# Gravitational waves in the inhomogeneous Universe

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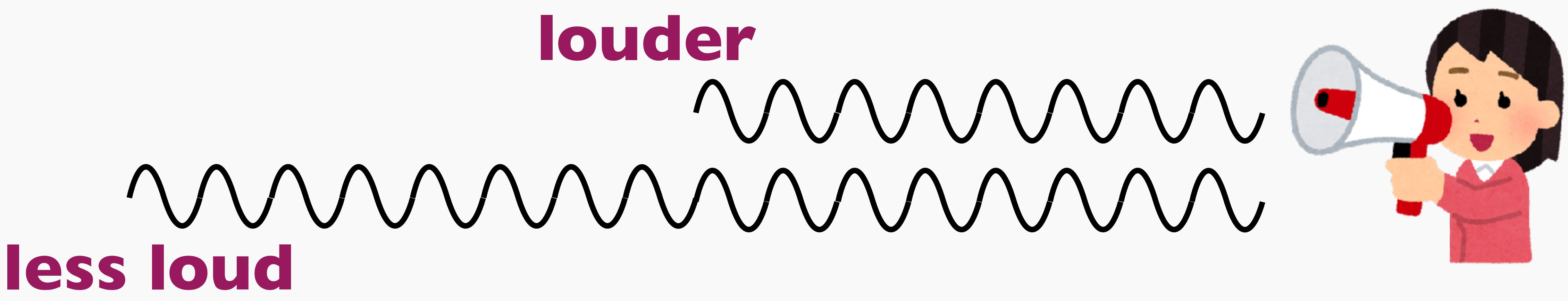
# Plan of this talk

- standard siren without redshift info with cross-correlation approach
  [MO Phys. Rev. D **93**(2016)083511]

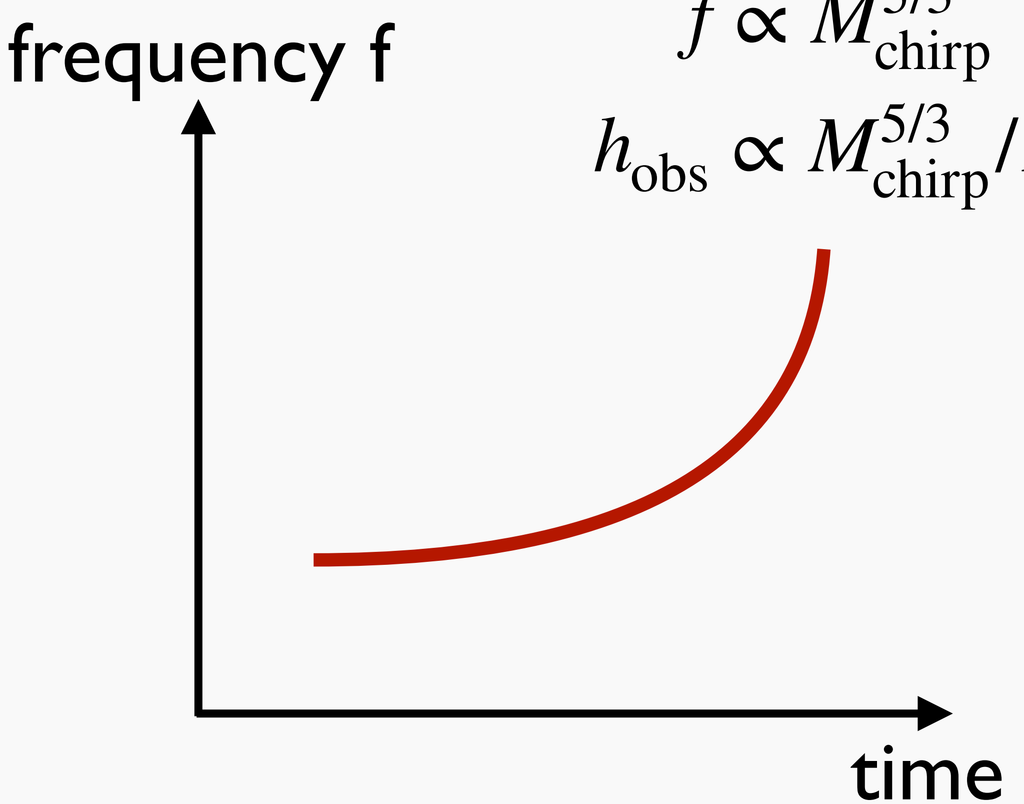
- effect of gravitational lensing on the distribution of binary black hole mergers
  [MO MNRAS **480**(2018)3842]

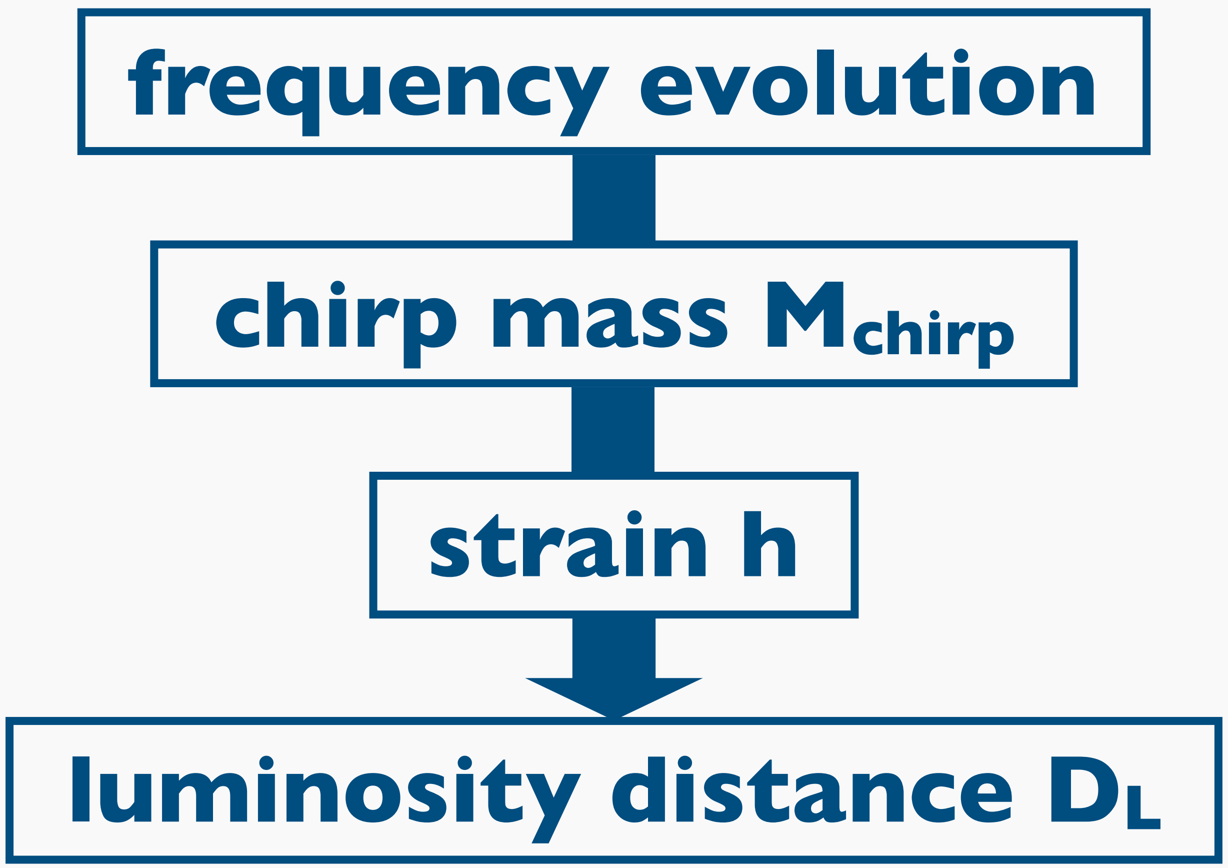
# Gravitational wave standard sirens




$$\dot{f} \propto M_{\rm chirp}^{5/3}$$

$$h_{\rm obs} \propto M_{\rm chirp}^{5/3}/D_{\rm L}$$




proposed by Schutz (1986), first demonstrated with GW170817

# Extracting cosmological info

- need **redshift**

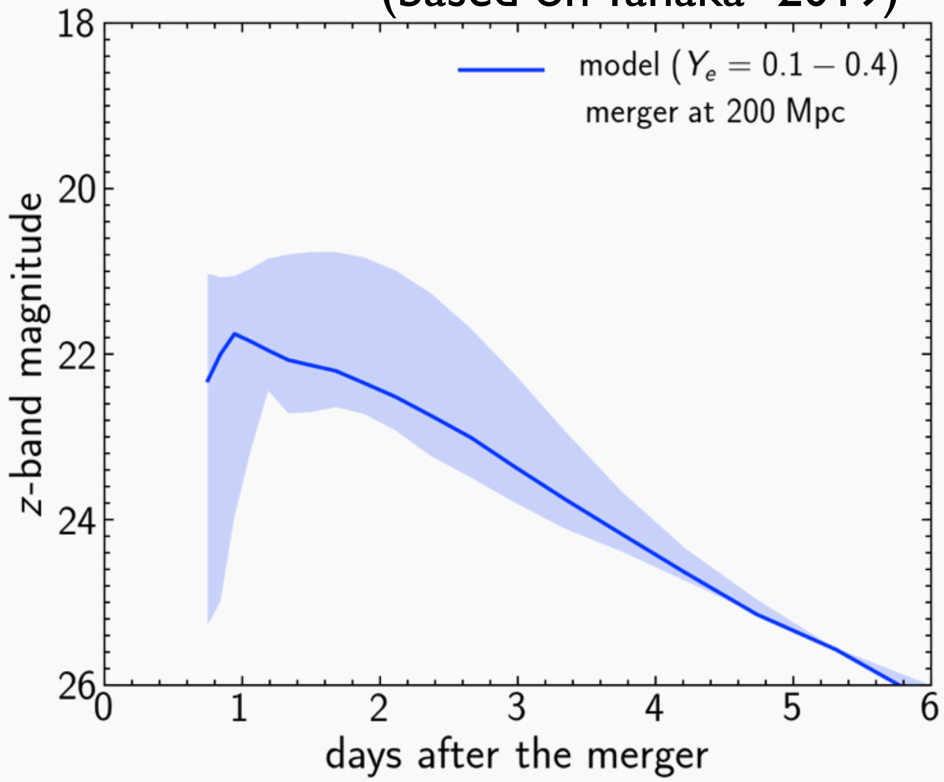
**luminosity distance $D_L$**
**from gravitational waves**

