New directions in strong lensing

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Strong gravitational lensing of explosive transients

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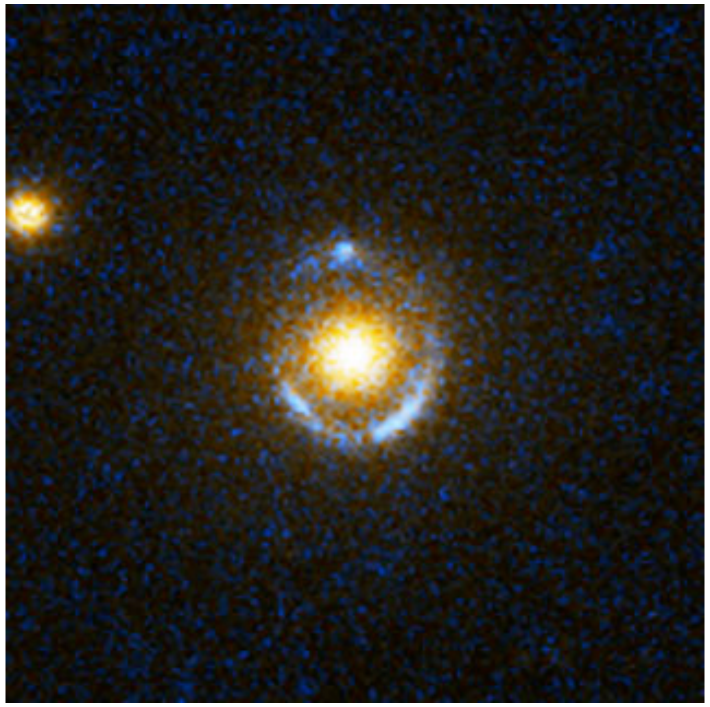
Abstract. Recent rapid progress in time domain surveys makes it possible to detect various types of explosive transients in the Universe in large numbers, some of which will be gravitationally lensed into multiple images. Although a large number of strongly lensed distant galaxies and quasars have already been discovered, strong lensing of explosive transients opens up new applications, including improved measurements of cosmological parameters, powerful probes of small scale structure of the Universe, and new observational tests of dark matter scenarios, thanks to their rapidly evolving light curves as well as their compact sizes. In particular, the compactness of these transient events indicates that the wave optics effect plays an important role in some cases, which can lead to totally new applications of these lensing events. Recently we have witnessed first discoveries of strongly lensed supernovae, and strong lensing events of other types of explosive transients such as gamma-ray bursts, fast radio bursts, and gravitational waves from compact binary mergers are expected to be observed soon. In this review article, we summarize the current state of research on strong gravitational lensing of explosive transients and discuss future prospects.

Keywords: cosmology, gravitational lensing, transients

Strong gravitational lenses

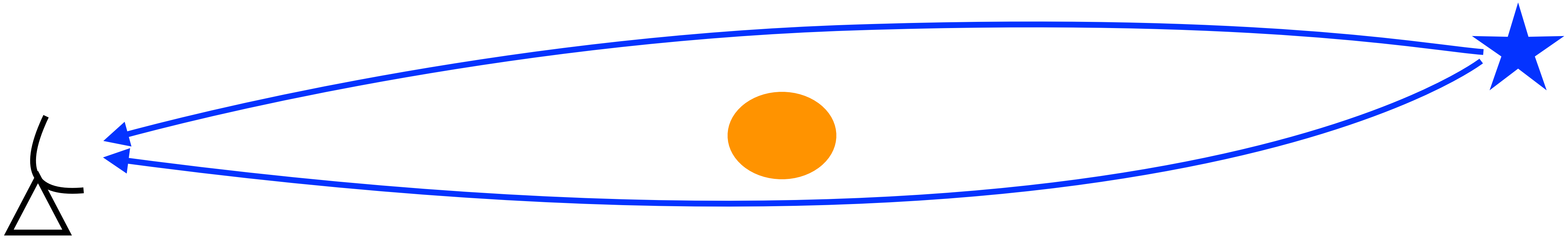
- multiply imaged, highly magnified
- many applications
  - **cosmology**
  - **dark matter distribution**
  - **distant/faint sources**
  - **resolving fine structure**

lensed quasar (SQLS)



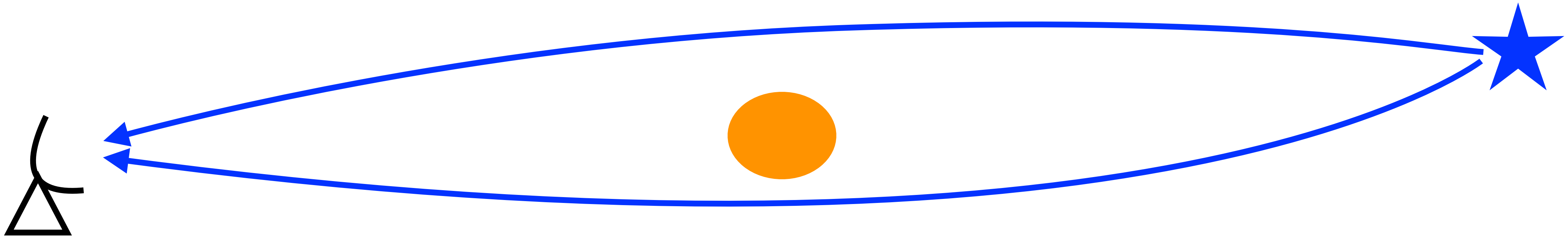
lensed galaxy (SLACS)

observer **lens** **source**



- galaxy
- cluster

- quasar
- galaxy



observer **lens** **source**

- galaxy
- cluster

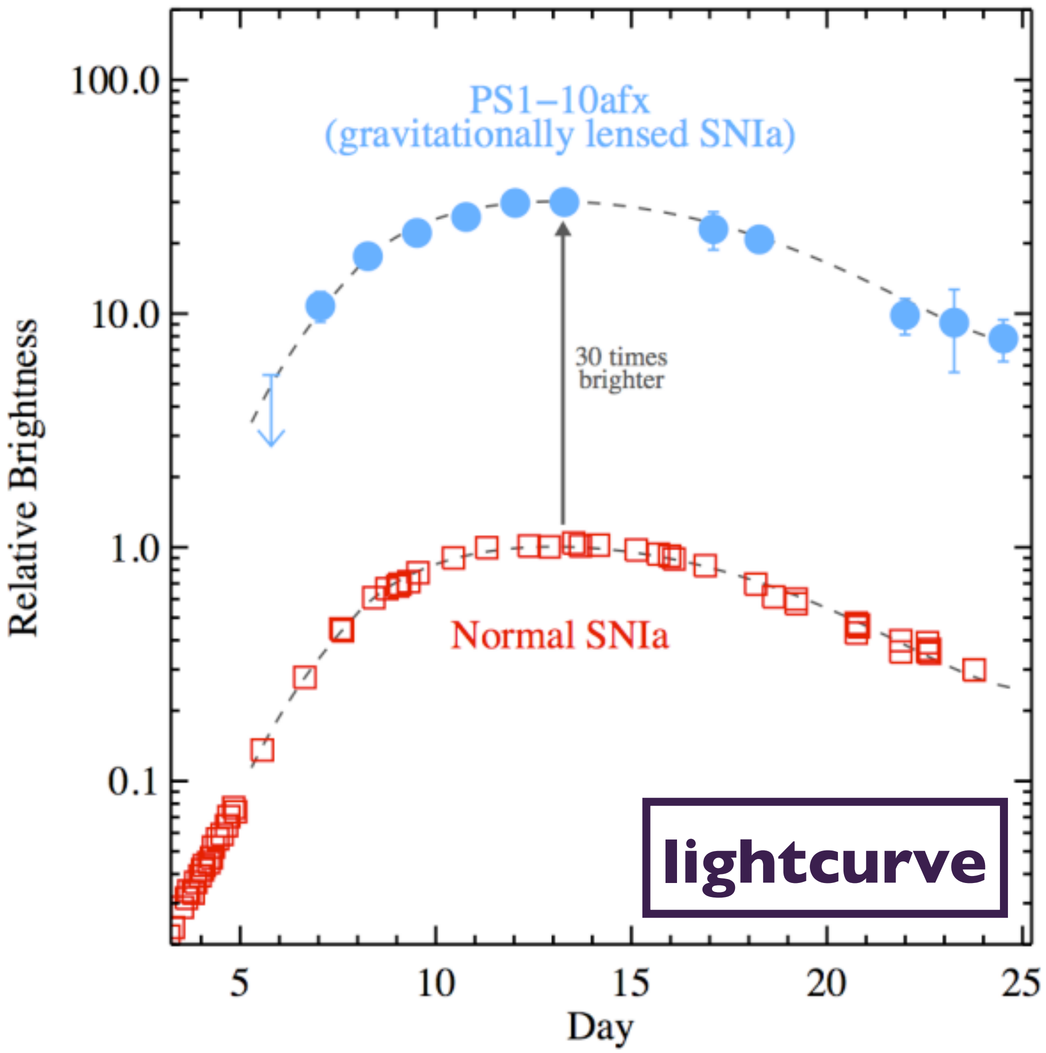
- quasar
- galaxy
- **SN**
- **GRB**
- **FRB**
- **GW**
- …

Strong lensing of explosive transients?

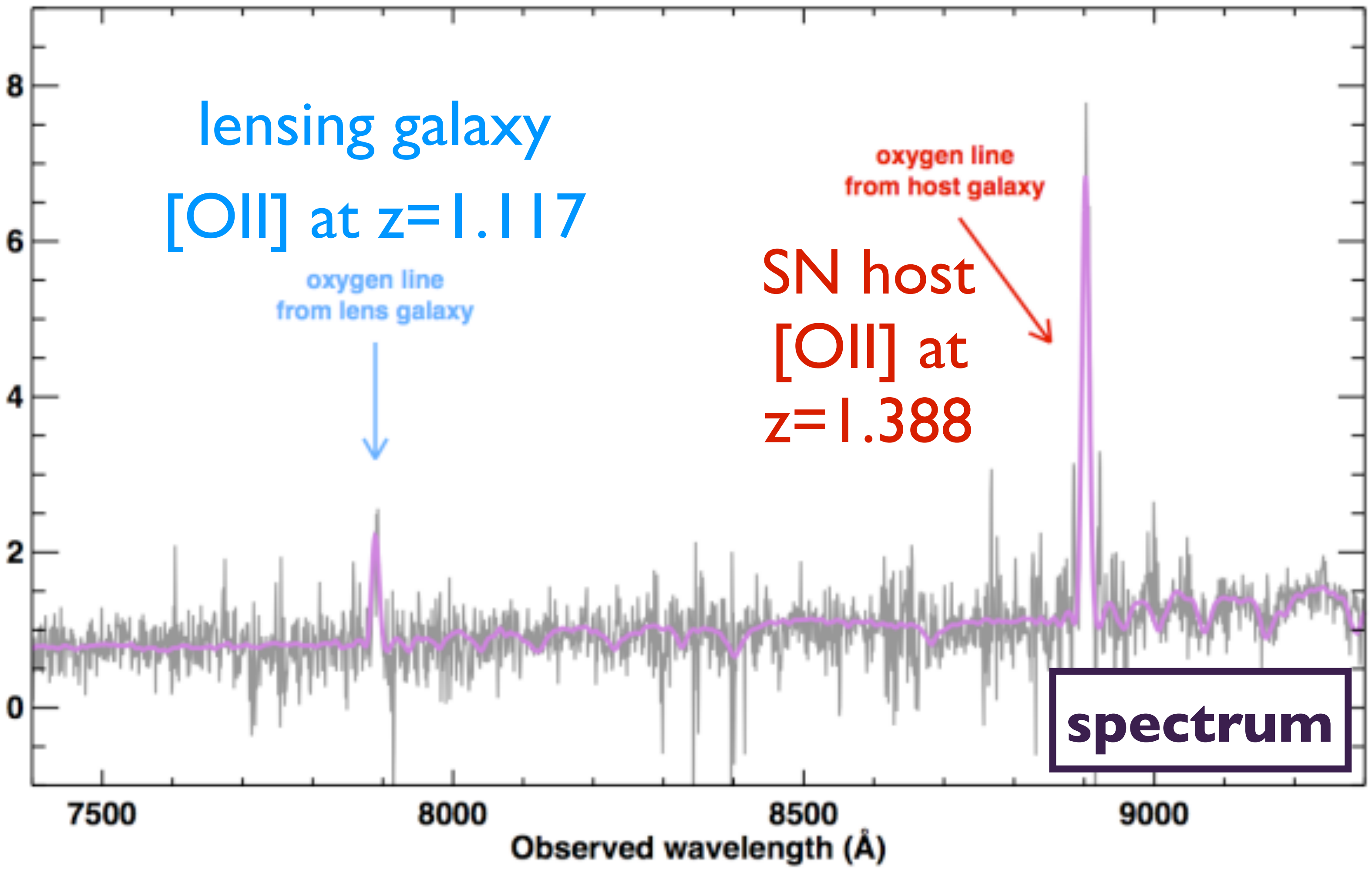
- supernova (SN)
  PS1-10afx, **SN Refsdal**, **iPTF16geu**
- gamma-ray burst (GRB)
  not yet
- fast radio burst (FRB)
  not yet
- gravitational wave (GW)
  not yet

