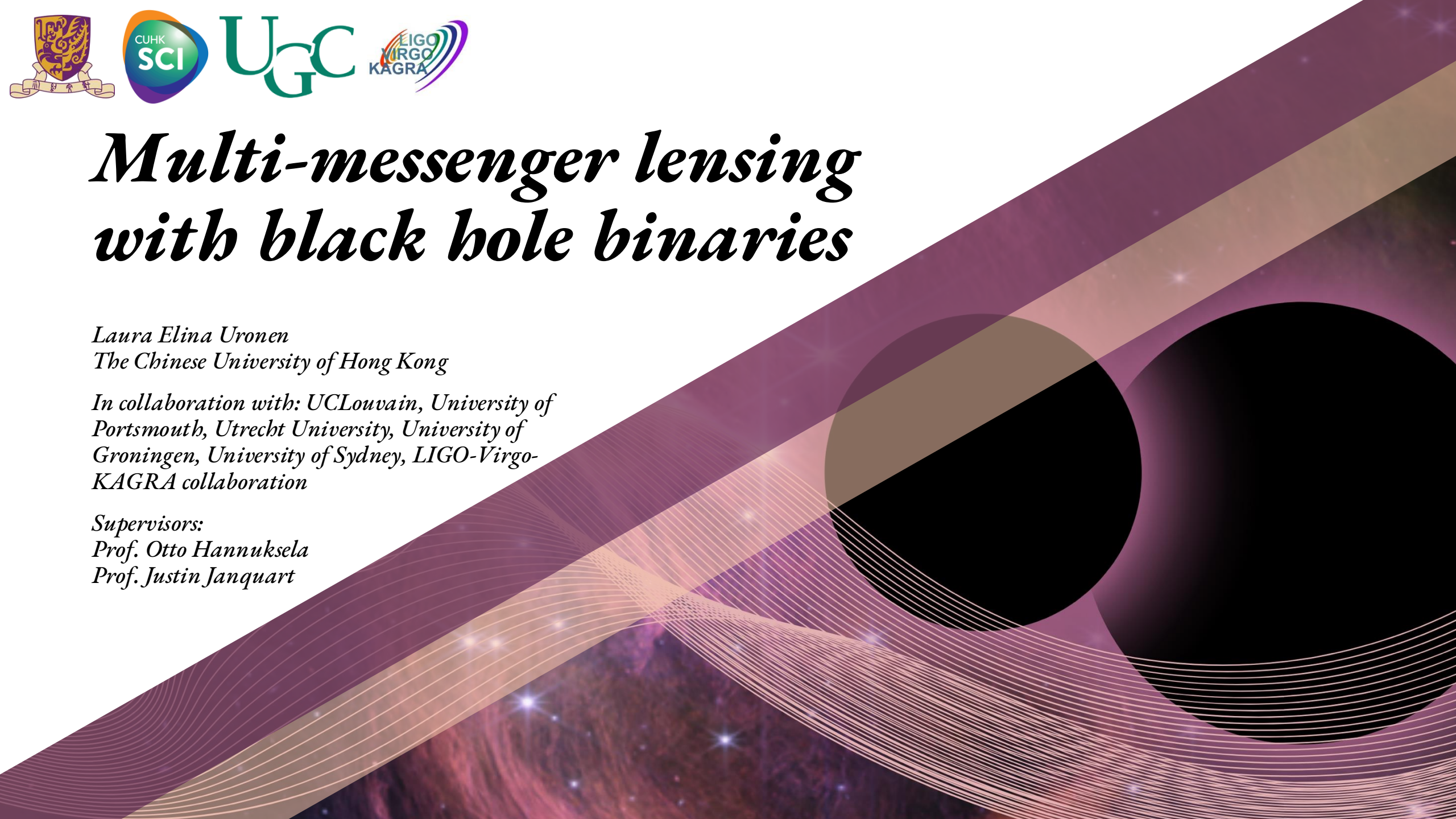
Multi-messenger lensing with black hole binaries