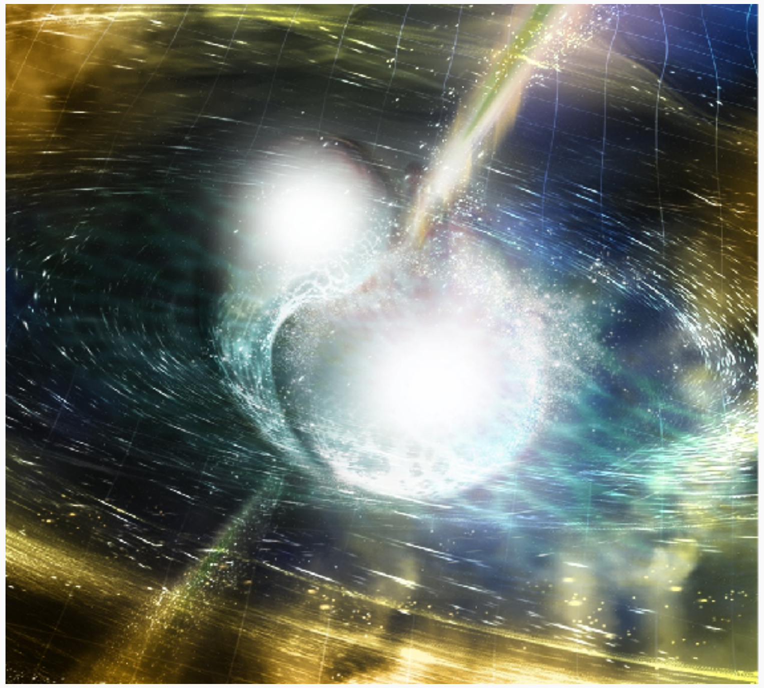
$D_L(z) \rightarrow H_0, \ldots$

**redshift z**
**from electromagnetic (EM) counterparts/host galaxy**

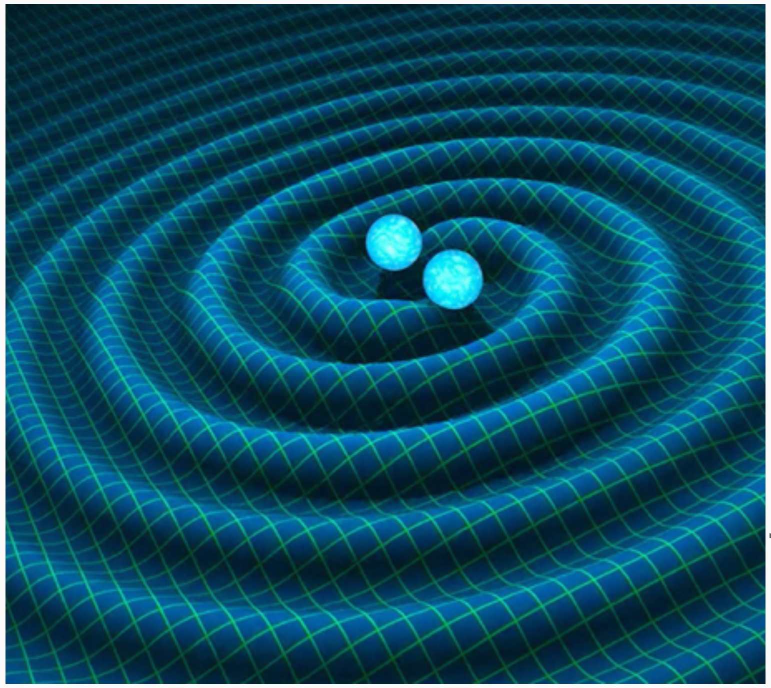
# Future?

(based on Tanaka+2019)



NSF/LIGO/SSU/A. Simonnet



R. Hurt/Caltech-JPL/EPA

**kilonova**
is faint

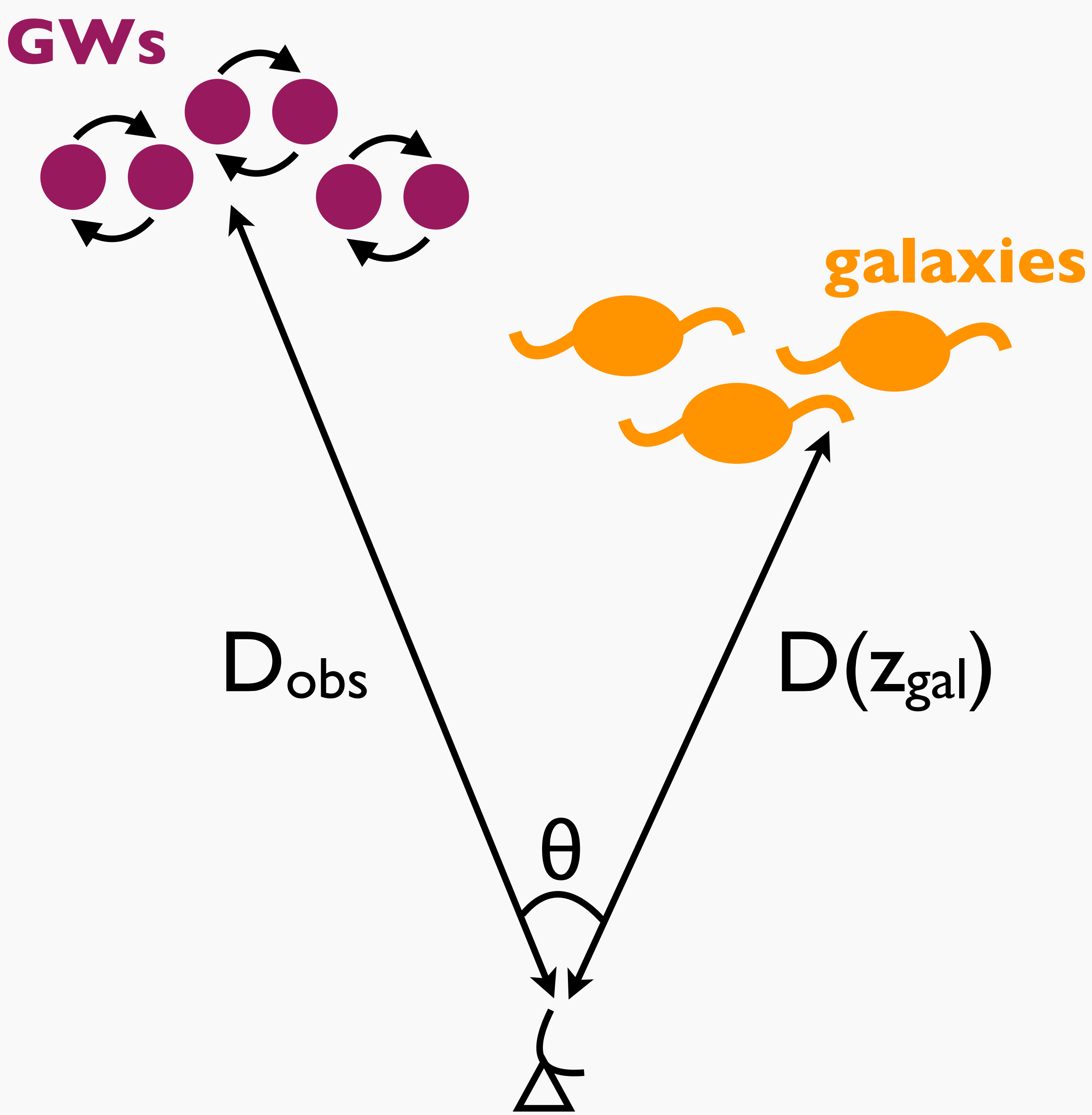
**short GRB**
observed only on-axis
(e.g., Dalal+2006; Nissanke+2010)

**BH-BH merger**
has no EM counterpart?

# Cross-correlation approach

- I propose standard siren cosmology with **cross-correlation** of GW sources (**known $D_L$**) and galaxies (**known z**)
- no follow-up needed for GW sources

