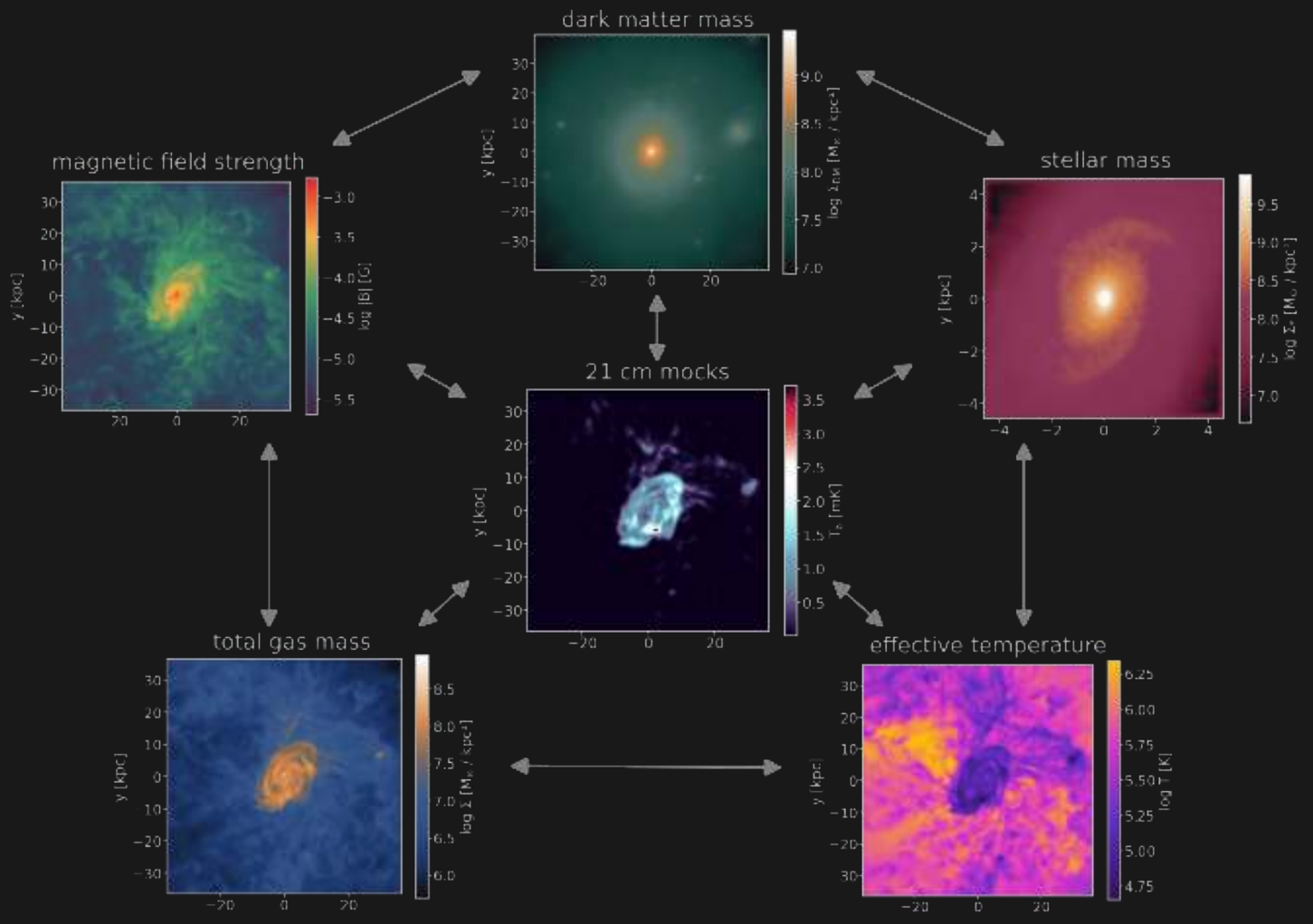


Mandelbaum et al. (2014)

Map-to-map translation



Denzel et al. (2025, in prep.)

GENERATIVE DEEP LEARNING FOR GALAXIES

- Recent work:
  - map-to-map translation of simulated galaxies
- Roadmap to a physical & plausible lens models:
  - ☑ Physical model: map-to-map translation models
  - ☐ Sampling halos: (random/guided) generation
  - ☐ Applications to observations

DEEP GENERATIVE MODELS

- match some data distribution $p(x)$ with a neural network $p_\theta(x)$
- our models are trained on simulated galaxy samples Γ_i
    - caveat: each simulation implements a specific feedback model ϕ
- unconditional generation of galaxies g:
  $g \sim p_\theta(\Gamma|z;\phi) \quad \text{where} \quad z \sim \mathcal{N}(0,1)$
- conditional generation of galaxies g including some information c:
  $g \sim p_\theta(\Gamma|z,c;\phi)$