Laura Elina Uronen
The Chinese University of Hong Kong

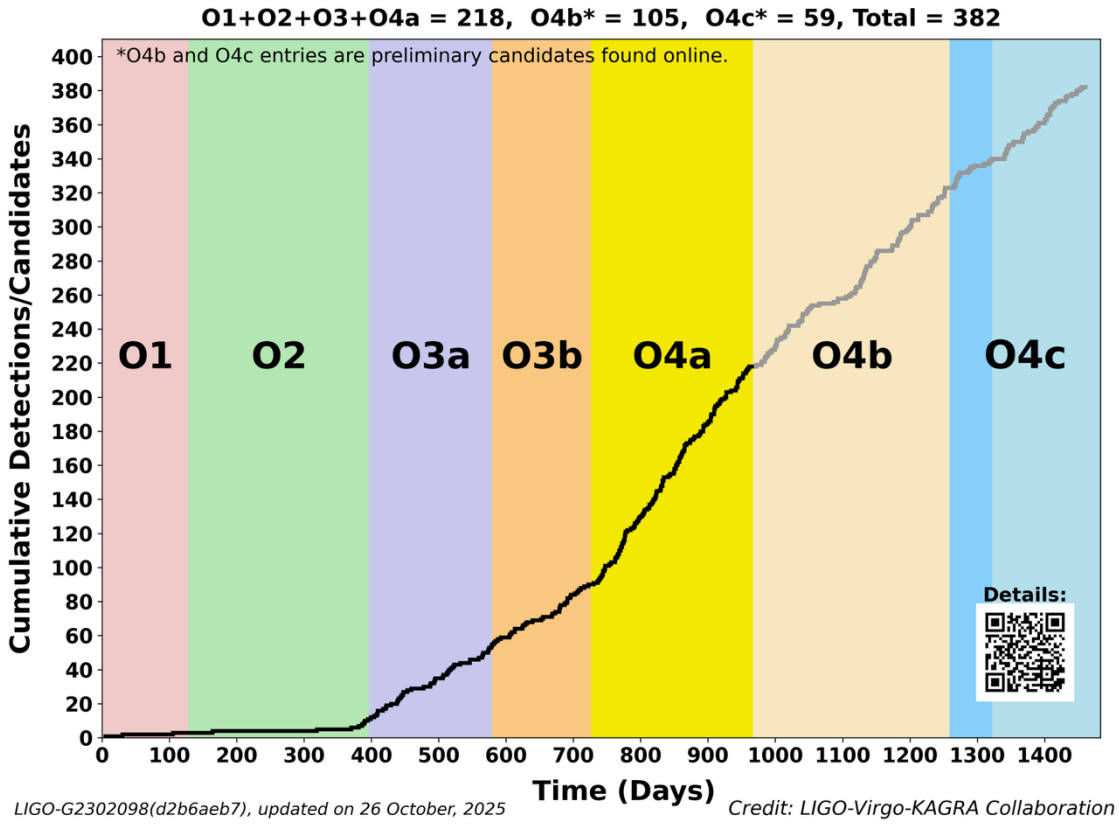
In collaboration with: UCLouvain, University of Portsmouth, Utrecht University, University of Groningen, University of Sydney, LIGO-Virgo-KAGRA collaboration