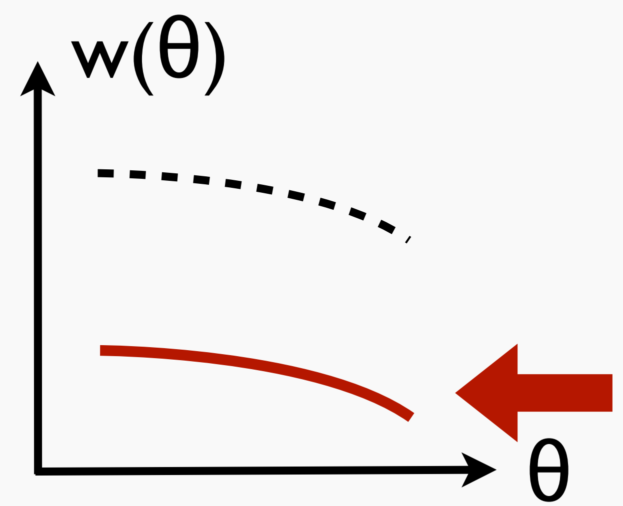
# Cross-correlation approach



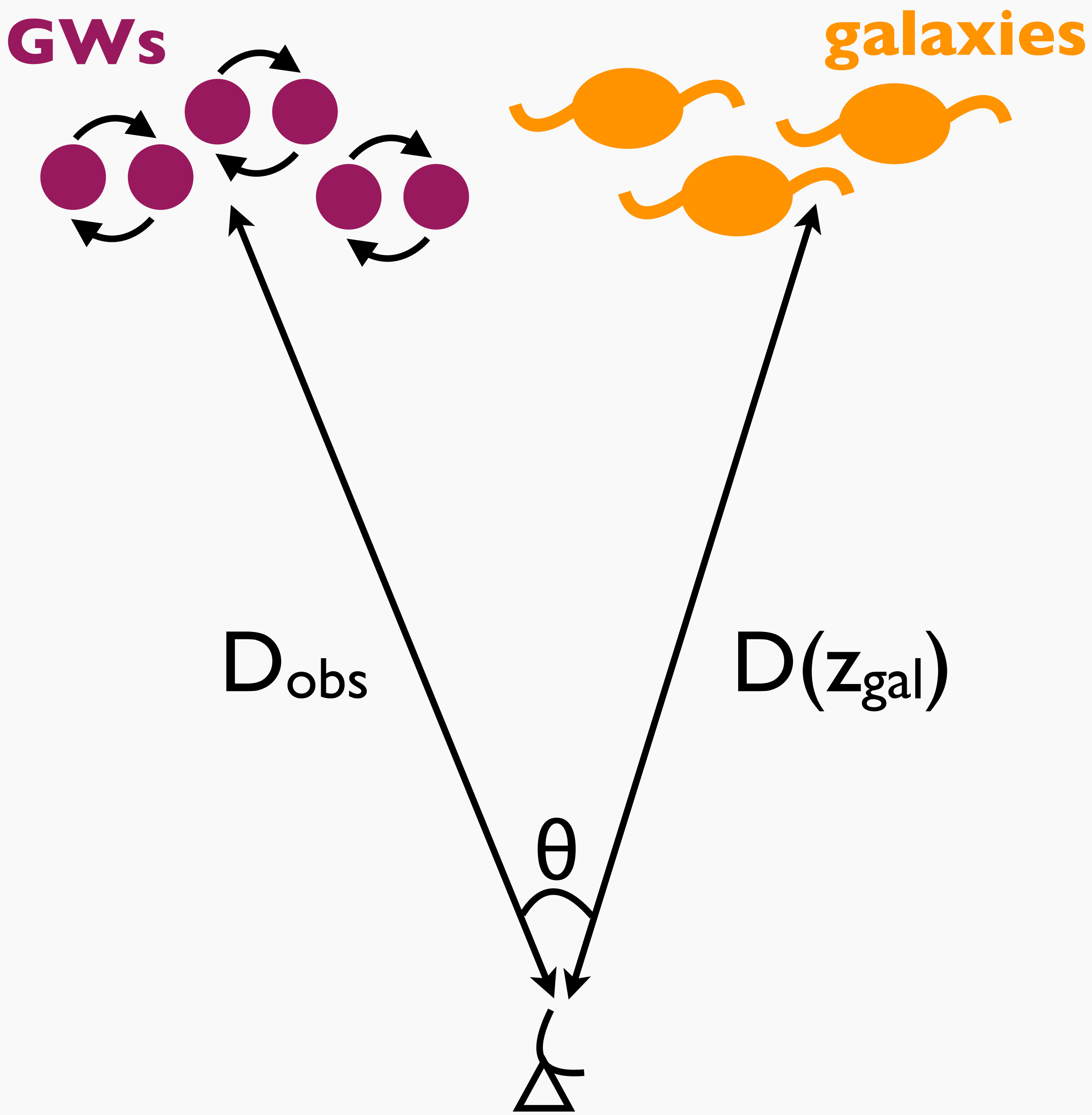

- cross-correlation of spatial distributions

$$w(\theta) = \langle \delta_{\rm GW}(\vec{\theta}')\delta_{\rm gal}(\vec{\theta}' + \vec{\theta})\rangle$$

- when **$D_{obs} > D(z_{gal})$** cross-correlation is **small**



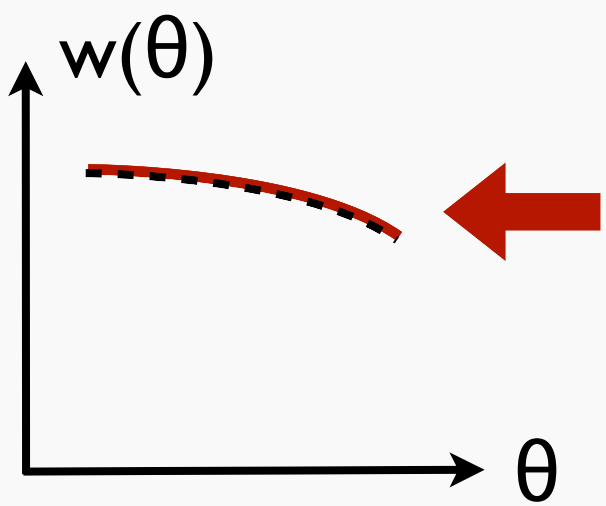
# Cross-correlation approach



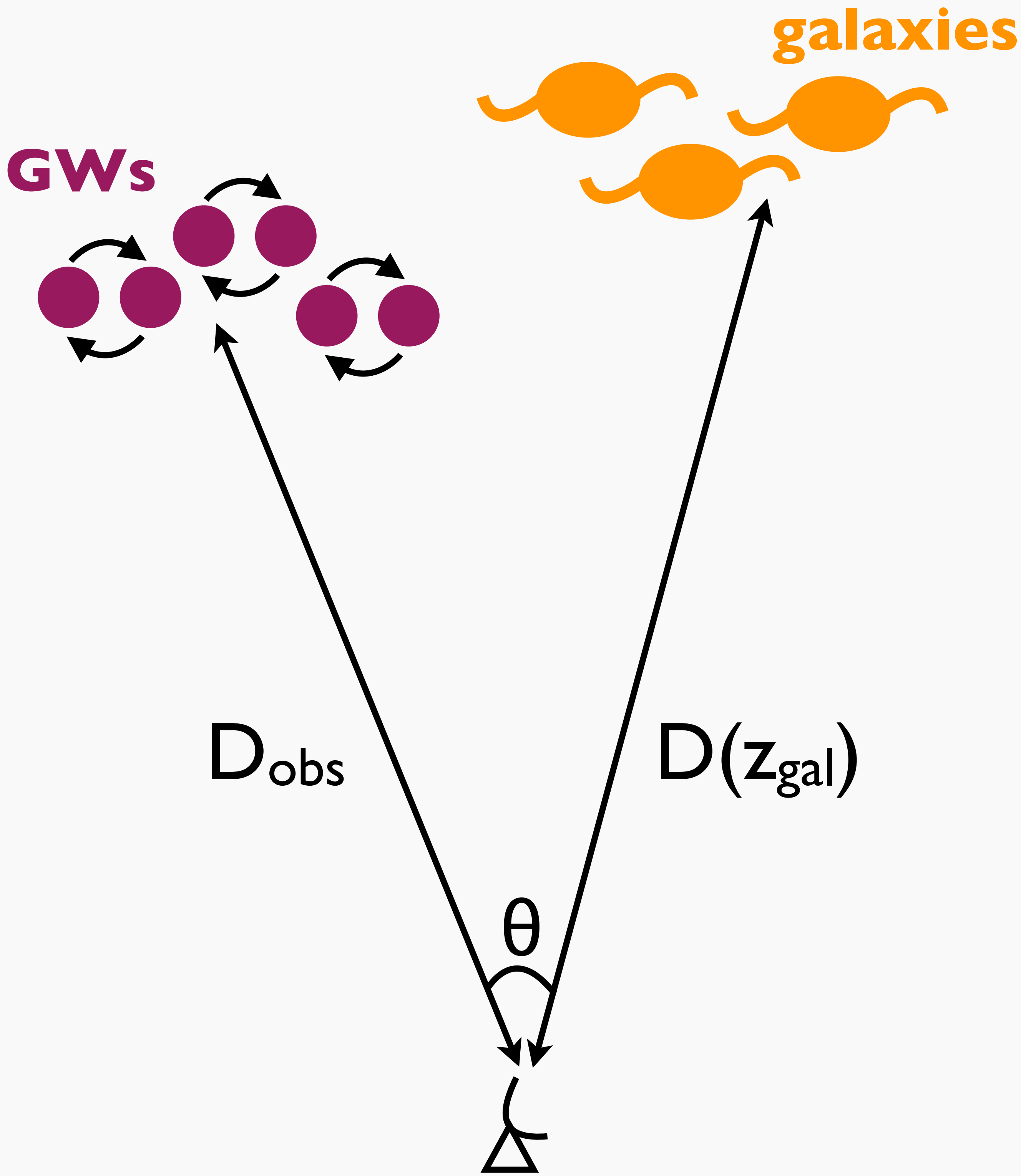

- cross-correlation of spatial distributions

$$w(\theta) = \langle \delta_{\rm GW}(\vec{\theta}')\delta_{\rm gal}(\vec{\theta}' + \vec{\theta})\rangle$$