Quimby, MO+ Science **344**(2014)396

PS1-10afx



lightcurve



lensing galaxy
[OII] at z=1.117

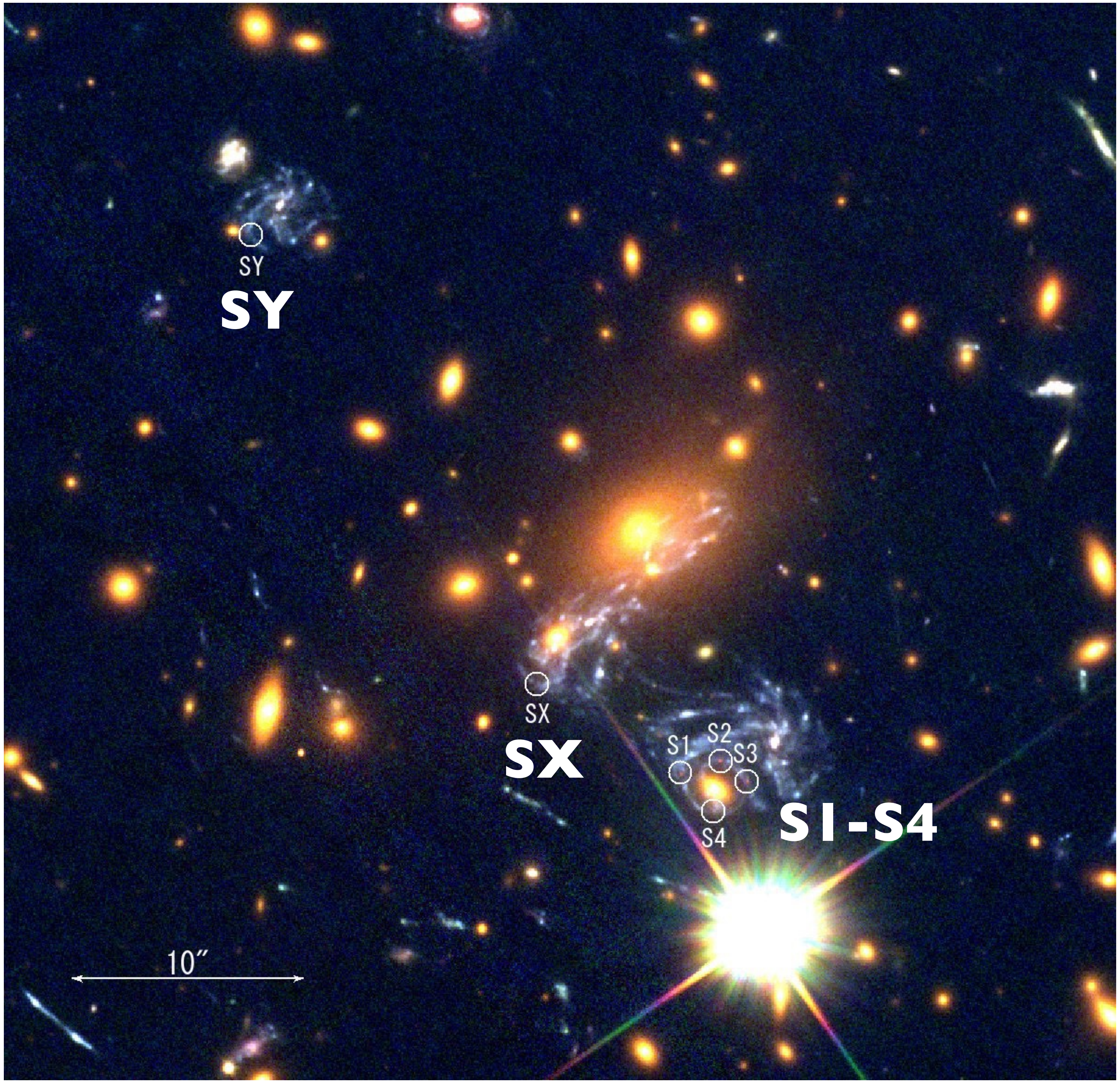
SN host
[OII] at
z=1.388

spectrum

- **Type Ia** supernova magnified by a factor of 30!
- multiple images were not resolved

Kelly+ Science **347**(2015)1123

SN Refsdal

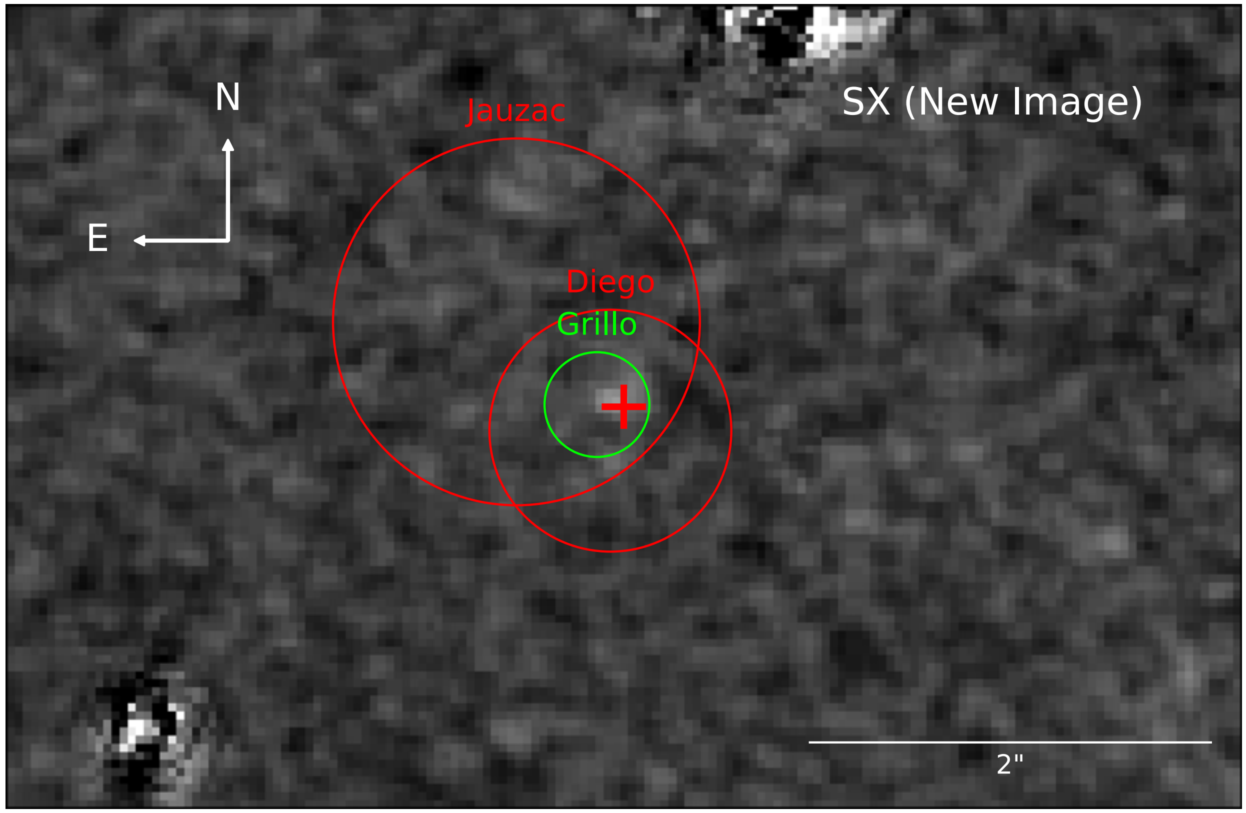


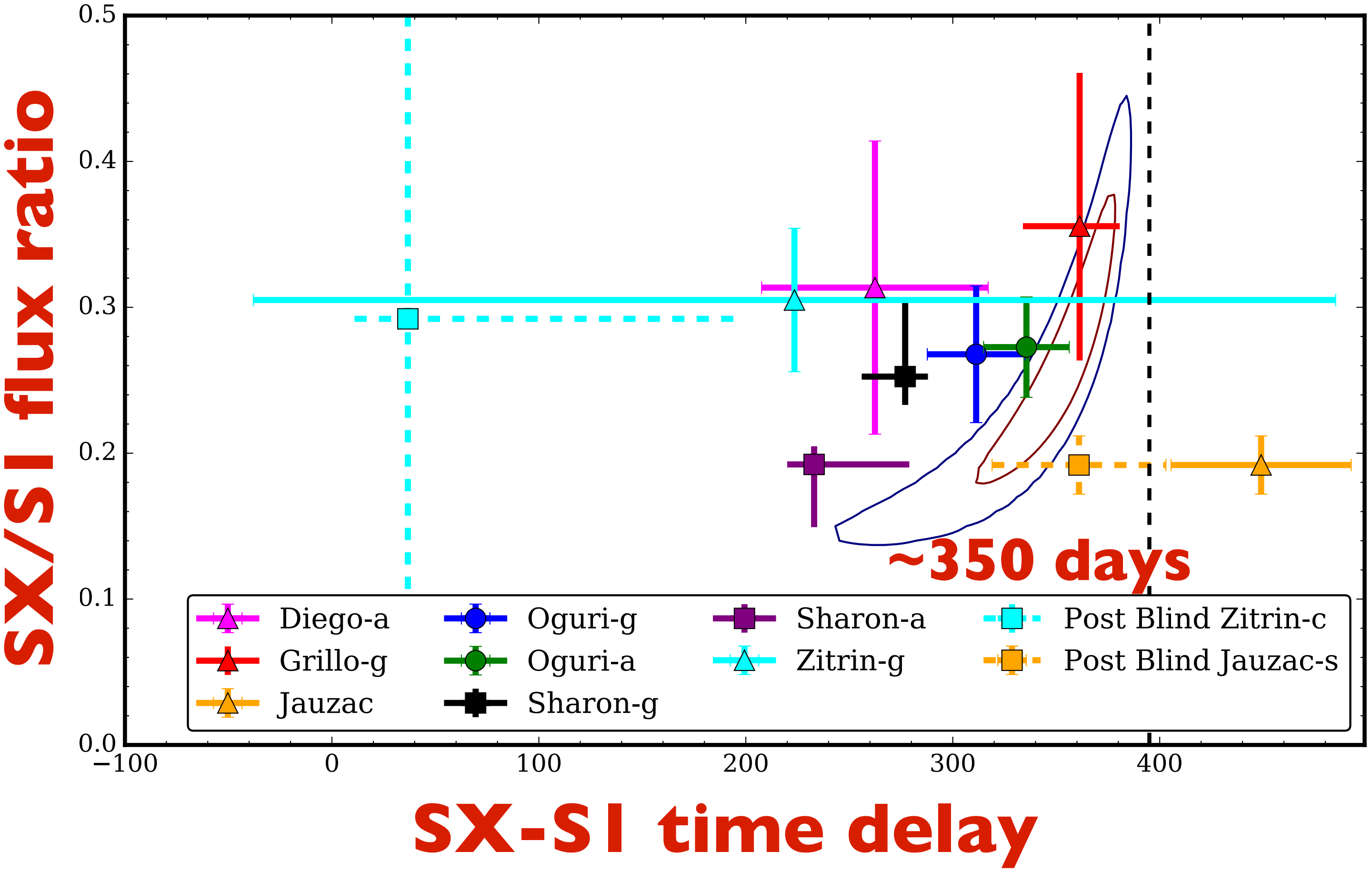
HST image

- core-collapse SN strongly lensed by a cluster
- 4 images **S1-S4** discovered in 2015 October
- 2 more images **predicted**
- **SX** : 2016-2017
- **SY** : <2005

Kelly+ ApJ **819**(2016)L8

“Reappearance” of Refsdal

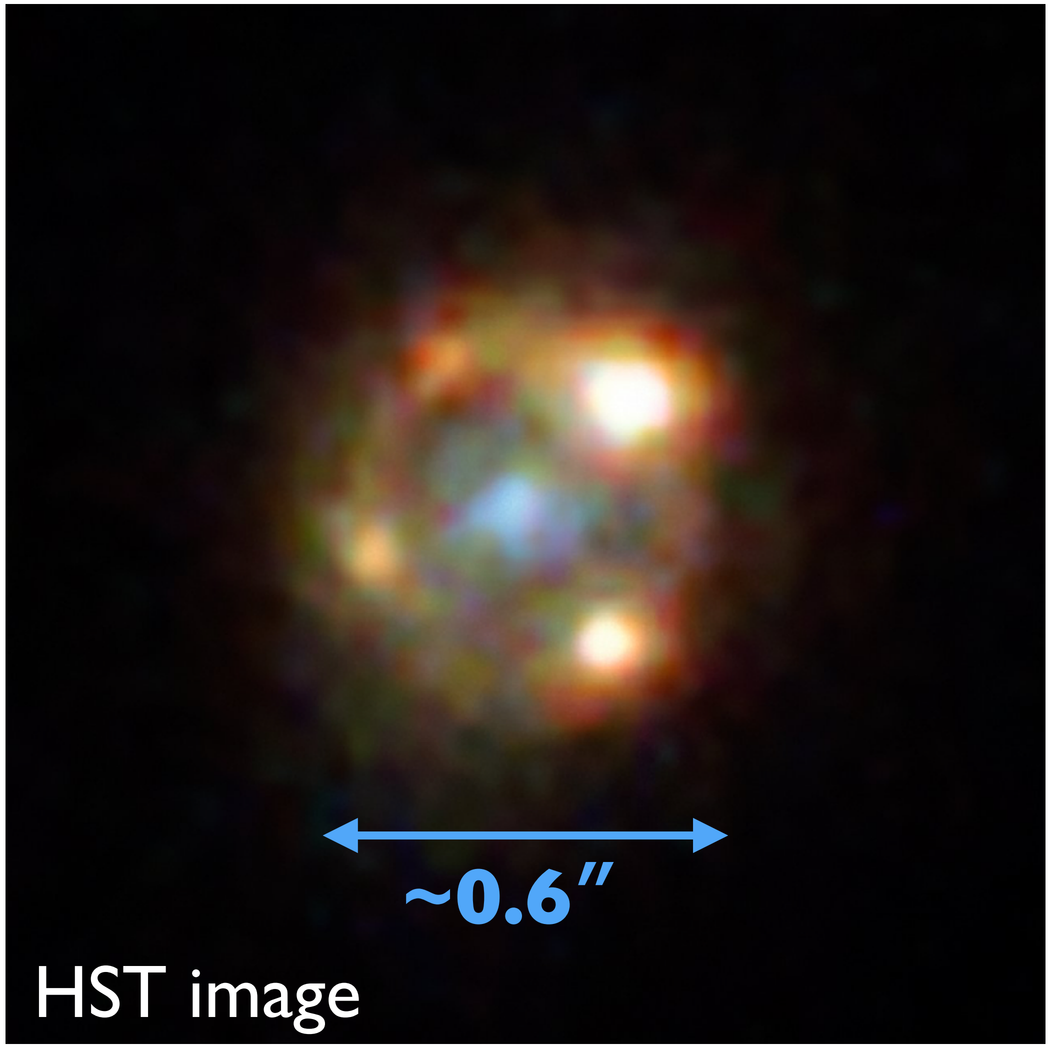




- image SX appeared exactly at the predicted position and time!
- fully blind test of cluster mass models

Goobar+ Science **356**(2017)291

iPFT16geu



- **Type Ia** supernova magnified by a factor of 52!
- 4 images separated by ~0.6″
- time delays are predicted to be short, <1 day

Advantages?

- simple and fast light curves
- standardizable candles
- wave effect?