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  - efficient, fast, good distribution coverage
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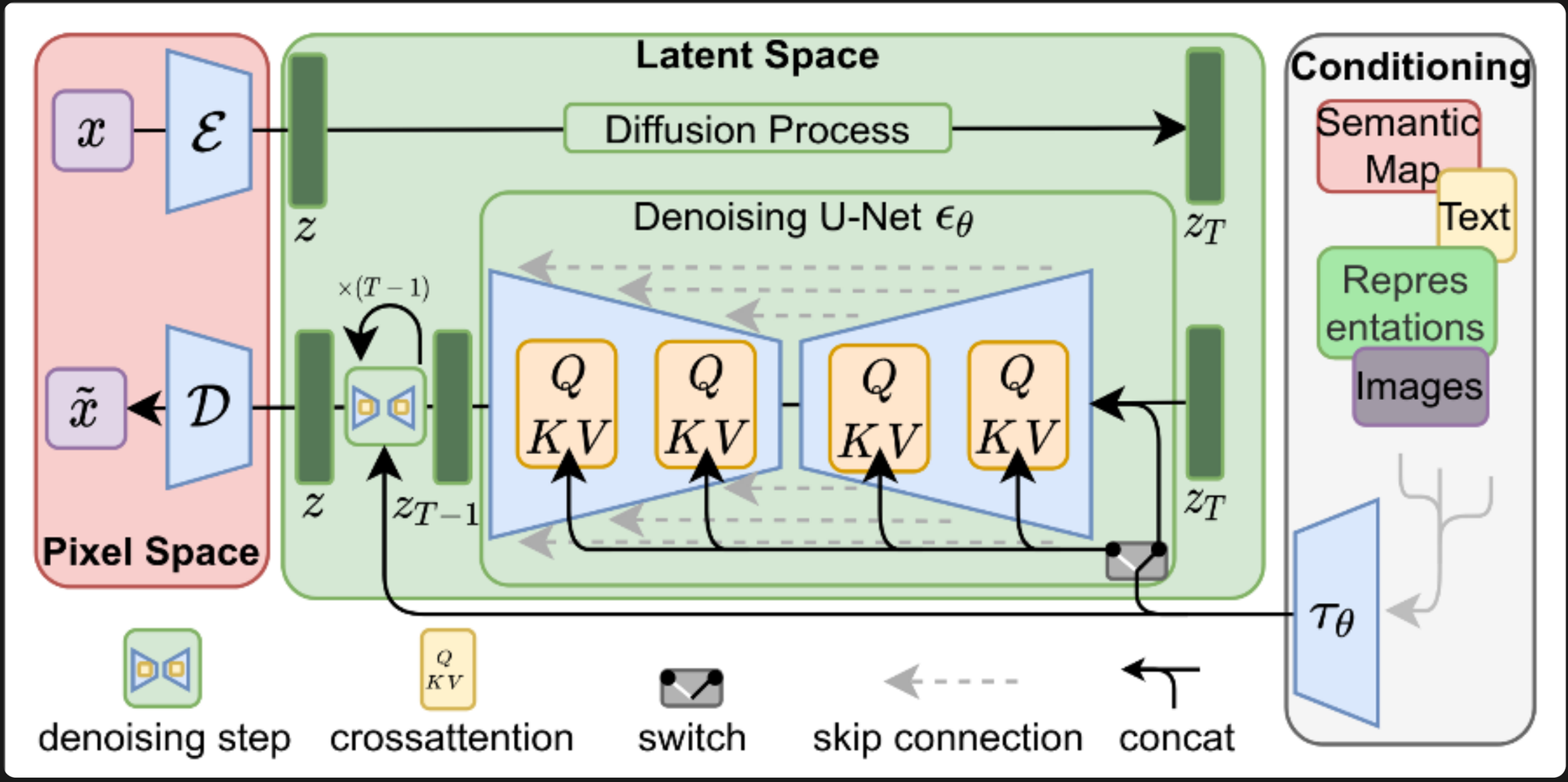
    - Compromise: all of them

LATENT DIFFUSION



Latent diffusion by Rombach et al. (2022)