- when **$D_{obs} \approx D(z_{gal})$** cross-correlation is **large**



# Cross-correlation approach

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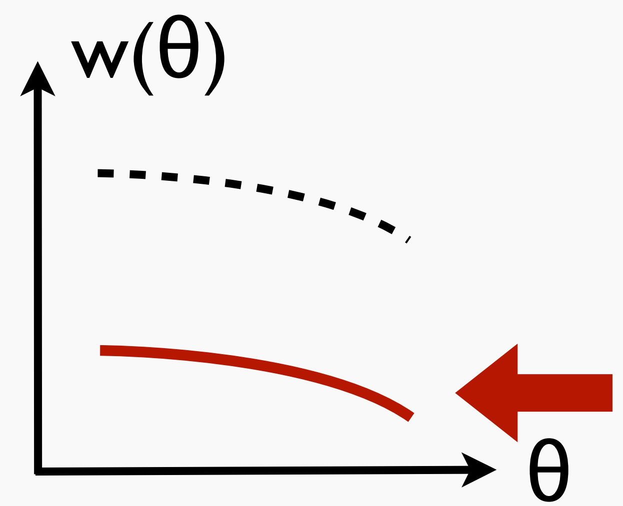
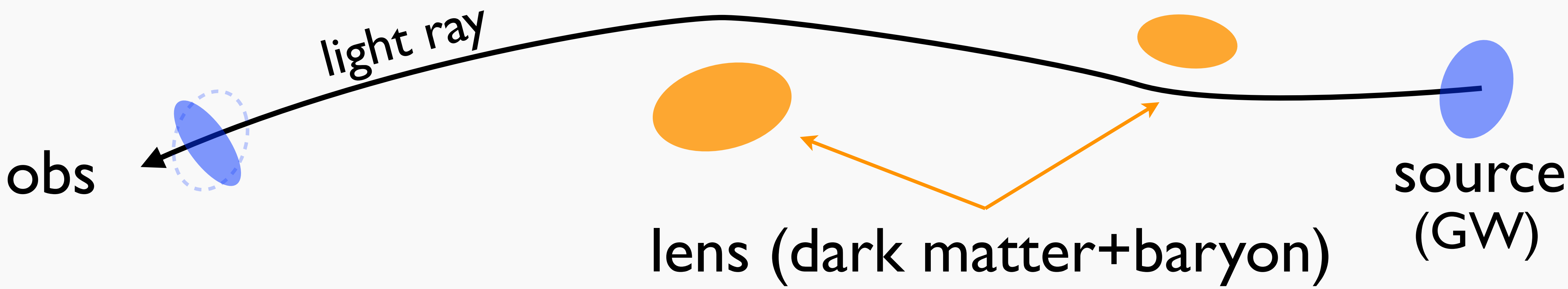


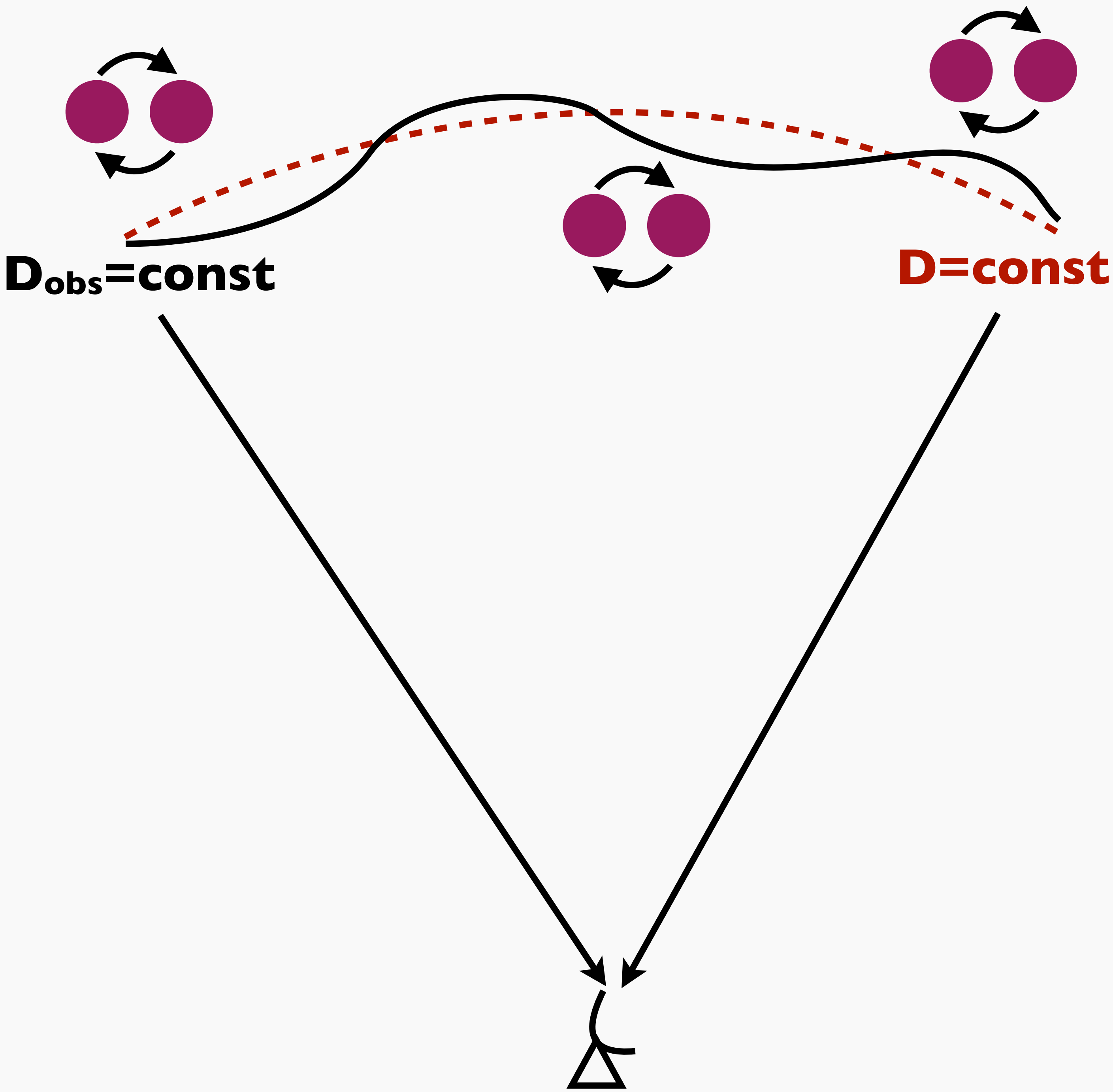
# Gravitational lensing as noise




- gravitational lensing magnification μ **changes observed luminosity distance**

$$D_{\mathrm{obs}} = \bar{D}\mu^{-1/2} \approx \bar{D}\left[1 - \kappa(\vec{\theta}, z)\right]$$

# Apparent clustering due to lensing




lensing depends on sky position

**additional clustering pattern** on the sky

MO Phys. Rev. D**93**(2016)083511

# Cross-correlation signals

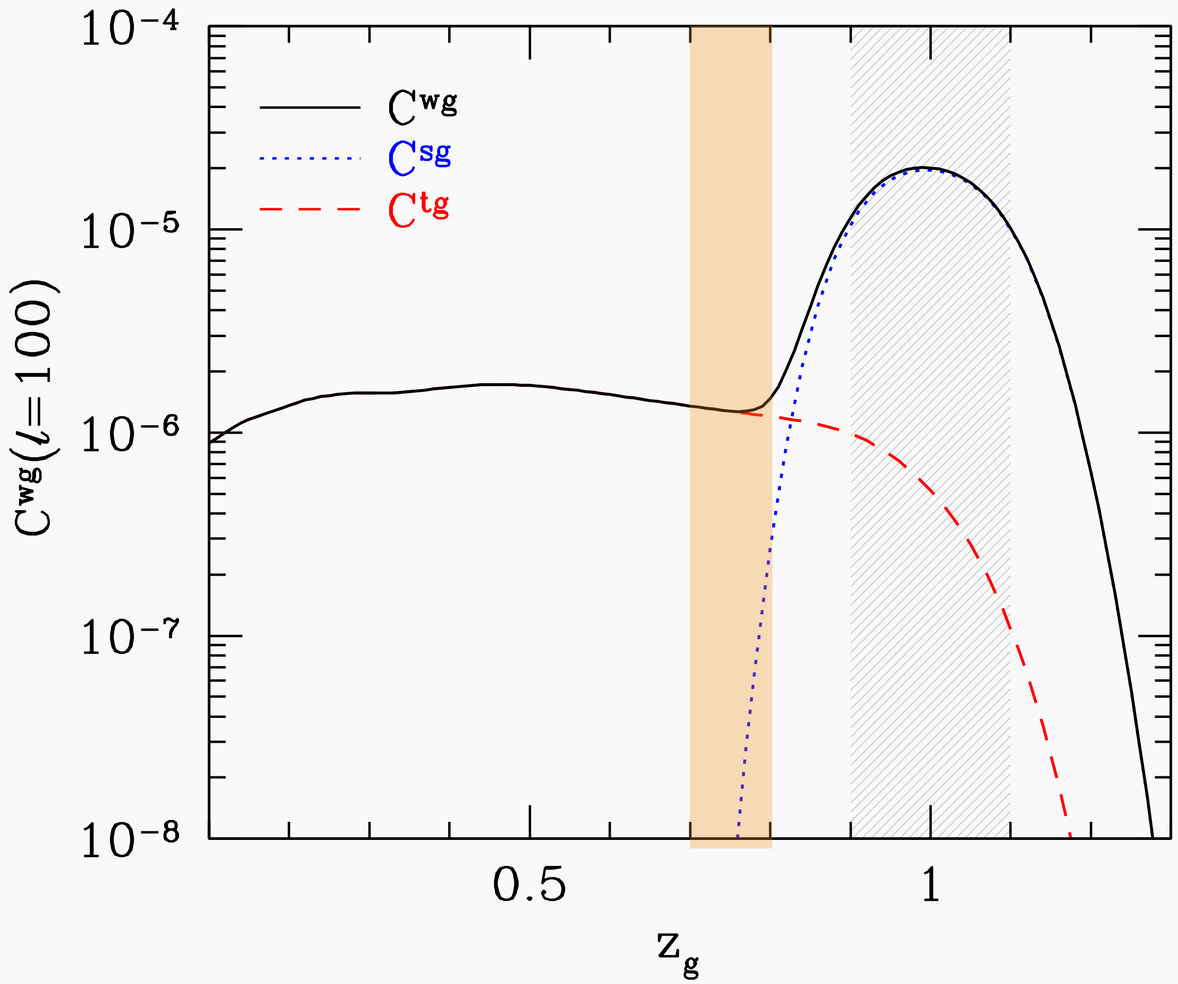
$$C^{\mathrm{w}_i\mathrm{g}_j}(\ell) = C^{\mathrm{s}_i\mathrm{g}_j}(\ell) + C^{\mathrm{t}_i\mathrm{g}_j}(\ell)$$