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- simple and fast light curves
- standardizable candles
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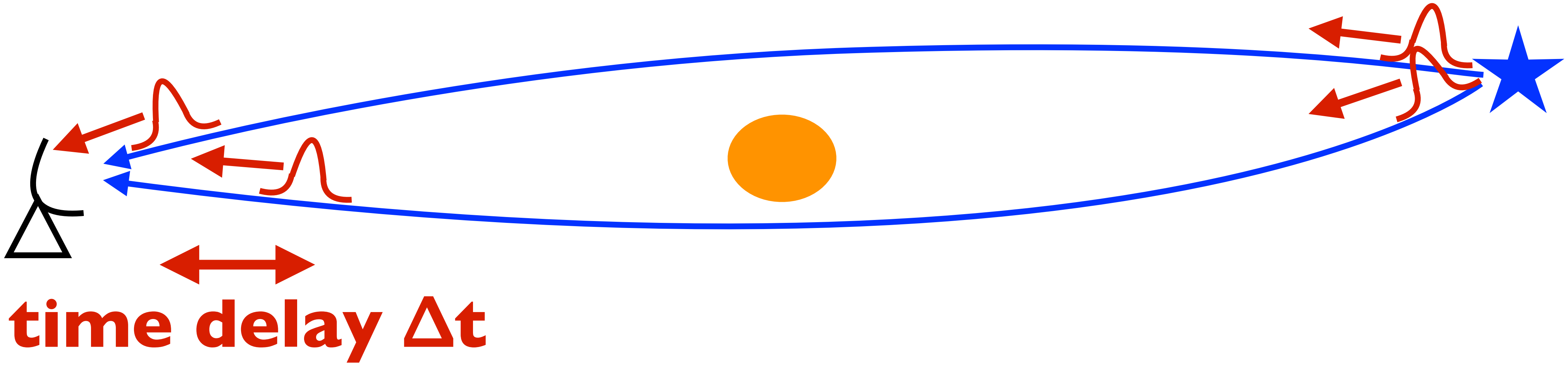
Simple and fast light curves

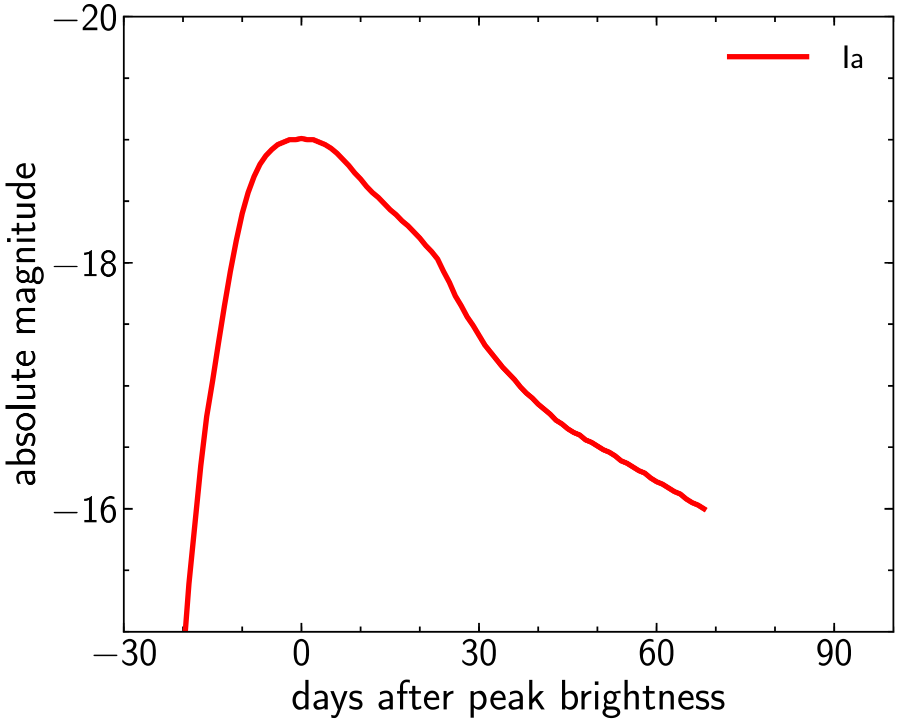
- simple light curves with a rise and fall (**SN**, **GRB**, **FRB**) or theoretical templates (**GW**)
- short time scales, month (**SN**) or sec-msec (**GRB**, **FRB**, **GW**)
- robust and accurate measurements of **time delays**!

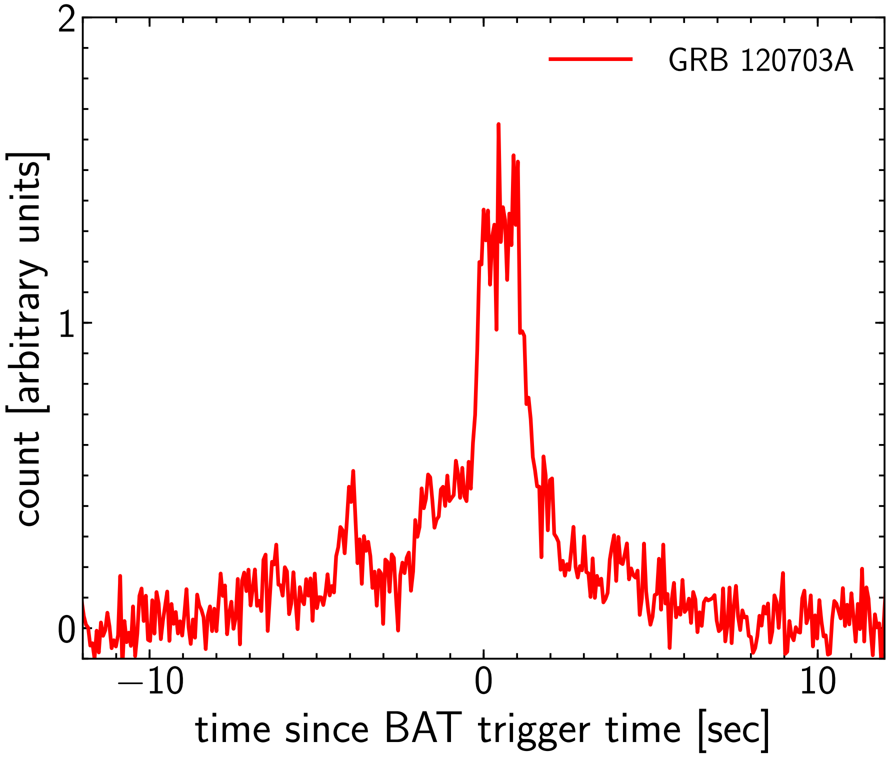


Light curves of explosive transients

SN

month





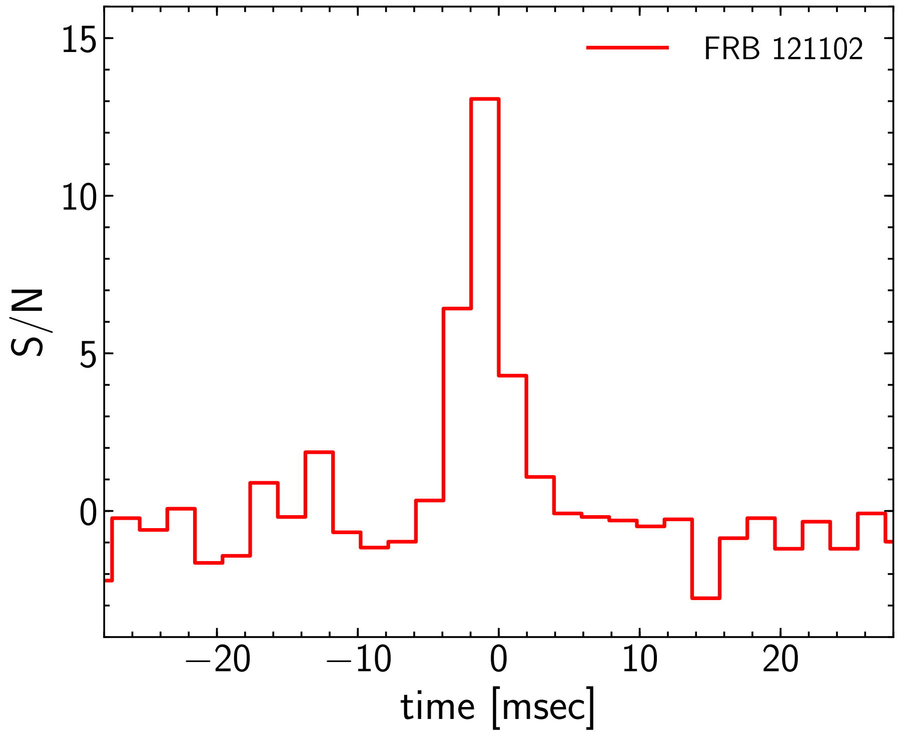
GRB

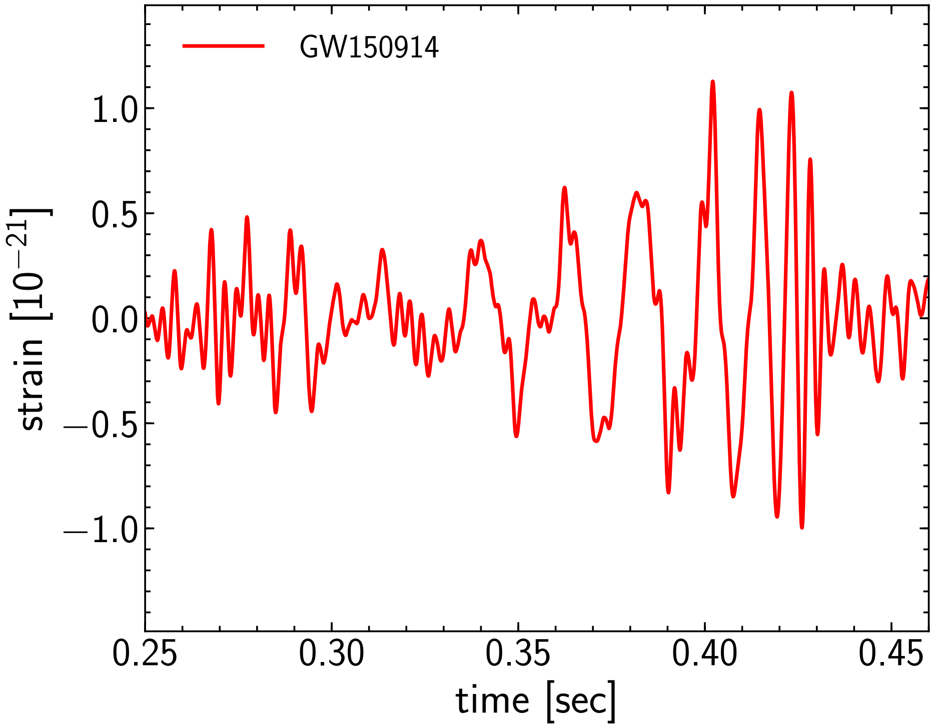
sec

– msec

FRB

msec

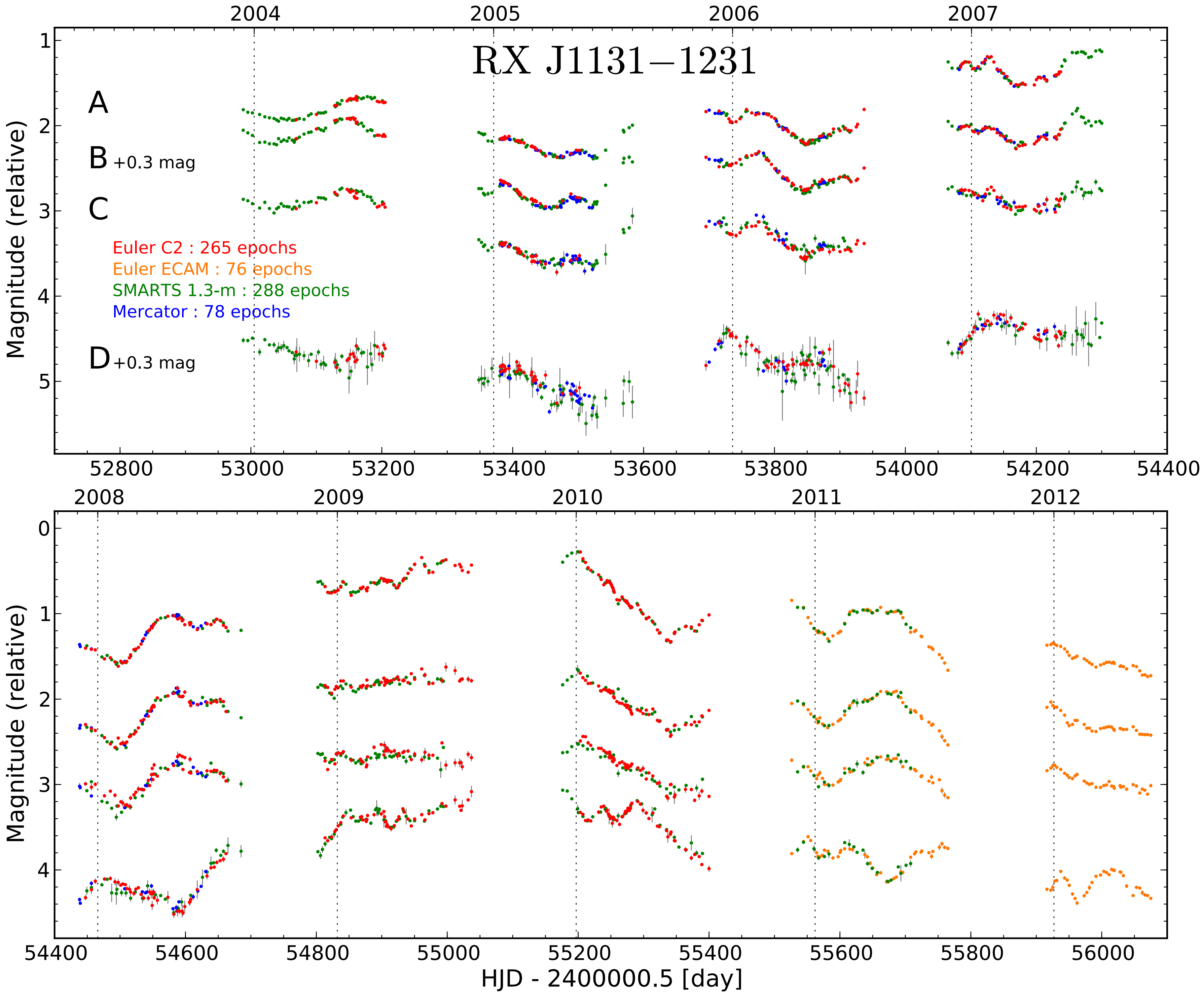




GW

msec

Time delays for quasar lenses



Tewes+2013

- quasar light curves are **stochastic**
- monitoring for years required
- precision of ~1 day at most

