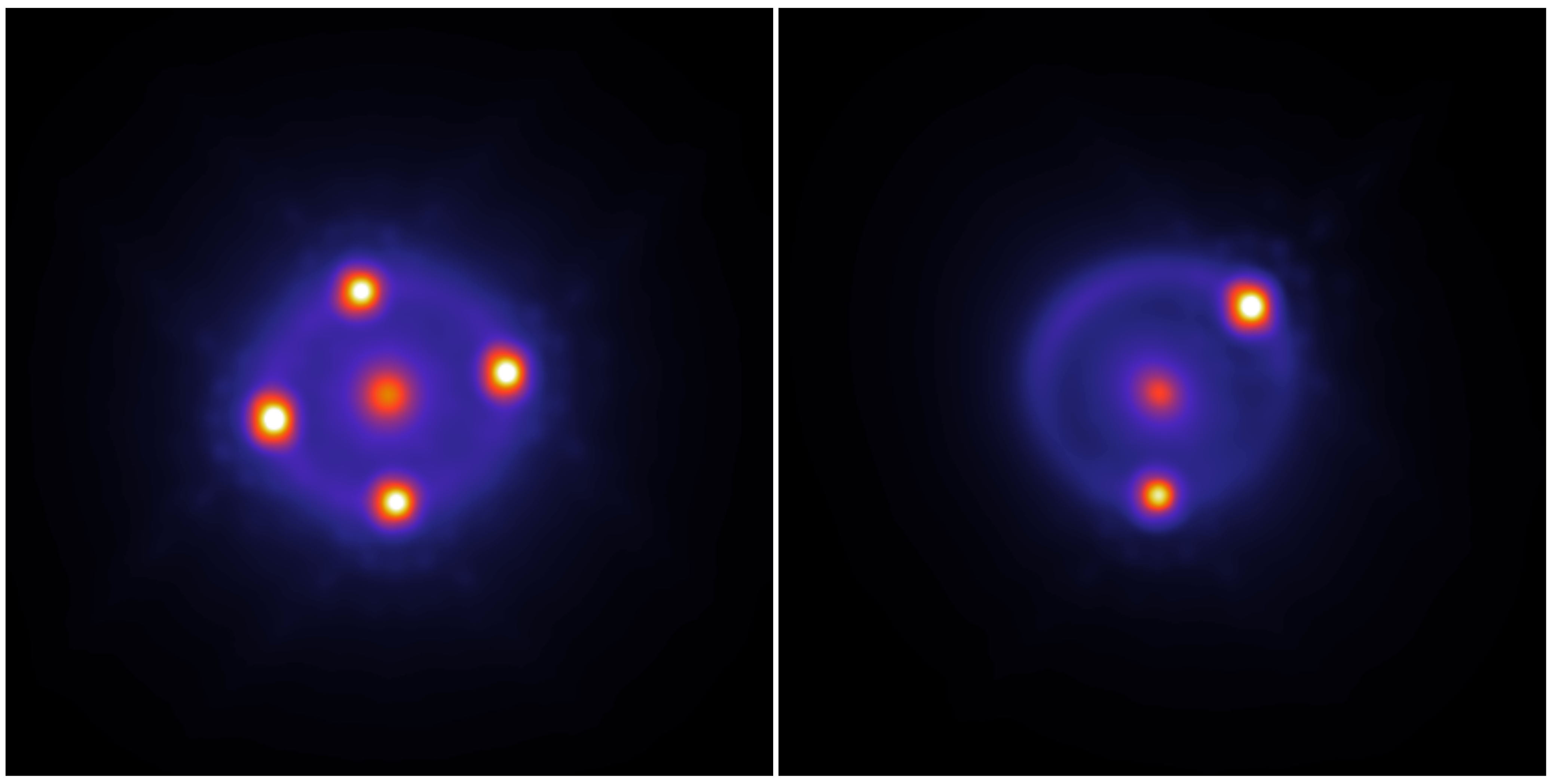
# Pictures of Dark Matter through Gravitational Lenses

**Philipp Denzel, Prasenjit Saha**

in collaboration with Jonathan Coles, Liliya Williams

Universität Zürich[UZH]

Galaxies have been observed in great numbers and variety. The detected light from galaxies is almost exclusively related to their mass in stars, but their gravitational fields are dominated by some exotic non-baryonic matter. This was first noticed in 1933 by the Swiss astronomer and physicist Fritz Zwicky who called it simply ‘Dunkle Materie’ or ‘**Dark Matter**’.