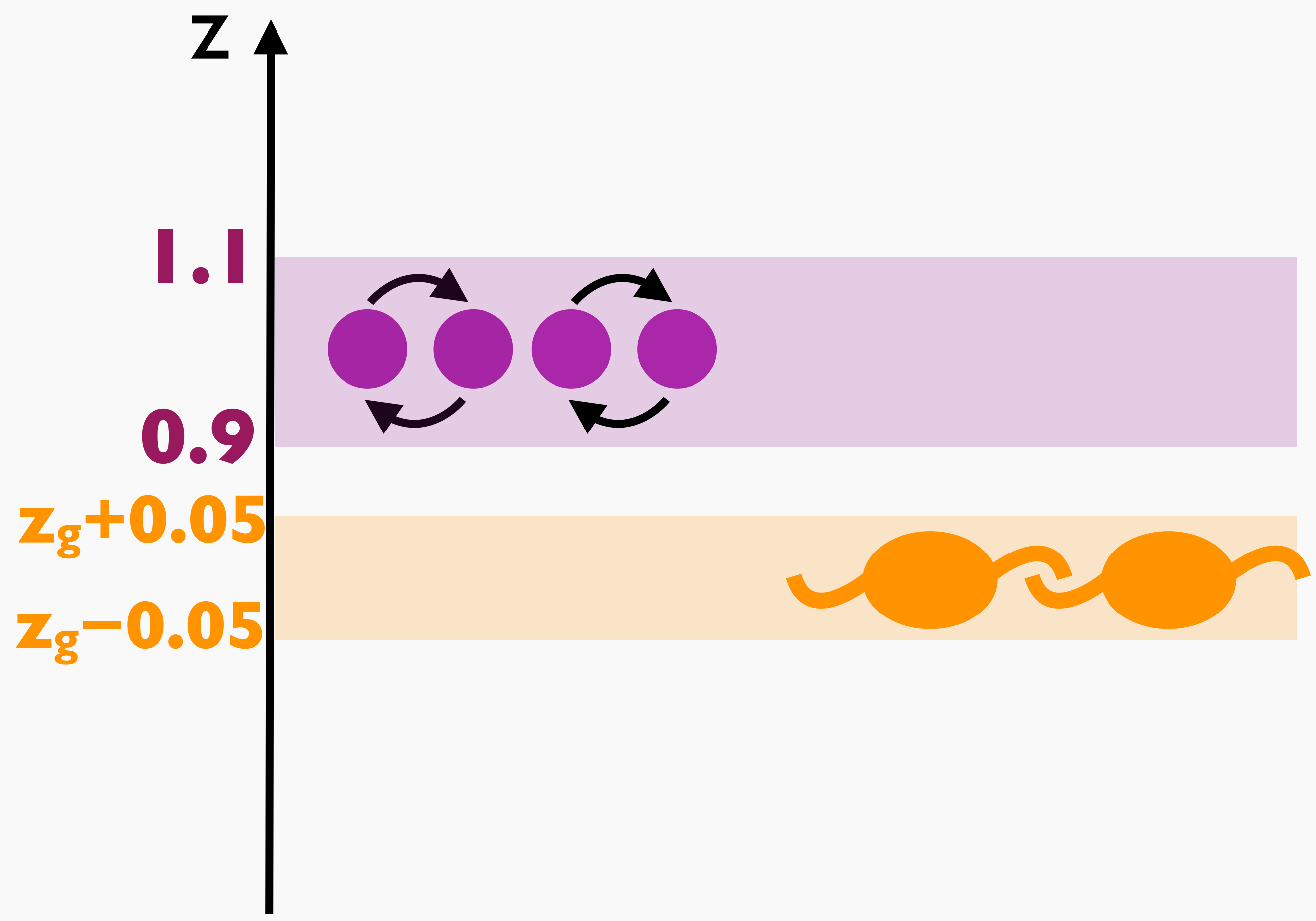
$$C^{\mathrm{s}_i\mathrm{g}_j}(\ell) = \int_0^\infty dz\, W_i^{\mathrm{s}}(z) W_j^{\mathrm{g}}(z) \frac{H(z)}{\chi^2} b_{\mathrm{GW}} b_{\mathrm{g}} P_{\mathrm{m}}\left(\frac{\ell+1/2}{\chi}; z\right)$$

**physical spatial correlation**

$$C^{\mathrm{t}_j\mathrm{g}_j}(\ell) = \int_0^\infty dz\, W_i^{\mathrm{t}}(z) \int_0^z dz' W_j^{\mathrm{g}}(z') W^{\kappa}(z'; z) \frac{H(z')}{\chi'^2} b_{\mathrm{g}} P_{\mathrm{m}}\left(\frac{\ell+1/2}{\chi'}; z'\right)$$

**apparent clustering due to weak lensing**



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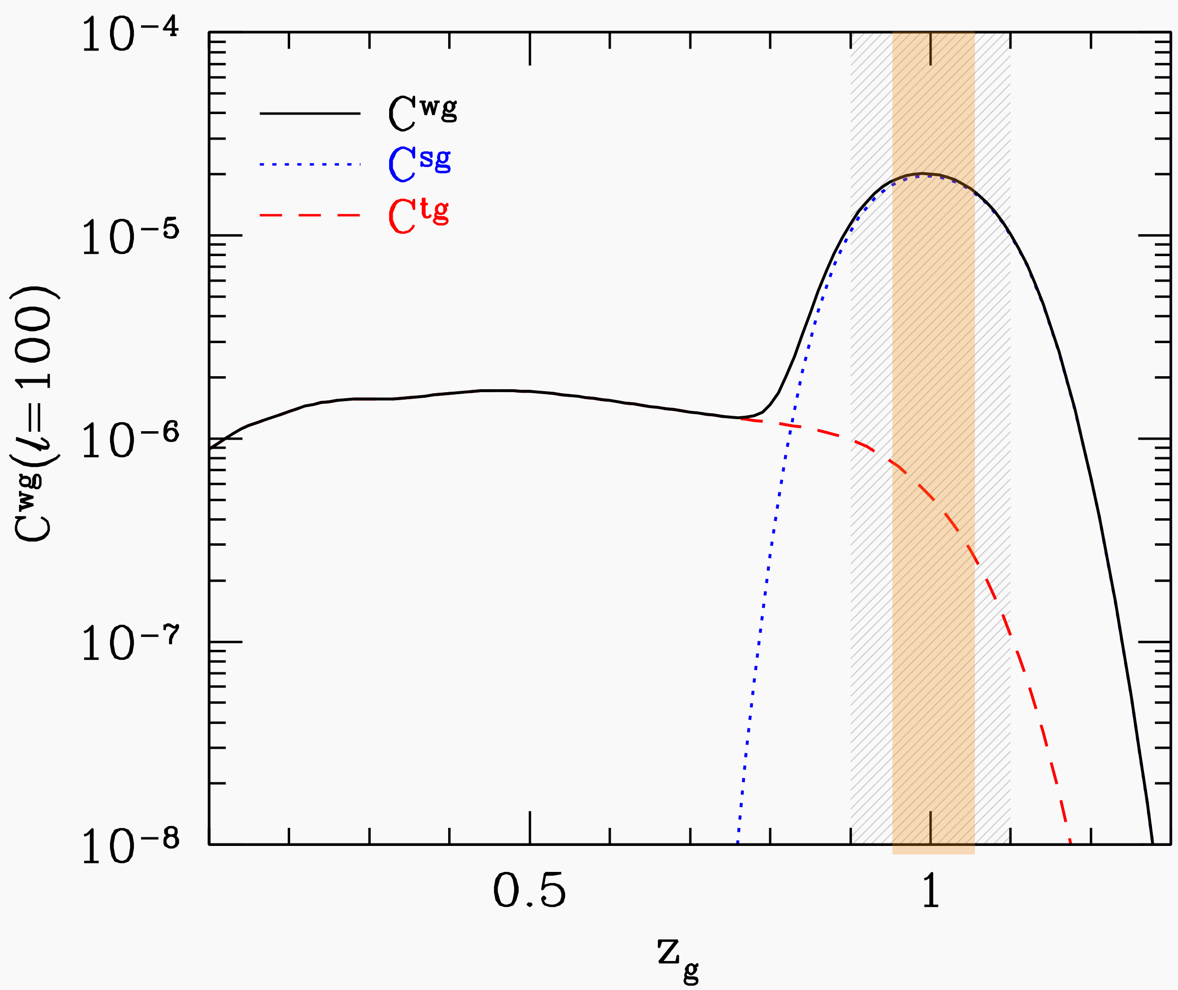
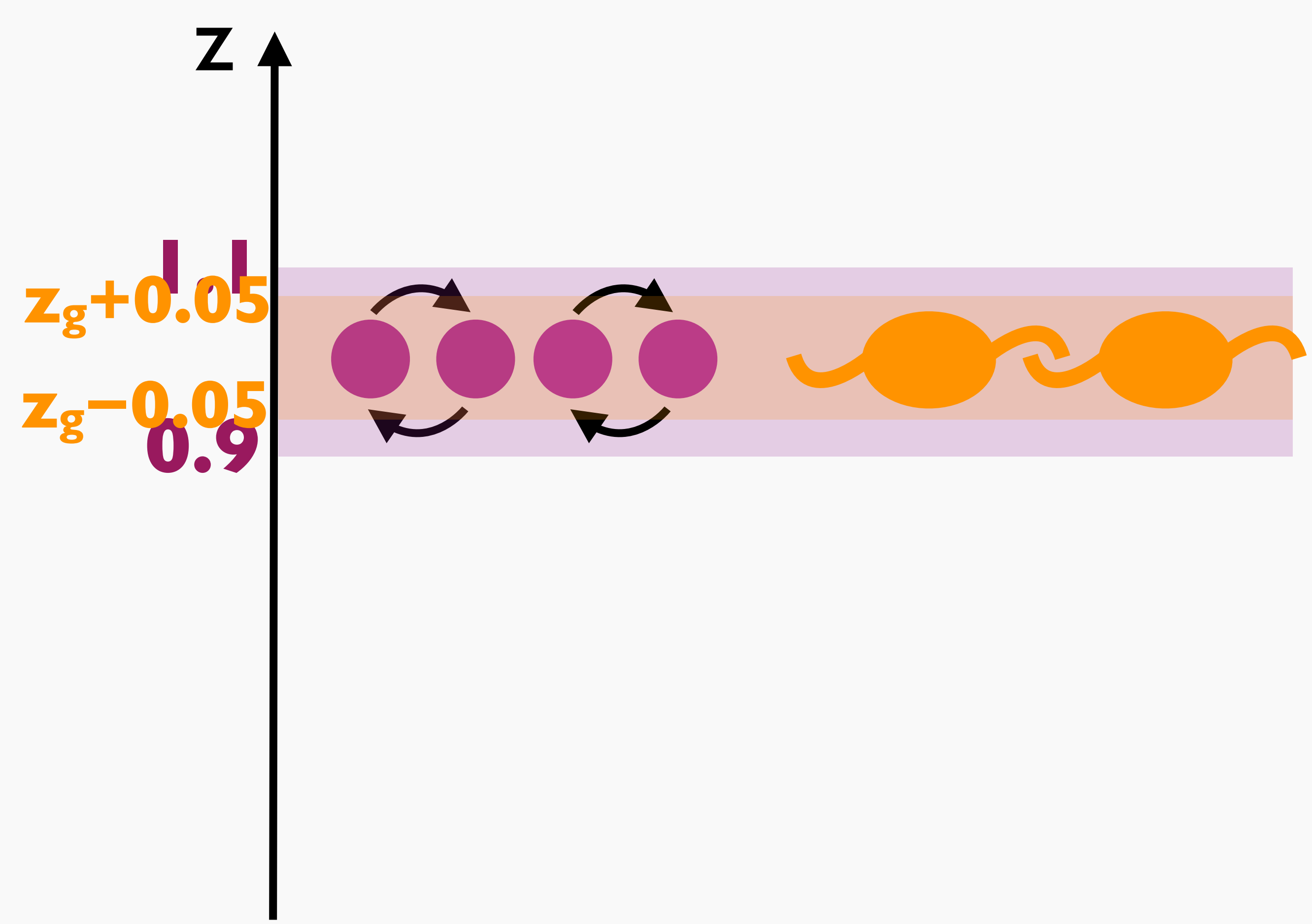
**apparent clustering due to weak lensing**