KEY INGREDIENT

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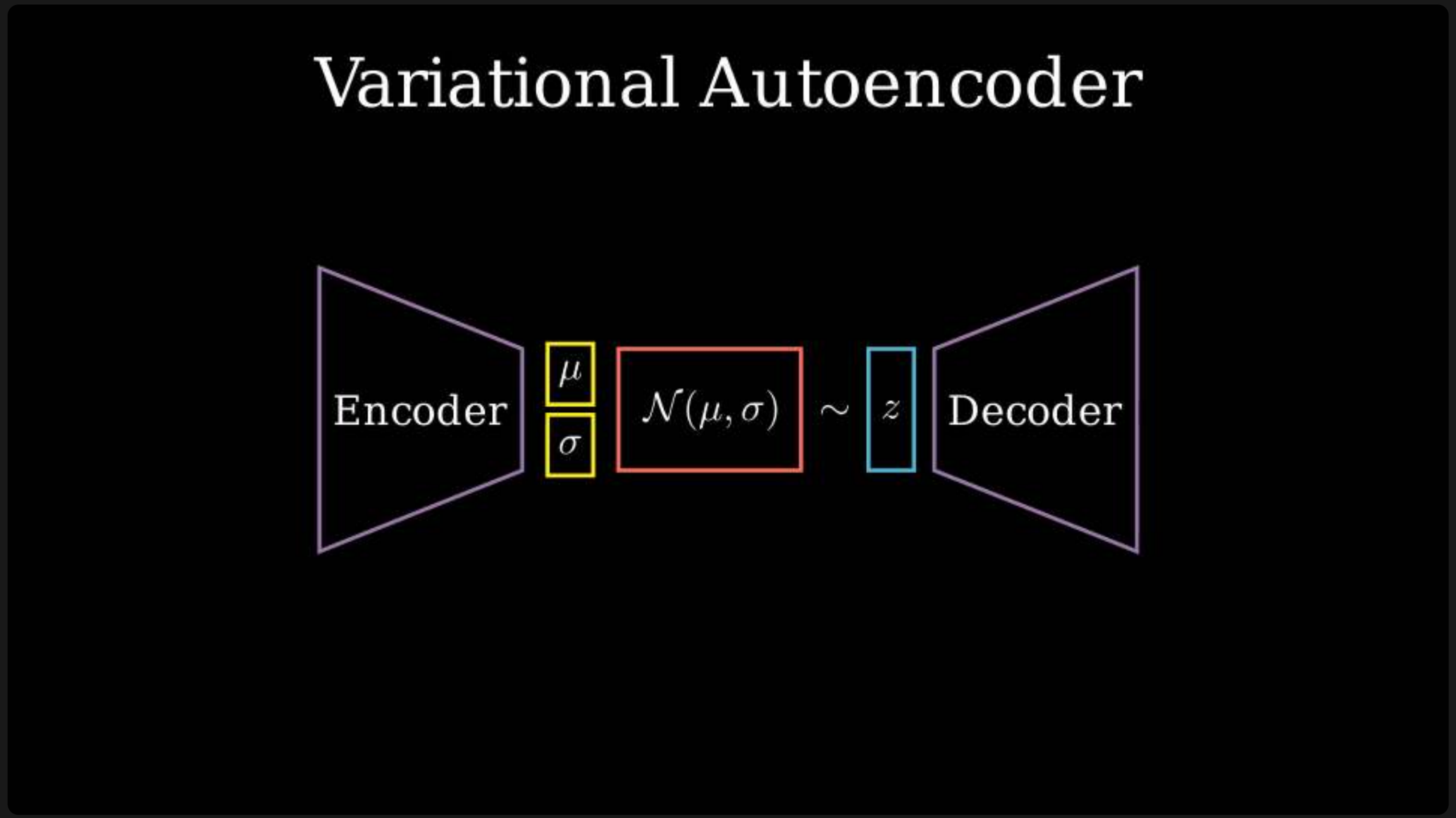
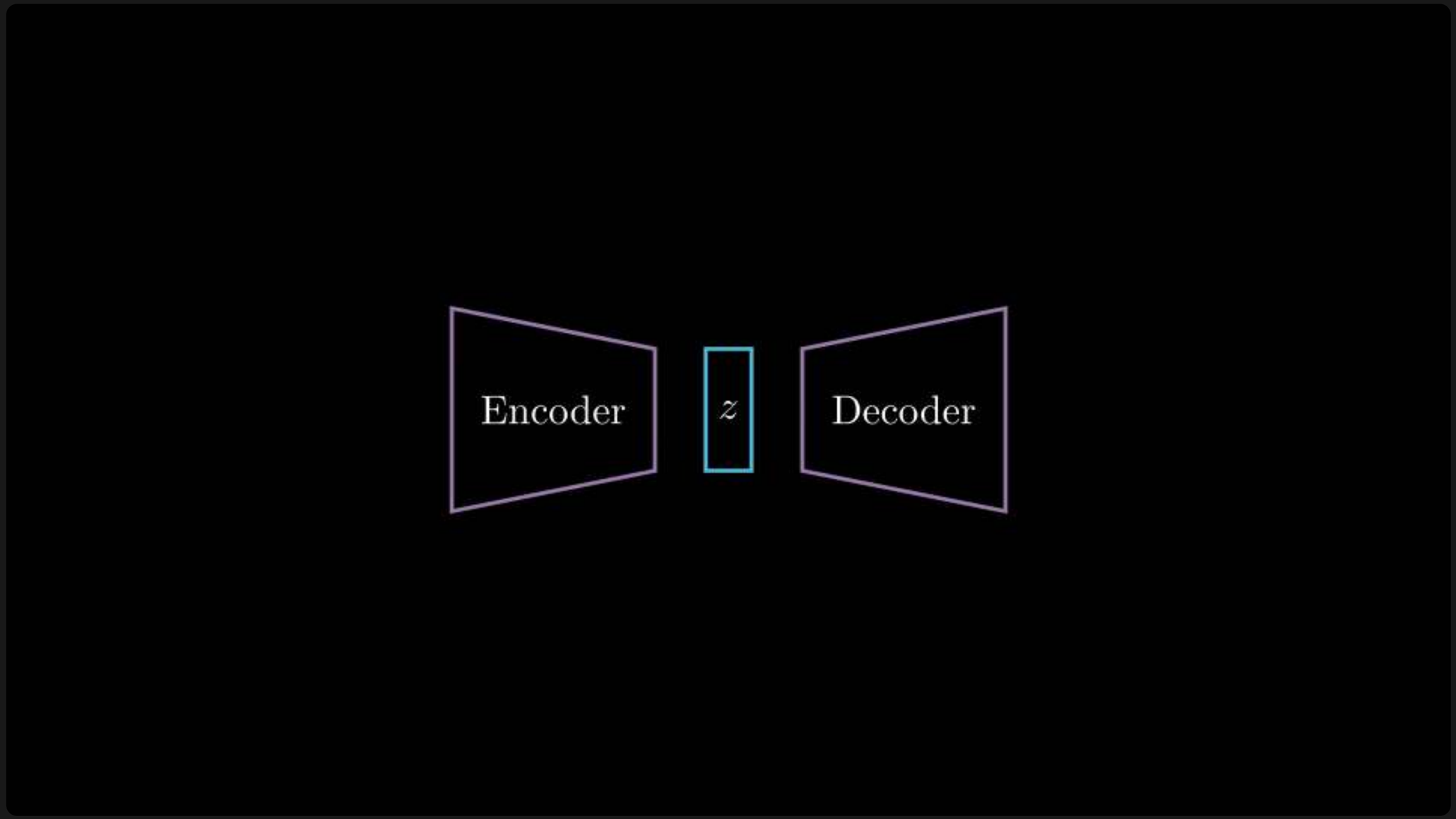