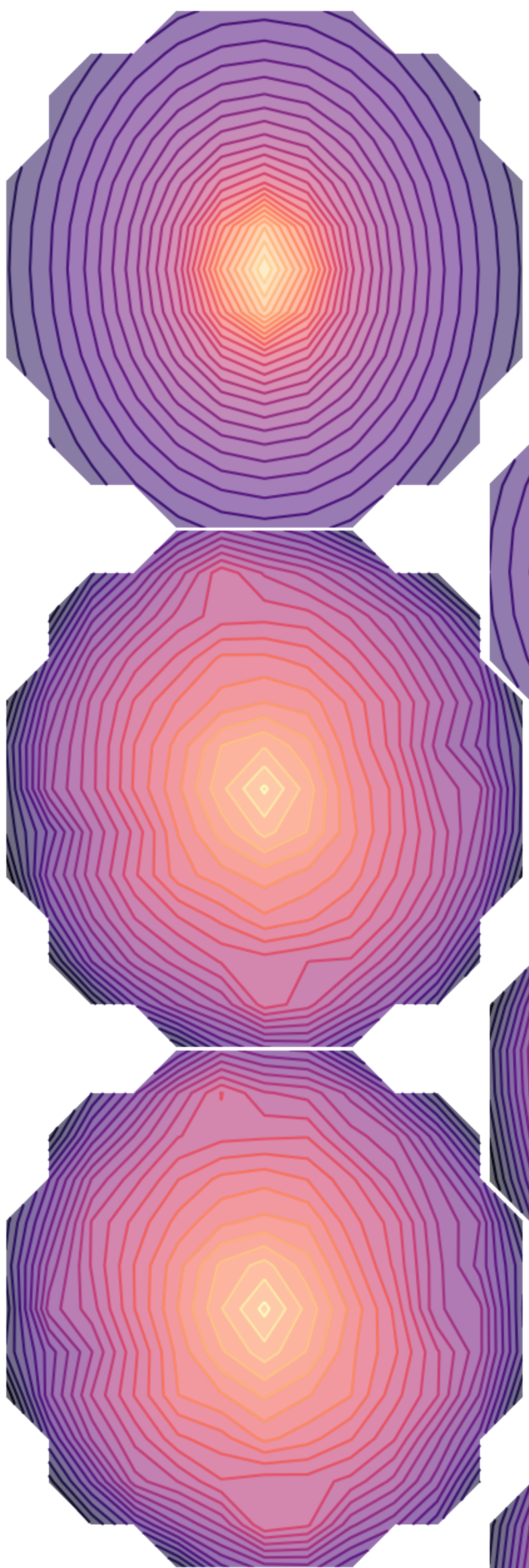
We can use **gravitational lensing** to measure the total mass content of a galaxy, that is the baryonic as well as the dark matter. So far this is the most direct way measure dark matter.
Why is it called gravitational lensing? A lens is basically a glass sheet of varying thickness which deflects light by an amount proportional to the local thickness. In gravitational lensing the same effect is produced by a gravitational field. If β is the “true” position of the source and θ describes the position of an image produced by the deflection through a mass distribution, these are related by

