Gravitational Wave Astronomy

A New Frontier in Astrophysics

Dr. Sreekanth Harikumar

(On behalf of GW group at CAMK)

YAM 2026

LIGO
VIRGO
KAGRA

CAMK
PAN

NARODOWE CENTRUM NAUKI

PL
GRID

POLgraw

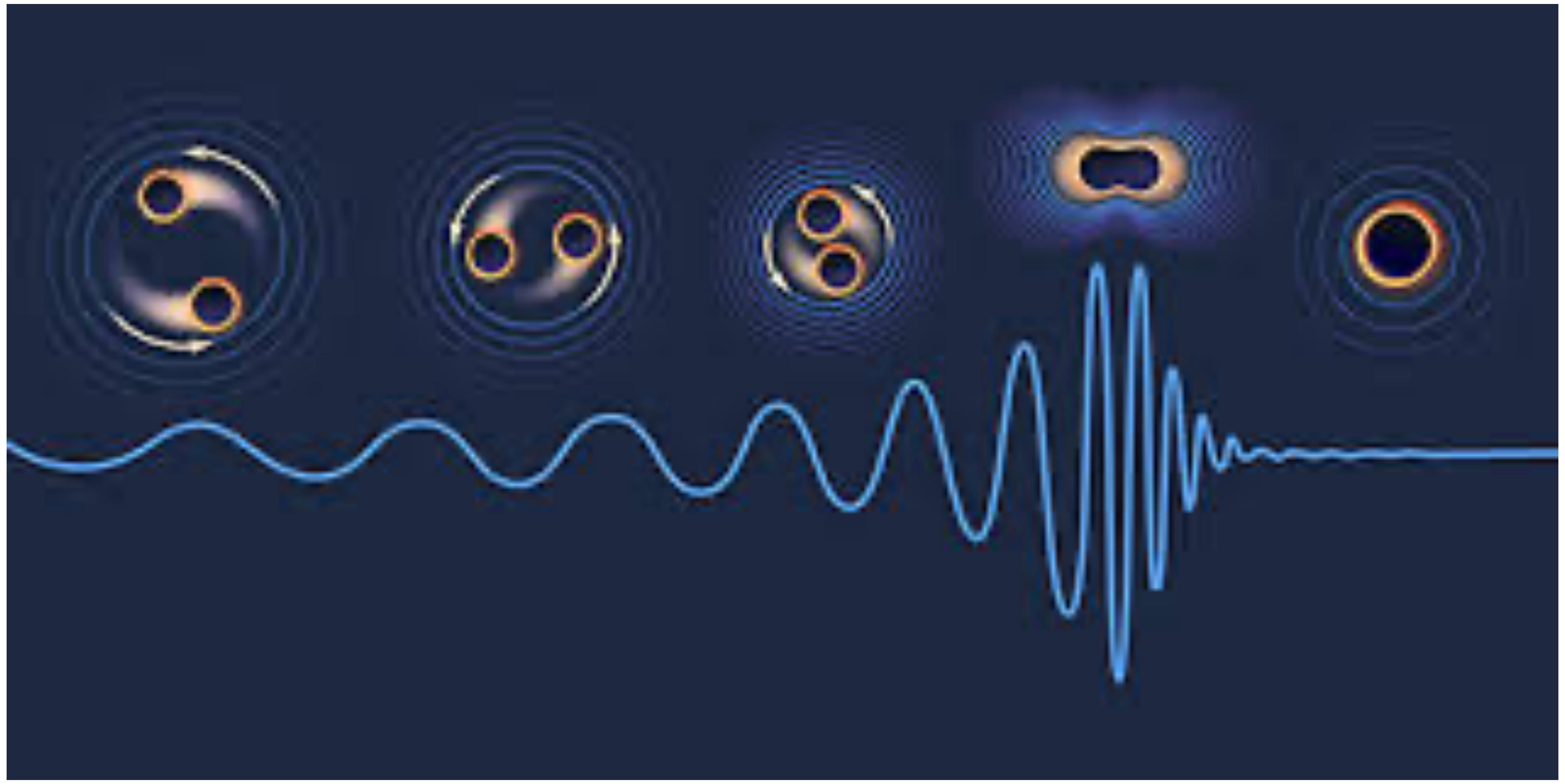
Overview

- **Gravitational Wave astronomy**
- **Research activities in CAMK GW group**
- **Gravitational Wave Lensing**
  - Determining globular cluster σ_v with lensed GWs
  - Signatures of continuous waves lensed by dark matter
- **GW open data workshop**
- **Summer student opportunities**

Listening to the black holes for the first time - GW150914

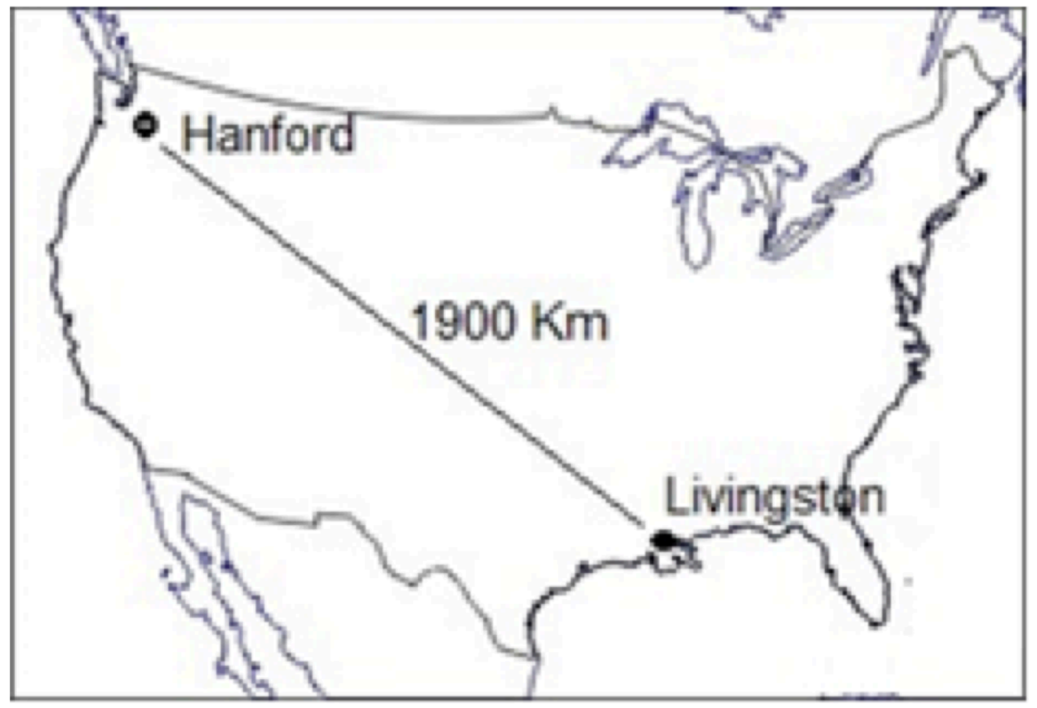
at 11:50:45 am CET on 14 September 2015

Phys. Rev. Lett. 116, 061102



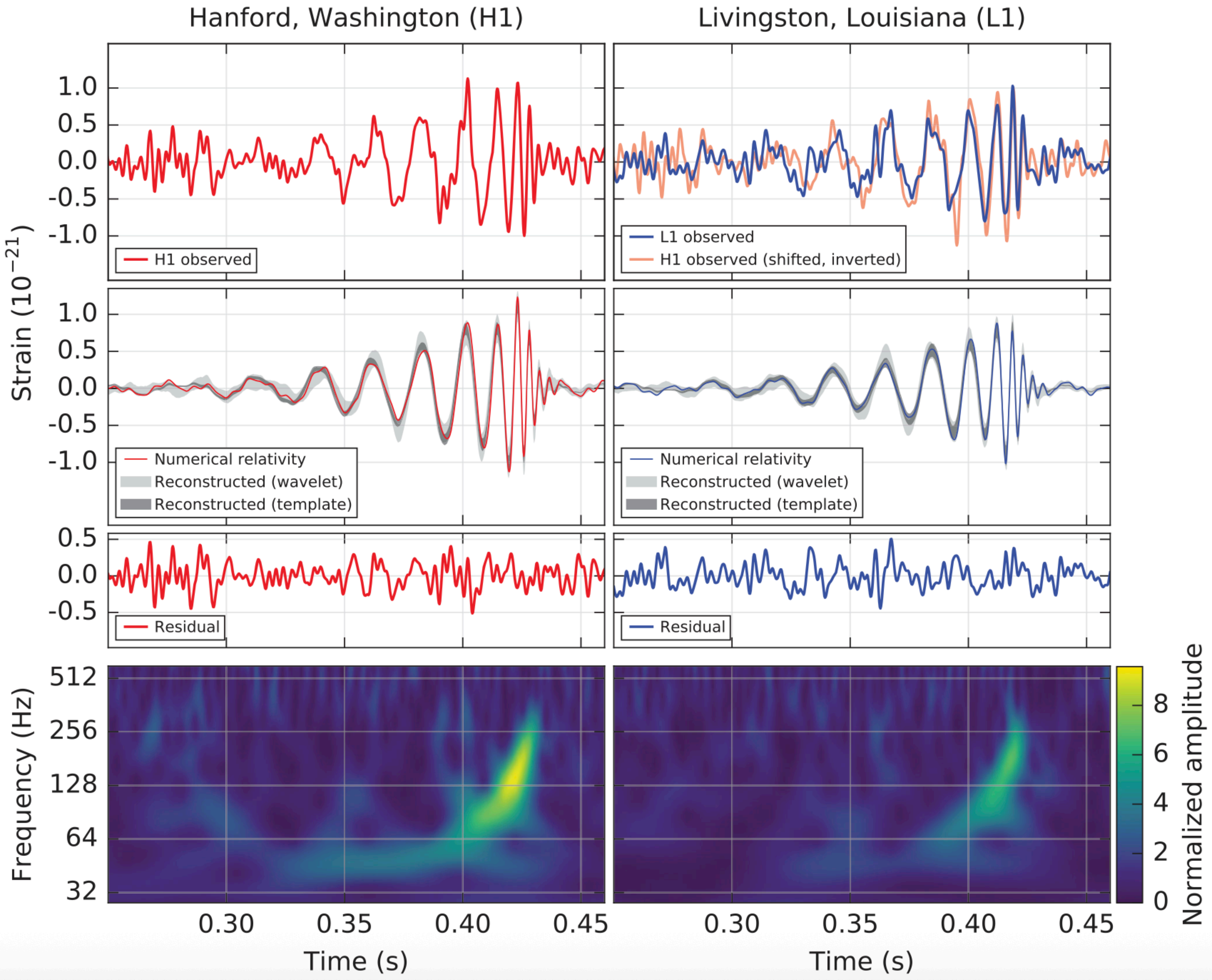
This marked the birth of gravitational wave astronomy

Most important discovery in this century



GW150914

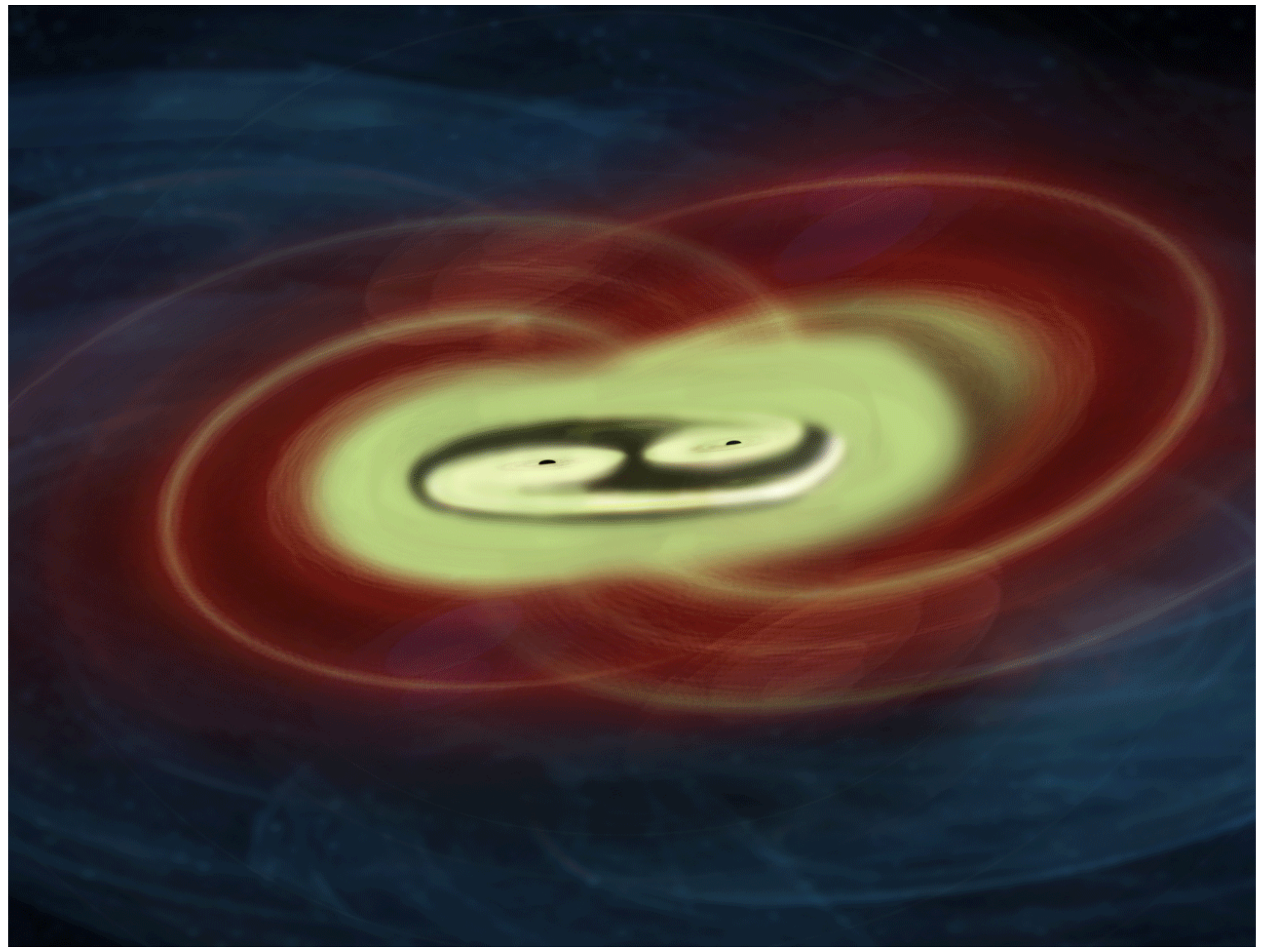
YY MM DD



60 years of experimental efforts and 100 years since its prediction we detected it.