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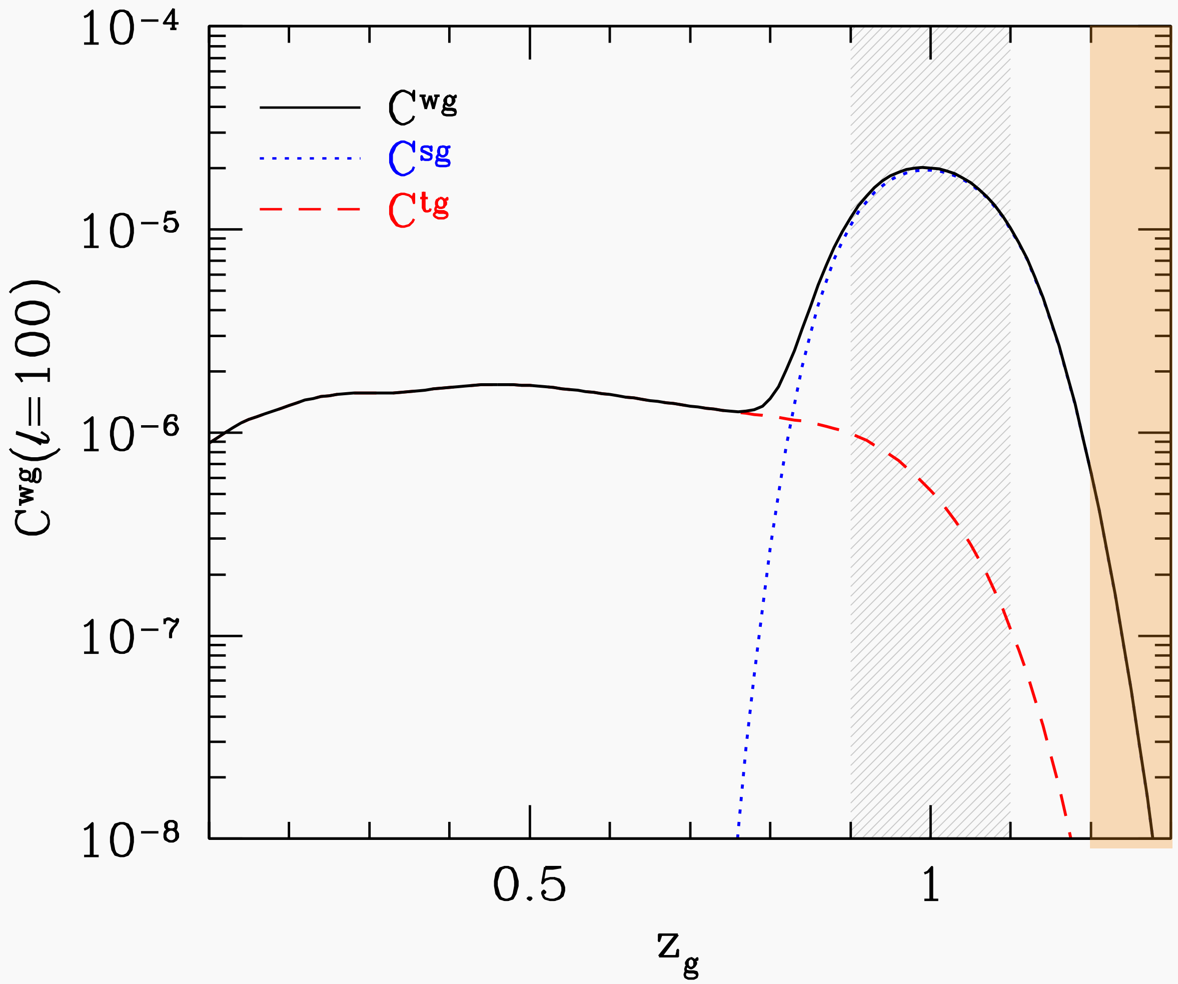