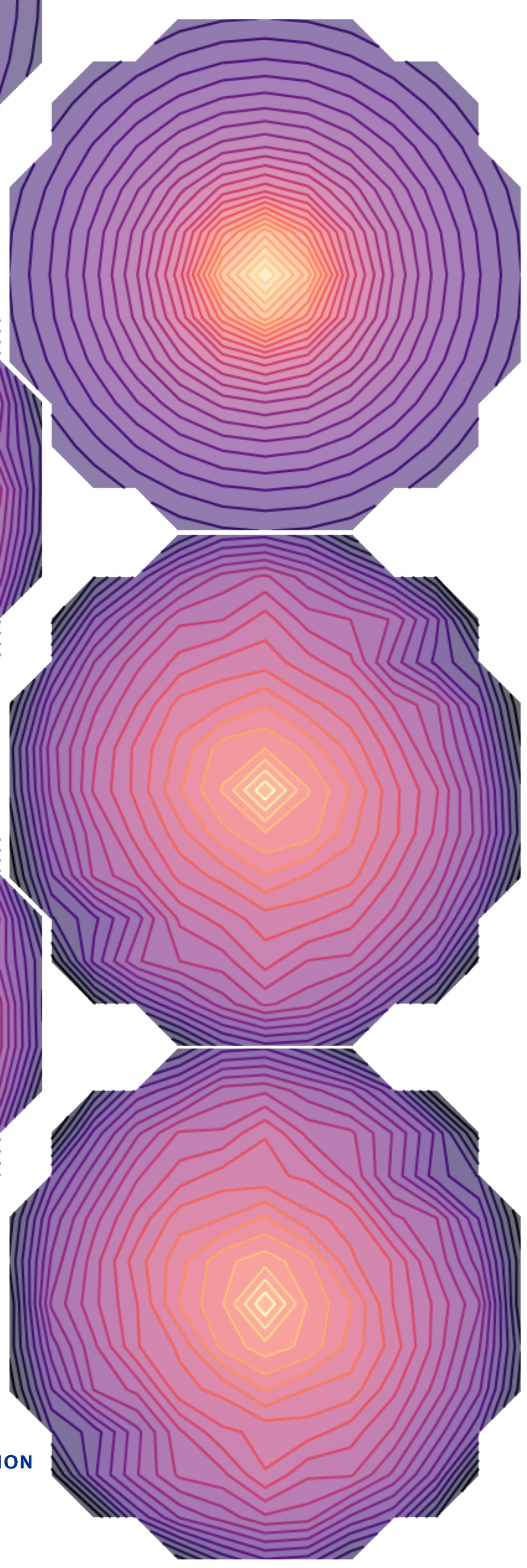
$$\vec{\beta} = \vec{\theta} - 2\vec{\nabla}(\nabla^{-2}\kappa(\vec{\theta}))$$

where κ is the mass distribution. This relatively simple **mapping** also allows us to simulate such lensing effects using analytical mass profiles producing multiple source images. Two examples of such simulations are depicted on the left.
arXiv:1801.01506

As opposed to simulating, **lens modelling** means solving the lens equation for a particular configuration of multiply imaged sources and extracting the lens’s unknown mass distribution.
However, there is a problem intrinsic to every gravitational lens: many different mass maps can produce the same image. This issue is known as degeneracy. So, how can we find the true mass distribution?
Our lens modelling tool GLASS (Coles et al. 2014) marginalises over these degeneracies by exploring the solution space with a Monte-Carlo sampling approach and constructs many different mass maps which result in the same configuration of source images. We end up with a model which contains an ensemble of mass maps all producing the same images. Still, individual mass maps of the ensemble might be unrealistic, or produce additional images. These models have to be filtered out.