Signal morphology

$$\mathrm{G}_{\mu\nu} + \Lambda \mathrm{g}_{\mu\nu} = \frac{8\pi \mathrm{G}}{c^4} T_{\mu\nu}$$



Credit: ESA

merger phase

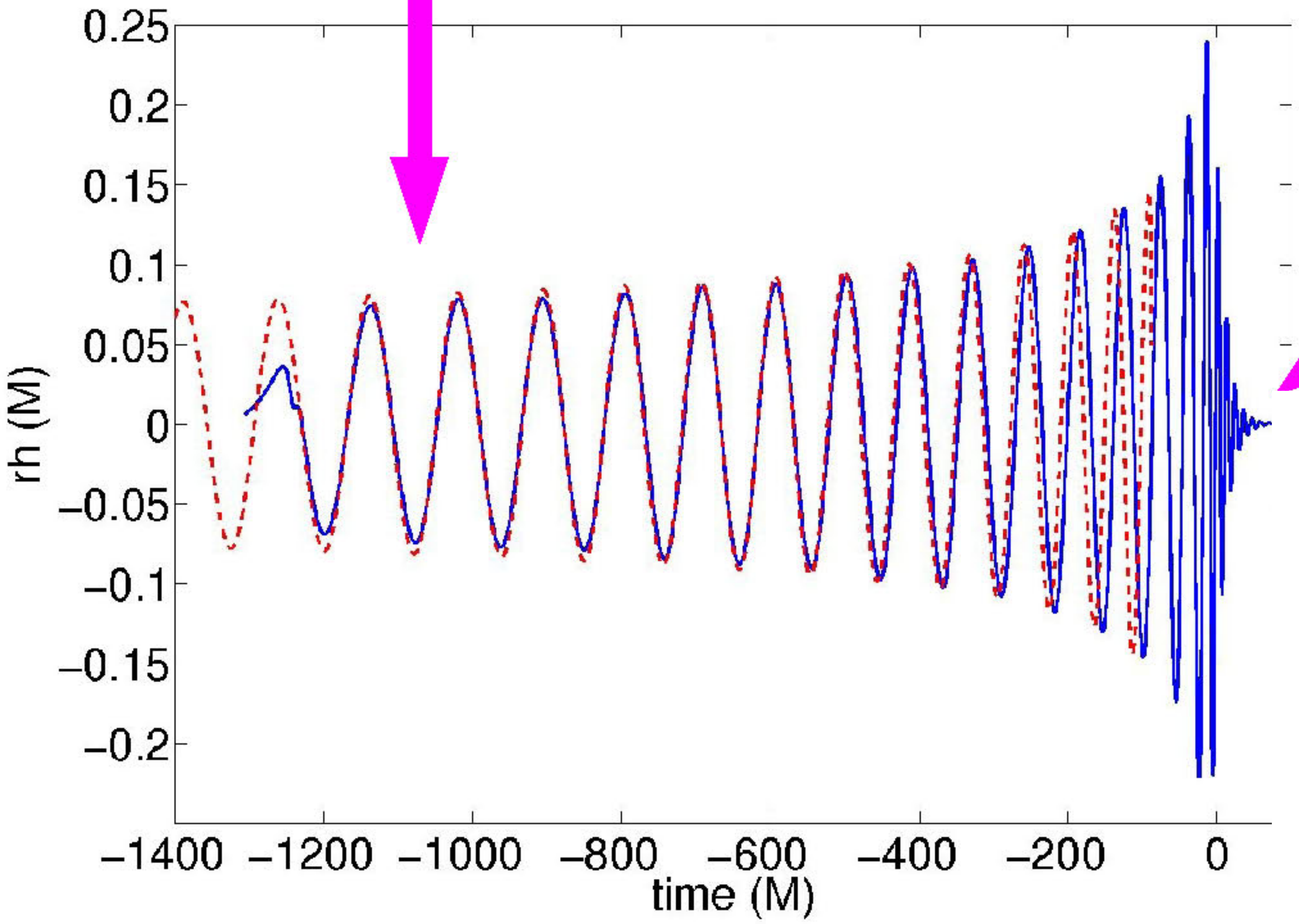
numerical relativity

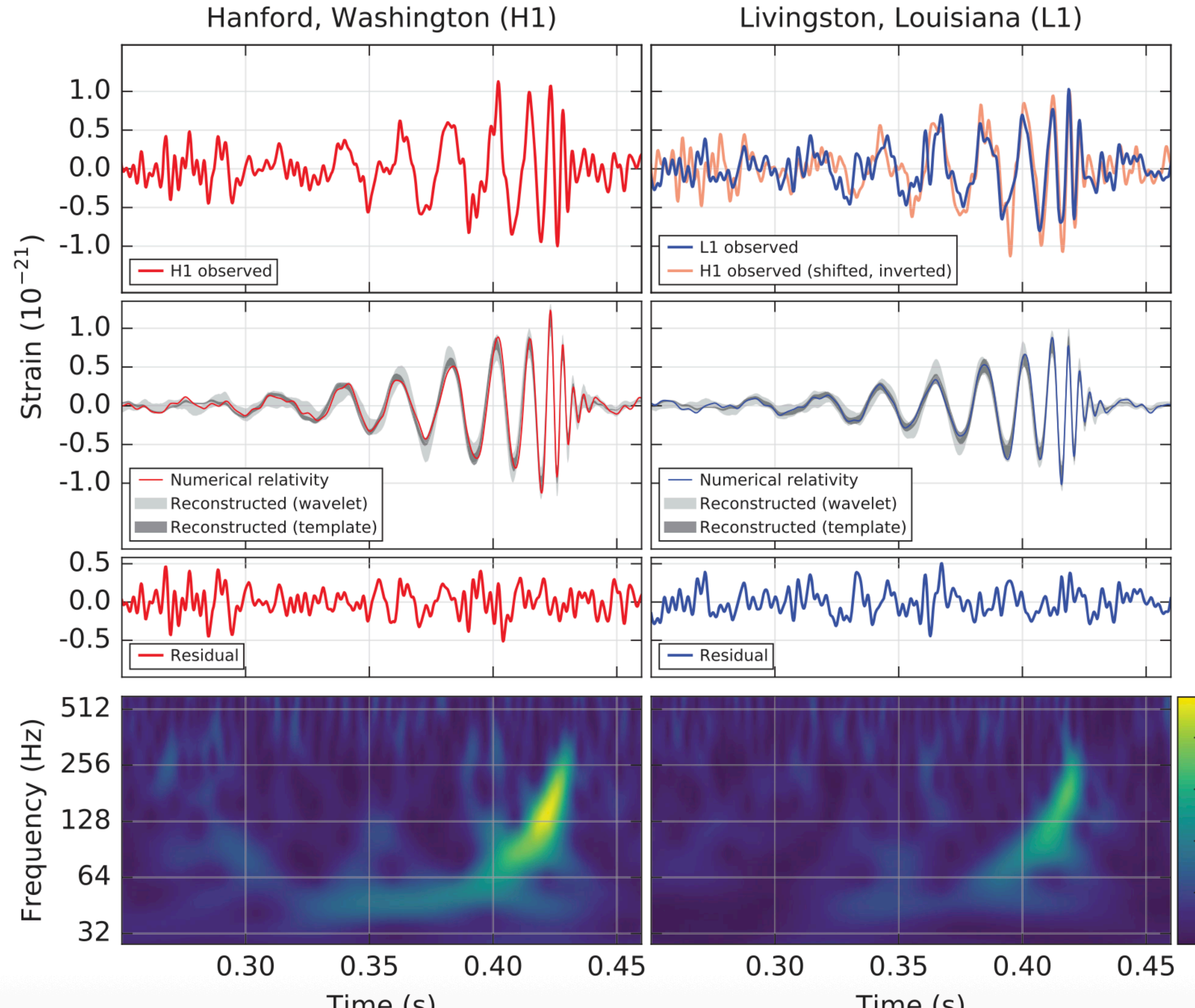
inspiralling phase

post-Newtonian theory

ringdown phase

perturbation theory



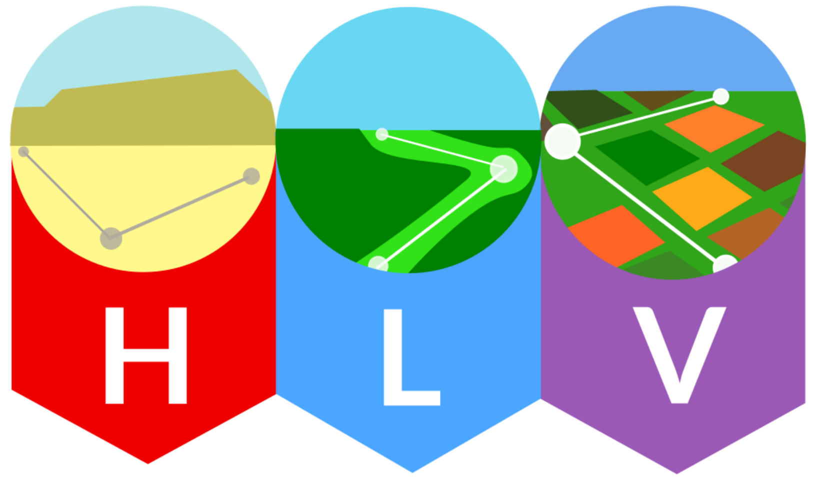


Credit: https://www.iap.fr/actualites/laune/2016/OndesGr/forme_onde_an.jpg

GW170817

Binary neutron star merger

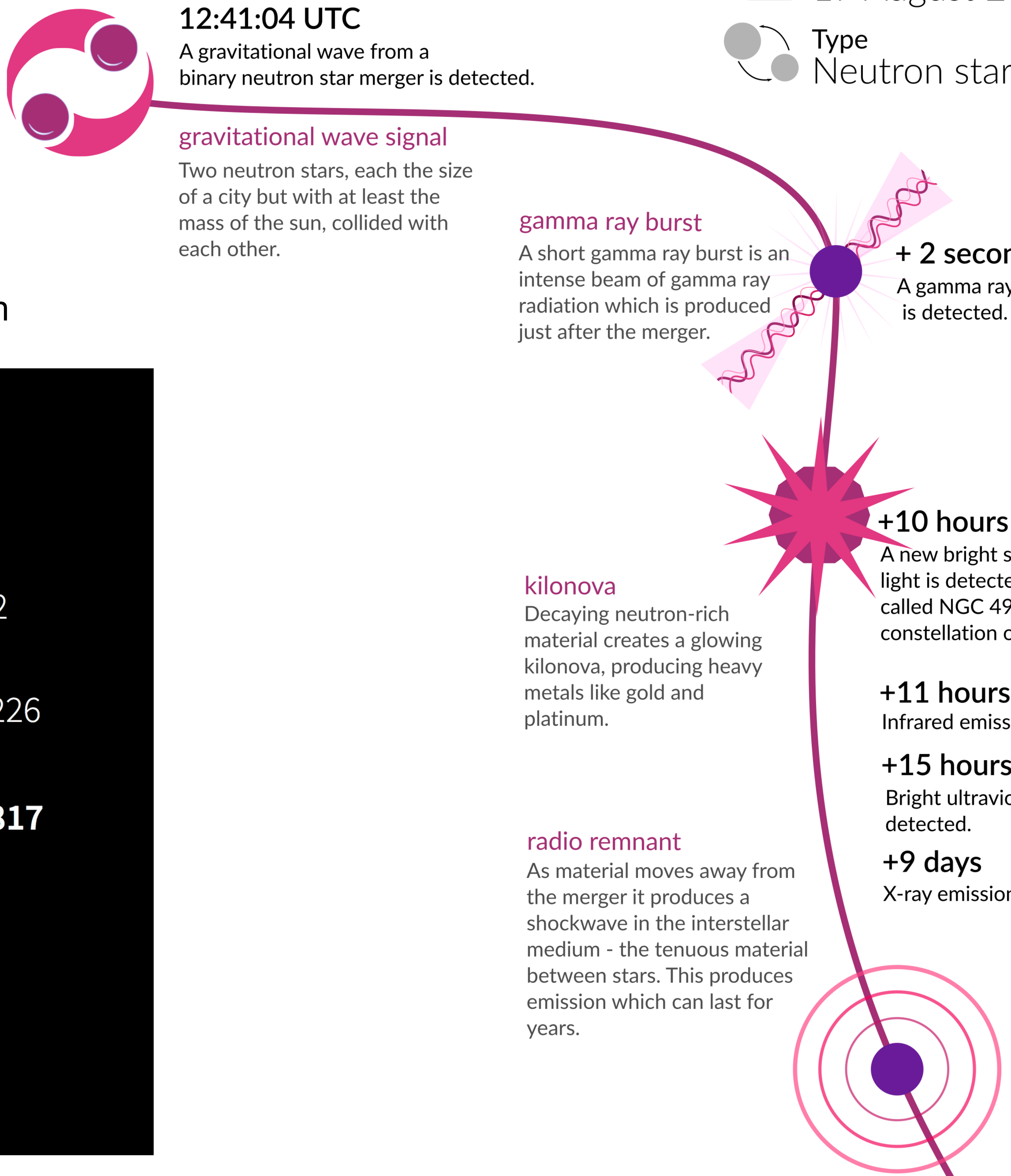
A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.



Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger



12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+11 hours 36 minutes
Infrared emission observed.

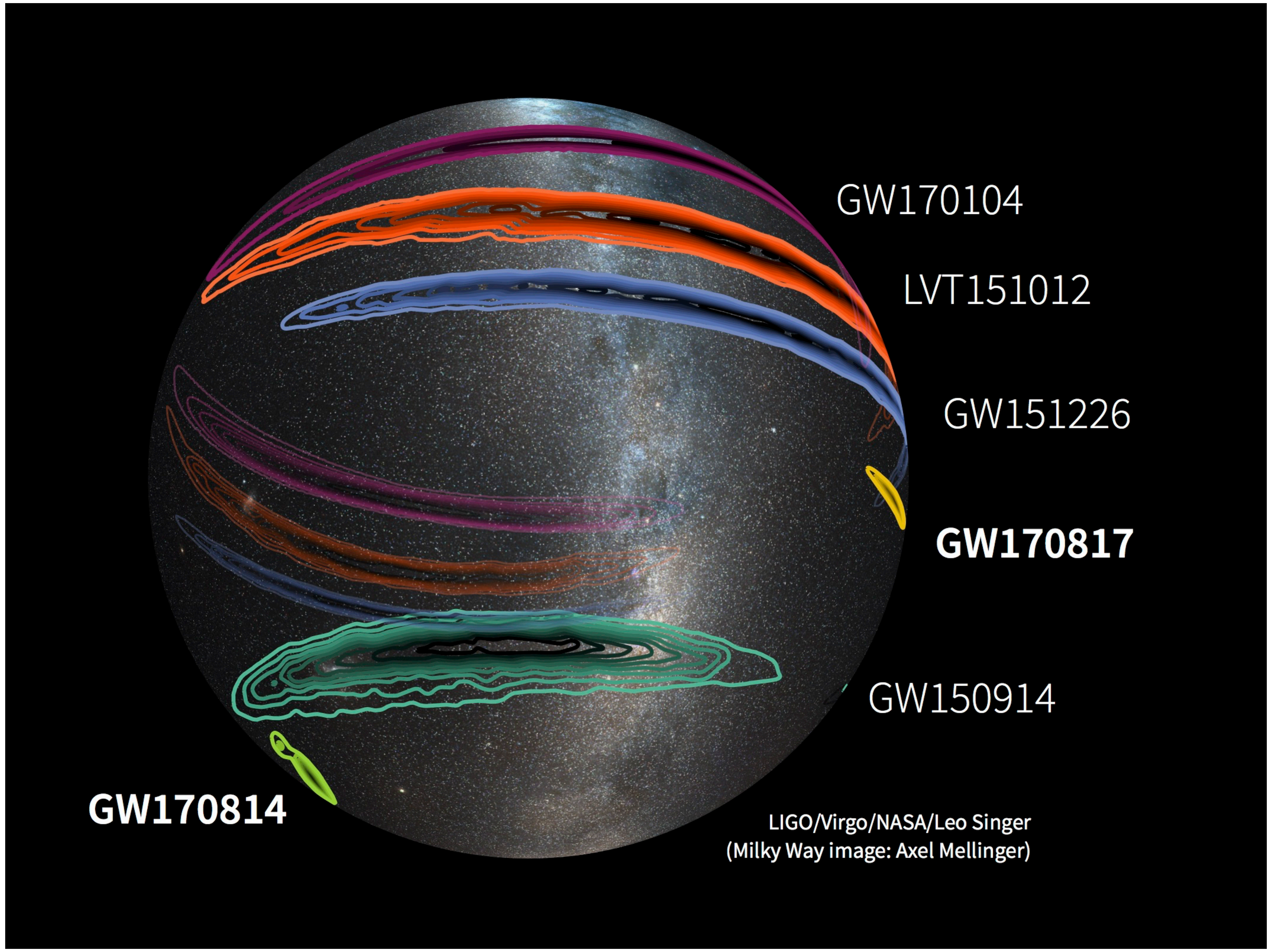
+15 hours
Bright ultraviolet emission detected.

+9 days
X-ray emission detected.

radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

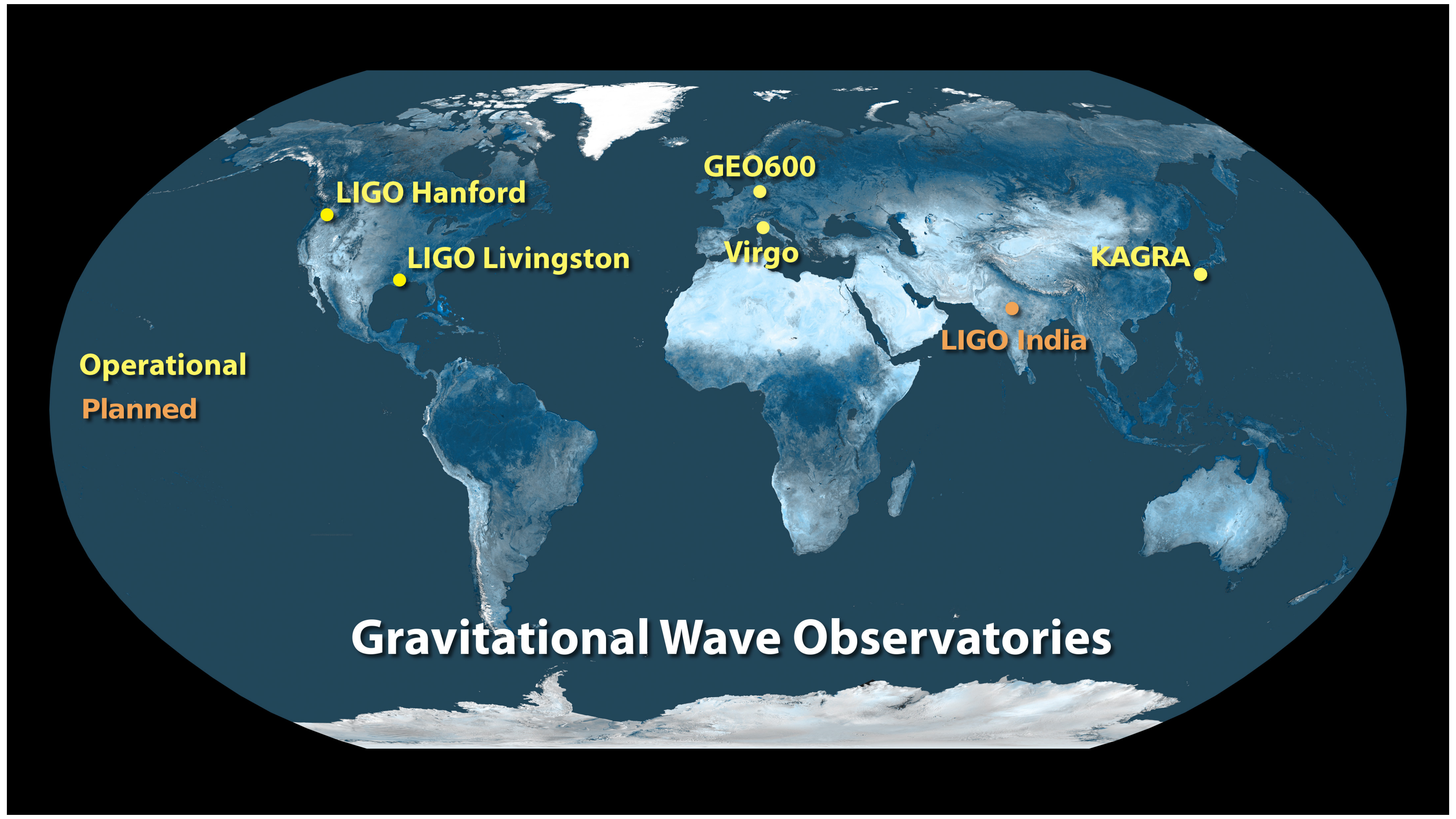
+16 days
Radio emission detected.