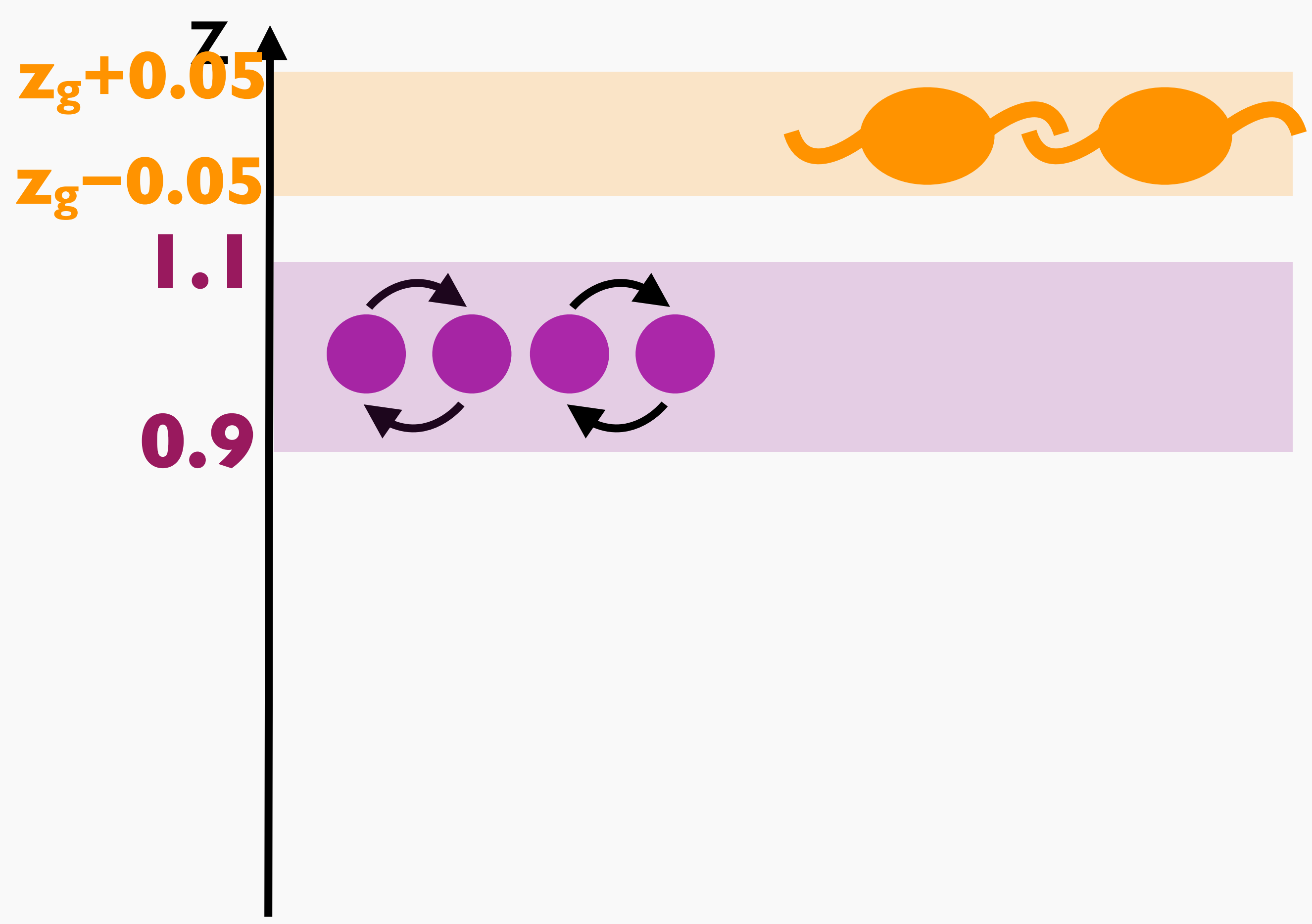

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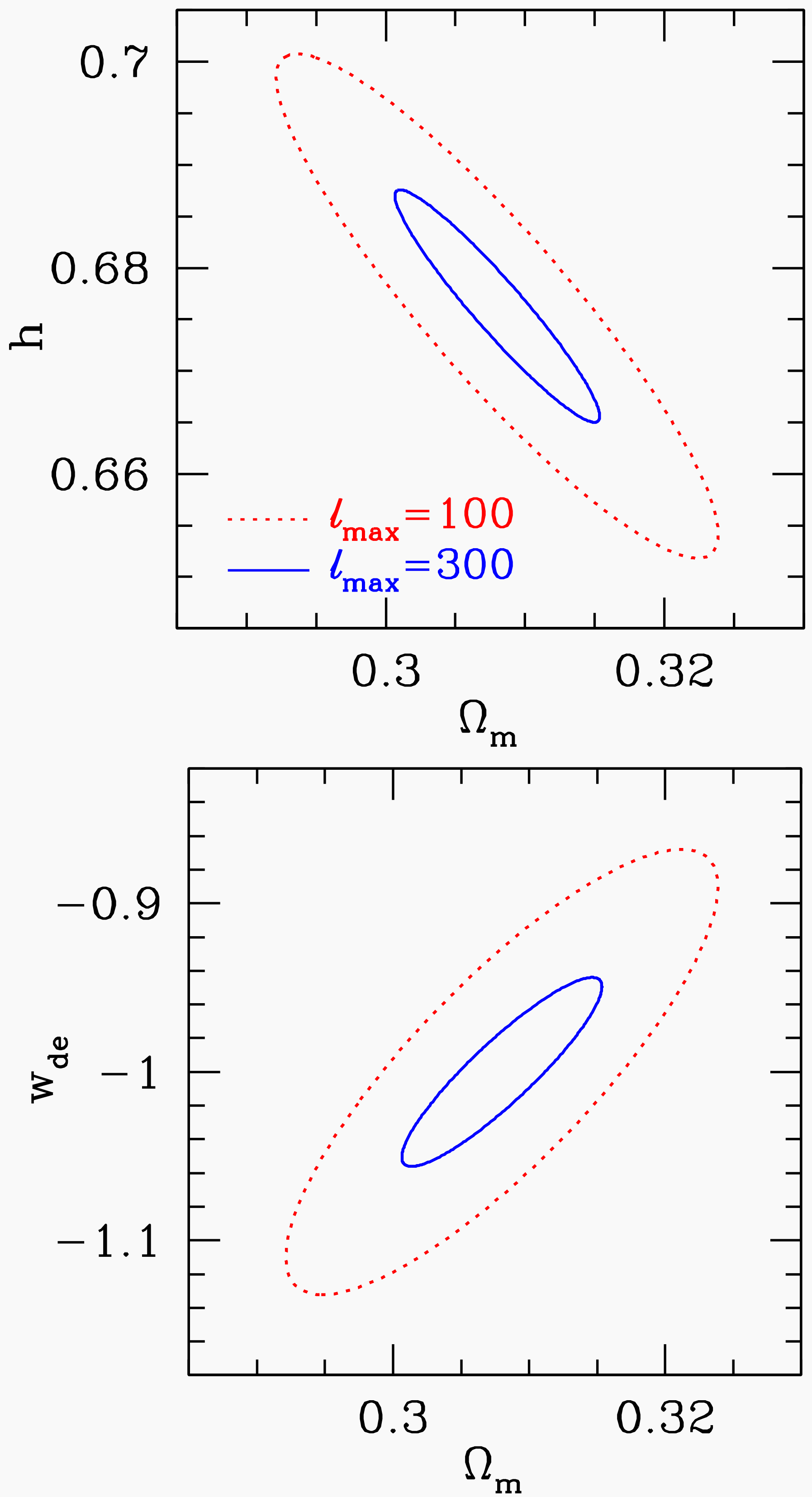
# Forecast

- assuming **3rd generation GW experiment** and **Euclid galaxies**
- $l_{max}$ ~ localization accuracy
- tight constraints



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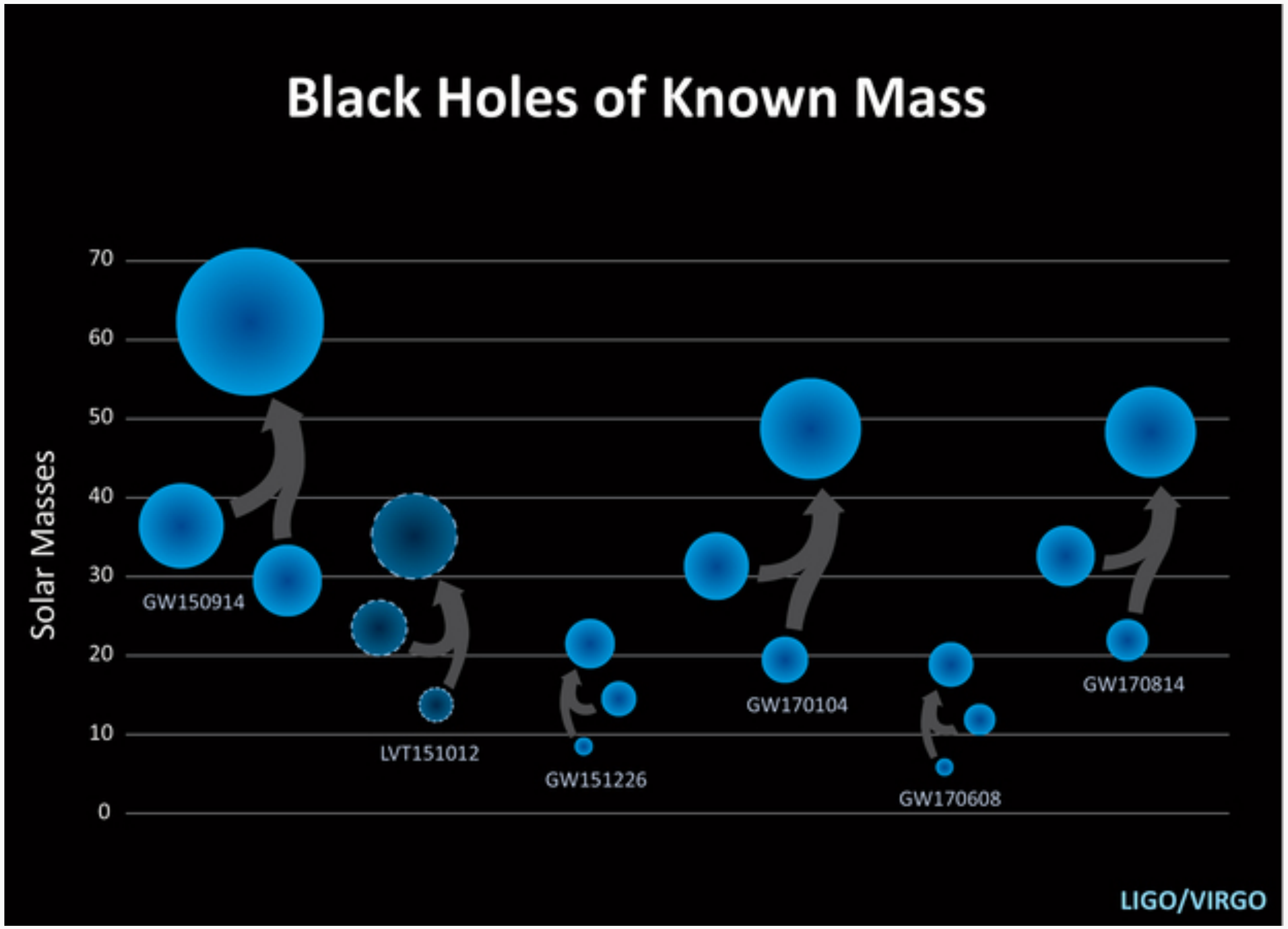
# Cross-correlation: summary

- proposed a new method to constrain $H_0$ and other parameters by **cross-correlation** of **GW sources** and **galaxies with known z**
  - standard siren cosmology without follow-up
  - applicable at high-z

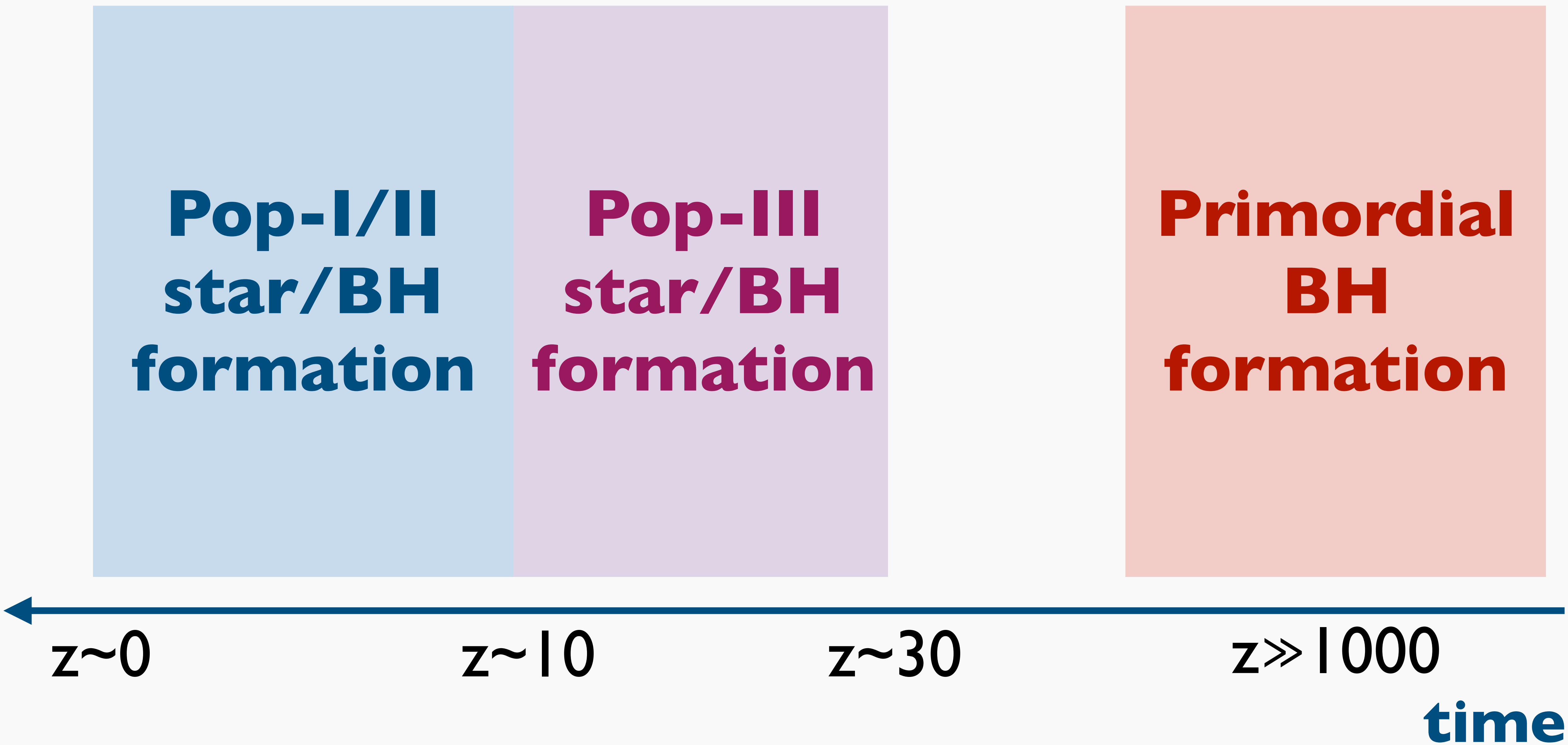
# Origin of binary BHs?




