Constraining Compact DM with lensed GWs

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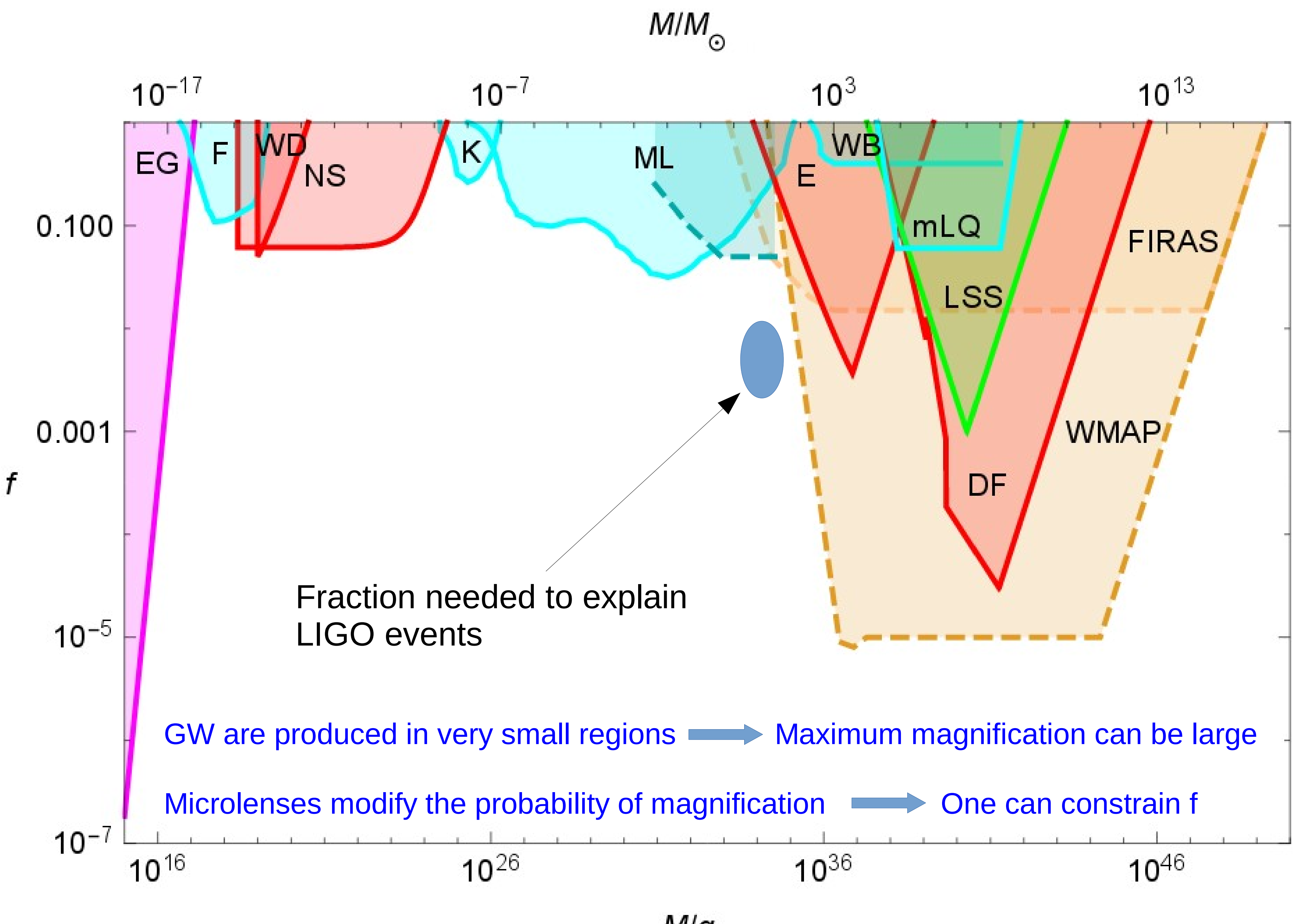
EXCELENCIA MARÍA DE MAEZTU

11 Iberian GW meeting, June 2021

Constraints on the total mass fraction in the form of PBH

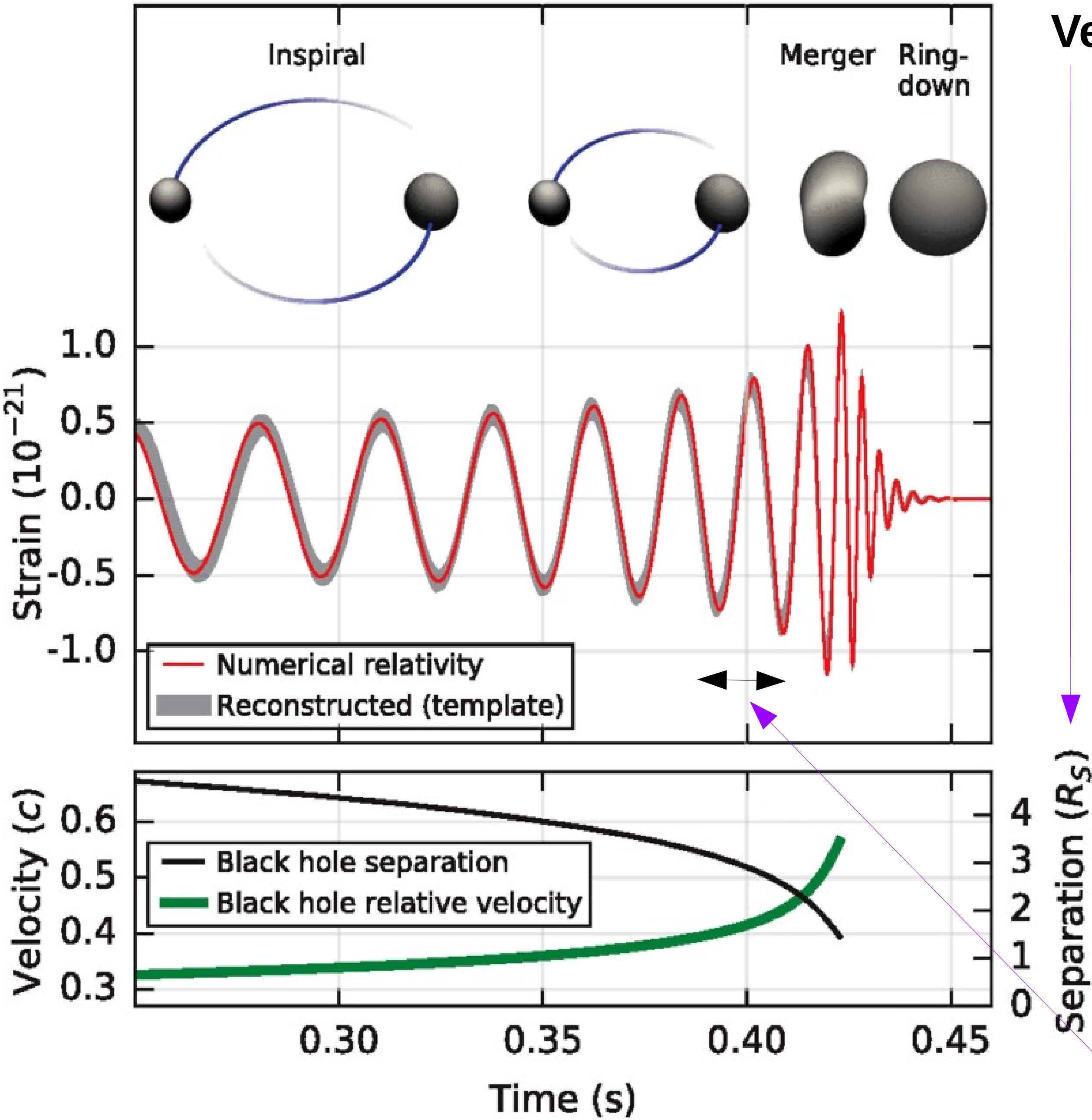


GW are produced in very small regions → Maximum magnification can be large

Microlenses modify the probability of magnification → One can constrain f

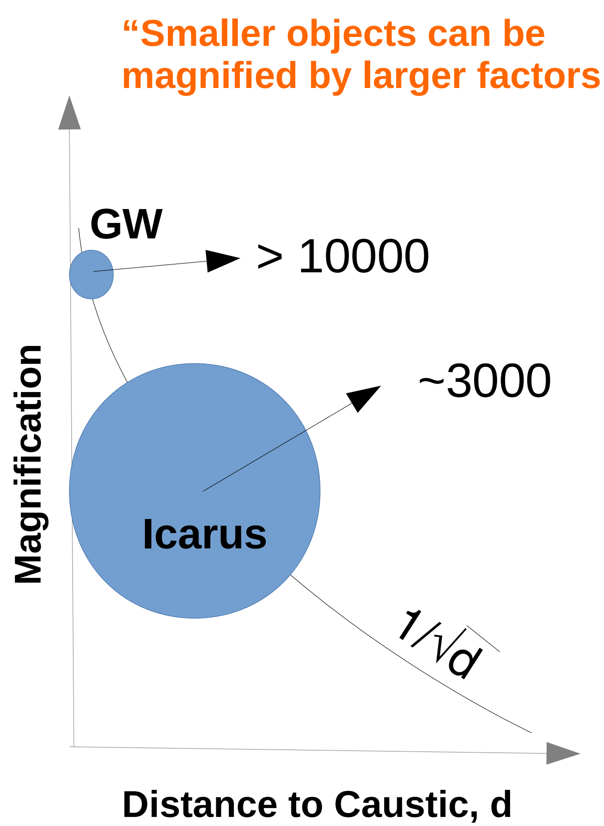
Carr et al. 2016

Gravitational Waves



Very small source

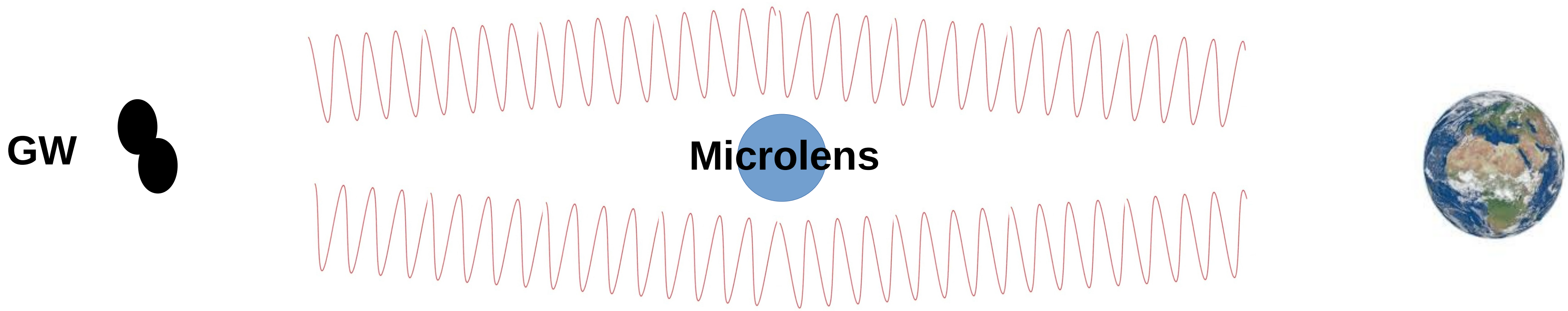
Subject to very large magnifications



Period ~ millisecond

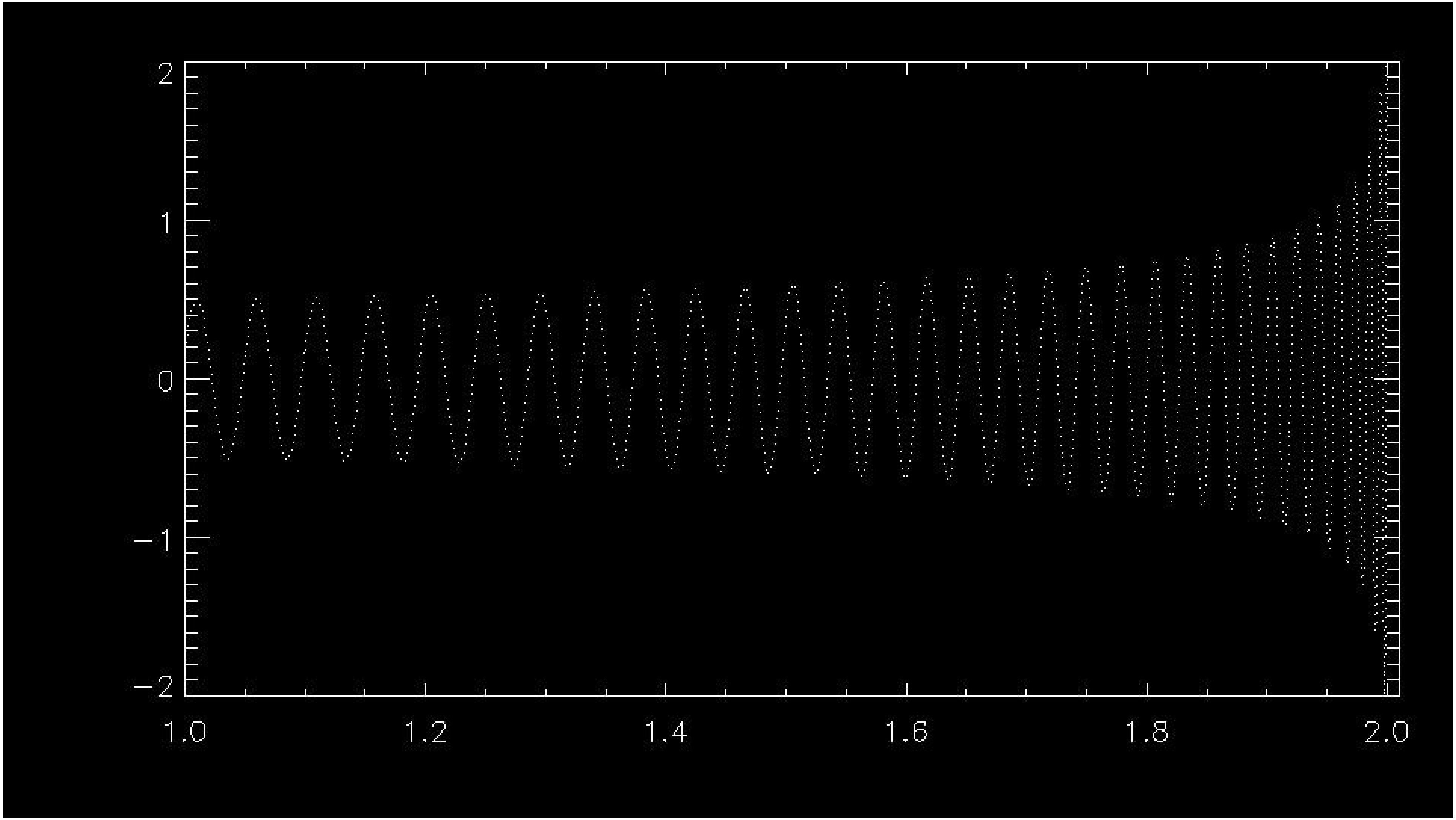
MOTIVATION

Since the period of GW is of order 1 millisecond, microlensing by objects which introduce time delays of order 1 millisecond will result in interference between the multiple microlensed images.