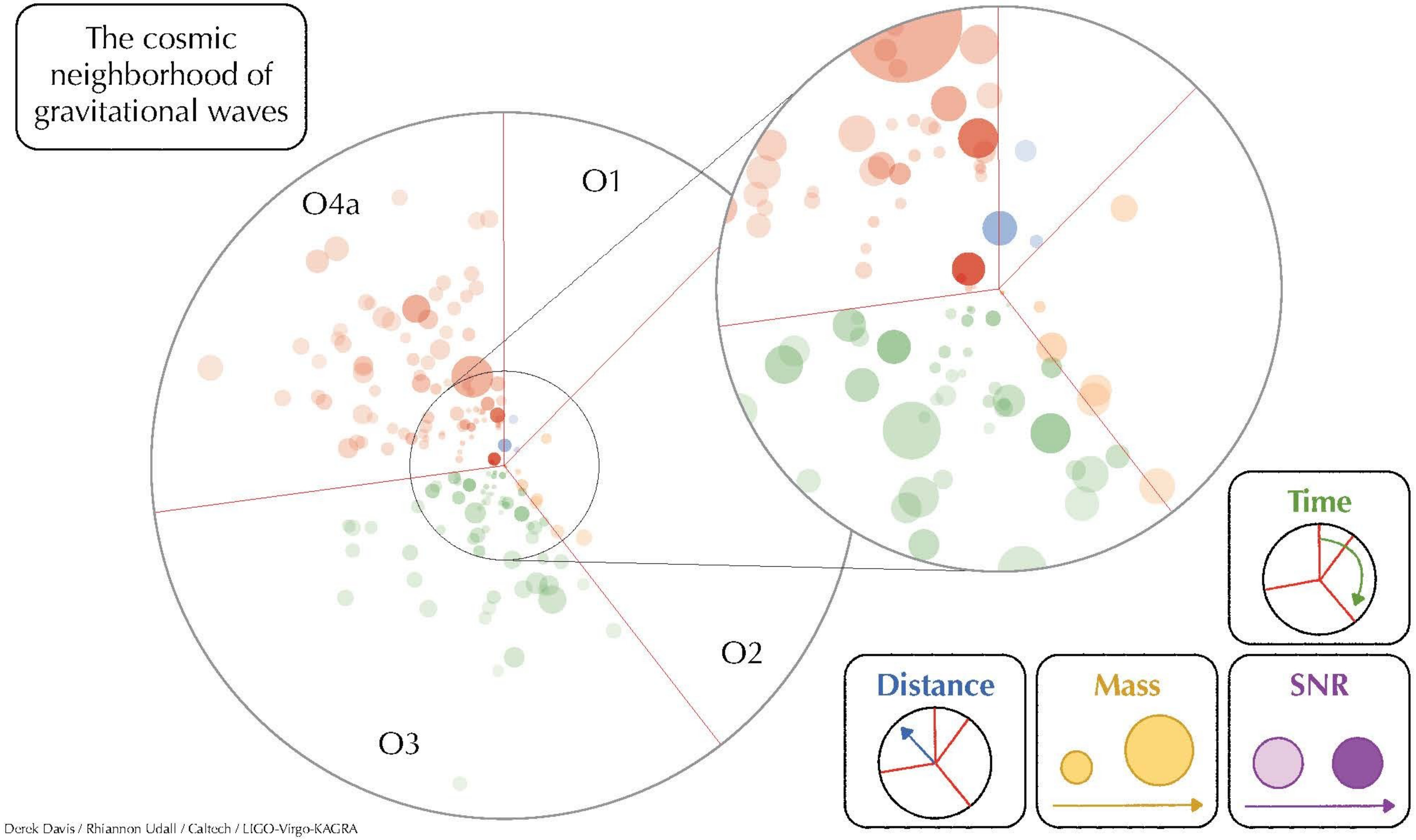
The electromagnetic counter helped in better sky localization



LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Current status of GW astronomy



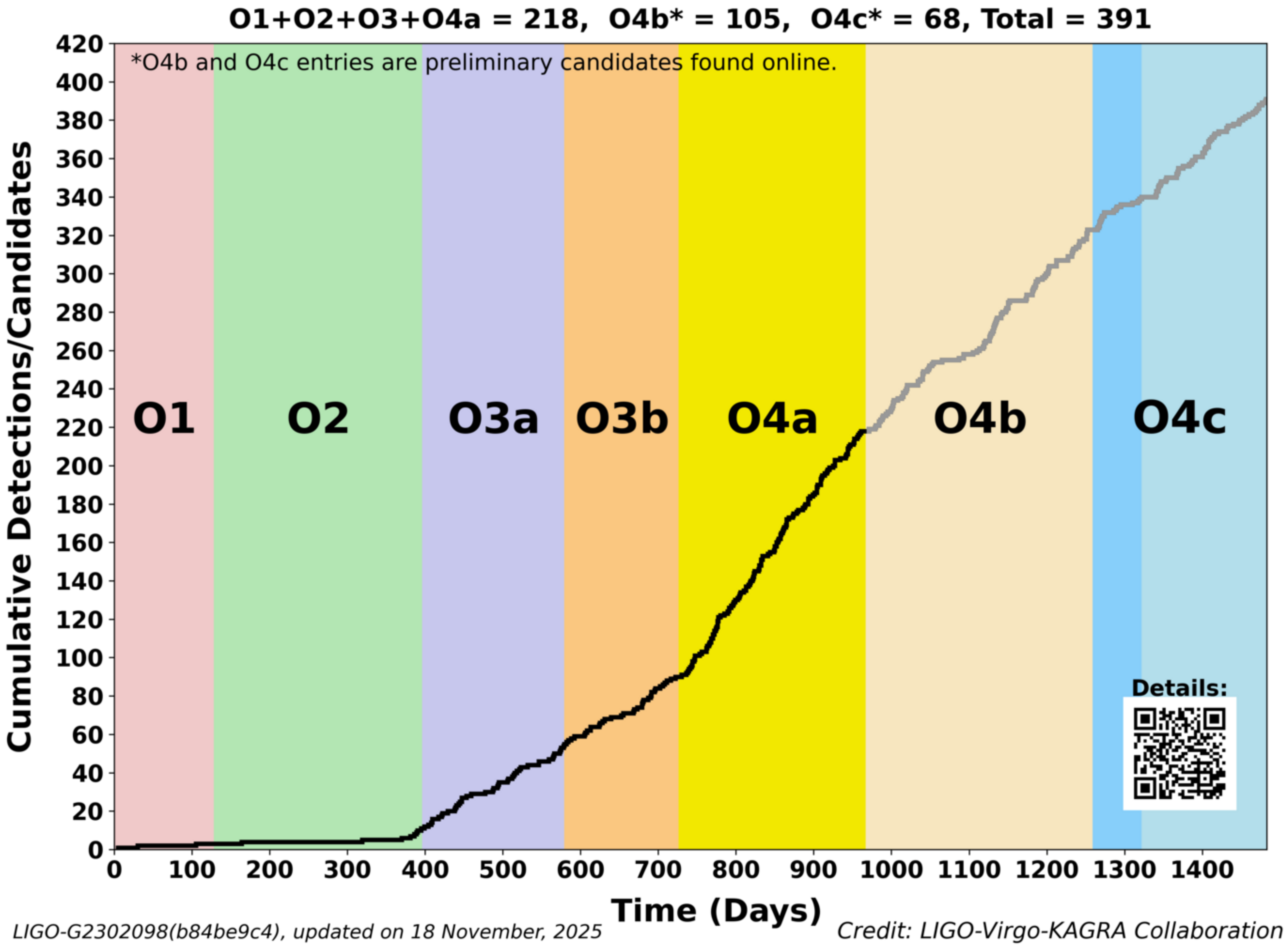


Derek Davis / Rhiannon Udall / Caltech / LIGO-Virgo-KAGRA

- Four observing detectors, LIGO India under construction
- More than 300 GW detections.
- These include **BBH, NSBH, BNS**
- One multi-messenger event GW170817
- Evidence of Stochastic GW background (PTA)

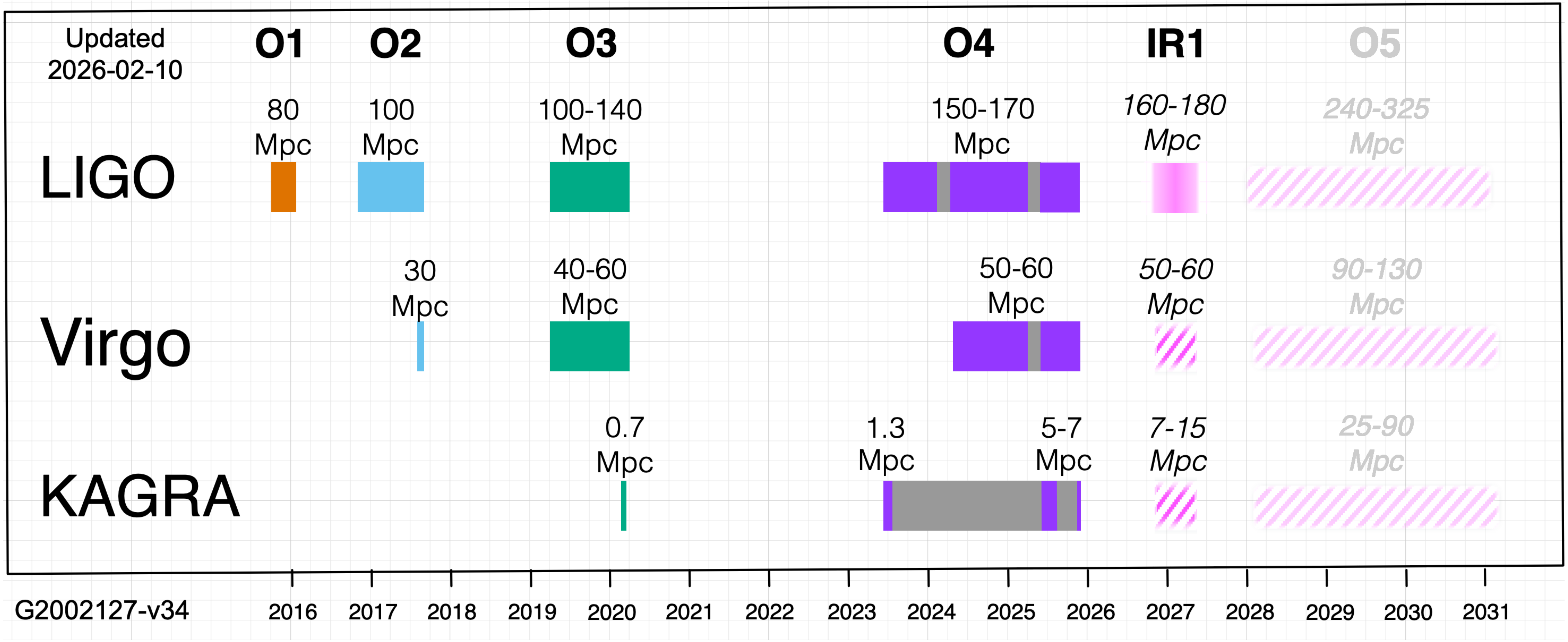
More about GW sources and detectors will be discussed in future lectures