Supervisors:
Prof. Otto Hannuksela
Prof. Justin Janquart



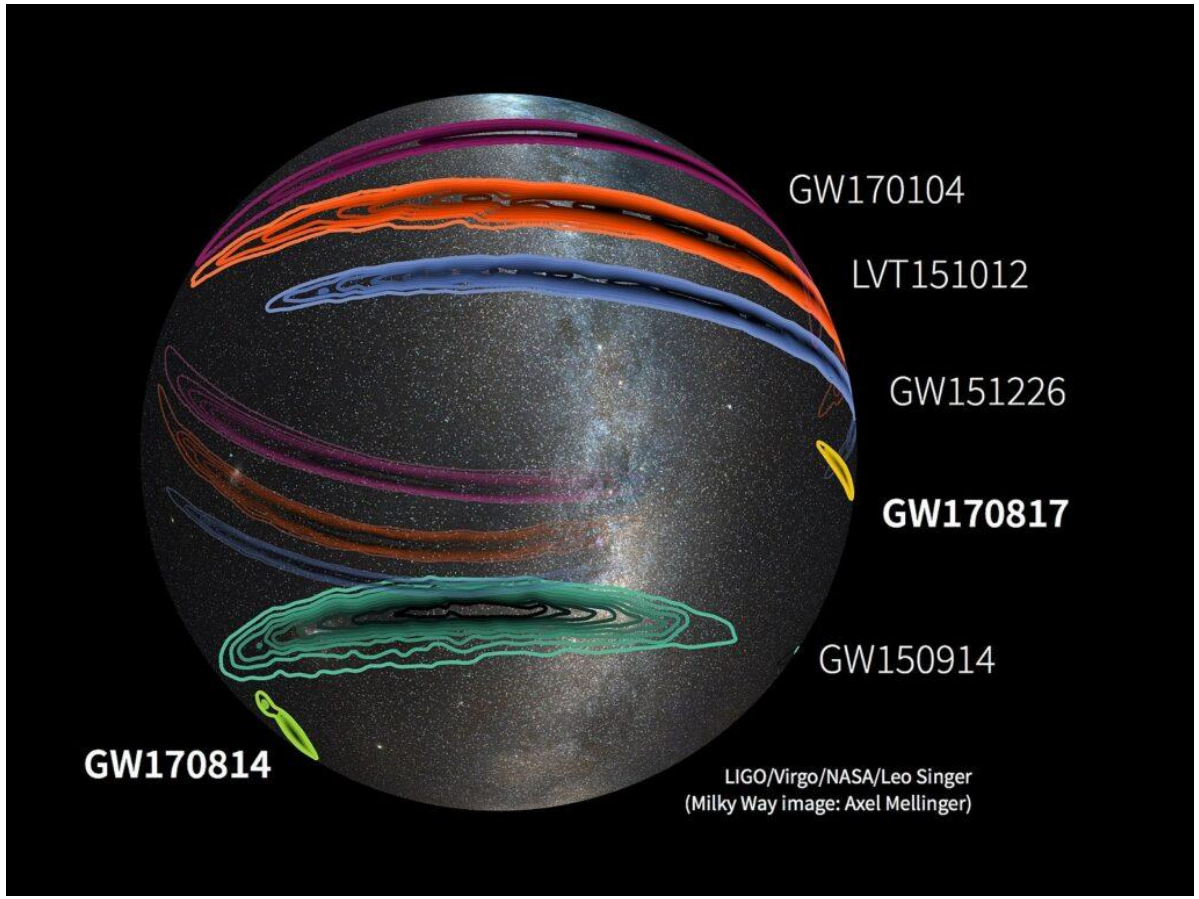
GR

- GWs and lensing both predicted by GR
- EM lensing a staple of astronomy and astrophysics for decades: applications in wide variety of fields
- GWs first observed in 2015: post-O4a cumulative number at > 200 confirmed GW events
- Can we connect these two pillars of GR?
- Search for GW lensing
  → rates estimate first detection within ~10 years
- First multi-messenger GW detection in 2017
  → multi-messenger lensing?



Localisation problem