REGULARIZATION OF THE LATENT SPACE



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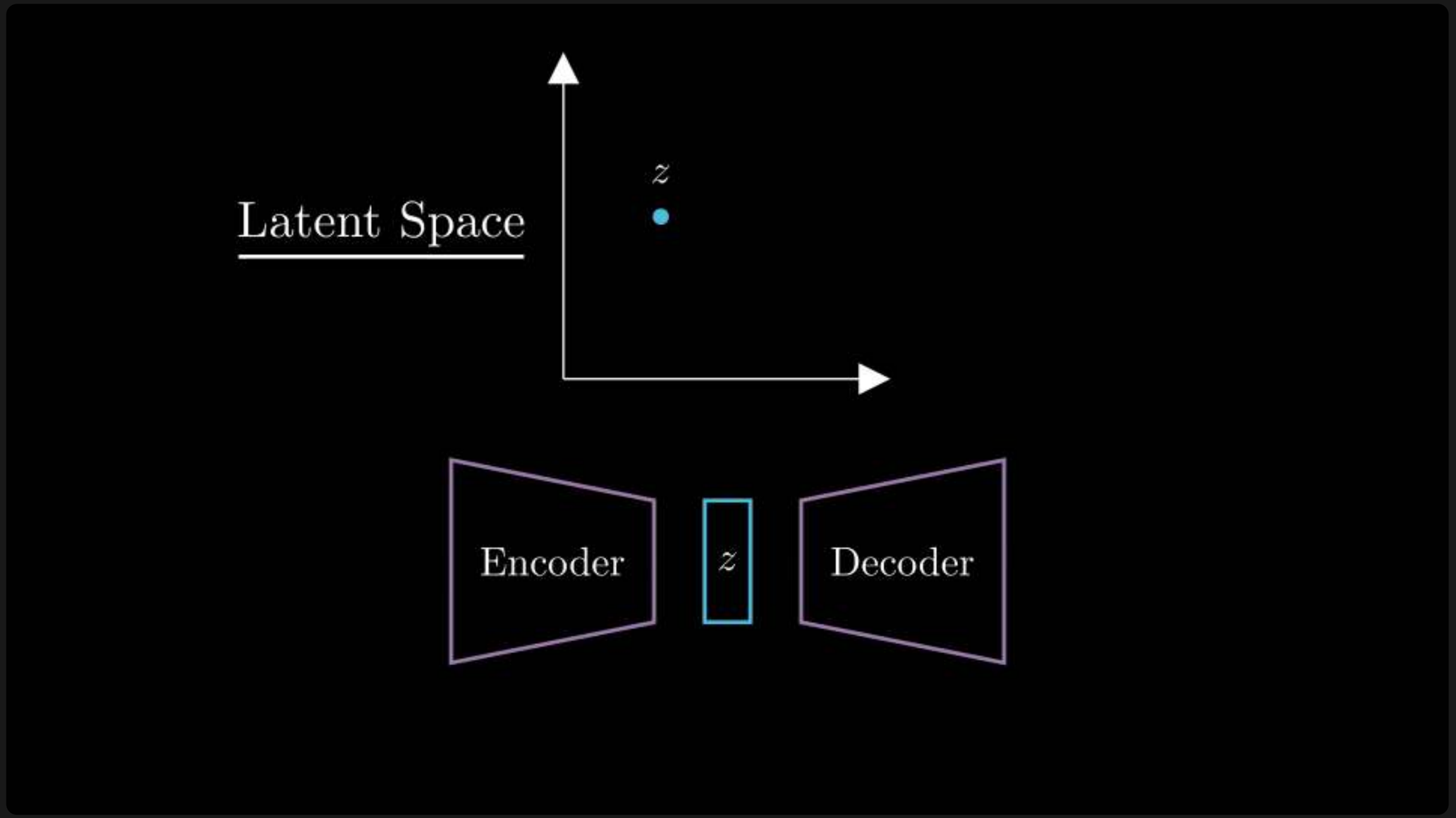
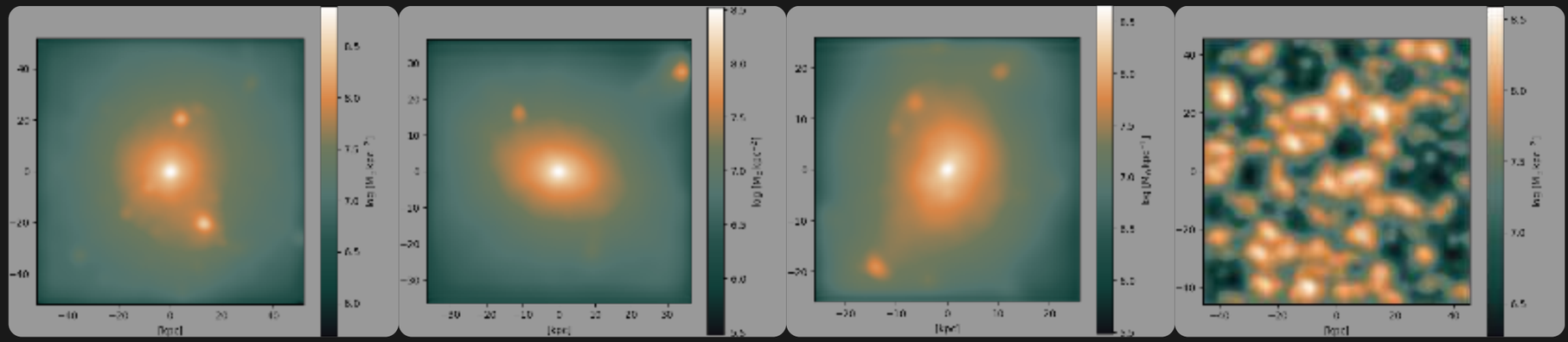