LIGO Virgo KAGRA (LVK) Observing runs

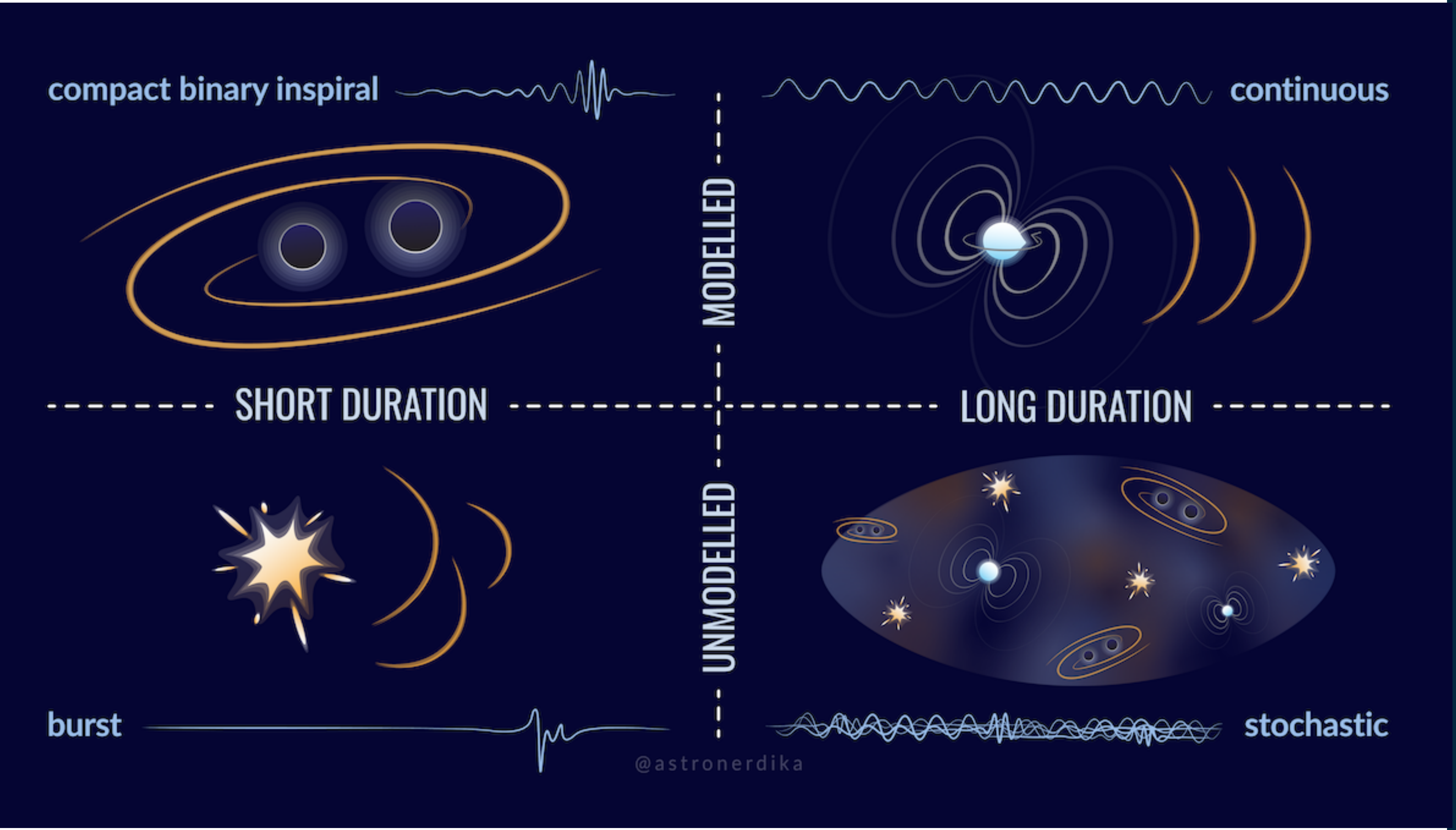


LIGO Virgo KAGRA (LVK) Observing runs

The sensitivity of different detectors during different observing runs are shown



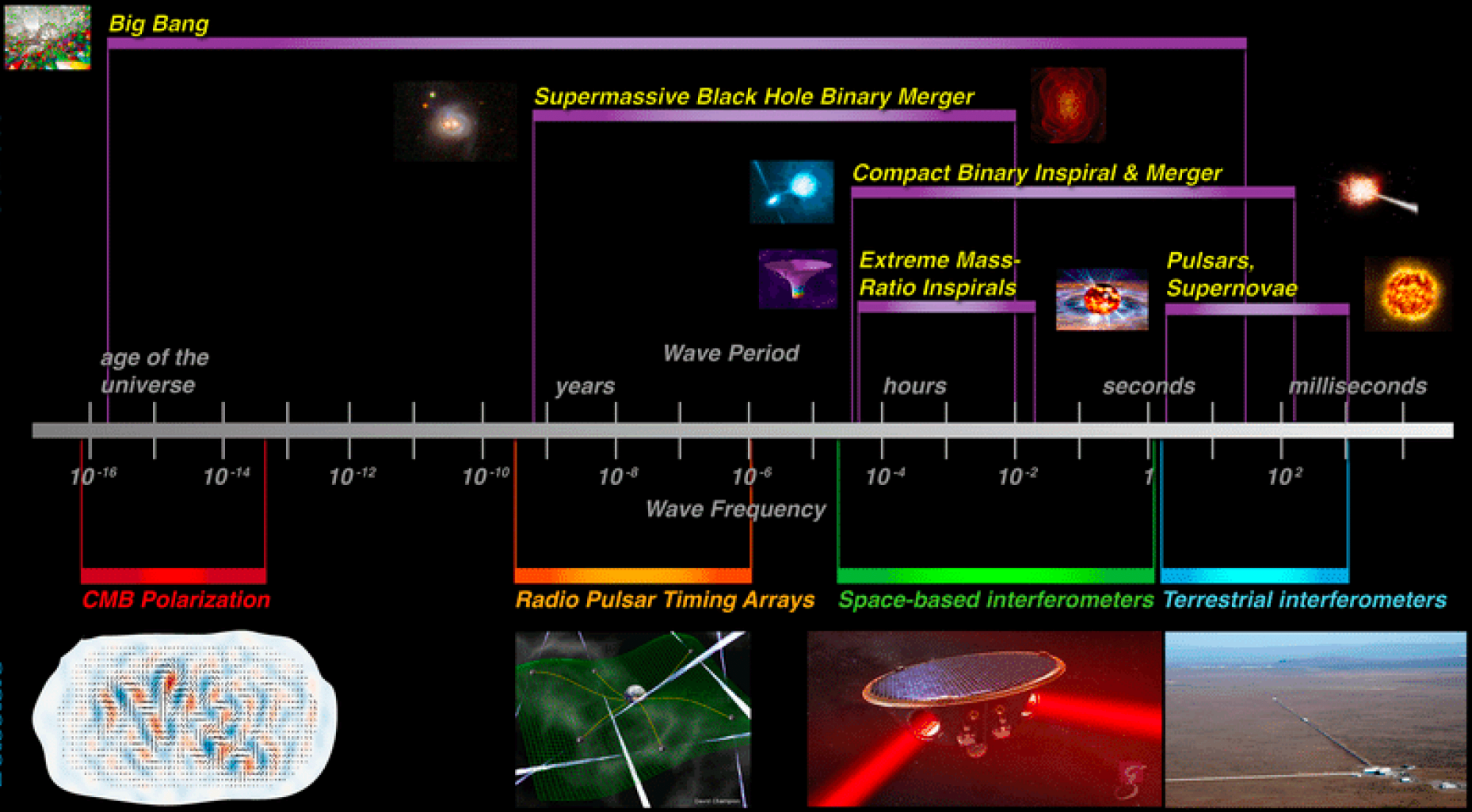
Typical sources of GWs



Any mass that undergoes an accelerated motion can generate gravitational signals

- Binary Black Holes
- Binary Neutron Stars
- Galaxy mergers
- SMBBH mergers
- EMRIs
- cosmic strings
- Supernovae
- primordial dark matter decay
- Primordial GW background

The Gravitational Wave Spectrum



Sources

Big Bang

Supermassive Black Hole Binary Merger

Compact Binary Inspiral & Merger

Extreme Mass-Ratio Inspirals

Pulsars, Supernovae

Wave Period

age of the universe

years

hours

seconds

milliseconds

10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

Wave Frequency

Detectors

CMB Polarization

Radio Pulsar Timing Arrays

Space-based interferometers

Terrestrial interferometers

CAMK GW group

Dr. hab. Michał Bejger

(Head)

Dr. Paweł Ciecieląg

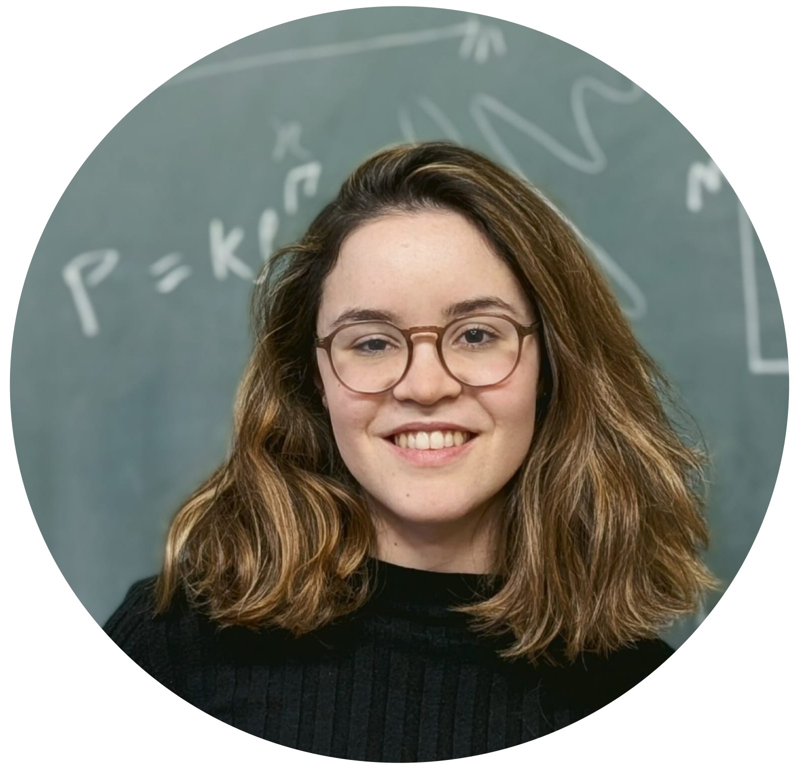
(Independent Specialist)

Dr. Przemysław Figura

(Postdoc)

Dr. Sreekanth Harikumar

(Postdoc)



Valéria Carvalho

(Visiting PhD student)

Sudhagar Suyamprakasam

(PhD student)

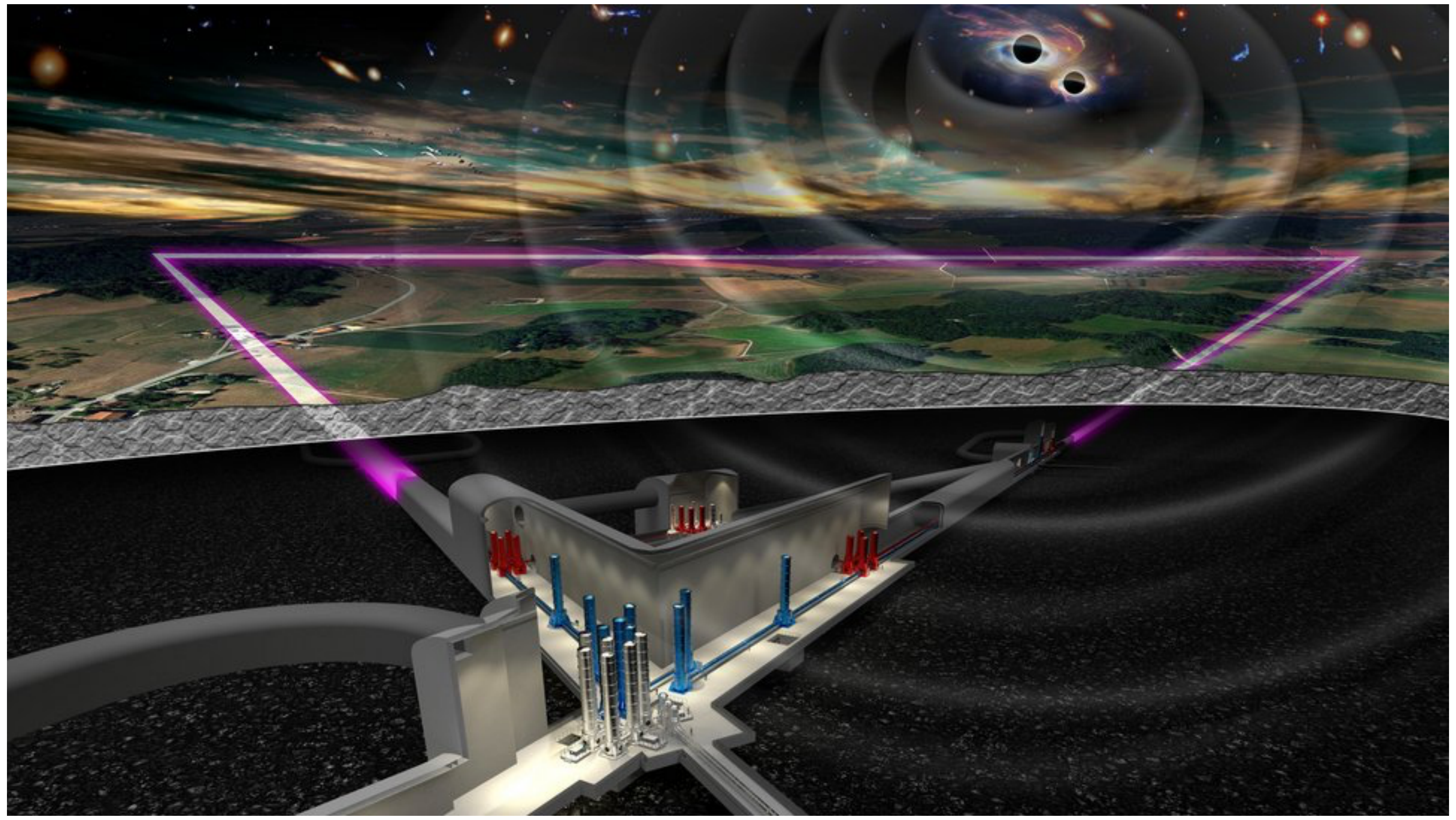
Anirudh Nemmani

(PhD student)

Scientific Collaborations

- **LIGO-Virgo-KAGRA collaboration**
  - All sky search for continuous GWs using Time Domain $\mathcal{F}$-Statistic pipeline,
  - Search for lensed gravitational signals
- **Einstein Telescope Science Collaboration**
- **Polgraw (Polish Gravitational Wave group)**

(Dedicated computing infrastructure in Cyfronet)



https://github.com/Polgraw/TDFstat

Jaranowski, Krolak, Schutz ,*Phys.Rev.D* 58 (1998) 063001

Research activities at our group

Data analysis and methods of analysis

- Searches for periodic gravitational waves (Time Domain $\mathscr{F}$ Statistic pipeline) (**see Anirudh's Talk**)
- CBC post-merger analysis
- Machine learning techniques in application to gravitational waves searches
- Searches and PE of lensed gravitational signals (**This Talk**)
- Population studies
- Parameter estimation of sub-solar masses

Modelling of astrophysical sources of gravitational waves

- models of extreme matter sources (Equation of State of compact objects..) (**See Valéria's talk**)
- models of lensed gravitational waves
- Globular cluster lensing and searches (**See Sudhagar's talk)**
- GWs in alternative theories of gravity

Presentations to keep an eye on…

This Talk

Gravitational Wave lensing

- Compact binary mergers
- Long duration sources (microlensing)

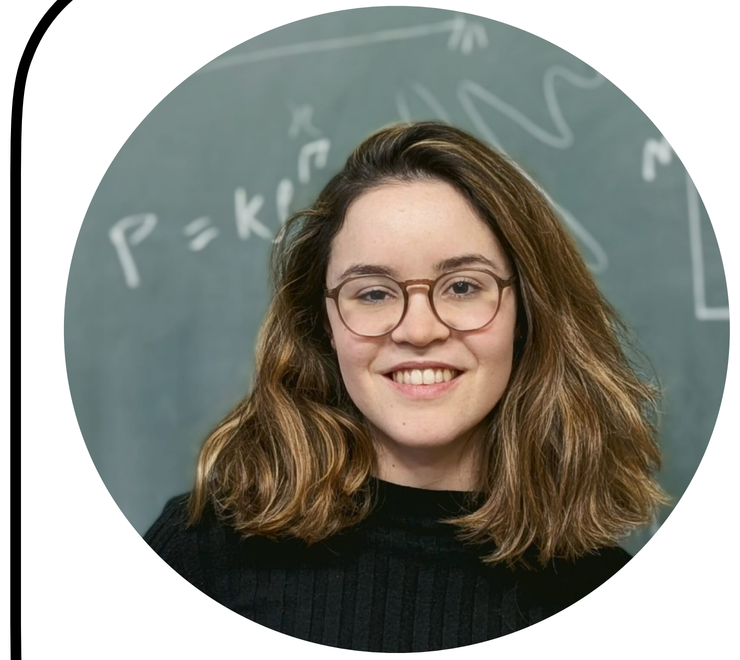
Sreekanth Harikumar

Microlensing effect in the long-duration gravitational wave signals

Sudhagar Suyamprakasam

Data analysis of long duration gravitational wave sources

Anirudh Nemmani



How can deep learning help us decipher neutron star composition ?

Valéria Carvalho

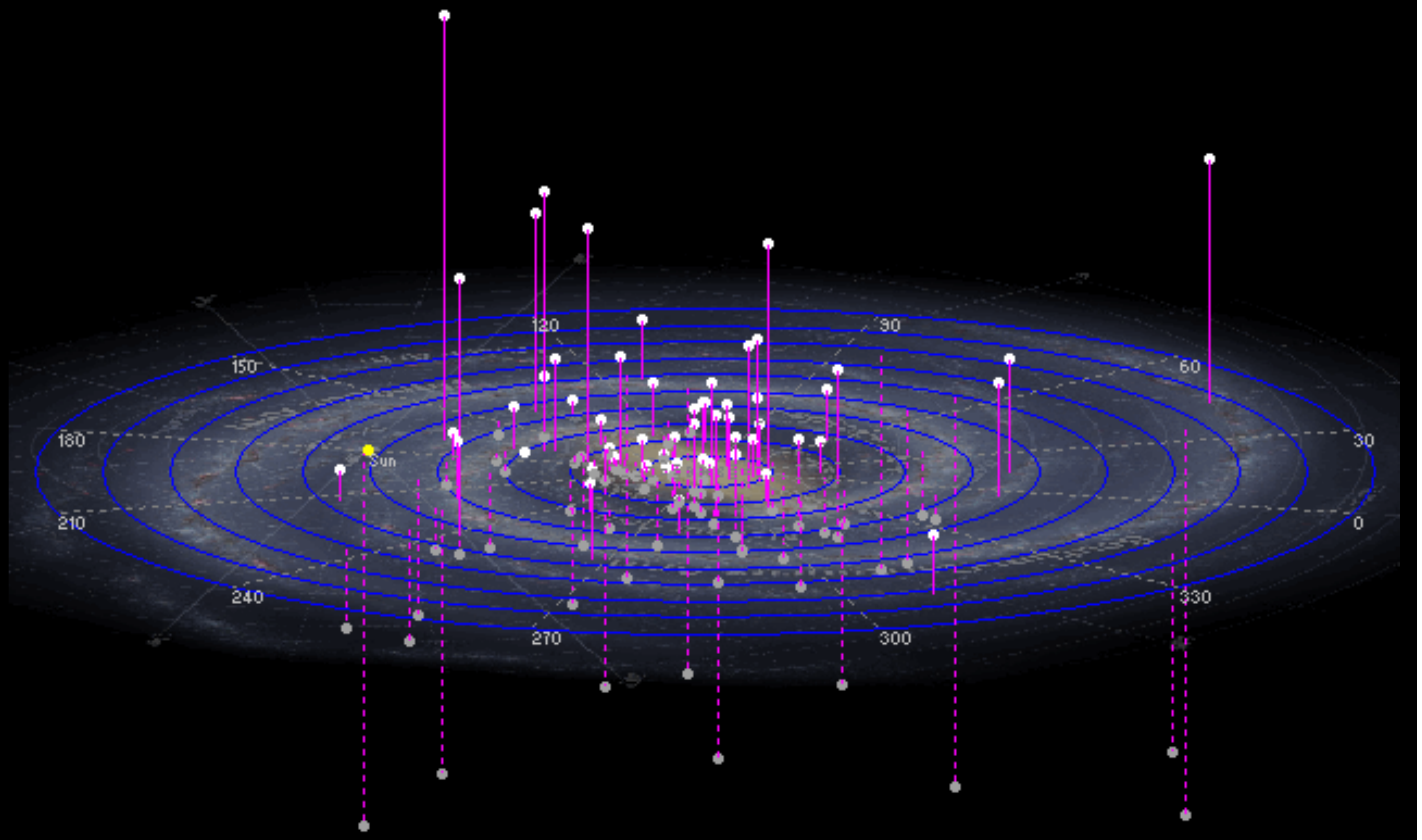
Globular clusters as lenses for gravitational waves emitted by stellar mass binaries

Collaborators:

Abbas Askar, Michał Bejger , Marek Biesiada, Martin Hendry, Justin Janquart, Sudhagar Suyamprakasam

Gravitationally-bound collection of approximately $10^4 - 10^6$ stars.