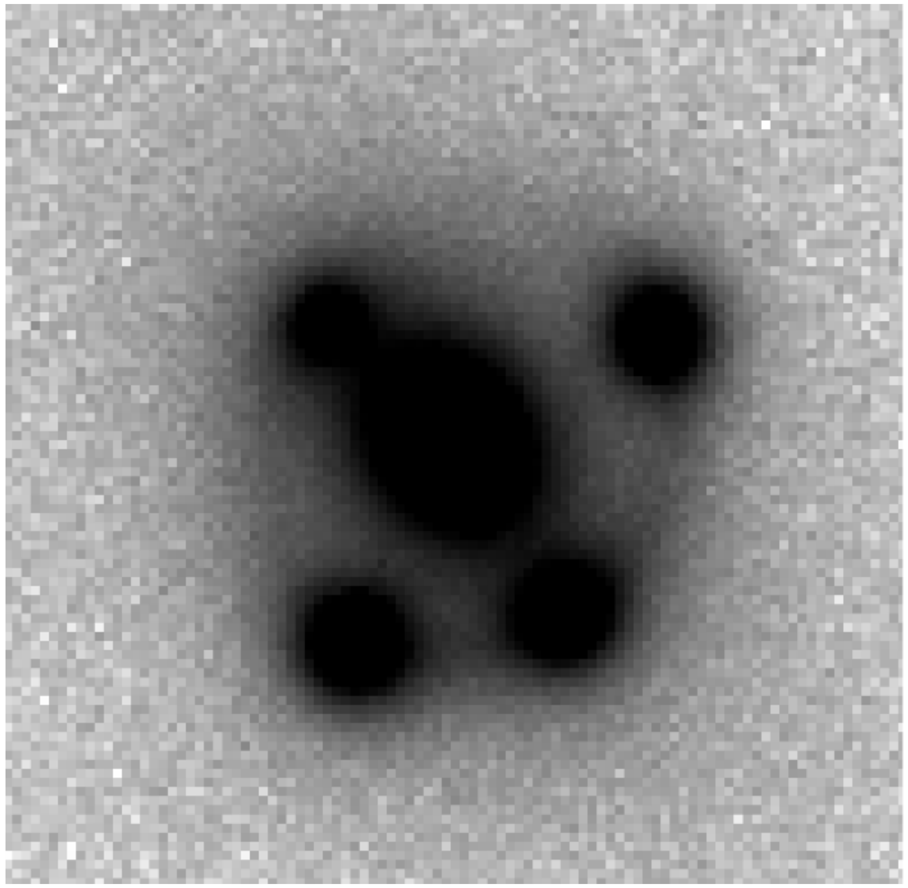
Improved time delays

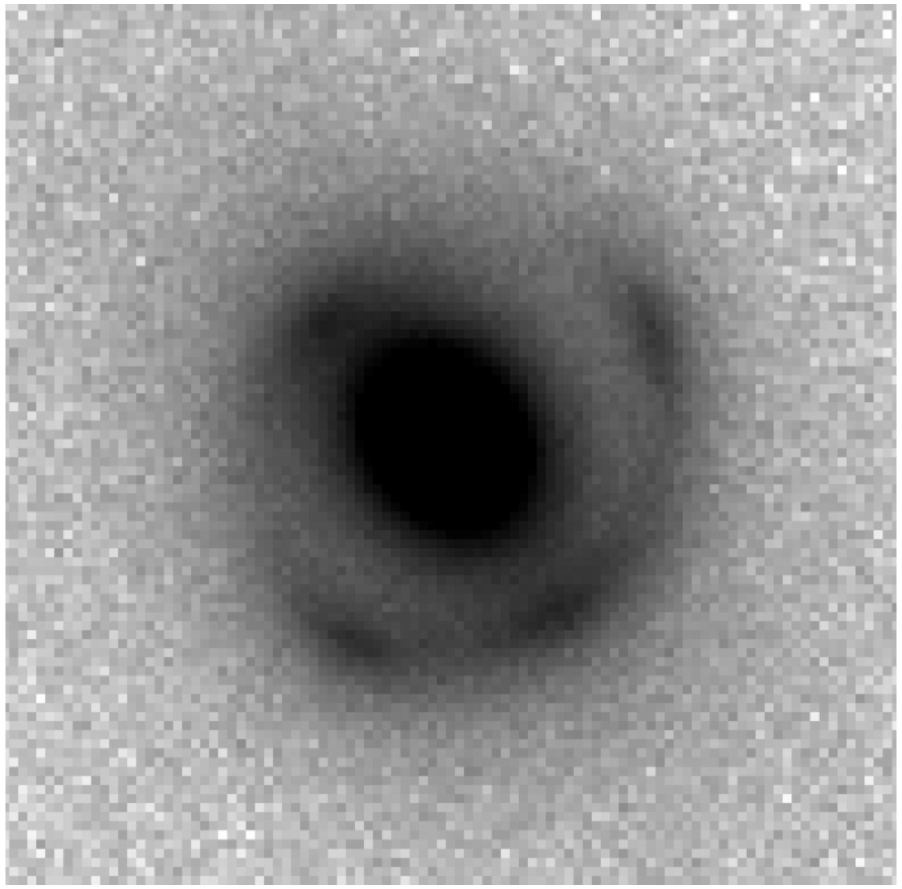
- improved constraints on H_0
  (see also Ken Wong's talk!)
- probing dark matter substructures
- probing compact dark matter

Improved constraints on H_0

- improved measurement errors on Δt (~day → up to ~msec!)
- better use of a lensed host galaxy

w/ SN images



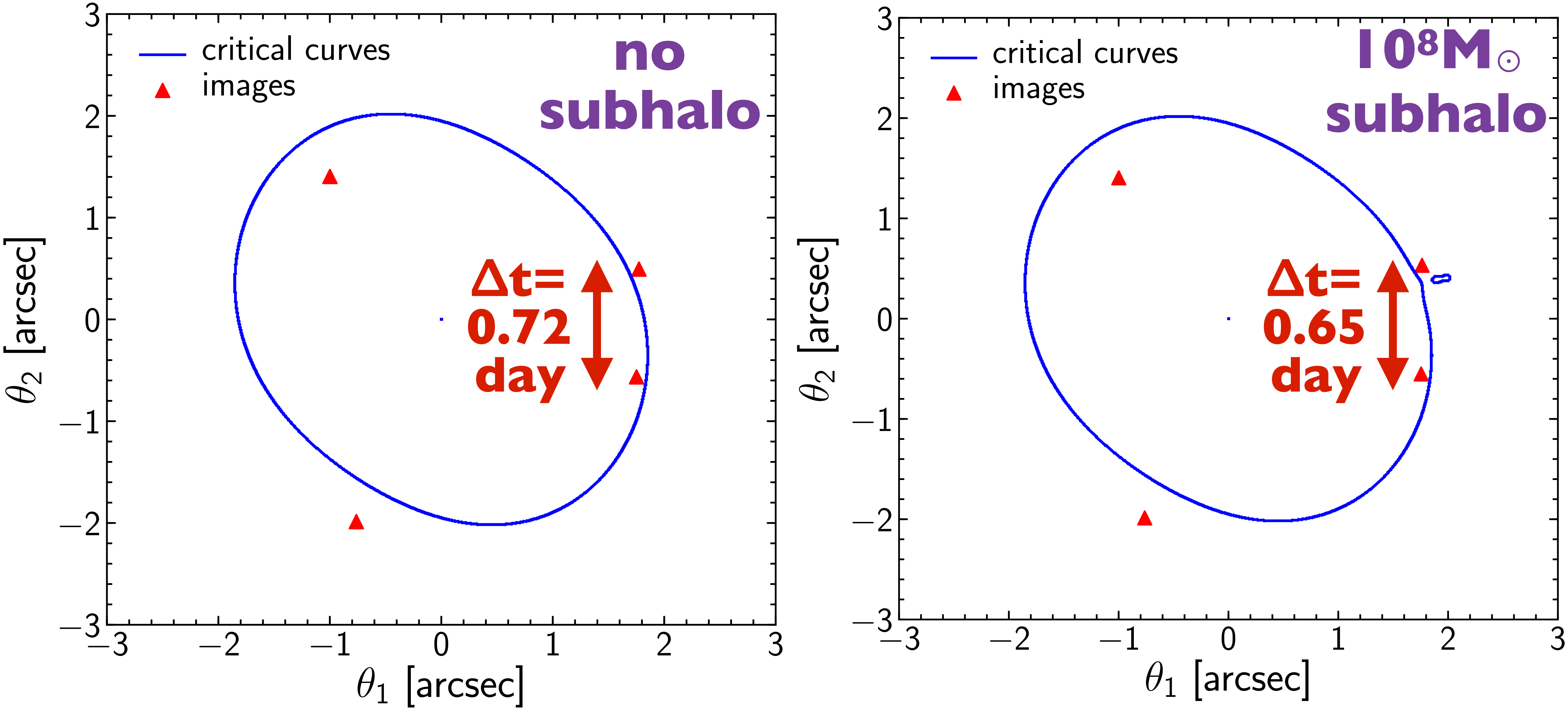


w/o SN images

simulated by *glafic*

e.g., MO 2007; Keeton & Moustakas 2009; Liao+2018

Substructure and time delays

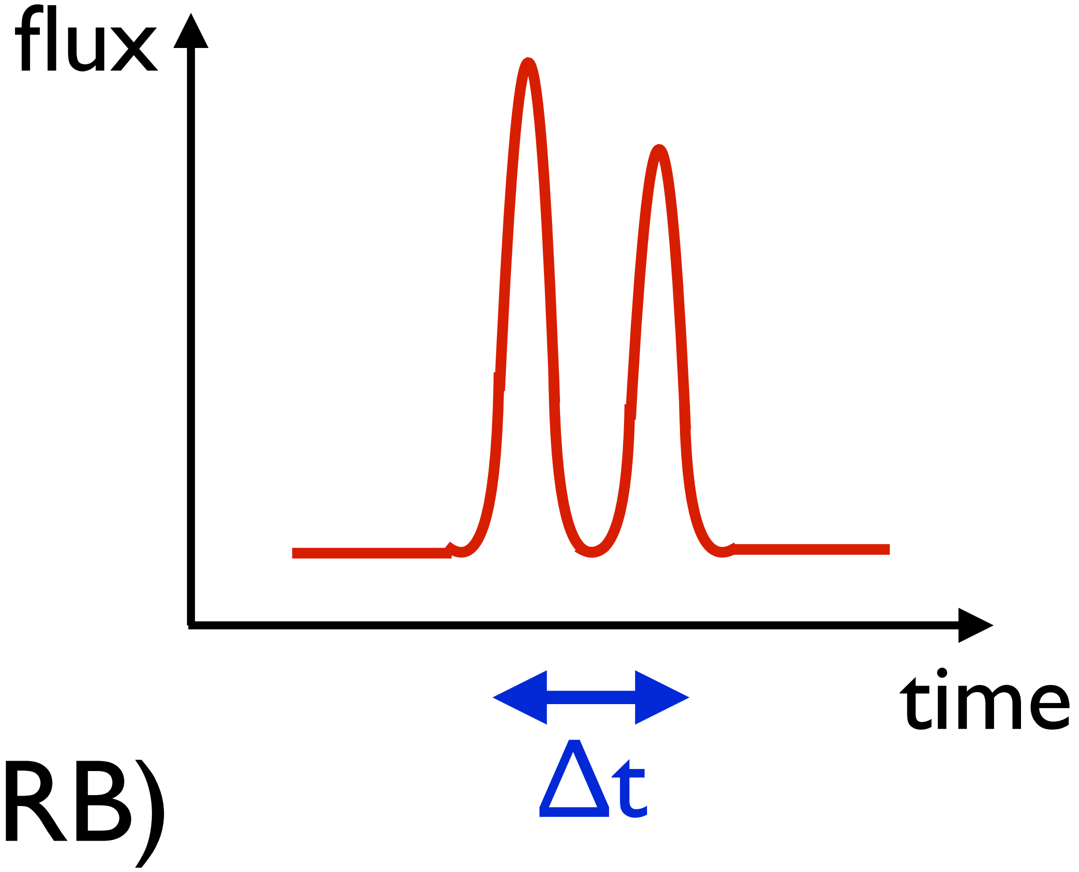


- substructure affect Δt, especially small ones
- can be easily detected by lensed GRB, FRB, GW

Searching for echo signals

- time delay for a point mass lens

$$\Delta t \sim 0.02 \ \mathrm{msec}\,(1+z_l)\left(\frac{M}{M_\odot}\right)$$



- **~msec transients** (e.g. FRB) can constrain **compact dark matter** with **$M \gtrsim 30\,M_\odot$** by searching for echo signals

(e.g., Munoz+2016)

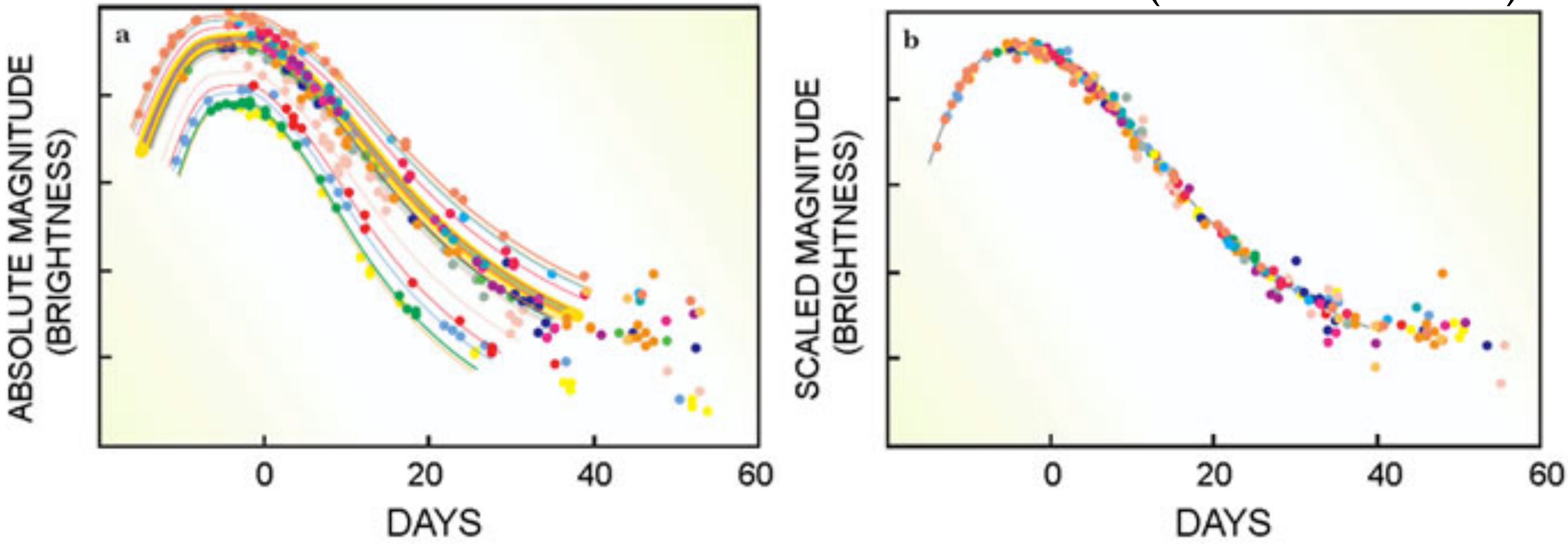
Advantages?

- simple and fast light curves
- standardizable candles
- wave effect?

