Using Transients at Extreme Magnification to Constrain Dark Matter

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Time-Domain Cosmology with Strong Gravitational Lensing

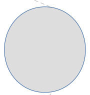
2021 Jan 25-26 & Feb 1-2 @ IPMU

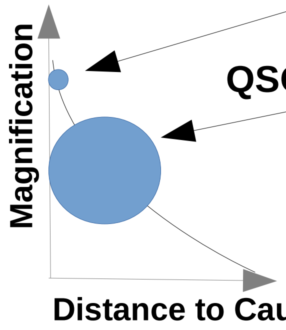
Extreme magnification allows to study intrinsically faint objects

$\mu_{max} \sim 20/\sqrt{R}$

$R \sim R_o \rightarrow \mu_{max} \sim 10^6$

→ $\Delta m \sim 15$ mag !



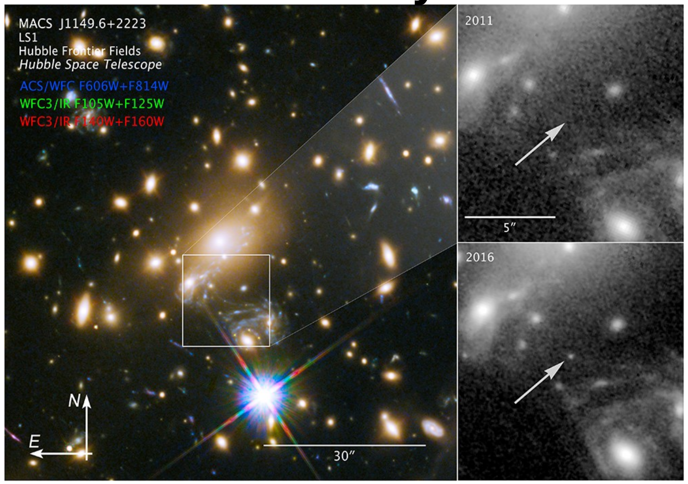


Stars, GWs

QSO's, SNe

Distance to Caustic

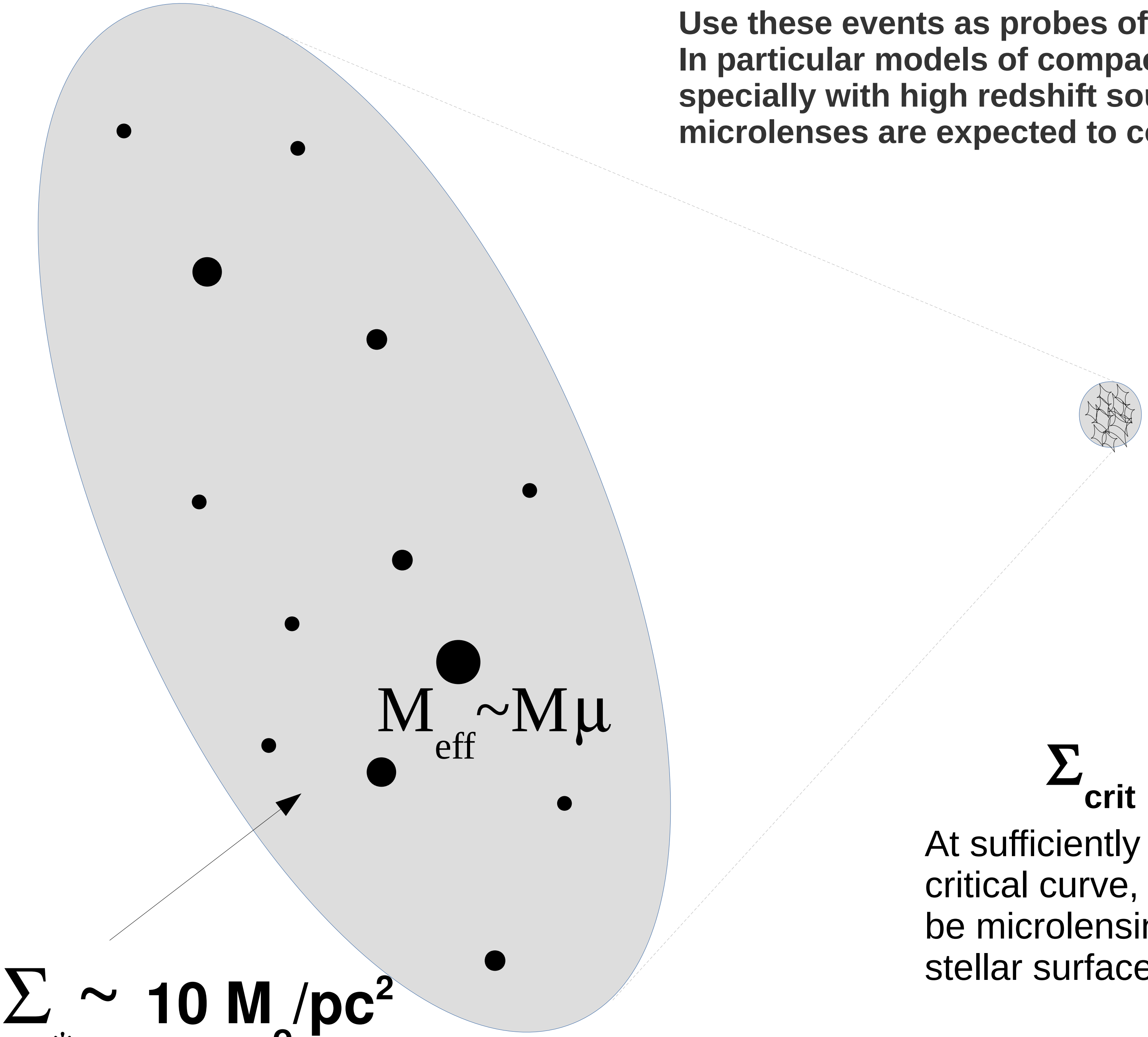
Icarus Kelly et al. 2018



Icarus was the first, but many more will be observed in the near future (see Pat Kelly's talk)

At extreme magnifications, microlensing becomes unavoidable

Use these events as probes of small scale structure. In particular models of compact dark matter like PBHs, specially with high redshift sources where stellar microlenses are expected to contribute less.



$$\Sigma_{eff} = \Sigma_* \mu$$

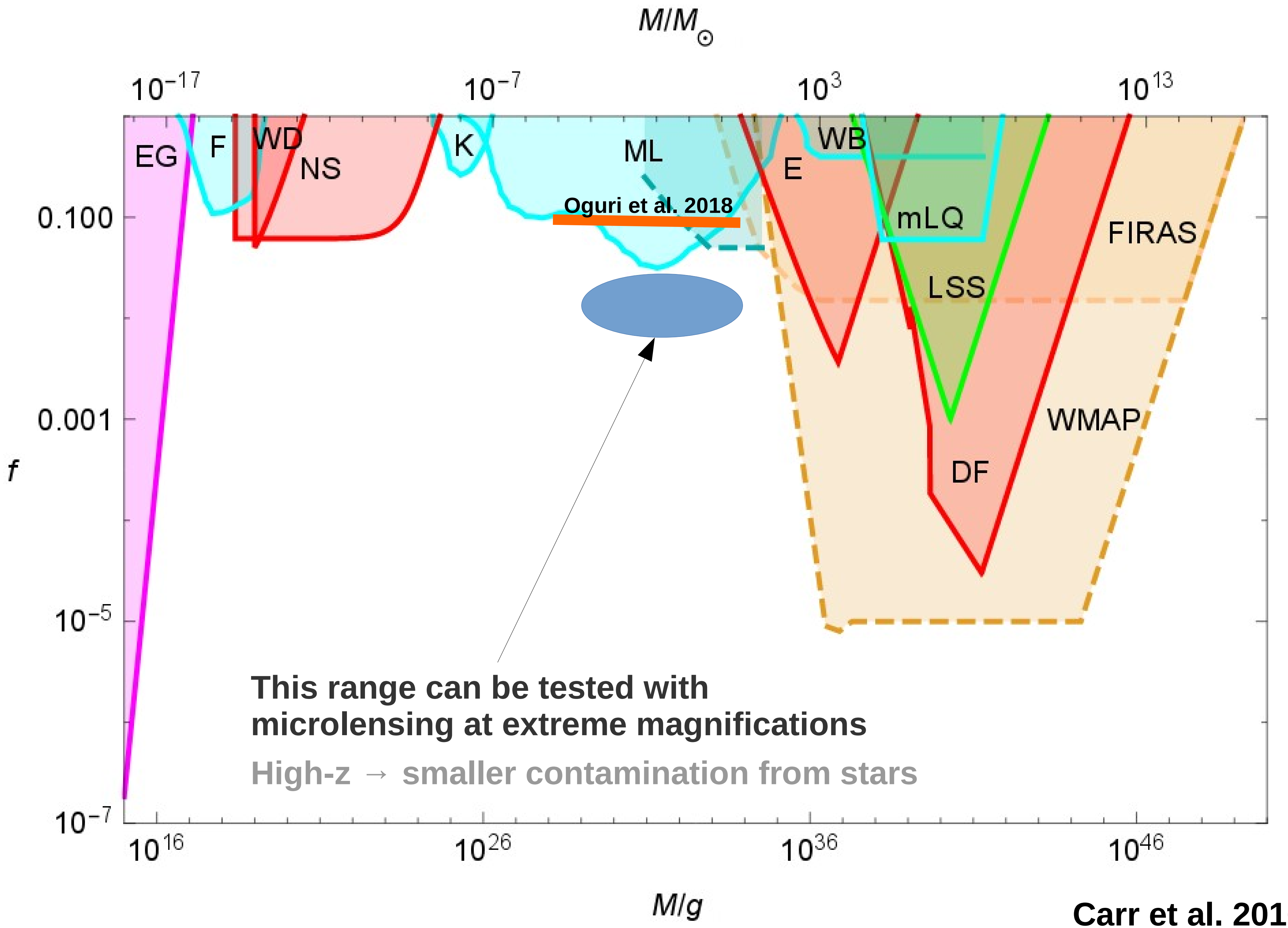
$$M_{eff} \sim M\mu$$

$$\Sigma_* \sim \mathbf{10\ M_o/pc^2}$$

$$\Sigma_{crit} \sim \mathbf{10{*}500\ M_o/pc^2}$$

At sufficiently short distances from the critical curve, there is always going to be microlensing effects, even at low stellar surface mass densities.