GCs and their velocity dispersion measurement



Data from William E. Harris, McMaster University
http://www.physics.mcmaster.ca/Globular.html

3D Diagram by Larry McNish

H. Baumgardt and M. Hilker, MNRAS 478, 1520 (2018),

- **Old stellar populations**
- **Good laboratories to study stellar dynamics, stellar evolution and early stages of galaxy formation.**
- **Prime sites for dynamical formation of BBHs.**

  - Milky Way - 165
  - Andromeda - 500
  - M87 ≈ 12000
  - Perseus ≈ 70000

Limitations:

Stellar crowding
Line -of sight projection effects

Fresnel-Kirchhoff Diffraction integral

Solving the GW equation in the lens background

$$\overset{B}{\Box} h_{\mu\nu} - 2h_{\alpha\beta}\overset{B}{R}{}^{\alpha}{}_{\mu\nu}{}^{\beta} = 0$$

Takahashi & Nakamura 2003

Nakamura & Deguchi 1999

Dimensionless frequency

$$w = \frac{8\pi G M_{Lz}}{c^3} f$$

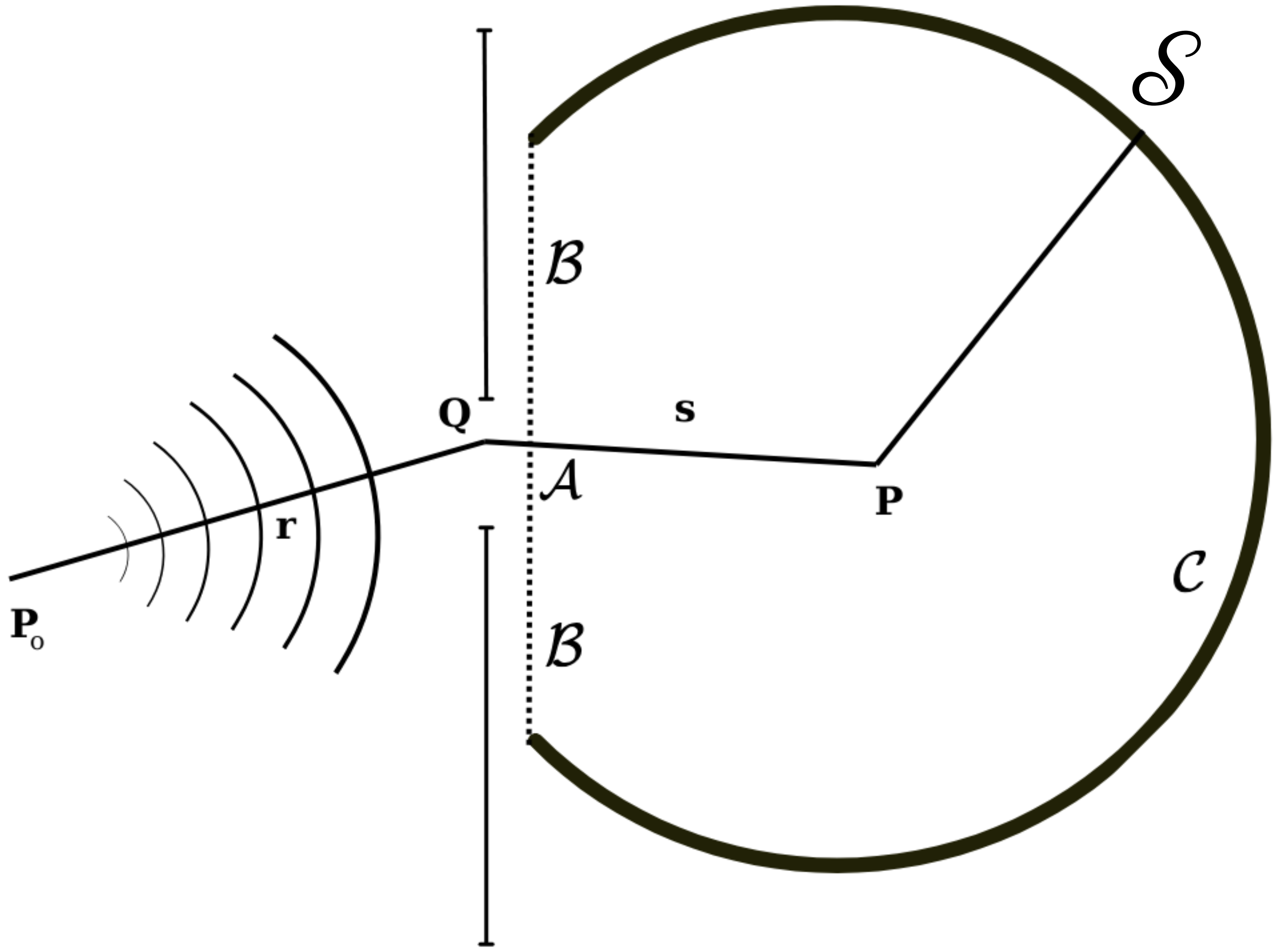
$$F(w,y) = \frac{w}{2\pi i}\int d^2\mathbf{x}\, e^{iwT(\mathbf{x},\mathbf{y})}$$

Impact parameter

Time delay function:

$$T(\mathbf{x},\mathbf{y}) = \frac{1}{2}|\mathbf{x}-\mathbf{y}| - \psi(\mathbf{x}) + \phi_m(y)$$

Lensing potential



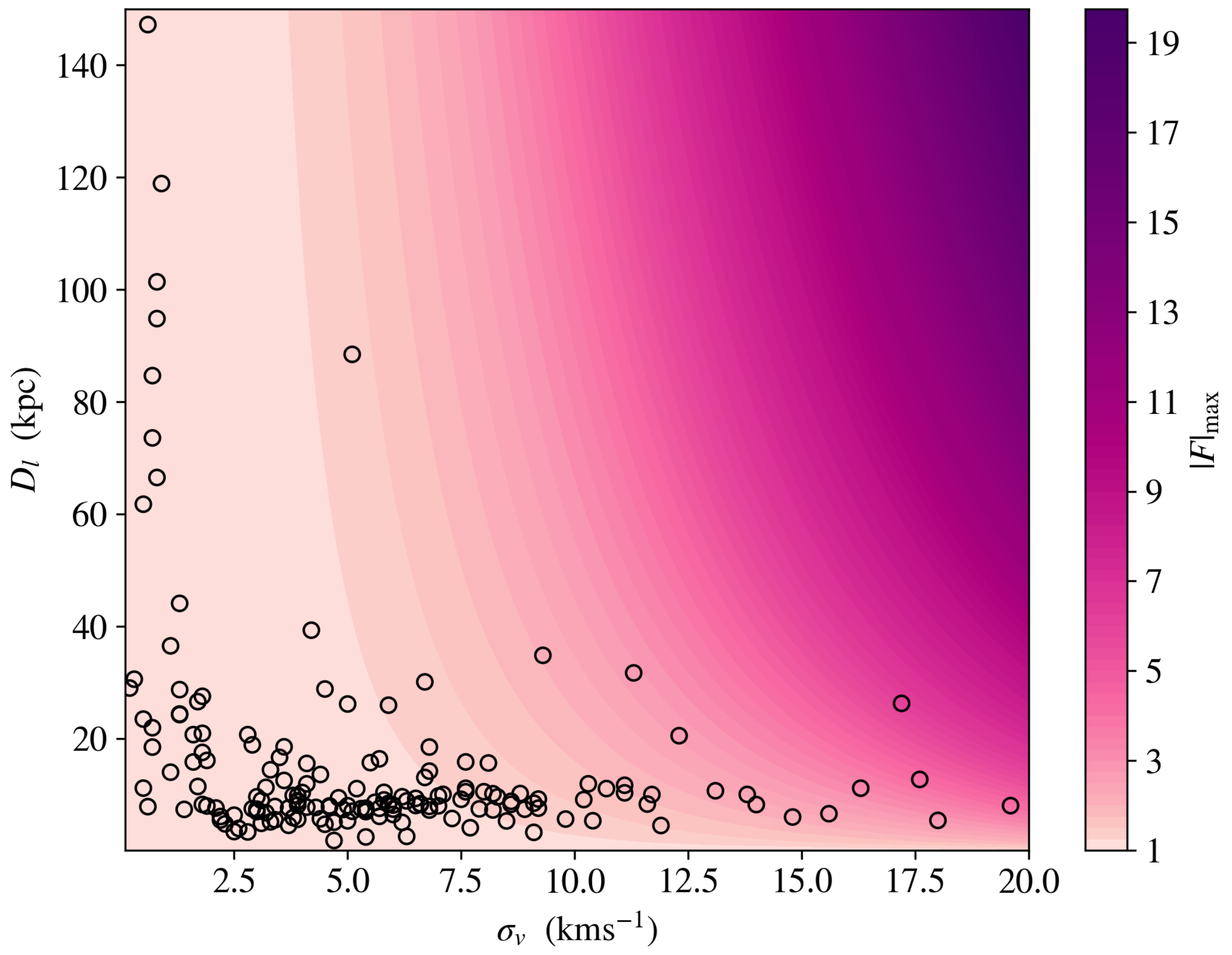
Lensed Waveform

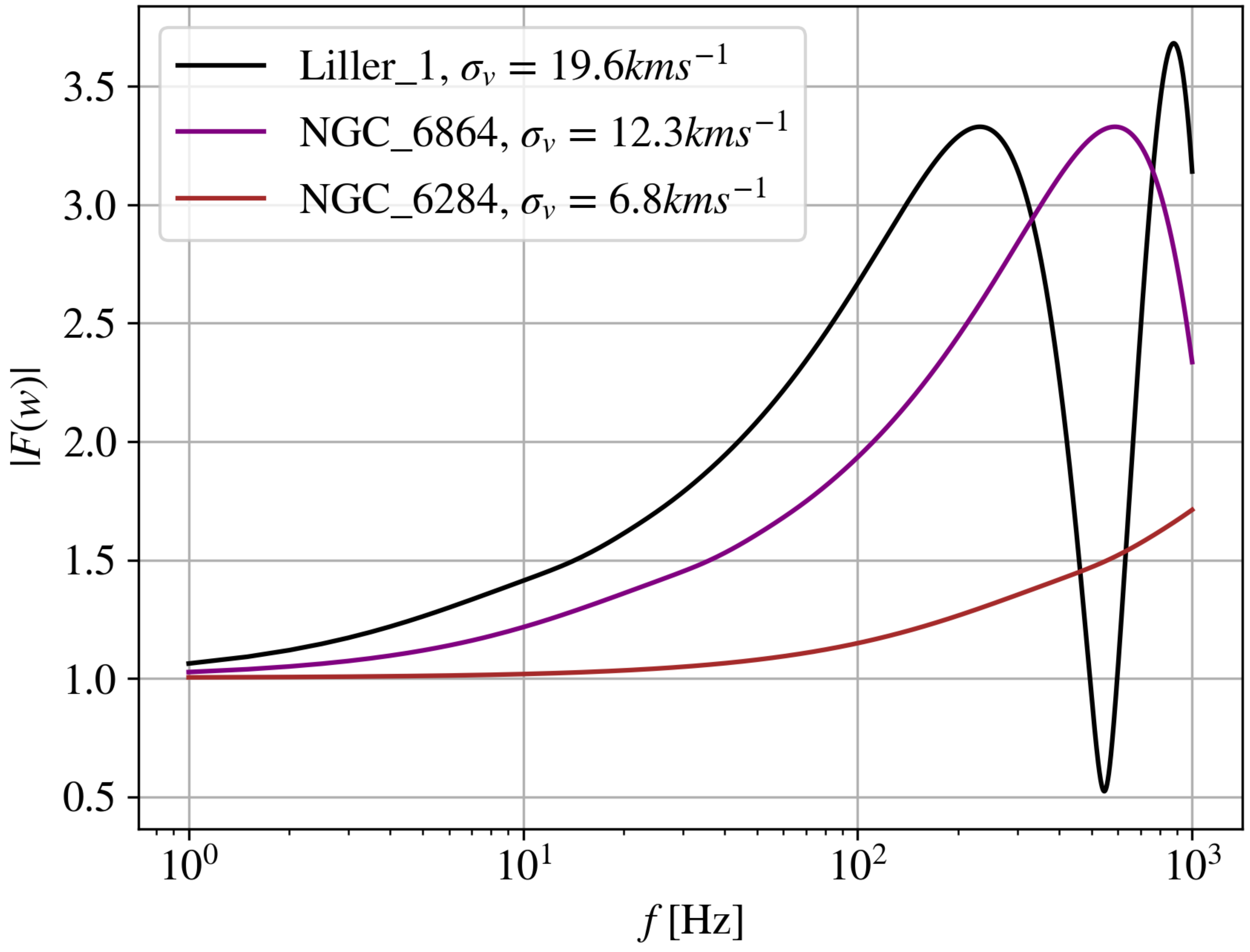
$$\boxed{h_l = F(w,y)\,.\,h_u}$$

Polarizations are not always parallel propagated

Harikumar et. al. *Phys.Rev.D* 109 (2024) 12, 124014

MW globular clusters and their amplification





Amplification factor for SIS model

$$F(w) = e^{\frac{1}{2}wy^2}\sum_{n=0}^{\infty}\frac{1+n/2}{n!}(2we^{i3\pi/2})^{n/2} \times {}_1F_1\left(-\frac{n}{2};1;\frac{i}{2}wy^2\right)$$

Matsunaga et. al. 2006, *JCAP* 01 (2006) 023

Dimensionless frequency

$$w = \frac{32\pi^3}{c^5}\sigma_v^4\frac{D_l D_{ls}}{D_s}f(1+z_l)$$

Methodology

Injection

- Un-lensed signal - GW150914
- Waveform approximant - IMRPhenomXPHM
- Three detector network is used.
- O4 PSD

Lens

Cluster	σ_v (kms^{-1})	D_l (kpc)
Liller 1	19.6	8.08
NGC 6093	11.1	10.34
NGC 2409	5.1	80