Type Ia supernovae

- correlation between peak luminosities and width of light curves
- **standardizable candle** to measure $D_L(z)$

(from LBL website)



Gamma-ray bursts

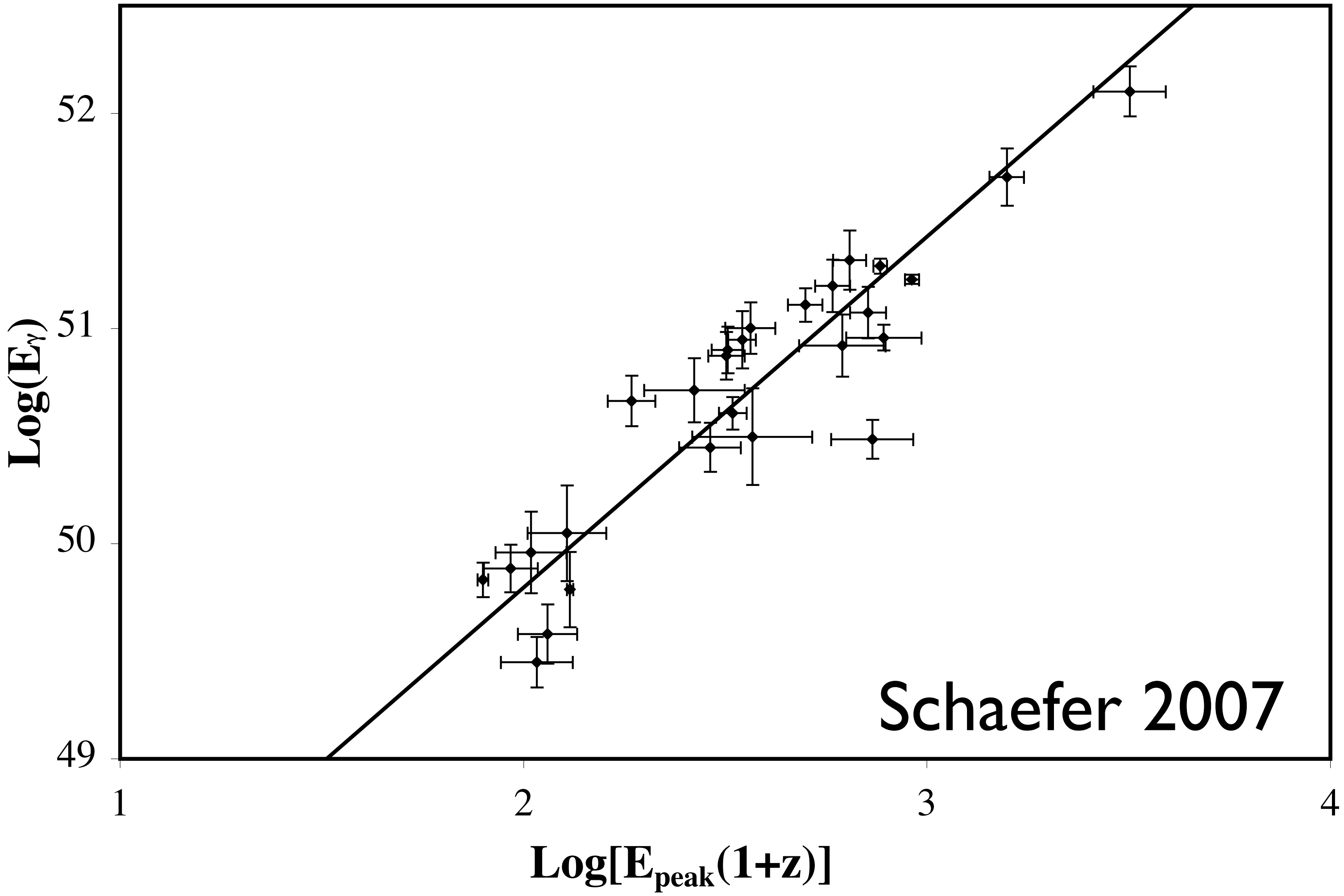
- several relations to measure $D_L(z)$ proposed

  E_{iso}-E_{peak} (Amati+2002)

  L_{peak}-E_{peak} (Yonetoku+2004)

  E_γ-E_{peak} (Ghirlanda+2004)

  …



Gravitational waves

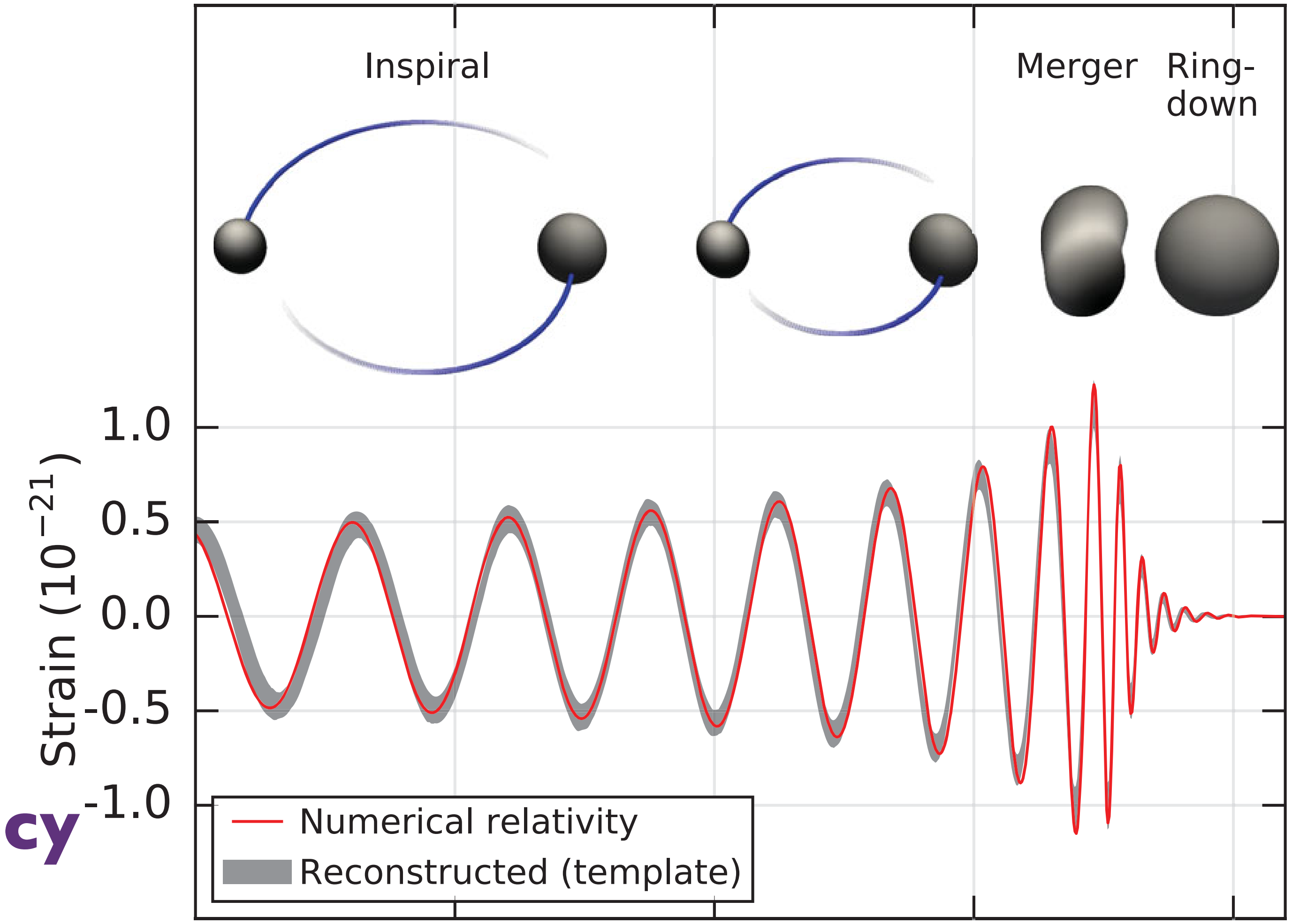
- direct measurements of D$_L$(z) from inspiral compact binaries (**standard siren**)

strain

$$h \propto \frac{M_z^{5/3}}{D_L(z)} f^{2/3}$$

$$\dot{f} \propto M_z^{5/3} f^{11/3}$$

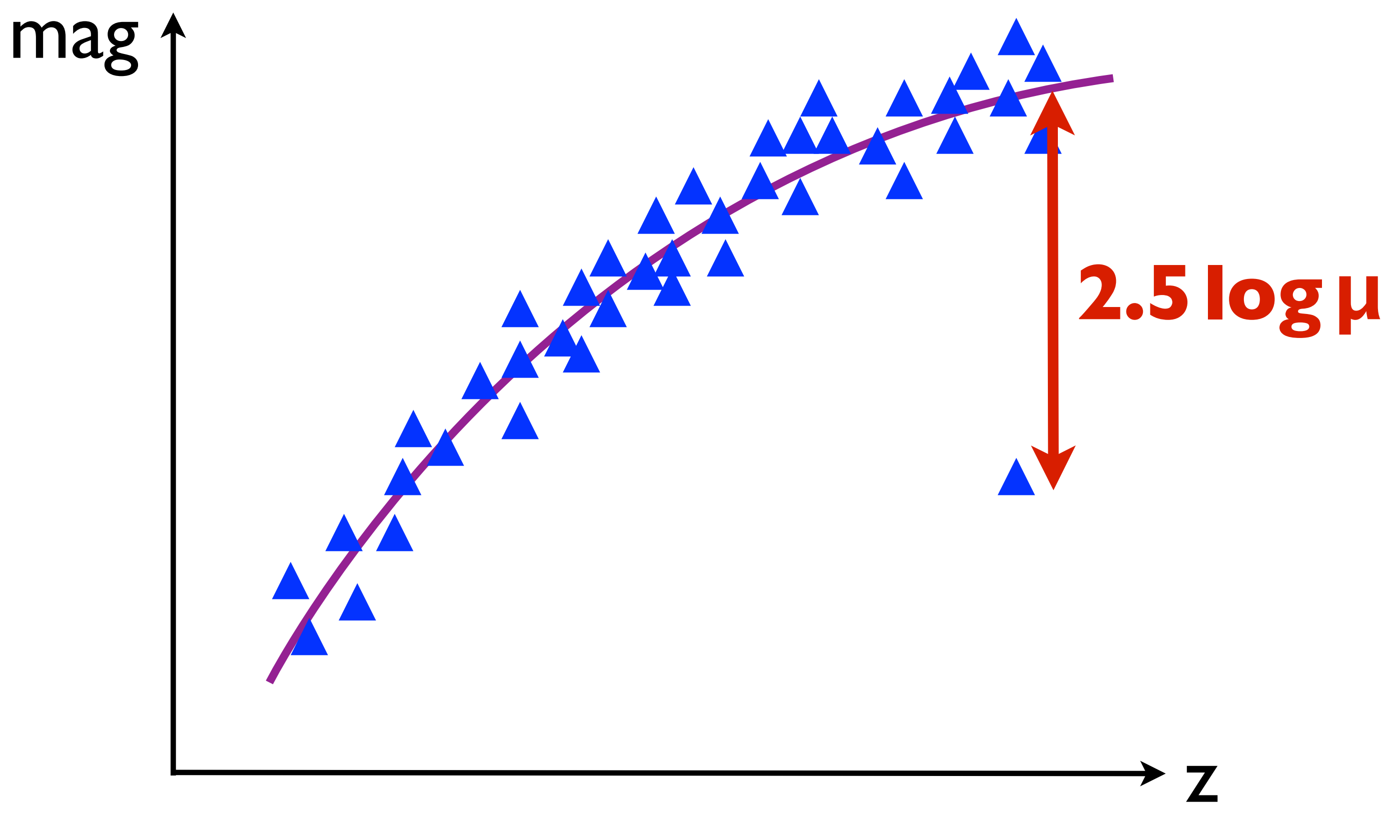
chirp mass **frequency**



Abbott+2016

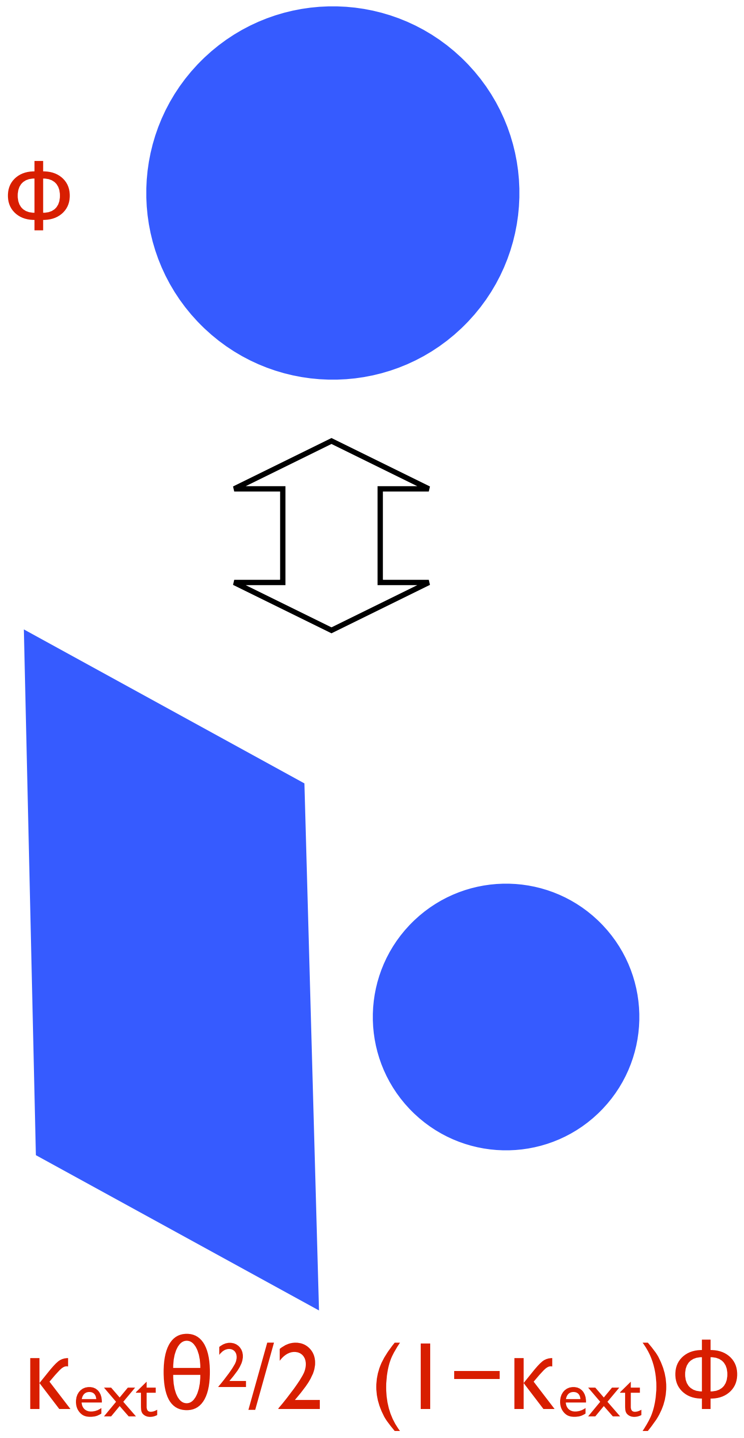
Strongly lensed standardizable candle

- direct measurement of **magnification factor μ**
- precious info that breaks various degeneracies