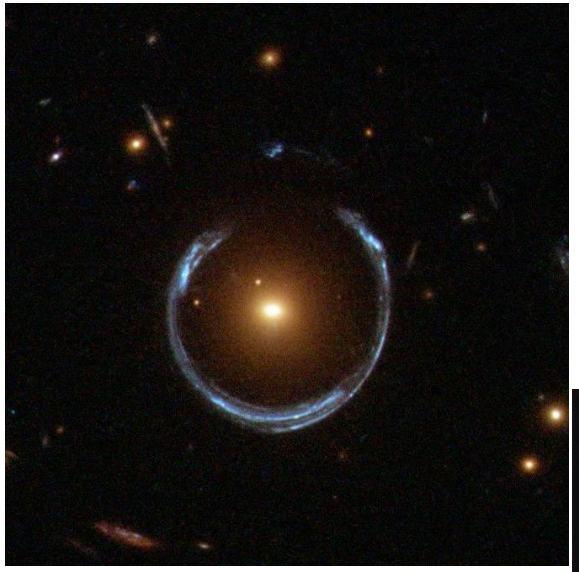
- Most GWs are BBHs, no optical counterpart
- Localisation relies entirely on GW detector triangulation
- Usually 2-3 detectors online: poor sky localisations ~ O(10-1000) sq. deg.
- Impossible to connect GW to a single galaxy host
- GW lensing may offer a solution to connect GW to host galaxy



LIGO/Virgo/NASA/Singer, 2017

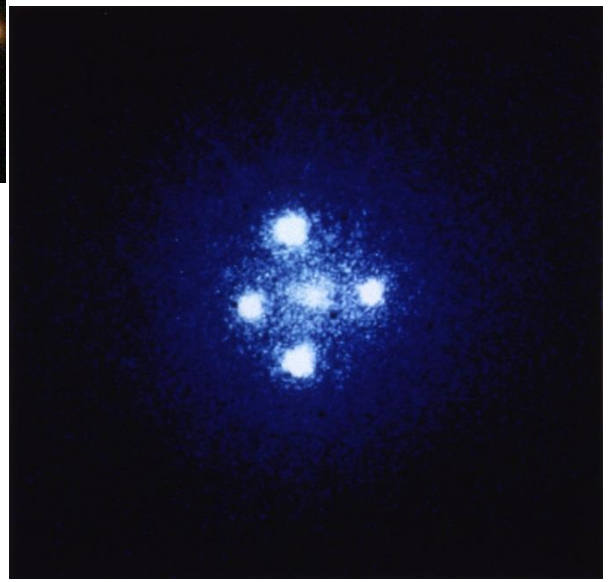
GWs and lensing

- Lensing of supernovae/galaxies:
  - Multiple copies of source image
  - Magnification
  - Time delays between images
  - Image 'parity'