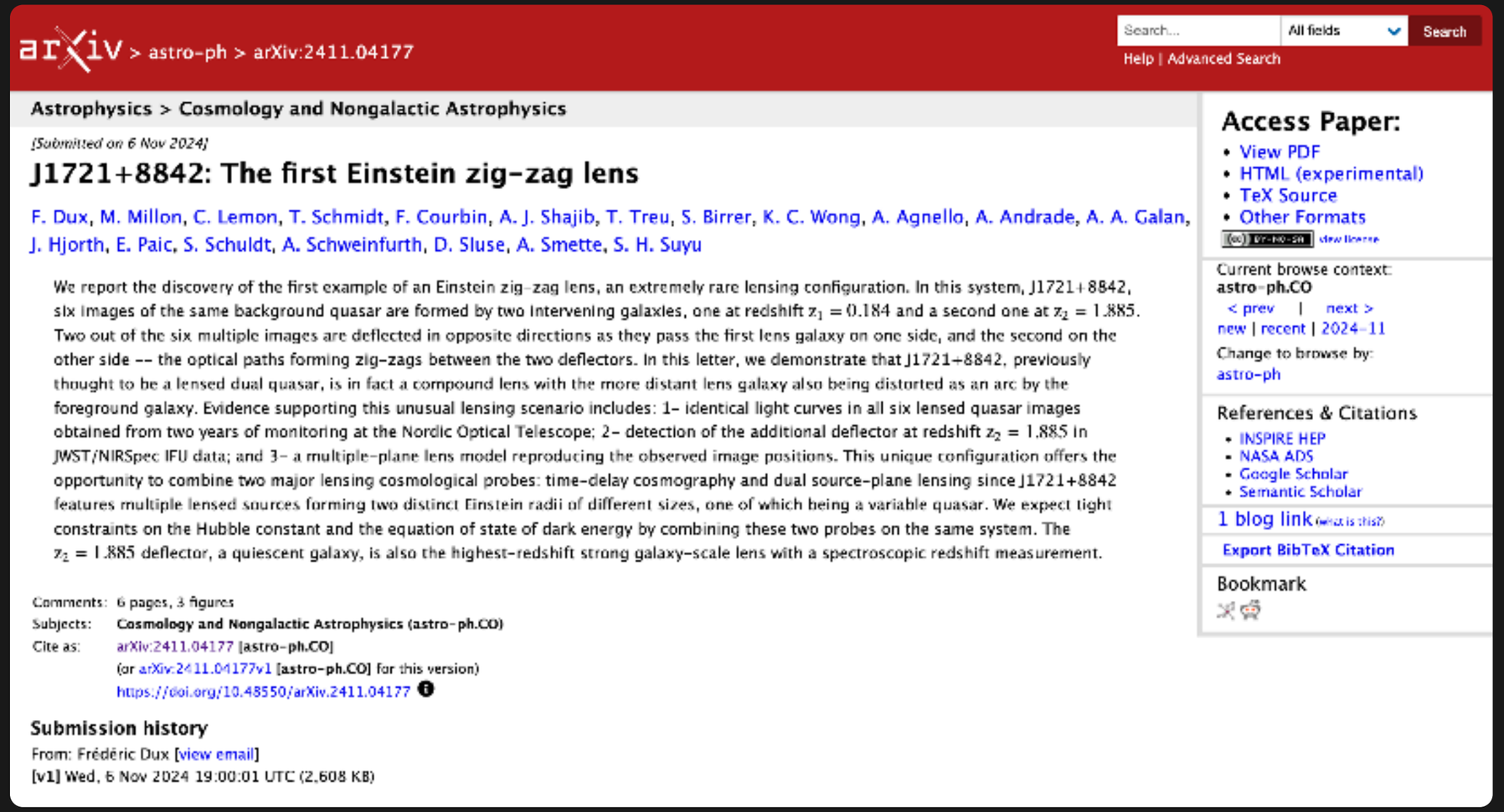
DIFFUSION

CURRENT STATUS

- basic VAE version is trained
    - regularization of latent space is difficult…
- results need fine-tuning, more elaborate objective
  $\mathcal{L}_{\mathrm{VQGAN}} = \mathcal{L}_{\mathrm{L2}} + \mathcal{L}_{\mathrm{KL/VQ}} + \mathcal{L}_{\mathrm{PatchGAN}} + \mathcal{L}_{\mathrm{LPIPS}}$
- some samples from recent VAE trial runs:



APPLICATION: STRONG GRAVITATIONAL LENSING



arXiv > astro-ph > arXiv:2411.04177

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 6 Nov 2024]