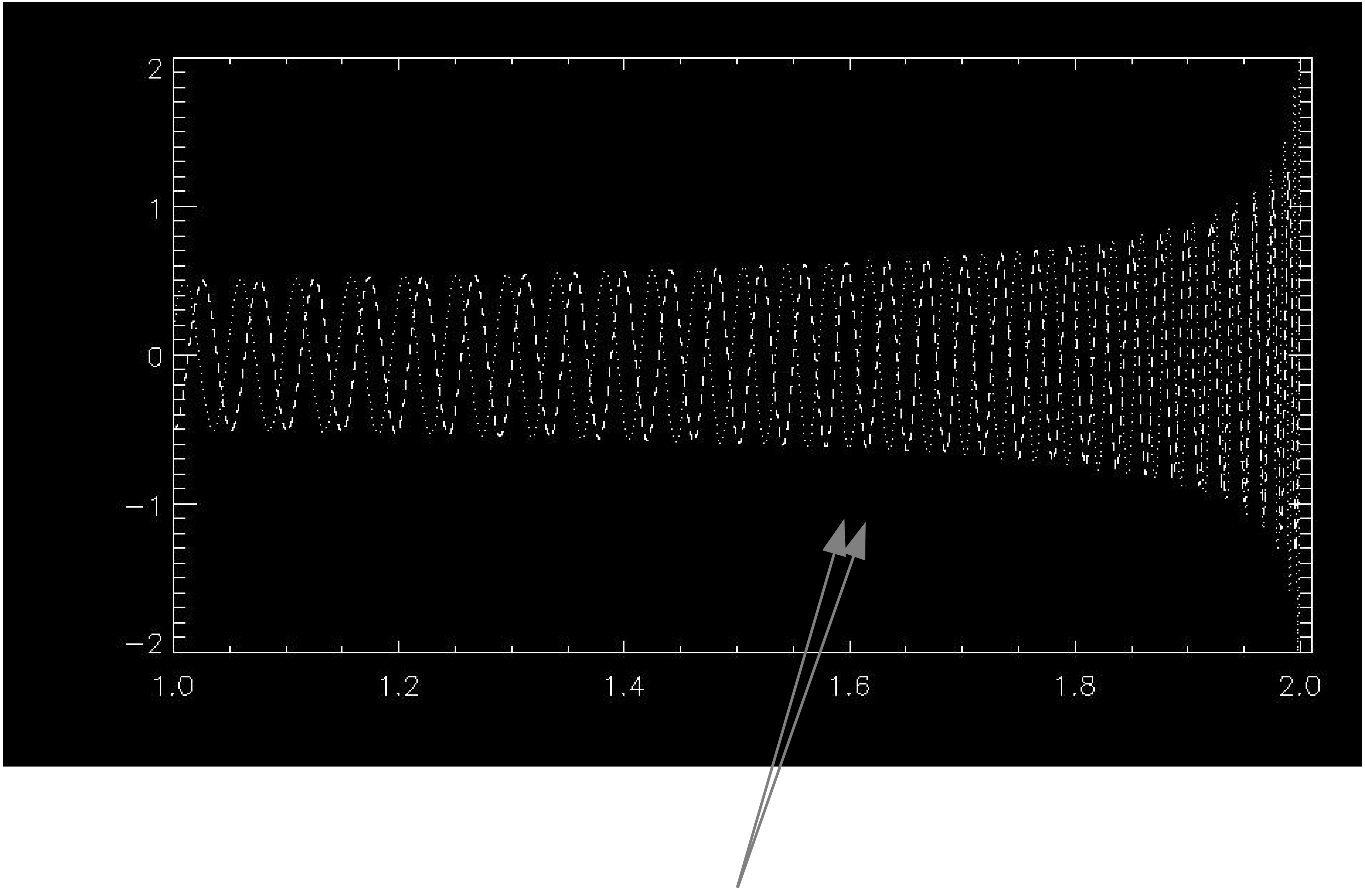


PBHs at cosmic distances with masses a few tens of solar masses, can produce such time delays.