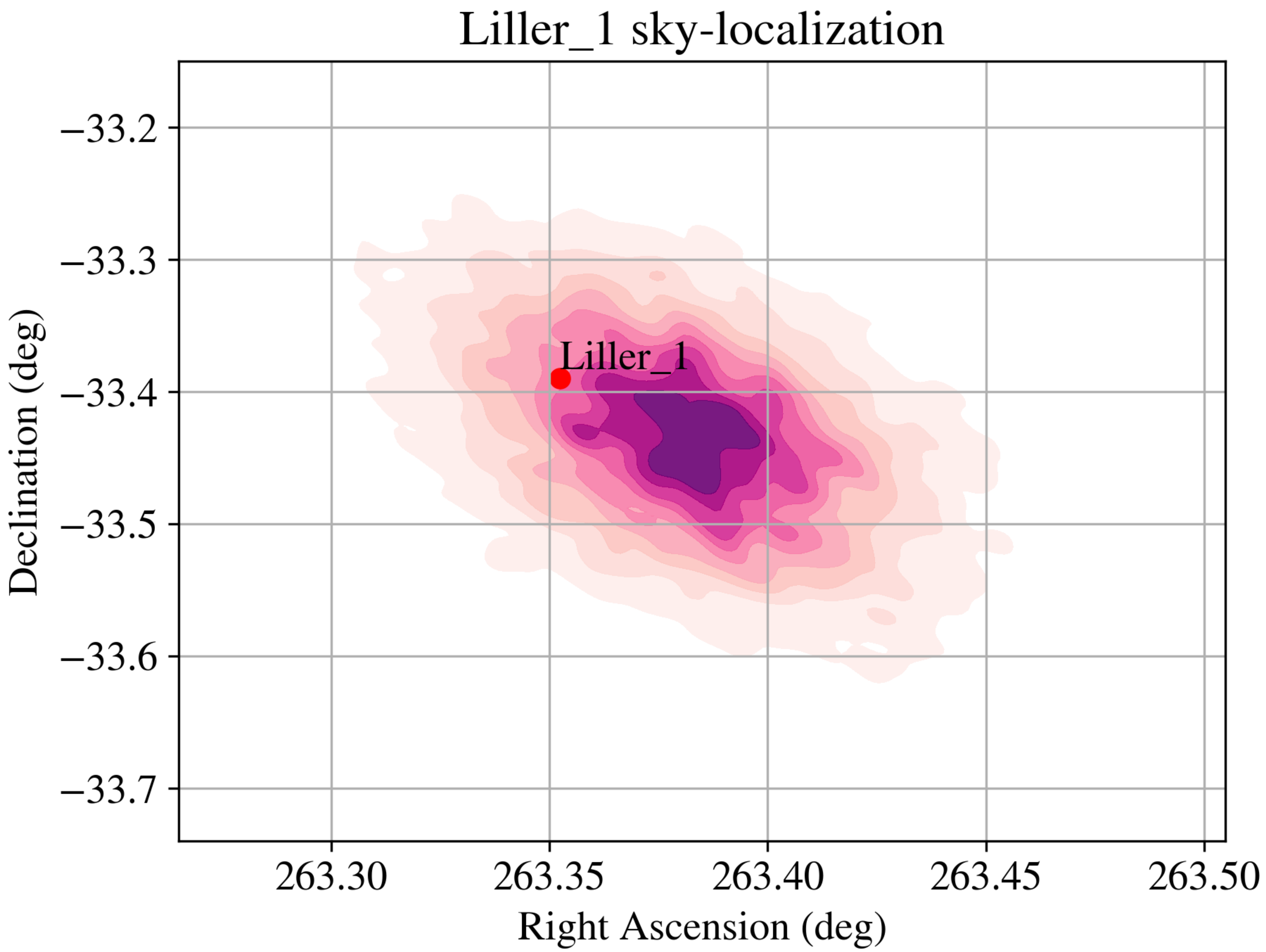
Source is placed behind the cluster

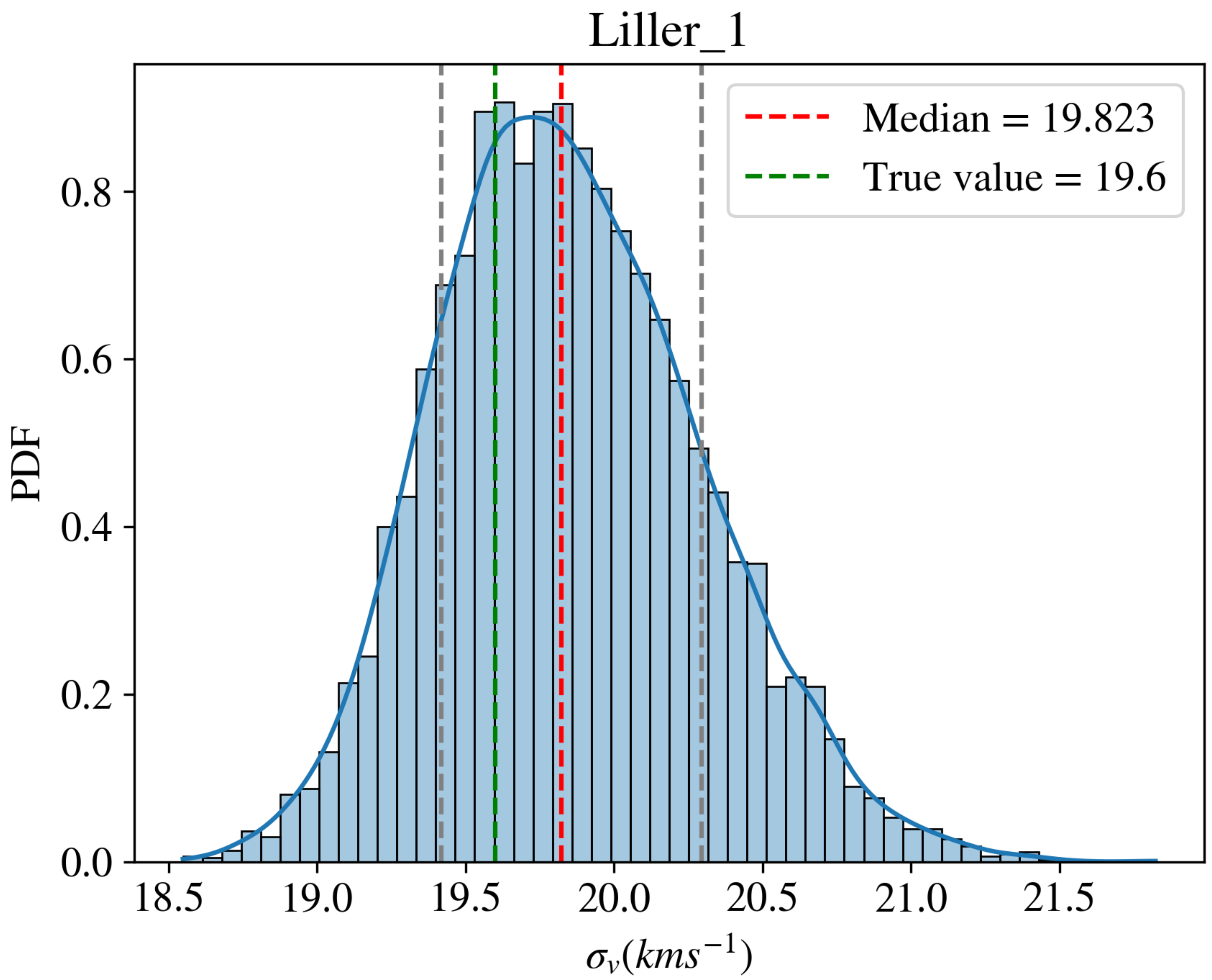
$$\alpha' = \alpha \qquad \delta' = \delta + \frac{y\xi_0}{D_l}$$

We identify the cluster by cross matching with the catalog,

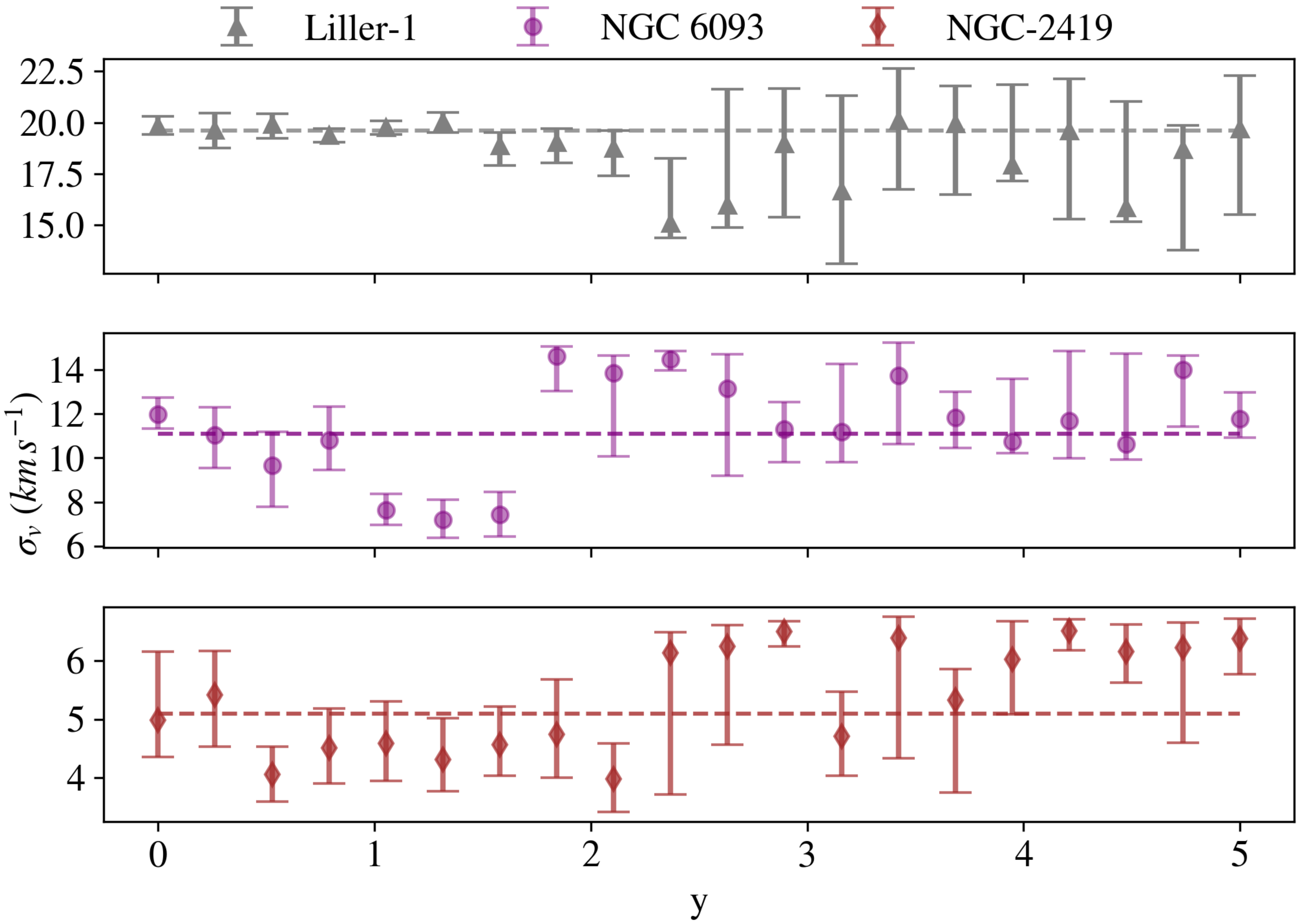
$$\sigma_v = \left[\frac{c^2 G}{4\pi^2}\frac{M_{Lz}}{D_l}\right]^{1/4}$$

Recovered sky area and velocity dispersion (an example)





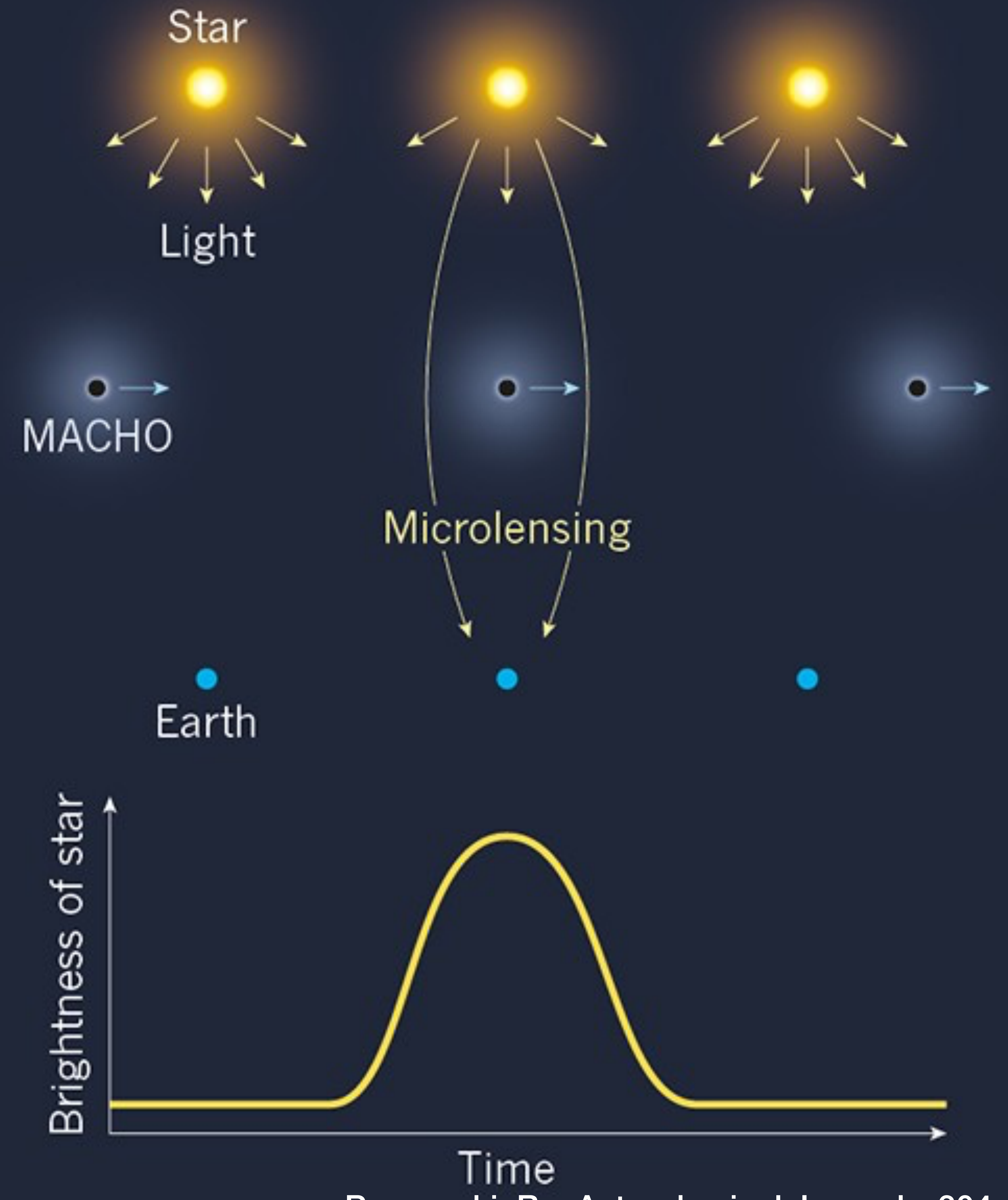
Recovered velocity dispersion….



Some remarks

- **GW lensing can serve as a complimentary tool to study GCs and determine their properties like velocity dispersion σ_v**
- **New surveys like LSST will enlarge the existing catalogs, however the velocity dispersion measurements in EM is still challenging.**
- **Accurate identification of the cluster depends on the accuracy of sky-localization.**
- **A detailed study with extra-galactic clusters and other lens models are in progress**

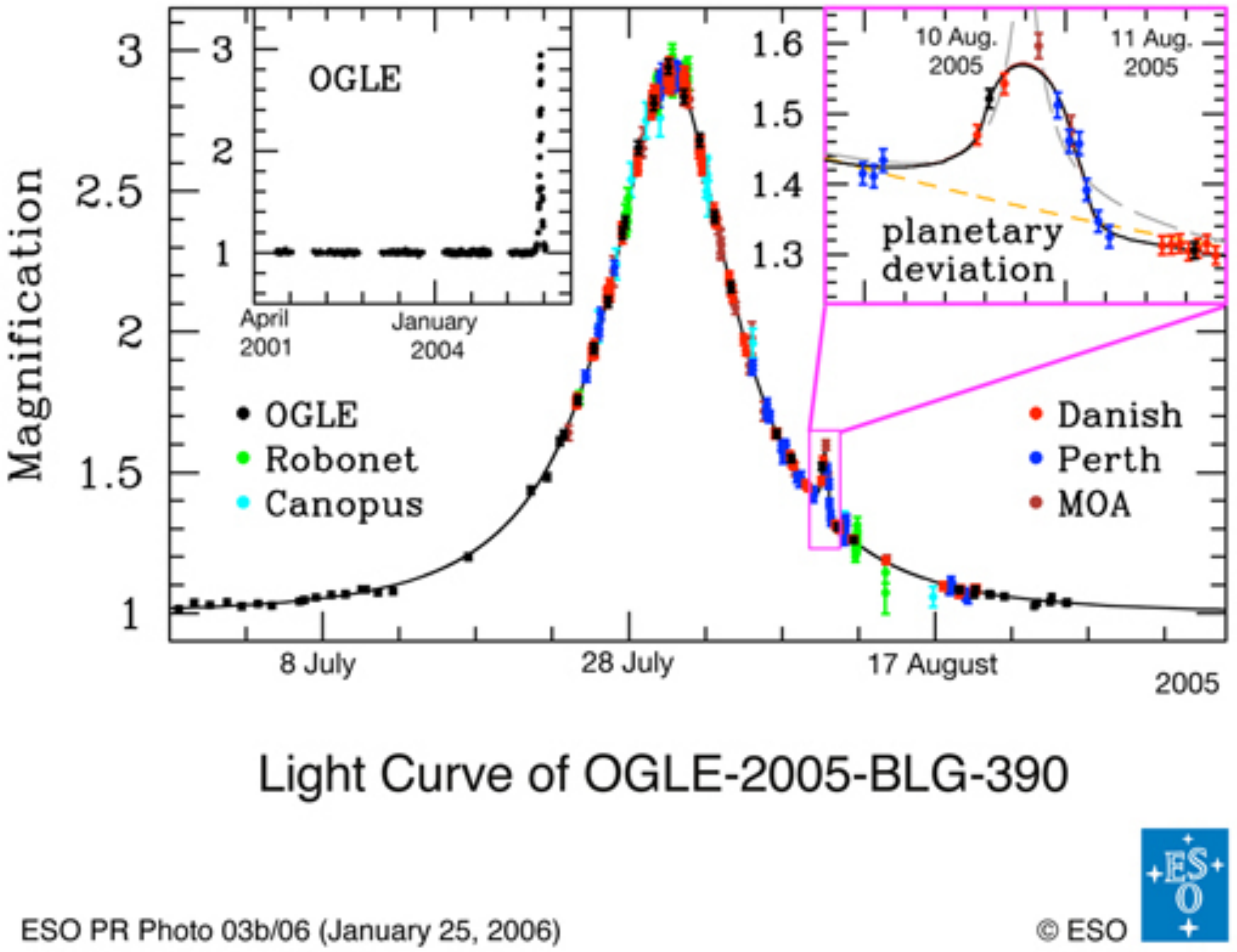
Signatures of continuous waves lensed by dark matter



Paczynski, B., Astrophysical Journal v.304, p.1,1986ApJ...304....1P/doi:10.1086/164140