J1721+8842: The first Einstein zig-zag lens

F. Dux, M. Millon, C. Lemon, T. Schmidt, F. Courbin, A. J. Shajib, T. Treu, S. Birrer, K. C. Wong, A. Agnello, A. Andrade, A. A. Galan, J. Hjorth, E. Paic, S. Schuldt, A. Schweinfurth, D. Sluse, A. Smette, S. H. Suyu

We report the discovery of the first example of an Einstein zig-zag lens, an extremely rare lensing configuration. In this system, J1721+8842, six images of the same background quasar are formed by two intervening galaxies, one at redshift $z_1 = 0.184$ and a second one at $z_2 = 1.885$. Two out of the six multiple images are deflected in opposite directions as they pass the first lens galaxy on one side, and the second on the other side -- the optical paths forming zig-zags between the two deflectors. In this letter, we demonstrate that J1721+8842, previously thought to be a lensed dual quasar, is in fact a compound lens with the more distant lens galaxy also being distorted as an arc by the foreground galaxy. Evidence supporting this unusual lensing scenario includes: 1- identical light curves in all six lensed quasar images obtained from two years of monitoring at the Nordic Optical Telescope; 2- detection of the additional deflector at redshift $z_2 = 1.885$ in JWST/NIRSpec IFU data; and 3- a multiple-plane lens model reproducing the observed image positions. This unique configuration offers the opportunity to combine two major lensing cosmological probes: time-delay cosmography and dual source-plane lensing since J1721+8842 features multiple lensed sources forming two distinct Einstein radii of different sizes, one of which being a variable quasar. We expect tight constraints on the Hubble constant and the equation of state of dark energy by combining these two probes on the same system. The $z_2 = 1.885$ deflector, a quiescent galaxy, is also the highest-redshift strong galaxy-scale lens with a spectroscopic redshift measurement.

Comments: 6 pages, 3 figures
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
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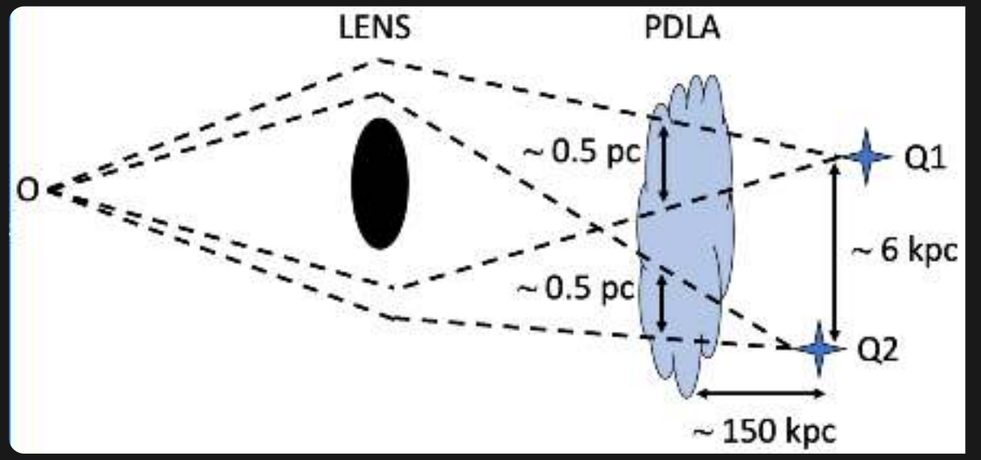
J1721+8842: The first Einstein zig-zag lens

A lens with an interesting history

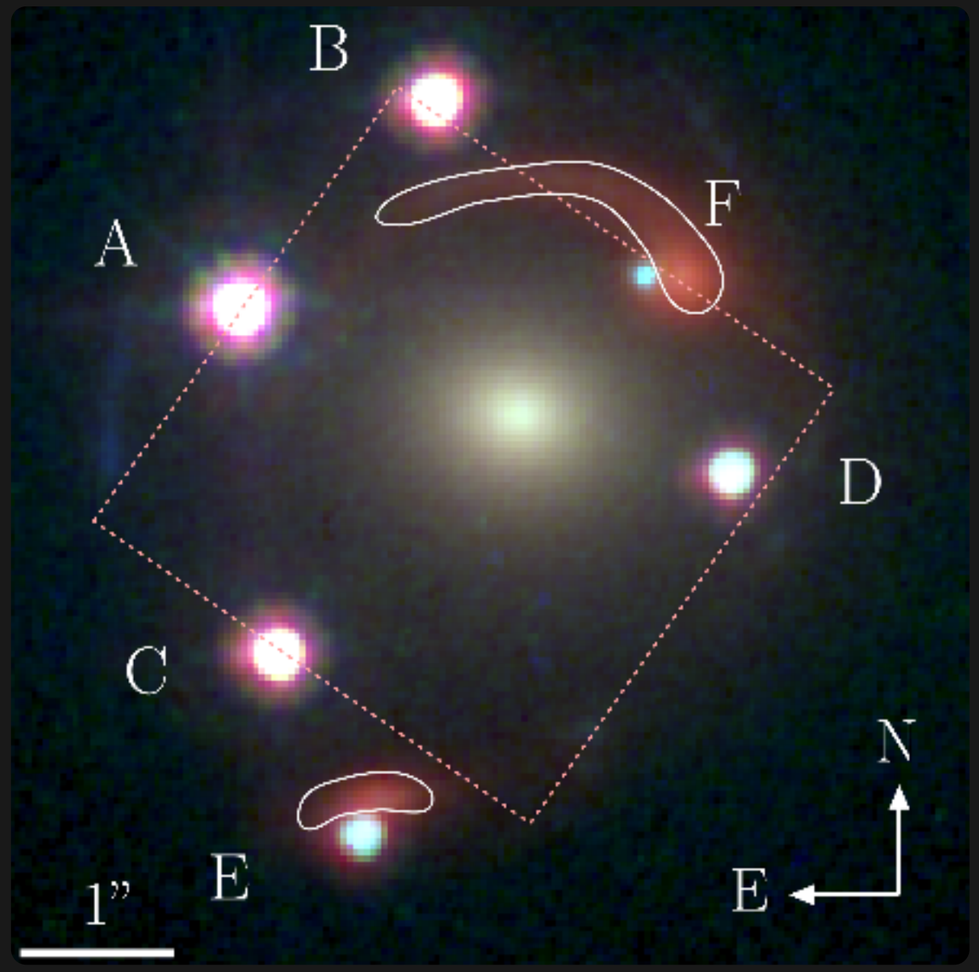
- The "polar" quad (time delays without seasonal gaps)
- First discovered in Gaia D2: Lemon et al. (2018)
    - as a quadruply imaged quasar
- Confirmed PDLA by Lemon et al. (2022)
    - Proximate Damped Lyman-α Absorber quasar

