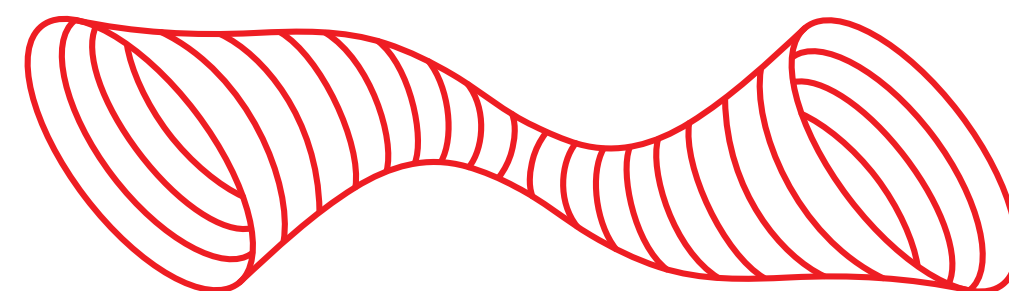


The next frontier in gravitational-wave physics

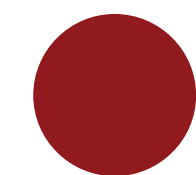
Jose María Ezquiaga

Niels Bohr Institute

ezquiaga.github.io



THE CENTER OF GRAVITY



KØBENHAVNS
UNIVERSITET

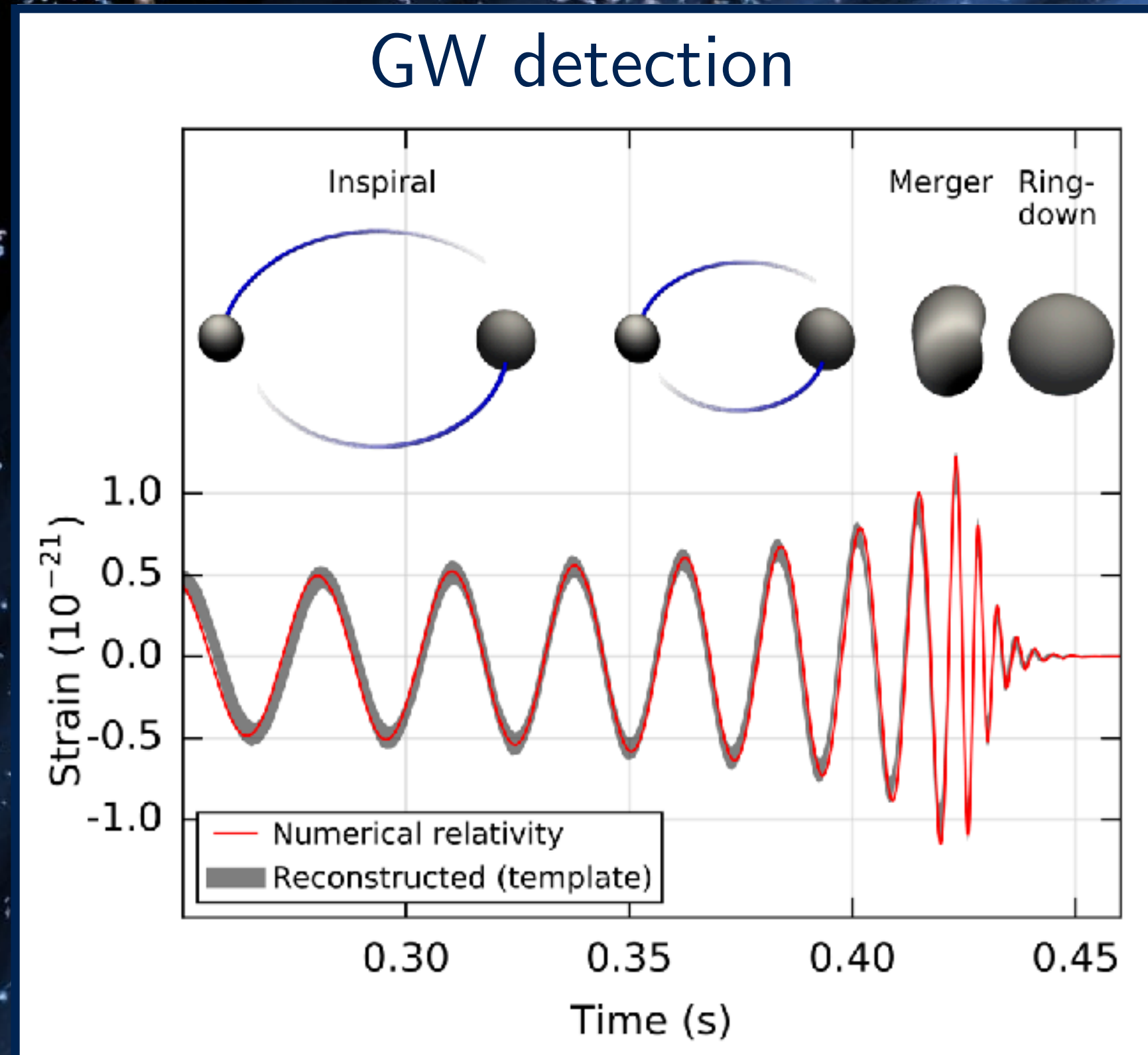
Every time we have been able to look *further*, we have found fascinating surprises

Why does the Universe
expand ever faster?

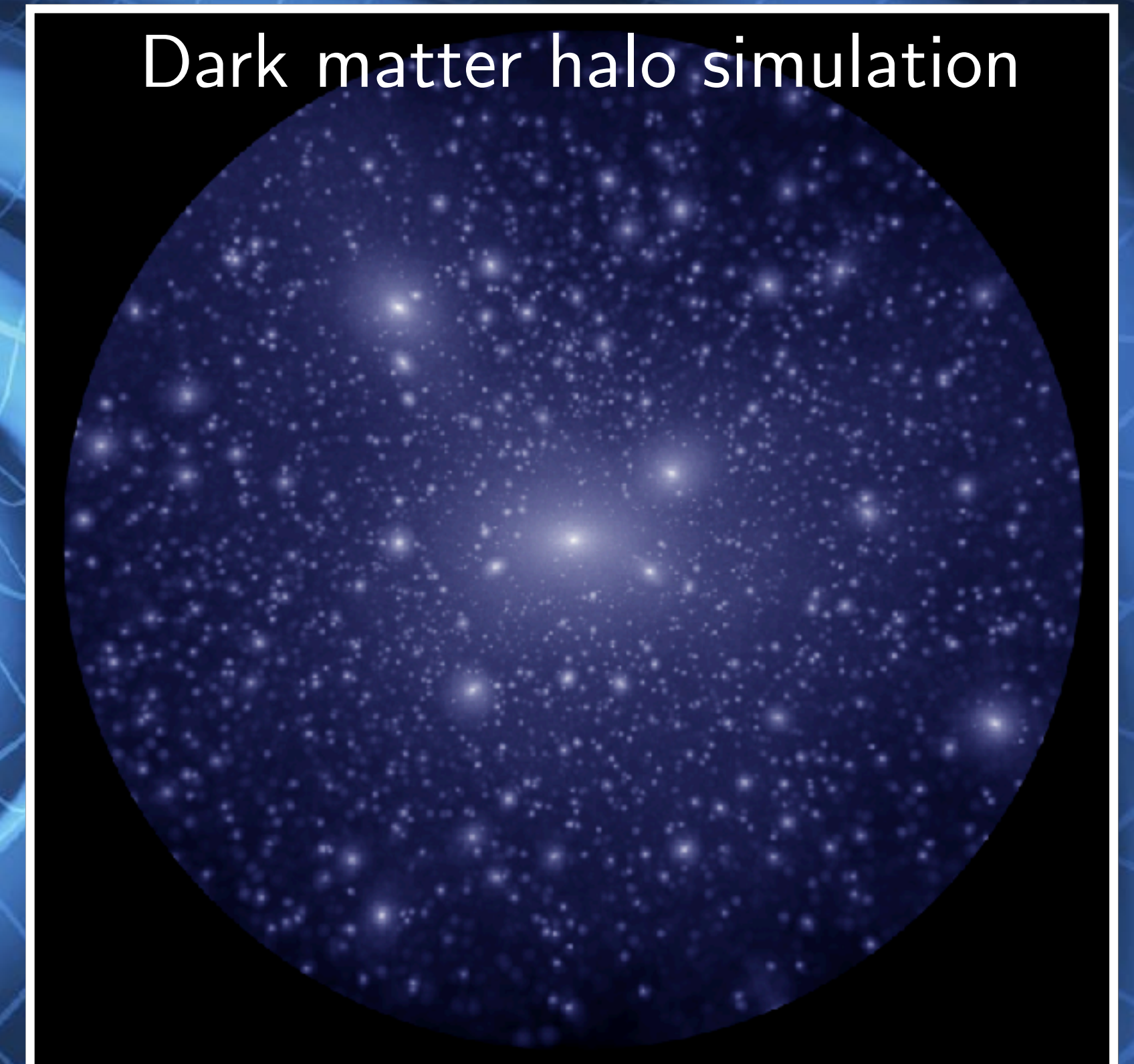
What holds galaxies
together?

How does gravity
work?

Gravitational waves (GWs) from binary black holes (BBHs) offer a *unique* opportunity to answer these fundamental open questions

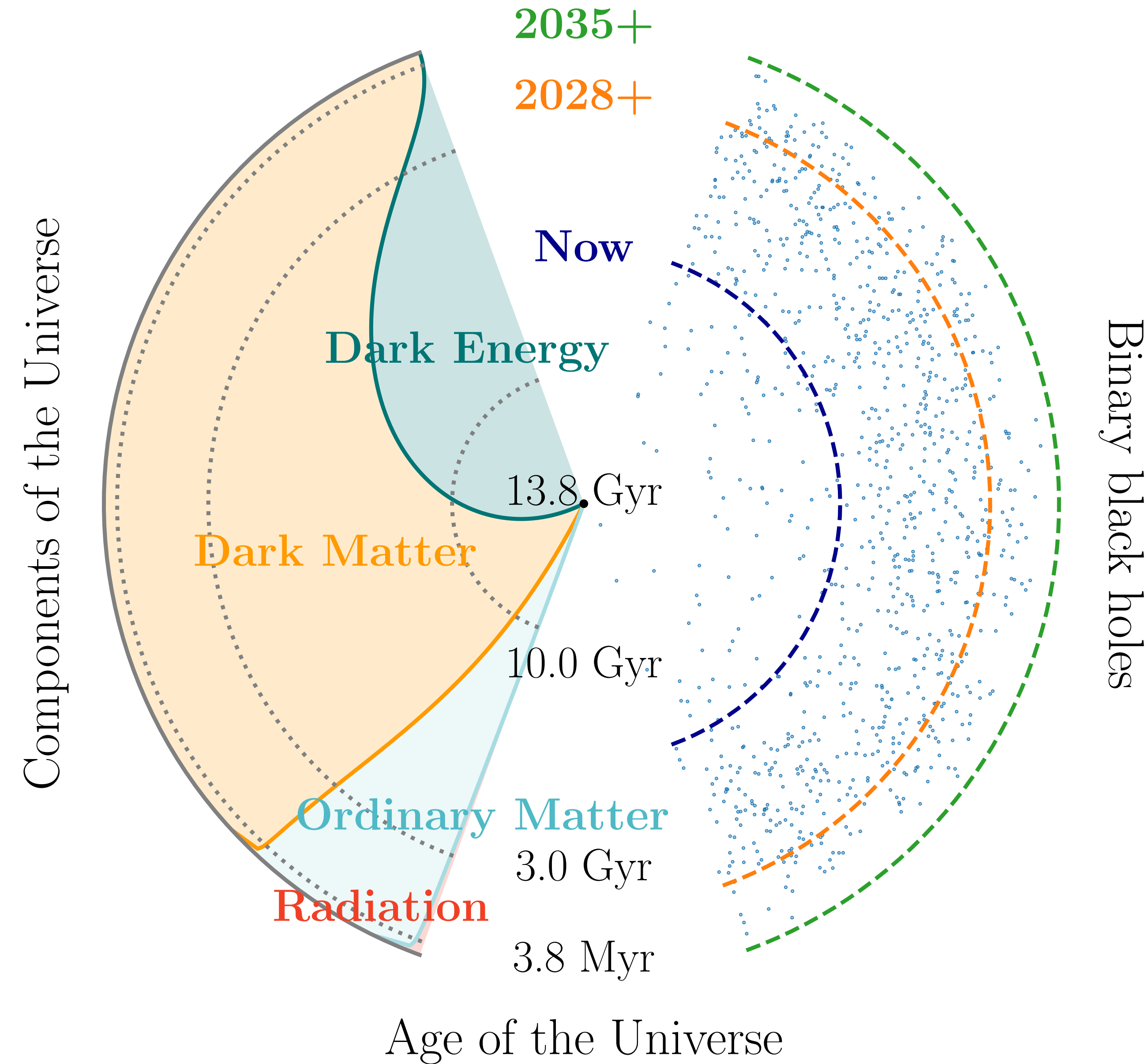


**Signals well understood
& *precisely* measured**



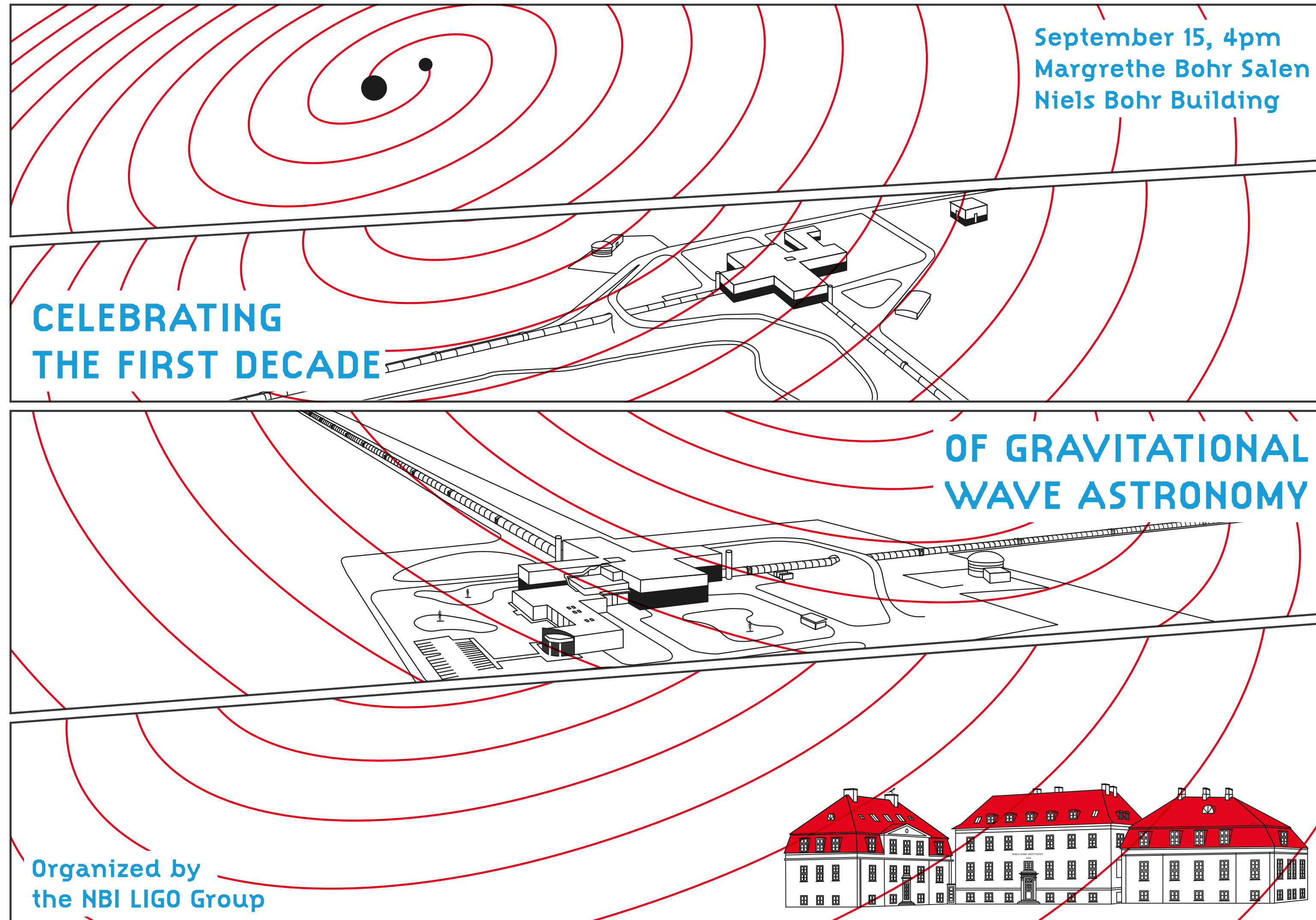
**Travel *unaltered* except for
gravitational interactions!**

GWs open a *unique window* onto the Universe's history.



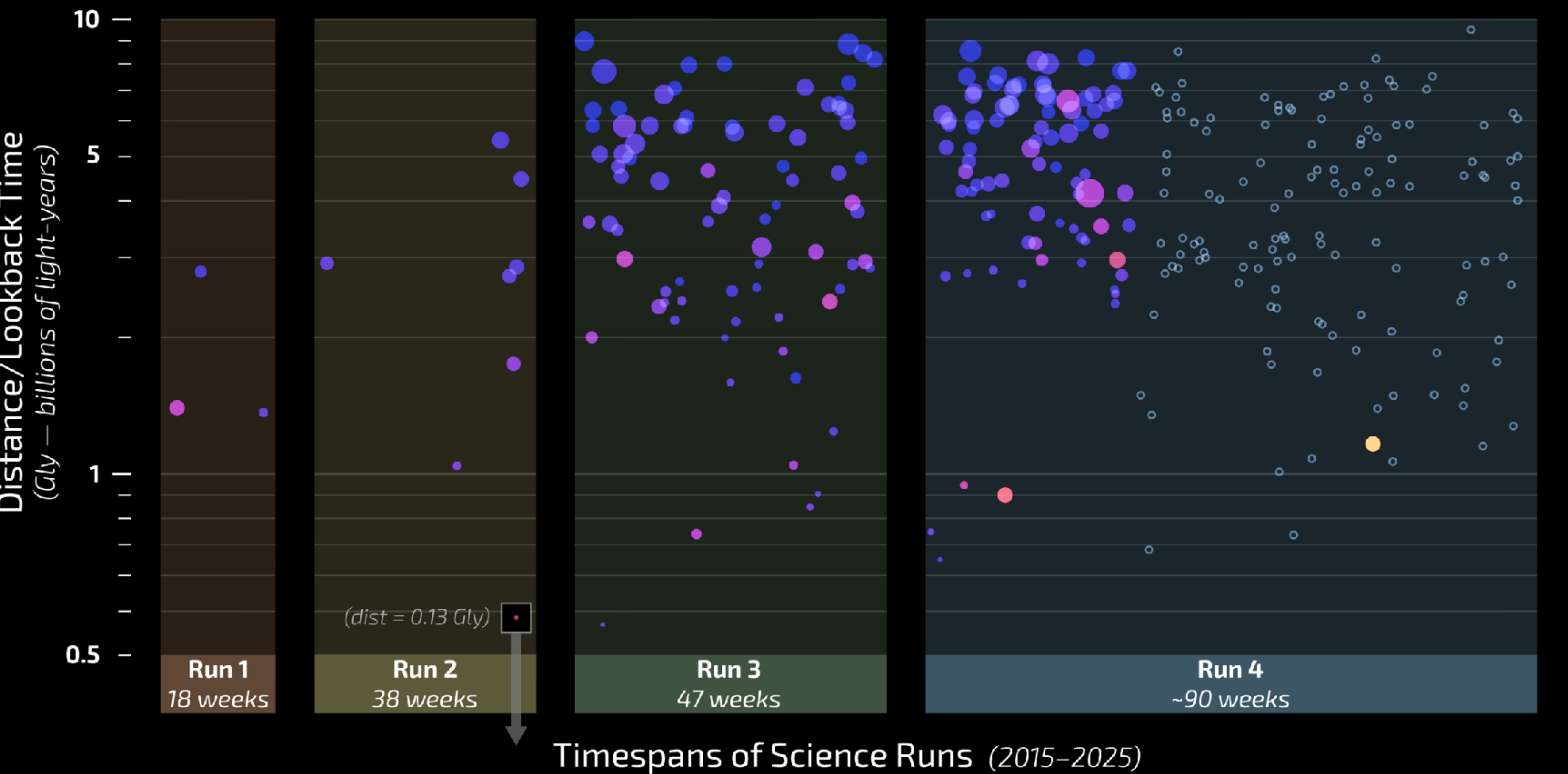
*stellar-mass
binary black holes

My research exploits *data* from gravitational-wave observatories to learn about gravity, cosmology and astrophysics.

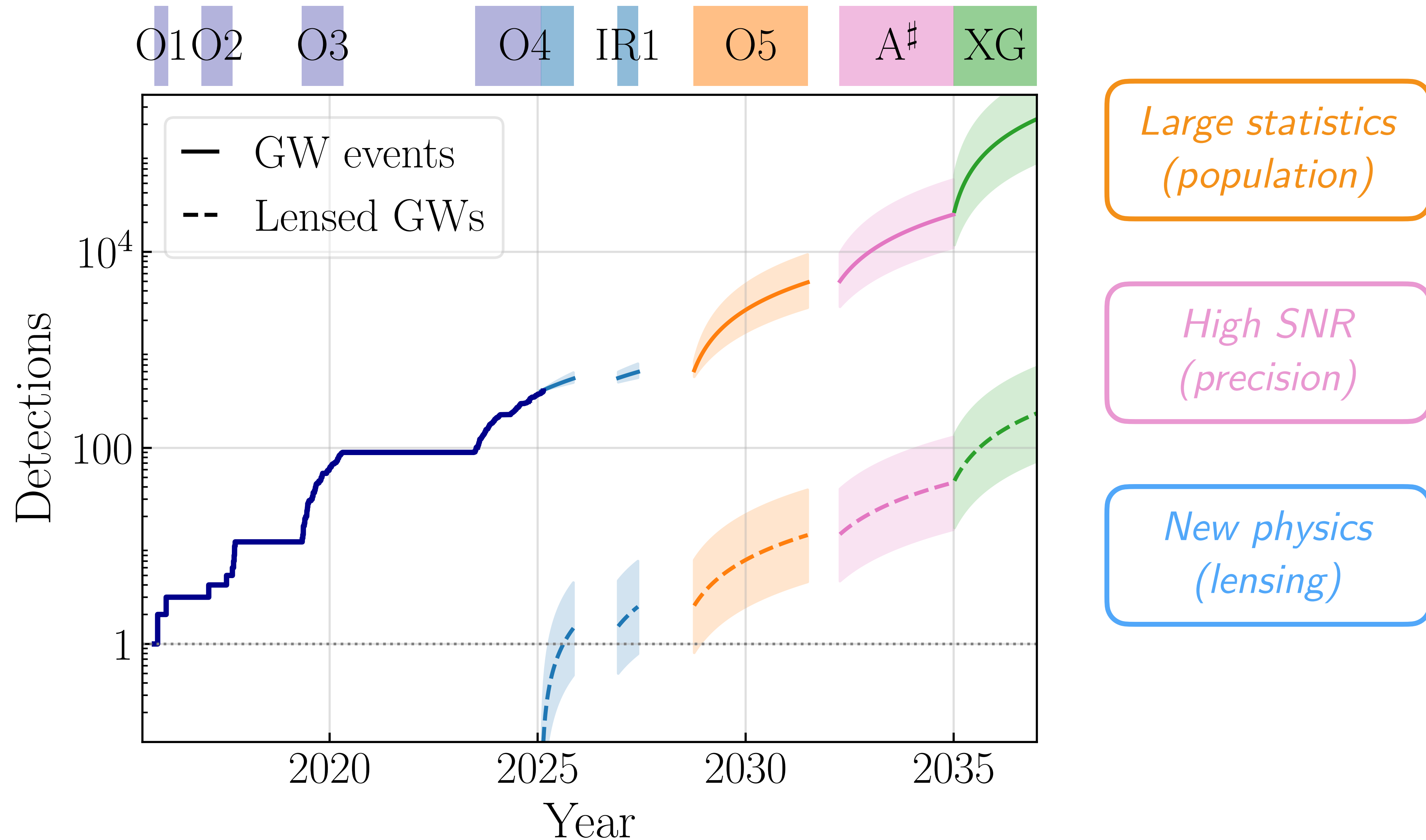


10 Years of LVK Black Hole* Mergers

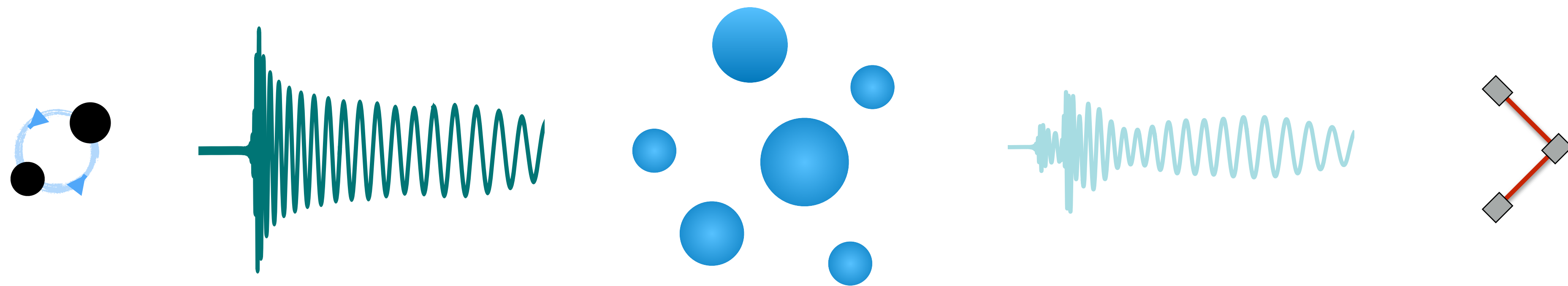
*plus several neutron stars!



What comes next in gravitational-wave astronomy?