Interference of GW

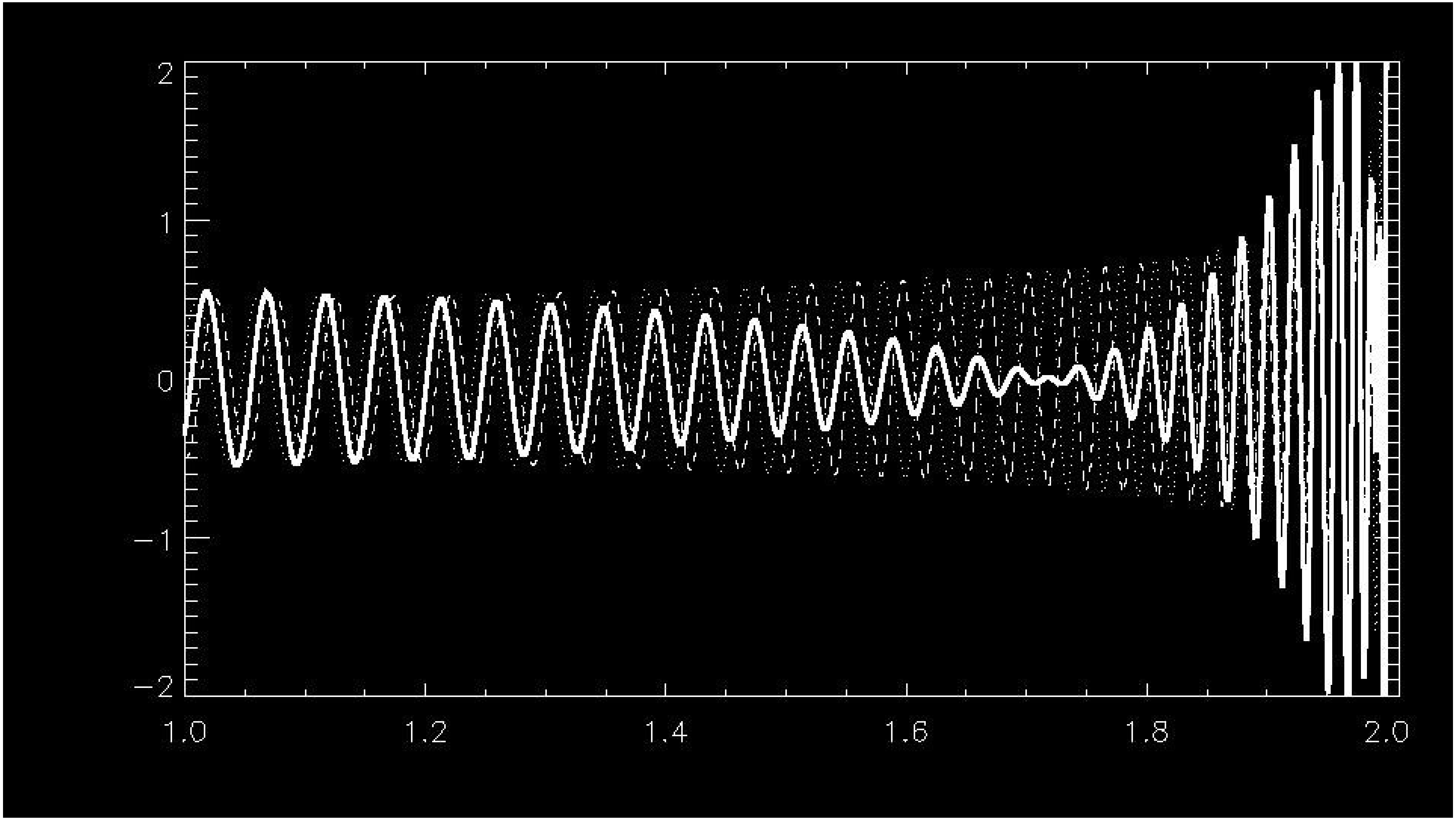


Interference of GW



Relative shift proportional to the mass of the microlens

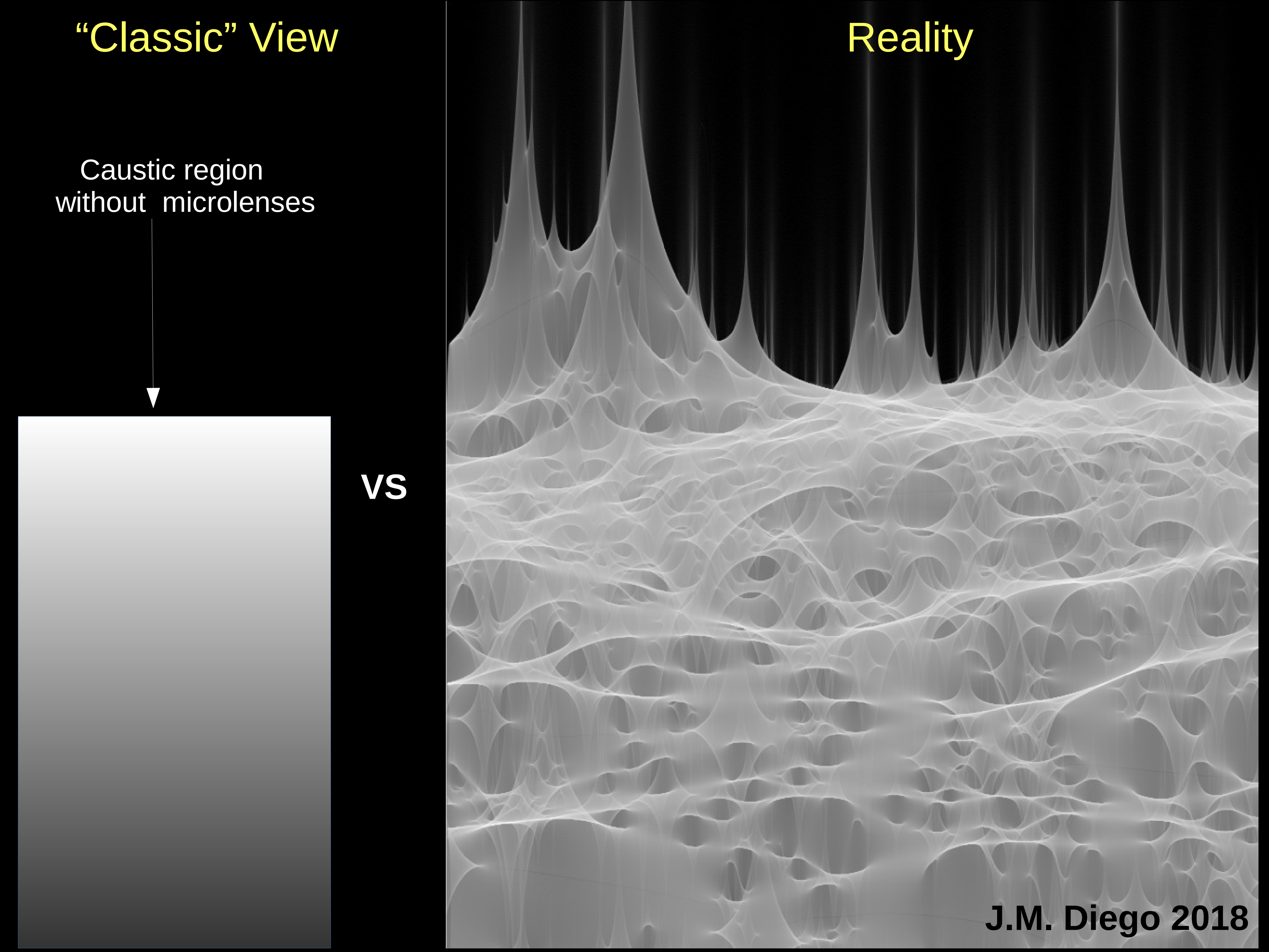
Interference of GW



Magnification depends on Frequency

Assume wave optics and solve diffraction integral in Fourier space

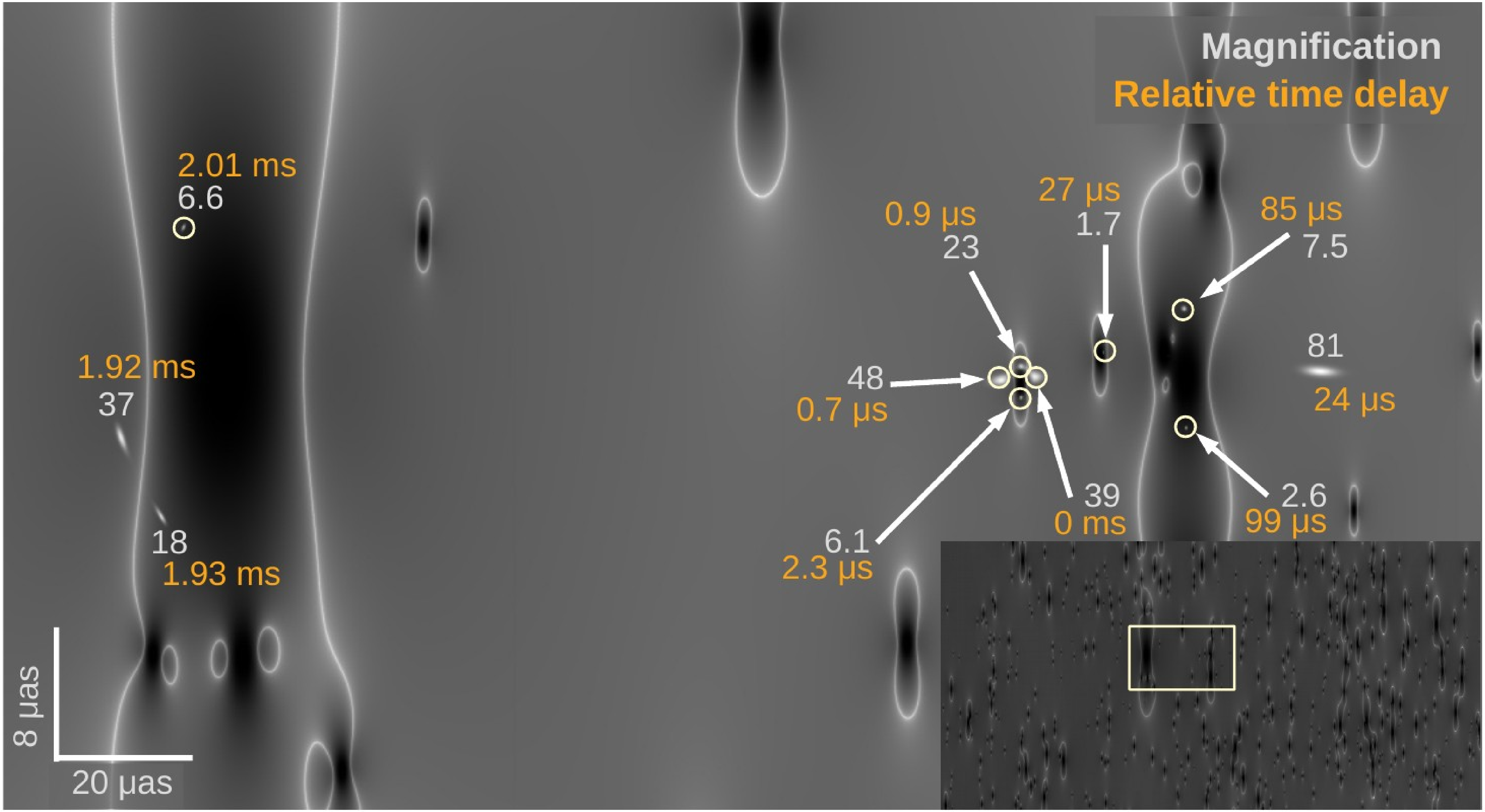
Looks like misalignment of spins



“Classic” View
Reality
Caustic region
without microlenses
VS
J.M. Diego 2018

If lensing is degenerate with the mass, how can this be tested?

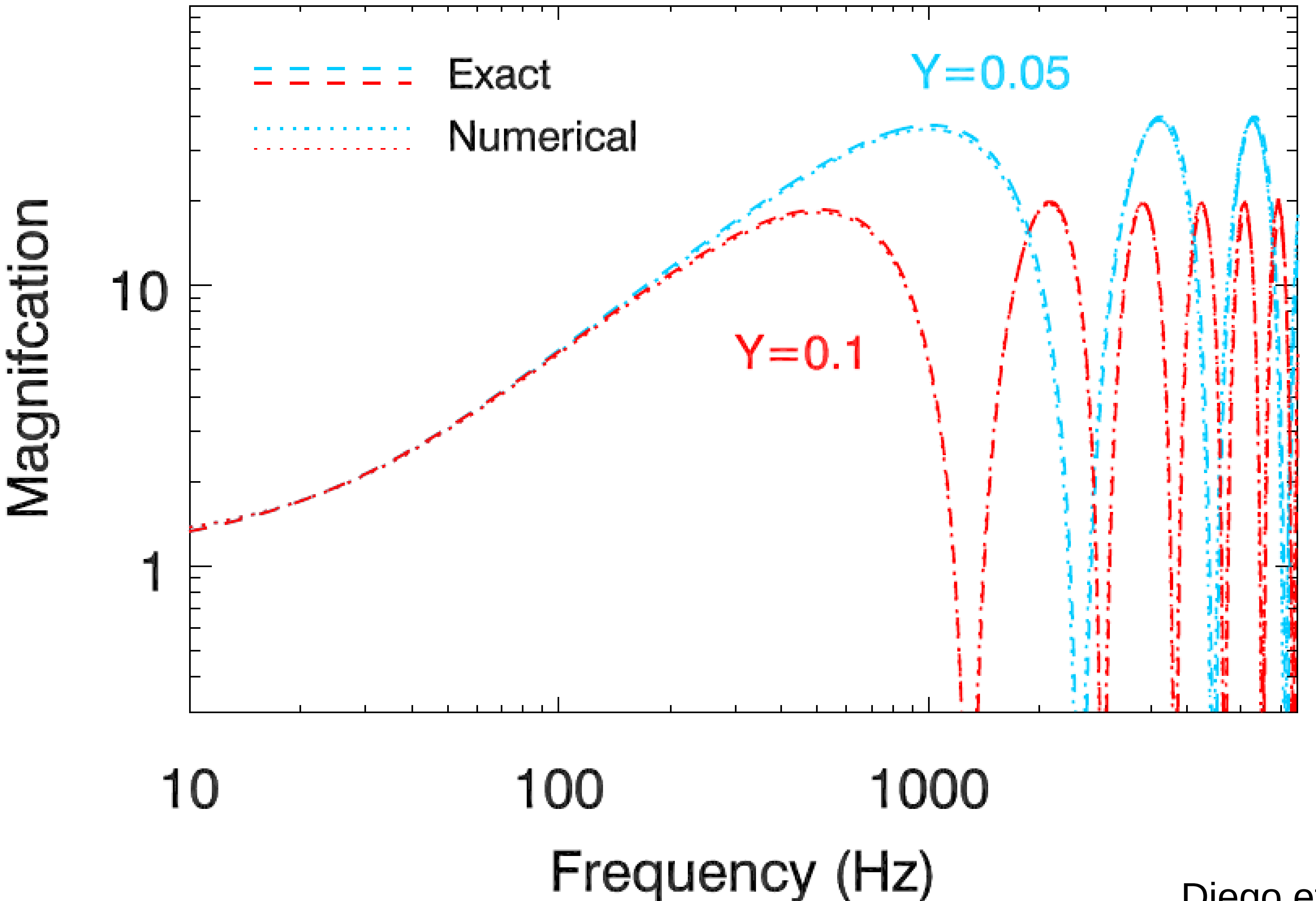
Microlensing of highly magnified GW is not only possible, is unavoidable.
Then, interference effects should be observable at LIGO frequencies.



Diego et al. 2019

Diffraction integral

$$F(w,\beta) = A_o \frac{\nu}{2\pi i} \int d^2\theta \, e^{i2\pi\nu\Delta T(\theta,\beta)}$$



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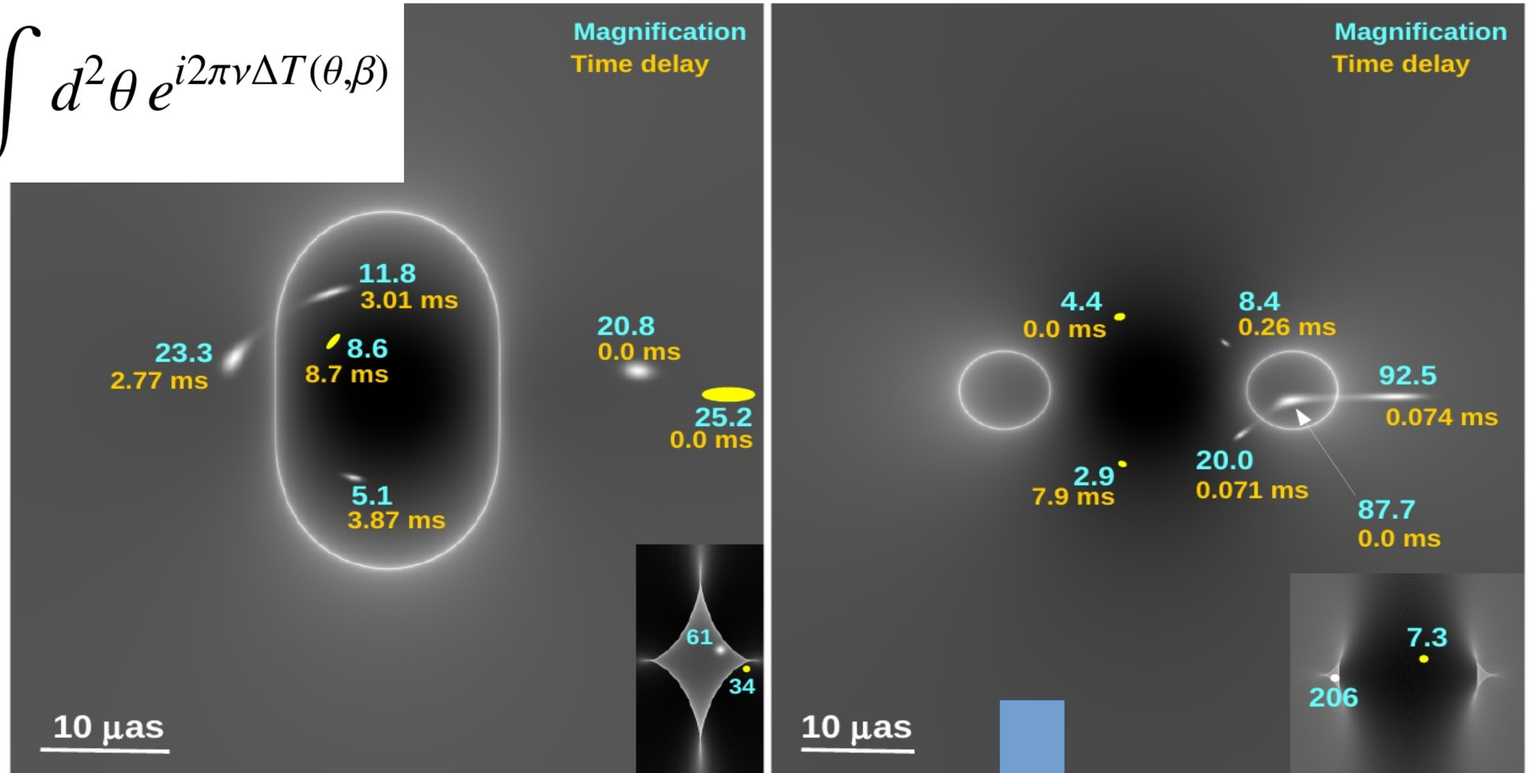
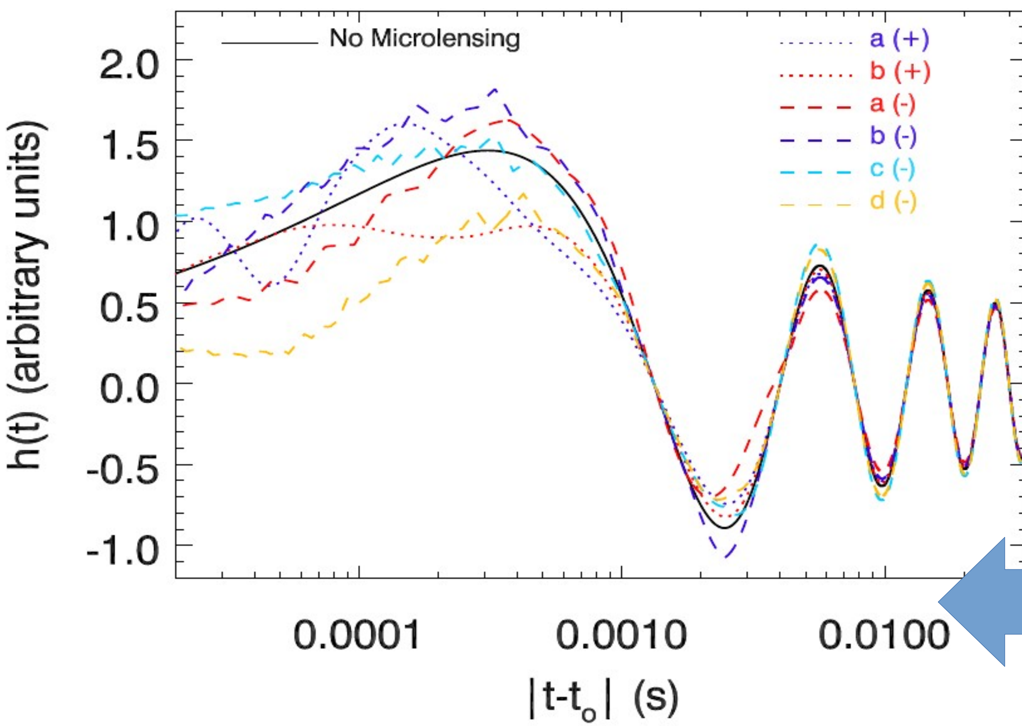
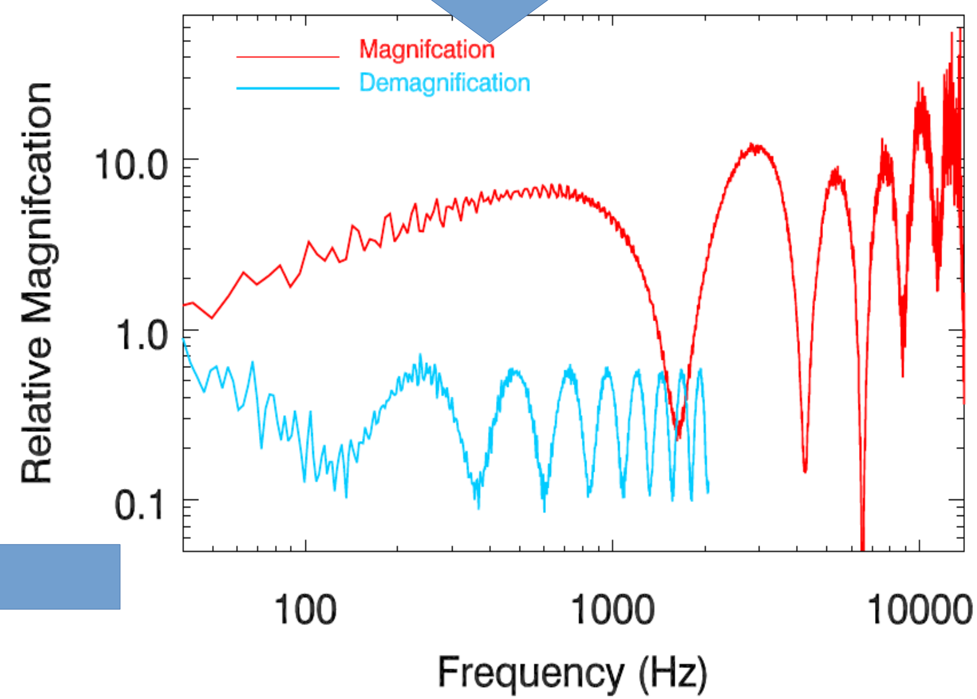
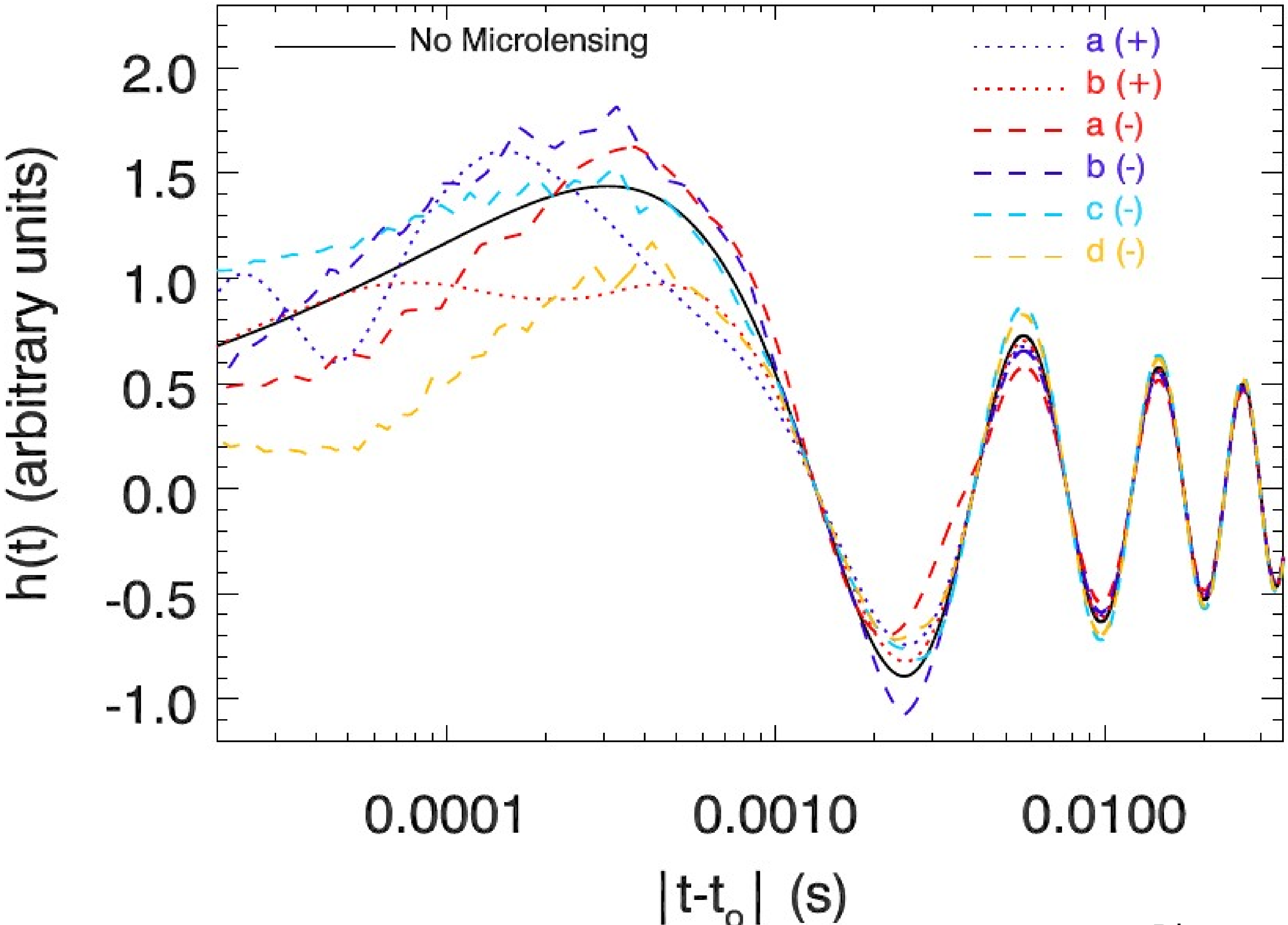