Lemon+ (2018)



Lemon+ (2022)

Zig-zag lens



Dux et al. (2024)

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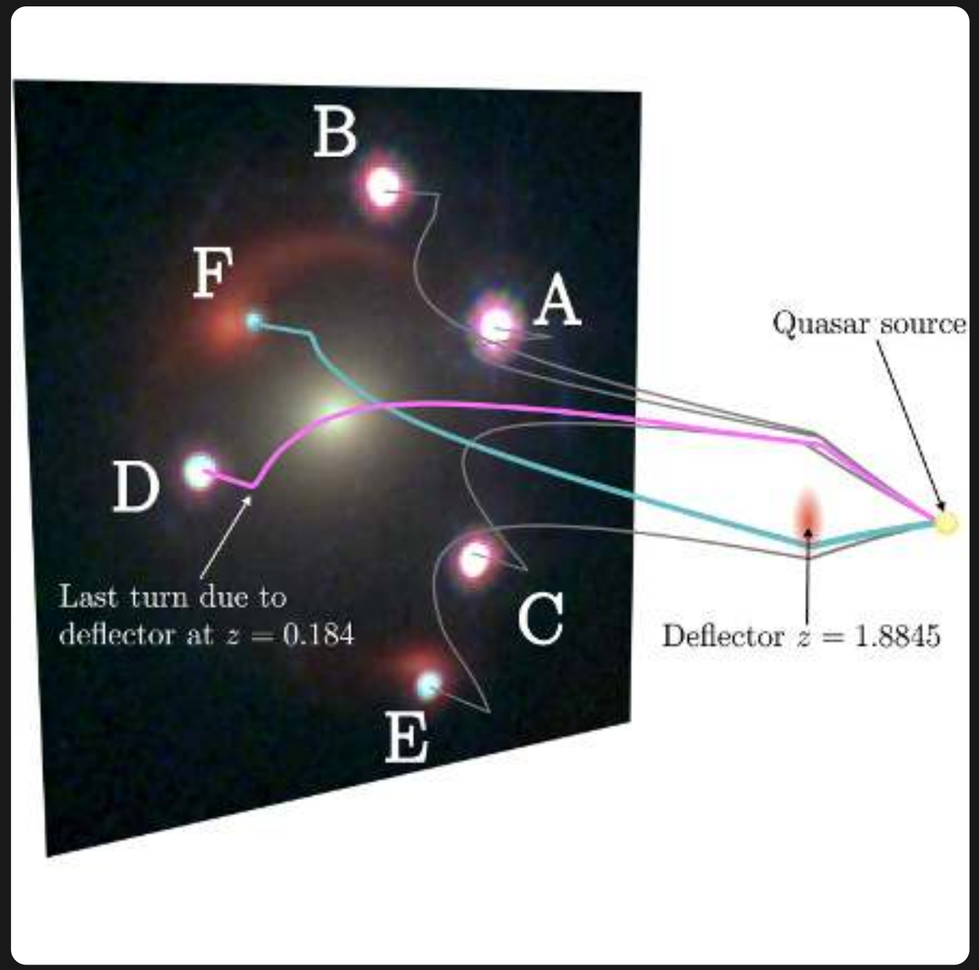
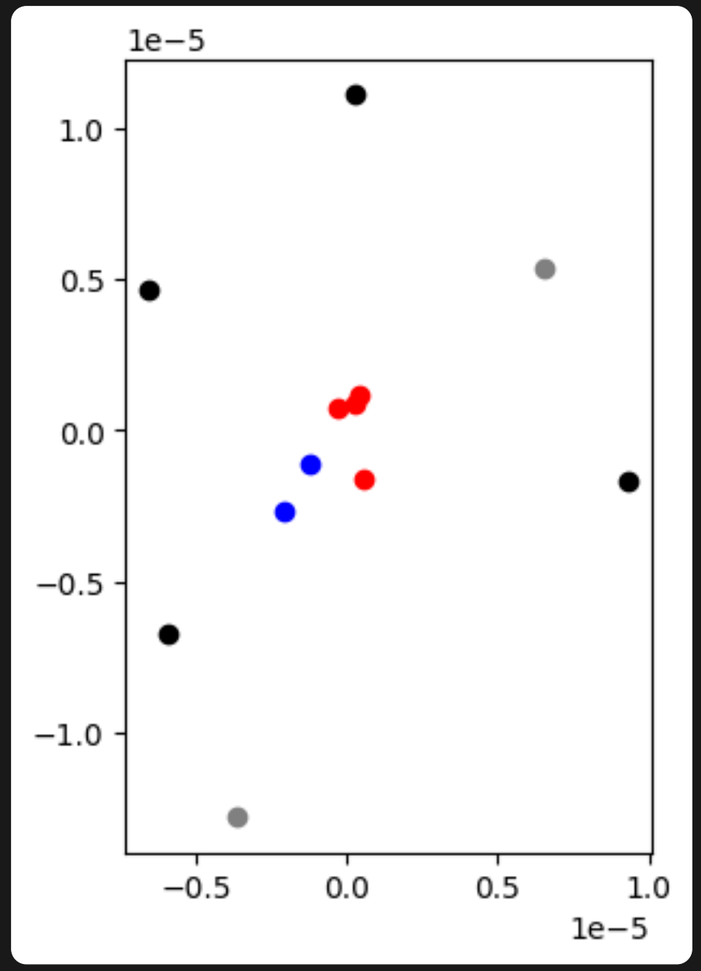