GW lensing will open *discovery frontiers* at high redshifts, zooming into dark matter



Source

Lens

GW Detector

*High- z black hole
populations*

*Dark matter
substructures*

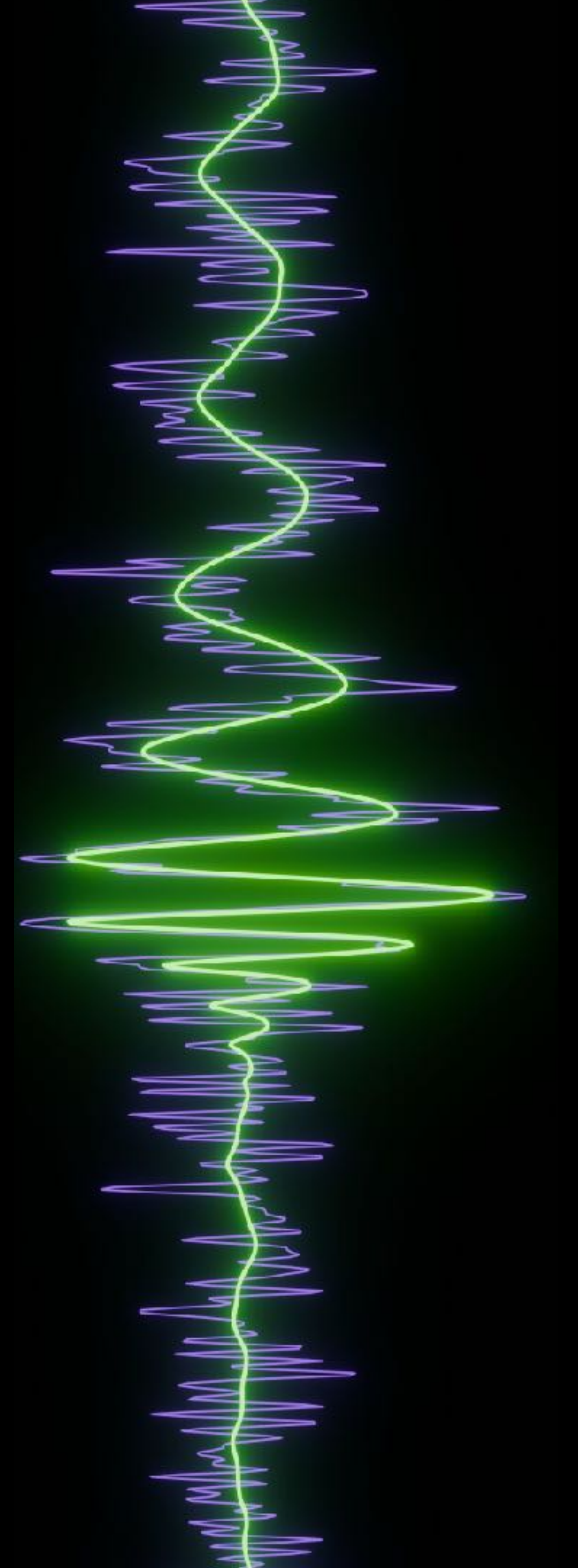
*Uncharted wave
optics lensing*

The big goals

- Discover/constrain *new* BBH formation channels at $z > 3$
- Resolve *unexplored* dark matter substructures $\sim 10 - 10^6 M_{\odot}$

Today's plan

- Motivation
- Gravitational-wave lensing physics
- The data analysis problem
- Accelerating the discovery of lensed GWs
- New probes of Cosmology & Astrophysics
- The road ahead



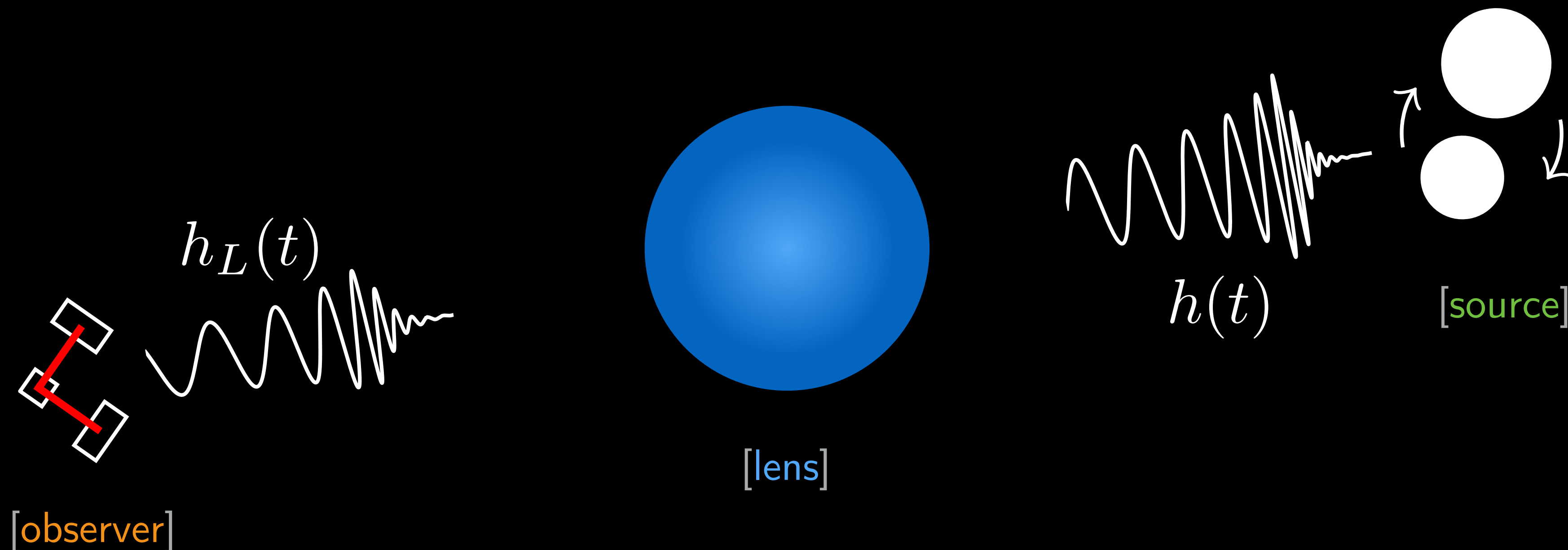
Gravitational-wave lensing physics

Gravitational-wave lensing

- Solve GW propagation on a **curved** background:

$$\square \bar{h}_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu}\bar{h}^{\alpha\beta} = 0$$

- Map between the **source** and the **observer** through the **lens**

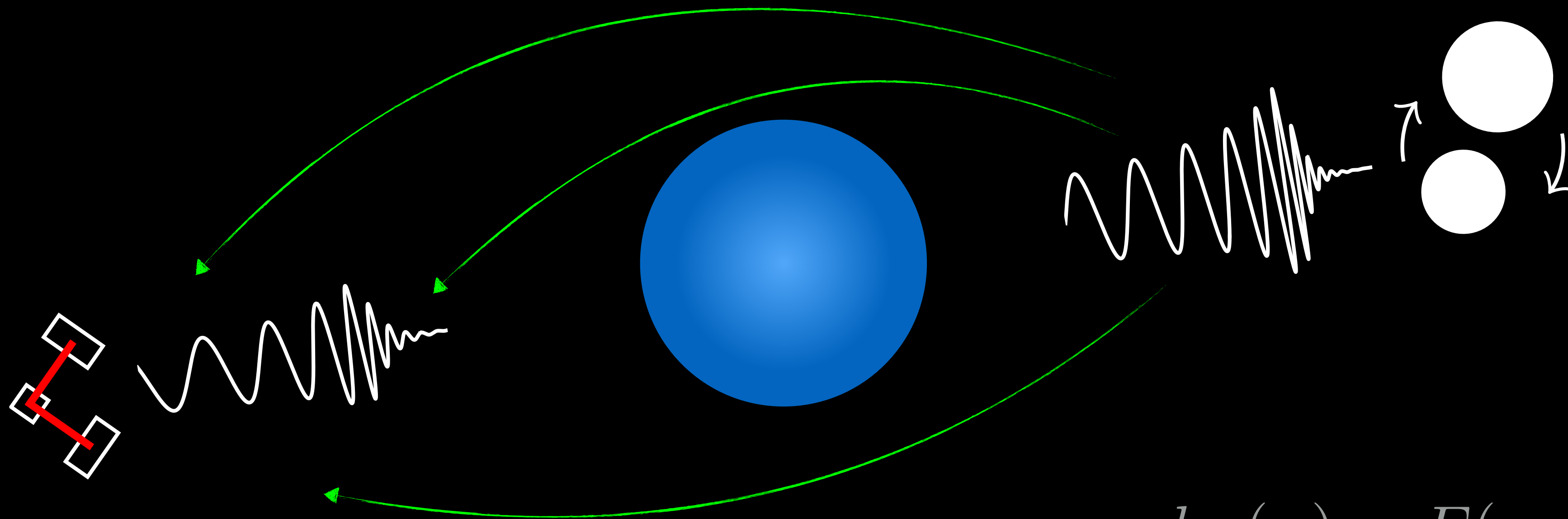


Gravitational-wave lensing: distorted waveforms

- In the *weak-gravity* and *thin lens* approximation, solve the *diffraction integral* in *Fourier* space:

$$F(\omega, \vec{y}) = \frac{\omega}{2\pi i} \int d^2x \exp[i\omega T_d(\vec{x}, \vec{y})]$$

Frequency-
dependent
distortions



$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$

Gravitational-wave lensing: repeated chirps

- When the time delay is *larger* than the duration of the signal: $\Delta t_d \cdot \omega \gg 1$

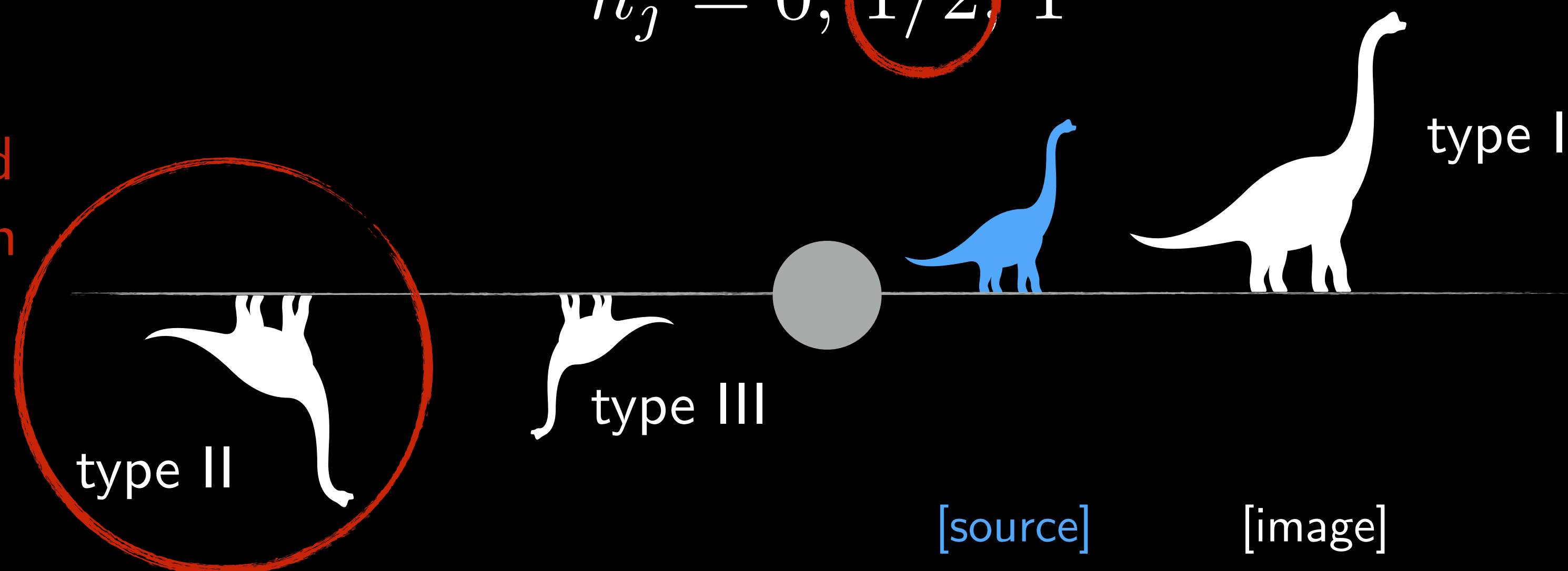
$$F \approx \sum_j |\mu_j|^{1/2} \exp(i\omega t_j - i\pi n_j)$$

Magnification
Time delay
Phase shift

- Different *extrema* of the time-delay surface acquire *different* phase shifts

$$n_j = 0, 1/2, 1$$

Distorted
waveform

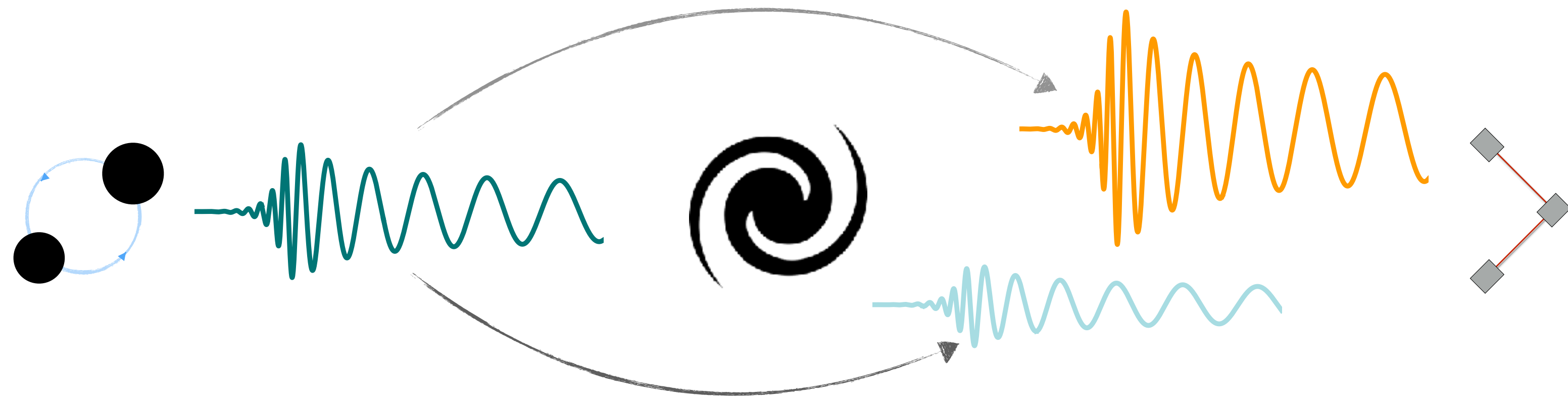


[Dai & Venumadhav; 2017]

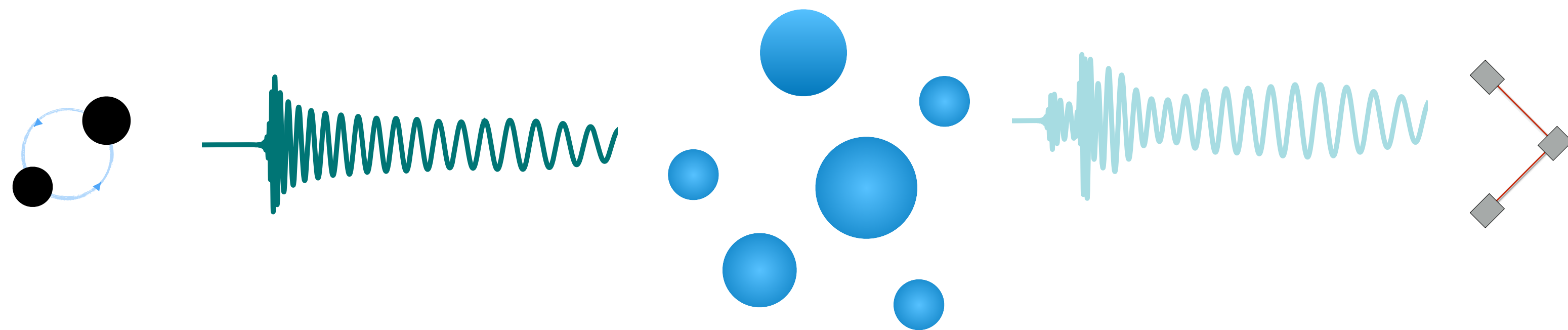
[Ezquiaga *et al.*; PRD'20]

Gravitational lensing — gravitational-wave spectrum

Repeated chirps due to strong lensing



Waveform distortions by substructures

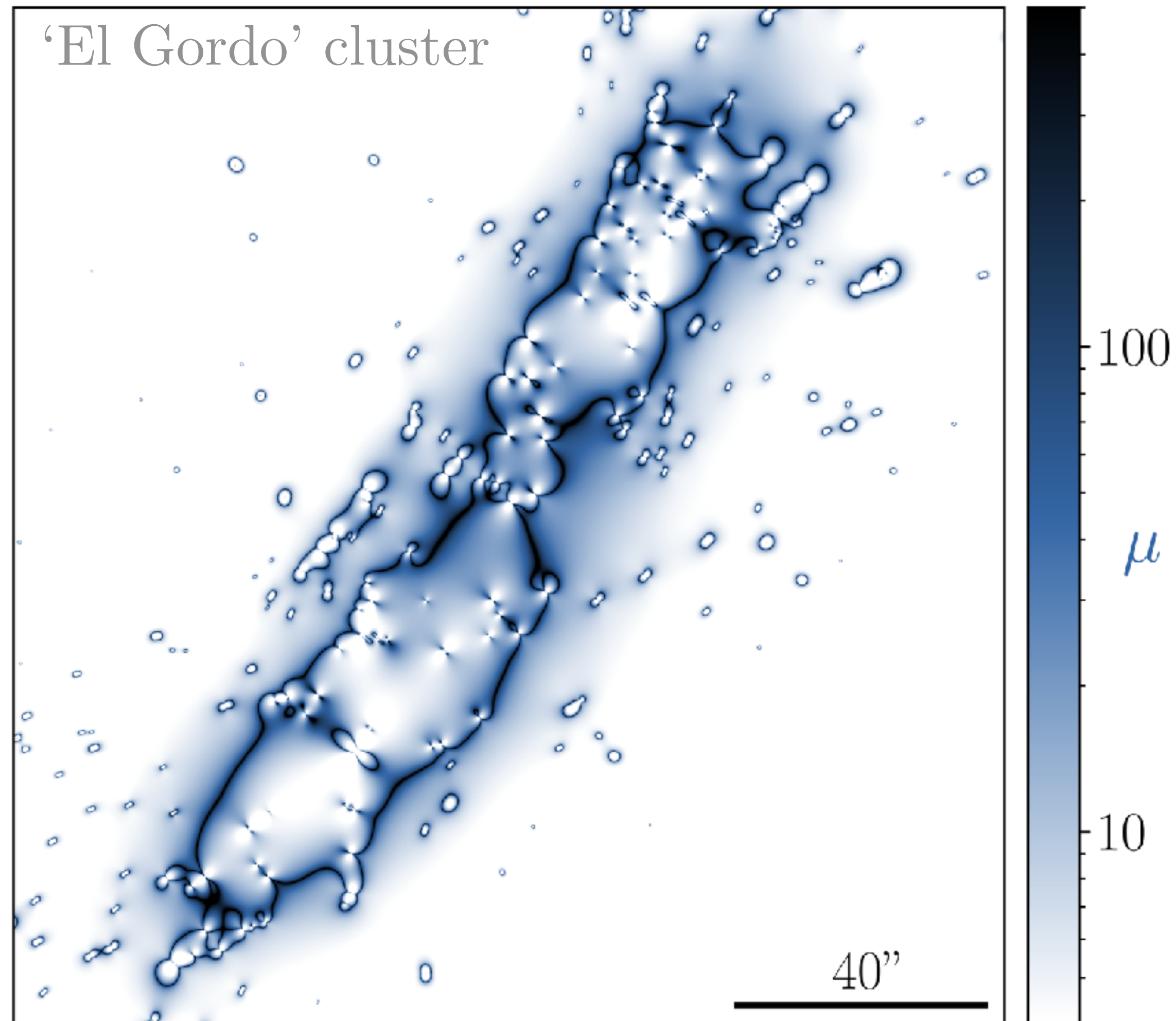


Source

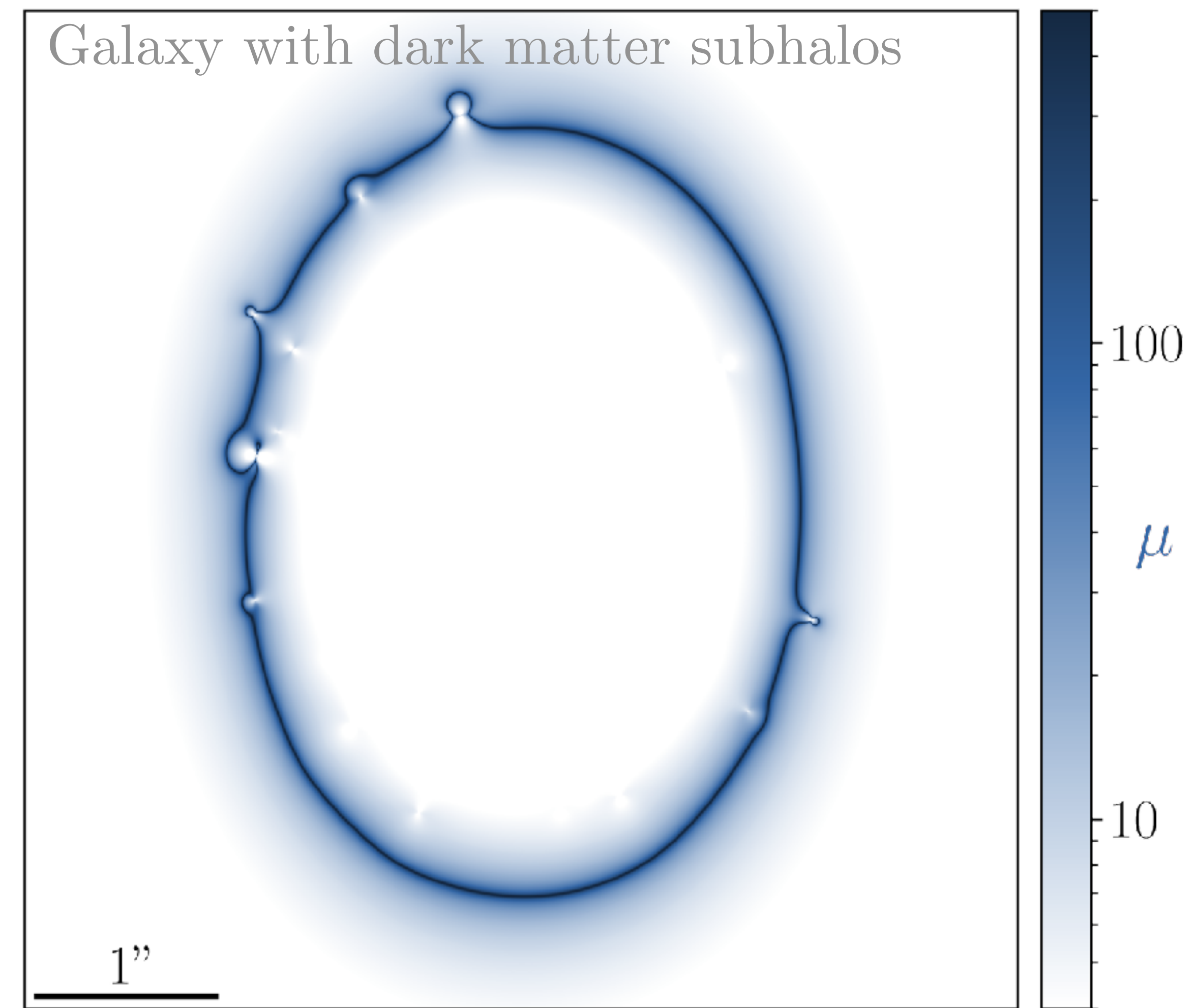
Lens

Detector

Probing cosmic (sub)structures: GWs are sensitive to time delays from milliseconds (solar-mass objects) to years (clusters of galaxies)

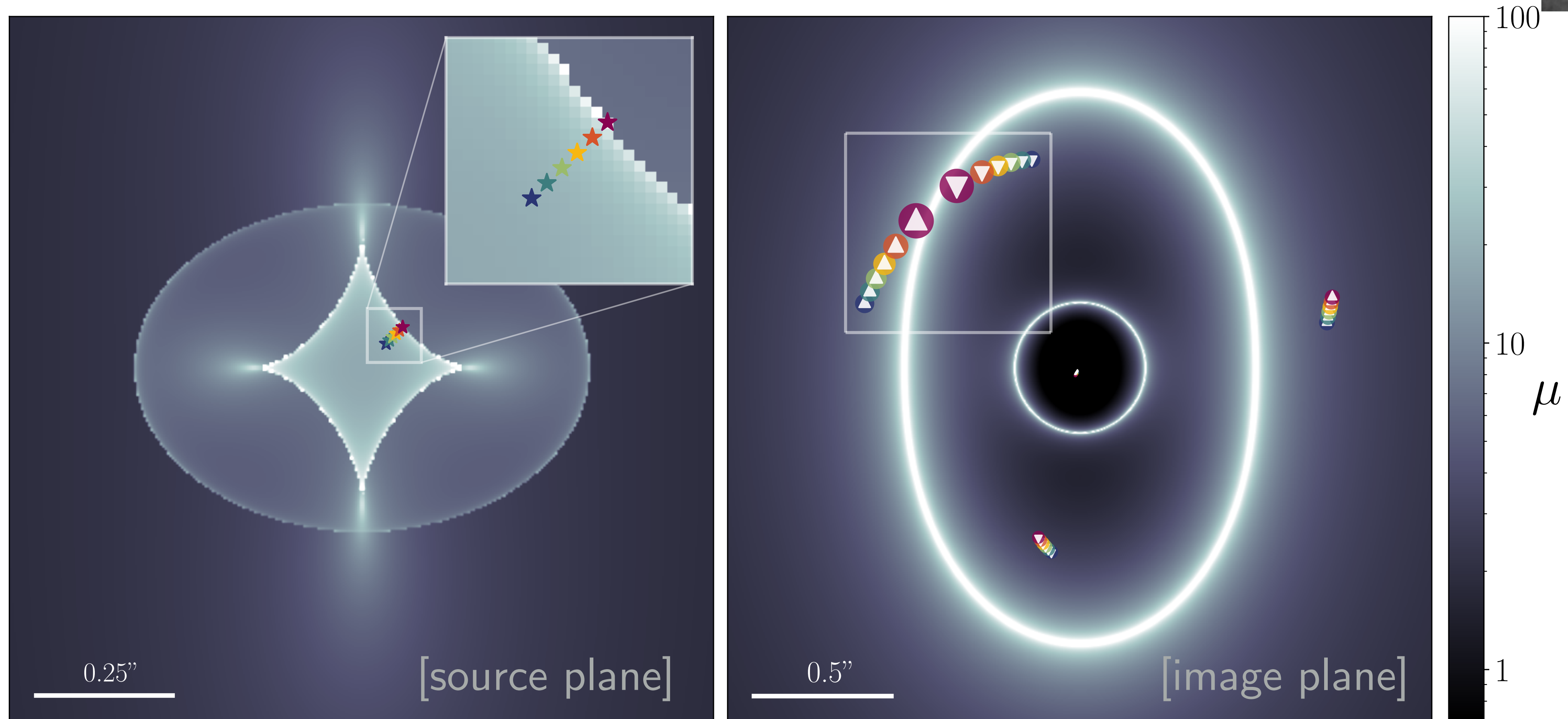


[Vujeva, **Ezquiaga**, Lo, Chan; PRD'25]



[Vujeva *et al.*; PRD'26]

When is lensing more probable? *Caustics* are the regions of highest magnification



[galaxy lens with a cored singular isothermal ellipsoid density profile]

Lensing near caustics

- For *point sources*, there are **singular** points in the lens mapping

$$\det \left(\frac{\partial^2 T_d(\theta_j)}{\partial \theta_a \partial \theta_b} \right) \rightarrow 0 \quad \Rightarrow \quad \mu(\theta_j) \rightarrow \infty$$