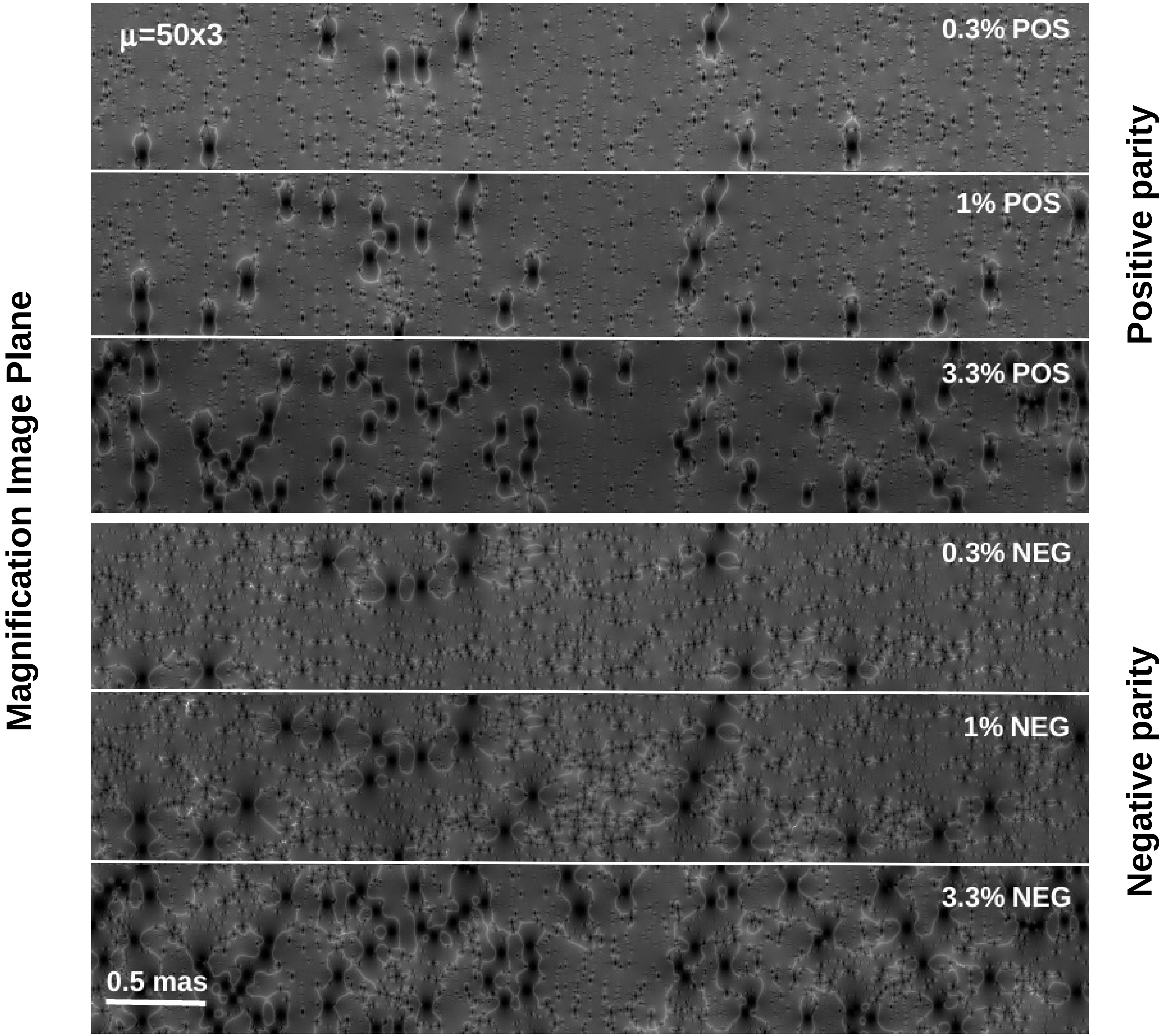


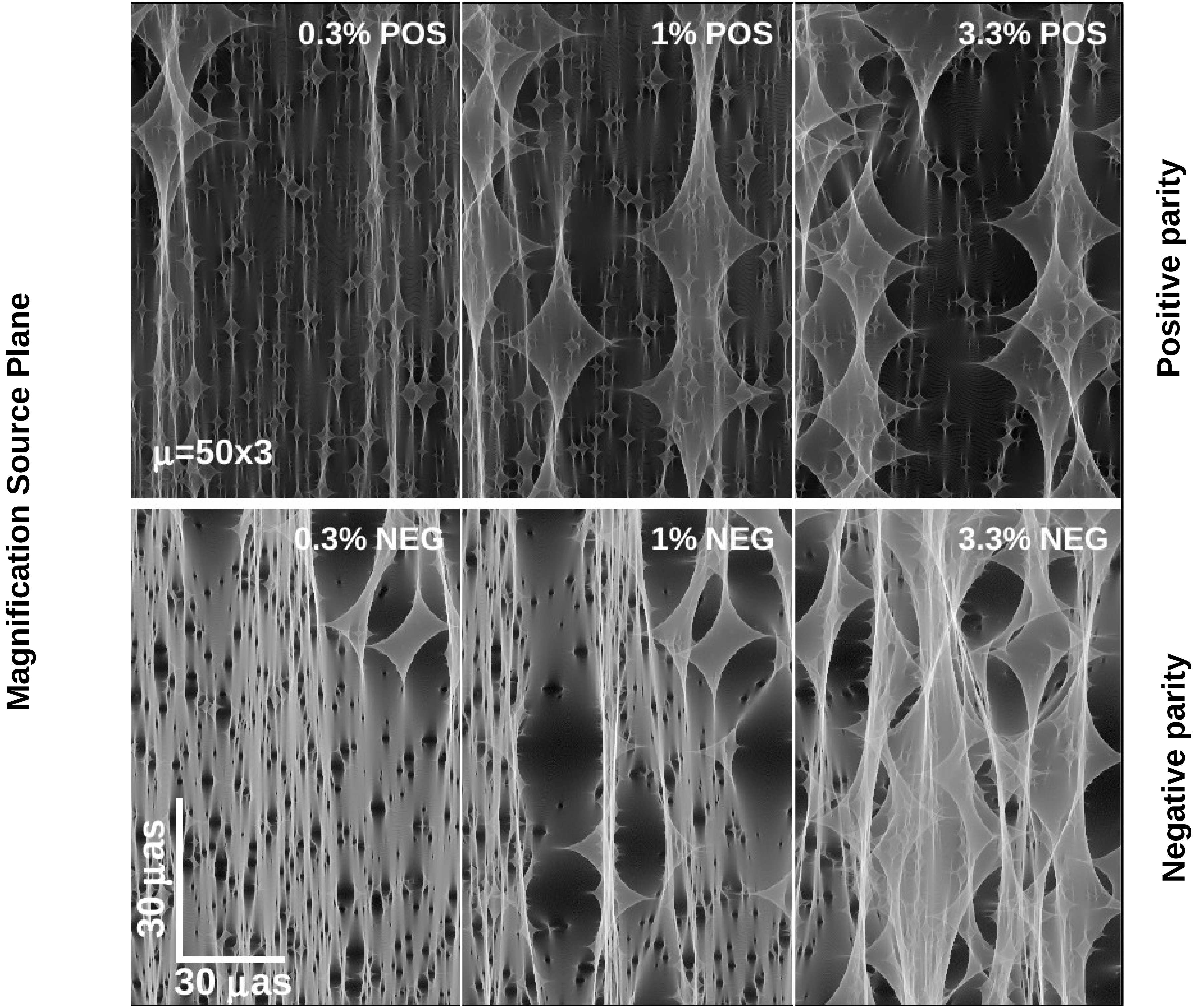
Effects on the strain (from stellar/remnants microlenses)