Constraints on the total mass fraction in the form of PBH



This range can be tested with microlensing at extreme magnifications

High-z → smaller contamination from stars

Carr et al. 2016

Microlensing at extreme macromodel magnification

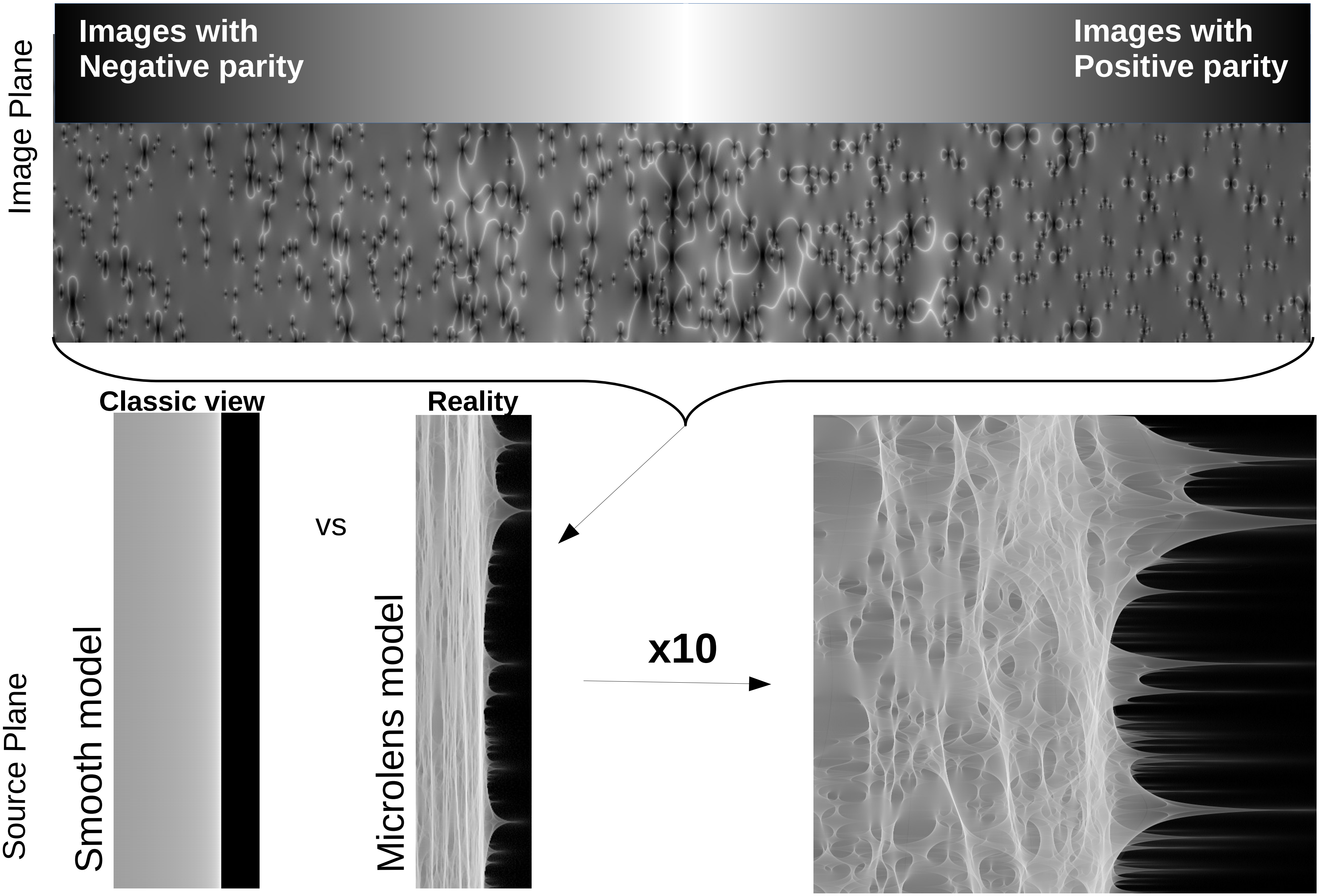


Image Plane

Images with Negative parity

Images with Positive parity

Classic view

Reality

vs

x10

Source Plane

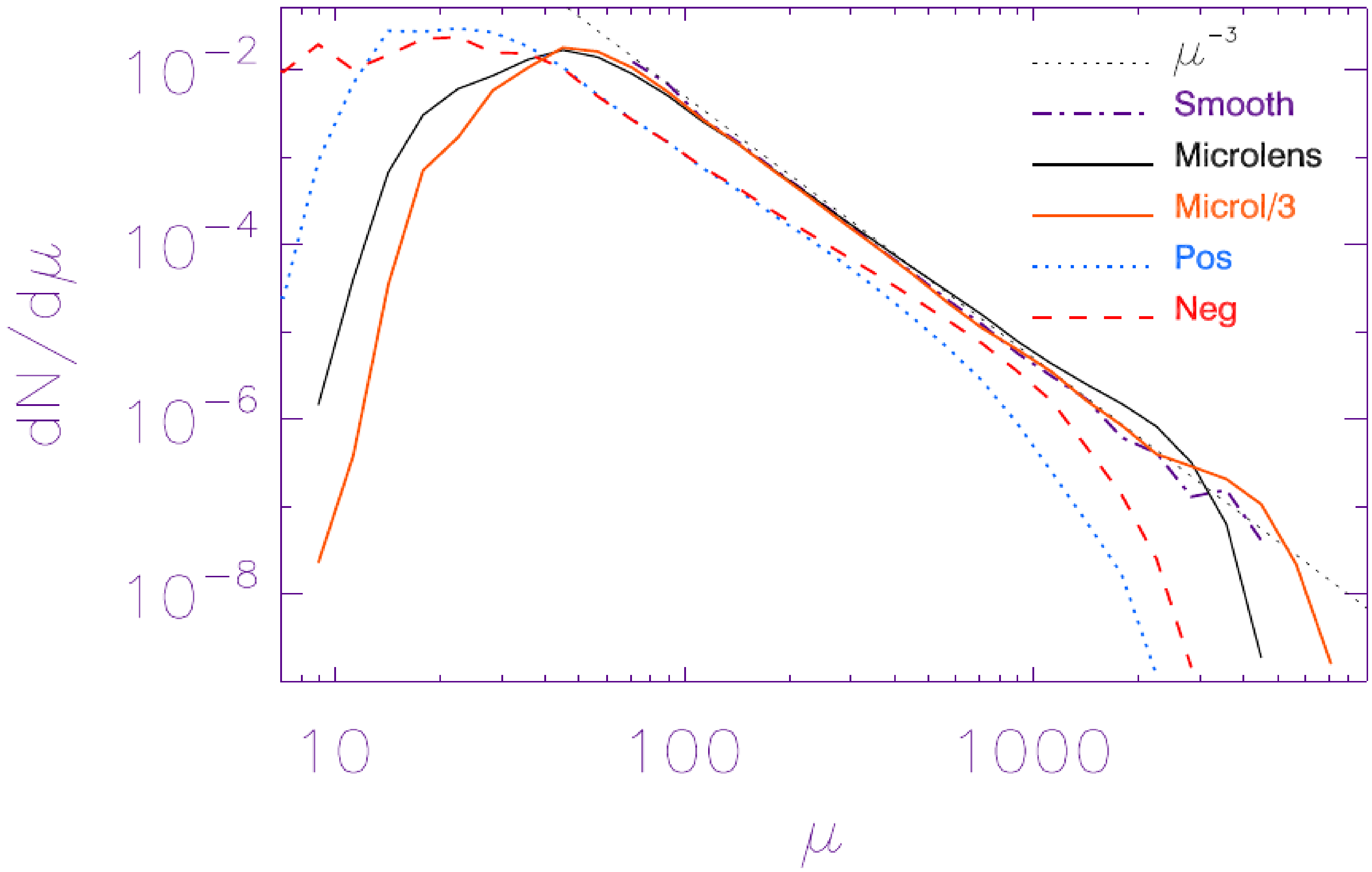
Smooth model

Microlens model

More microlenses → More distortion? Not necessarily

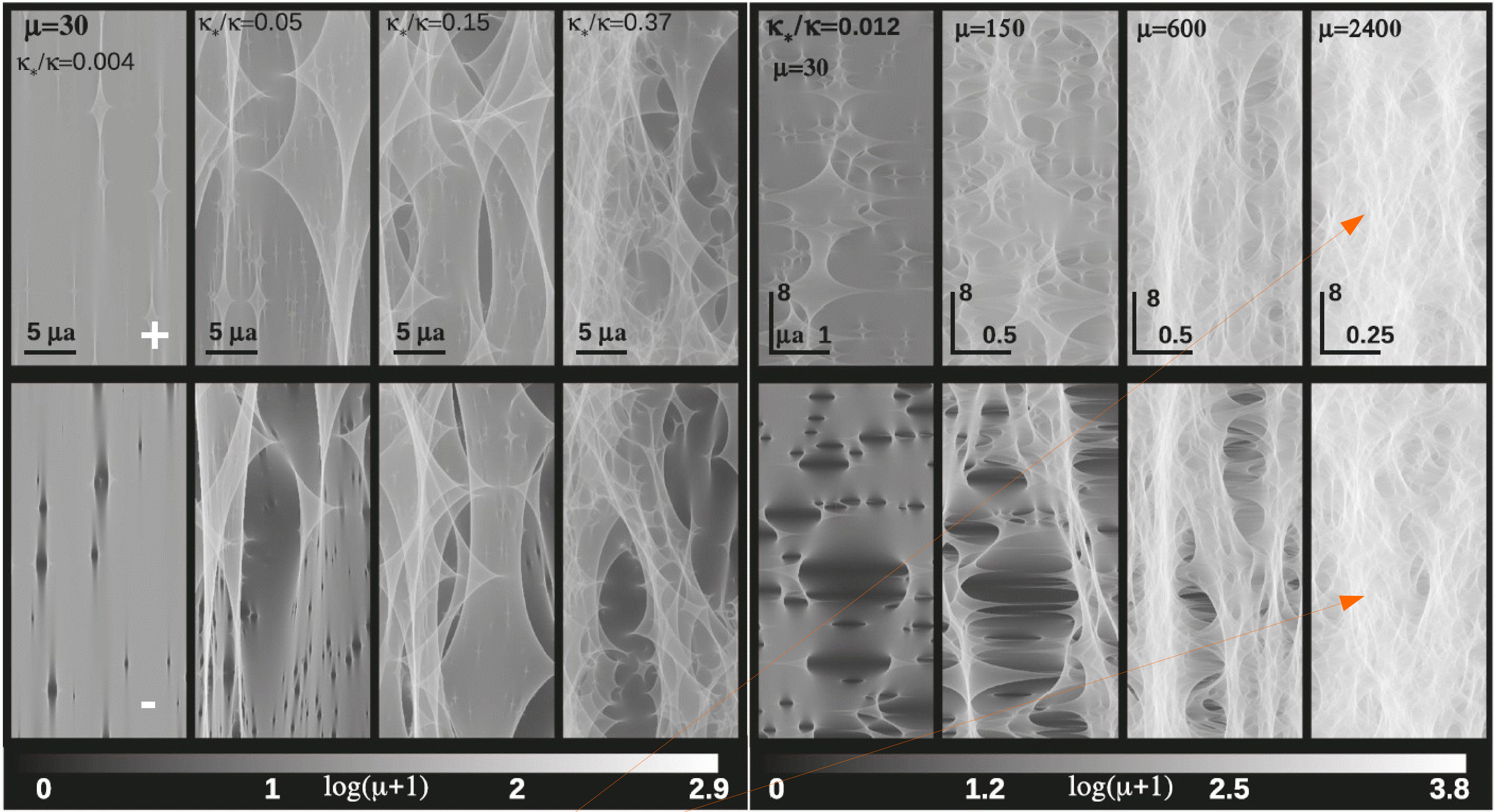
Diego et al., 2018 & Diego 2019
See also Venumadhavi et al. 2018

Microlenses reduce the maximum magnification to << 10^6



Microlenses near Critical Curves

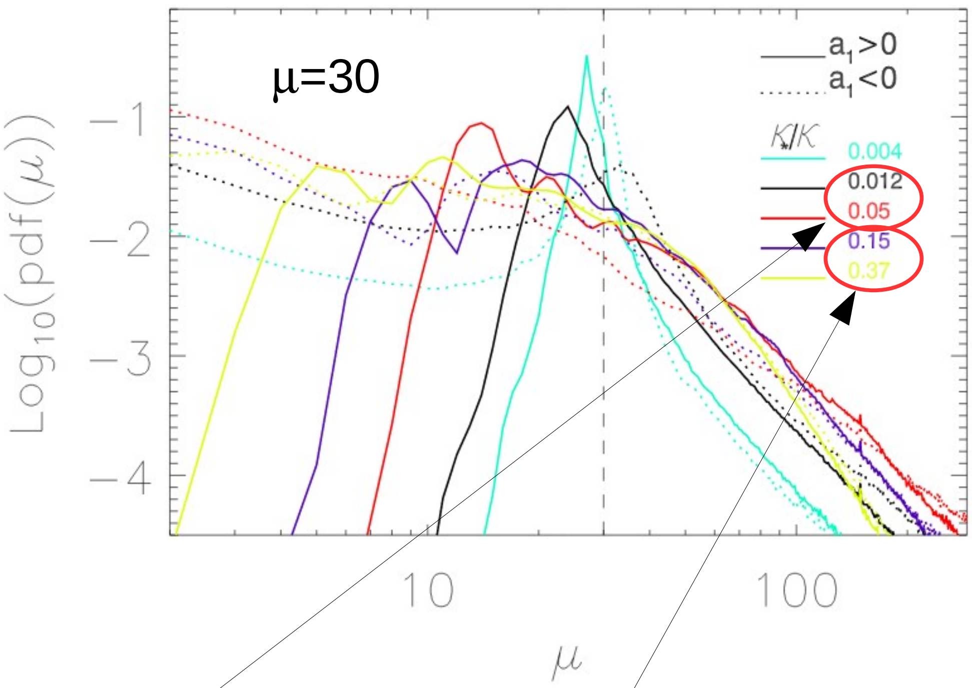
Constant magnification **Constant surface mass density**

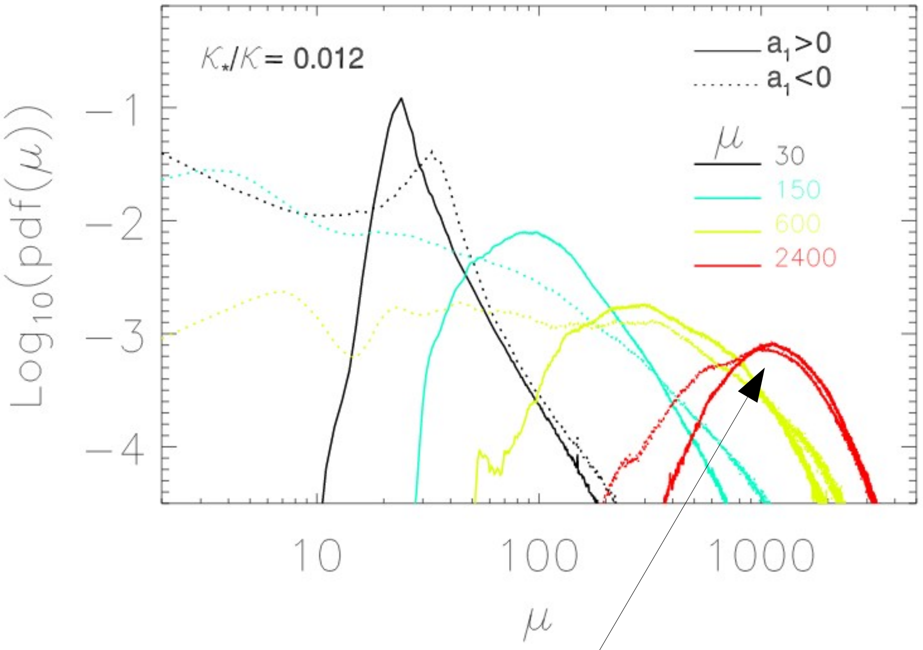


Saturation regime

Diego, Kaiser et al. 2018, ApJ, 857, 25,

Microlenses near Critical Curves





Typical values for low-z sources.

Typical values for high-z sources.