ESA/Hubble/NASA

NASA/ESA/STScI



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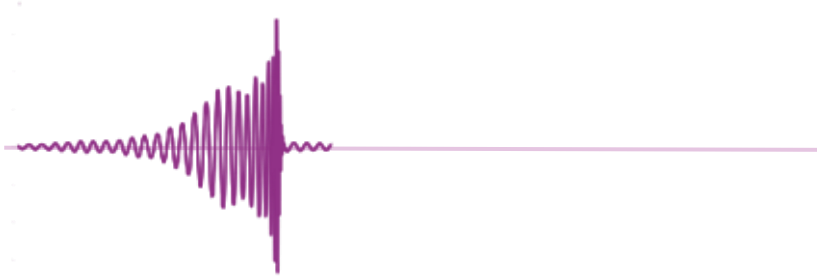
  - *Magnification* of amplitude
  - *Time delays* between images
  - Phase shift from image parity, *morse phase*



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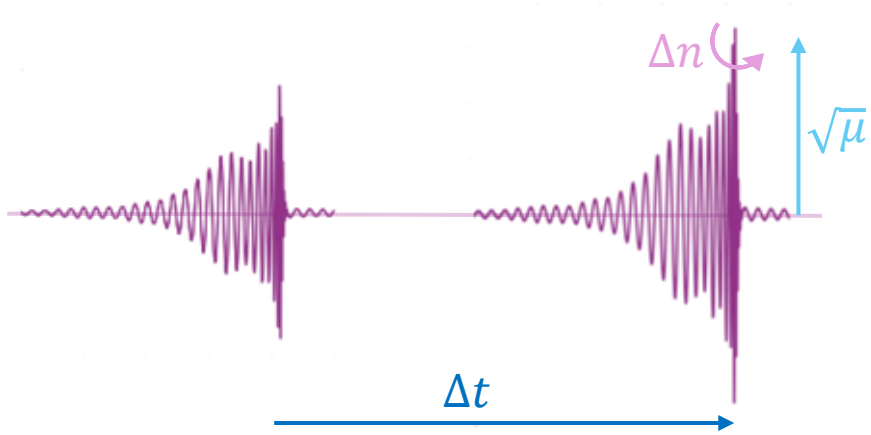

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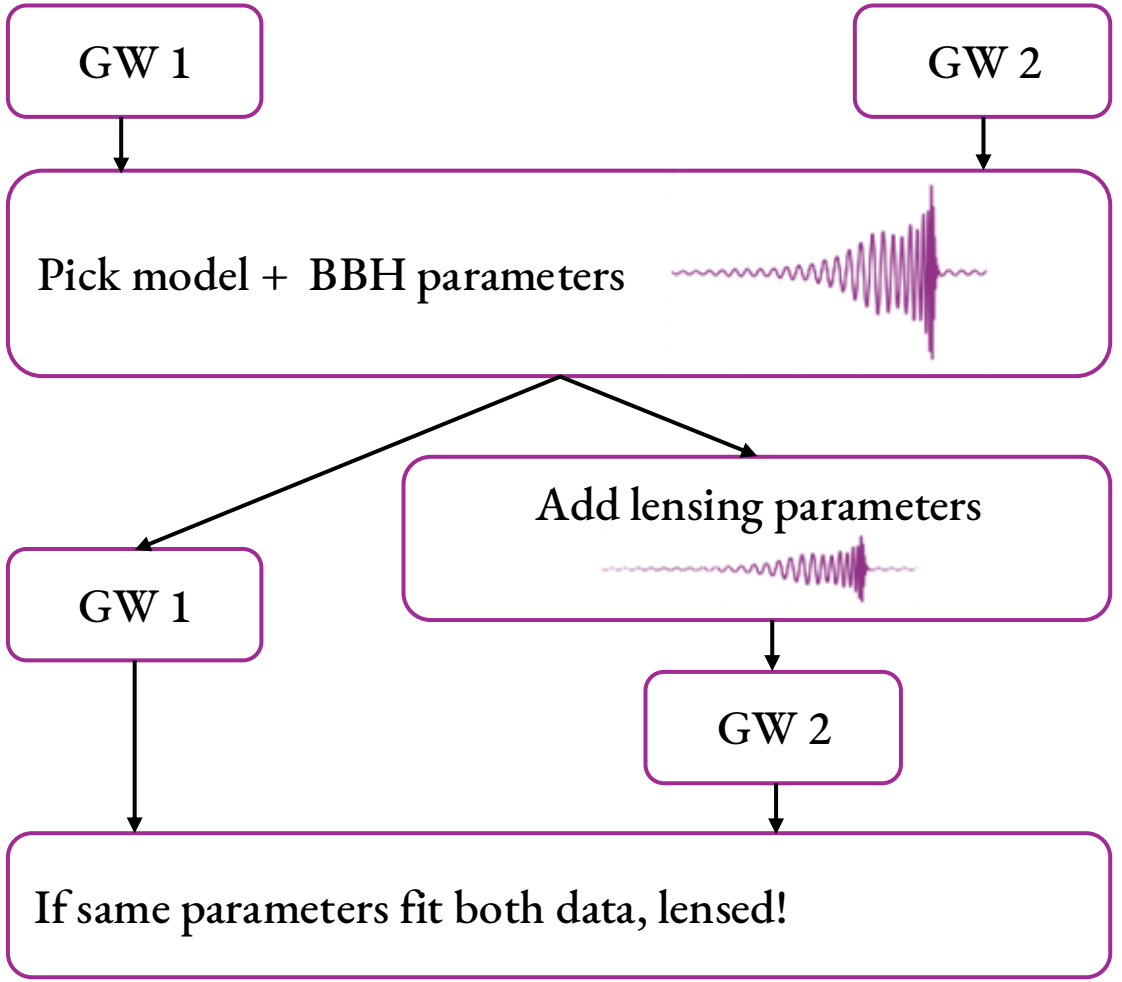
- Relative values can be recovered