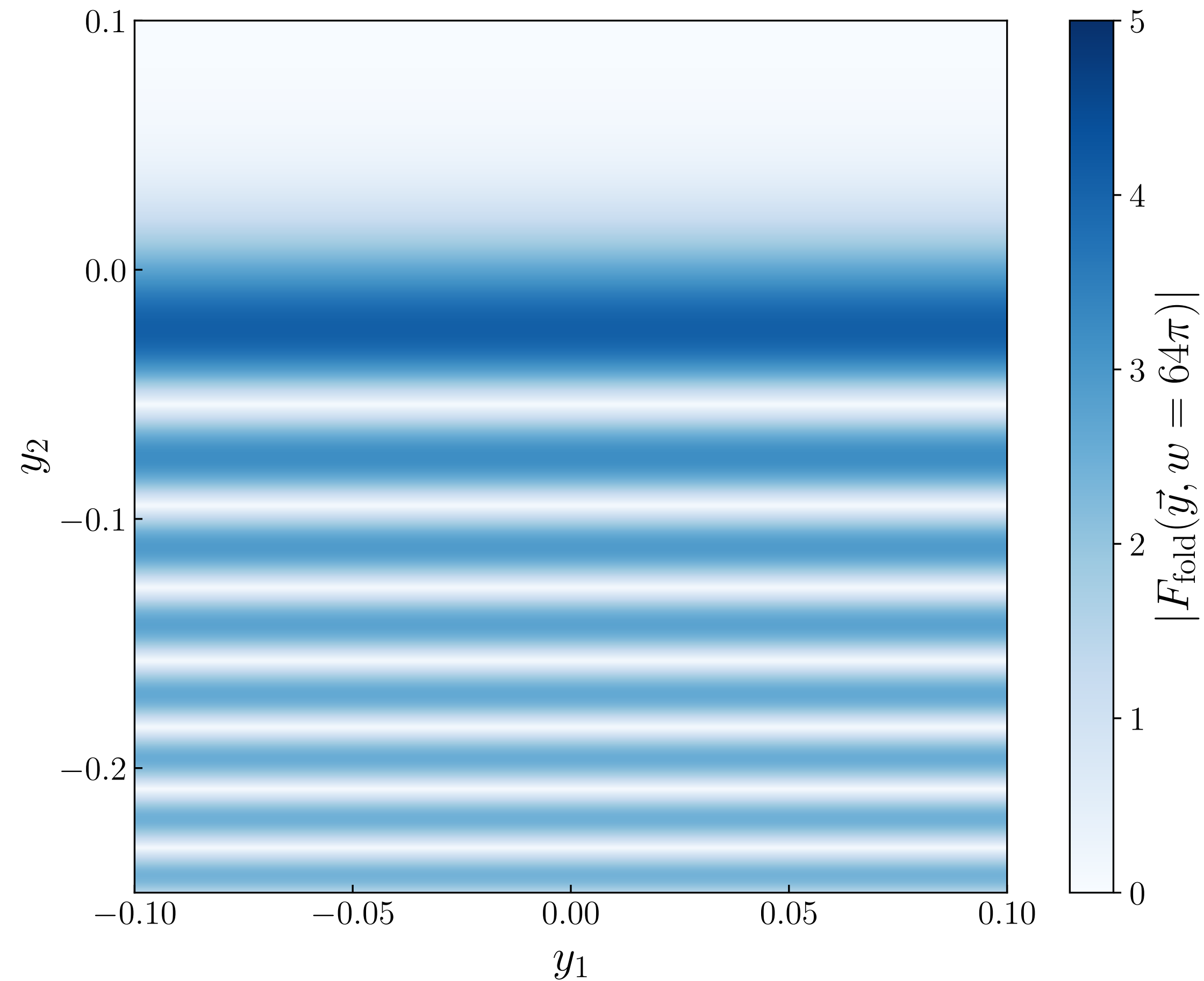
- Caustics exhibit **universal** behaviors (described by catastrophe theory)

$$\mu_{\pm} \sim 1/\sqrt{\Delta\theta_S} \sim \Delta t^{-1/3}$$

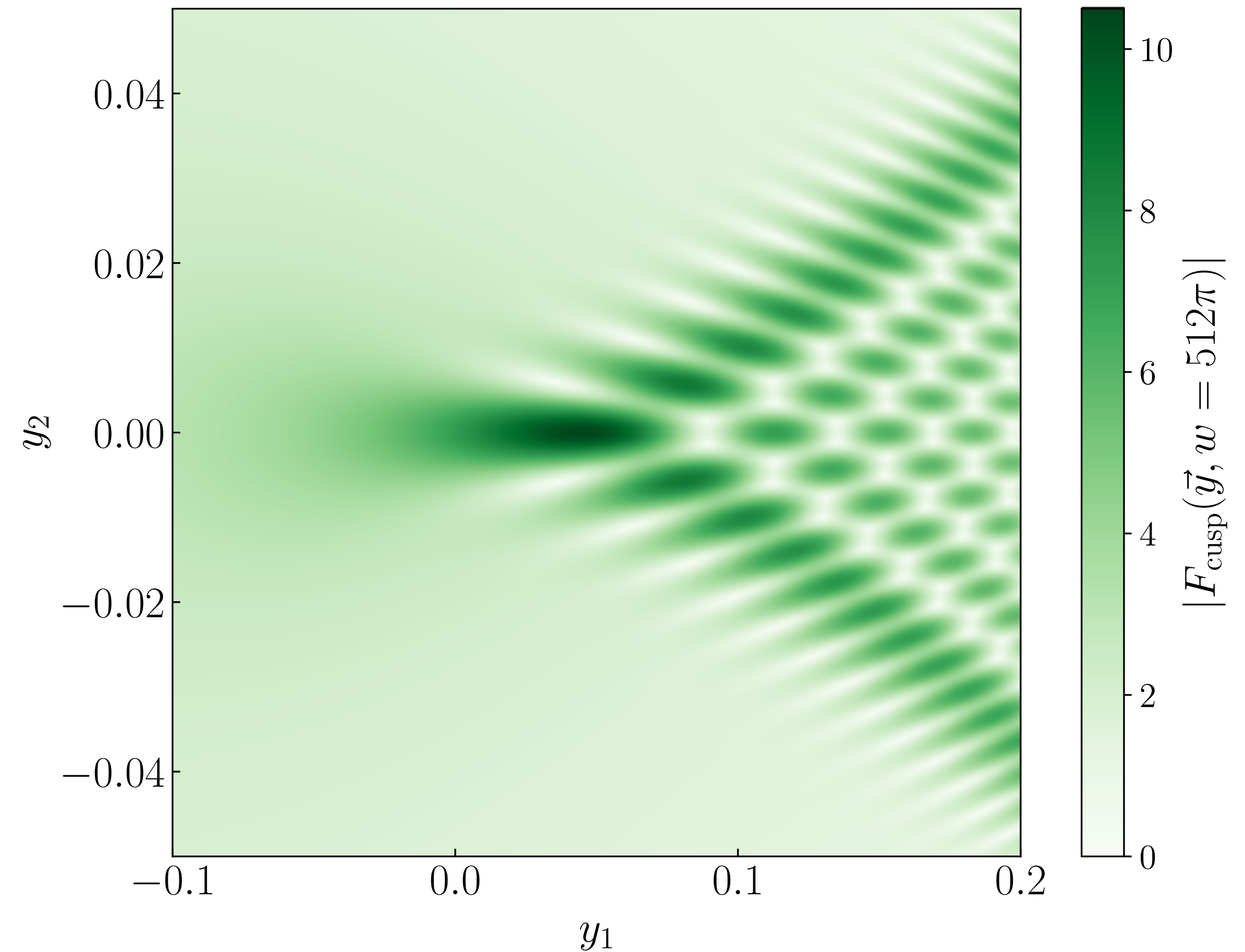
- *Stationary-phase approximation* is **broken** when approaching a caustic
- The **maximum magnification** is set by diffraction

Diffraction around caustics: universal behavior classified with catastrophe theory

Fold caustic

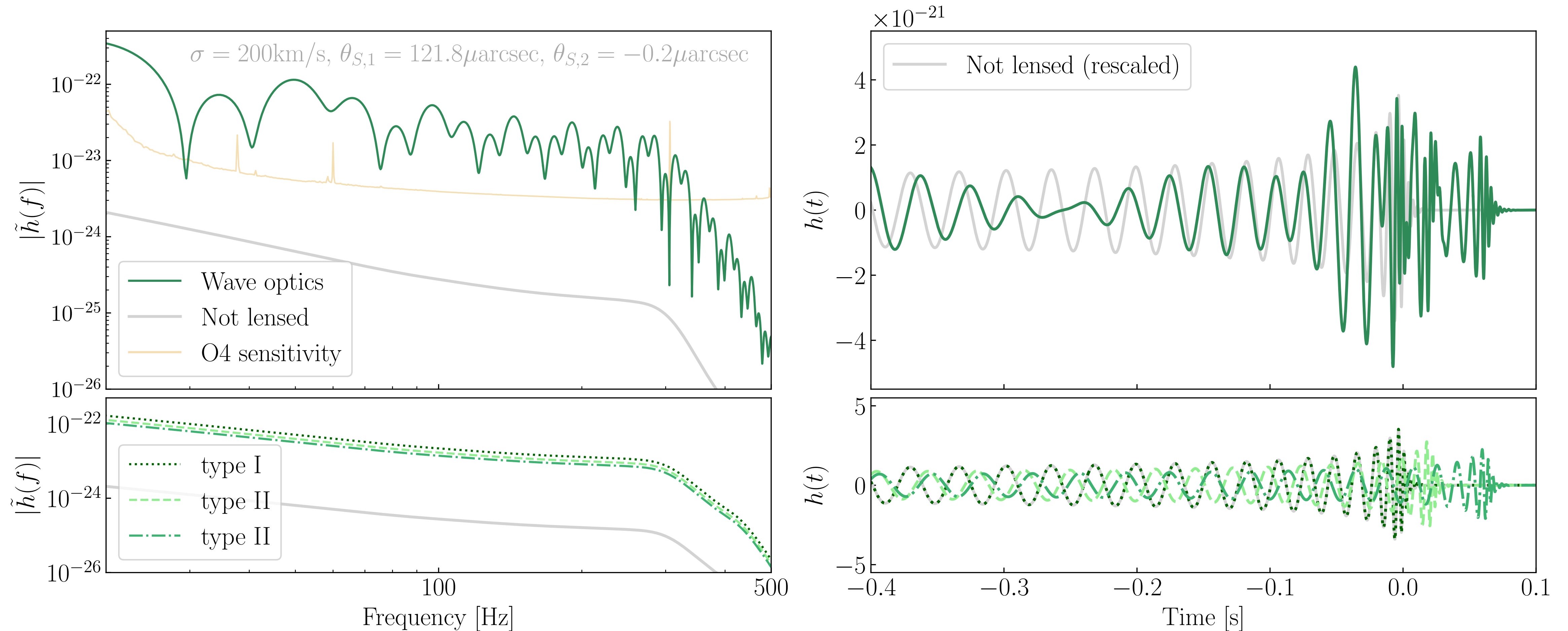


Cusp caustic

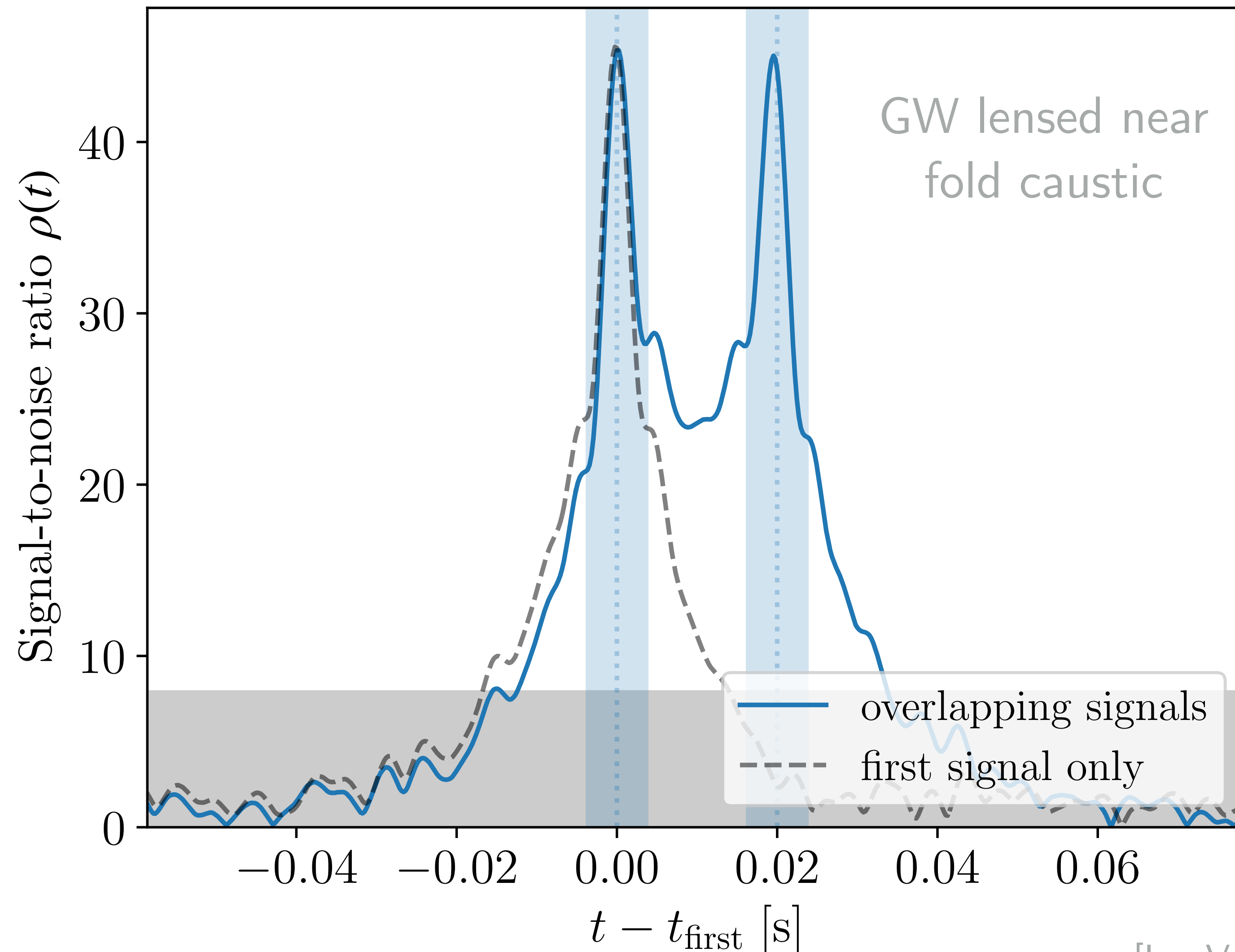


Diffraction around caustics: complex waveform distortions from simple physical principles

Cusp caustic



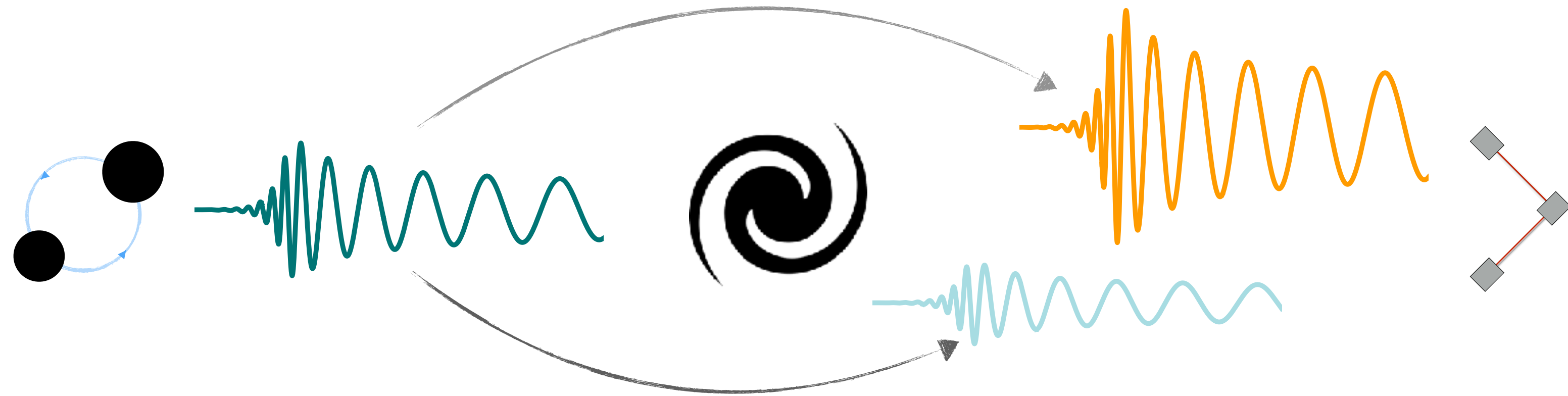
Searching for lensing: universality around *caustics* is a smoking gun!



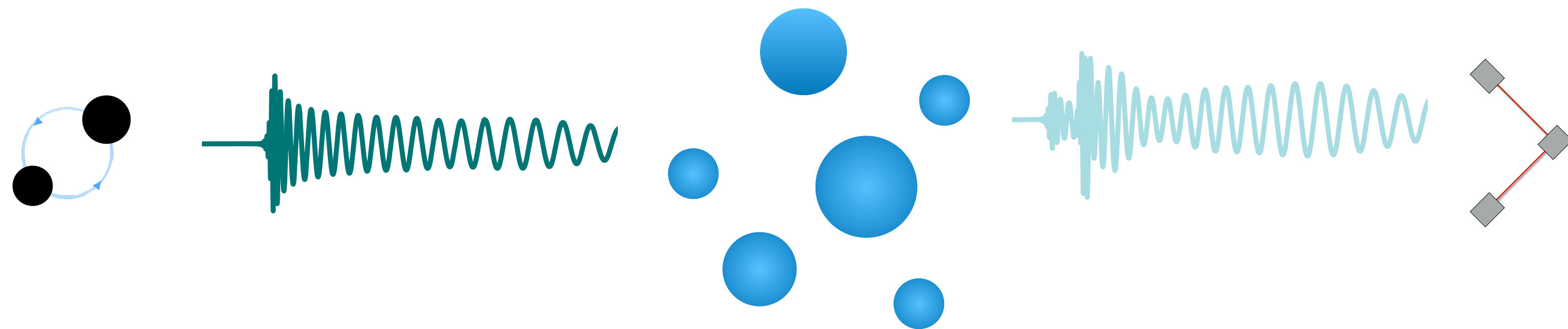
The data analysis problem

Searches for gravitational-wave lensing

Repeated chirps due to strong lensing



Waveform distortions by substructures

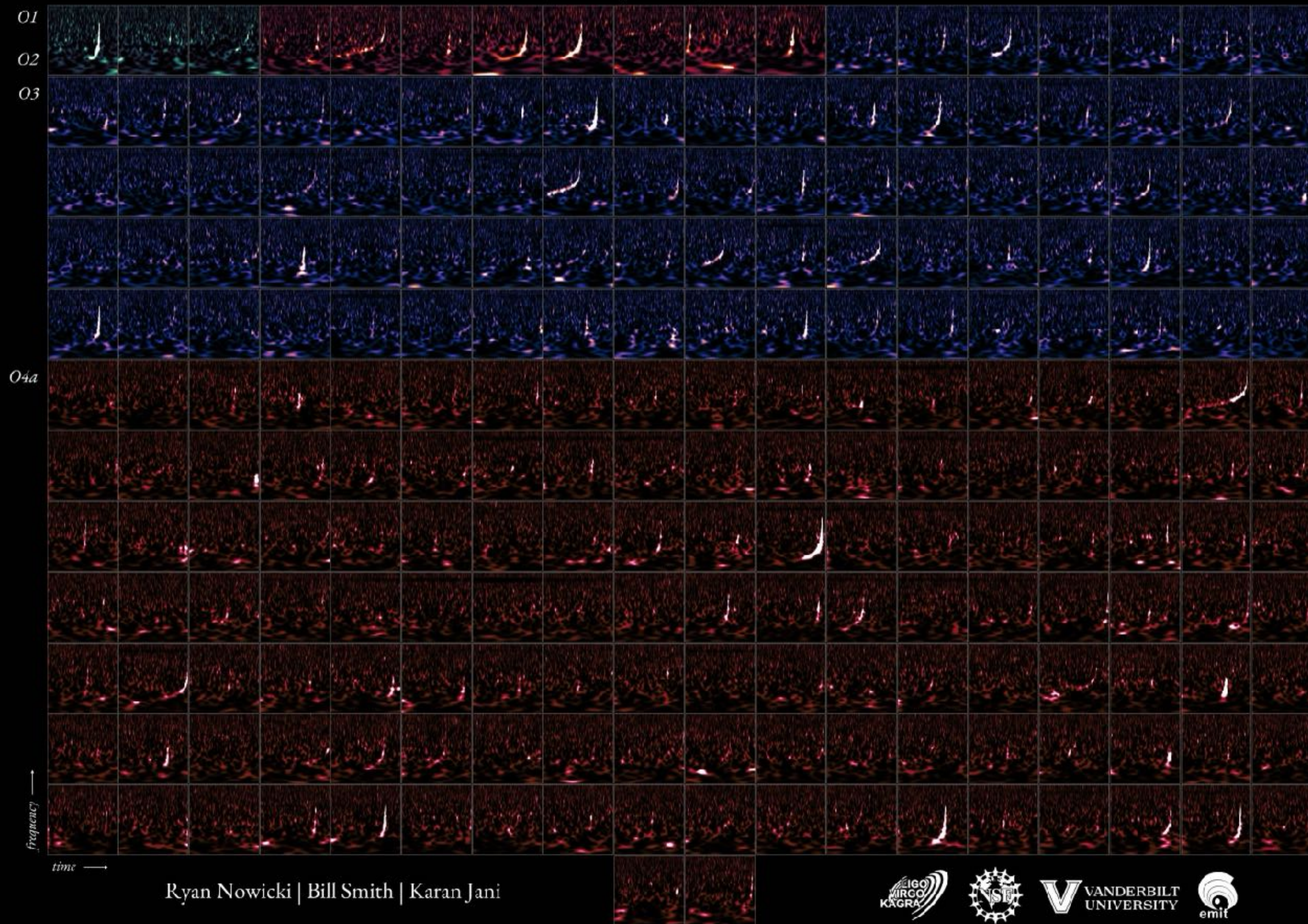


Source

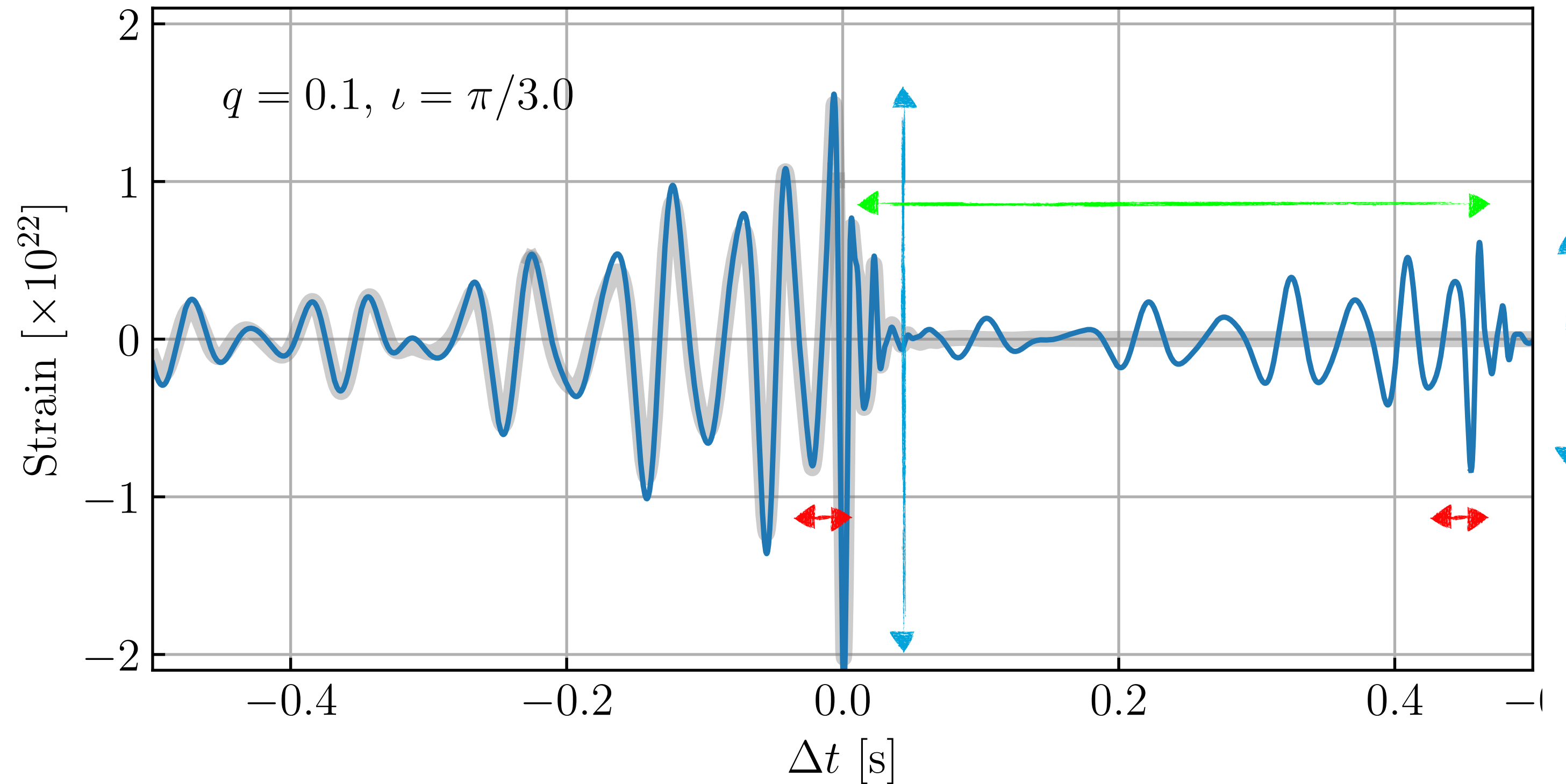
Lens

Detector

Key question: *are all the signals from independent sources?*



Strongly lensed GWs: *repeated, coherent signals*



$$d_L^j = d_L / \sqrt{|\mu_j|}$$

$$t_{\text{ref}}^j = t_{\text{ref}} + \Delta t_j$$

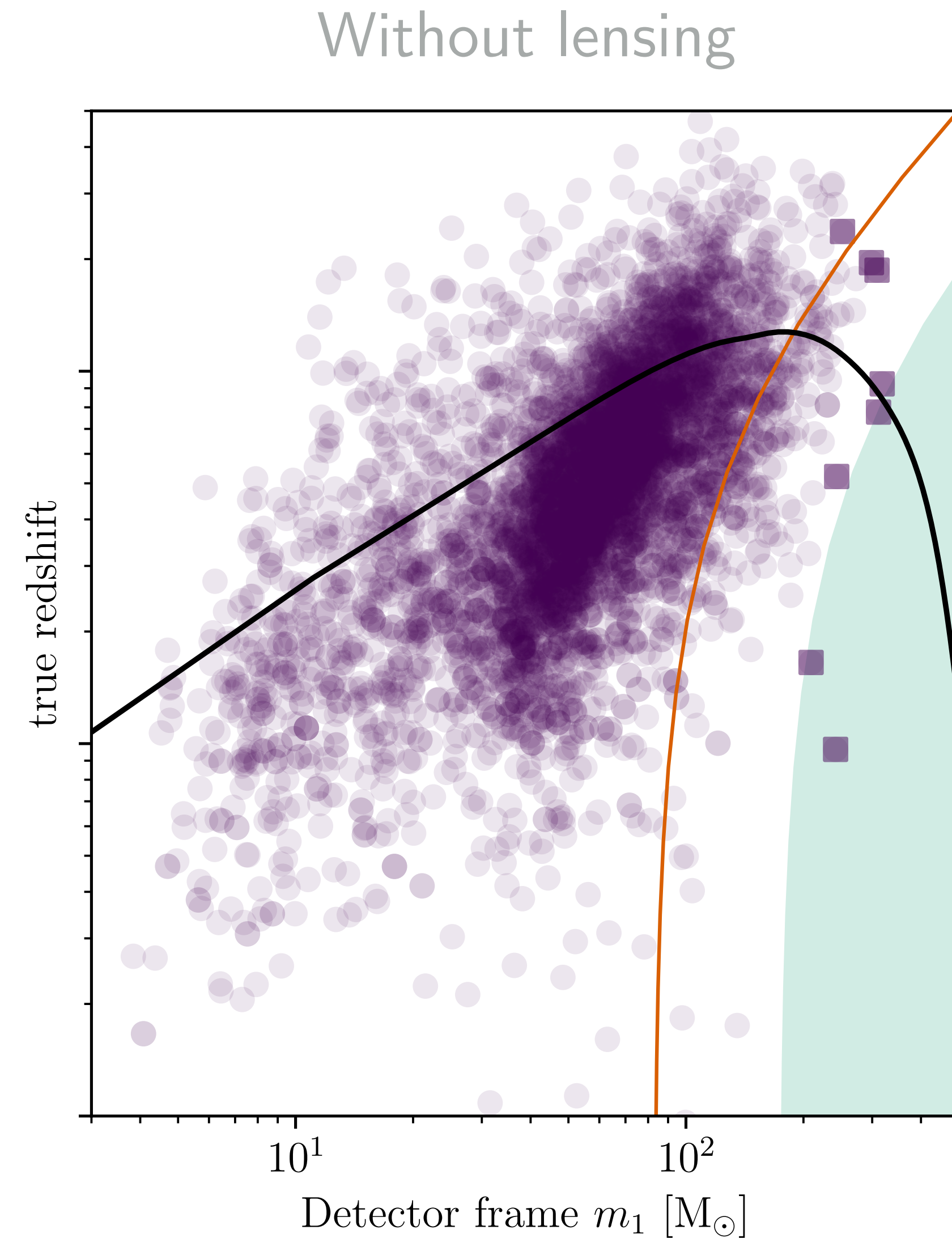
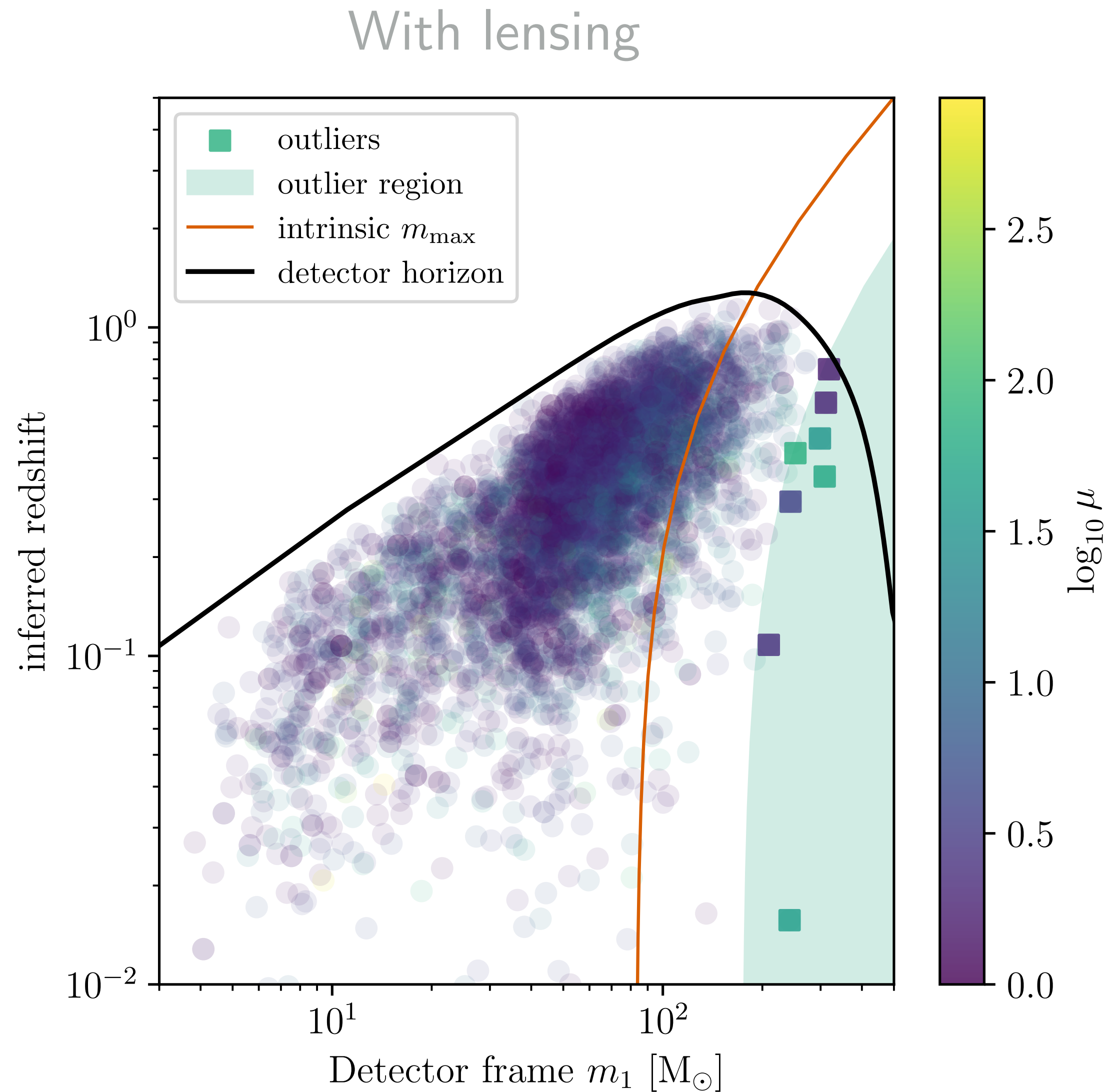
$$m_{\text{det}}^j = m_{\text{det}}$$