Dux et al. (2024)

Zig-zag lens model

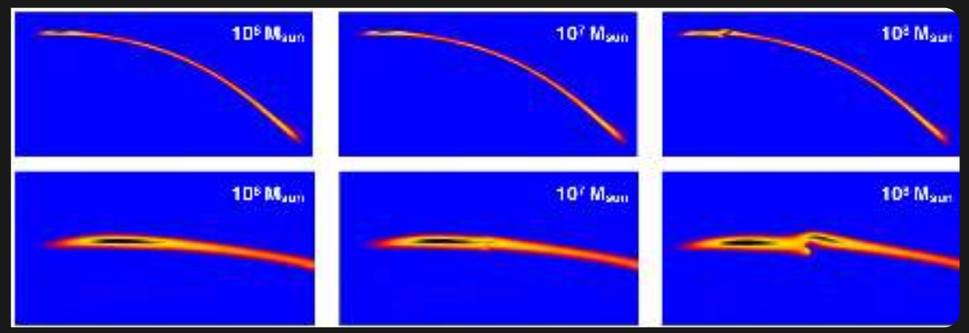
- Brute-force trial matching
  - feasible due to lensing degeneracies
  - as demonstrated by Morningstar et al. (2019)
- Raytracing and lens matching by UZH group

$$
\begin{aligned}
x_1 &= D_{01}\,\theta \\
x_2 &= D_{02}\,\theta - D_{12}\,\hat{\alpha}(x_1) \\
x_3 &= D_{03}\,\theta - D_{13}\,\hat{\alpha}(x_1) - D_{23}\,\hat{\alpha}(x_2)
\end{aligned}
$$

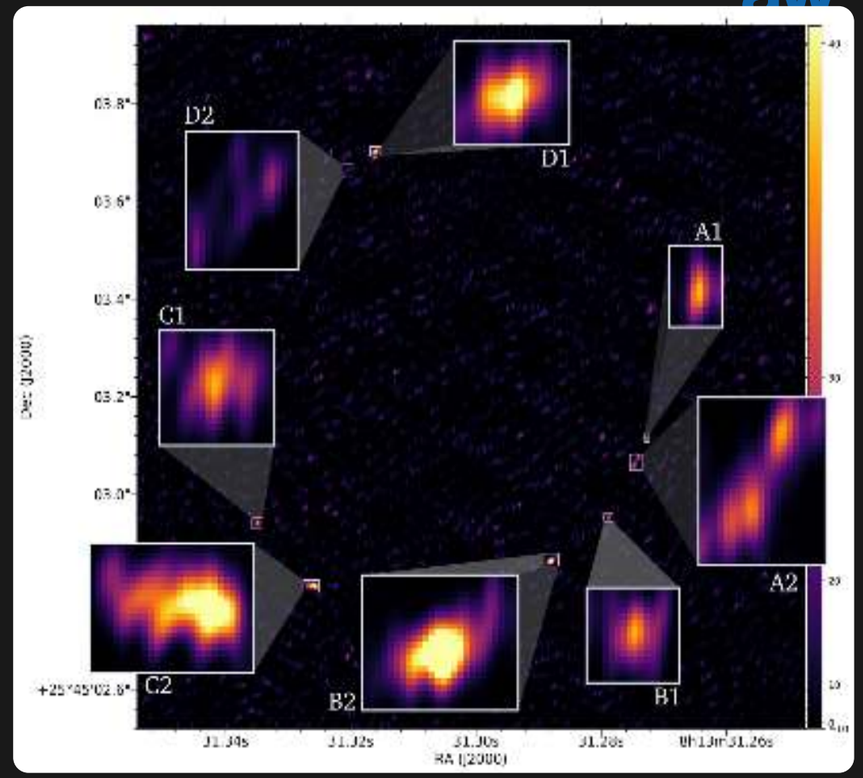


SUMMARY: IMPORTANCE FOR SKA?

- Good preparation for what's to come…
- VLBI & SKA-MID: Band 2/5/6
  - extended AGN jets on sub-parsec scales
  - CO (1–0) maps (Band 6 ~ ALMA scales)
  - sub mJy/beam arcs (≈ 5 mas) → nature of dark matter



McKean et al. (2015)



Hartley et al. (2019)