Saturation regime, τ_{eff}>>1

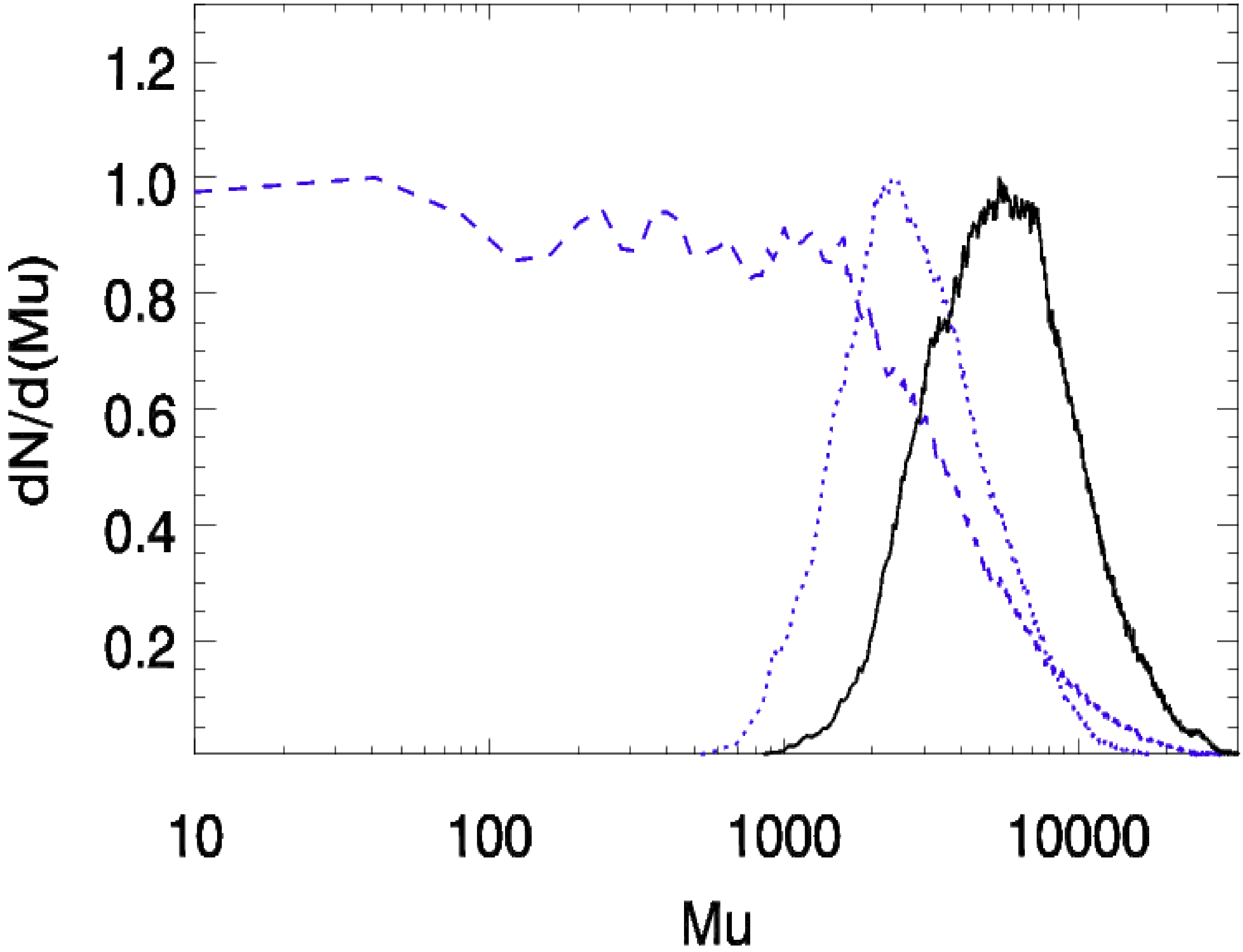
The median shifts to smaller values of the magnification, but the mean value remains unchanged

Negative parity counter-images, more likely to be demagnified, but their peaks are brighter

In saturation regime, the probability of magnification becomes log-normal, and both parities behave in a similar way

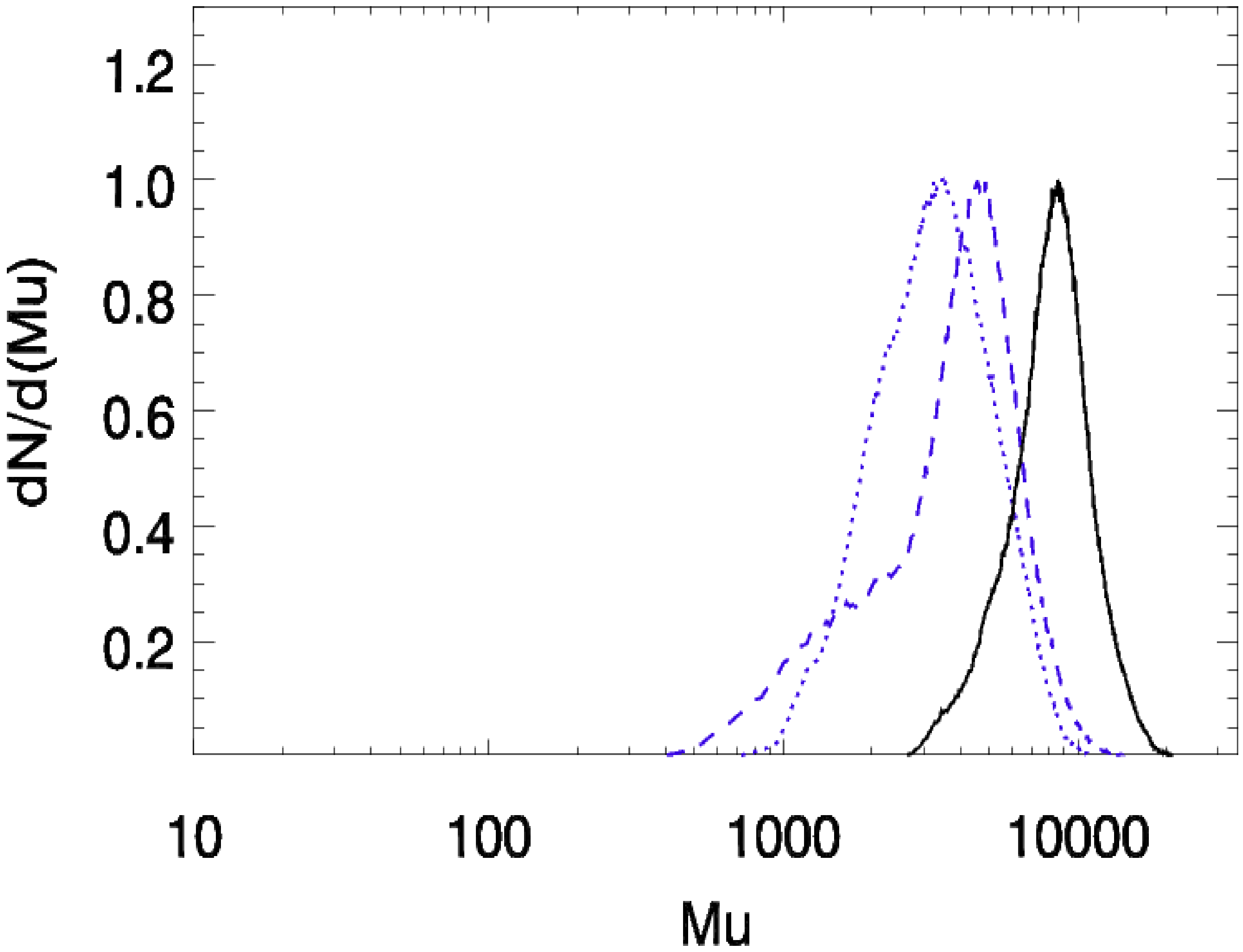
When more is less.

1 M_o/pc^2



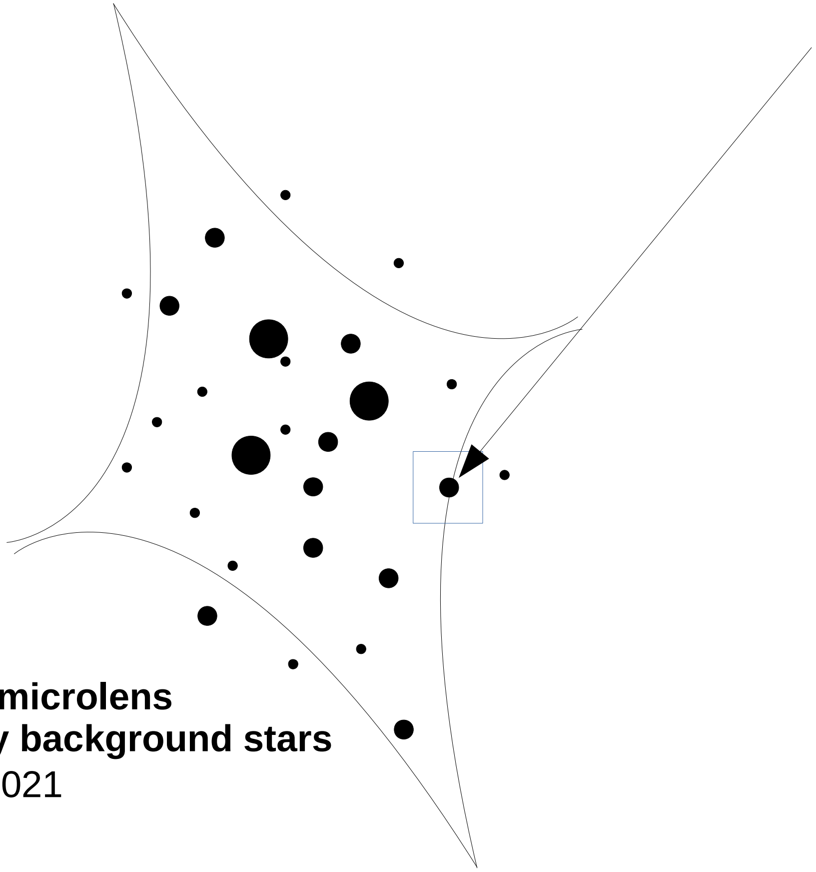
When more is less.

10 M_o/pc^2

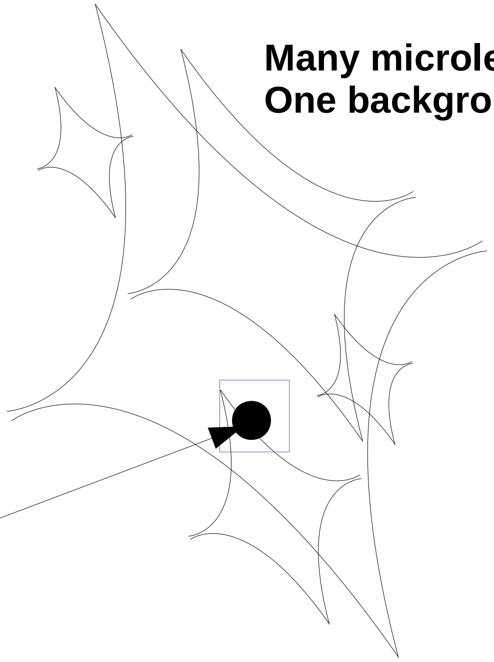


When more is less.

This star is undergoing a microlensing event, but the other stars in the cluster are not. The relative change in flux of the entire system is smaller than if the star were isolated. The more stars in the cluster, the smaller the relative change in total flux



One microlens
Many background stars
Dai 2021



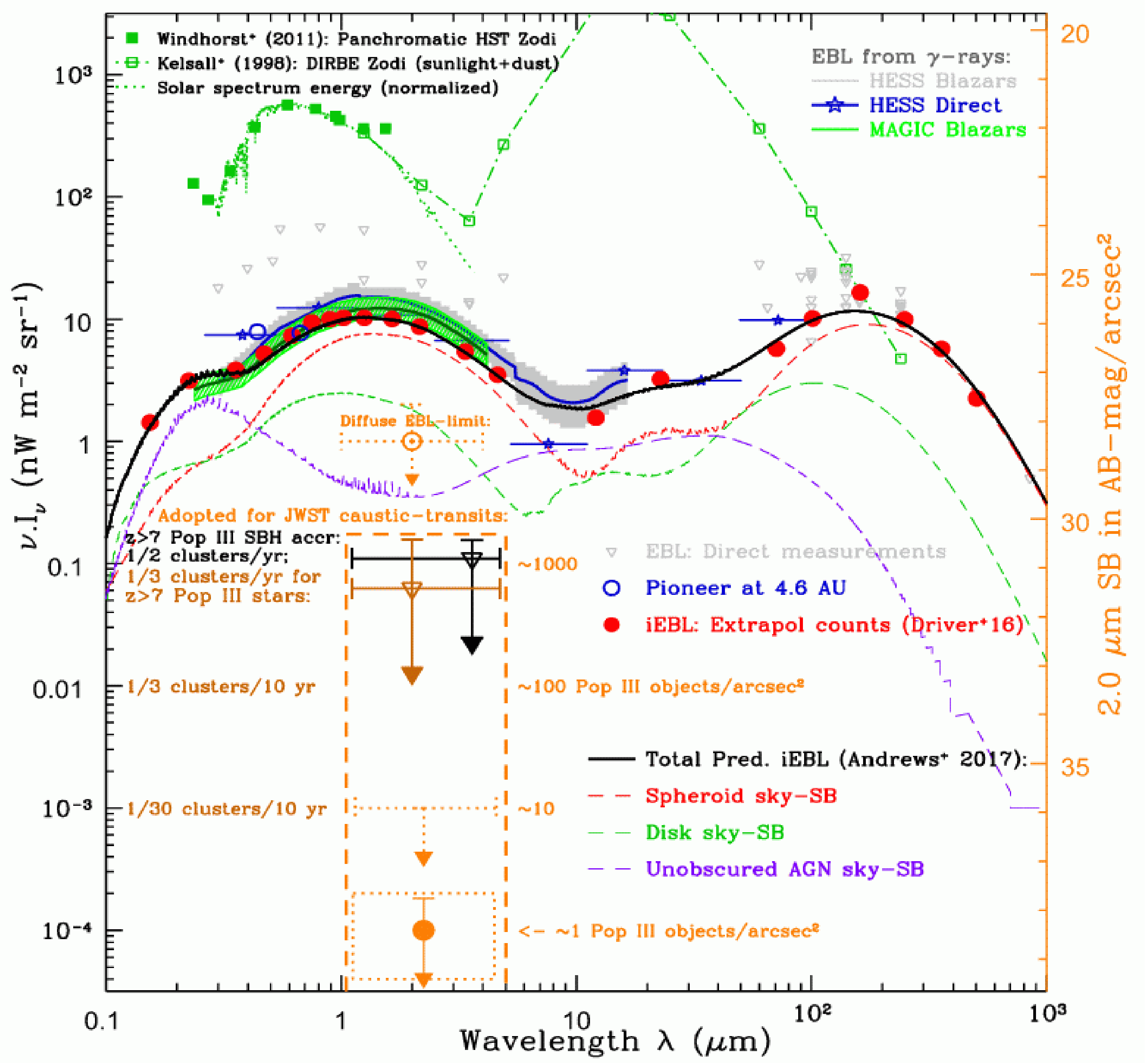
Many microlenses
One background stars

This star is undergoing a microlensing event by one microlens but the other microlenses are not contributing to the rapid change in flux. The relative change in flux of the entire system is smaller than if there was only one microlens. The more overlapping microlenses in the area, the smaller the relative change in total flux