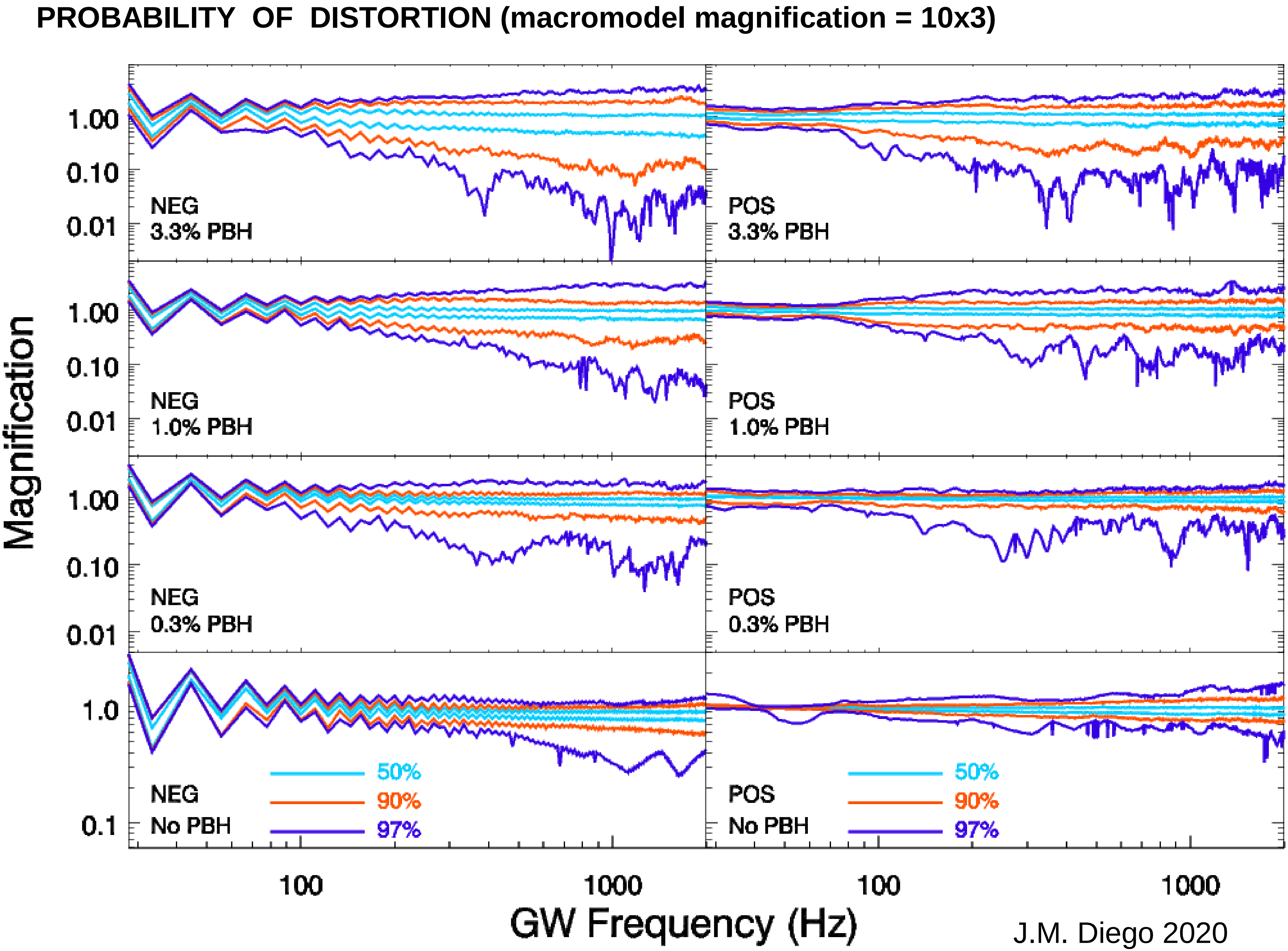


Diego et al. 2019

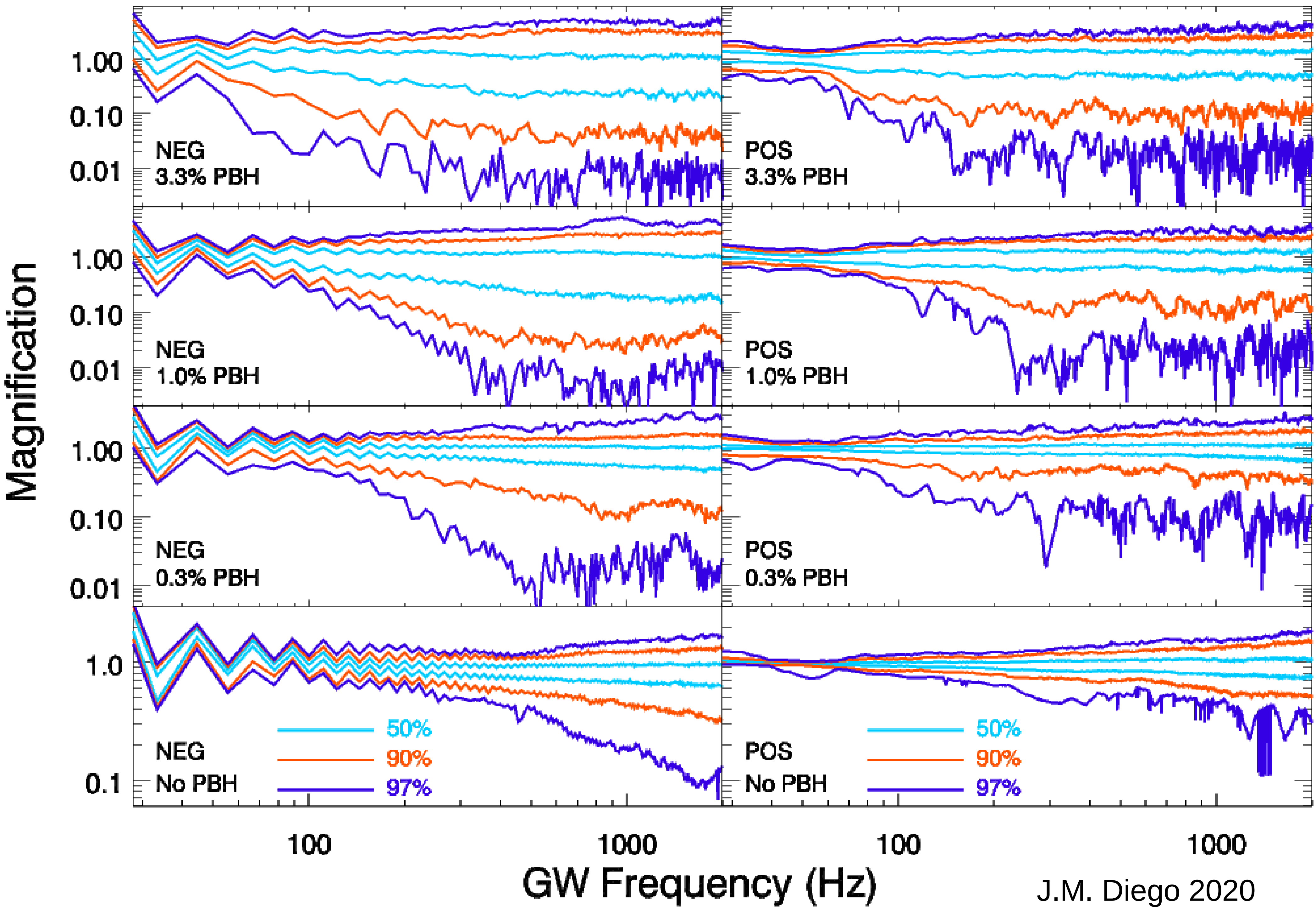
Microlensing by 30 M_o PBH near critical curves of galaxies and clusters




Magnification Source Plane
0.3% POS
1% POS
3.3% POS
Positive parity
μ=50x3
0.3% NEG
1% NEG
3.3% NEG
Negative parity
30 μas
30 μas

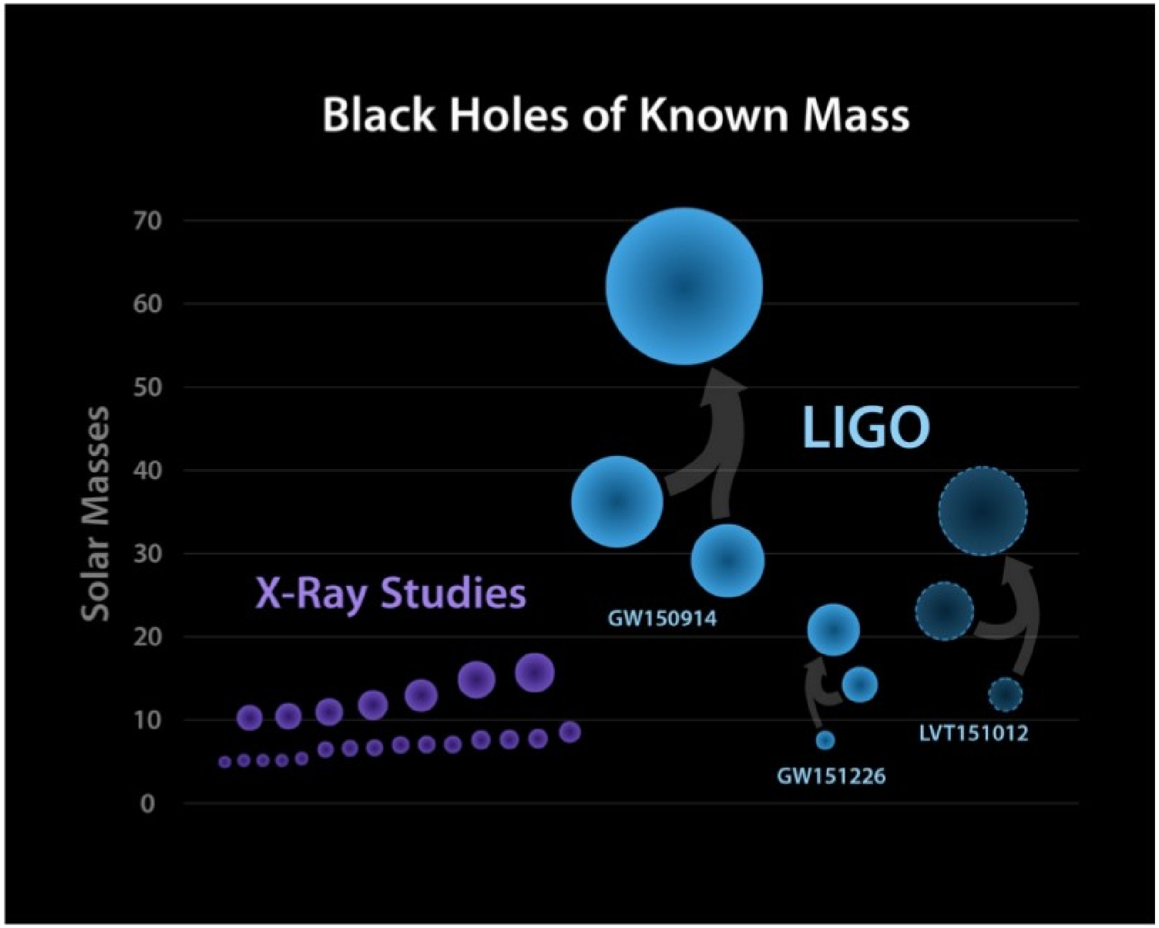

PROBABILITY OF DISTORTION (macromodel magnification = 10x3)
Magnification
1.00
0.10
0.01
1.0
0.1
NEG
3.3% PBH
POS
3.3% PBH
NEG
1.0% PBH
POS
1.0% PBH
NEG
0.3% PBH
POS
0.3% PBH
NEG
No PBH
POS
No PBH
50%
90%
97%
100
1000
GW Frequency (Hz)
J.M. Diego 2020

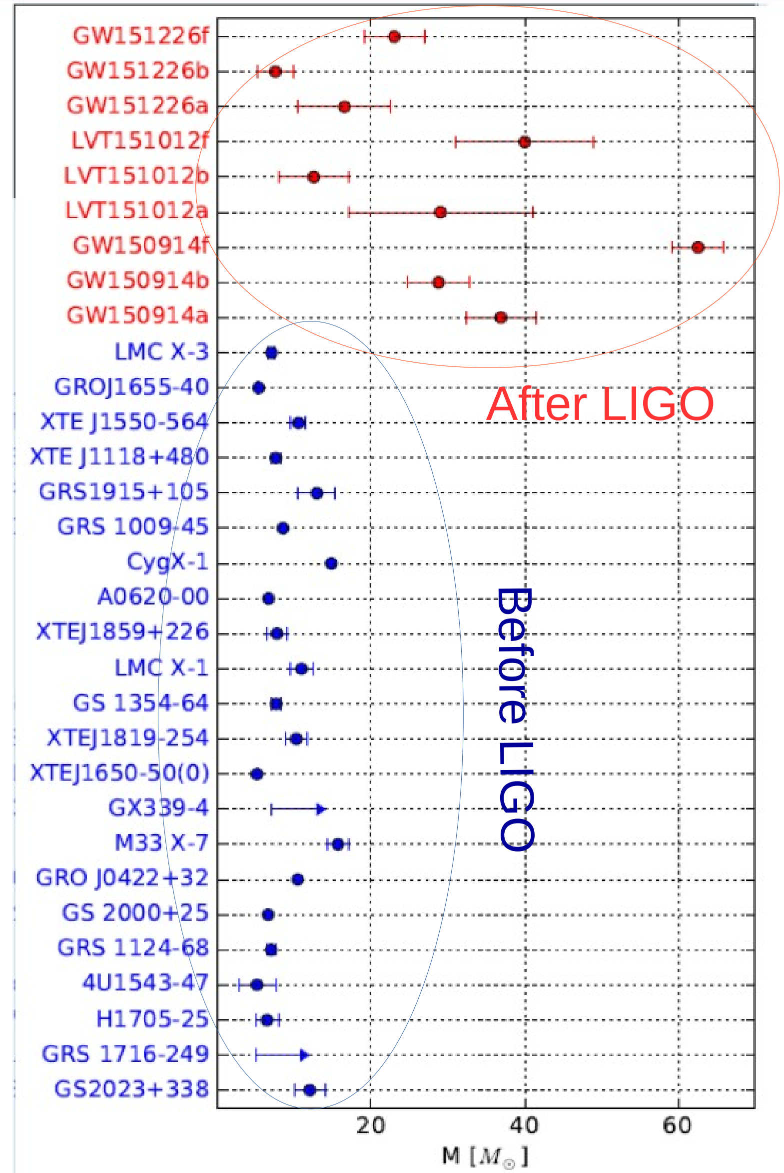
PROBABILITY OF DISTORTION (macromodel magnification = 50x3)



J.M. Diego 2020

Is LIGO already seeing Lensed GWs?





Credit: Marie Anne Bizourad & LIGO collaboration

Is LIGO already seeing Lensed GWs?

Observed

$$M = M_c(1+z)$$

Inferred

$$h(t) \sim \mathrm{sqrt}(\mu)\left(M^{5/6}/D(z)\right)F(t,M,\theta)$$

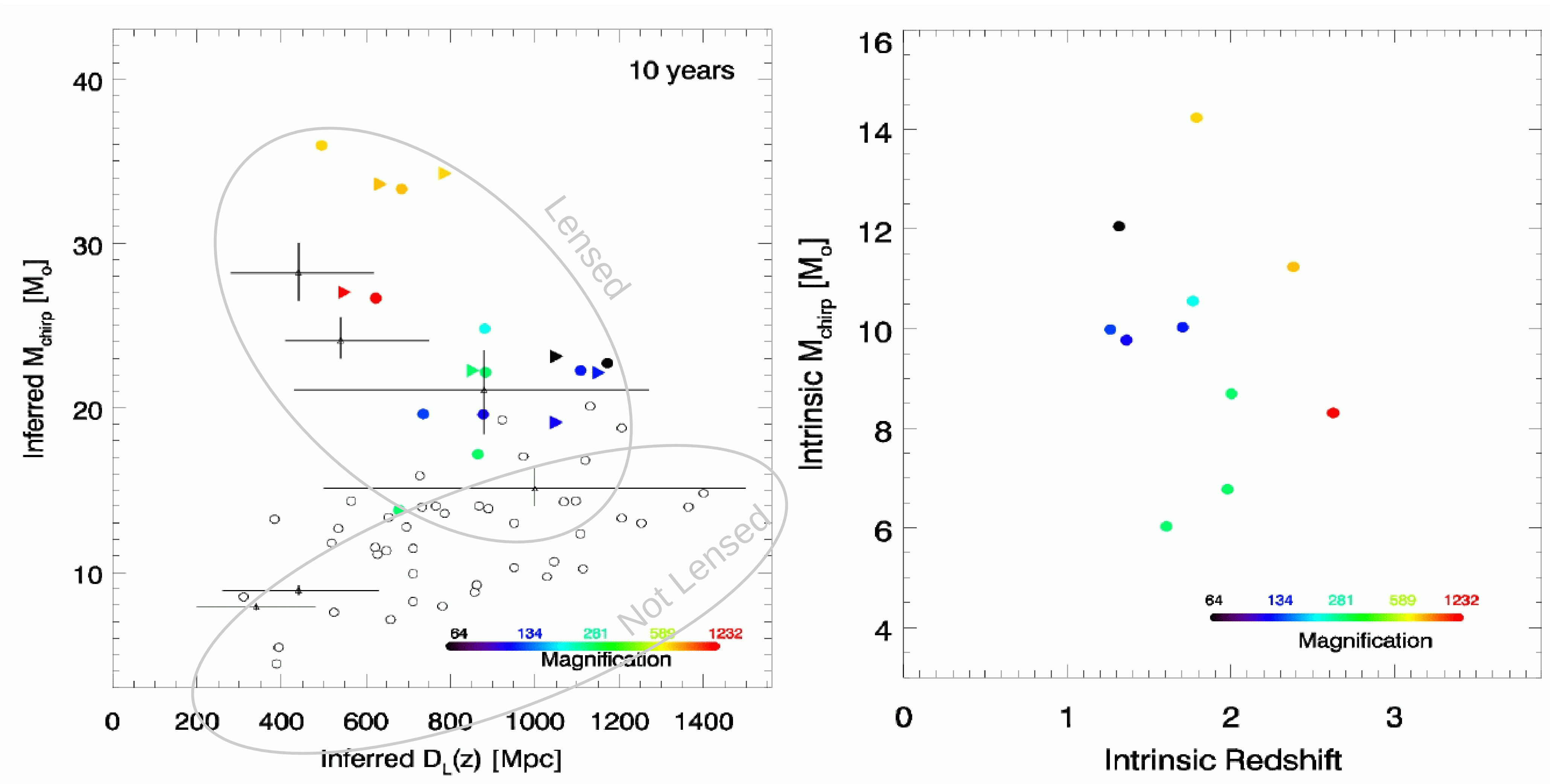
$$D(z_{est}) = D(z_{true})/\mathrm{sqrt}(\mu)$$

IF an event at high z is magnified by a large factor, μ, then if lensing is ignored, it will appear as a much closer event with a larger mass.