$$\phi_{\text{ref}}^j = \phi_{\text{ref}} - \pi/2$$

- If not identified as lensed, a *magnified* event appears *closer* and *more massive*

$$m_{\text{src}}^j = m_{\text{det}} / (1 + z(d_L^j))$$

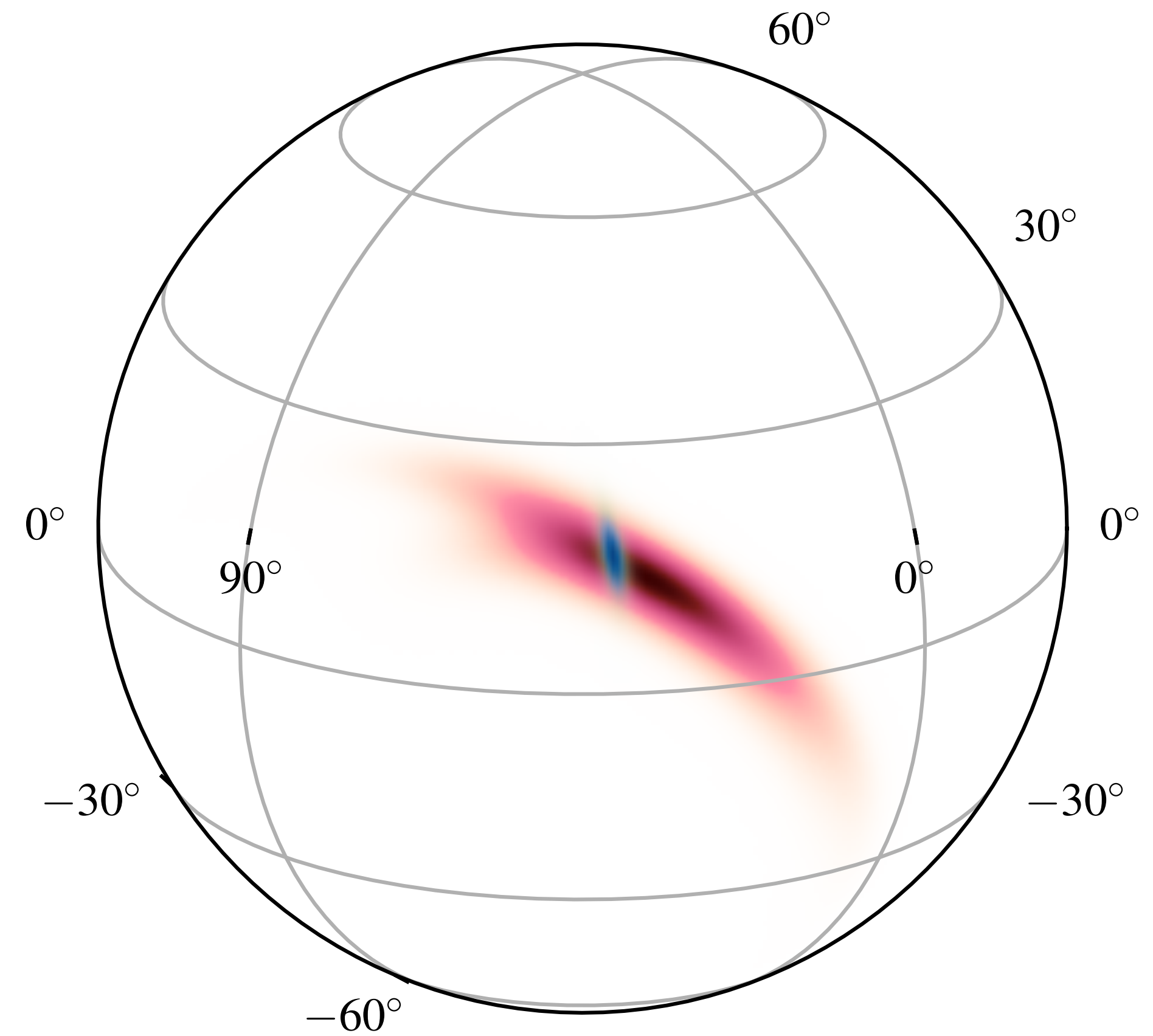
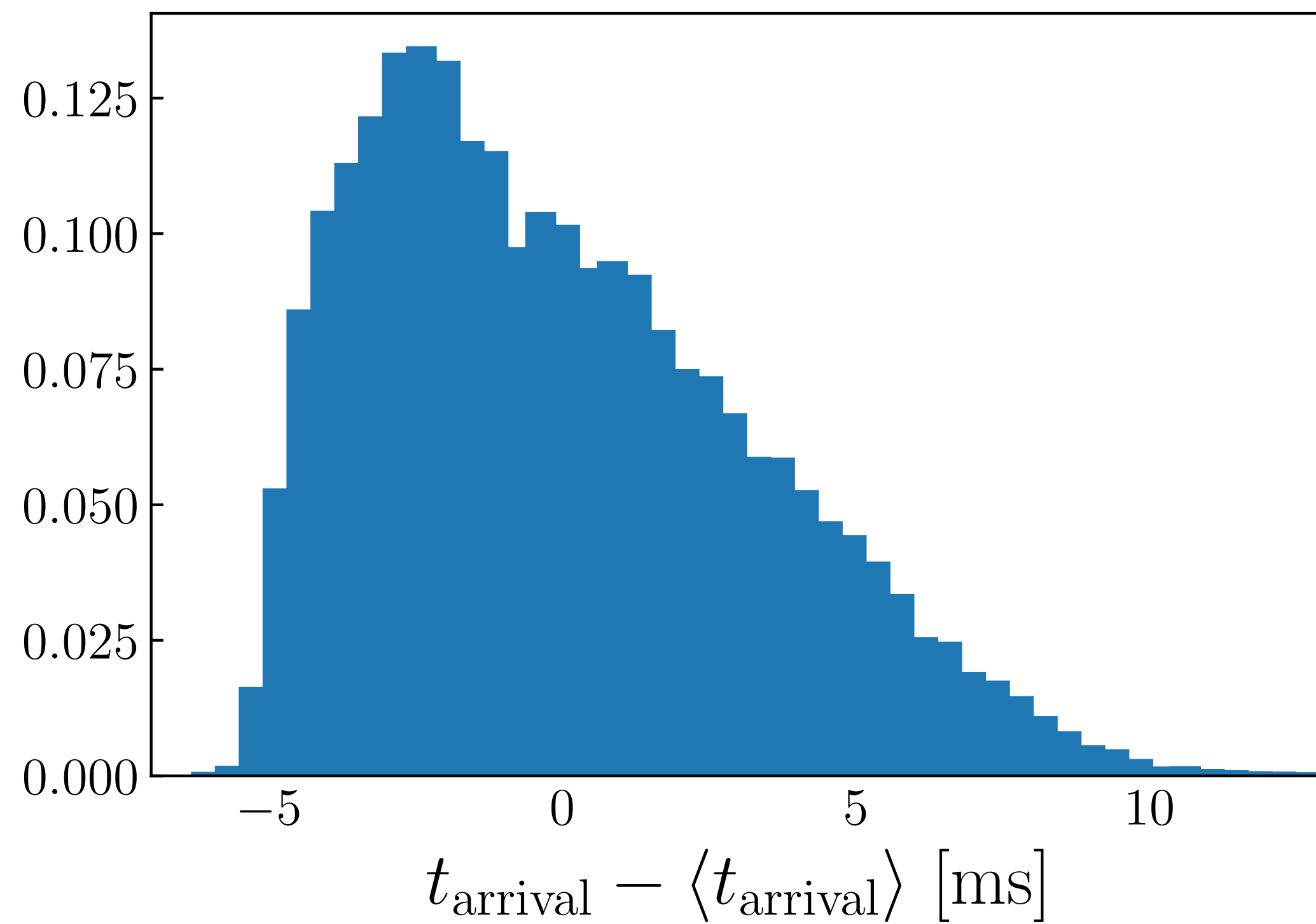
Gravitational lensing rarely produces high-mass outliers!



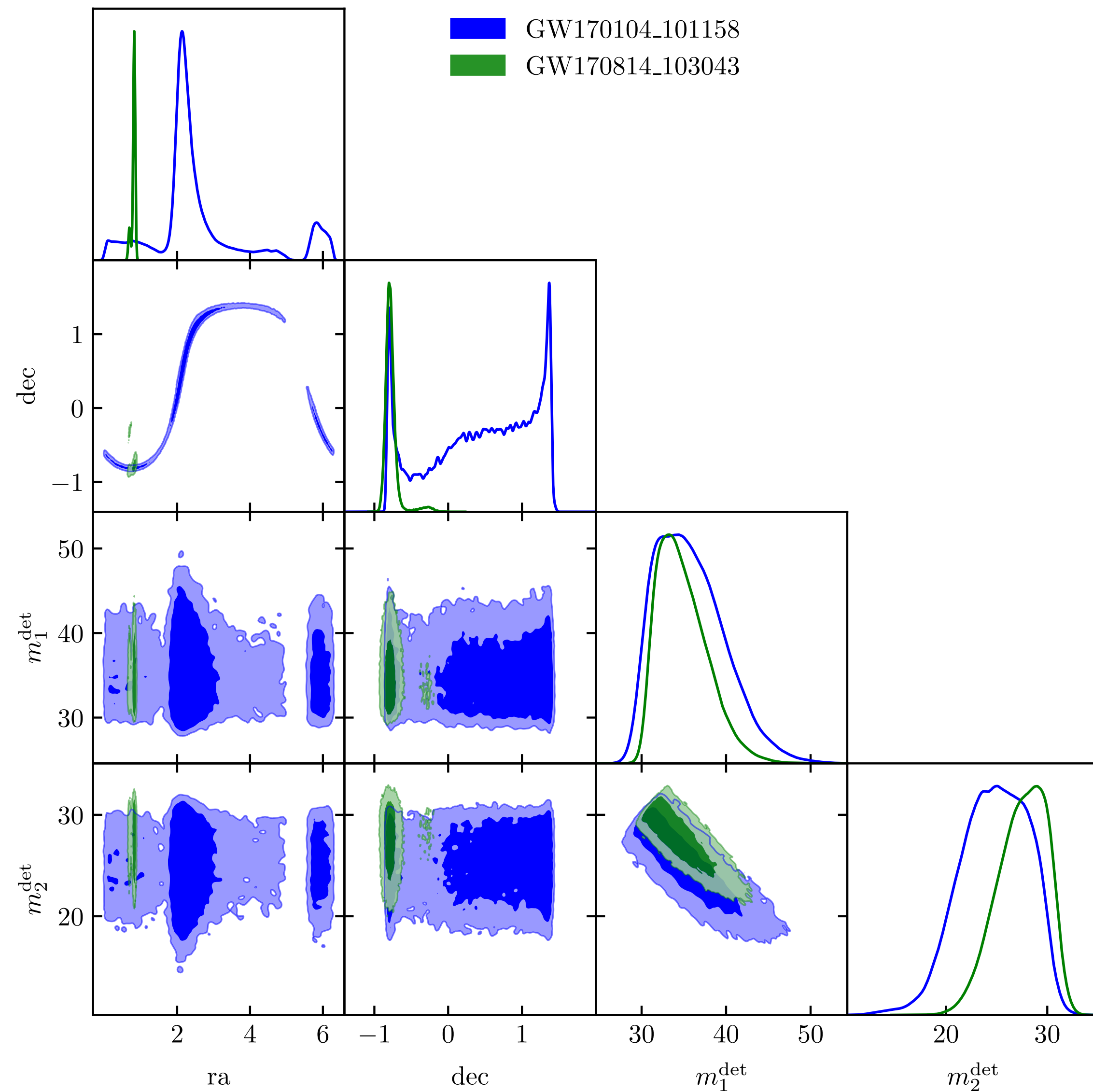
*high-magnification tail exaggerated for illustrative purposes

Strongly lensed GWs: *precise timing, poor sky localization*

$$\theta_E \sim 1'' \sqrt{\frac{M}{10^{12} M_\odot}} \sqrt{\frac{1 \text{ Gpc}}{D}}$$



Lensing or luck?

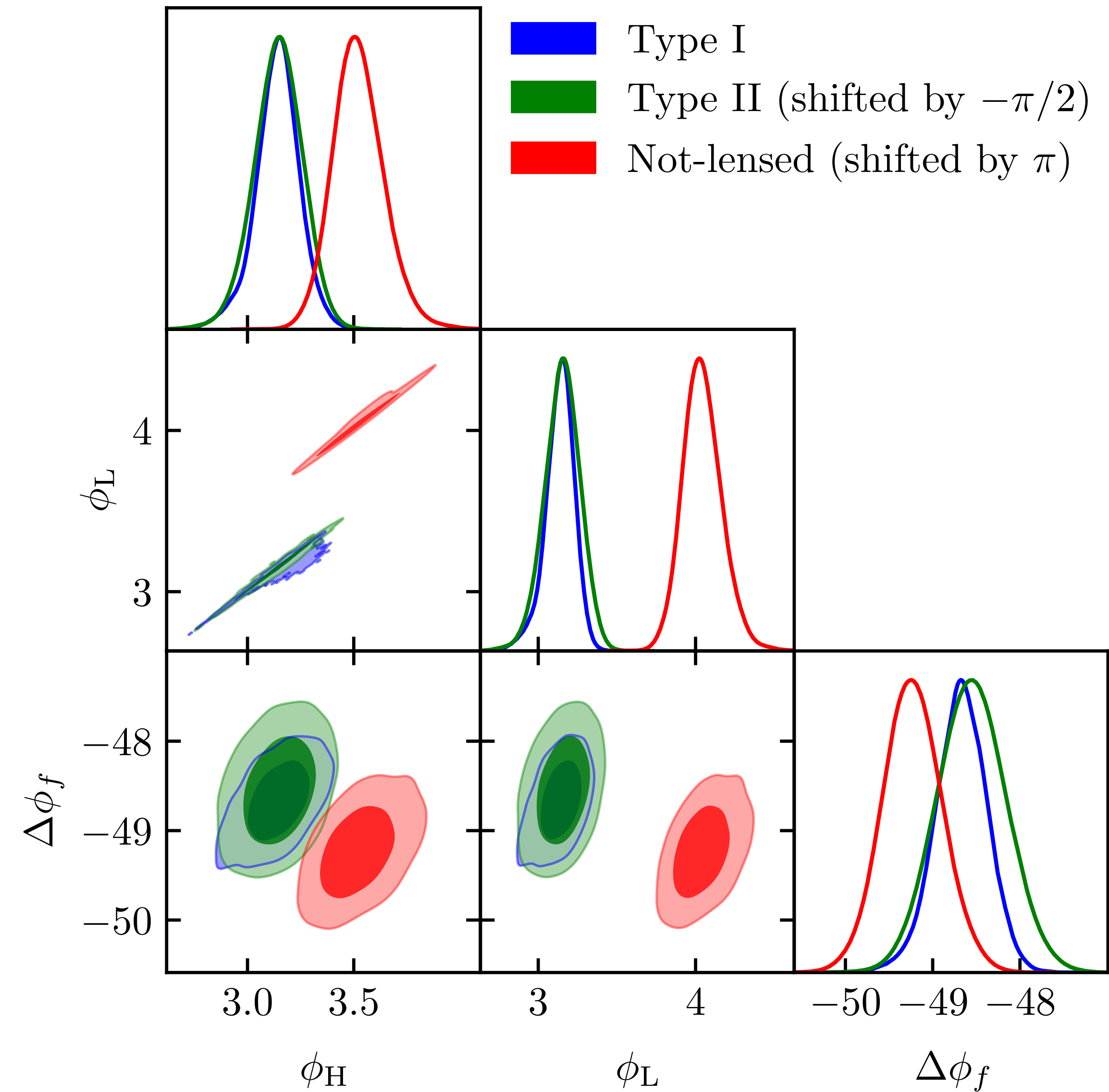


- False alarm probability rapidly increases

$$N_{\text{false alarm}} \sim N^2$$

[*Çalışkan, Ezquiaga, Hannuksela and Holz; PRD'22*]

Lensing or luck?



- False alarm probability rapidly increases

$$N_{\text{false alarm}} \sim N^2$$

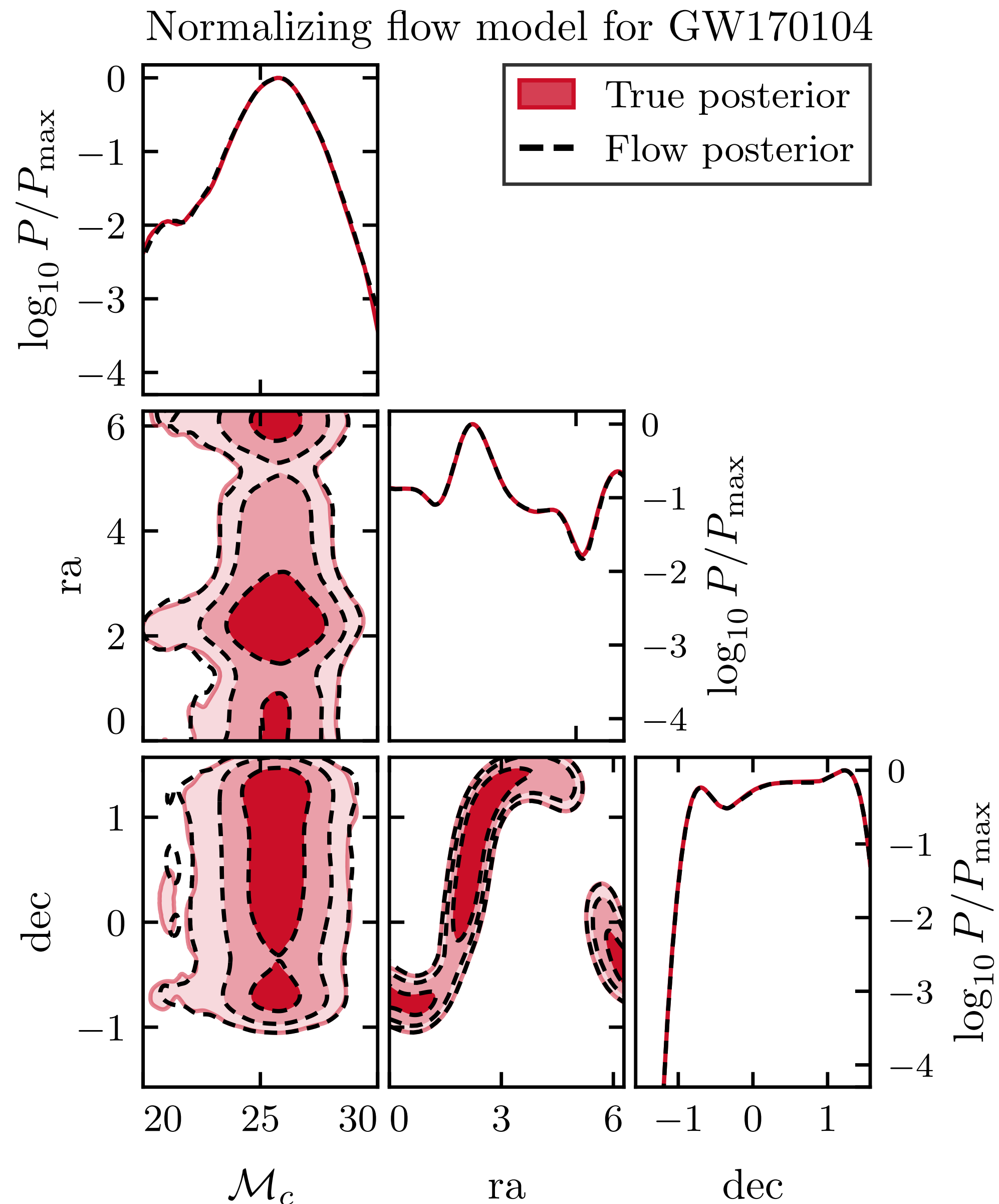
[Çalışkan, Ezquiaga, Hannuksela and Holz; PRD'22]

- Look at consistency of detector phase instead!

[Ezquiaga, Hu, Lo; PRD'23]

<https://github.com/ezquiaga/phazap>

Lensing or luck?



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[*Çalışkan, Ezquiaga, Hannuksela and Holz; PRD'22*]

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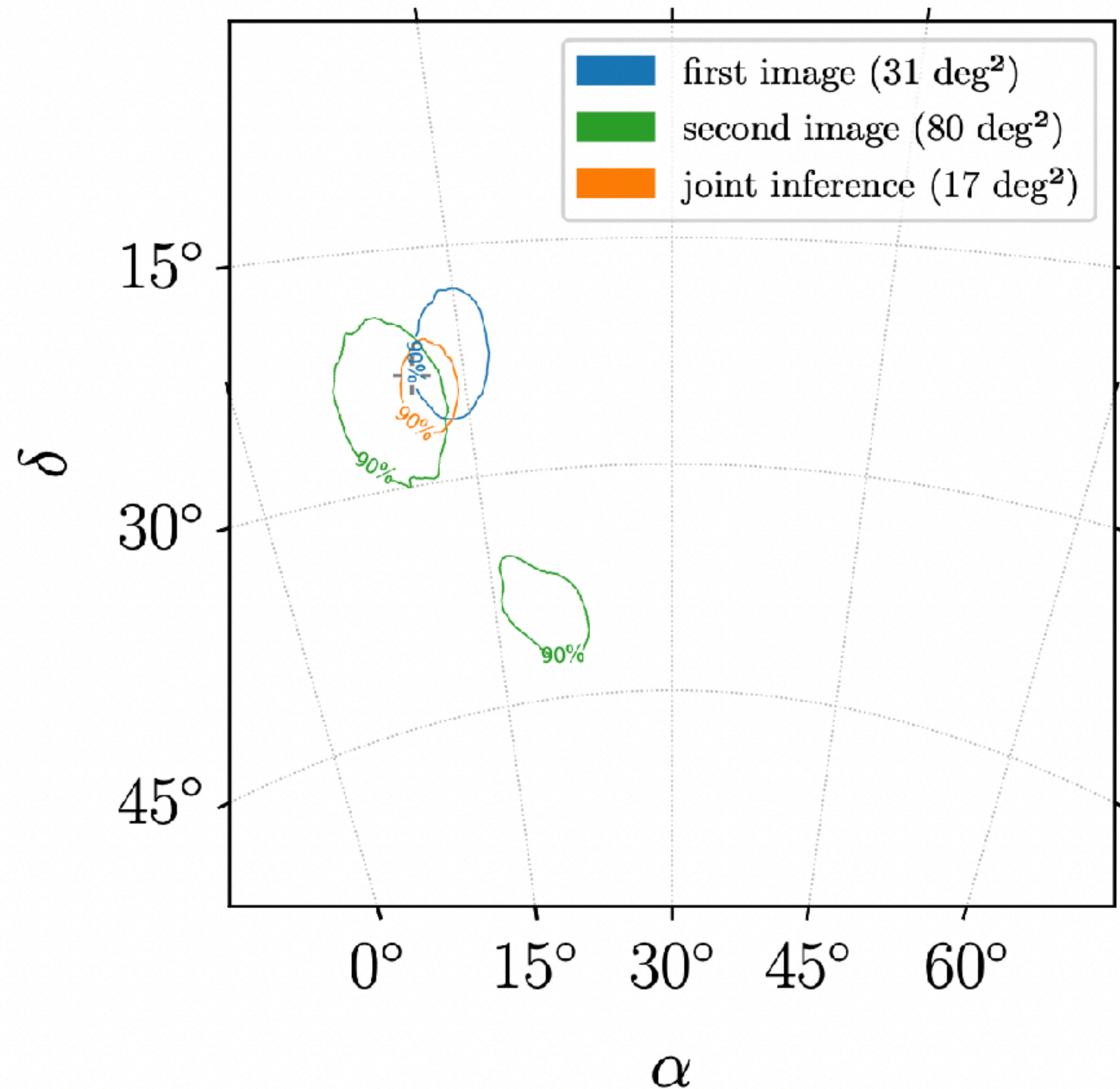
[**Ezquiaga, Hu, Lo; PRD'23**]

<https://github.com/ezquiaga/phazap>

- Consistency of detector phase instead without approximations using normalizing flows

[*Campailla, Raveri, Hu, Ezquiaga; '25*]

Lensing or luck?



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[*Çalışkan, Ezquiaga, Hannuksela and Holz*; PRD'22]

- Look at consistency of detector phase instead!