T H E F U T U R E

JWST

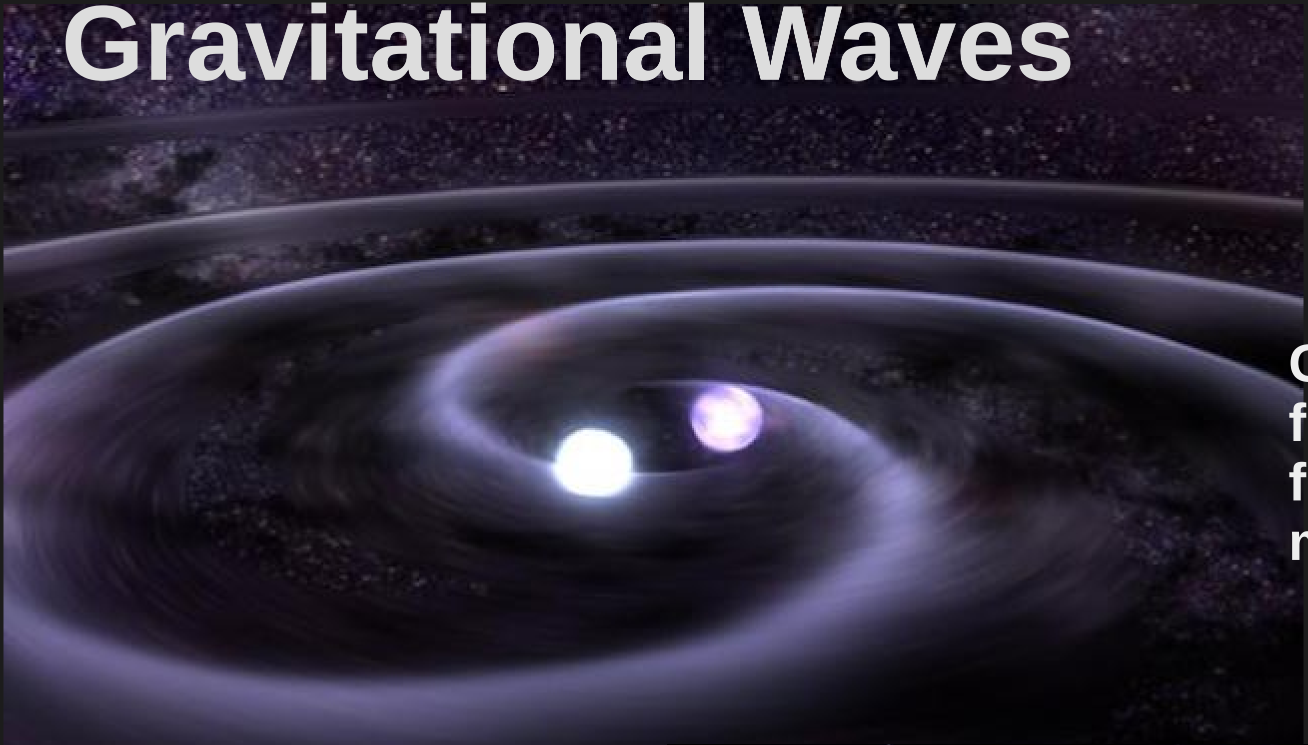
Pop III
SBH acc. discs



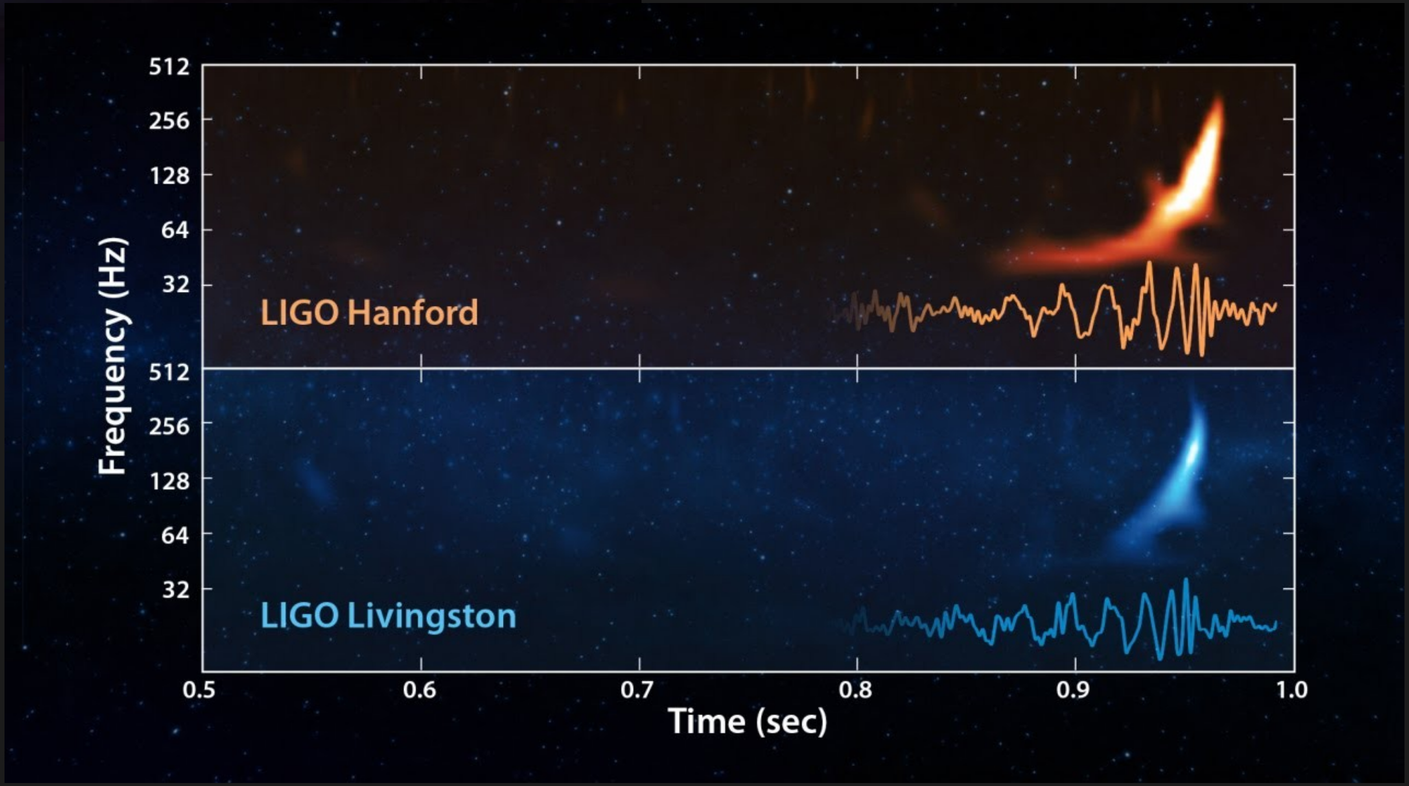
See Pat's talk !

Windhorst et al 2018

Gravitational Waves

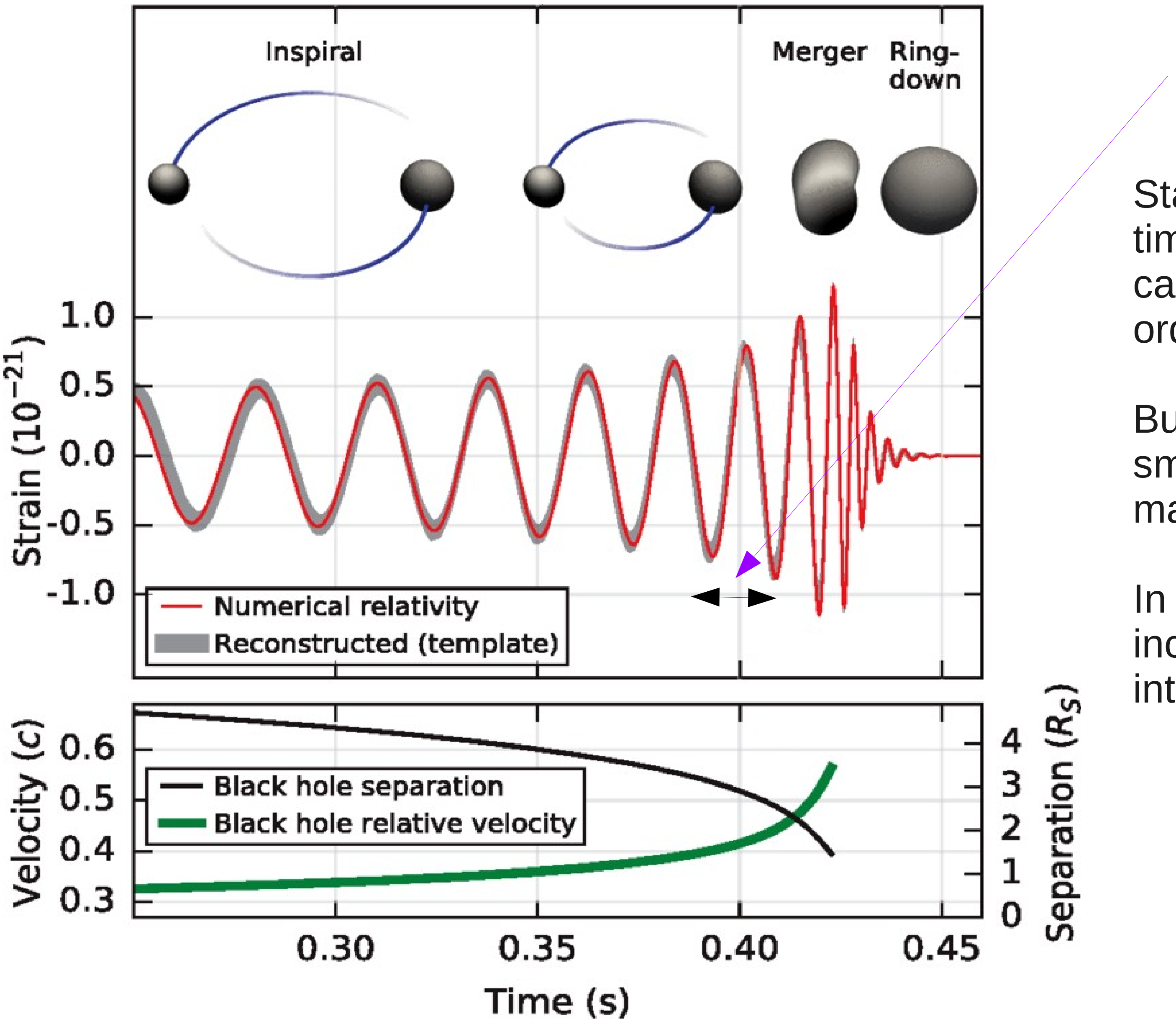


Gravitational Waves from BBH form in regions of sizes of a few kms, and can also be magnified by extreme values.



Gravitational Waves

GWs from BBH form in regions of sizes of a few kms
Can be magnified by extreme values.



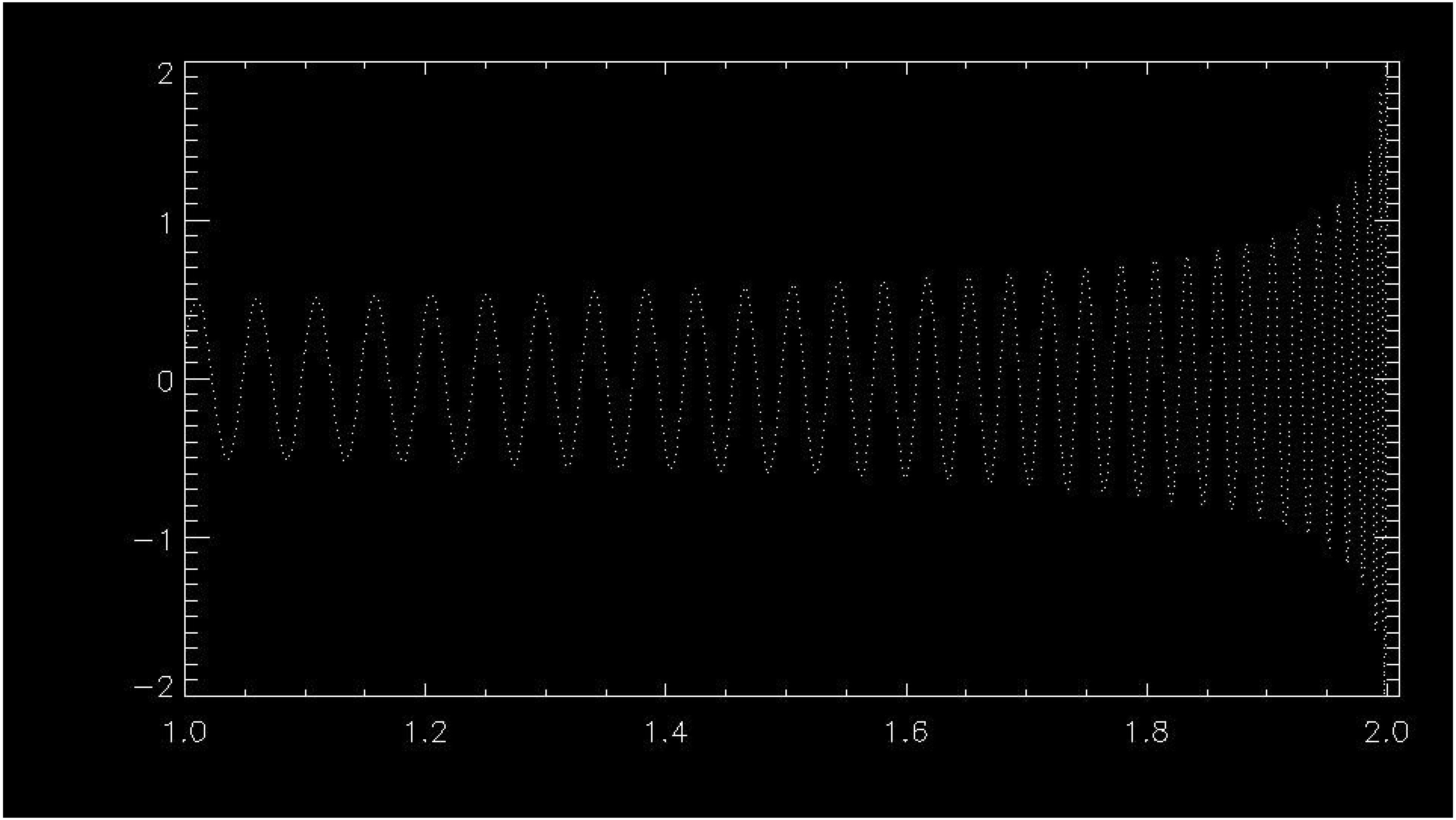
Period ~ millisecond

Stars with masses 100 times the mass of the Sun can create time delays of order 1 ms.