Then, **IF** the probability of lensing is reasonable, some of the LIGO events may be actually **distant** lensed events with **smaller masses**

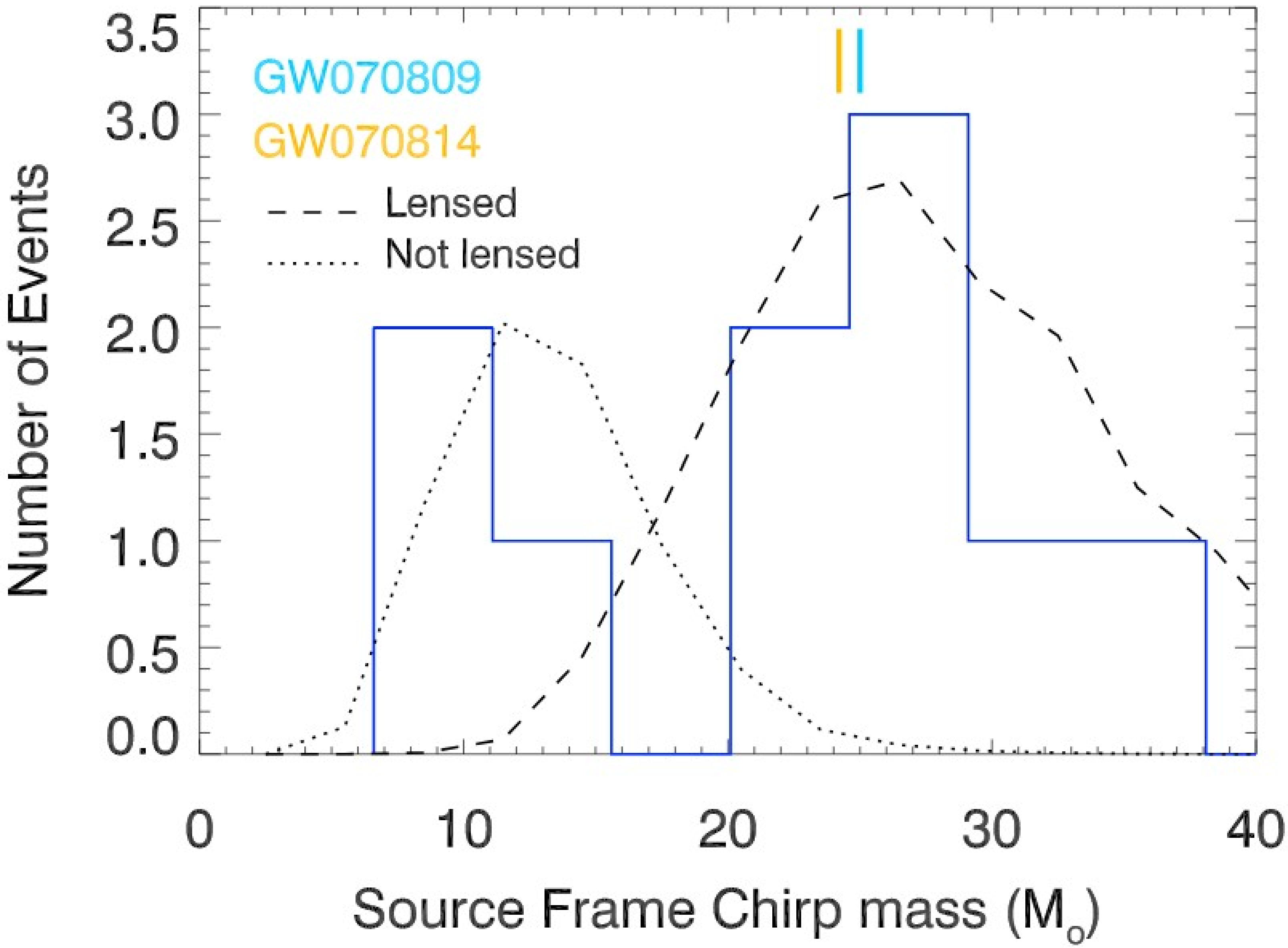
Unlike other events (SNe, GRB, etc) all sky is observed at once. The only limitations are dictated by the geometric factor, θ.

LENSING INTERPRETATION OF LIGO DETECTIONS



Broadhurst, Diego & Smoot 2018

Lensing predicts also a bimodal mass function



Broadhurst, Diego & Smoot, 2019

Is LIGO already seeing Lensed GWs?

Draft version 14 May 2021
Typeset using LaTeX **twocolumn** style in AASTeX62

Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run

The LIGO Scientific Collaboration and the Virgo Collaboration

(Dated: 13 May 2021)

ABSTRACT

We search for signatures of gravitational lensing in the gravitational-wave signals from compact binary coalescences detected by Advanced LIGO and Advanced Virgo during O3a, the first half of their third observing run. We study: 1) the expected rate of lensing at current detector sensitivity and the implications of a non-observation

Is LIGO already seeing Lensed GWs?

DRAFT VERSION 14 MAY 2021
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Evidence for lensing of gravitational waves from LIGO-Virgo

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(Dated: June 8, 2021)

Recently, the LIGO-Virgo Collaboration (LVC) concluded that there is no evidence for lensed gravitational waves (GW) in the first half of the O3 run [1], claiming "We find the observation

C O N C L U S I O N S

PBH are a candidate for DM which become popular after LIGO detected a relatively abundant of BH with >20 M_o

LIGO → IF the rate of events at z~2 is in the range of 10^4, the low frequency events observed by LIGO are (likely) gravitationally lensed WG at z>1 with BH masses ~ 10 Msun.

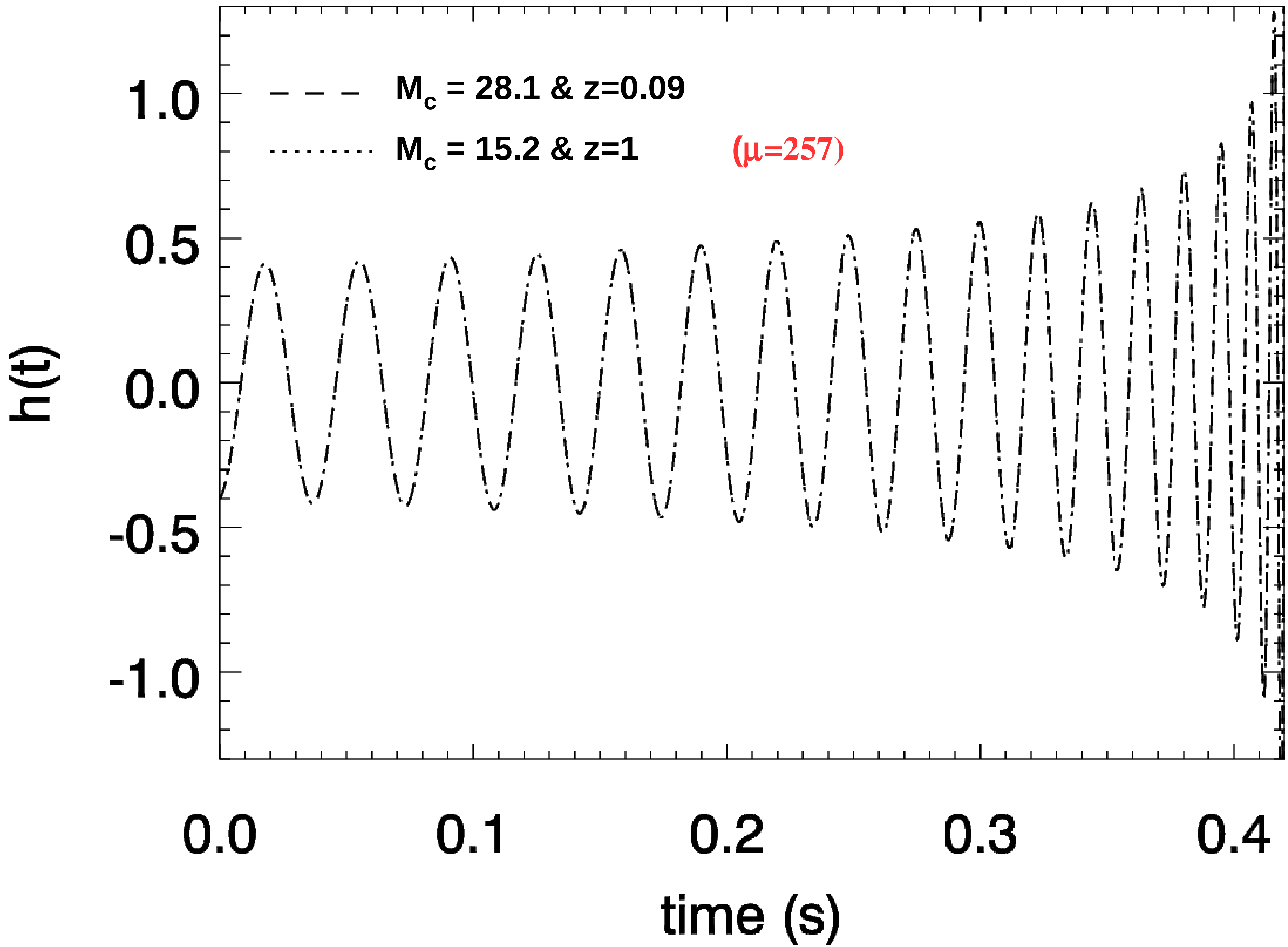
Lensing at high magnification should be affected by microlensing and interference (pattern needs to be incorporated in templates)

Microlensing can set limits on the abundance of BH (including PBH)

Images with negative parity should show interference signs more often

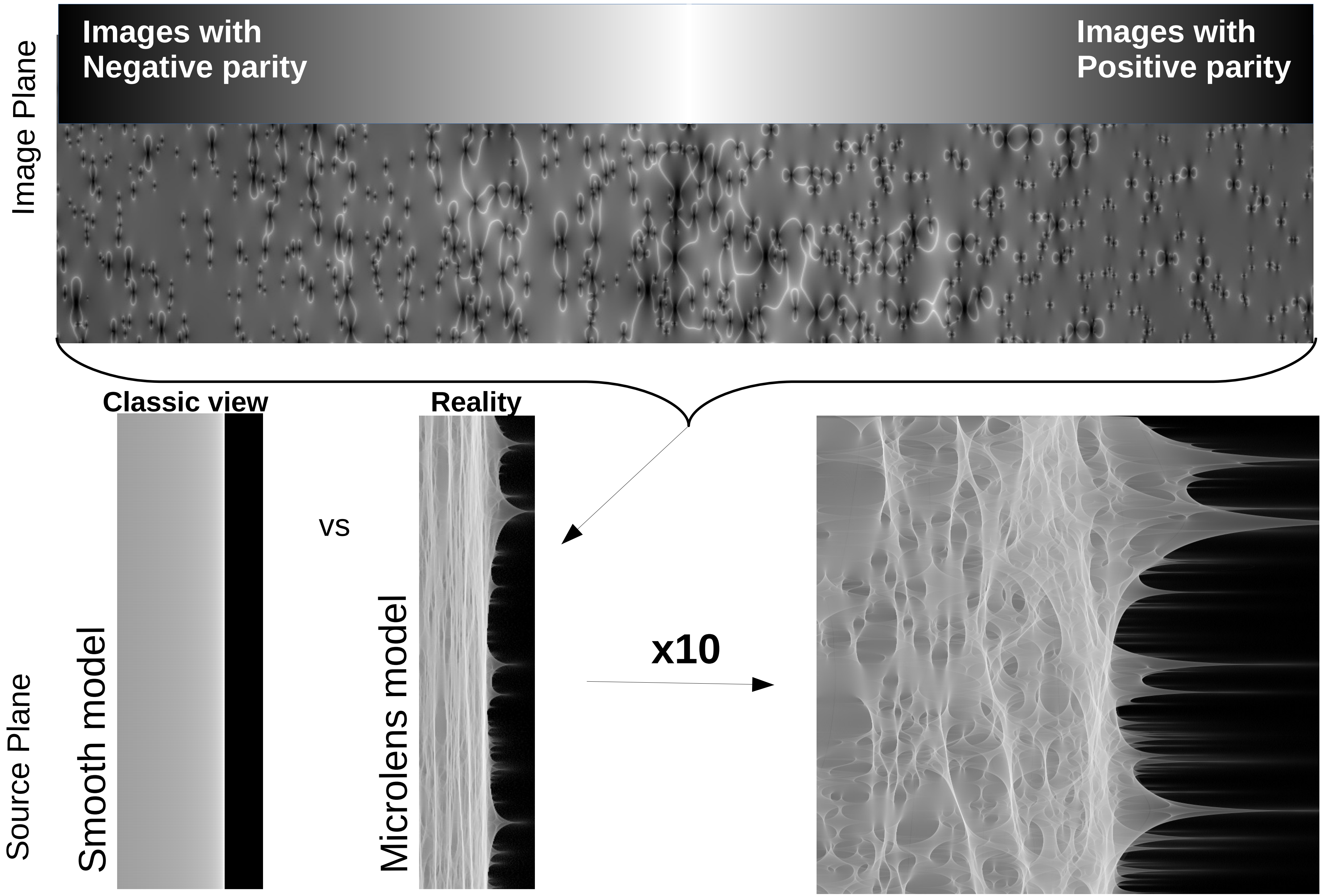
LIGO may be already observing strongly lensed GWs. Detailed analyses of their strains may reveal microlensing signatures from intervening compact dark matter structures.