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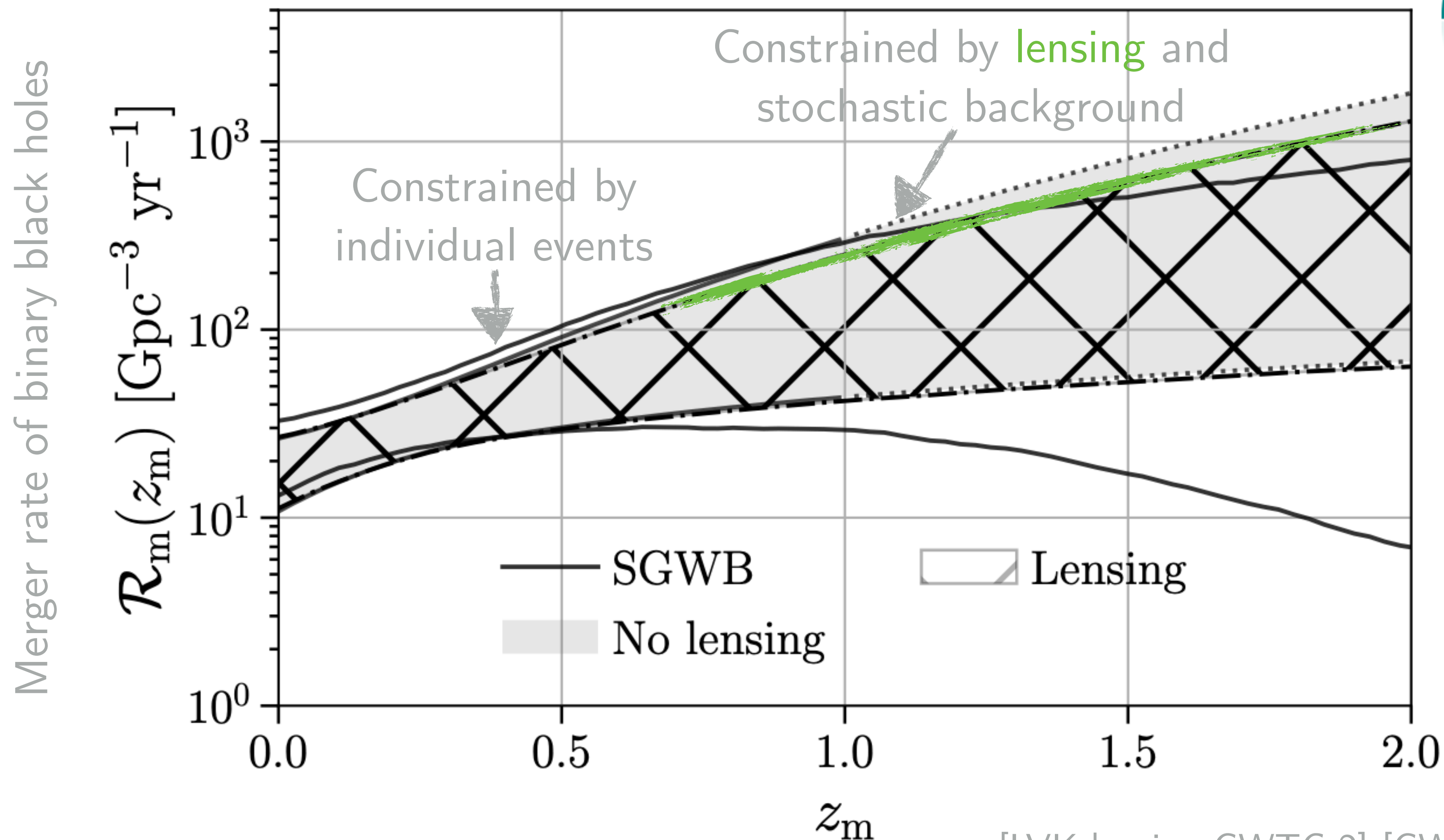
- Consistency of detector phase instead without approximations using normalizing flows

[*Campailla, Raveri, Hu, Ezquiaga*; '25]

- Final word: joint parameter estimation

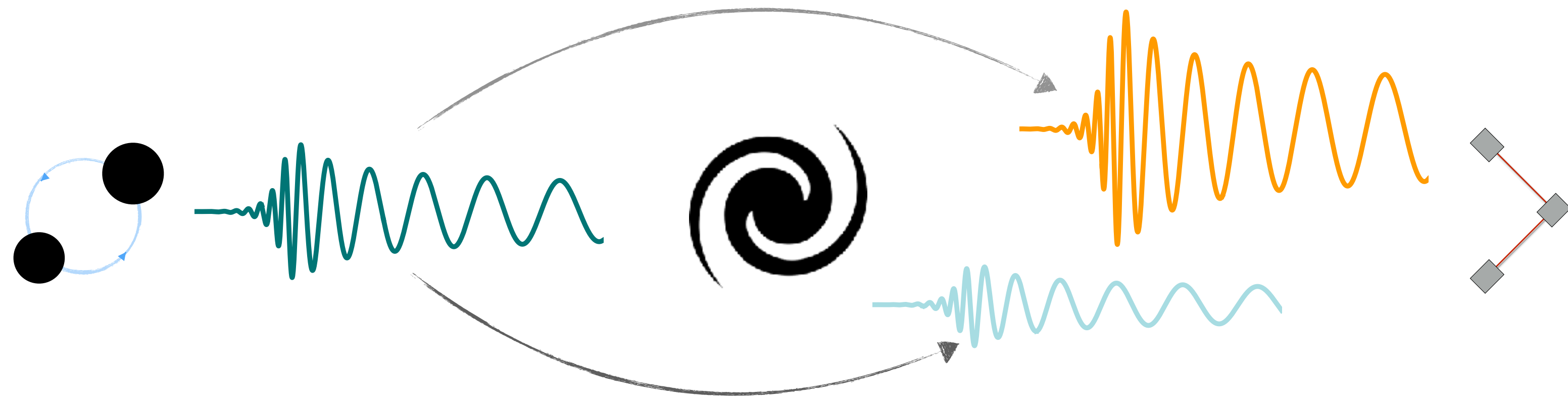
[*golum, Janquart et al.; hanabi, Lo et al.*]

LVK lensing searches: *no evidence* for repeated chirps in *GWTC-4*

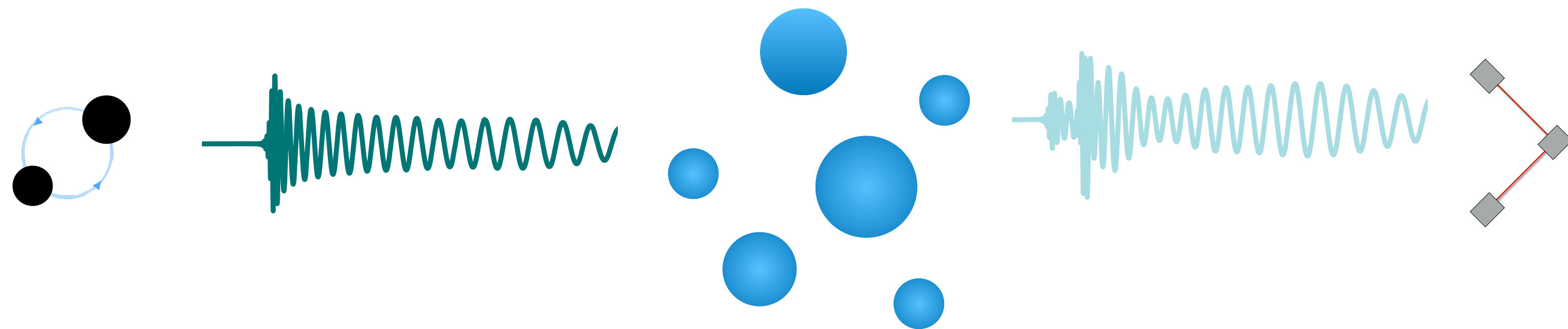


Searches for gravitational-wave lensing

Repeated chirps due to strong lensing



Waveform distortions by substructures

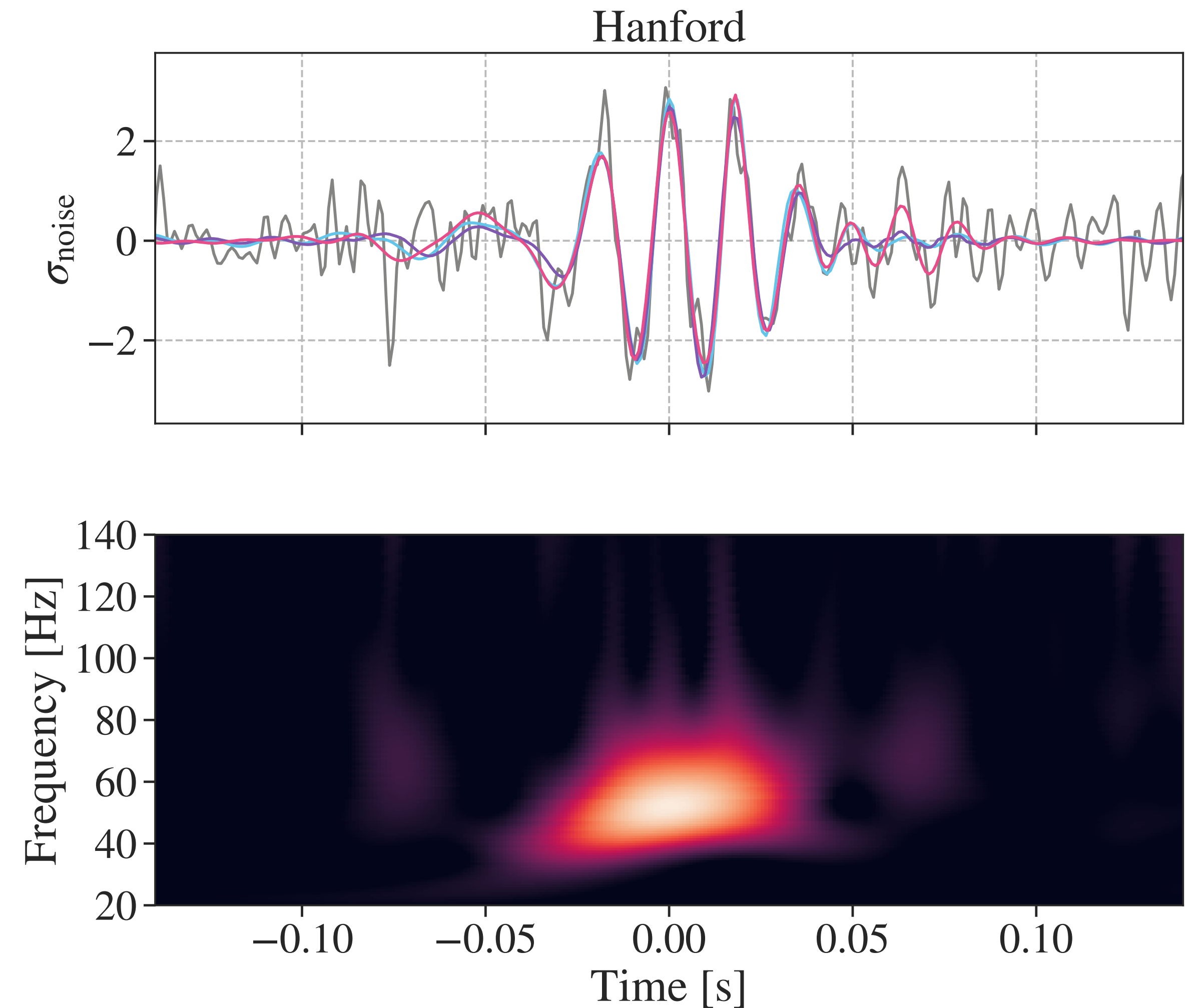
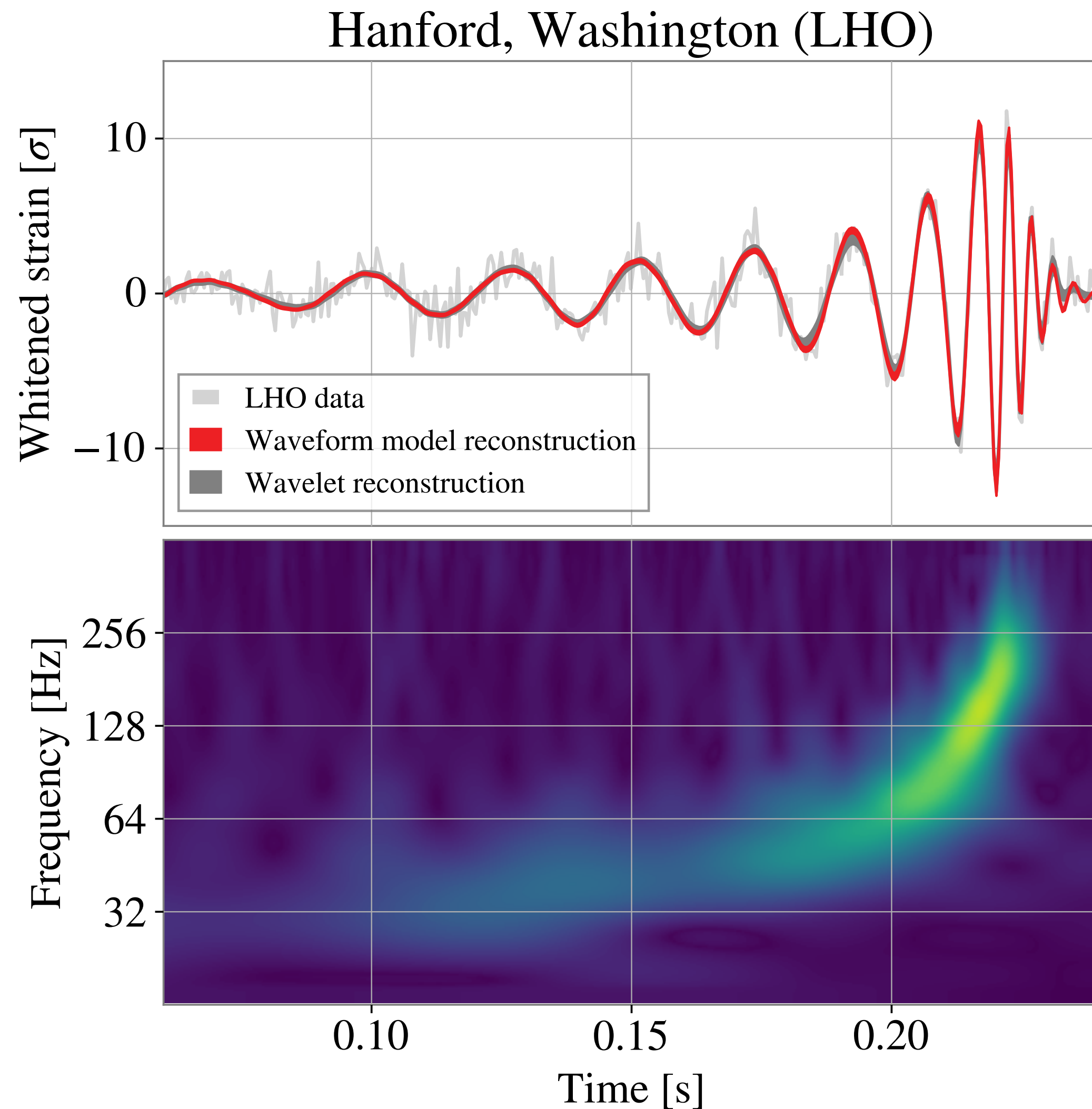


Source

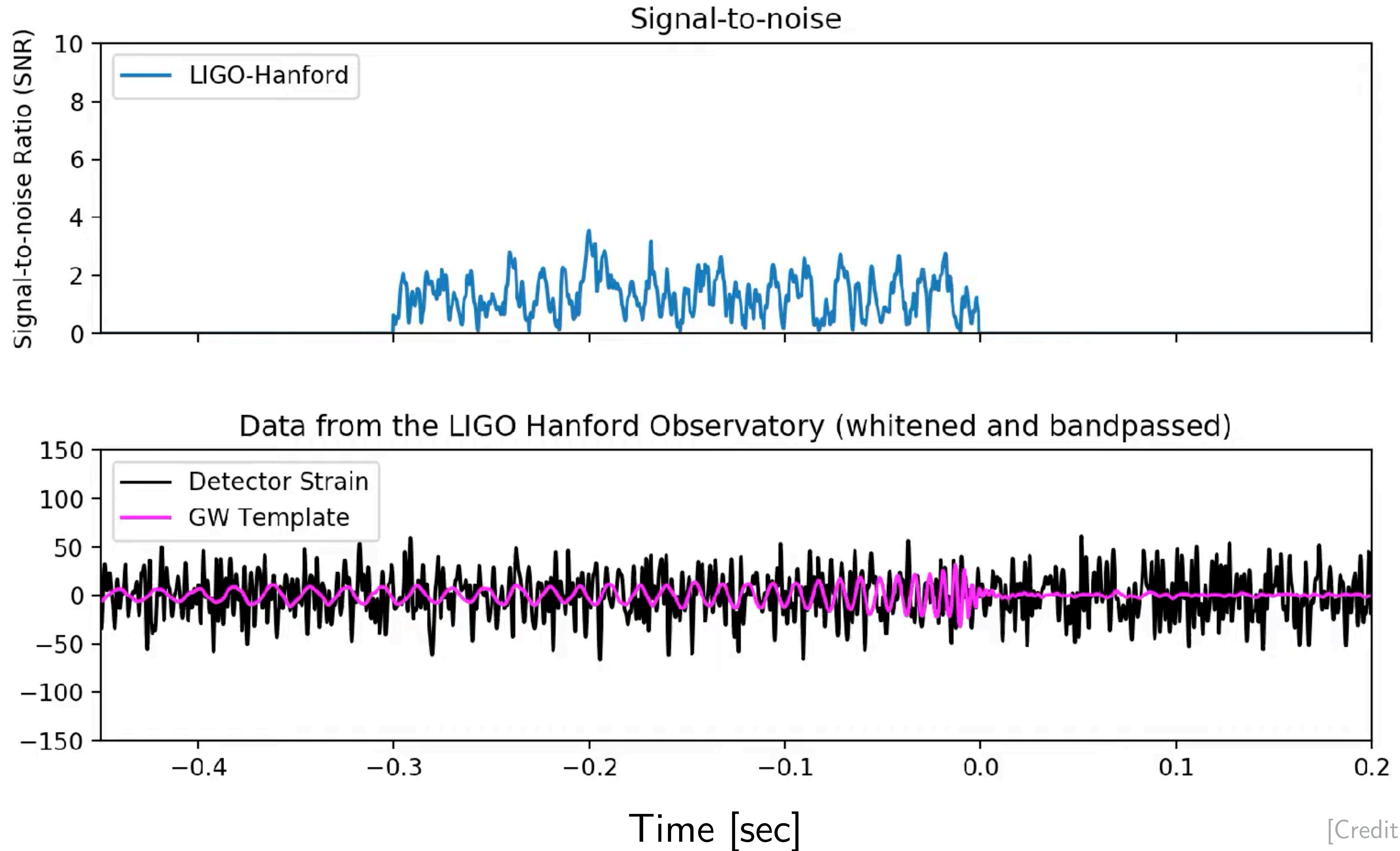
Lens

Detector

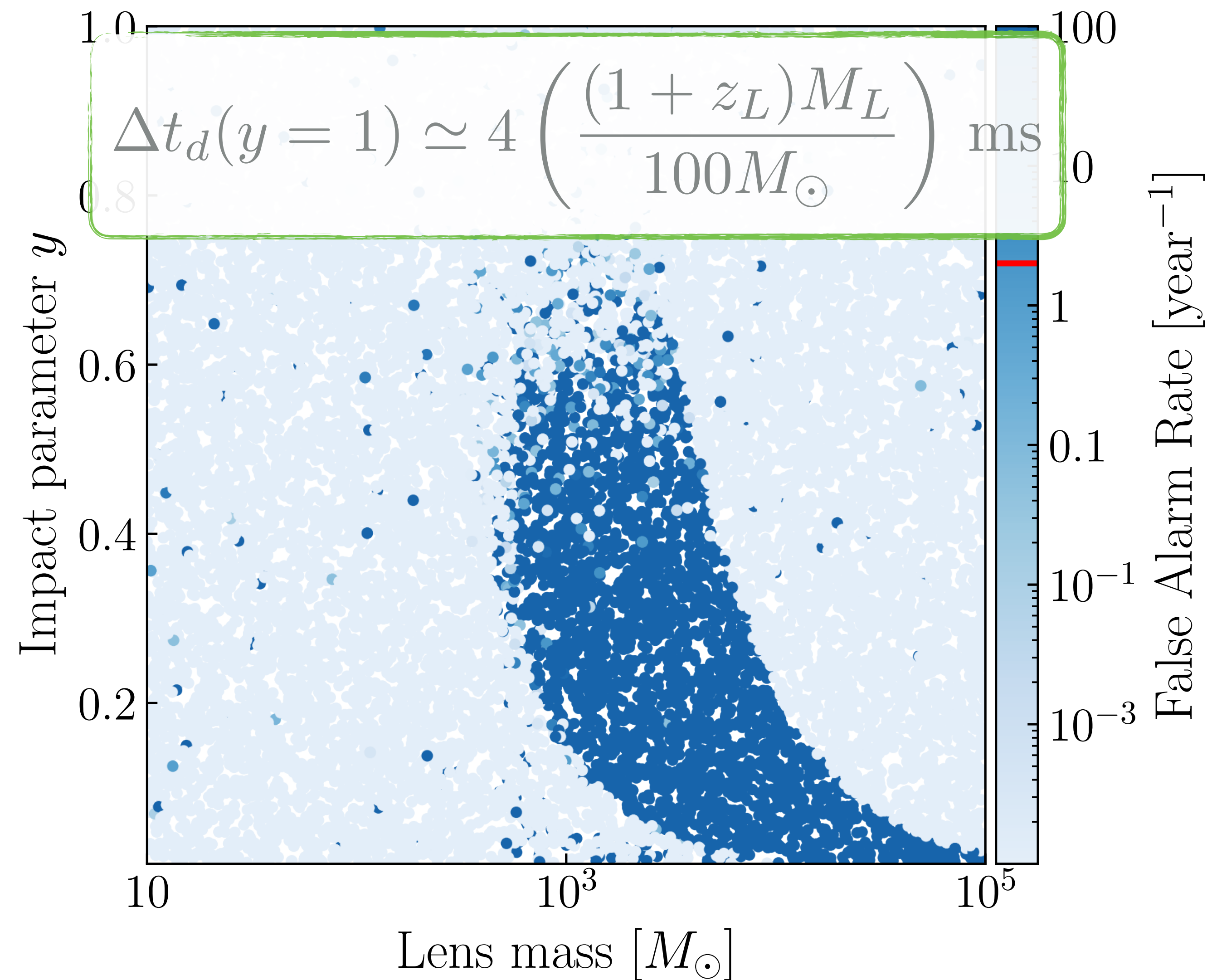
Key question: are GW signals described by nonlensed general relativity predictions?



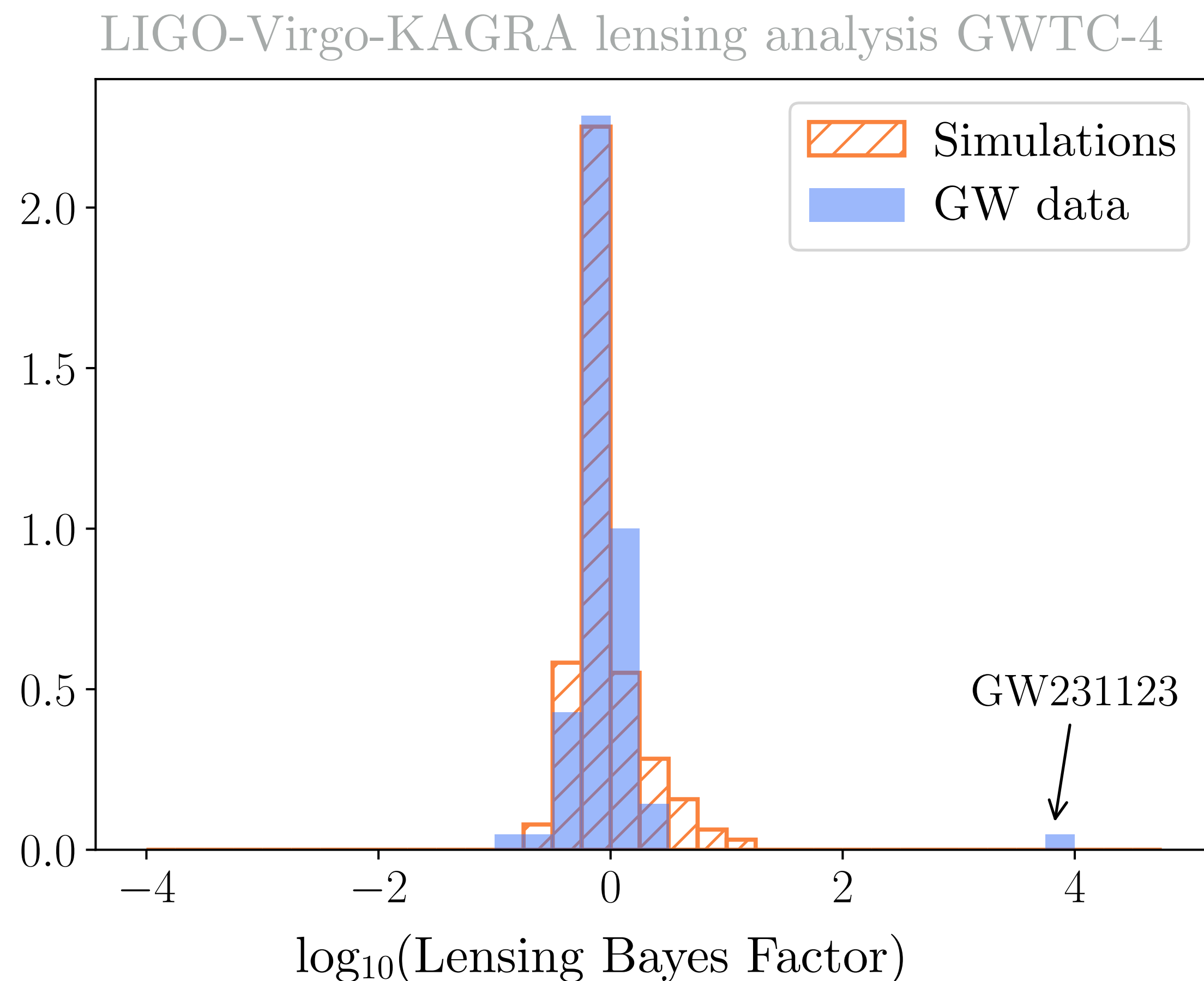
Matched-filtering



GW searches: distorted events could be *missed* by current matched-filtering pipelines



GW231123: an *intriguing* lensing candidate found in GWTC-4



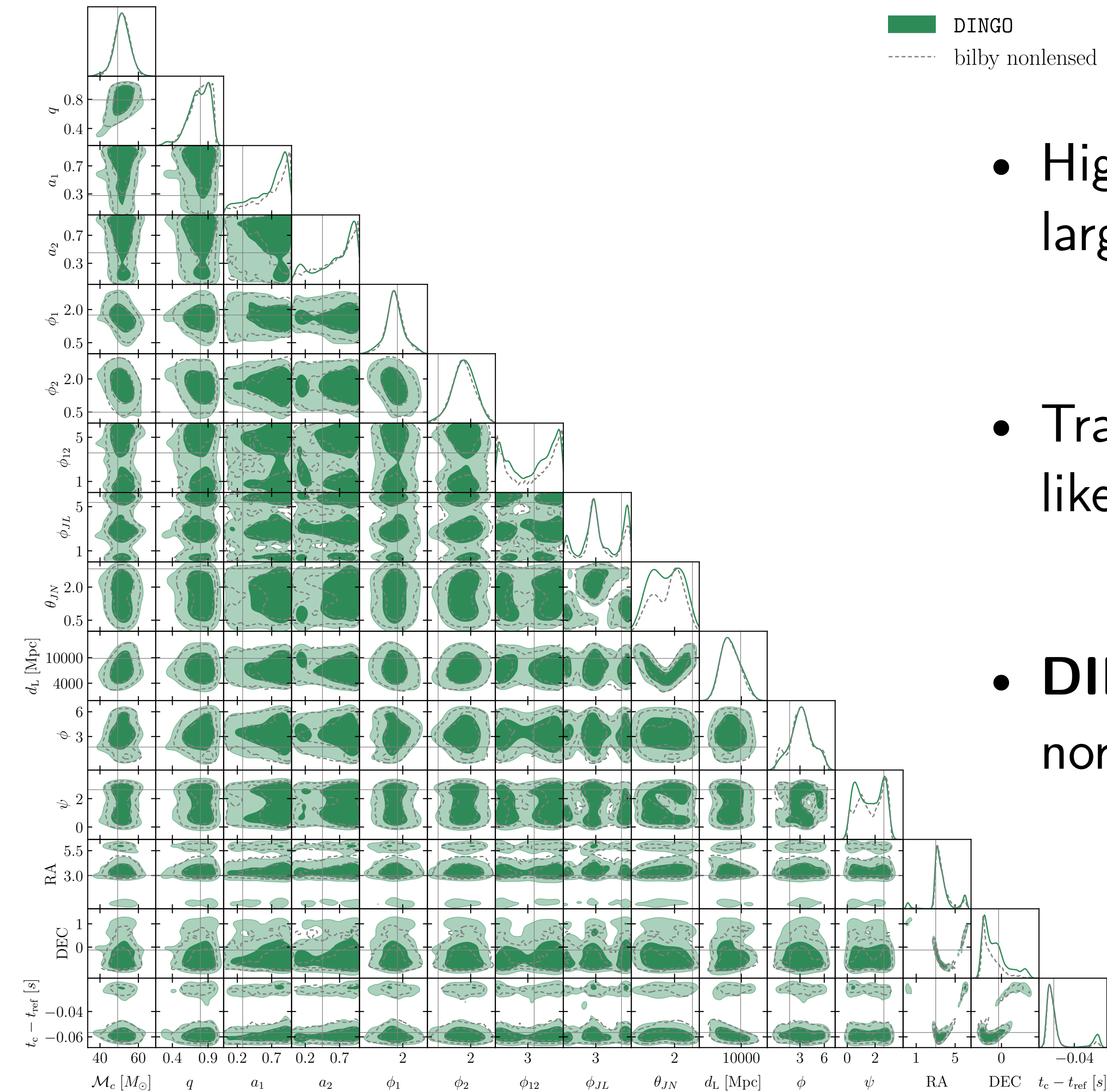
- GW231123 is the *most massive* and the *most highly spinning* BBH to date
- Also, the *highest-ranked* lensing candidate (inferred lens mass $\sim 1000 M_{\odot}$)