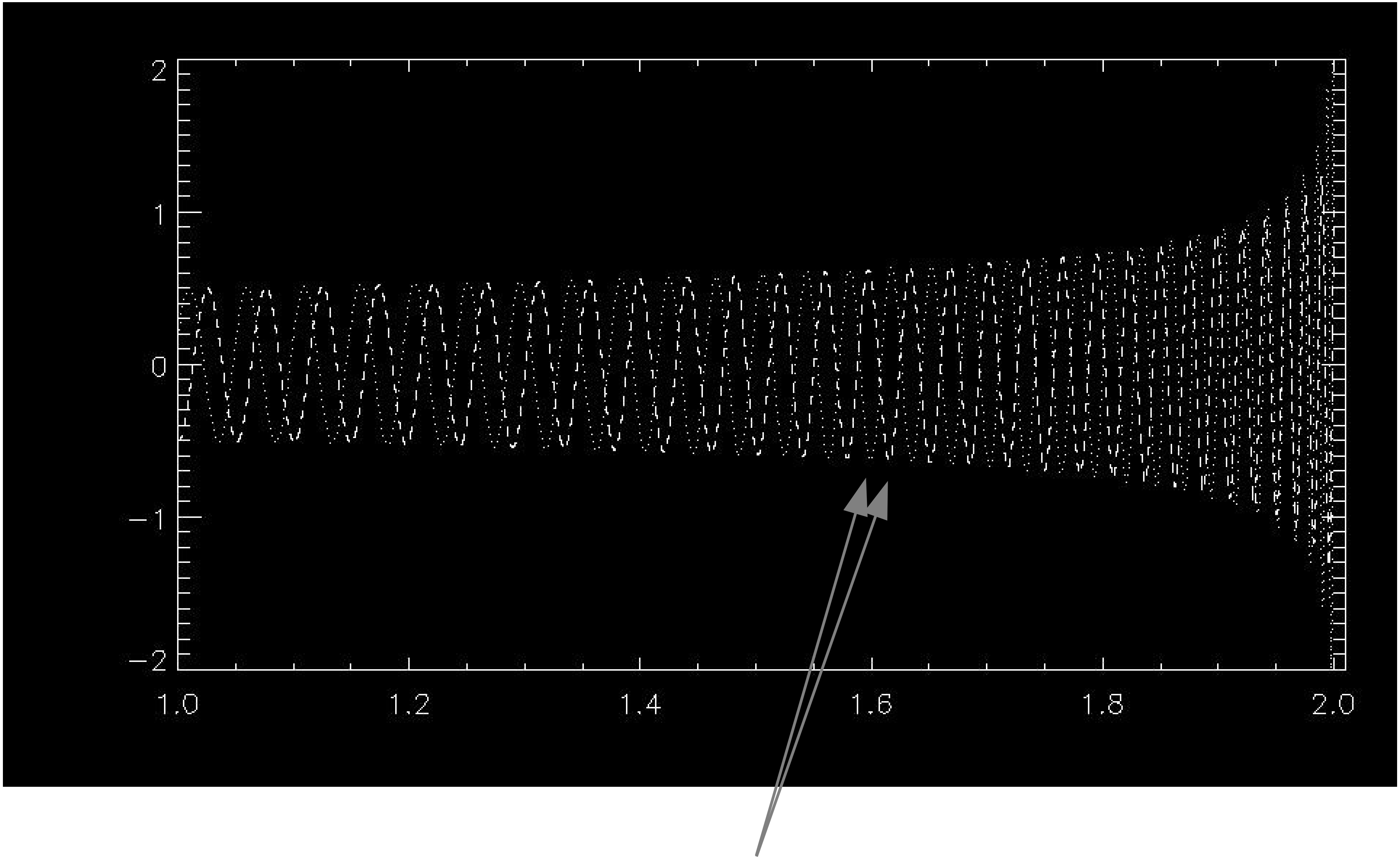
But also stellar bodies of smaller masses but magnified by large factors.