e.g. Janquart+21, Lo+23, Janquart+23



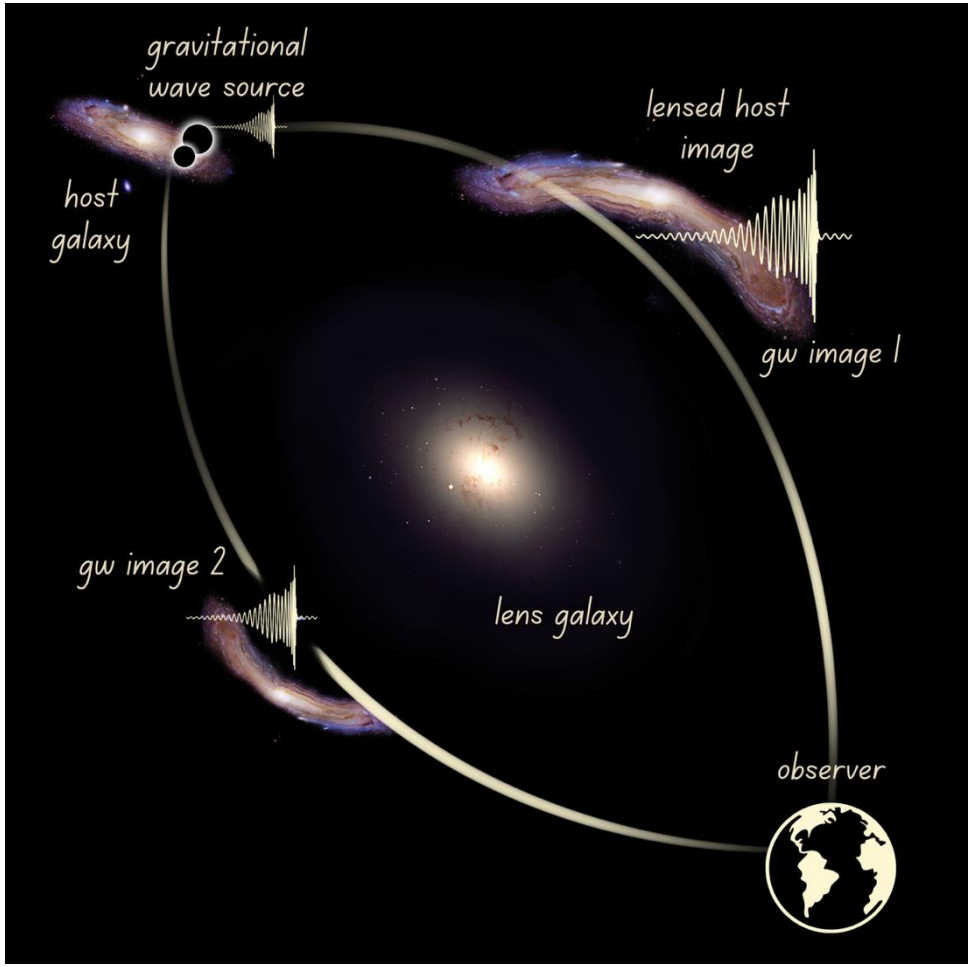
Multi-messenger lensing

- GW lensing effects caused by lens potential: have to connect directly back to the lens from which they came *Poon+24*