Microlensing in EM domain

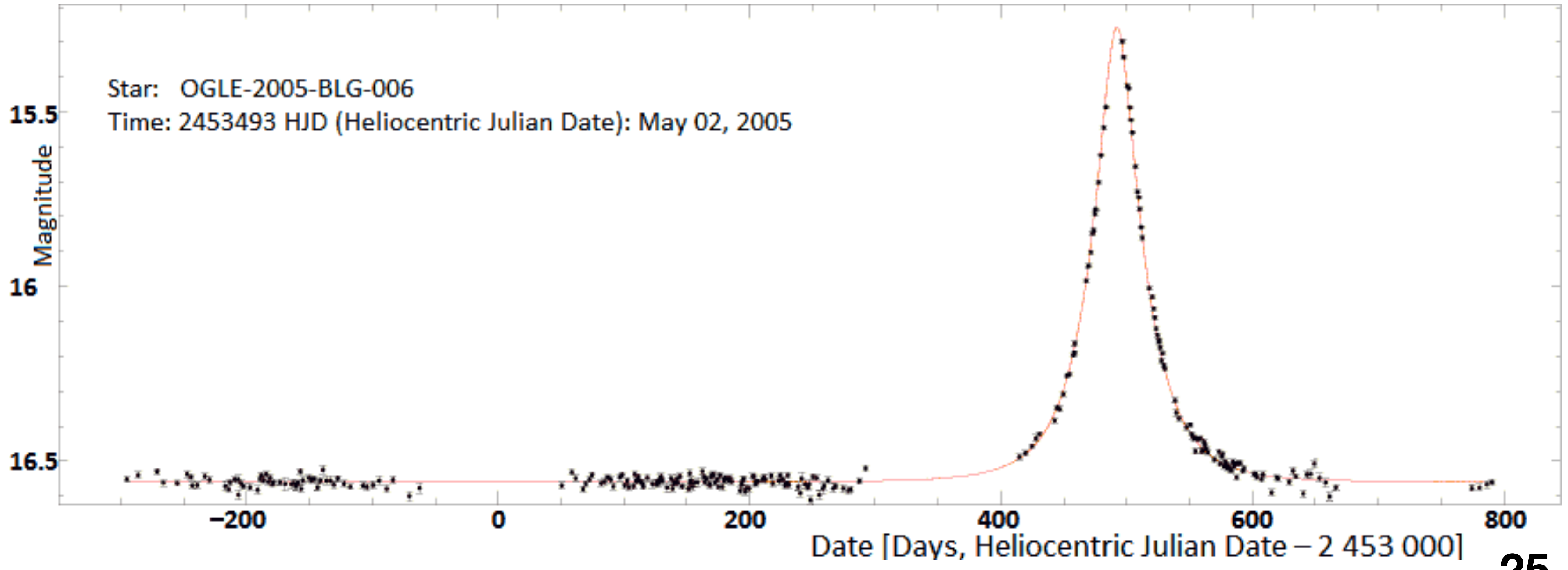
The source magnification varies as a function of time



Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

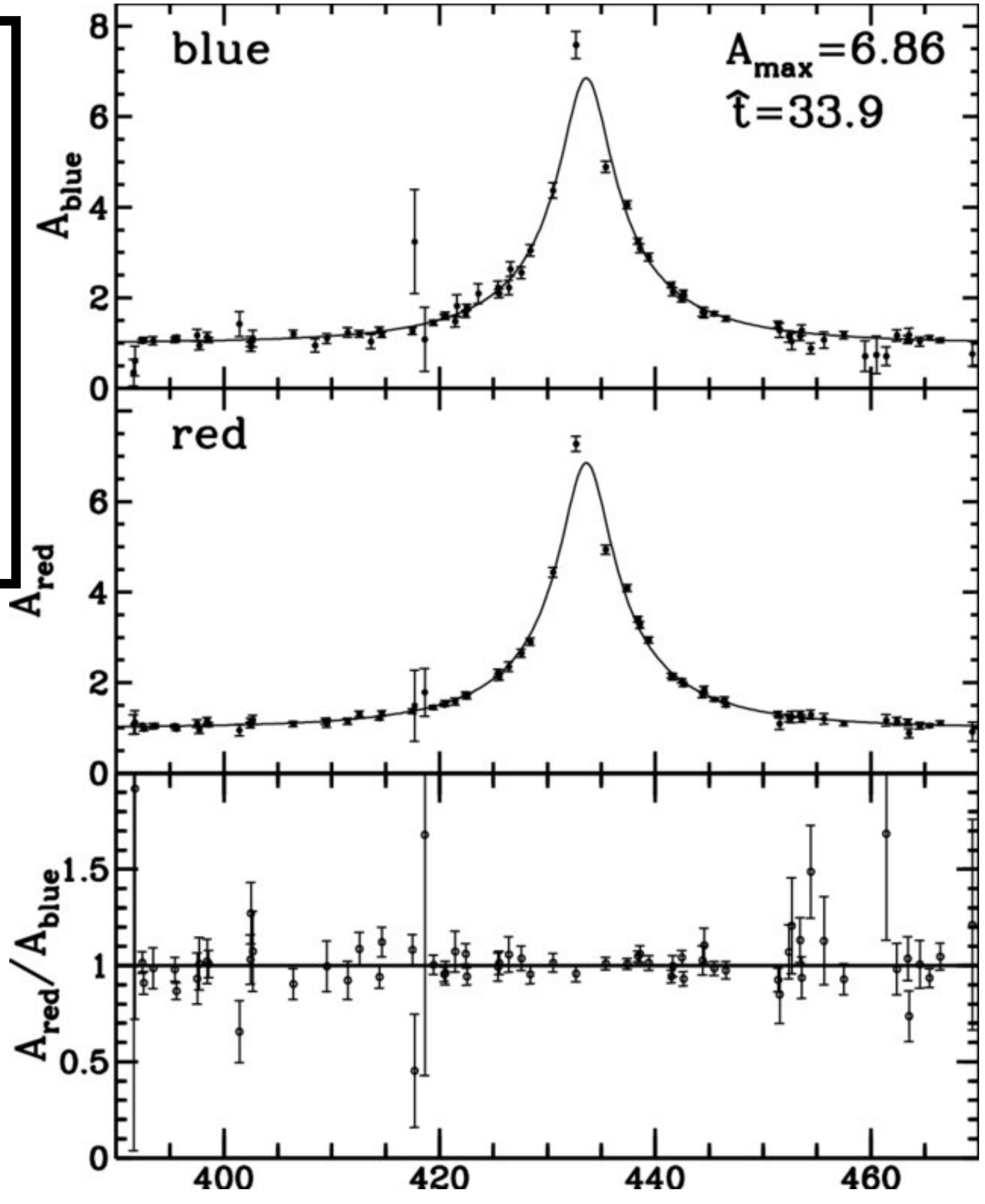
© ESO



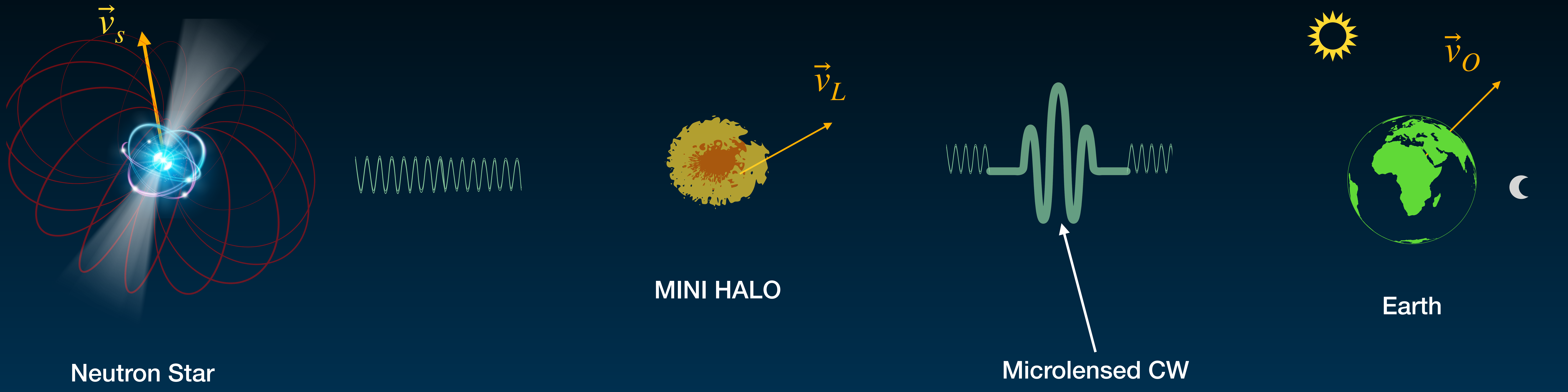
Some microlensing surveys

- **OGLE**
- **EROS**
- **MACHO**
- **MOA**

First Microlensing event



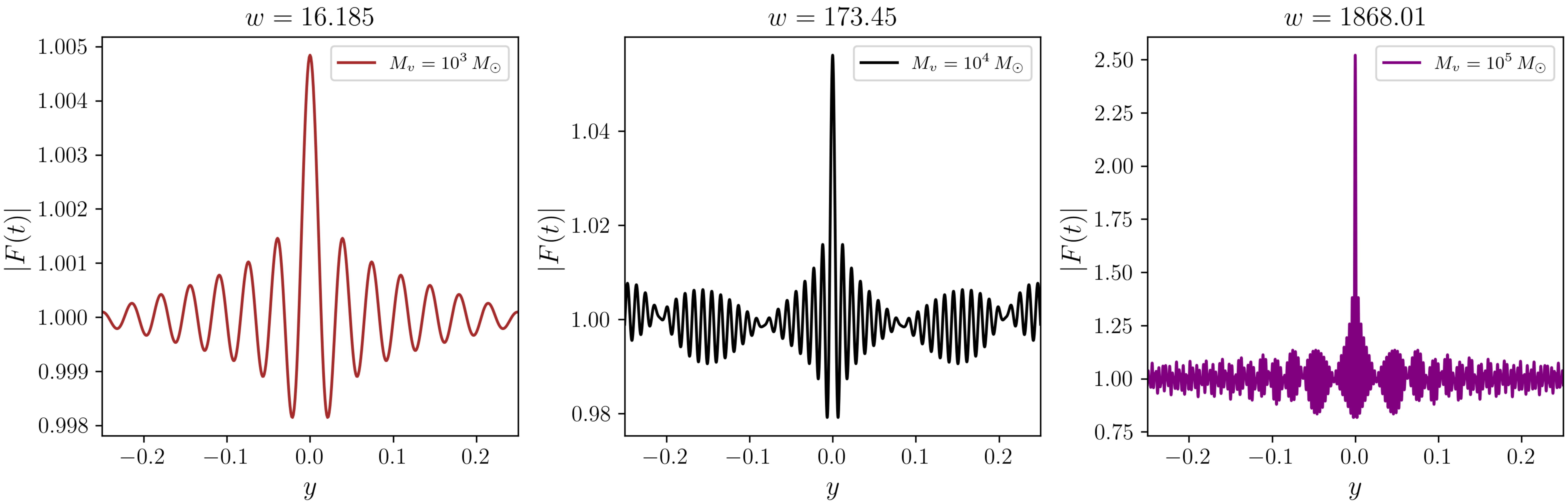
C. Alcock et al., Nat, 365, 621 (1993).

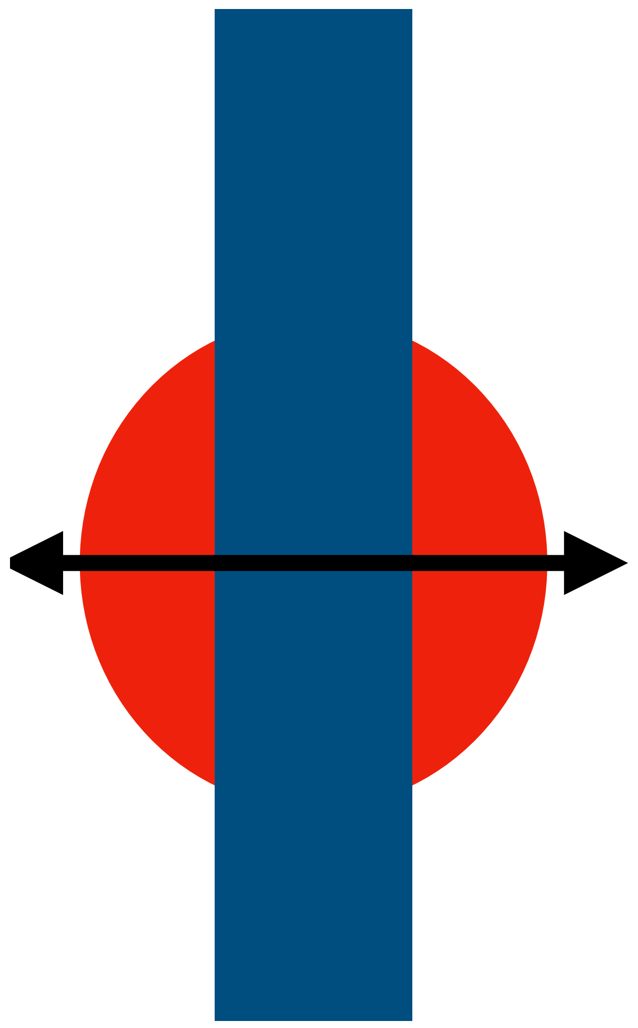


Relative velocity

$$\vec{v}_{eff} = \vec{v}_s - \frac{D_s}{D_l}\vec{v}_L + \left(\frac{D_s}{D_l} - 1\right)\vec{v}_o$$