Extra Slides



M_c = 28.1 & z=0.09
M_c = 15.2 & z=1
(μ=257)
h(t)
1.0
0.5
0.0
-0.5
-1.0
0.0
0.1
0.2
0.3
0.4
time (s)

Microlensing at extreme macromodel magnification

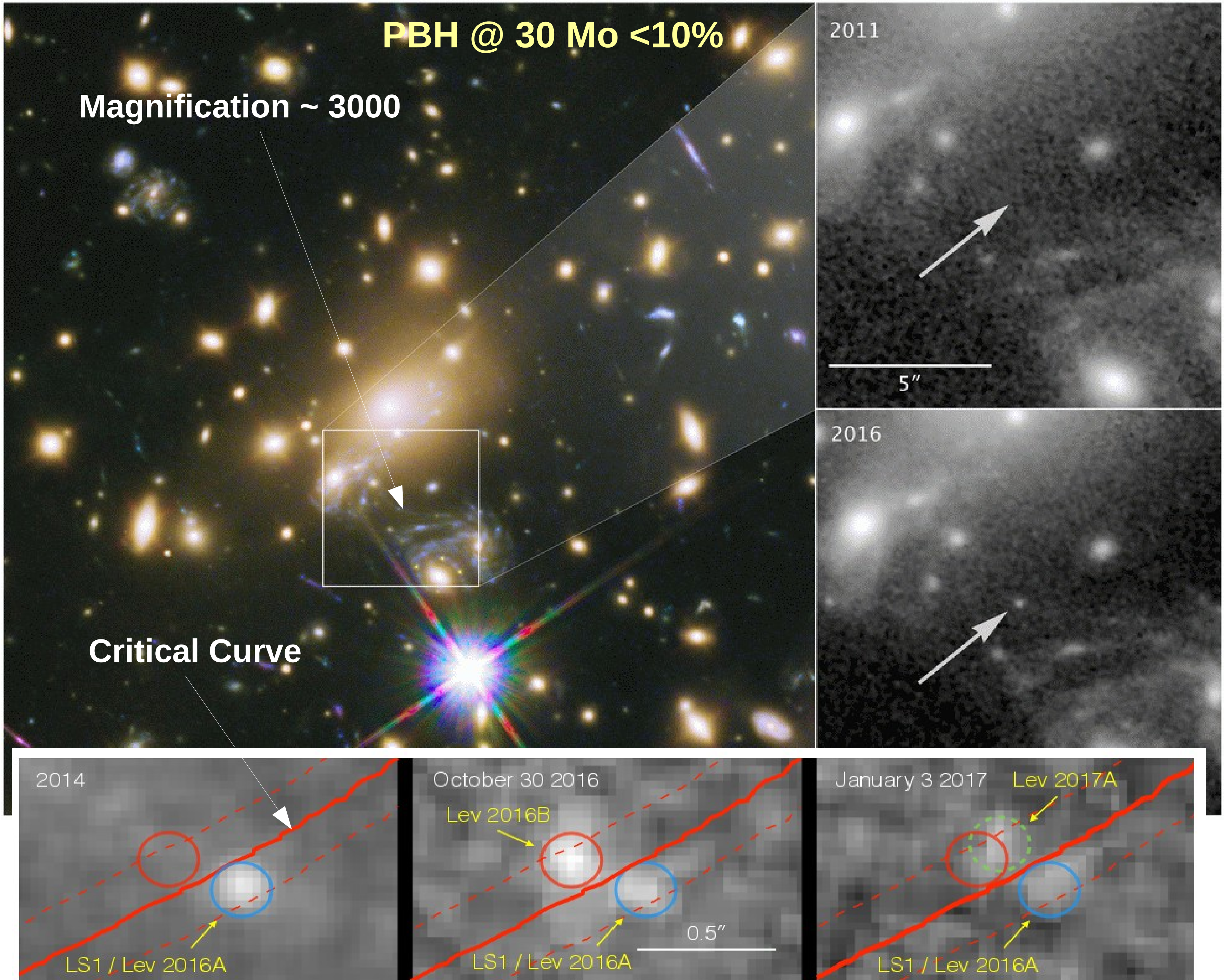


More microlenses → More distortion

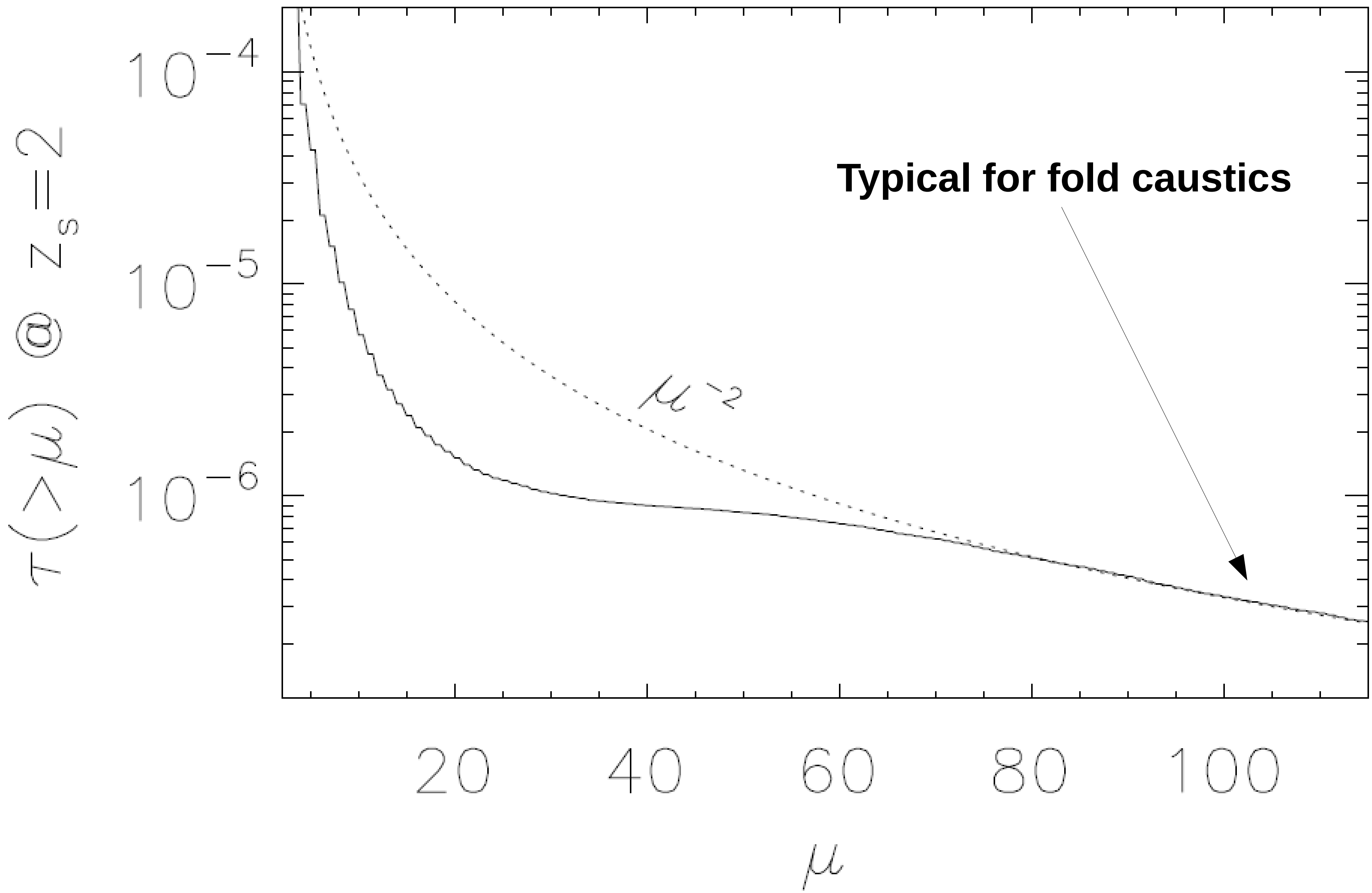
J.M. Diego, 2018

The Icarus Event

P. Kelly, J.M. Diego et al 2018, Nature Ast. 2, 334-342
Diego, J.M., Kaiser, N. et al. 2018, Apj, 857, 25



Net probability by all halos & at all redshifts for a source at z=2



Broadhurst, Diego & Smoot 2018

A back of the envelope calculation

Probability of having magnification larger than 100 : ~3E-7

Volume between z=1.9 and 2.1 : ~ 100 Gpc^3

Rate of events at z=2 : ~ 3E4 /(yr Gpc^3)

Compare with ~10^6 per yr & Gpc^3 for SNe

↓

Total Number of events between z=1.9 and 2.1 : 3E6 per year

Total Number of $\mu>100$ events between z=1.9 and 2.1 : ~ **1 per year**

Rate needs to be of order 10^4 for lensing hypothesis to work

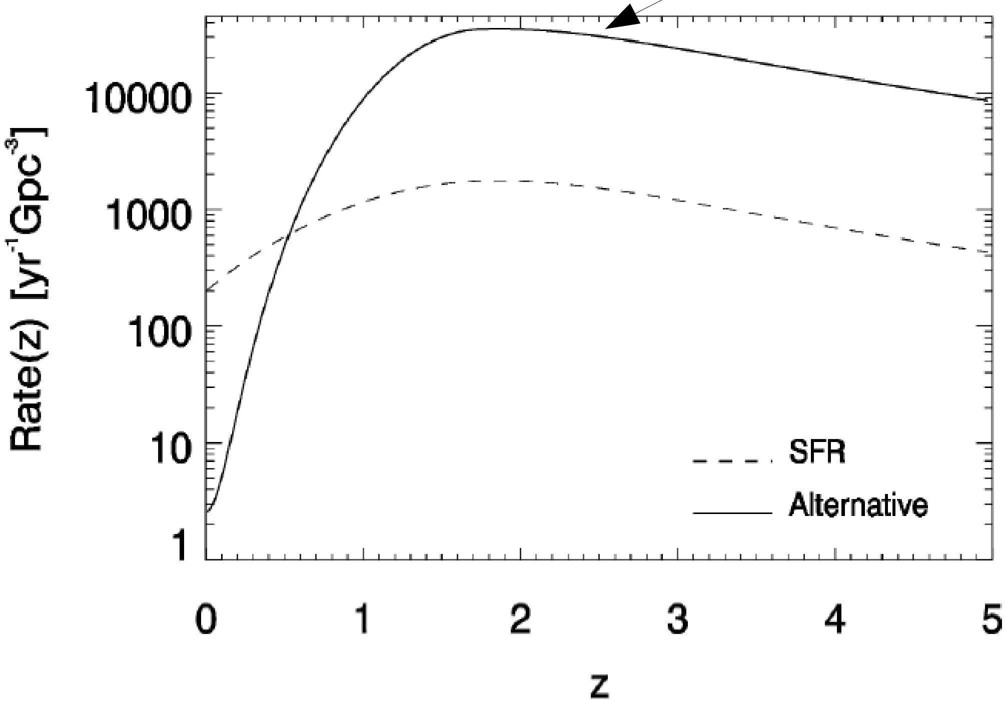
We do not know what the actual rate is !

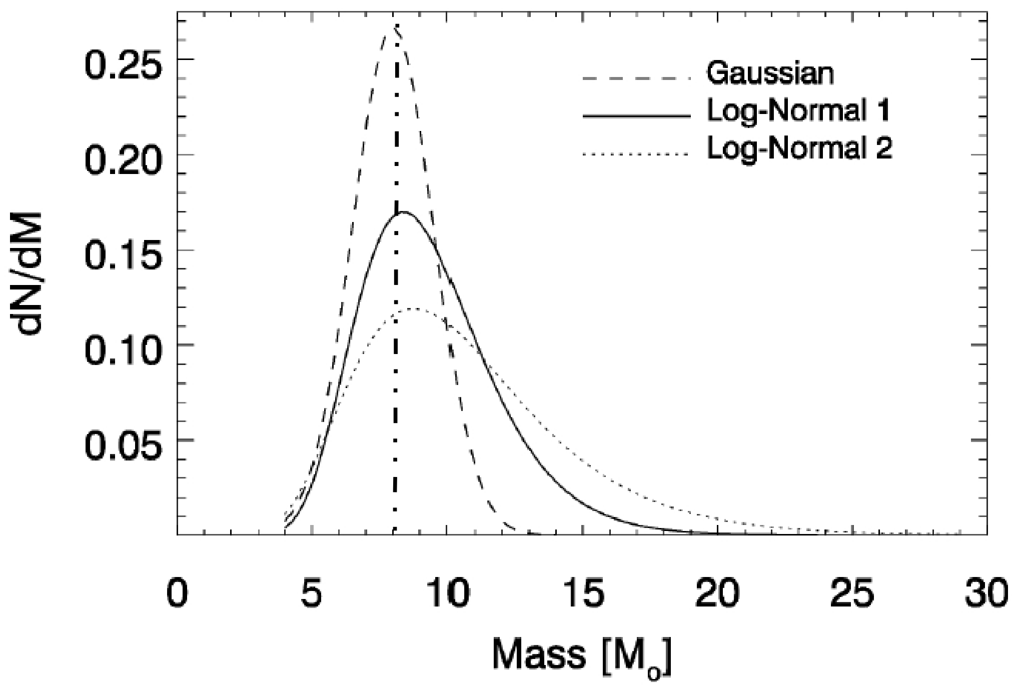
Model elements: Rates and BBH mass function