Challenges:

- A “ 5σ detection” requires *millions* of simulations
- Computationally intractable with conventional methods

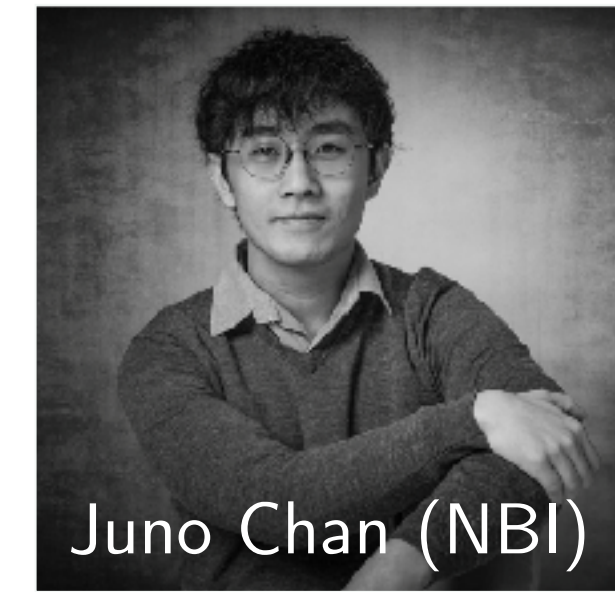
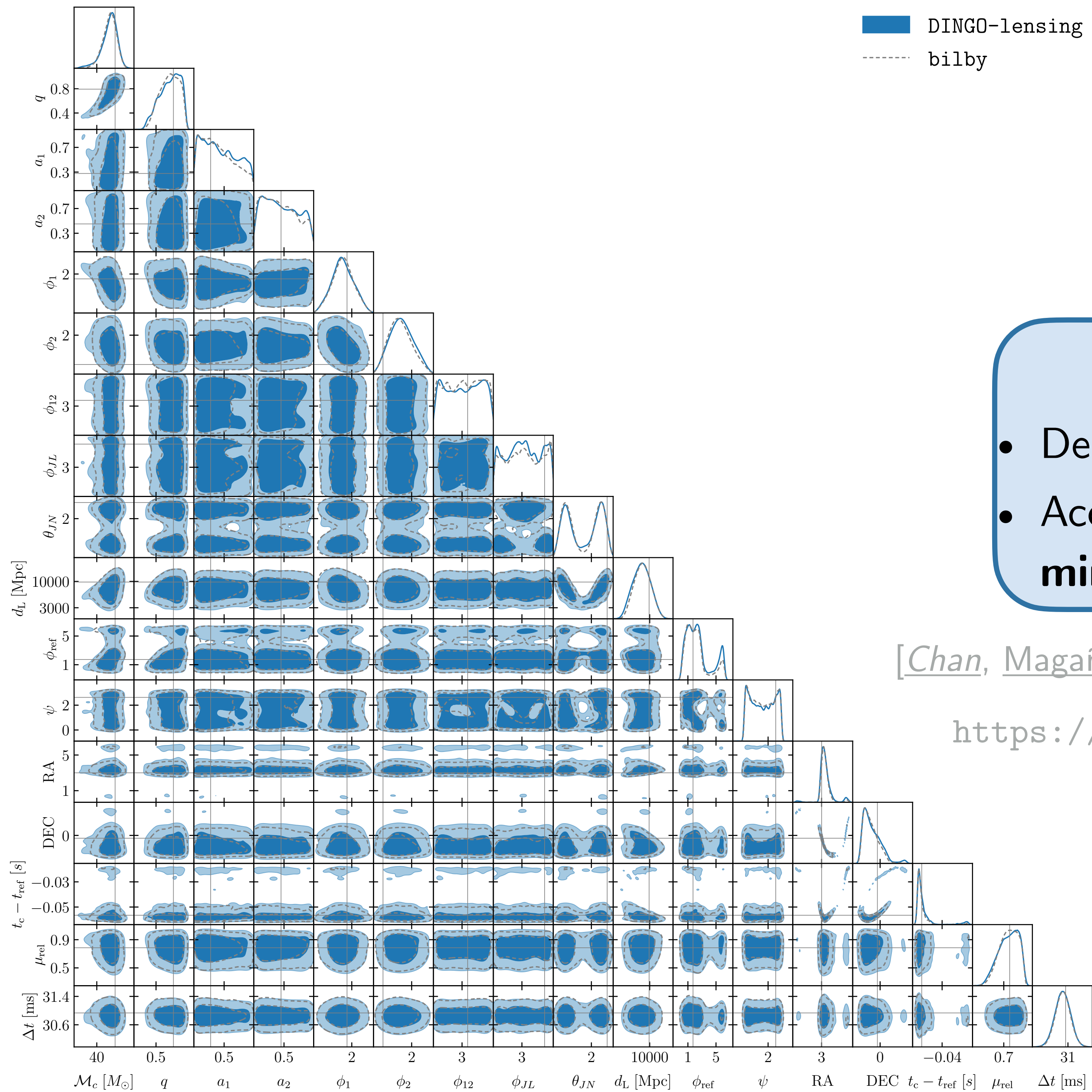
Accelerating the discovery
of lensed GWs

Accelerating gravitational-wave inference



- High-dimensional (15+) parameter estimation with large correlations, uncertainties and multimodality
- Traditional methods stochastically sample the likelihood millions of times (need fast waveforms!)
- **DINGO**: simulation-based inference with normalizing flows

[Dax et al. PRL'21]



Juno Chan (NBI)

Lorena Magaña

(NBI)

DINGO-lensing

- Deep-learning inference for lensed GWs
- Accelerate analysis from (CPU) **days to minutes**

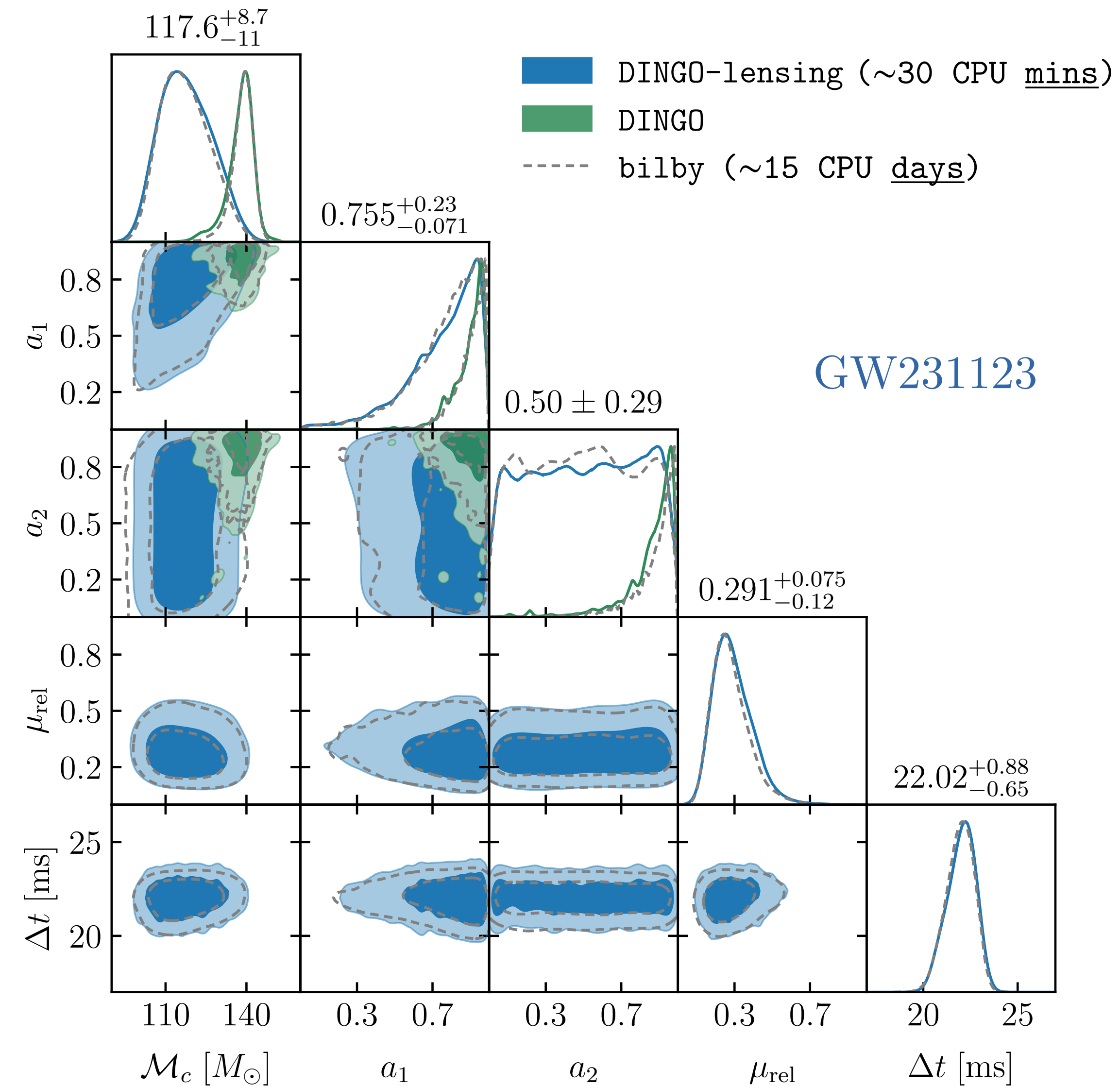
[[Chan](#), [Magaña-Zertuche](#), [Ezquiaga](#), Lo, Vujeva, Bowman PRD'25]

<https://github.com/dingo-lensing/dingo-lensing>



A deep-learning analysis of GW231123

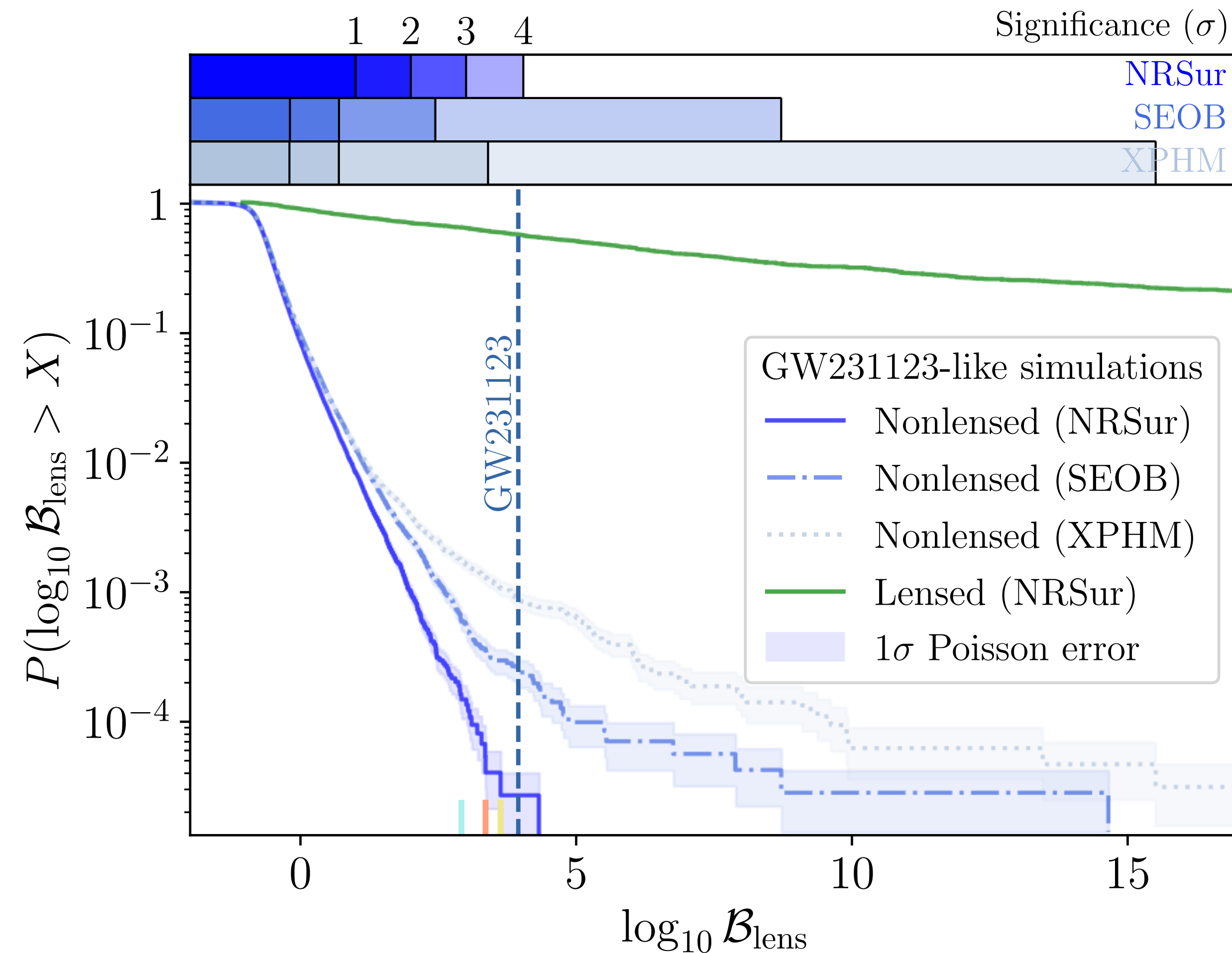
- With **DINGO-lensing**, we trained a neural network and performed *200,000+* simulations
- LVK and other groups only ~ 250 sims
- Neural networks key specifications:
 - Waveform: NRSur7dq4
 - Chirp mass $[30, 180]$ Msun
 - Mass ratio $[1/6, 1]$
 - Lensing time delay $(0, 0.1)$ sec
 - Relative magnification $(0, 1)$



A deep-learning analysis of GW231123

- With **DINGO-lensing**, trained neural network and performed *200,000+* simulations
- LVK and other groups only ~ 250 sims

- Statistical significance **cannot exceed 4σ**
- With waveform systematics, significance *drops* to $\sim 3\sigma$
- Lensing time delay matches the period of the signal



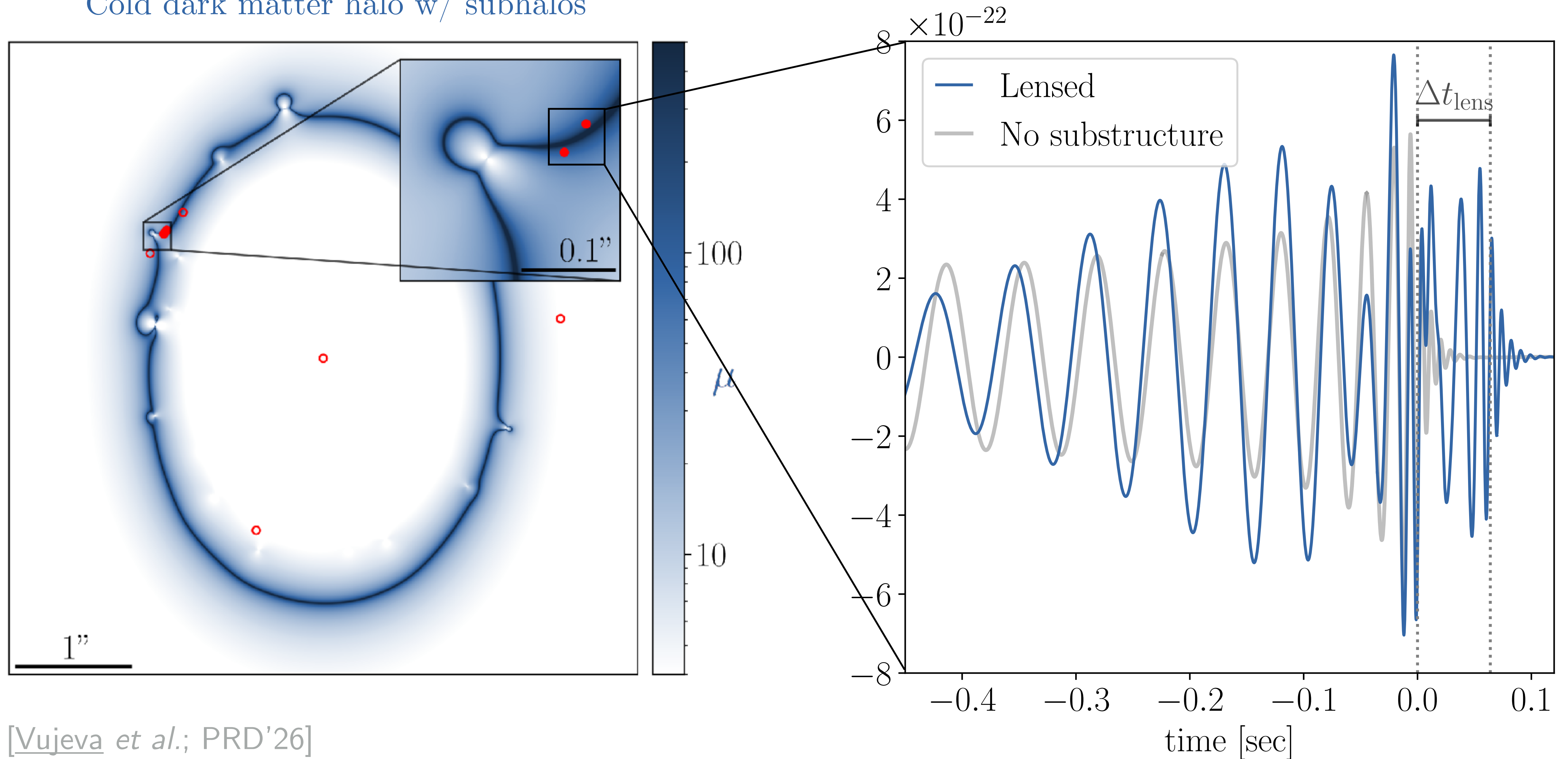
New probes of Cosmology & Astrophysics

Probing dark matter (sub)structures



Luka Vujeva (NBI)

Cold dark matter halo w/ subhalos

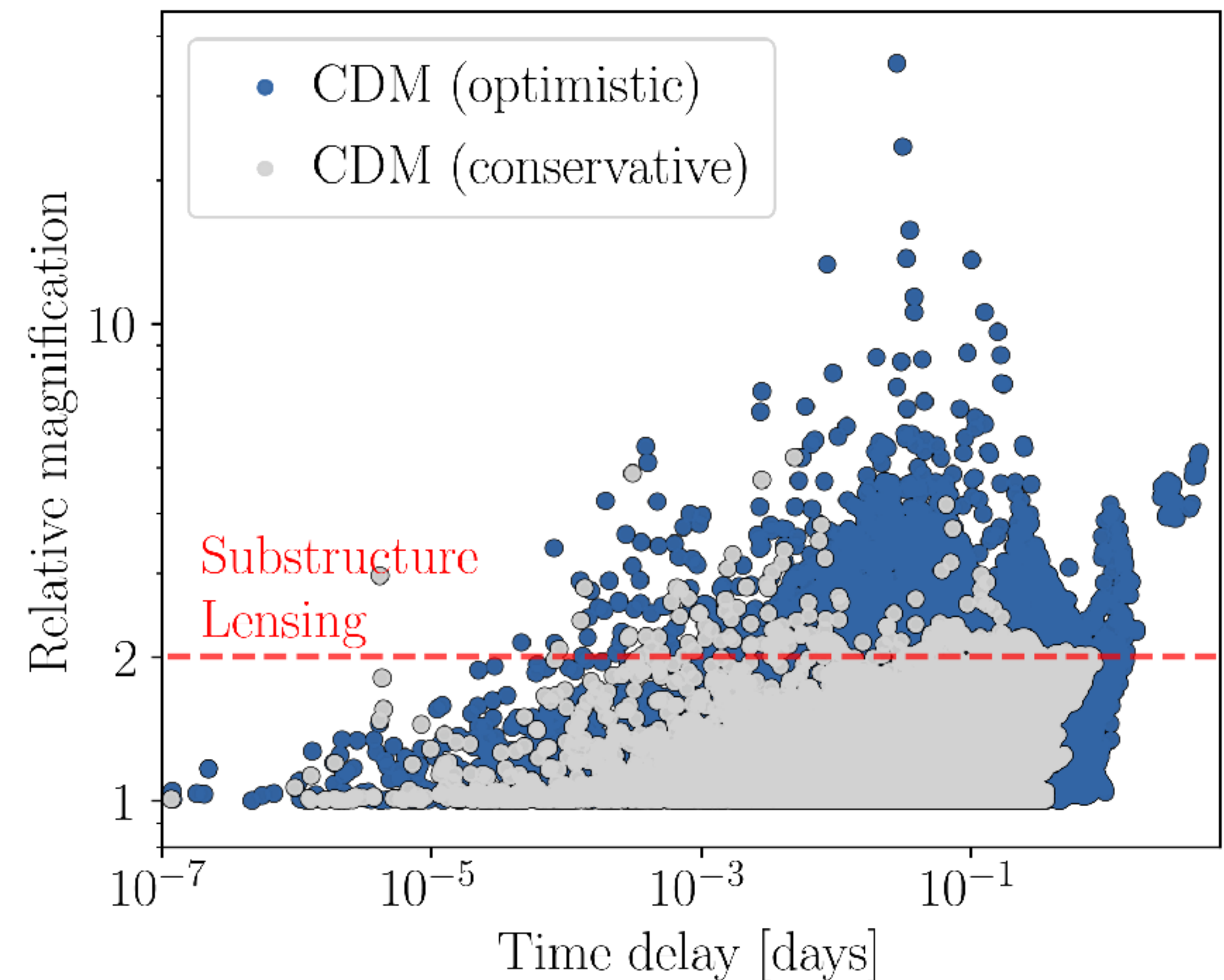


Probing dark matter (sub)structures: higher-order caustics



- Substructure produces more images, shorter time delays, relative magnifications > 2 and *distorted waveforms*

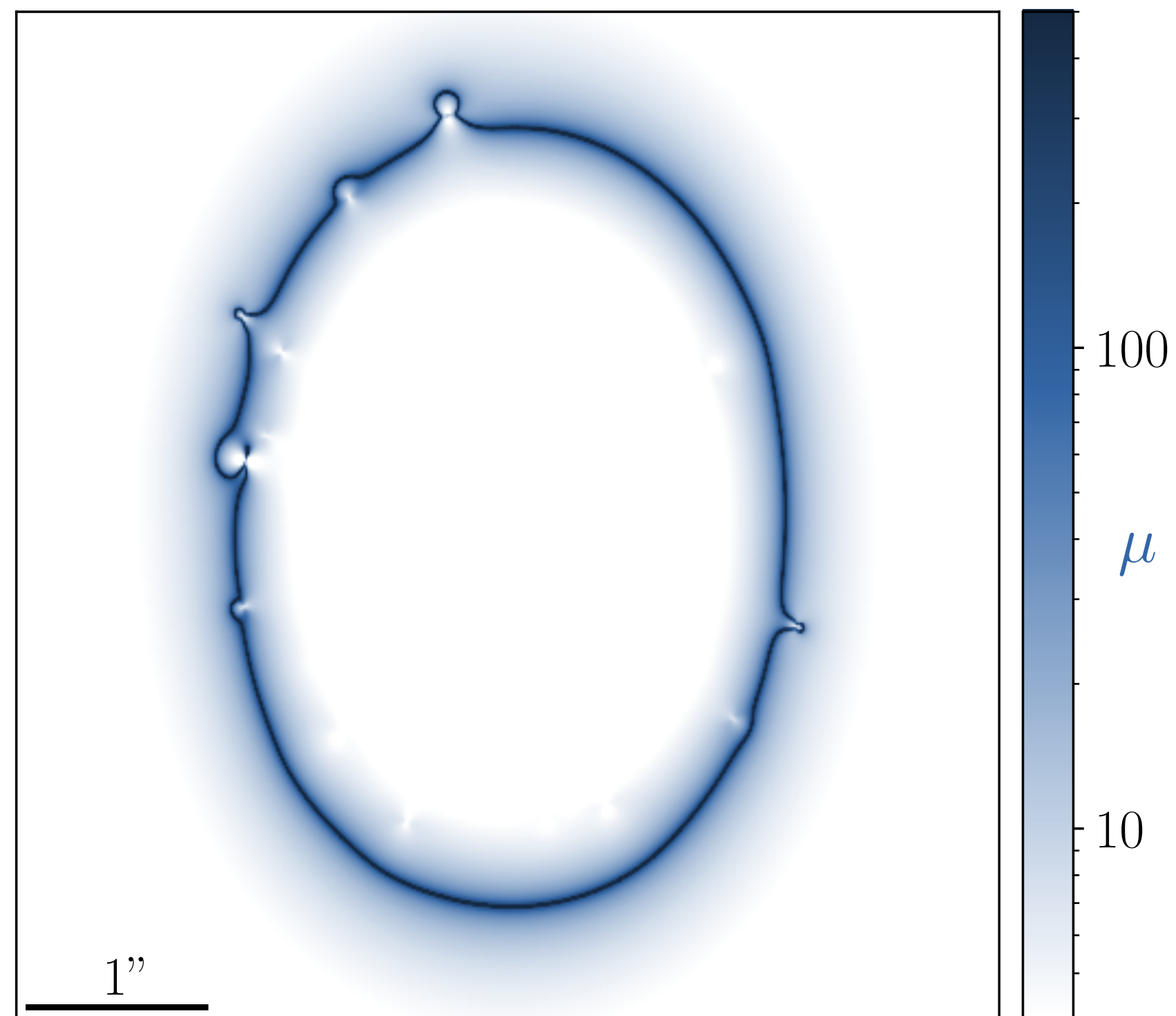
- A small change in subhalo *concentration* **boosts** effects of substructure
- Even larger for other scenarios! (e.g., self-interacting dark matter)