In these situations, two incomeing GWs will interfere at the detector

Interference of GW

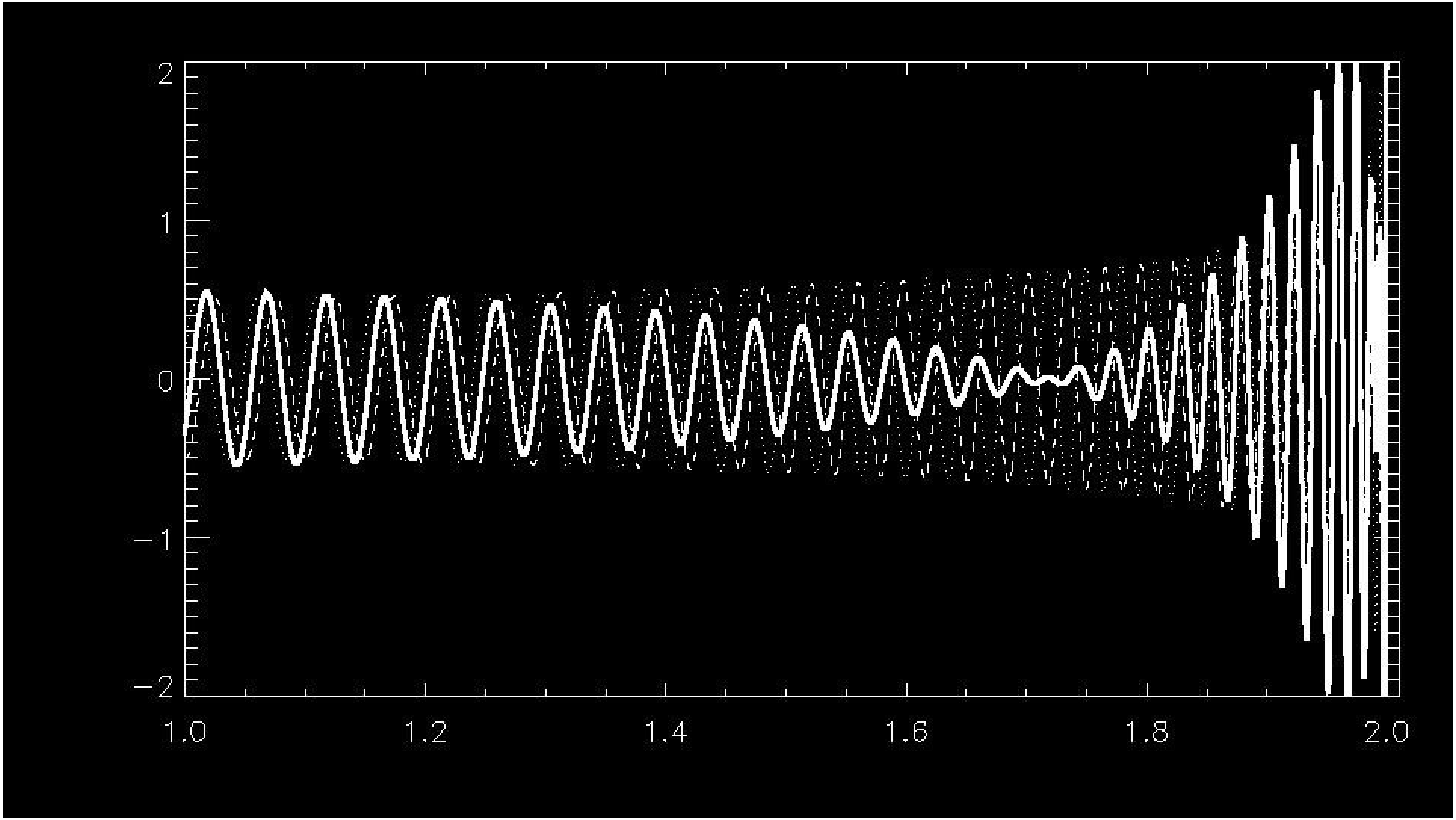


Interference of GW



Relative shift proportional to the mass of the microlens

Interference of GW

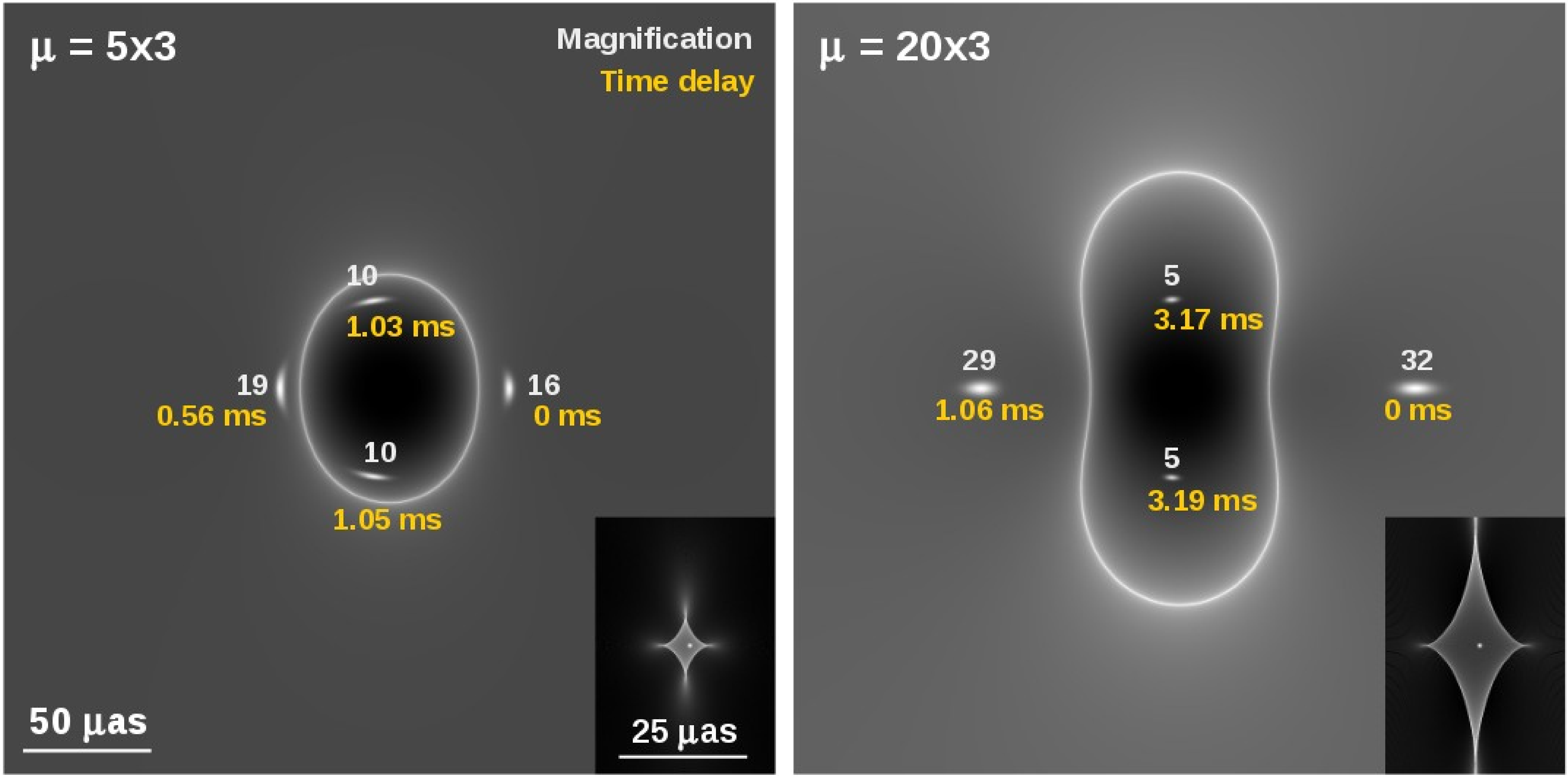


Magnification depends on Frequency

Assume wave optics and solve diffraction integral in Fourier space

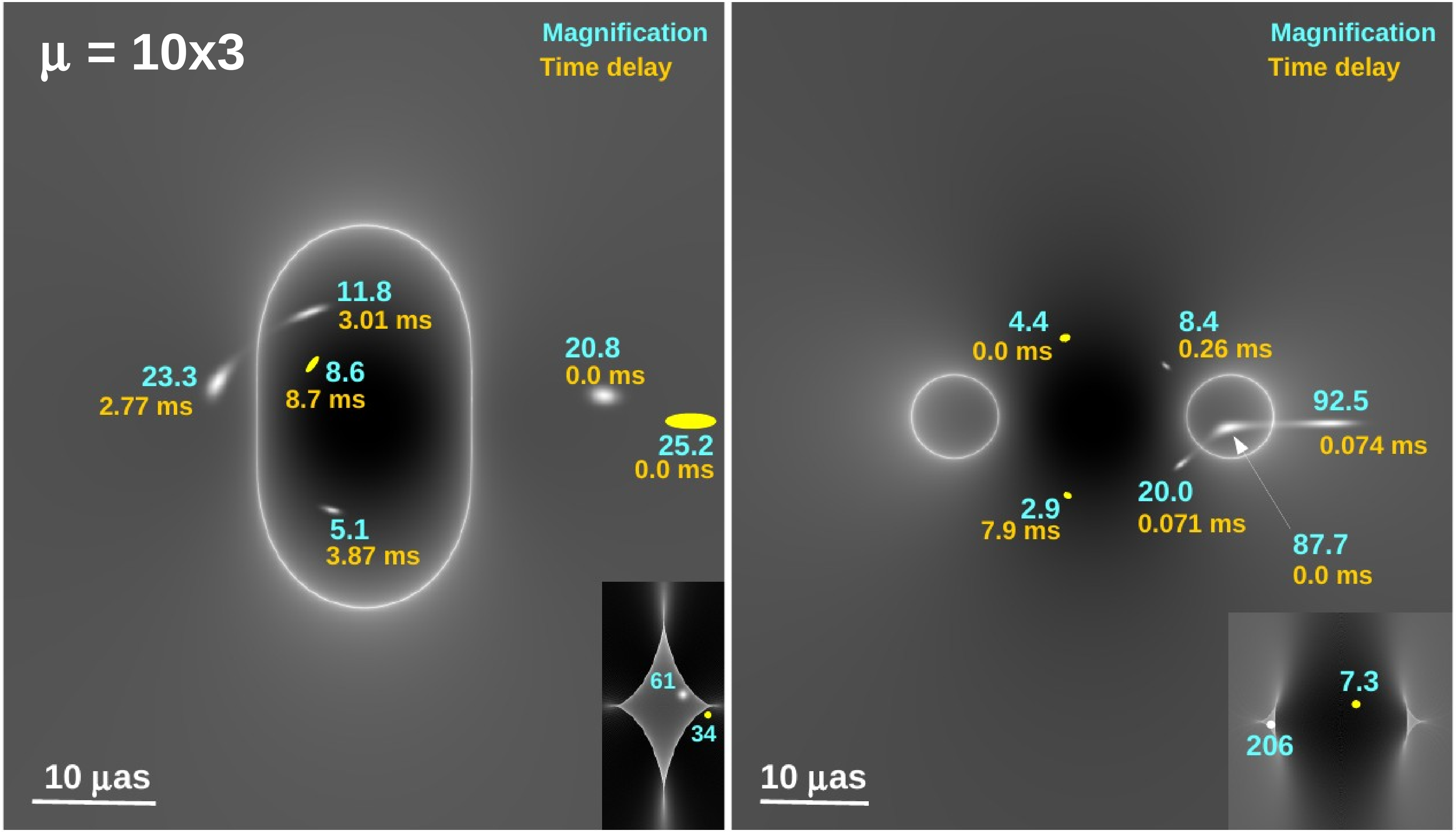
Time delay scales as sqrt(μ)

$M = 100\ M_o$



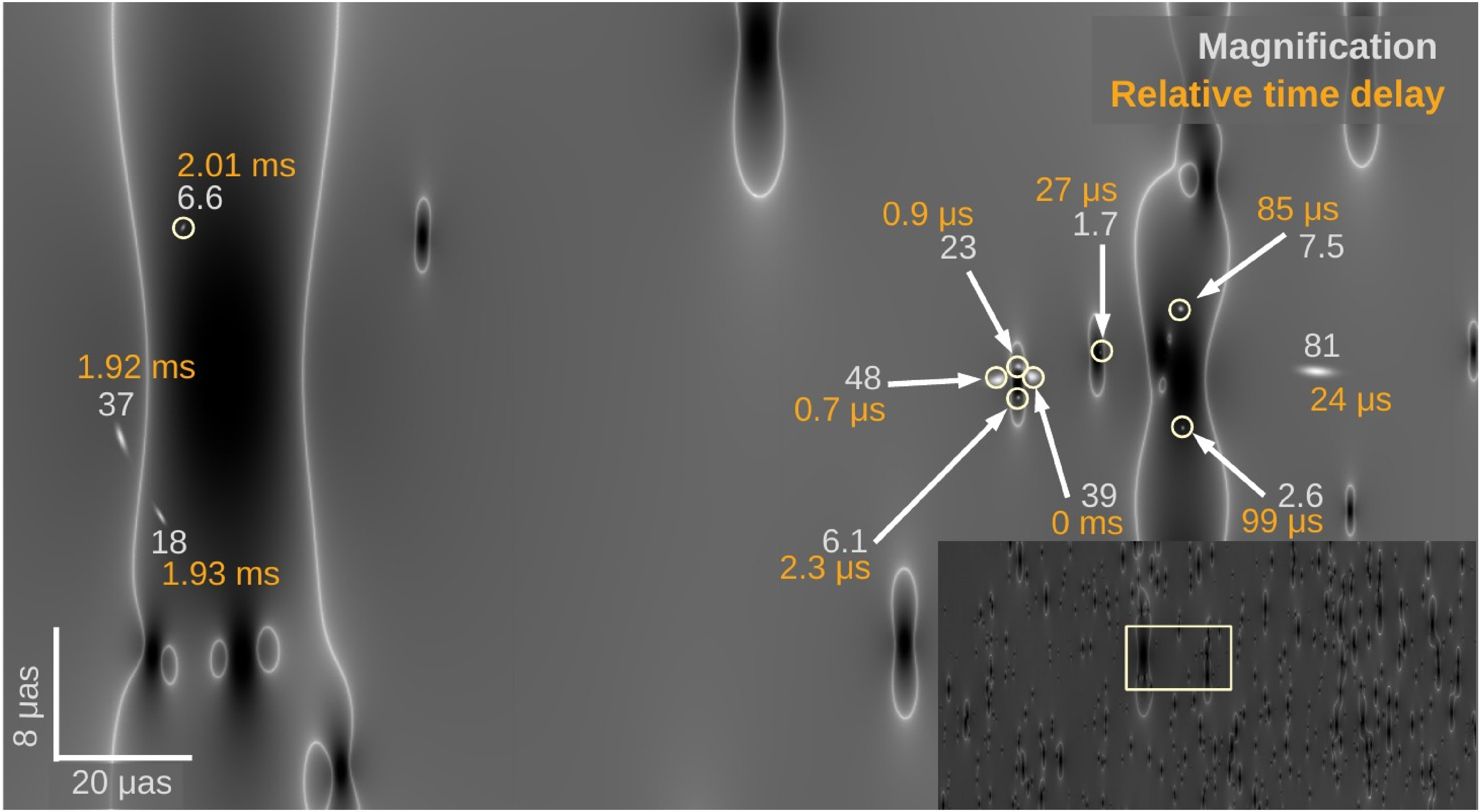
Effect is stronger in saddle points

M = 100 M$_o$



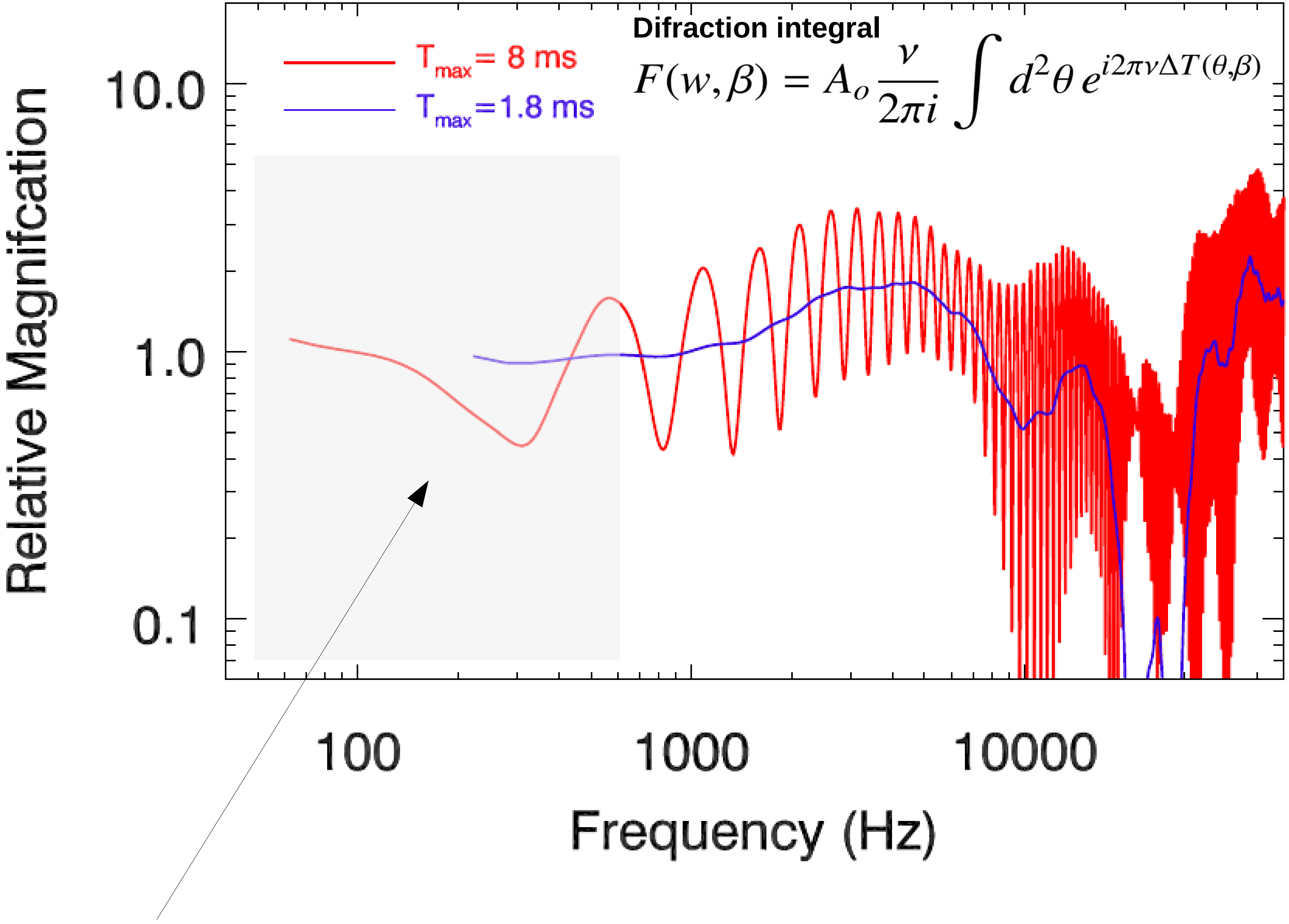
Wave effects by a population of stellar microlenses

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



Diego et al. 2019

Modulation of the magnification as a function of frequency



Difraction integral

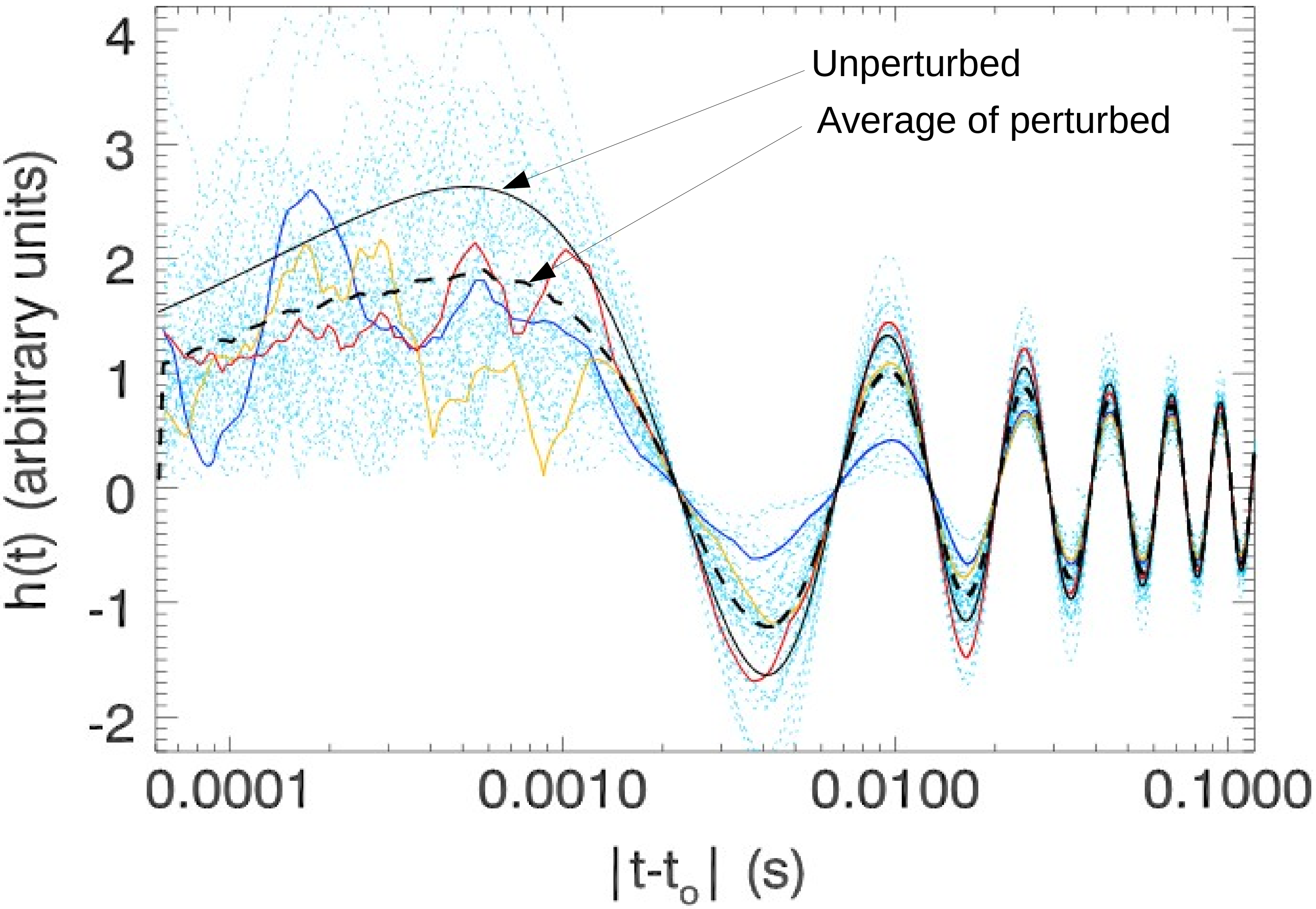
$$F(w,\beta) = A_o \frac{\nu}{2\pi i} \int d^2\theta\, e^{i2\pi\nu\Delta T(\theta,\beta)}$$