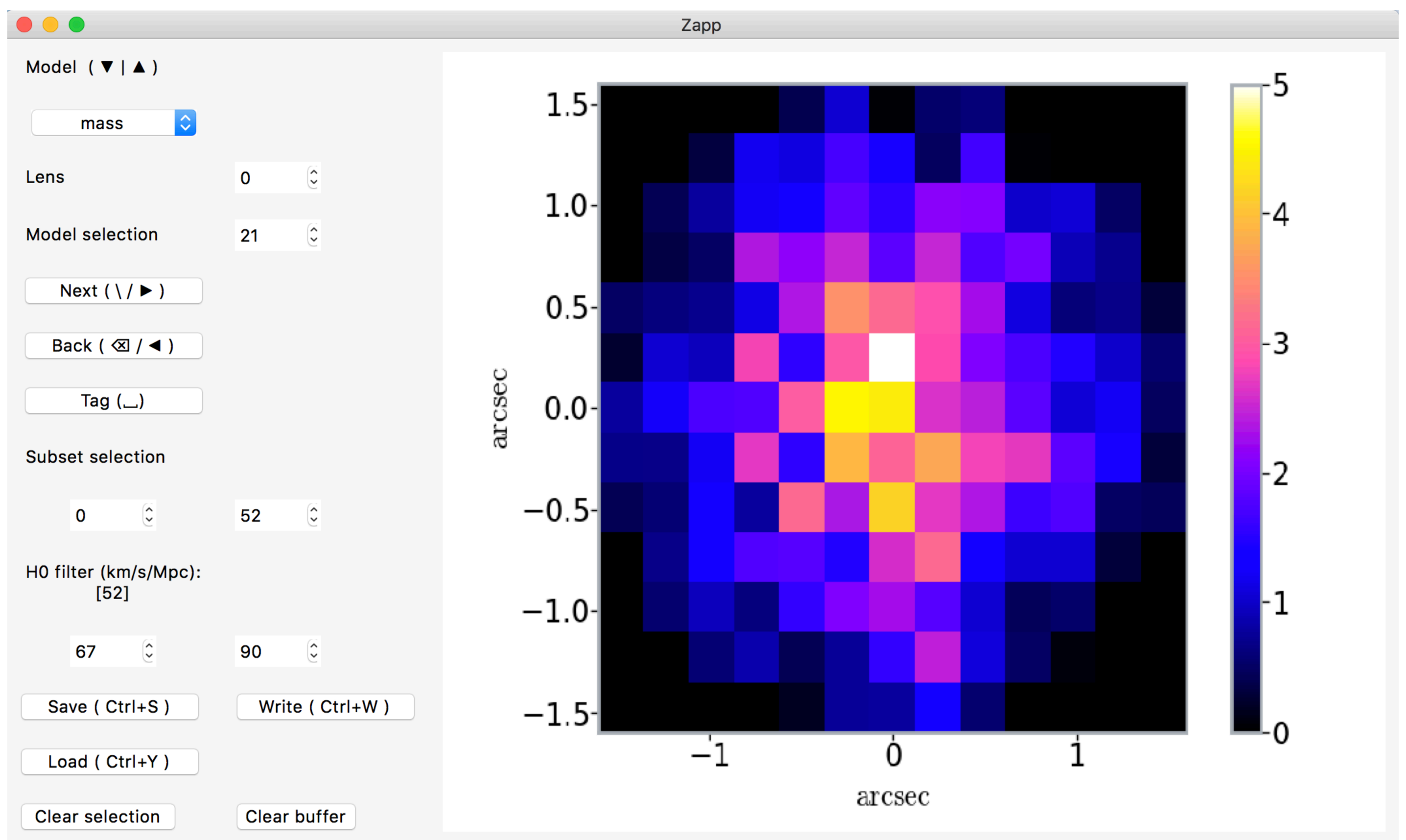
Only recently, we have developed a simple, supplementary, graphical post-processing tool called **ModelZapper** which does exactly that. It visualises several properties of the model and provides easy navigation through the entire ensemble of solutions. Valid and promising models can be tagged and saved into a new, filtered ensemble.