$$\Delta t = T_* \left[\frac{|x - y|^2}{2} - \psi(x) \right] \quad ; \quad \mu = \frac{x}{y} \frac{dx}{dy}$$

- If GW comes from bright galaxy, host should also be lensed
- We can try to connect observable EM lenses to GW characteristics: joint reconstruction
- MM reconstruction can also recover the pin-point position of the gravitational wave event

Hannuksela+19, Wempe+21, Uronen+24



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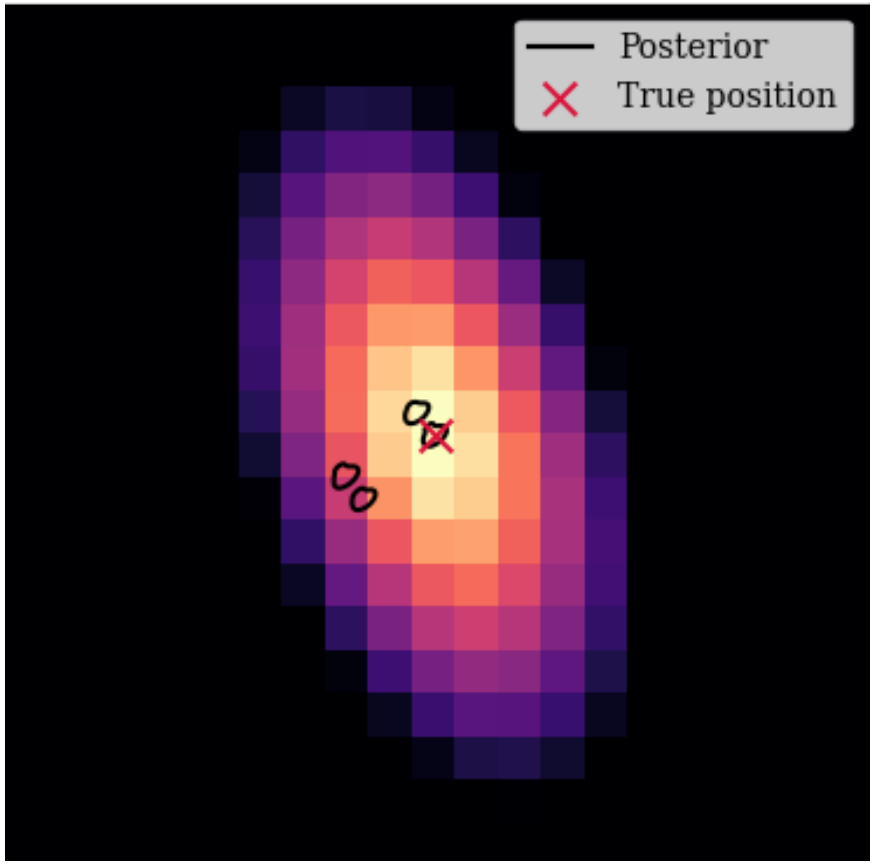
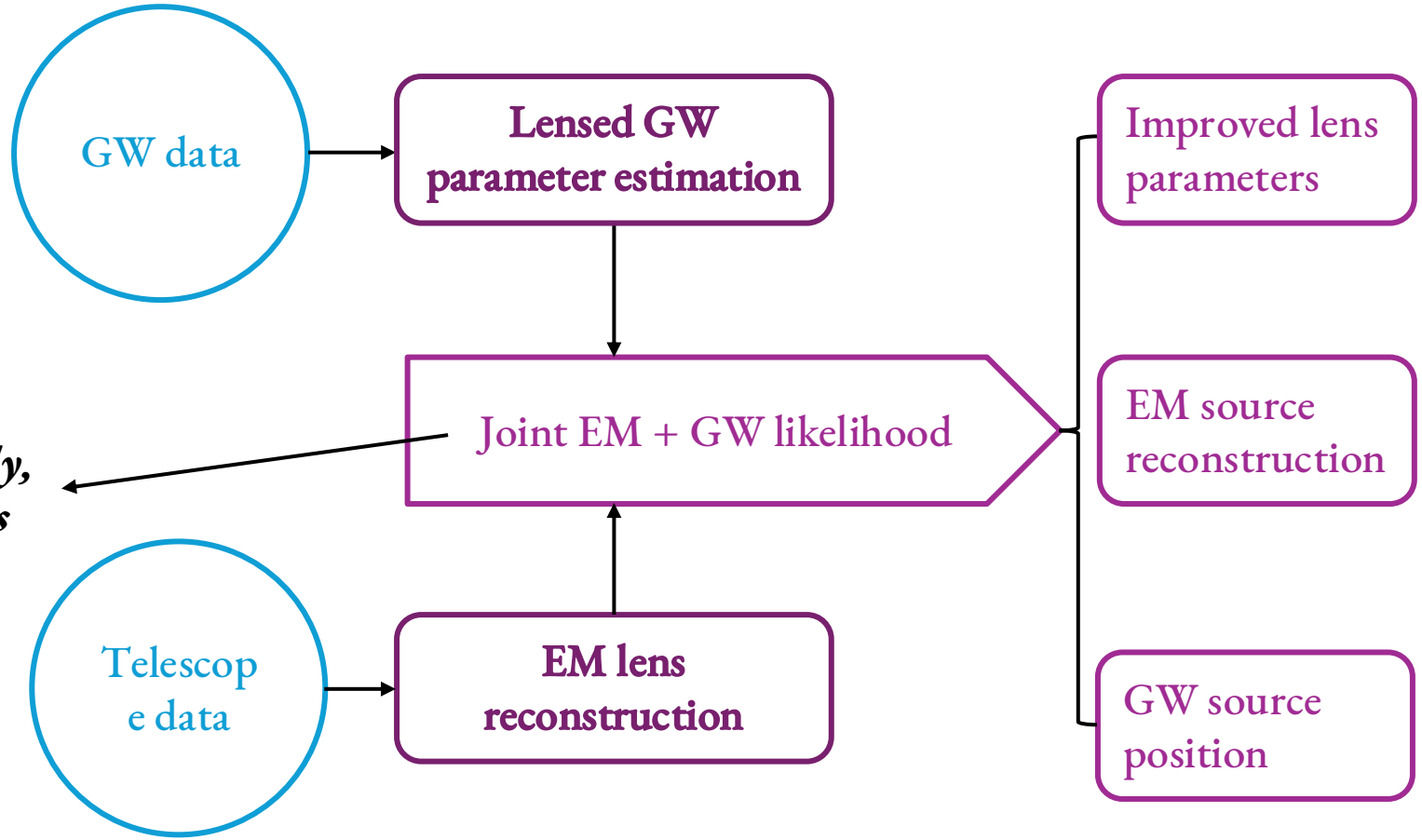