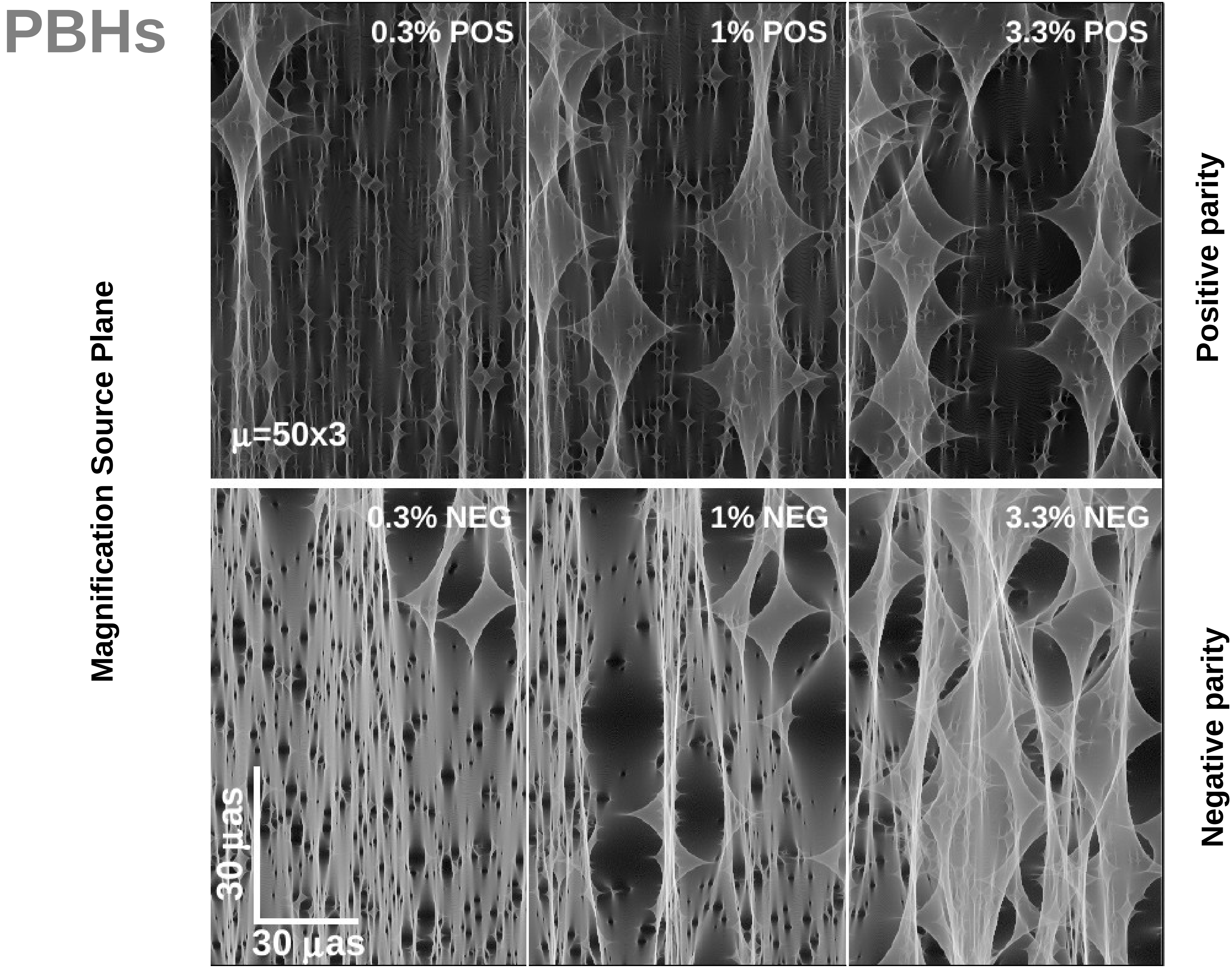
LIGO-Virgo frequency range.

Diego et al. 2019

GW Damping at high frequencies

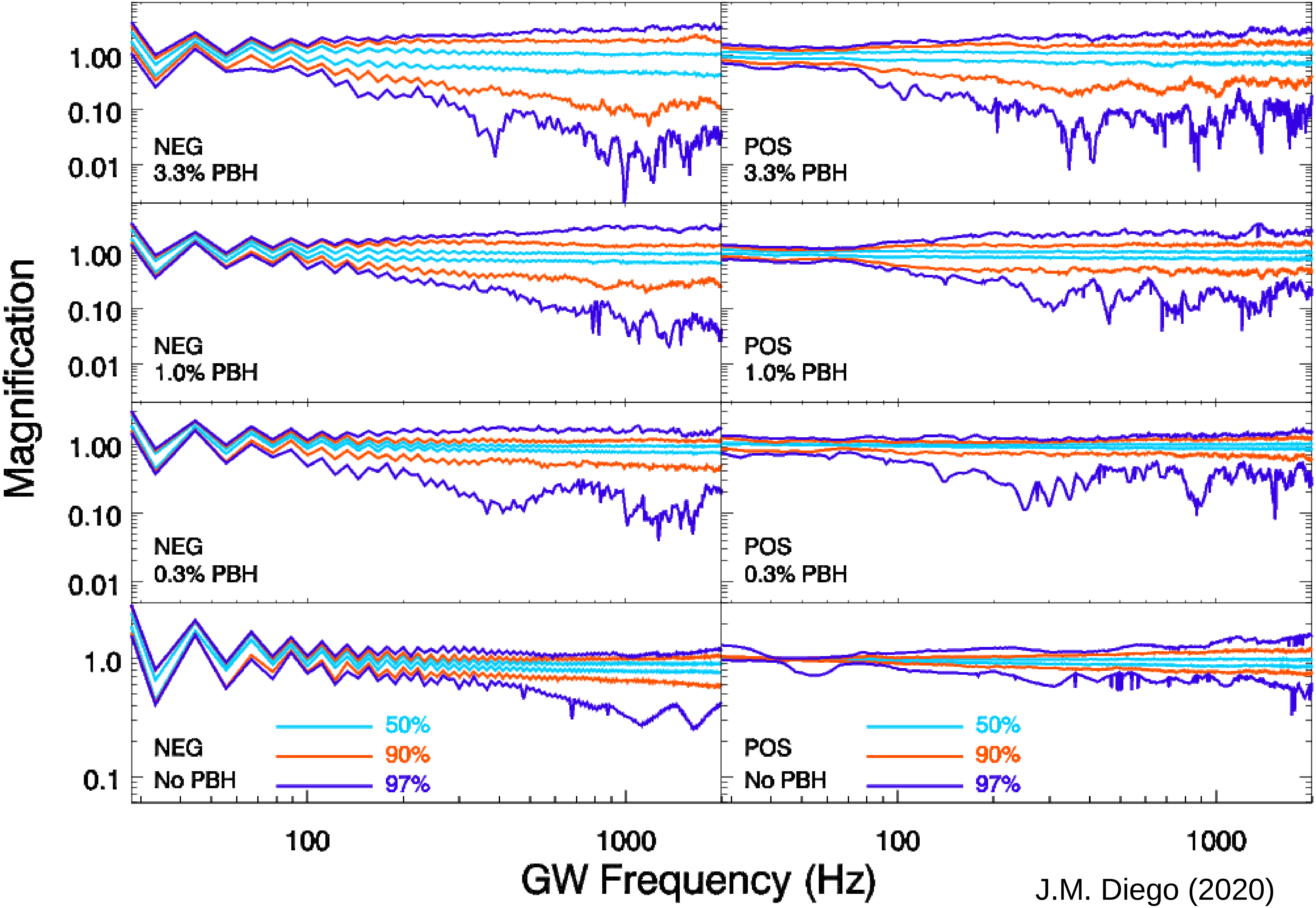
Highest frequencies are best to constrain the fraction of PBHs.
On average, highly magnified GWs are damped at large frequencies.




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

PBHs

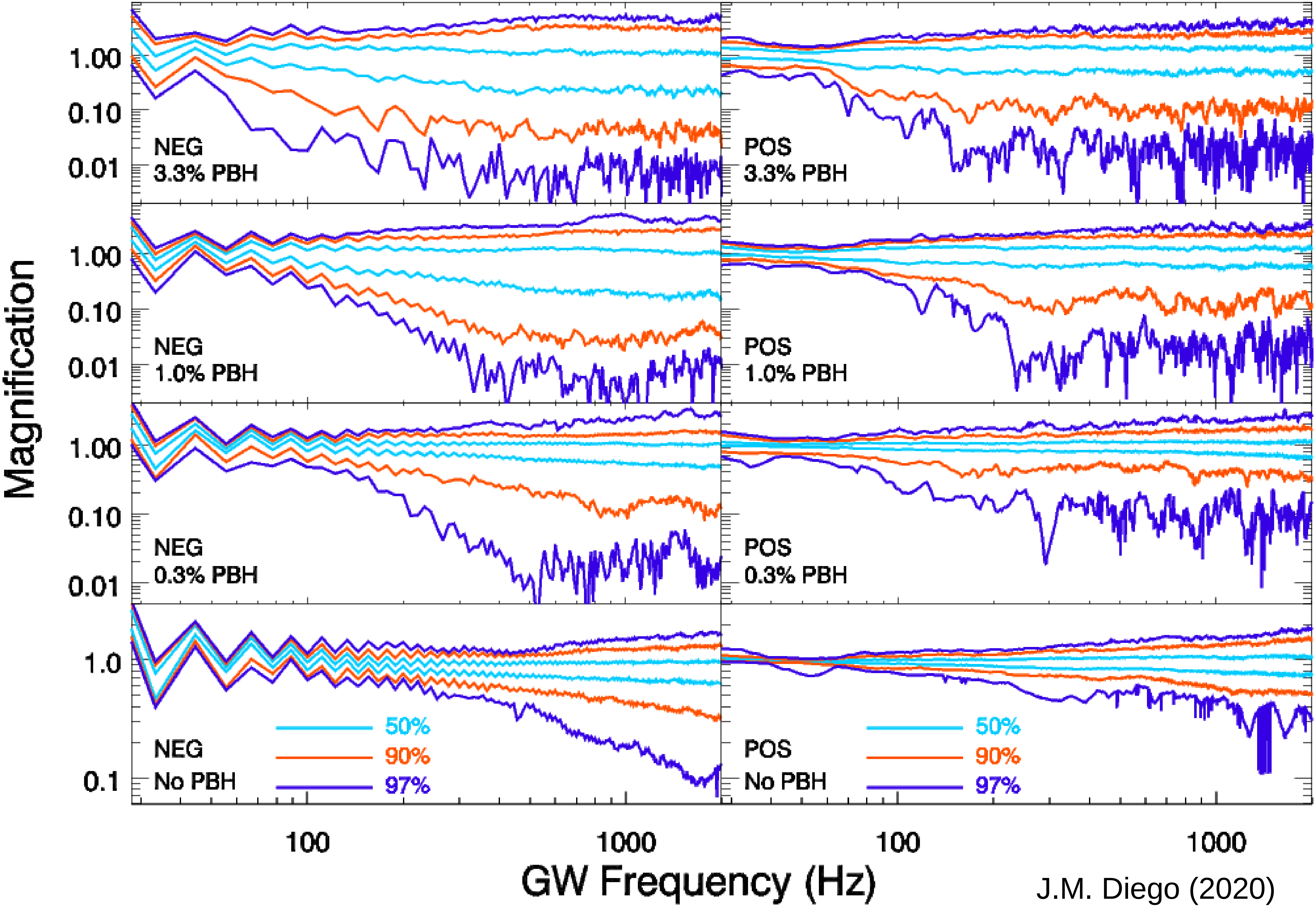
PROBABILITY OF DISTORTION (macromodel magnification = 10x3)



J.M. Diego (2020)

PBHs

PROBABILITY OF DISTORTION (macromodel magnification = 50x3)



J.M. Diego (2020)

CONCLUSIONS

PBH are a candidate for DM which become popular after LIGO detected a relatively abundant of BH with >20 M_o (see Broadhurst, Diego & Smoot)

Compact DM can be tested with microlensing events at extreme magnification. They will be more common in the near future (JWST).

For lensed stars, magnifications above 50000 can not take place due to the unavoidable distortion from microlenses.

Counter-images with negative parity are more affected, and can be demagnifed for periods lasting years.