Kolatt & Bartelmann MNRAS **296**(1998)763

Breaking mass-sheet degeneracy



- mathematically exact degeneracy, image positions unchanged

$$\phi(\boldsymbol{\theta}) \to (1-\kappa_{\rm ext})\phi(\boldsymbol{\theta}) + \kappa_{\rm ext}\frac{\theta^2}{2}$$

lens potential

$$\boldsymbol{\beta} \to (1-\kappa_{\rm ext})\boldsymbol{\beta}.$$

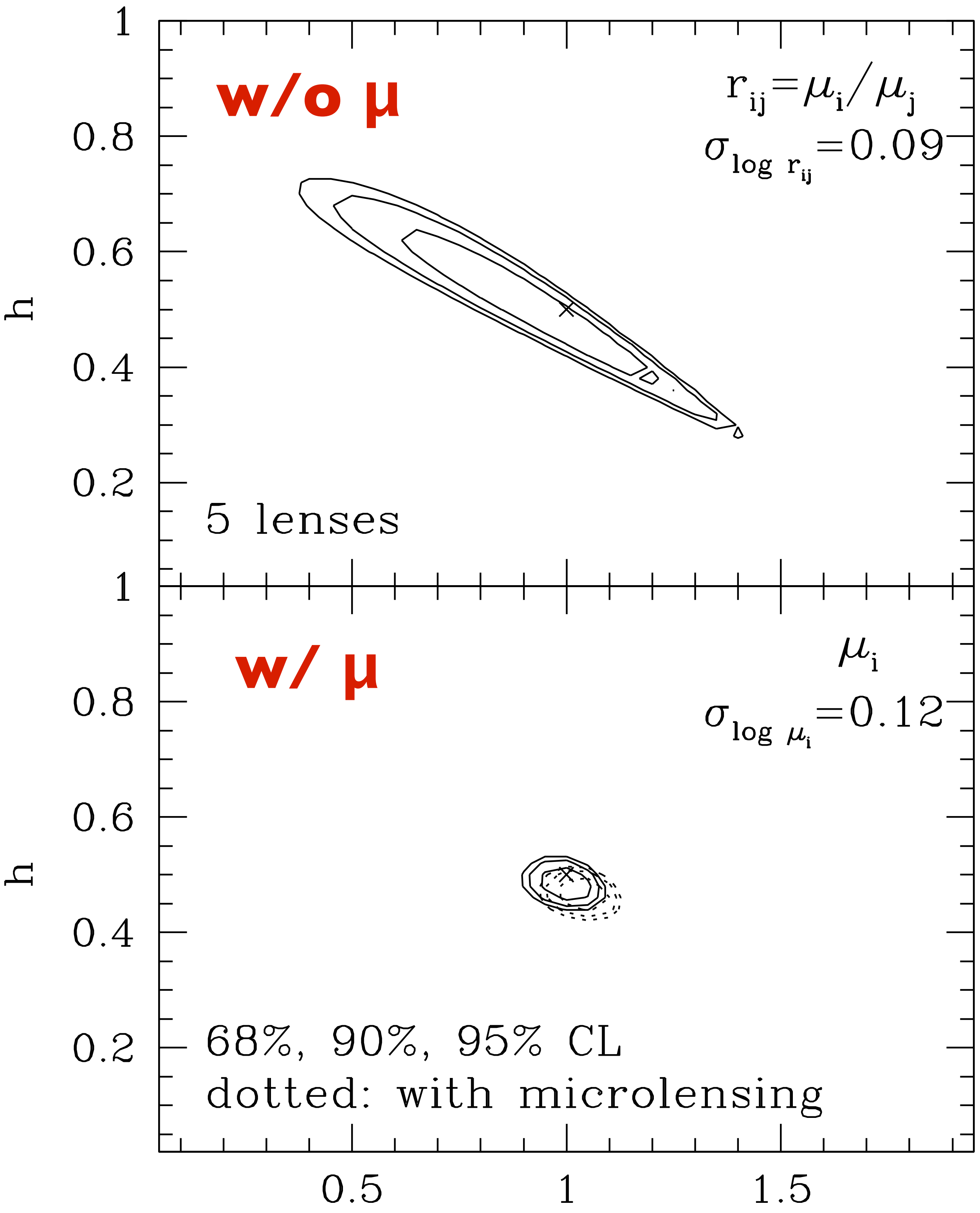
source position

- **measurement of μ breaks this degeneracy**

$$\mu \to (1-\kappa_{\rm ext})^{-2}\mu$$

MO & Kawano MNRAS **338**(2003)L25

Breaking slope-H_0 degeneracy



dimensionless Hubble constant $h=H_0/100$km/s/Mpc

radial slope β [$\rho(r) \propto r^{\beta-3}$]

- H_0 from time delays vs radial density slope
- approx. degeneracy due to mass-sheet degeneracy
- **measurement of μ break degeneracy**

Advantages?

- simple and fast light curves
- standardizable candles
- wave effect?

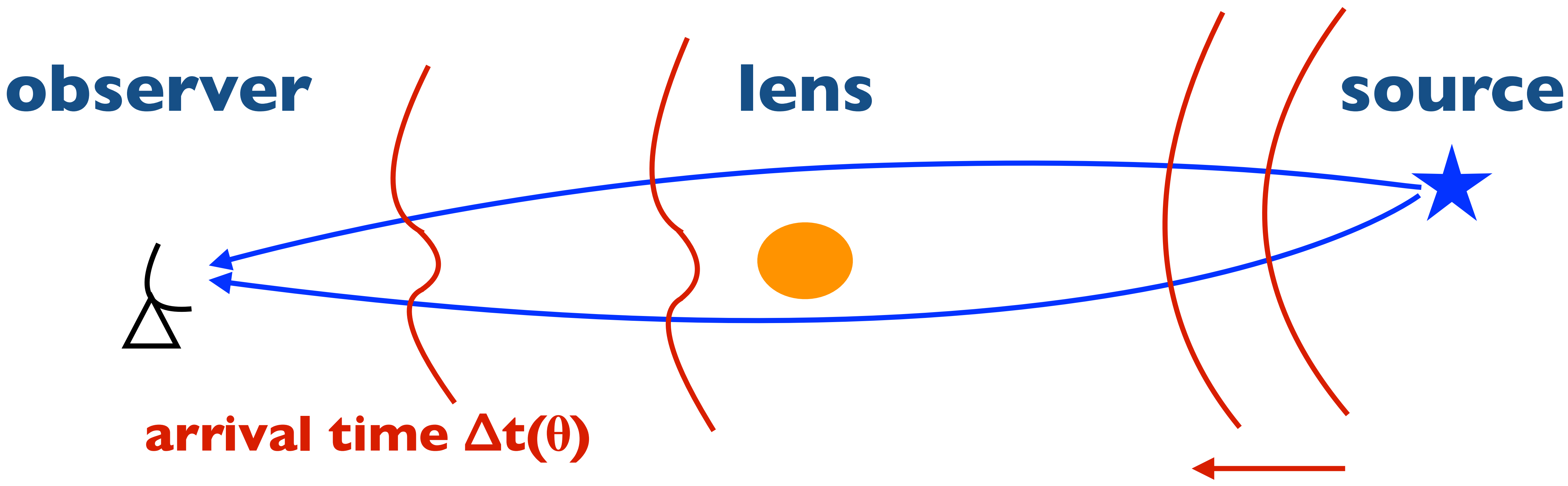
e.g., Schneider+1992; Nakamura & Deguchi 1999

Wave optics effect

- in most cases, we can safely assume **geometric optics** for calculating lensing effects
- **geometric optics** is λ→0 limit approximation of **wave optics** that is more fundamental
- **wave optics** effect can play an important role in some cases

Wave vs. geometric optics

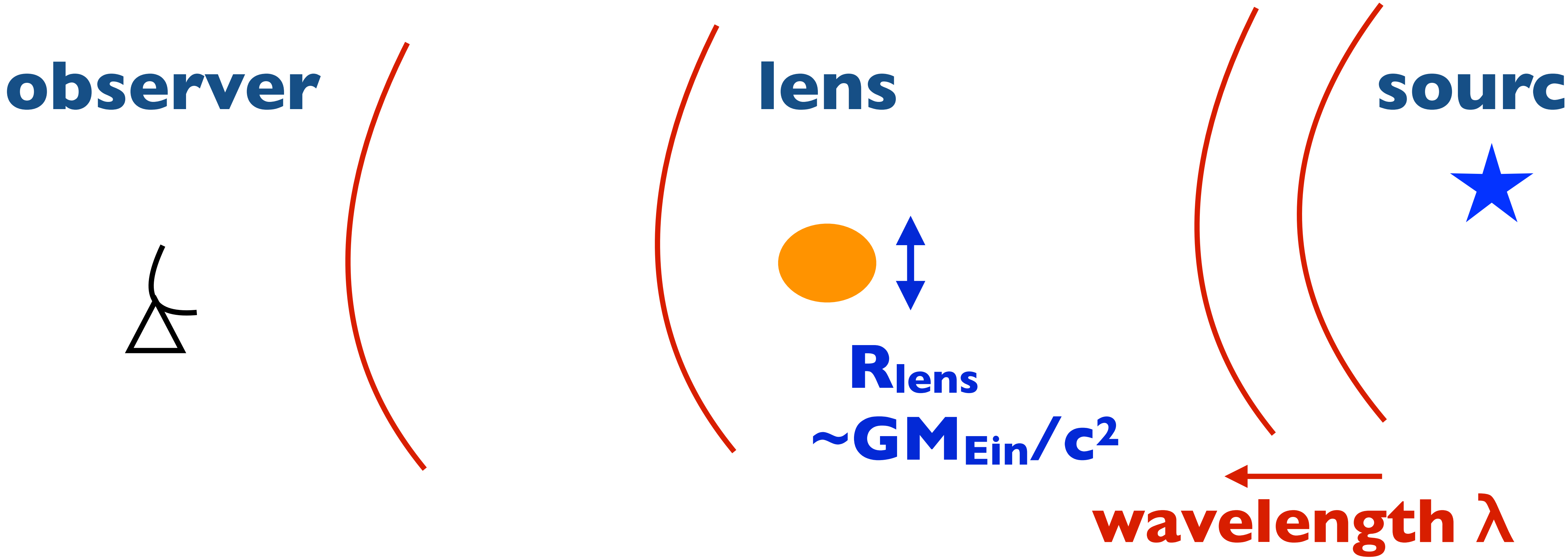
wave optics $\psi \propto \int d^2\boldsymbol{\theta}\, e^{2\pi i f \Delta t(\boldsymbol{\theta})}$



geometric optics $\nabla_{\boldsymbol{\theta}} \Delta t(\boldsymbol{\theta}) = 0$ (Fermat's principle)

Wave effect: Diffraction

- when **$\lambda \gg R_{lens}$** wave propagation is not affected by the lens
- no magnification, **$\mu \sim 1$**