Amplification of the NFW Halos

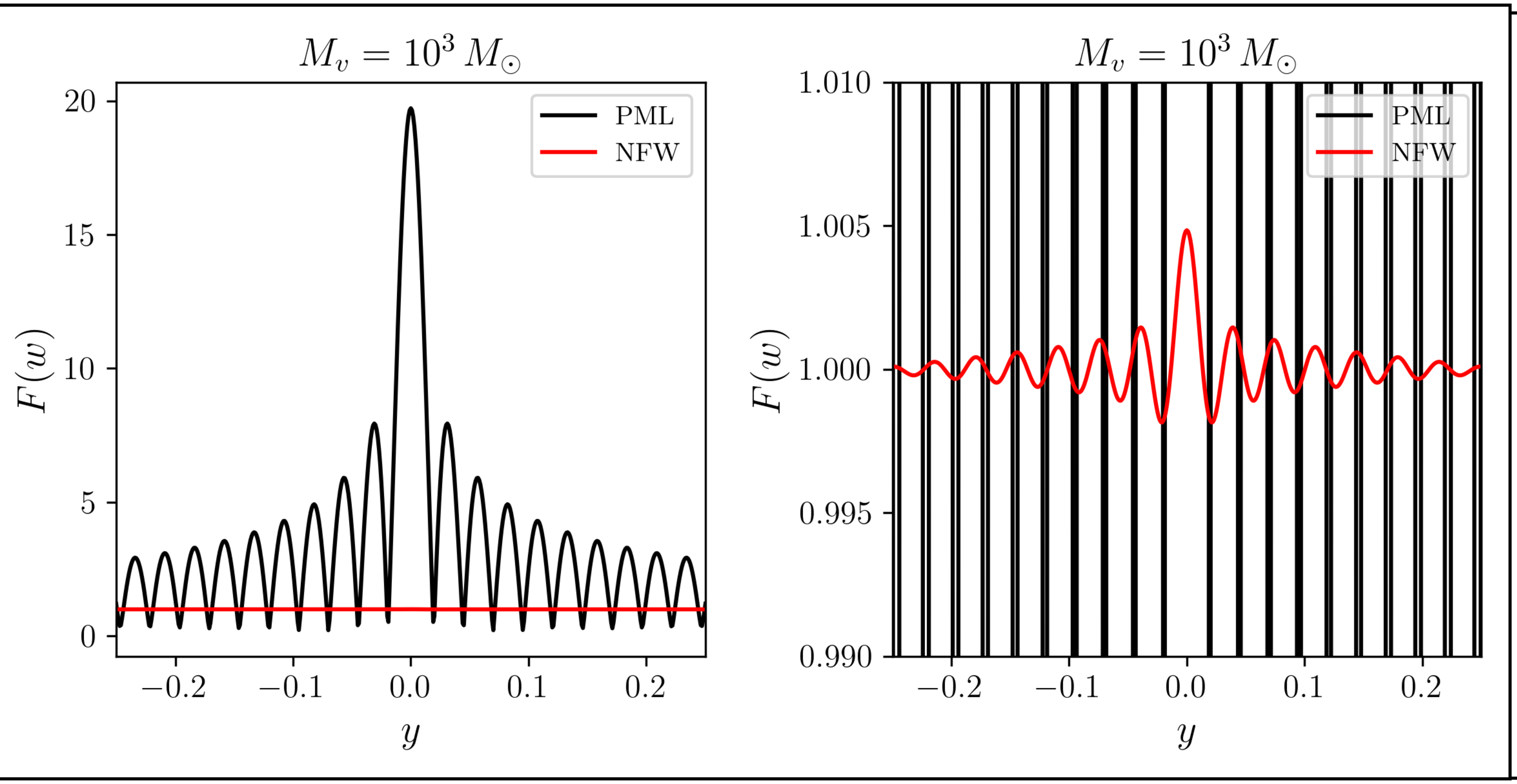


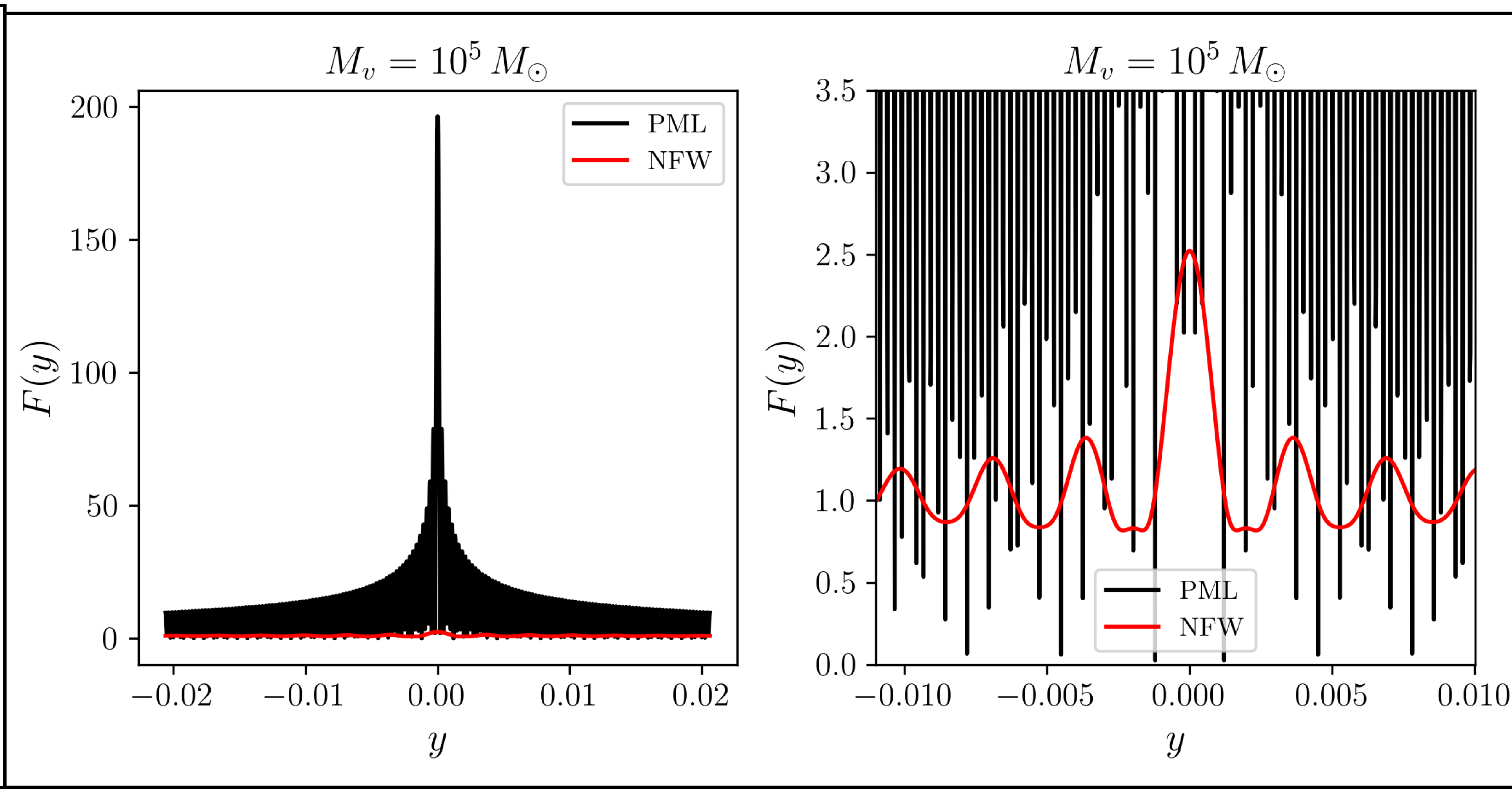


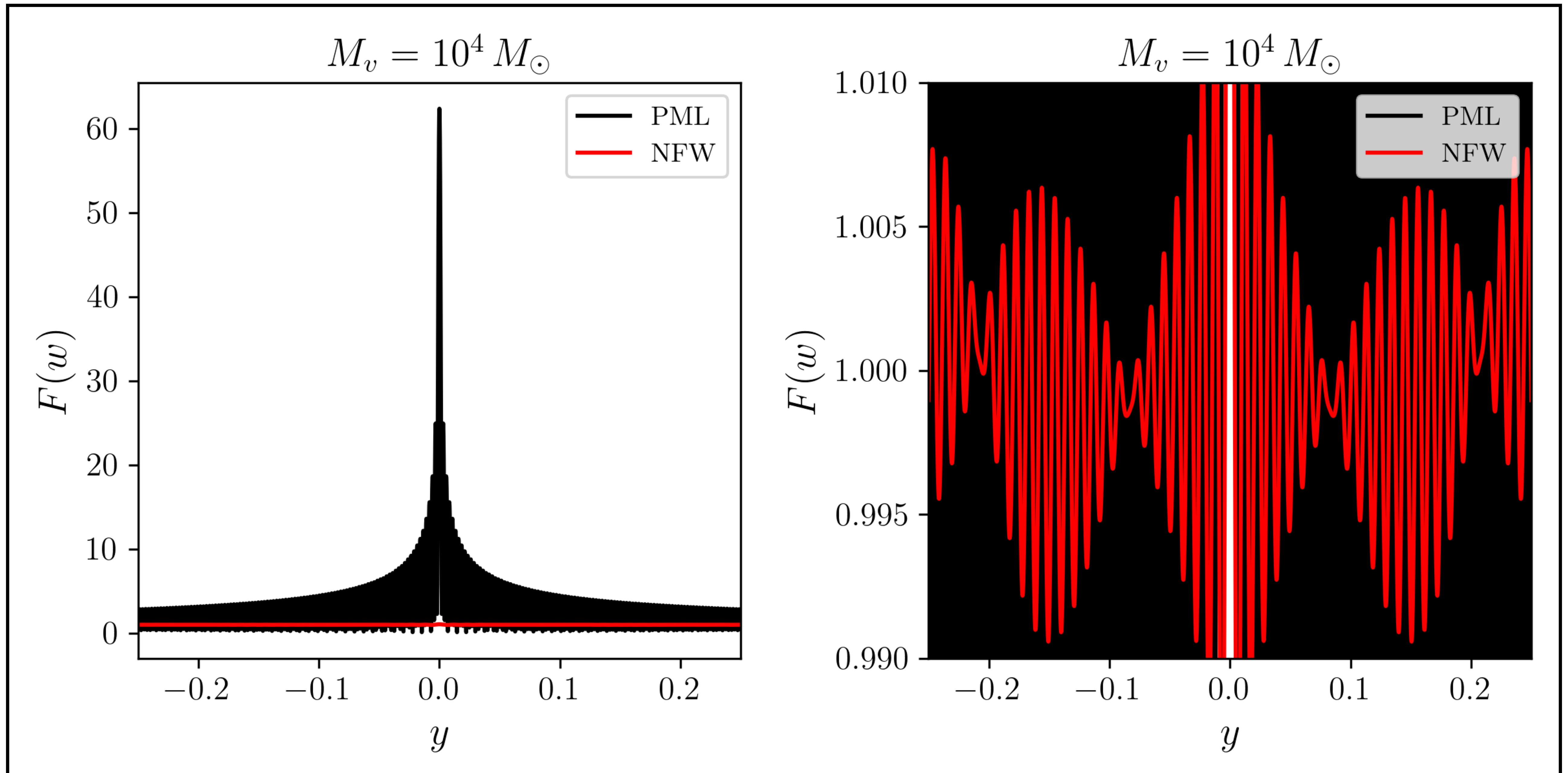
Lens Mass	**Dimensional Frequency**	ξ_0/r_s
$10^3\ M_\odot$	16.185	3.8×10^{-4}
$10^4\ M_\odot$	173.459	4.3×10^{-4}
$10^5\ M_\odot$	1868.010	4.9×10^{-4}

- **The source frequency $f = 1\ kHz$, $D_l = 10$ kpc and $D_s = 20$ kpc**
- **The impact parameter is a function of time $y(t)$**
- **Time required to observe the full oscillation could be several years.**

Can we identify and distinguish different lenses ?

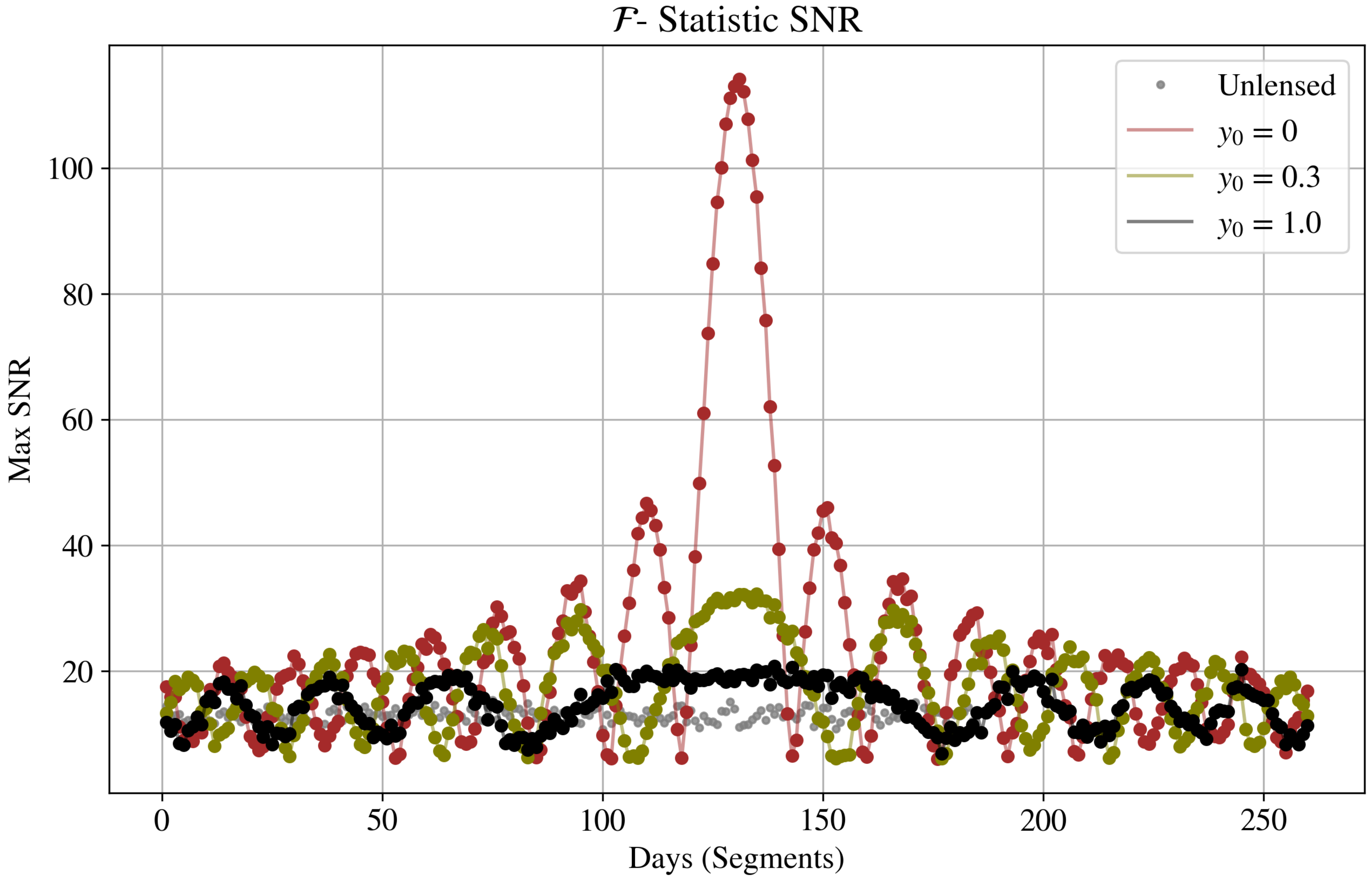




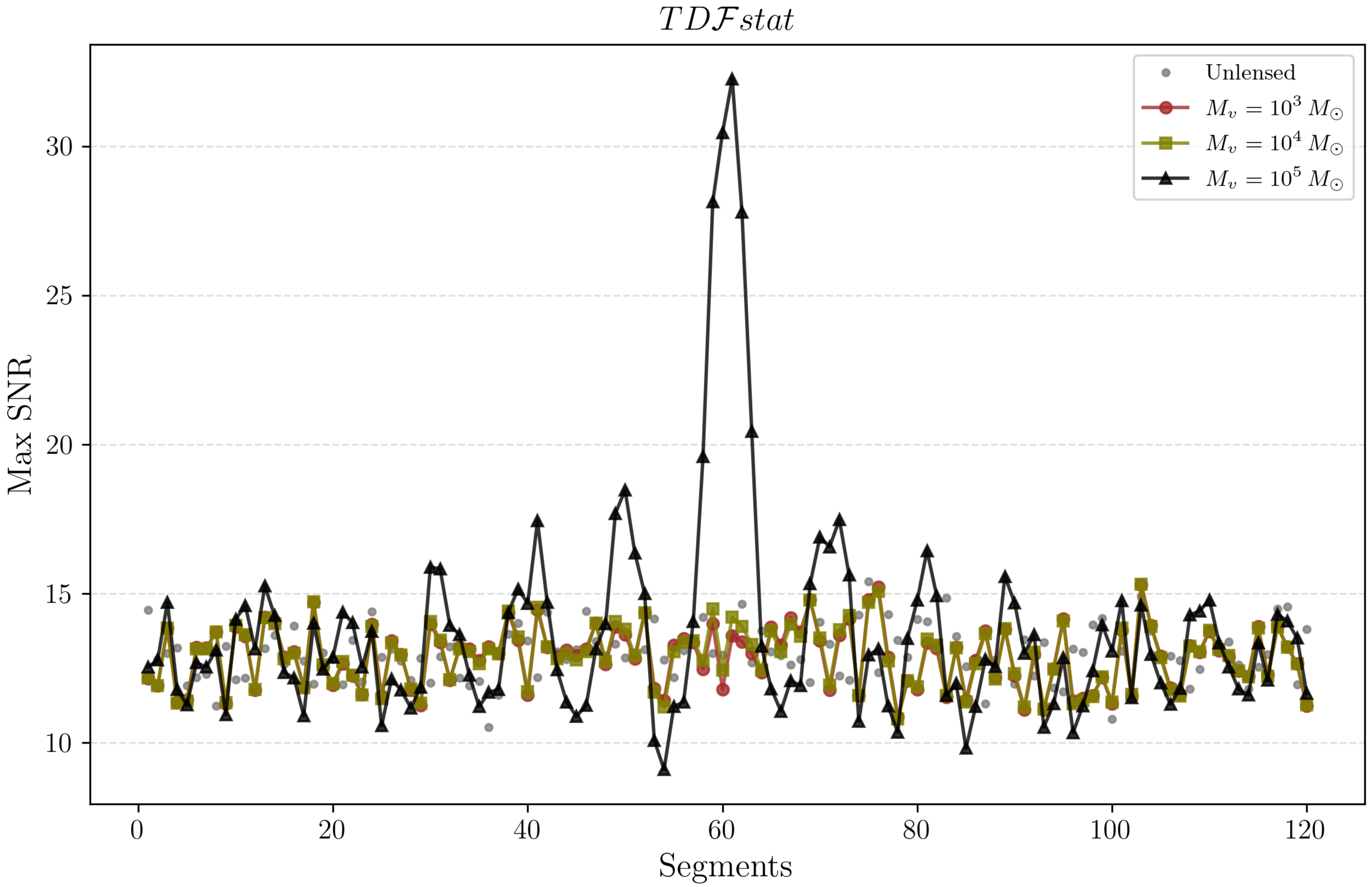


Time Domain $\mathscr{F}-$Statistics result

Point Mass lens



NFW lens



- Each point is the maximum of the $\mathscr{F}$ statistic in the respective segment.
- The maximum SNR also oscillates along the segments.

$$\rho = \sqrt{2\mathscr{F} - 4}$$

https://github.com/Polgraw/TDFstat

Jaranowski, Krolak, Schutz ,*Phys.Rev.D* 58 (1998) 063001

Conclusion

- **Continuous gravitational waves are amplified in lensing. This enhances the detectability**
- **Lensing leads to an SNR pattern analogous to microlensing curves observed in EM surveys**
- **The fluctuations in amplitude $F(t)$ and phase $\phi(t)$ are proportional to lens mass distribution.**
- **Massive halos ($M_v > 10^6\ M_\odot$) can lead to phase shifts that oscillate between +180 and -180**

Acknowledgements:

NARODOWE CENTRUM NAUKI

We acknowledge the support from the Polish National Science Center through the support from the grant no. 2025/56/C/ST9/00480 and 2023/49/B/ST9/02777.

If you are interested in gravitational waves or lensing or continuous waves

Write to us

sreekanth@camk.edu.pl

bejger@camk.edu.pl

Summer Students are welcome

GW Open Data Workshop