Basic assumption is that the rate of events at high-z is high to compensate the small probability for lensing

Mass function is assumed to be “natural”, that is, consistent with observational constrains from our Galaxy

>1 order of magnitude smaller than SNe rate





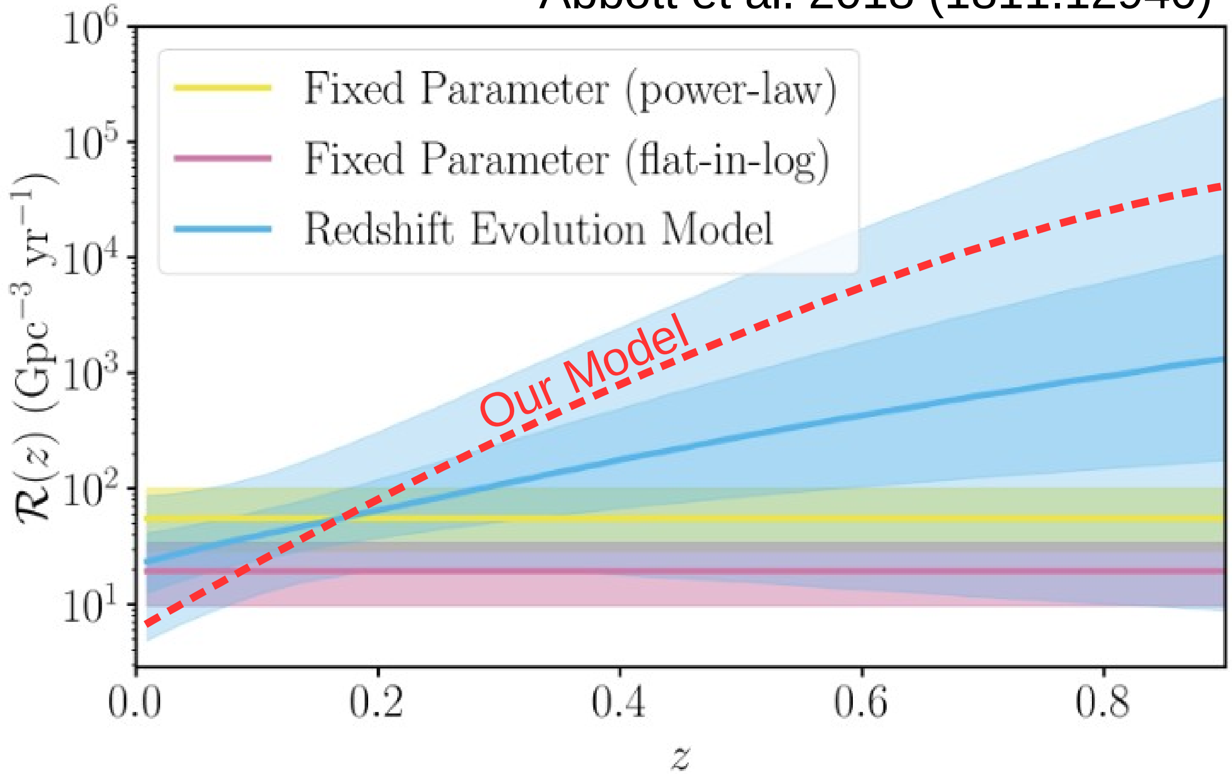
Broadhurst, Diego & Smoot 2018

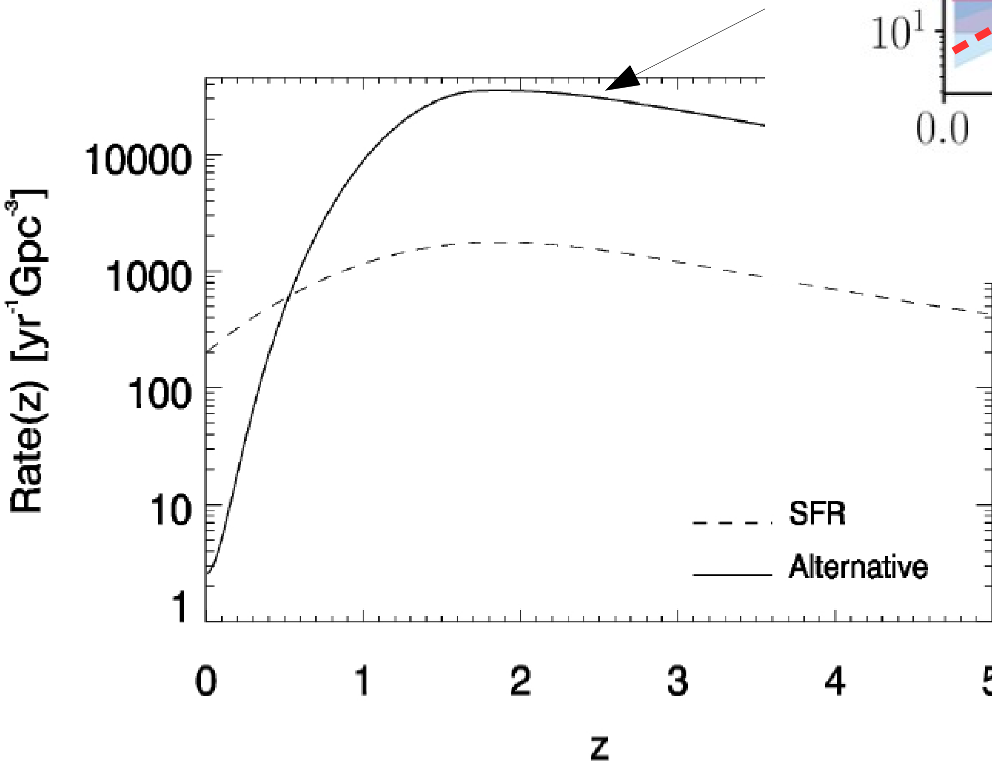
Model elements:

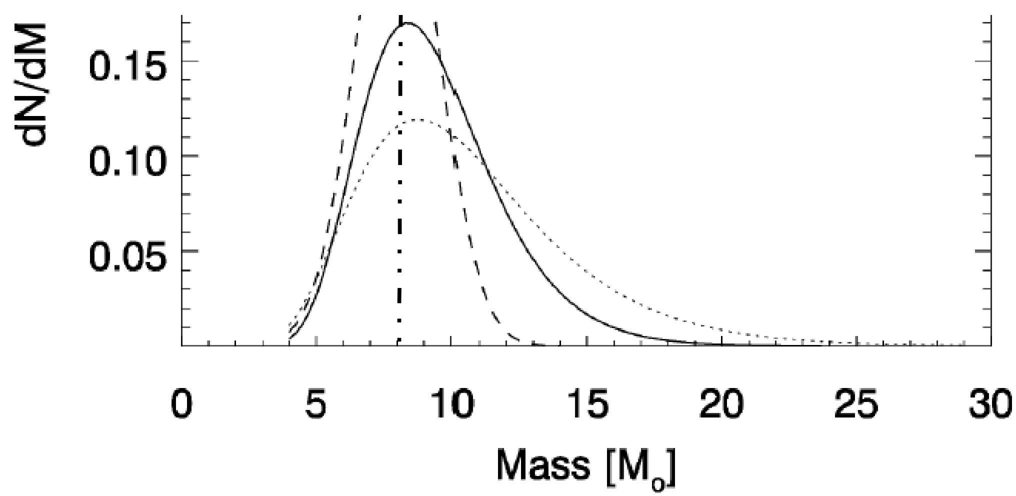
Basic assumption is that the rat
compensate the small probabili

Mass function is assumed to be
observational constrains from c

Abbott et al. 2018 (1811.12940)



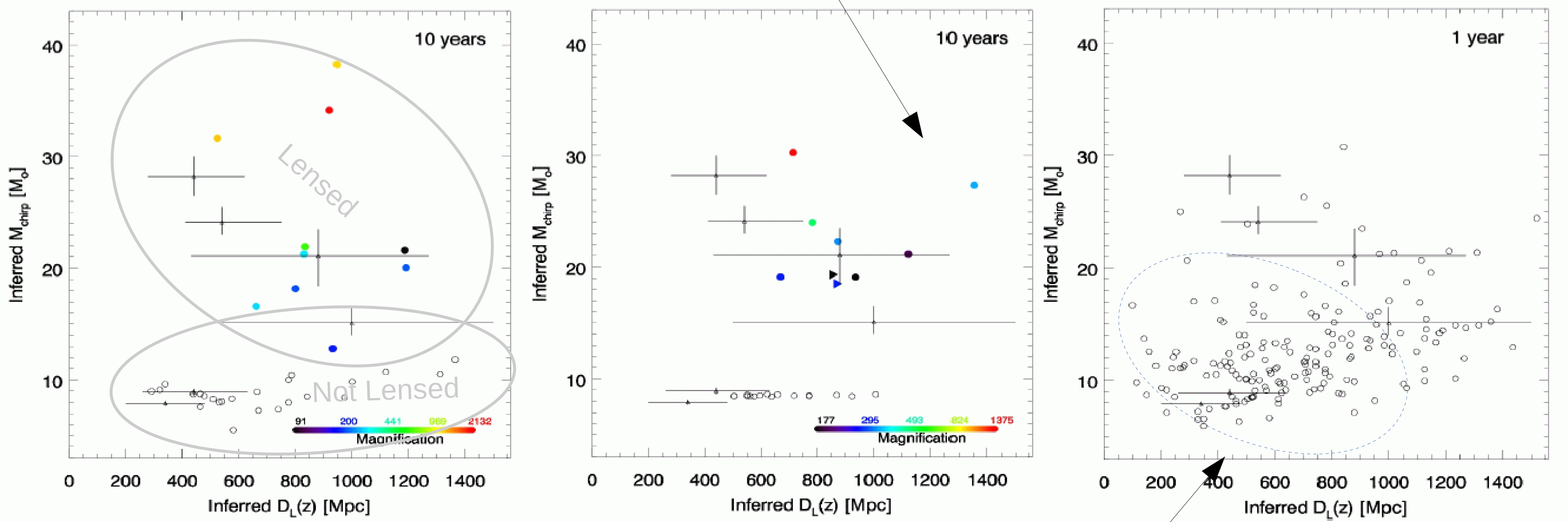




Broadhurst, Diego & Smoot 2018

Strong Evolution + Monochromatic MF

A simple monochromatic mass function already does a decent job at reproducing the data



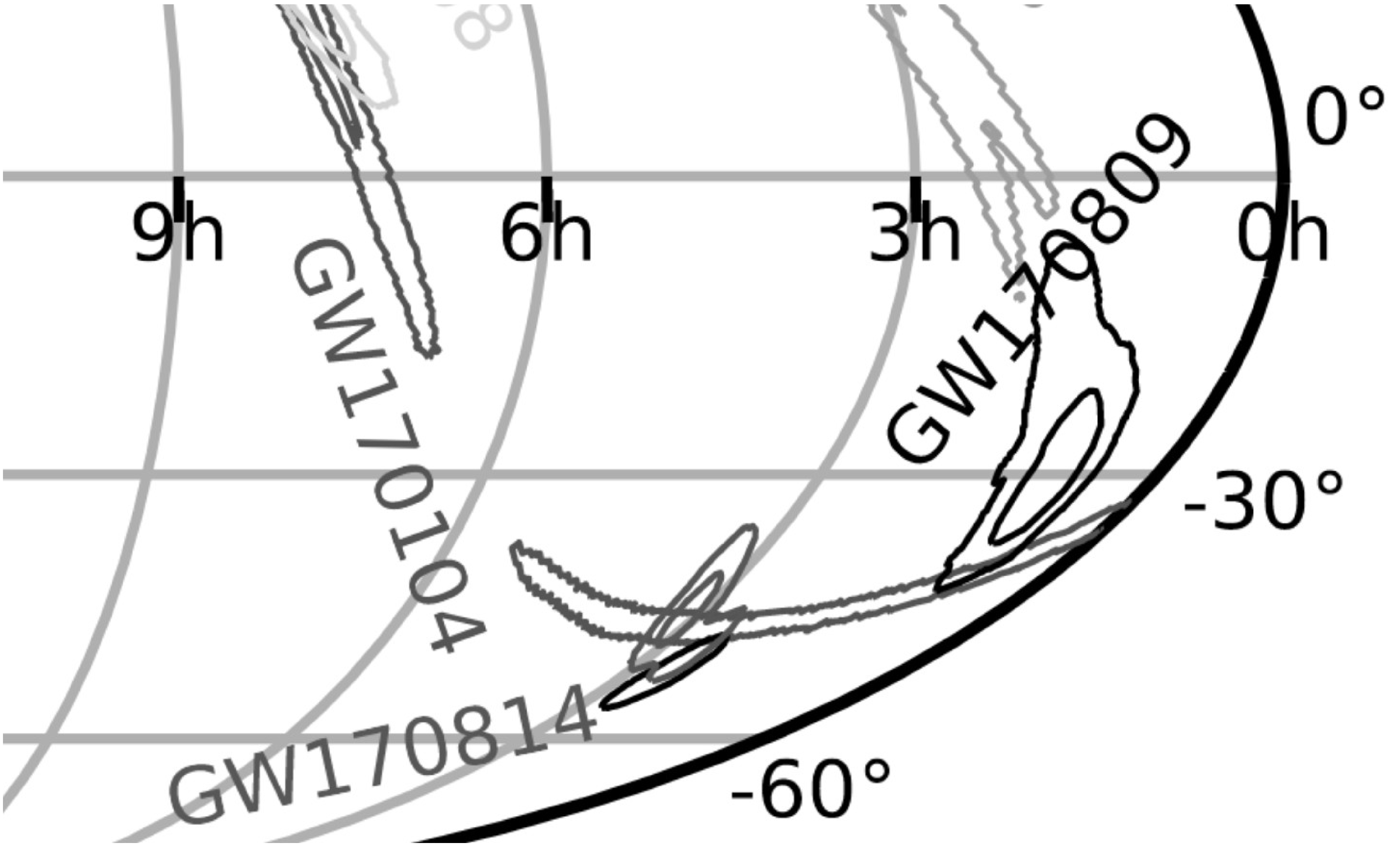
Modest Evolution +Broad MF

Many events should have been detected by LIGO in this regime. Where are they?

Strong Evolution + Gauss MF

A Gaussian mass function goes in the right direction

Broadhurst, Diego & Smoot 2018



0°
9h
6h
3h
0h
-30°
-60°
GW170104
GW170809
GW170814