observer

lens

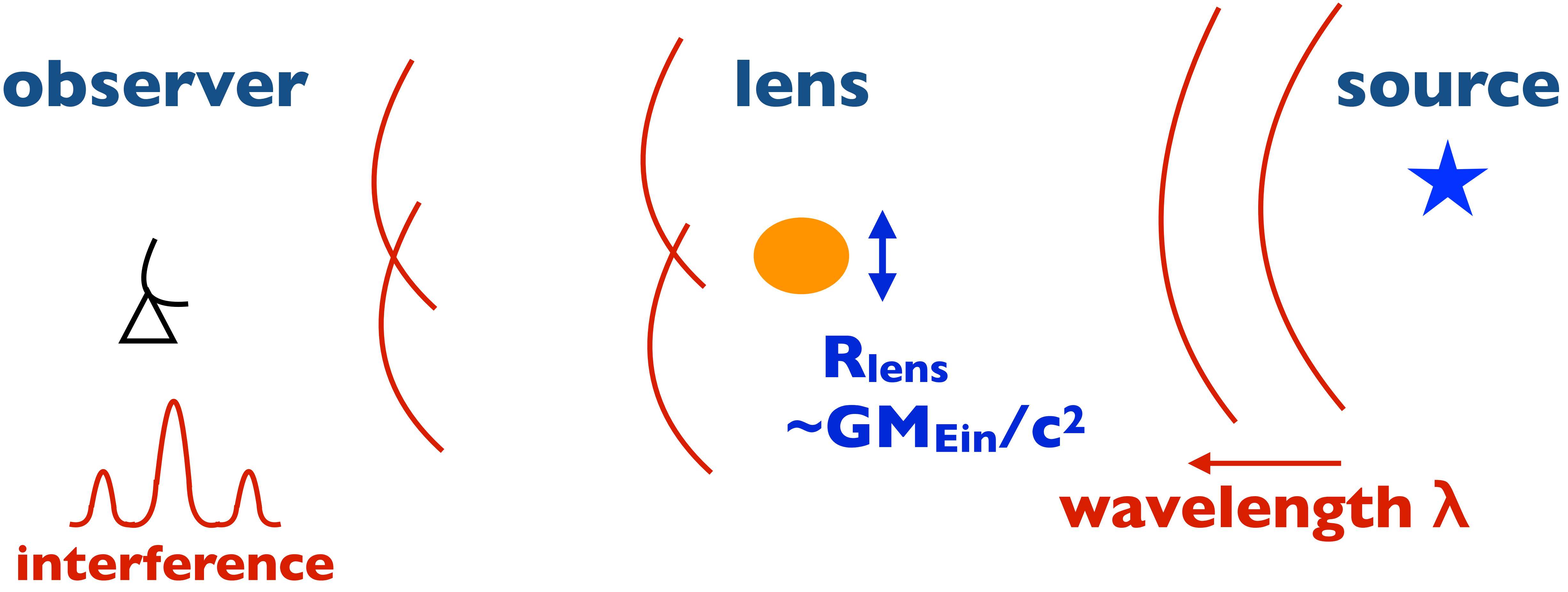
source

R_{lens}
$\sim GM_{Ein}/c^2$

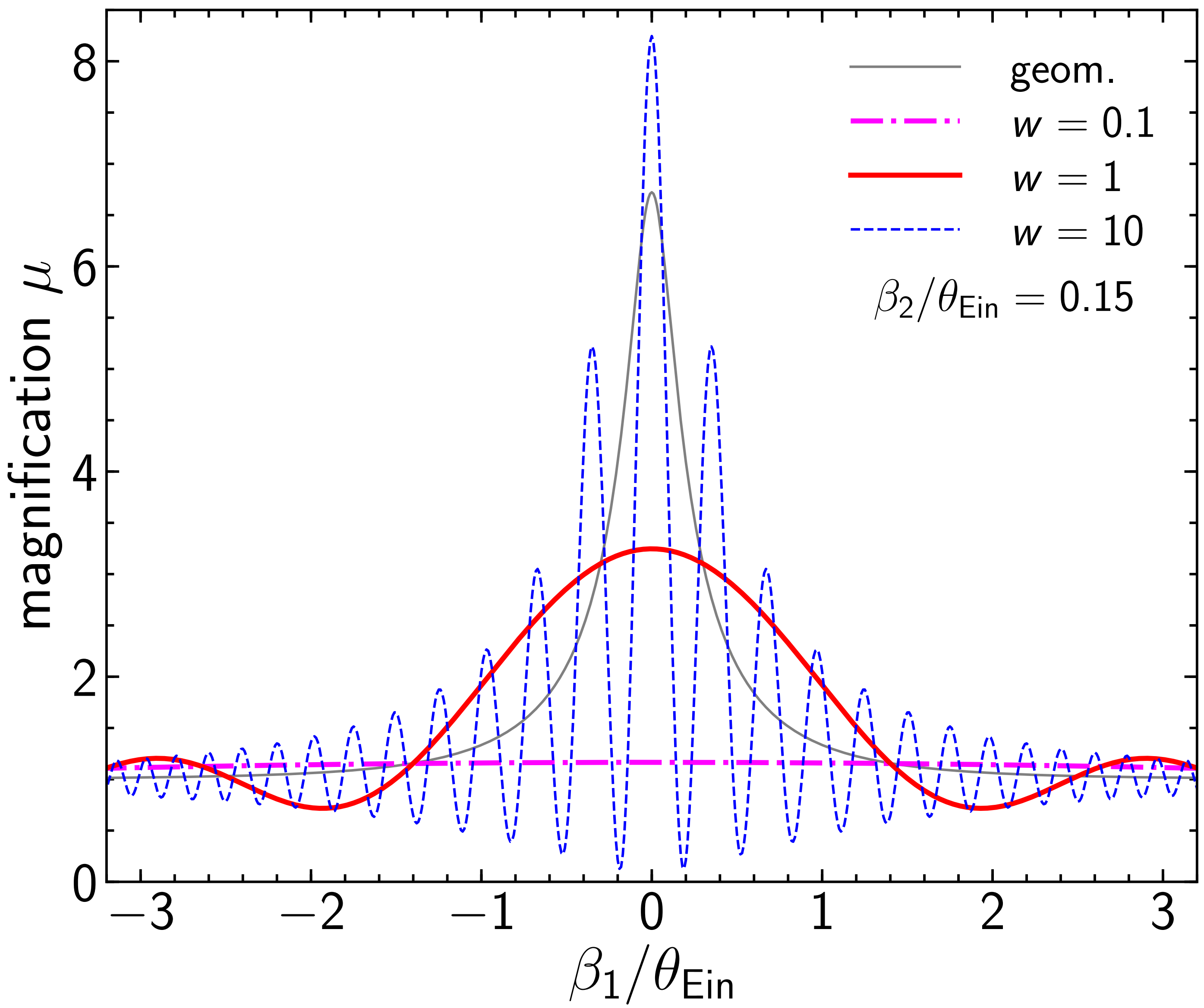
wavelength λ

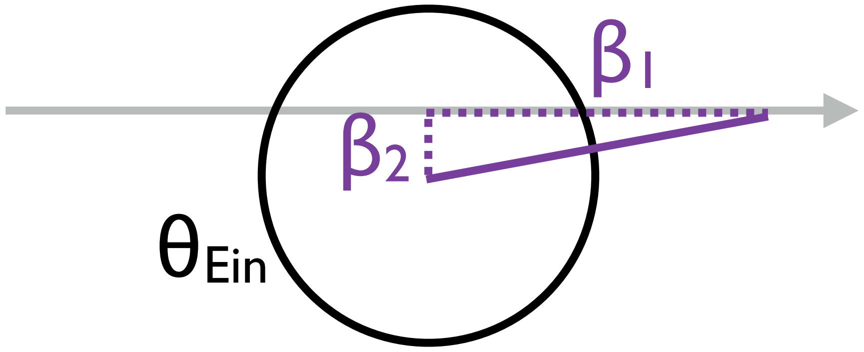
Wave effect: Interference

- when **$\lambda \lesssim R_{\rm lens}$** multiple light ray paths interfere
- magnification **oscillates** as a function of source position and wavelength



Magnification in wave optics





- parameter w controls wave effect

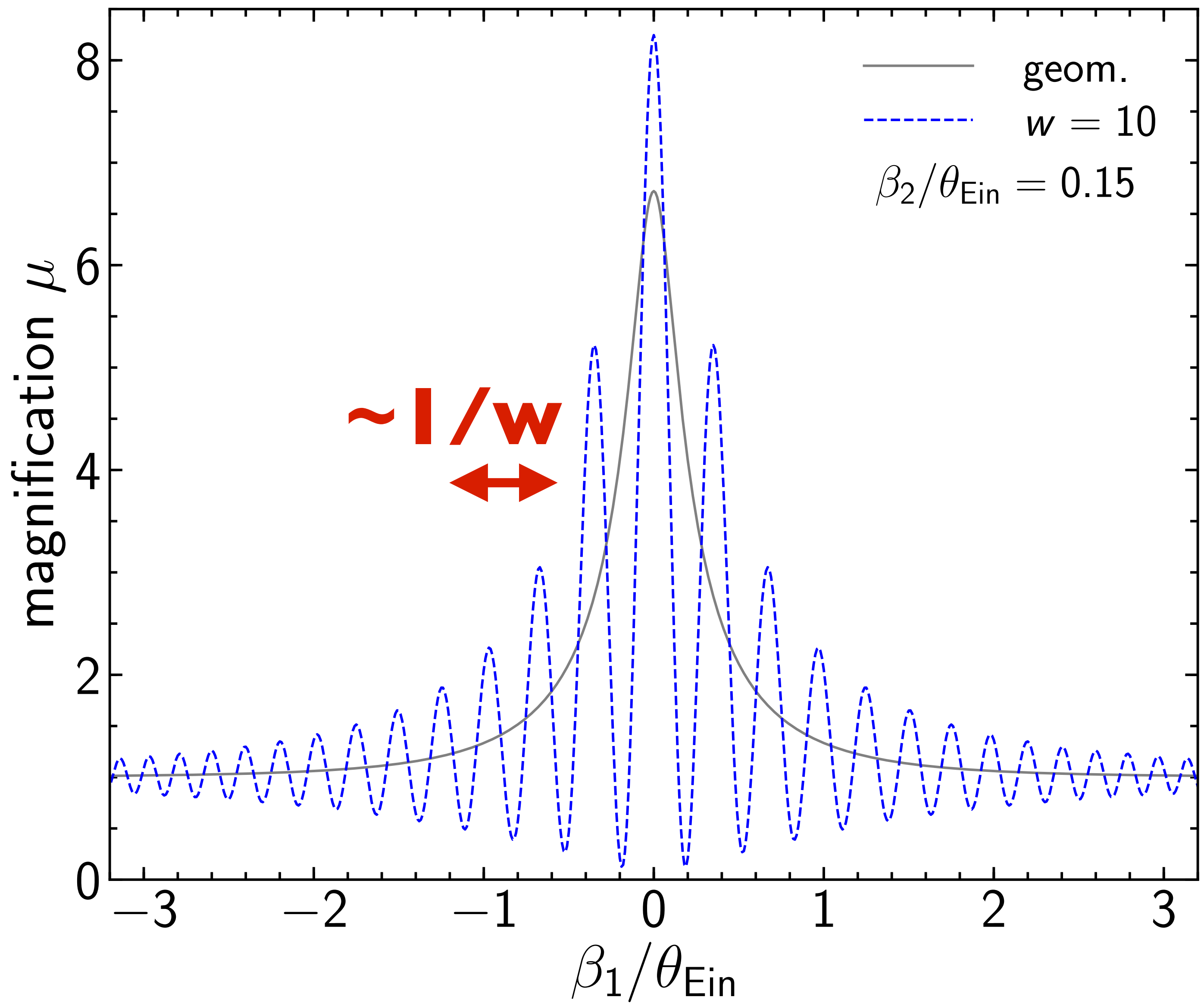
$$w \sim \frac{R_{\rm lens}}{\lambda}$$

gravitational radius

wavelength

- **diffraction** at w ≪ 1
- **interference** at w ≳ 1

Finite source size effect



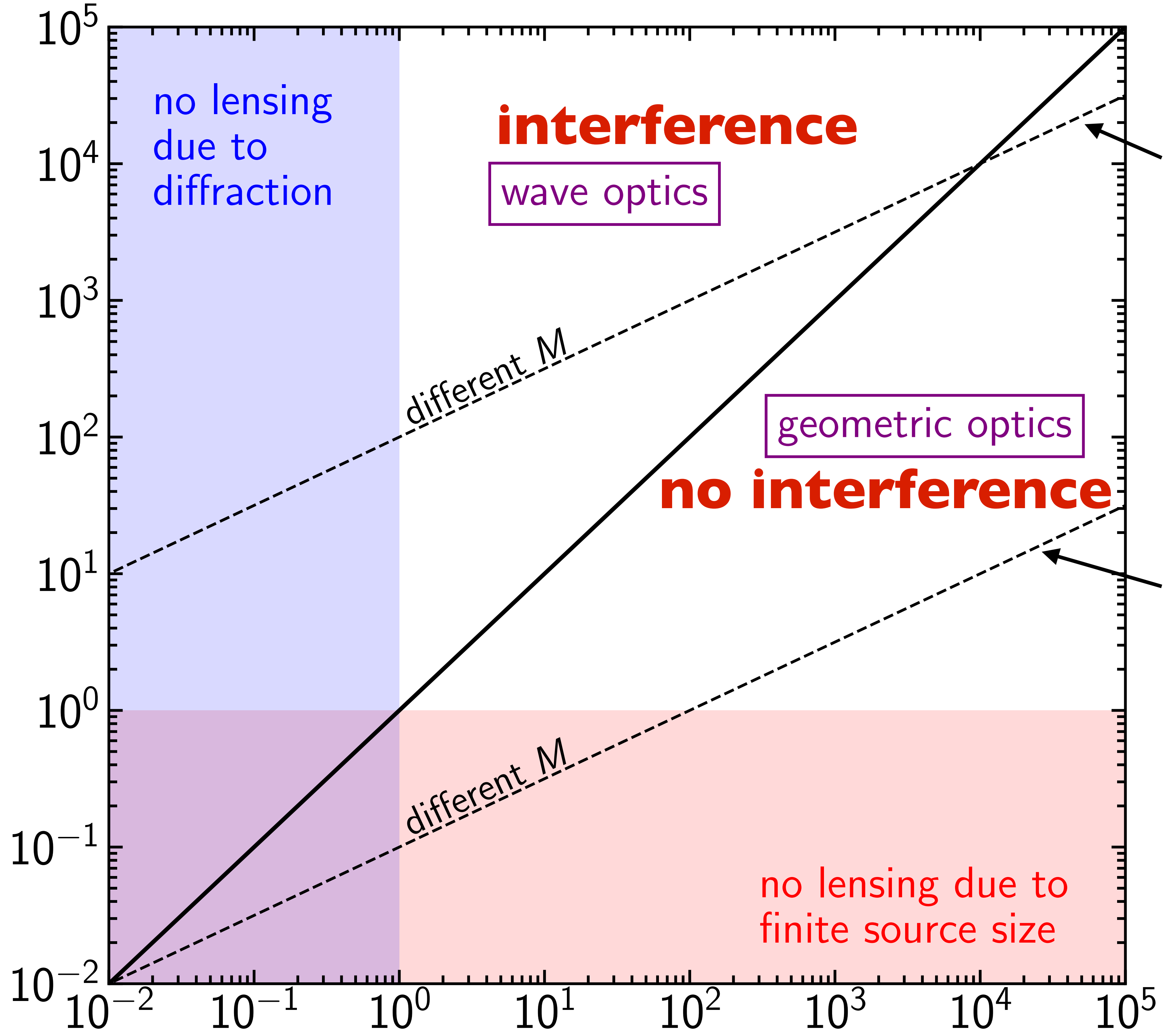
- source needs to be compact to observe interference pattern

$$\beta_{\mathrm{src}} \lesssim \frac{\theta_{\mathrm{Ein}}}{w}$$

$$w \sim \frac{R_{\mathrm{lens}}}{\lambda}$$

- at λ→0 we recover geometric optics

Can we observe wave effect?



Einstein radius/source size

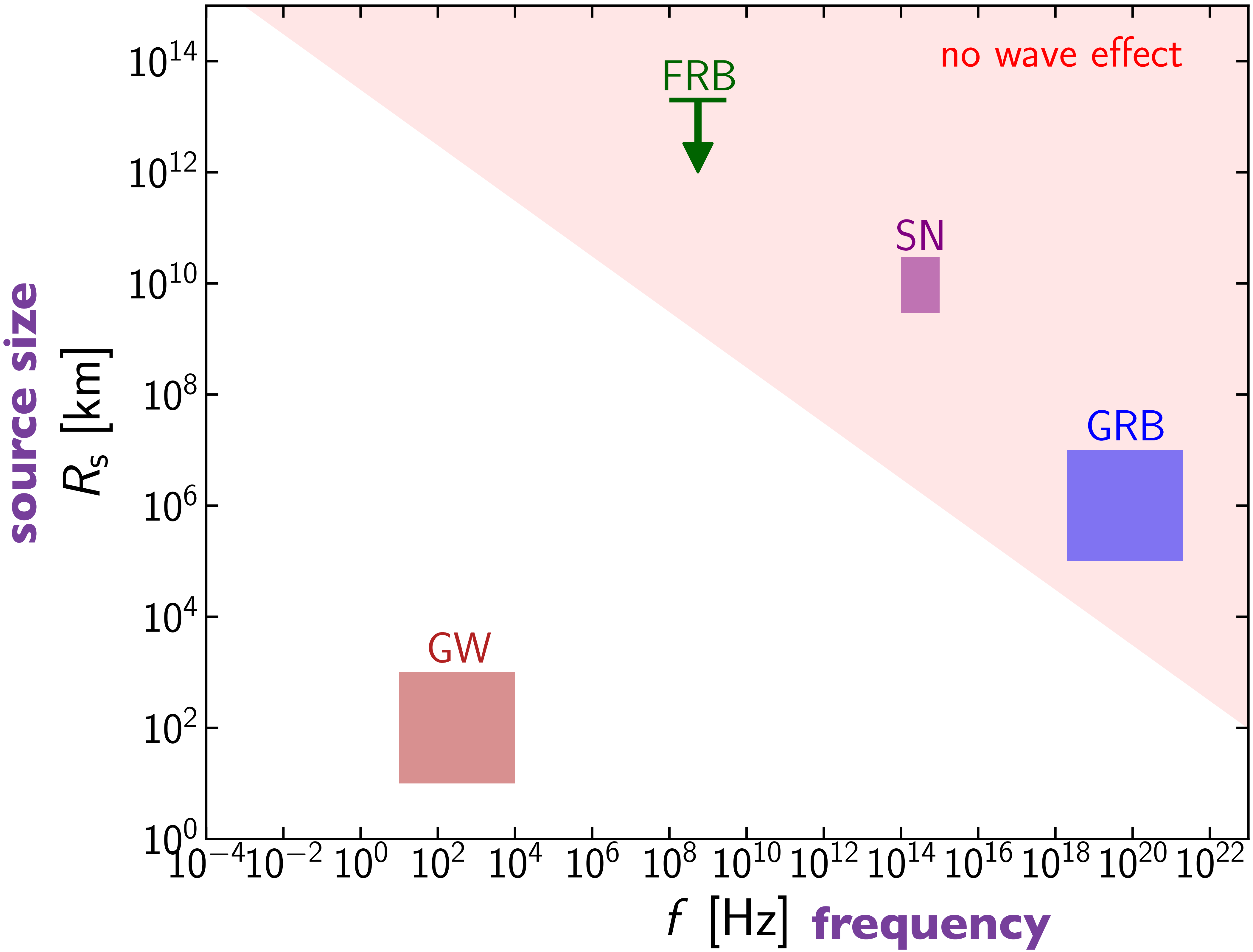
$1/\hat{\beta}_s = D_{os}\theta_{Ein}/R_s$

gravitational radius/wavelength w

wave effect may be observed

wave effect is never observed

Can we observe wave effect?