Statistical Inference for Lens Modelling And Reconstructing Localisation — SILMAREL

Alpha-version now on github



Unsolved problem! Active subject of study, only partial solutions available for now

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$$\mathcal{B}^{\mathcal{A}}_{\mathcal{N}} = \frac{p(d_{GW}, d_{EM}|\mathcal{H}_{\mathcal{A}})}{p(d_{GW}, d_{EM}|\mathcal{H}_{\mathcal{N}})} = \frac{p(d_{EM+GW})}{p(d_{EM})p(d_{GW})}$$

$$p(d) = \int p(d^{all}_{GW}|\varphi_{BBH}, \varphi_L, \vec{y}, z_l, z_s)\, p(d_{im}|\varphi_L, \varphi_{light}, z_l, z_s, \alpha, \delta)\; p(d_{spect}|z_l)\, p(\vec{\theta})\, d\vec{\theta}$$

$\mathcal{L}(lens\ reconstruction)$ $\mathcal{L}(spectral) \propto \delta(z_l)$

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- ➢ ***Expensive to analyse***
- ✓ ***Likelihoods share lens parameters***
- ✓ ***Most BBH parameters 'unnecessary'***
- ➢ ***Use LVK analysis posteriors!***

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Silmarel solution:

$$p(d^{all}_{GW}|D^{eff}_{L}, \Delta t, \alpha, \delta) \approx \exp\left[\frac{(\overline{D^{eff}_{L}} - D^{eff}_{L,model})^2}{2(\sigma_{D^{eff}_{L}})^2} + \frac{(\overline{\Delta t} - \Delta t_{model})^2}{2(\sigma^{model}_{\Delta t})^2}\right]$$

model uncertainty ≫ data uncertainty

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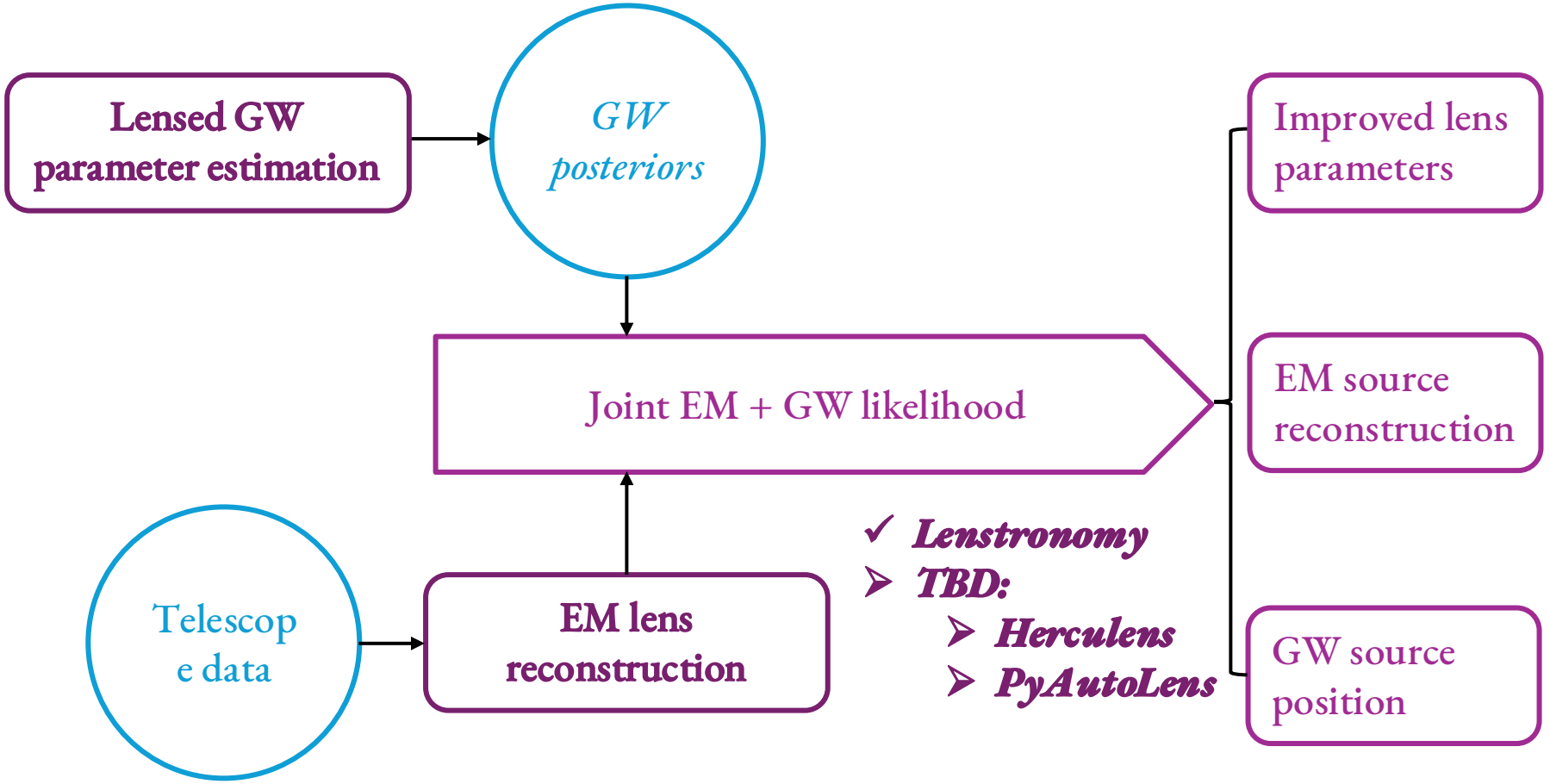

Conclusions

silmarel alpha version on github!

- Rate estimates expect first GW lensing observation in the coming decade
- Lensing allows for multi-messenger studies with BBHs
  - Improved localization by several orders of magnitude
  - Potential applications in host-merger links, formation environments, cosmology, dark matter...
- Multi-messenger reconstruction is computationally expensive
  - Full joint analysis not yet possible
  - Silmarel uses posteriors/approximations instead
  - Simple reconstruction already implemented, and more elaborate models under development
  - Great potential for further development using FIM, ML...
  - Want to work towards a ***full*** solution, to truly model GW + EM data jointly
- Broad range of science cases only just starting to be explored
- Exciting challenge mathematically, physically, and computationally!