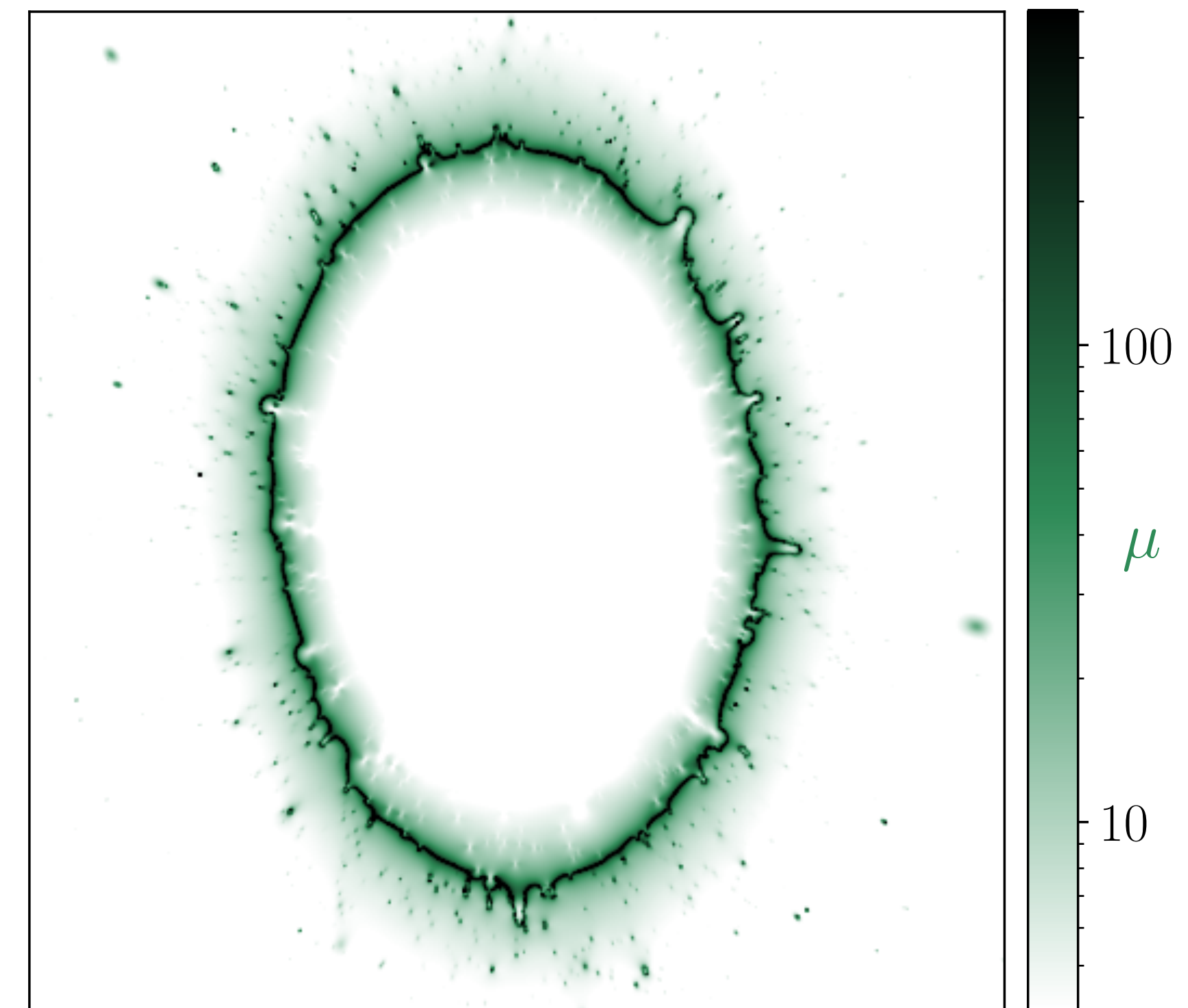
Probing dark matter (sub)structures: self-interactions



- Self-interacting dark matter subhalos may undergo gravothermal collapse
- Effects of substructure increase both in *geometric optics* (number of repeated signals) and in *wave optics* (*waveform distortions*)

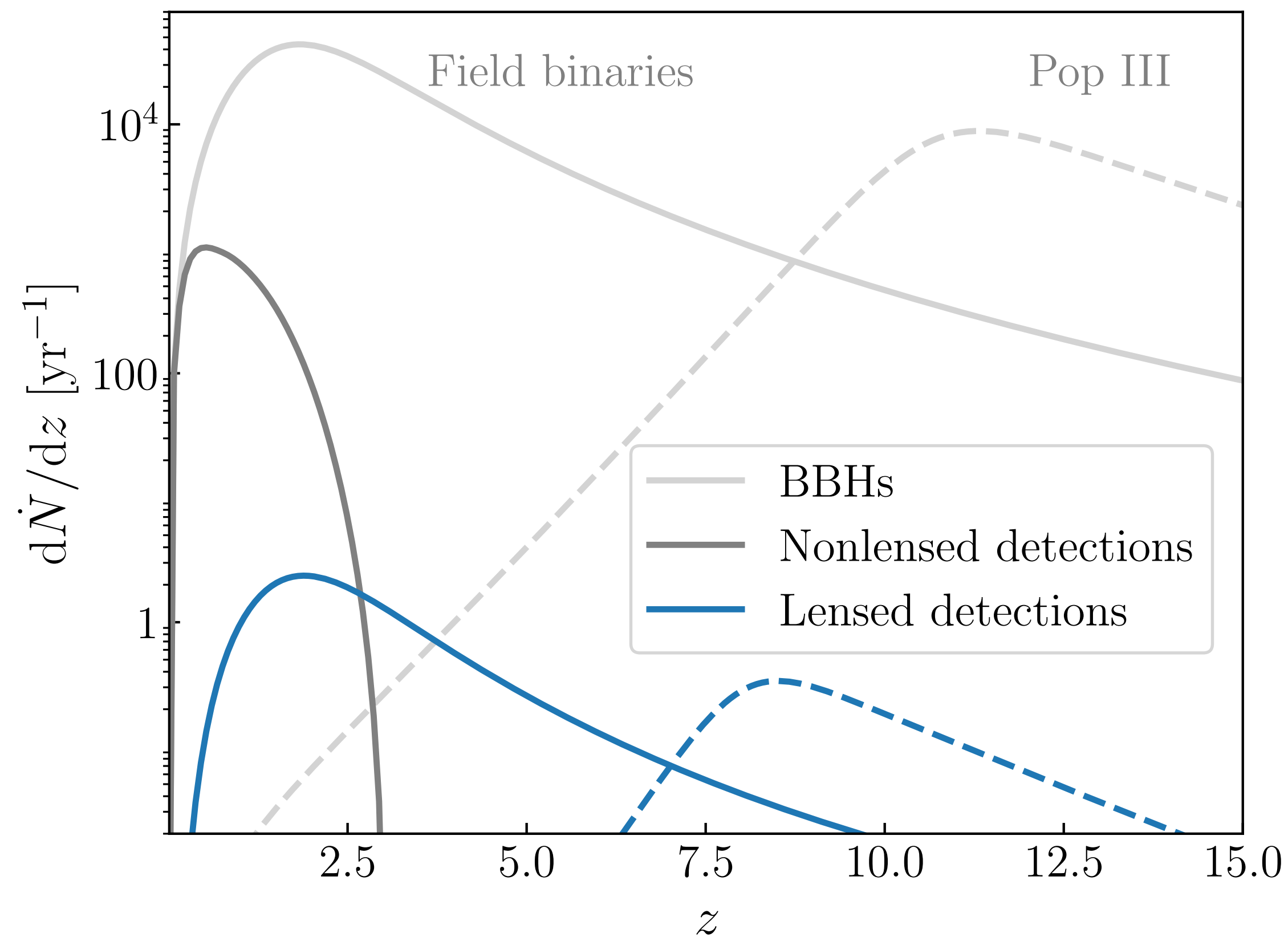


Cold dark matter



Self-interacting dark matter

Discover new black holes and lenses: population inference

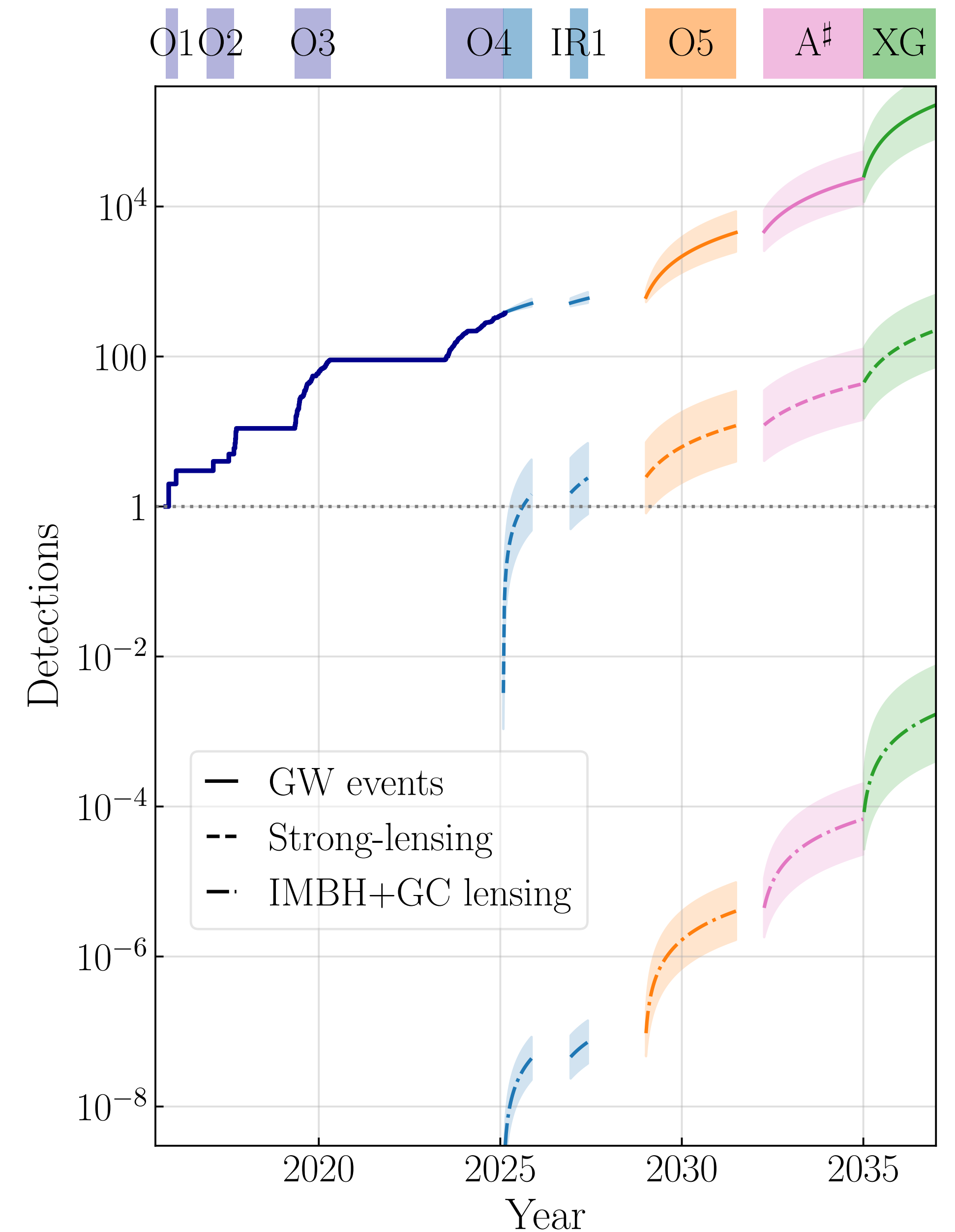


- *Certain*: BBHs **beyond** peak star formation
- *Likely*: high- z formation channels (Pop III)
- *Possible*: **new** physics (primordial BHs)

- Goal: *joint GW population analysis* including astrophysics, cosmology and lensing
- Improve constraints on compact lenses by **two orders of magnitude**

GW lensing by intermediate-mass black holes & globular clusters

- *At most*, 1 in every 10,000 strongly lensed GWs
- Isolated IMBHs only *if* $\sim$ few % dark matter

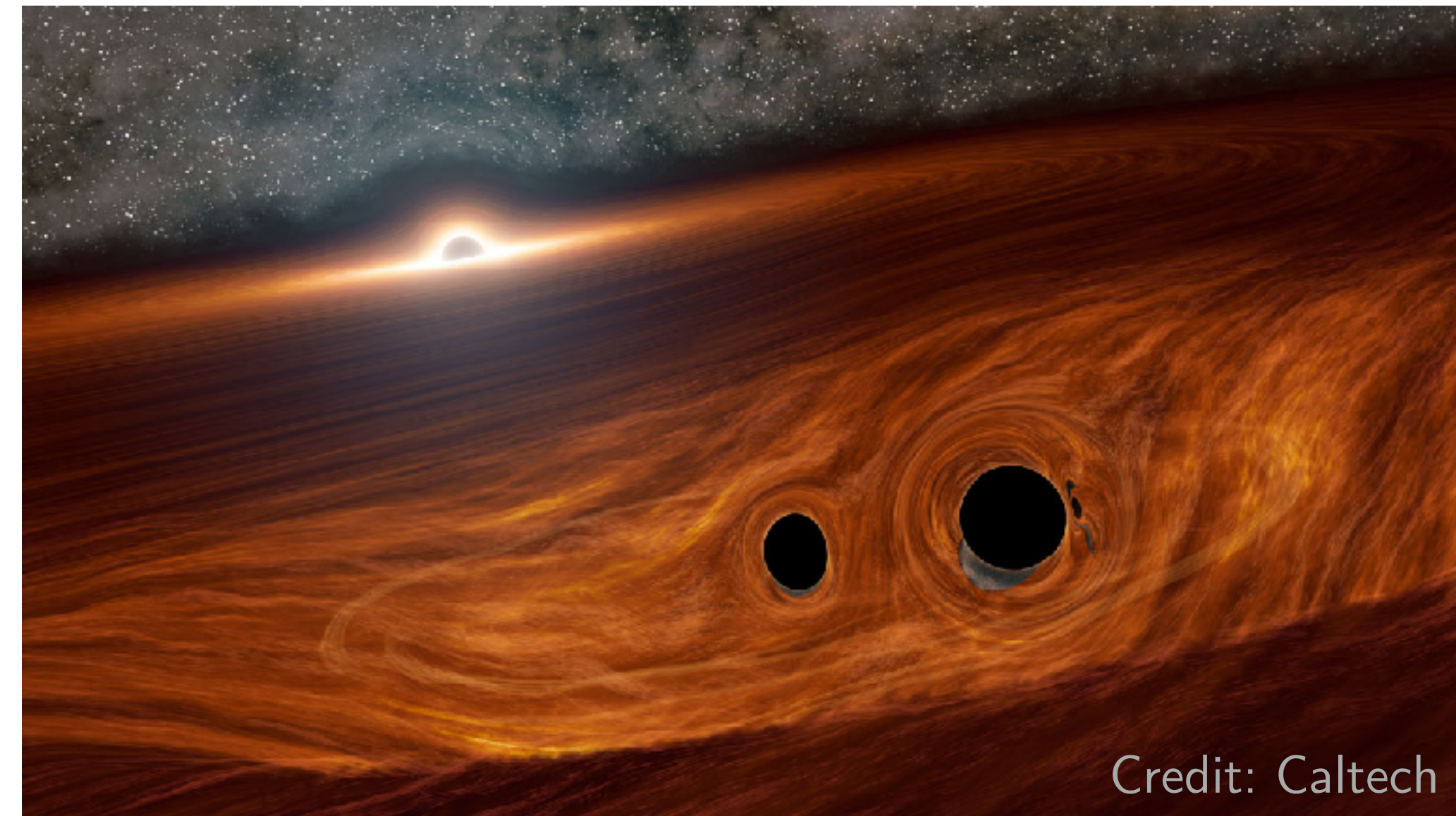
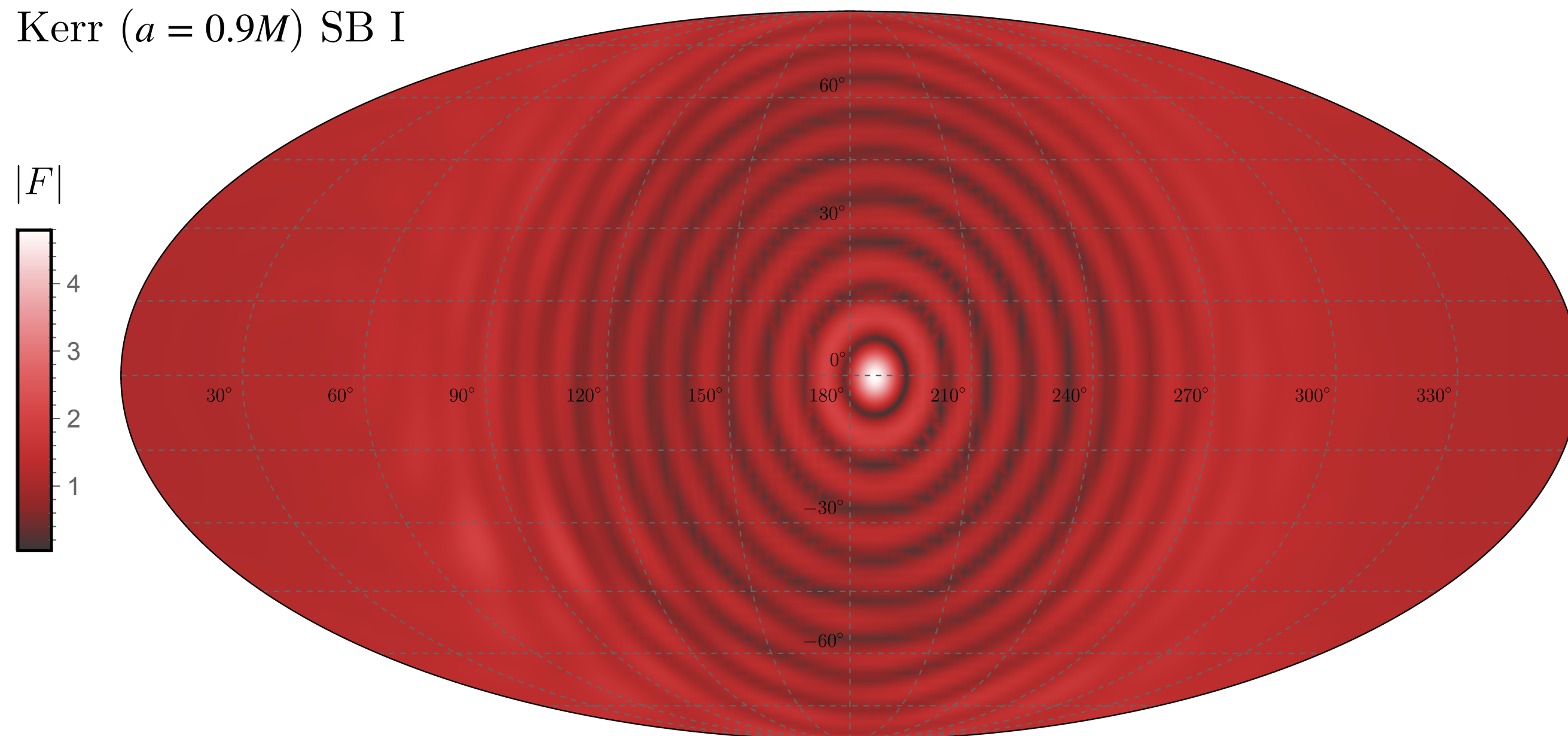


Binaries near supermassive black holes: strong-field lensing



- Black holes may merge in migration traps near active galactic nuclei
- The closer to the supermassive black hole, the more probable lensing and *strong-field* effects become

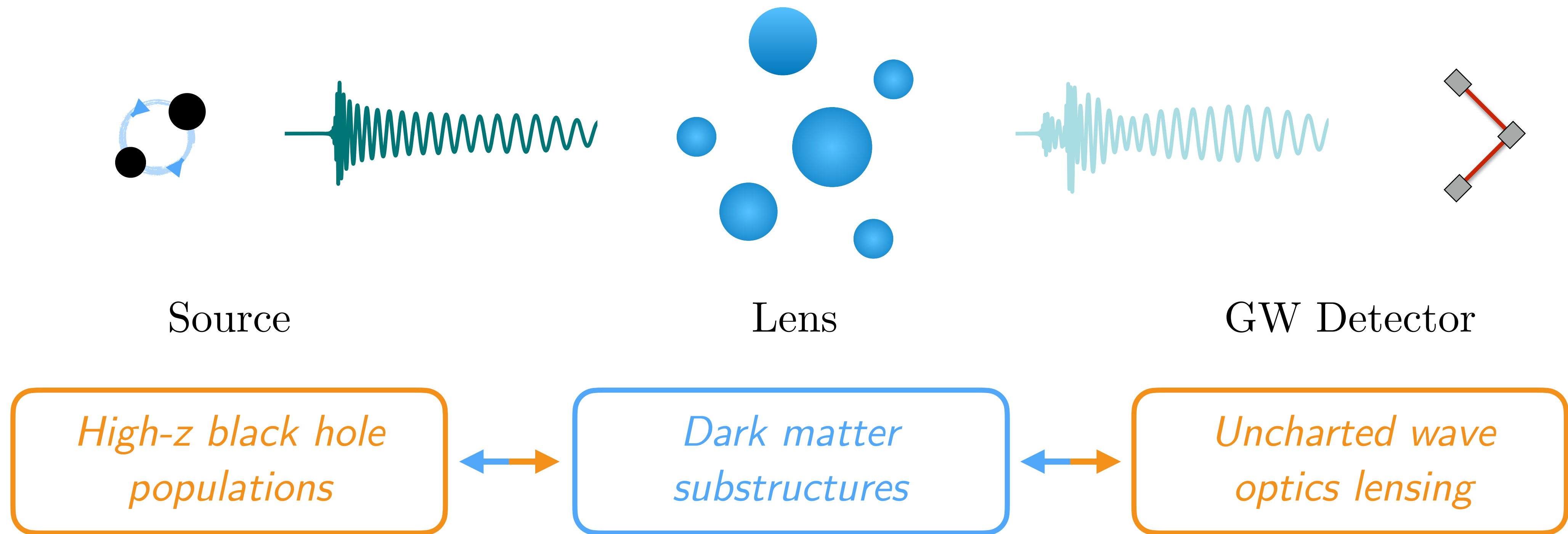
Kerr ($a = 0.9M$) SB I



Credit: Caltech

The road ahead

GW lensing will open *discovery frontiers* at high redshifts, zooming into dark matter



GW lensing requires *synthesizing* advances *beyond the state-of-the-art* in *theory, simulations & data analysis*

Understand

Wave-optics lensing +
substructures

theory+simulations

Identify

Matched-filtering +
accelerated inference

new analysis tools

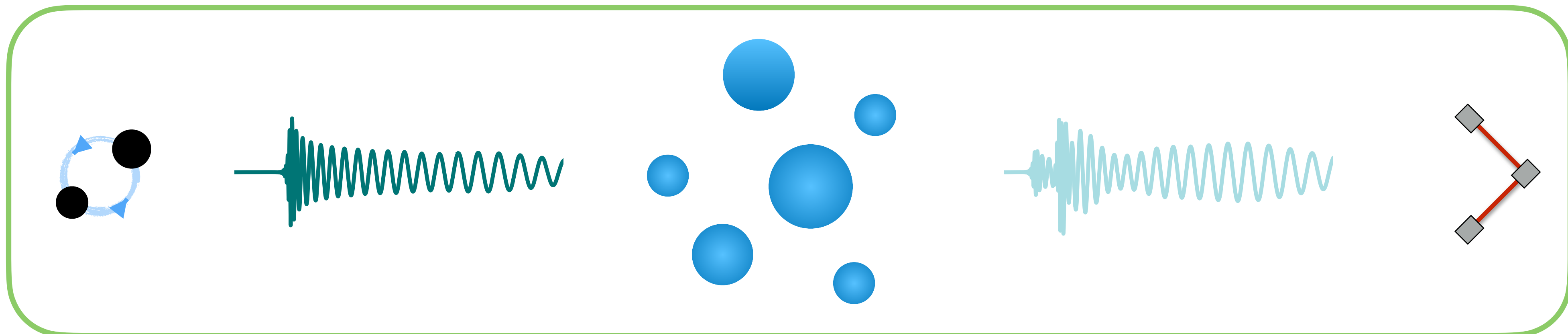
Discover

Population inference
+ constraints

LVK O4+O5 data

- First lensed GWs!
- Uncover high- z binary black holes
- Probe dark matter substructures

Goals



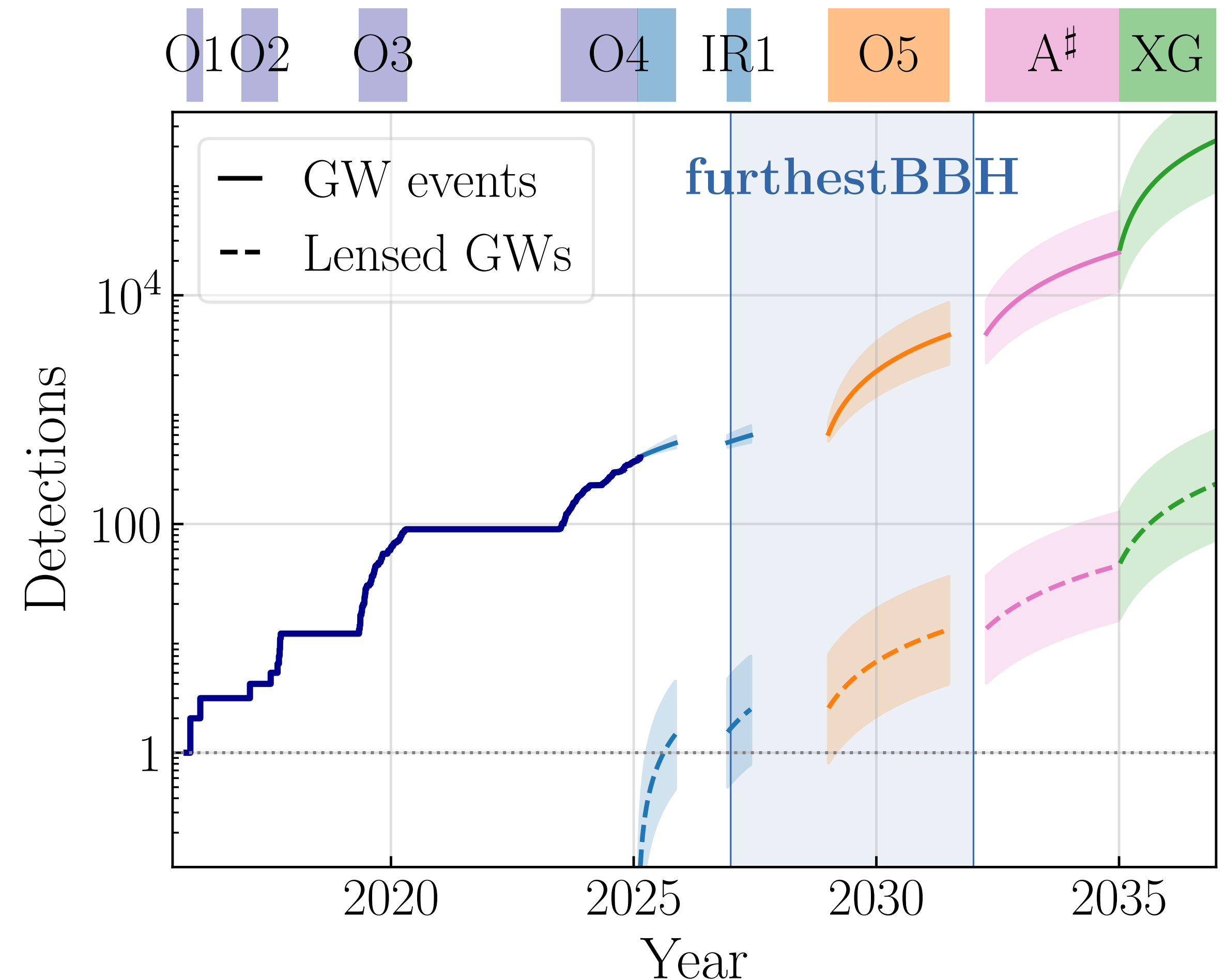
The furthest binary black holes: the next frontier in gravitational lensing

- Enable the *first* detections of lensed gravitational waves
- Uncover the *discovery* potential of the furthest binary black holes (gravity, cosmology & astrophysics)



European Research Council

Established by the European Commission



Gravitational Lensing in the era of Multi-Messenger Astronomy

19 - 23 October 2026, Leiden, the Netherlands @omega

Topics

- Gravitational lensing as seen by different messengers
- Towards detecting lensed binary neutron star mergers
- Astrophysics, Cosmology and Fundamental Physics with Multi-Messenger Lensing
- New frontiers in Multi-Messenger Lensing

Scientific Organizers

- Jose M. Ezquiaga, Niels Bohr Institute
- Anupreeta More, IUCAA
- Samaya Nissanke, DESY/DZA/University of Potsdam
- Graham Smith, University of Birmingham

The Lorentz Center organizes international workshops for researchers in all scientific disciplines. Its aim is to create an atmosphere that fosters collaborative work, discussions and interactions. For registration see: www.lorentzcenter.nl