Can we observe wave effect?

- **gravitational waves (LIGO band)**
  point mass lens w/ $M_{\rm lens} \sim 10^2 M_\odot$ (Nakamura 1998)
  subhalo lensing w/ $M_{\rm Ein} \sim 10^2 M_\odot$ (Dai+2018)
  microlensing in high μ region (Diego+2019)

- **gravitational waves (LISA band)**
  galaxy lens w/ $M_{\rm Ein} \sim 10^7 M_\odot$ (Takahashi+2003)

- **fast radio bursts**
  point mass lens w/ $M_{\rm lens} \gtrsim 10^{-5} M_\odot$ (Zheng+2004)

Can we observe wave effect?

- **gr**
  po
  ura 1998)
  su
  m
- **gr**
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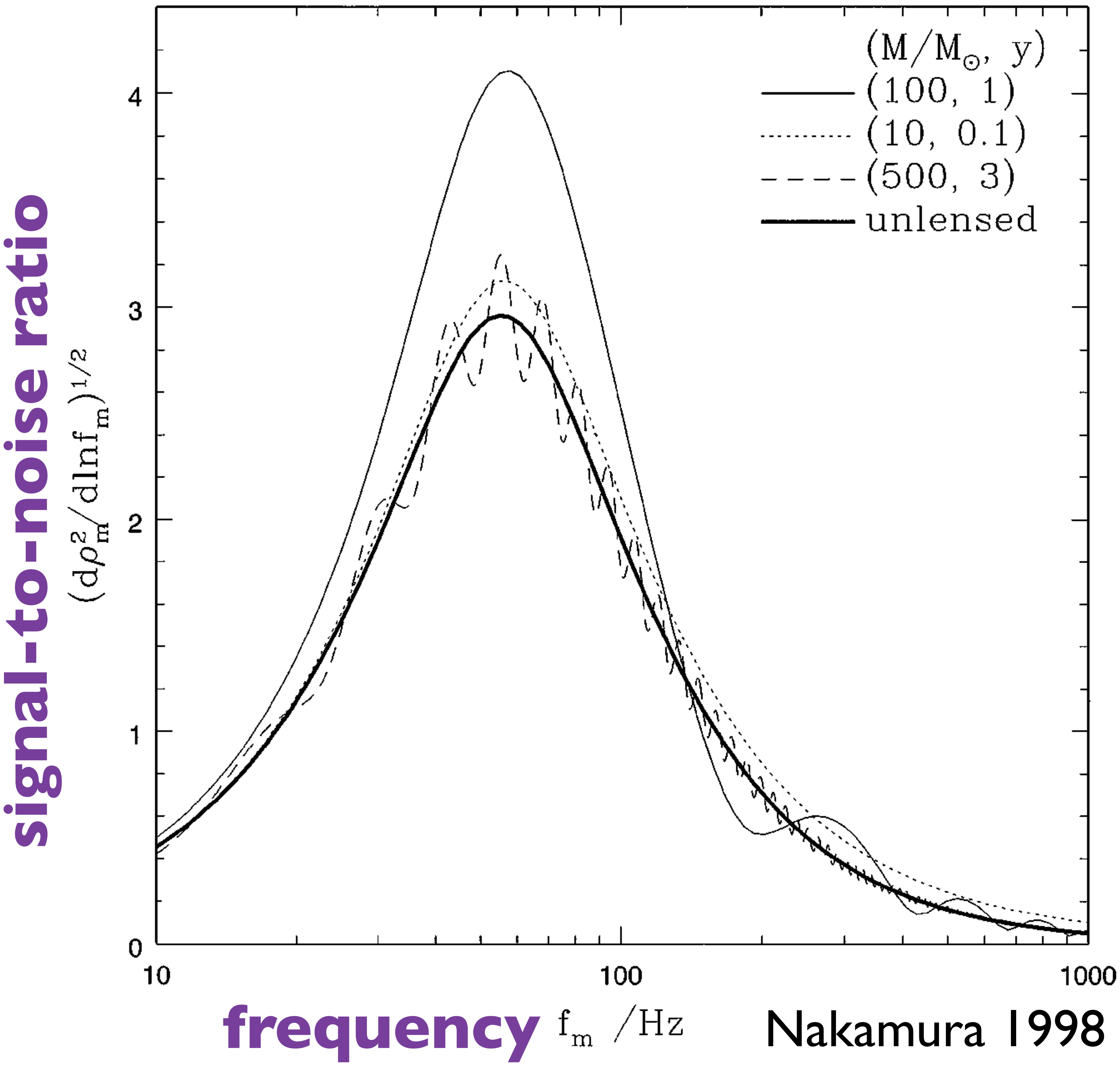
  2004)

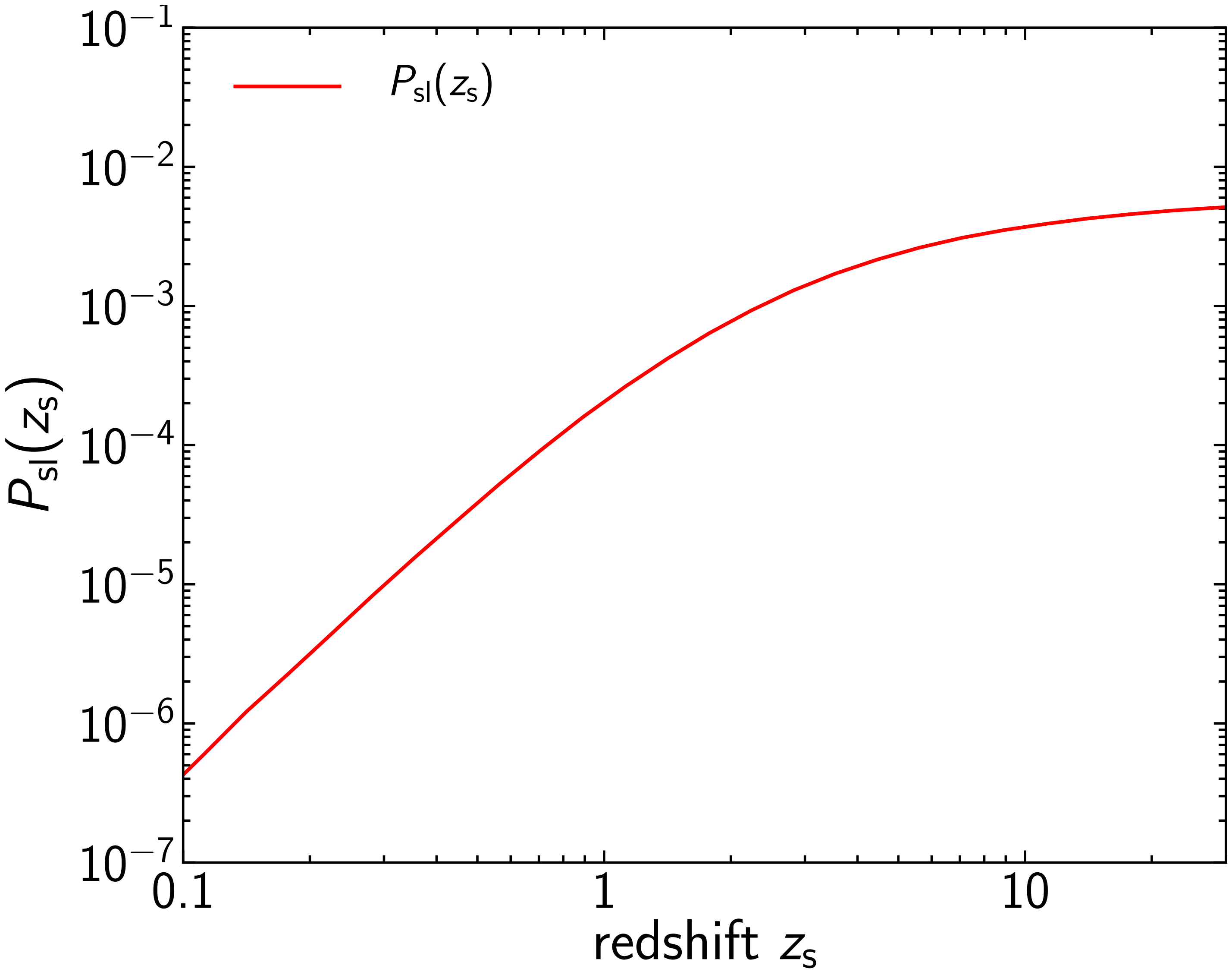


Nakamura 1998

Future detectability?

- supernova (SN)
  PS1-10afx, **SN Refsdal**, **iPTF16geu**
- gamma-ray burst (GRB)
  not yet
- fast radio burst (FRB)
  not yet
- gravitational wave (GW)
  not yet

Strong lensing probability



- steep function of redshift at low-z
- to observe strong lensing events:

reach out to z~O(1)

detect O(10^3) events

- **GRB**, **FRB**, **GW** satisfy these criteria in near future

Properties of first SN lens events

name	redshift	μ_{tot}	θ_{max}	discovery
PS1-10afx	1.388	~31	<0.4″	survey
SN Refsdal	1.49	~74	32″	targeted
iPTF16geu	0.409	~52	~0.6″	survey

- galaxy-scale lenses for those discovered in wide-field surveys
- **magnifications tend to be high, $\mu_{tot} \gtrsim 30$**

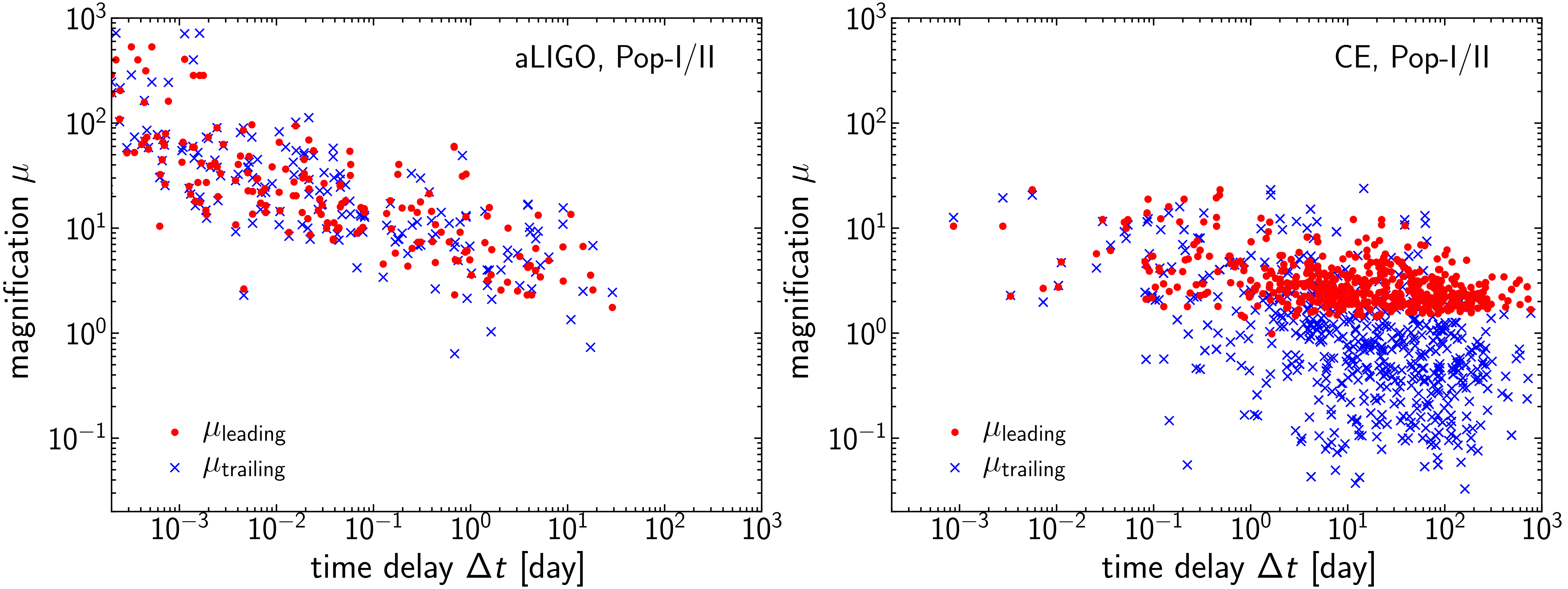
Selection effect

- at low-z, strong lensing probability is a steep function of redshift
- higher chance of observing highly magnified high-z events than moderately magnified low-z events
- therefore, in **shallow surveys** (**$z_{\mathrm{lim}} \lesssim 1$**), we tend to observe highly magnified strong lens events

(→ **first discoveries of lensed FRB, GW?**)

MO MNRAS **480**(2018)3842

Example: lensed GWs



- **advanced LIGO** highly magnified pair events with $\Delta t \lesssim 1$ day
- **Cosmic Explorer** pairs with modest μ and $\Delta t \sim 10$-100 days

Summary

- **strong lensing of explosive transients is next frontier!**
  - very accurate Δt for better constraints on cosmology and small-scale structure
  - make use of standardizable candle nature
  - possibility of observing wave effect
- first discoveries coming soon
- for more details, see **arXiv:1907.06830**