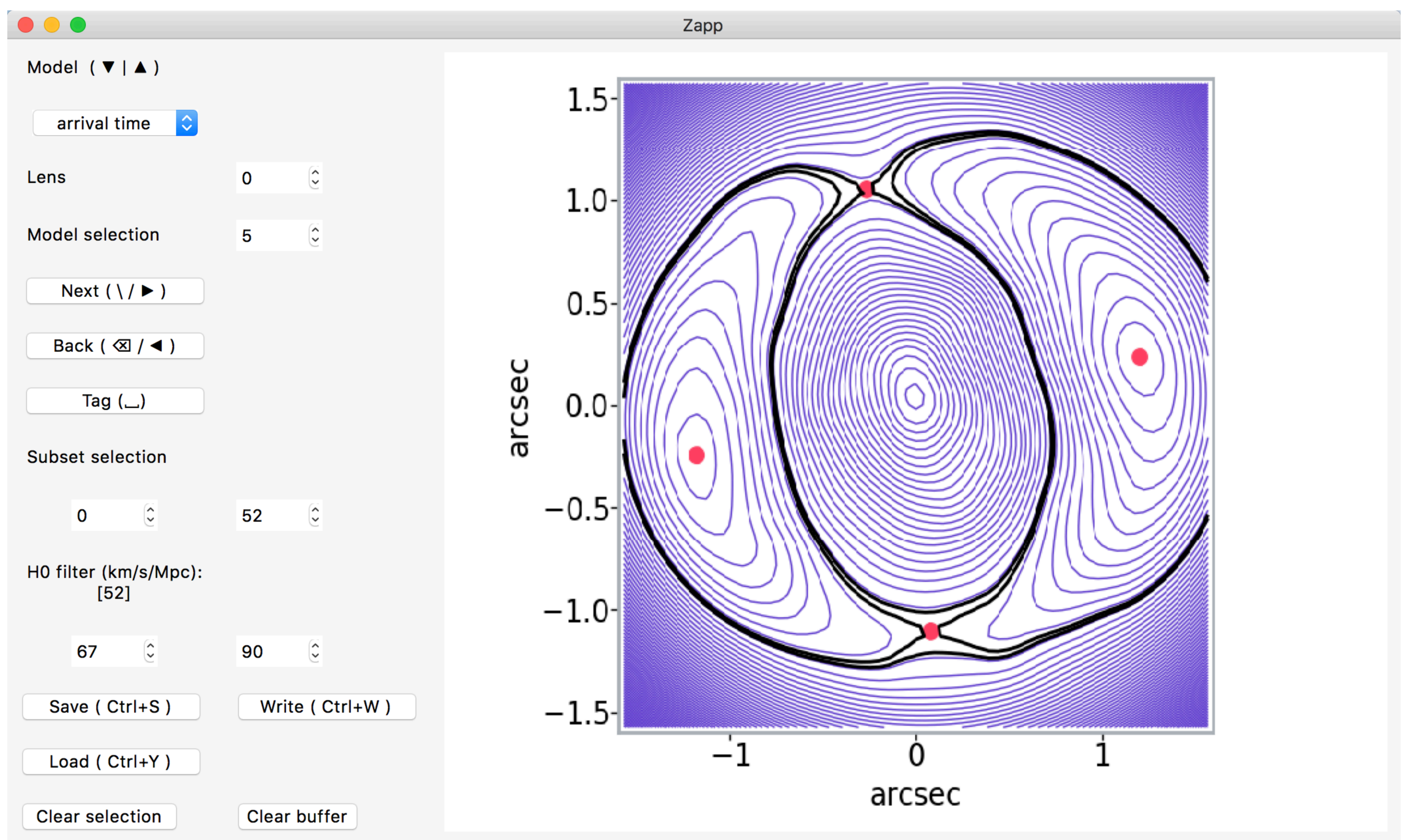




On the right, two example screenshots of the app show the pixellated mass map, and the so-called arrival time surface, a measure of the delay which a light ray would experience due to the lensing effect.
The ensemble average of this filtered model state will describe the true mass map much better than the strategically randomly sampled one produced by GLASS.

## ModelZapper




On the left (from top to bottom), (i) the analytical profiles used in the simulations of the lenses on top, the unfiltered, ensemble-averaged model, and the - with ModelZapper - filtered model are illustrated.
The lens models show differences most in the center and outskirts of the lens galaxy due to lack of information in this area. At the radius where the images are observed, the mass profile and overall shape seem to match very well.
At present, only some hundreds of lensing galaxies are known, and this technique could be applied possibly with the help of citizen science.
Over the next ten years, tens of thousands more are expected to be discovered. This would require a new strategy. Maybe machine learning?

FNSNF Swiss National Science Foundation

Email: phdenzel@physik.uzh.ch

https://github.com/phdenzel/model-zapper