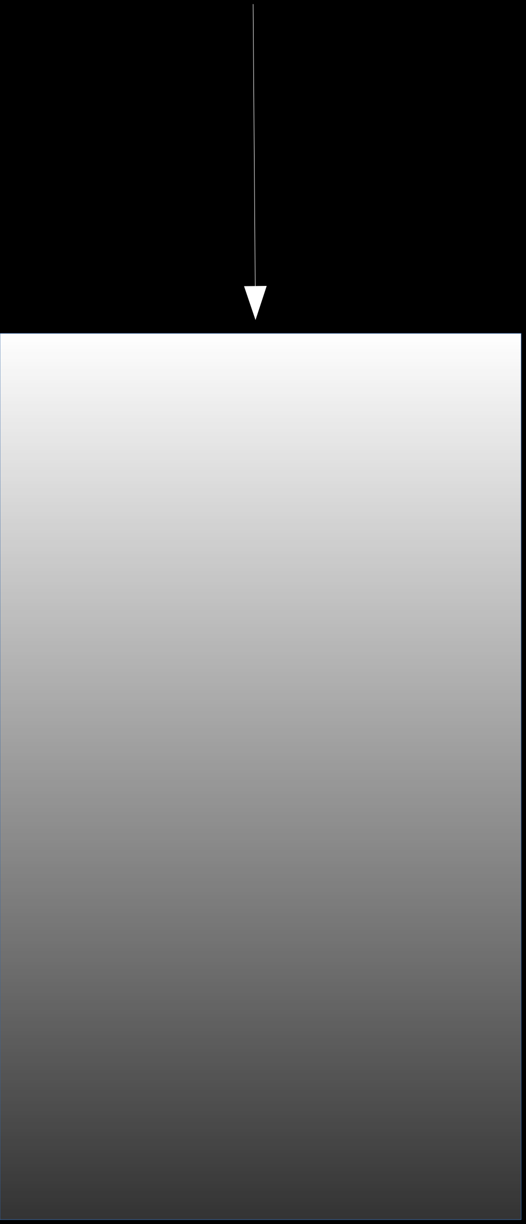
Constraints on the abundance of PBH limited by contamination from stellar microlenses, but for high-z sources, constrains can be better than 1%

Lensed GWs at high magnification will be affected by microlensing. Interference pattern needs to be incorporated in templates.

EXTRAS

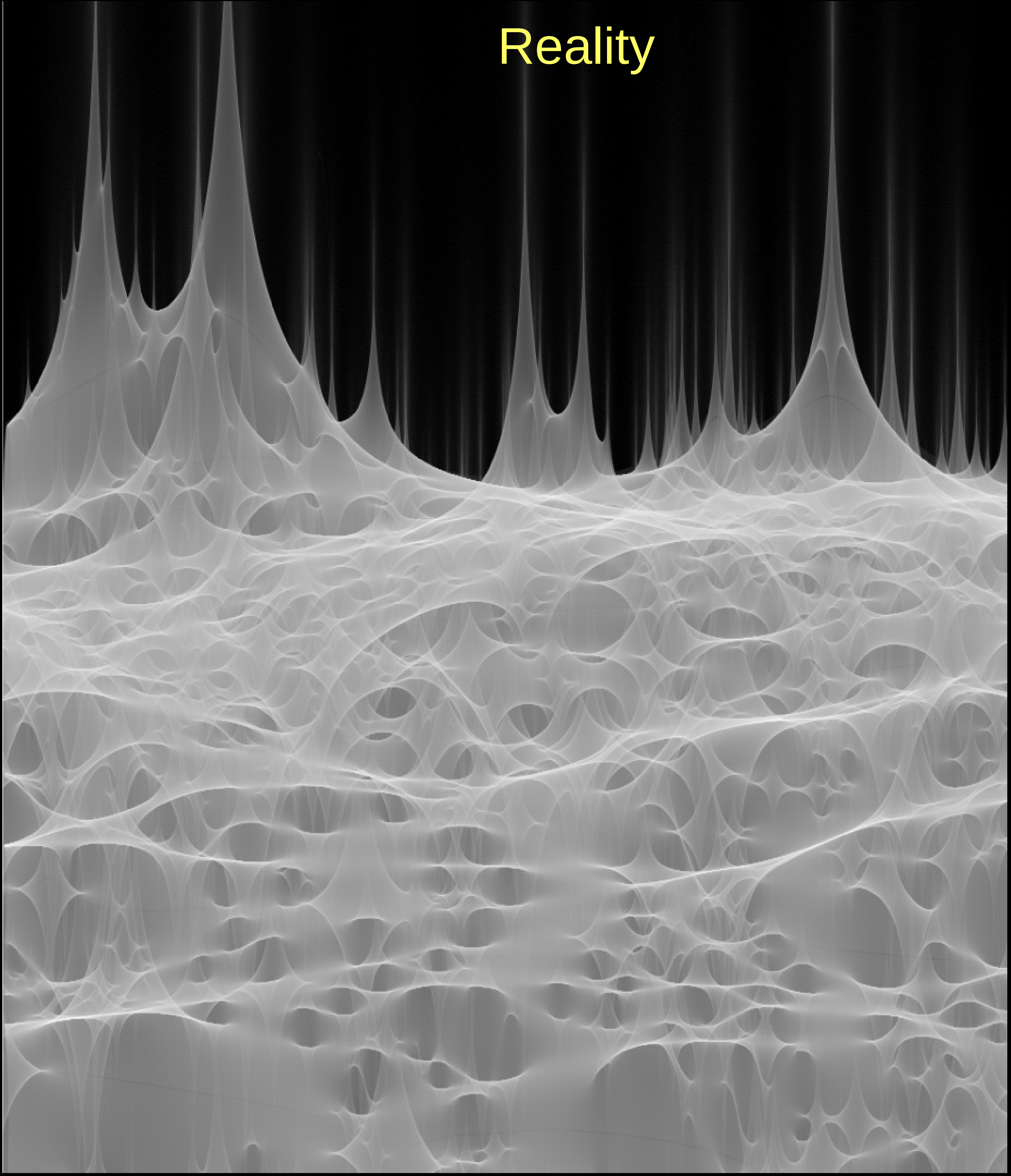
Classic View

Caustic region
without microlenses

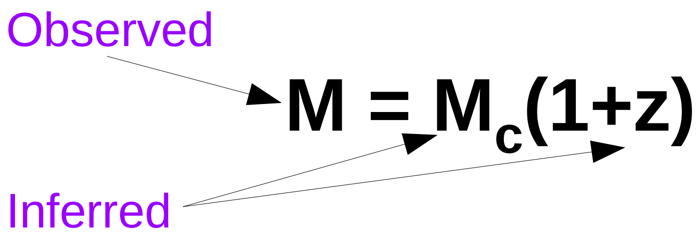


VS

Reality



Lensed GW. Basics



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

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

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

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.

A back of the envelope calculation

(see Broadhurst, Diego & Smoot)

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)

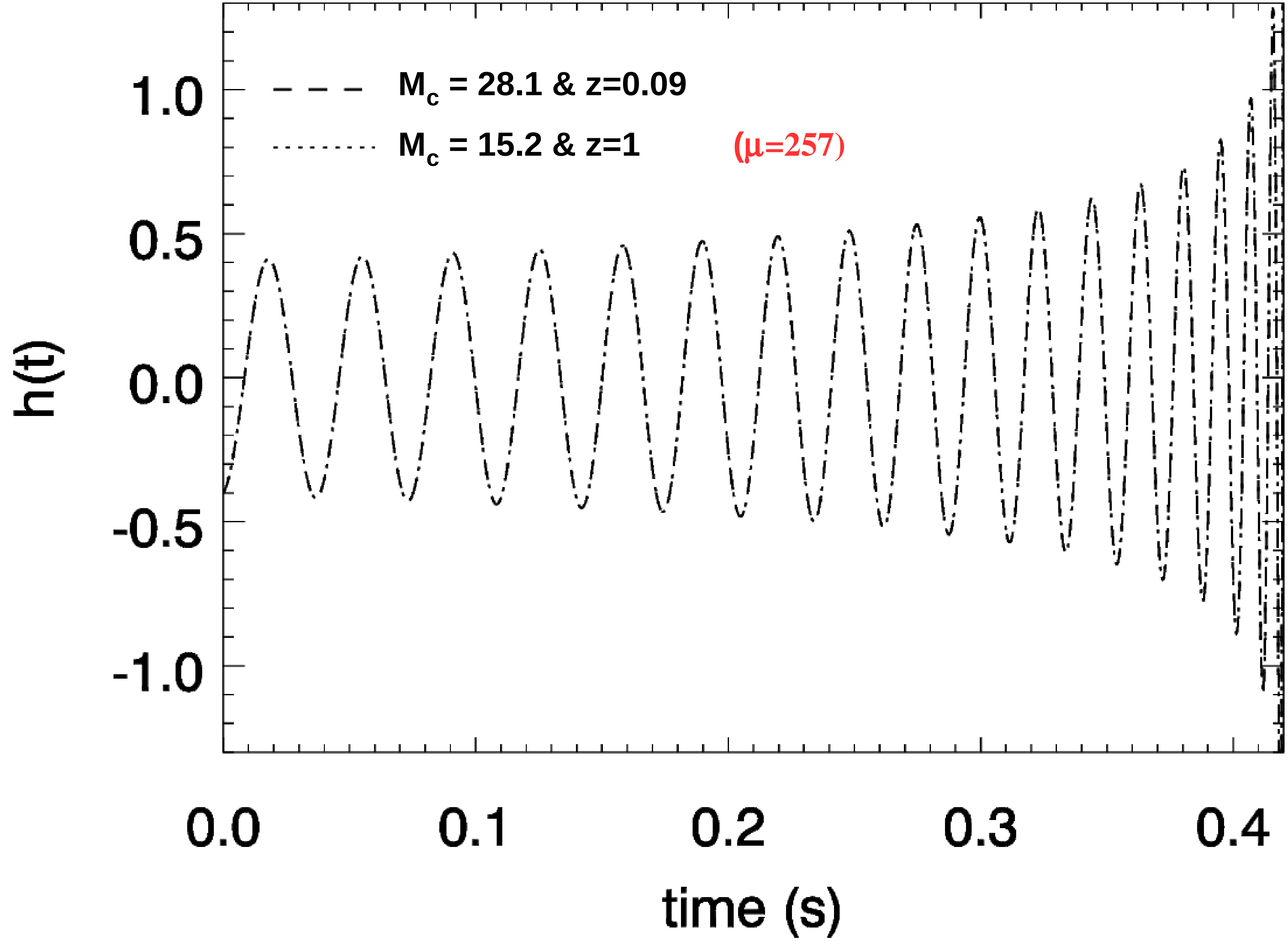
Compare with ~10^6 per yr & Gpc^3 for SNe

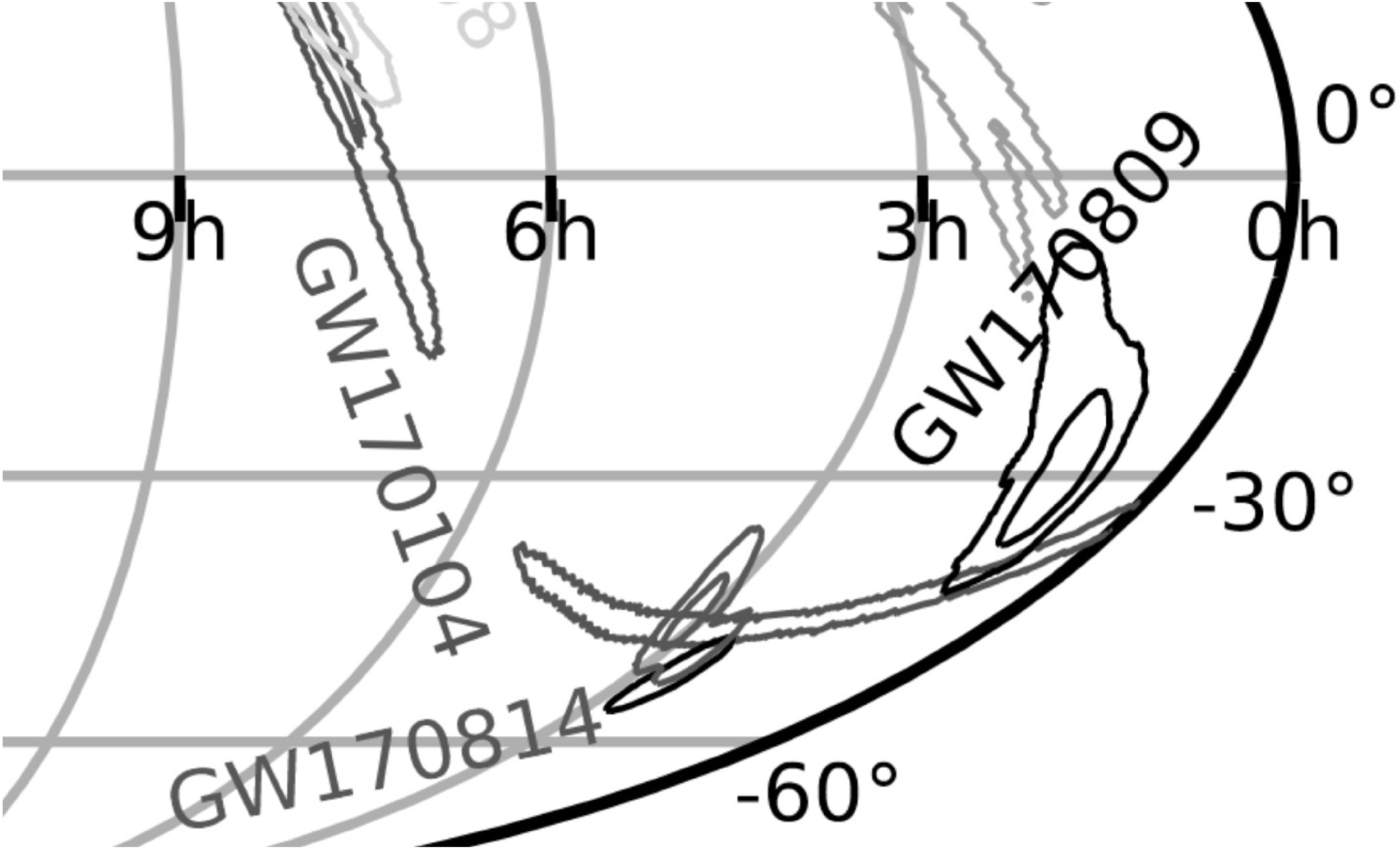
Total Number of events between z=1.9 and 2.1 : 3E6 per year

Total Number of μ>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 !


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


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