Multi-messenger lensing: lenscat

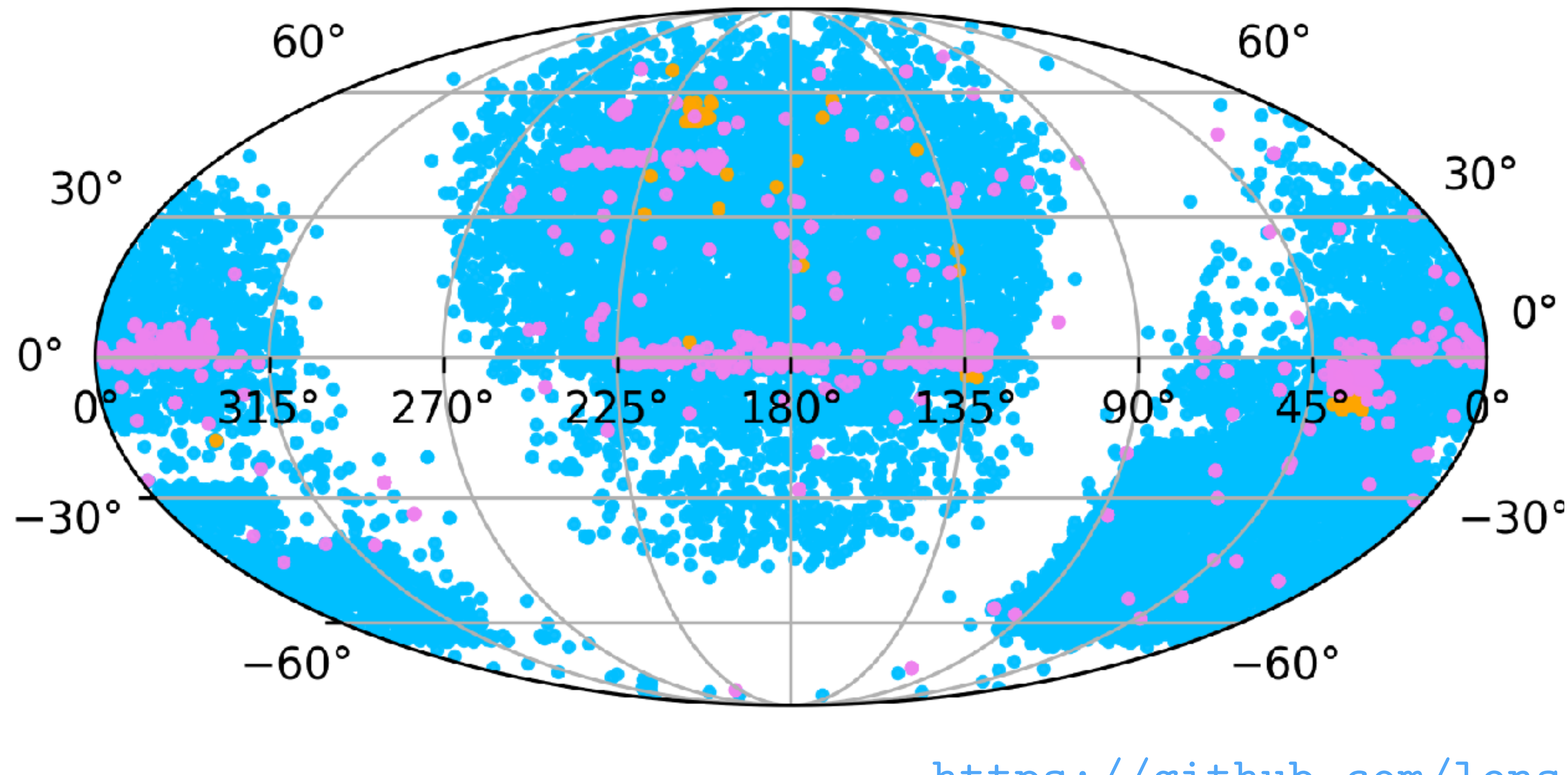
- Cross-match GWs with *lens catalogs*
- Identify host galaxy (*sky localization!*) + watchlist for efficient lenses



Luka Vujeva (NBI)



Rico Lo (NBI)



Multi-messenger lensing: lenscat

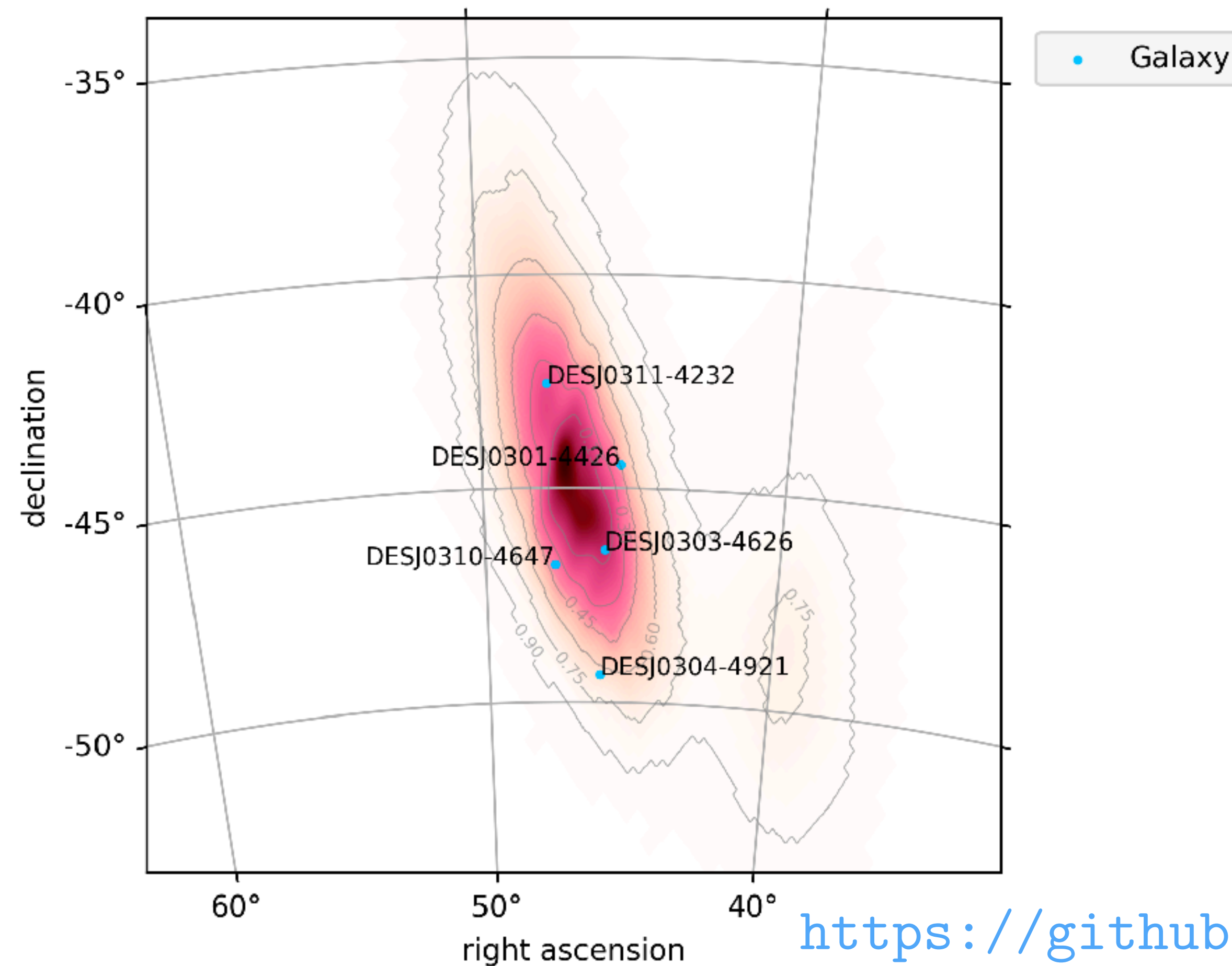
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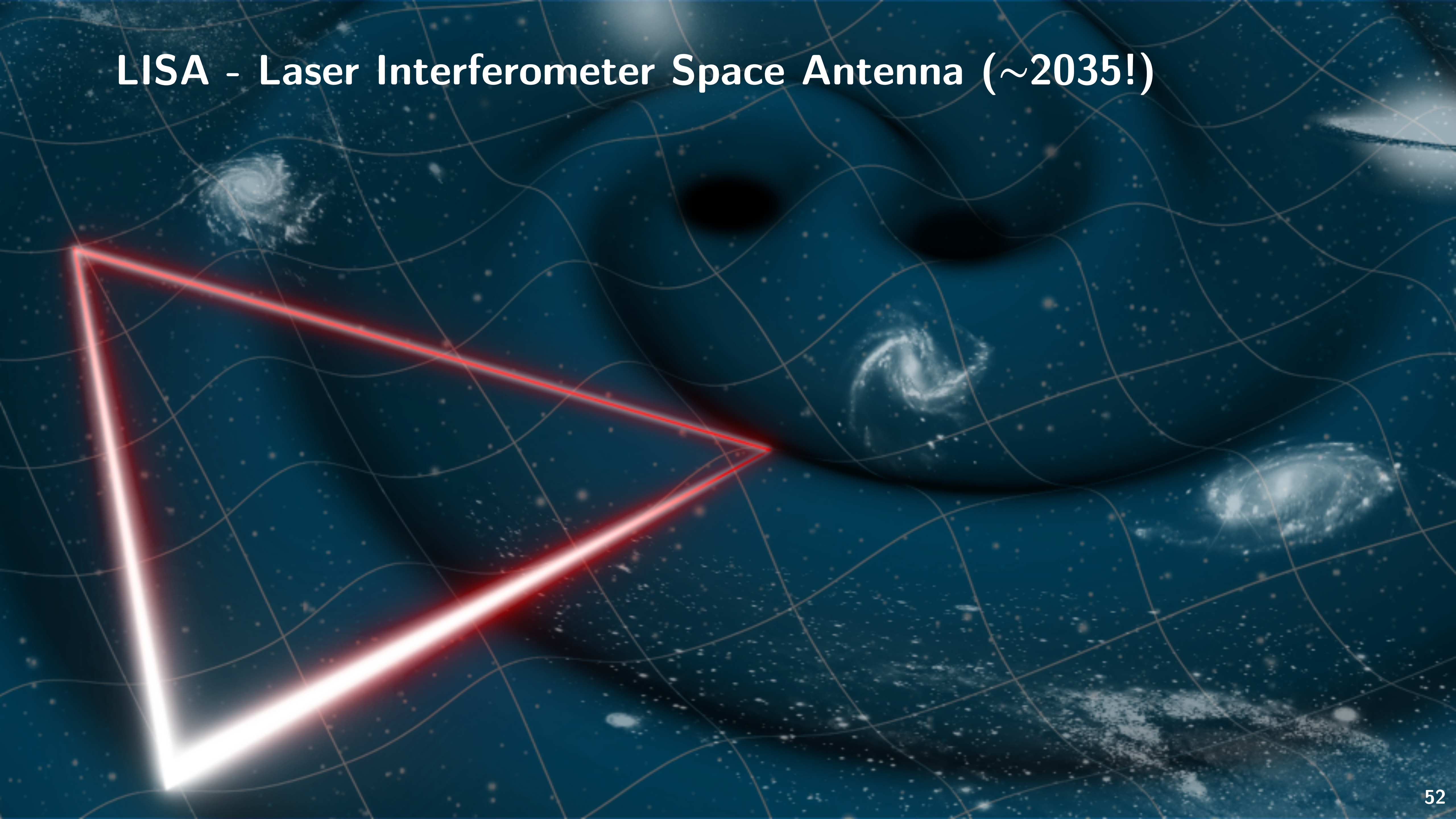
Luka Vujeva (NBI)



Rico Lo (NBI)



LISA - Laser Interferometer Space Antenna (~2035!)



THE SPECTRUM OF GRAVITATIONAL WAVES

Observatories
& experiments

Ground-based
experiment



Space-based observatory



Pulsar timing array



Cosmic microwave
background polarisation



Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

10^{-2}

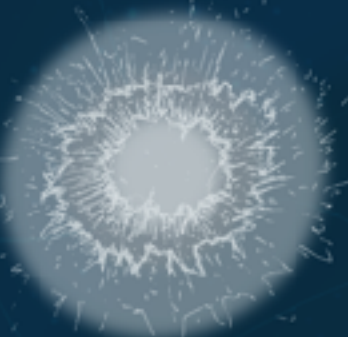
10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic
sources



Supernova



Pulsar



Compact object falling
onto a supermassive
black hole



Merging supermassive black holes



Merging neutron
stars in other galaxies



Merging stellar-mass black holes
in other galaxies



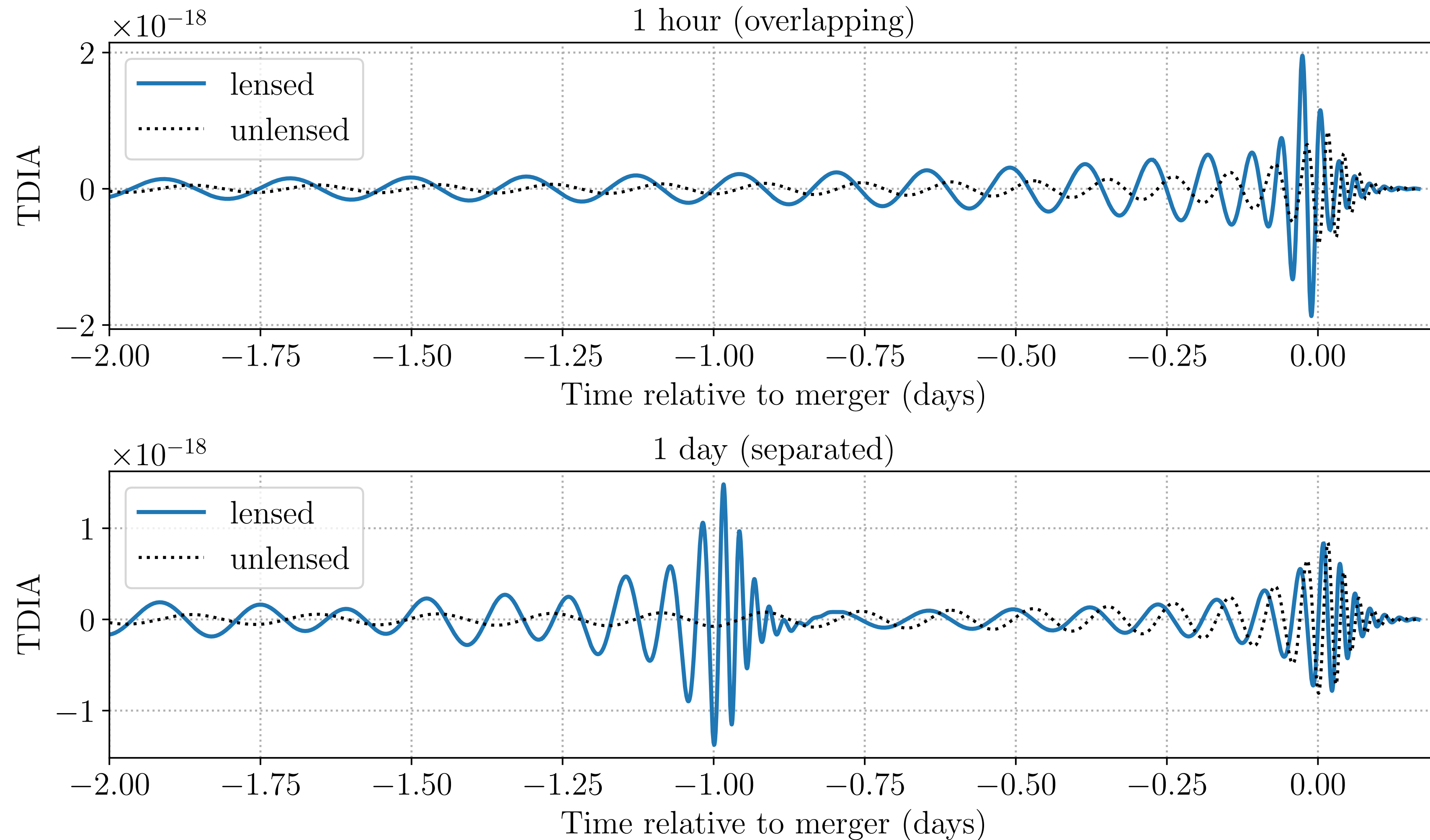
Merging white dwarfs
in our Galaxy

Cosmic fluctuations in the early Universe

LISA strong lensing: overlapping signals

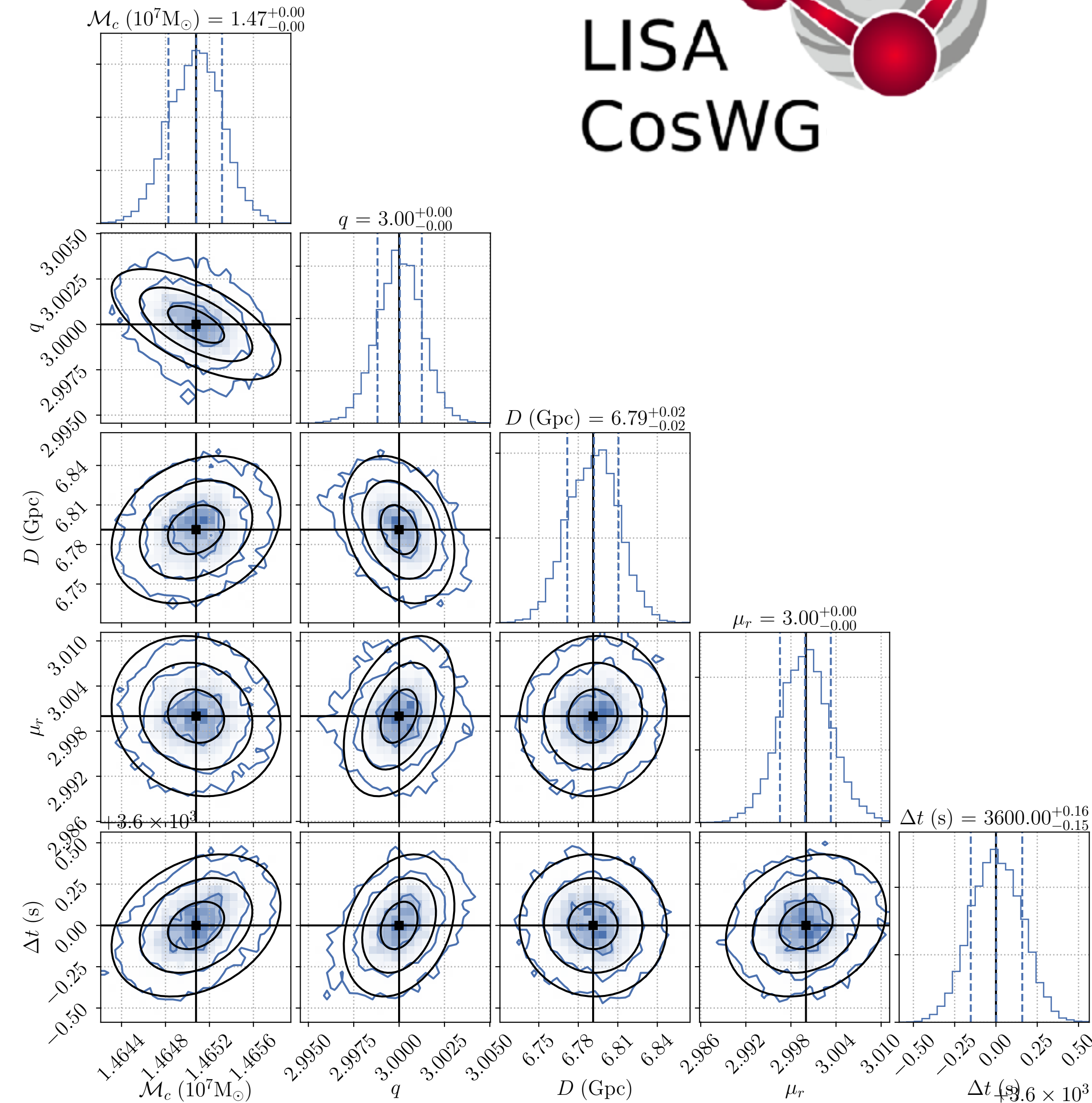


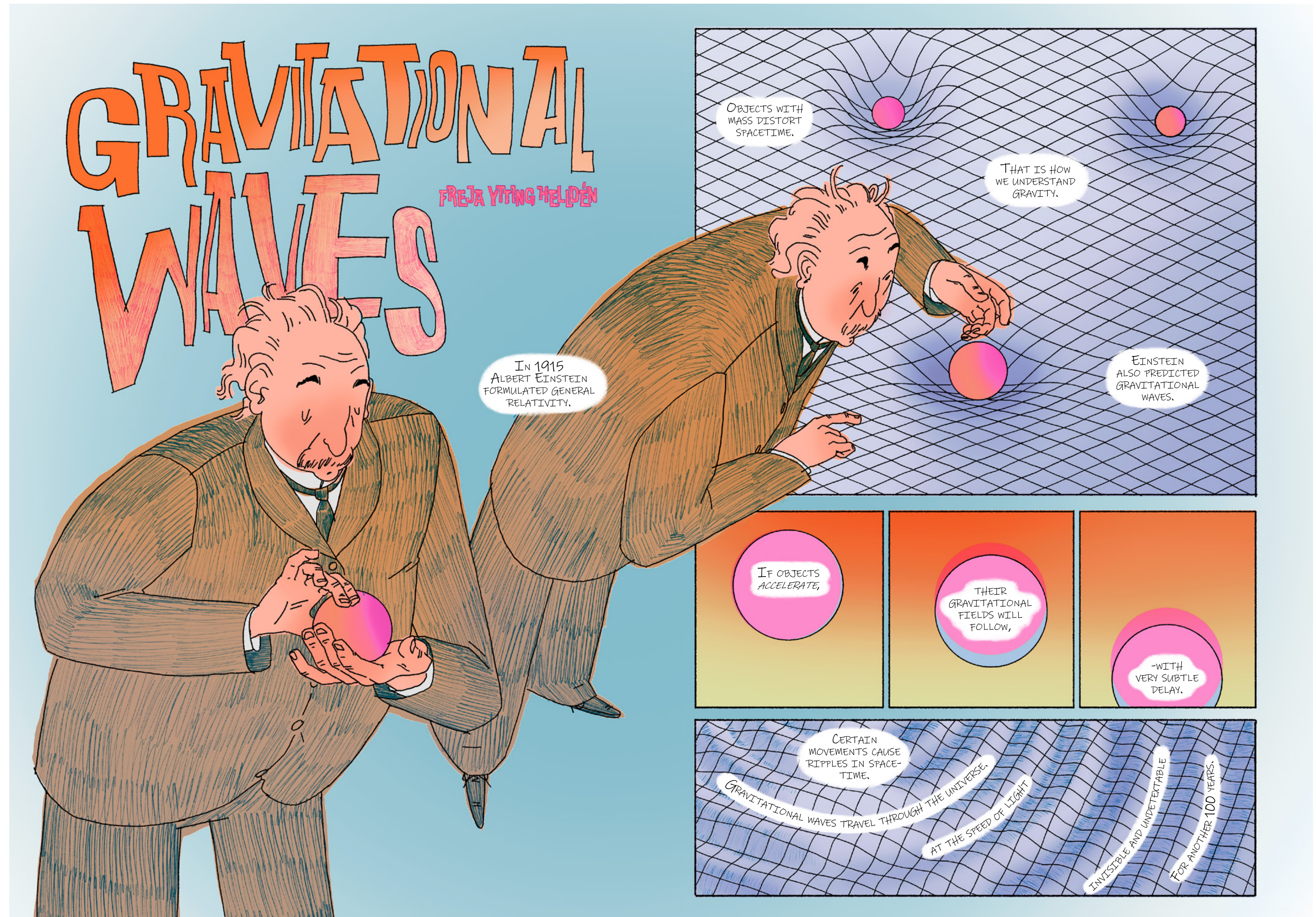
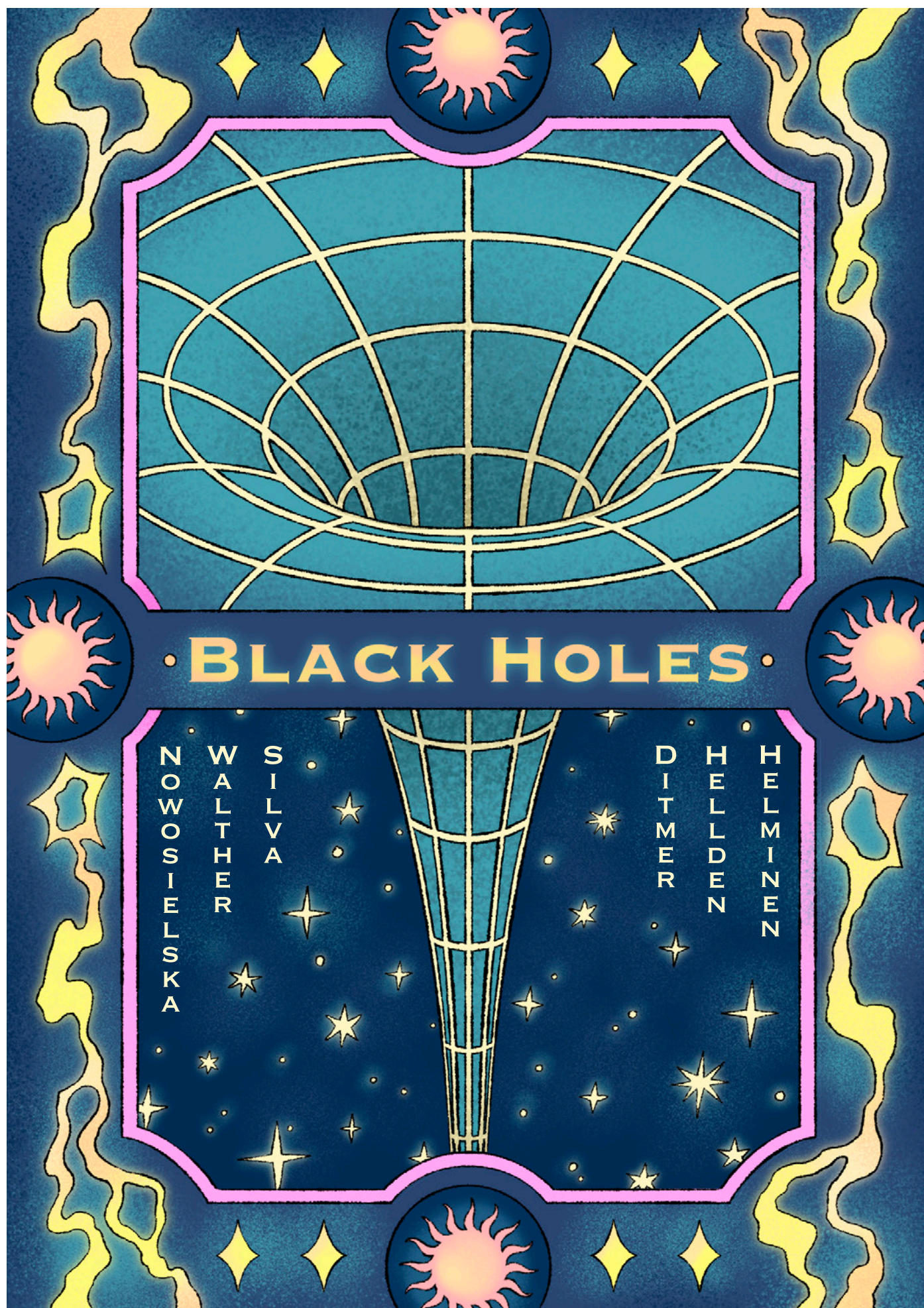
- Strongly lensed GWs may *overlap* in the LISA band



LISA strong lensing: overlapping signals

- Strongly lensed GWs may *overlap* in the LISA band
- *High precision* in the recovery of lensed parameters for *massive black hole binaries* and *extreme mass ratio inspirals*
- *Wave-optics* will add additional distortions





The next frontier in gravitational-wave physics

Gravitational-wave lensing science!

- *First* detection around the corner
- Probe *dark matter* substructures at otherwise inaccessible scales
- Unveil *high-redshift* binary-black-hole populations
- Test *gravity* in the uncharted wave-optics regime

Strong synergies
between theory,
simulations & data
analysis

[slides]





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