https://www.ligo.caltech.edu

- ~10-30 $M_\odot$ BHs by LIGO/VIRGO
- origin unknown
  - **Pop-I/II?**
  - **Pop-III?**
  - **PBH?**

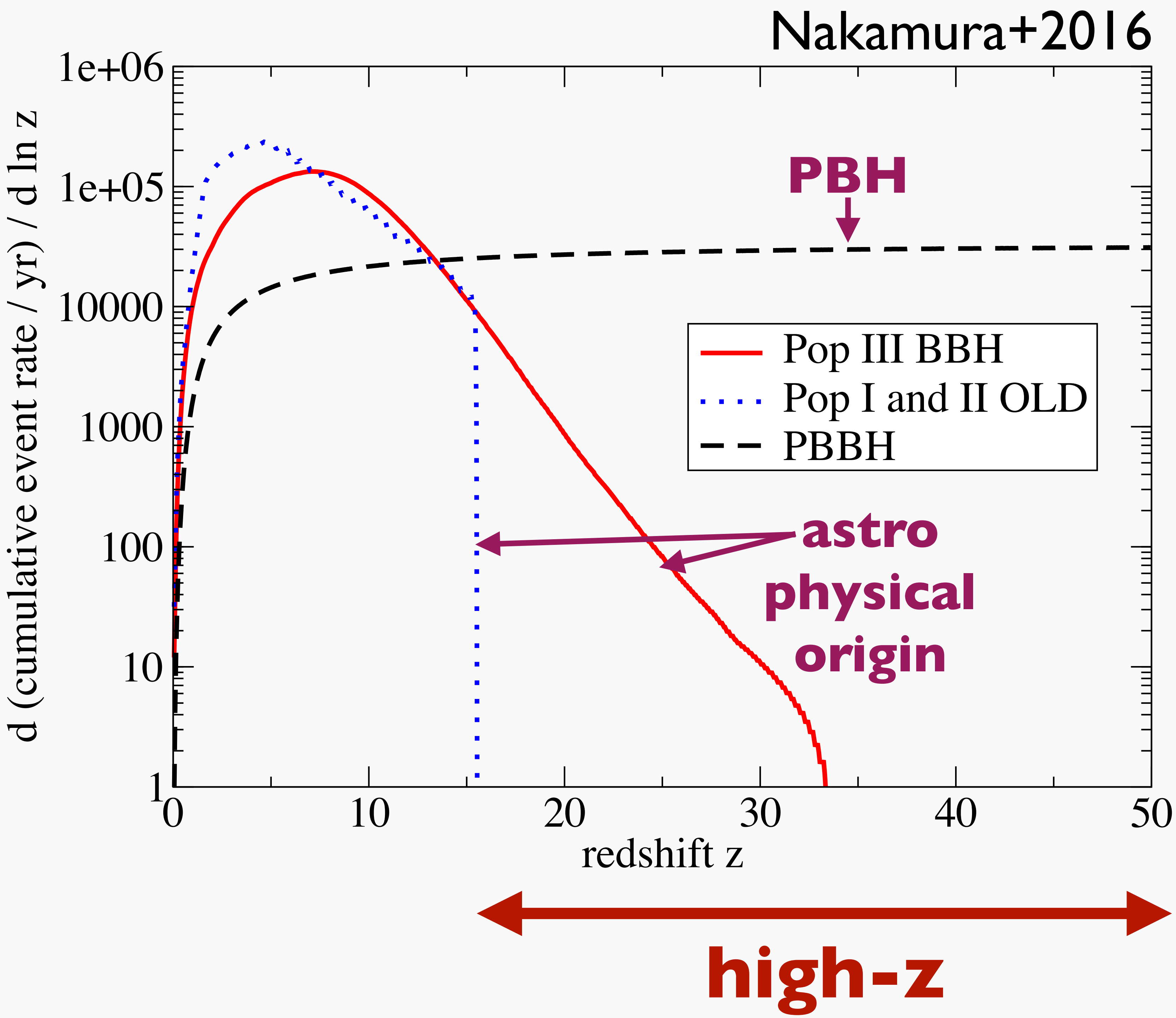
# Models of BH formation




- GW observed at z=0 due to long **delay time**

Nakamura+2016; Koushiappas & Loeb 2017

# Key observation: high-z events




accessible by
3rd generation
GW experiments

Nakamura+2016; Koushiappas & Loeb 2017

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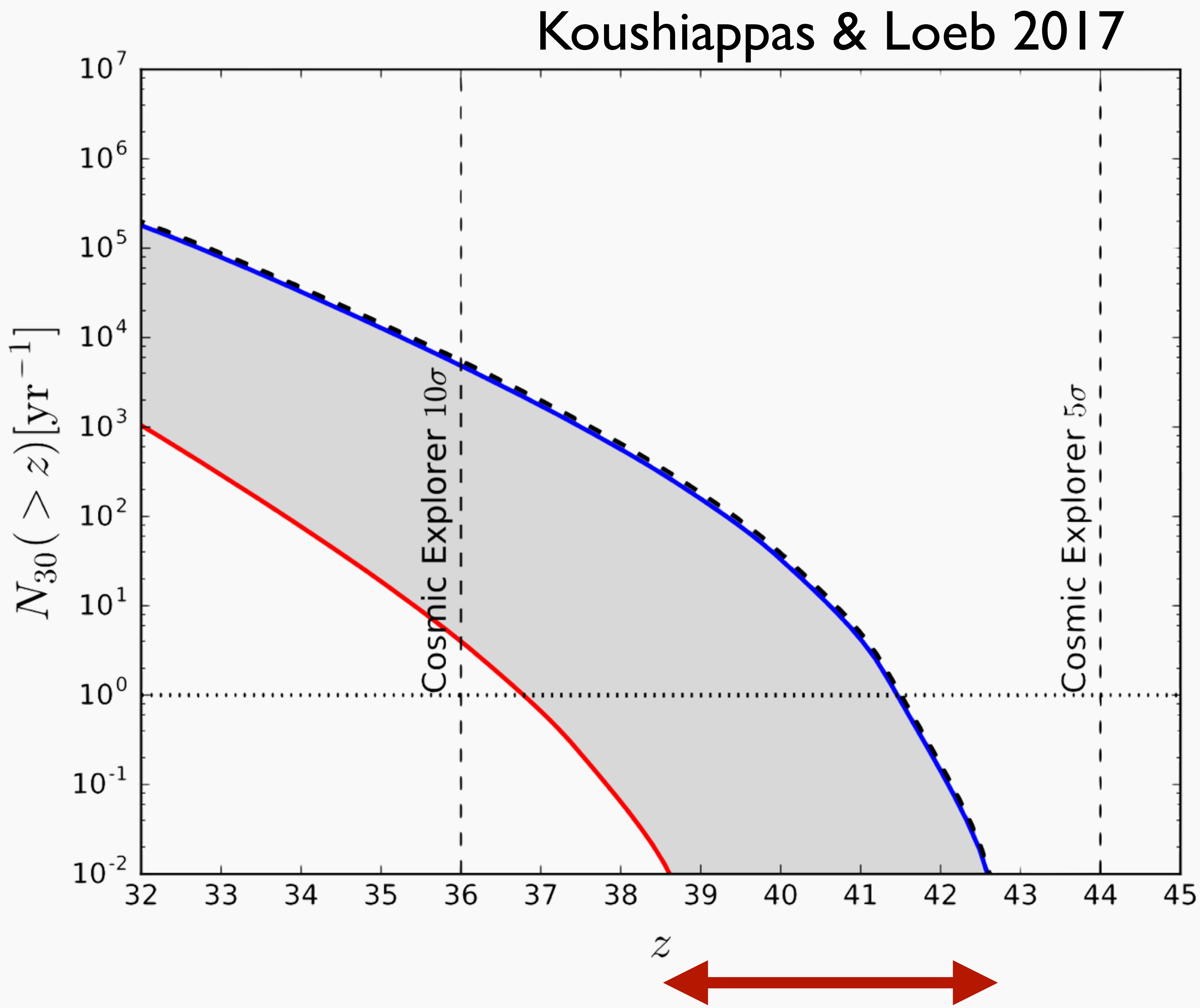
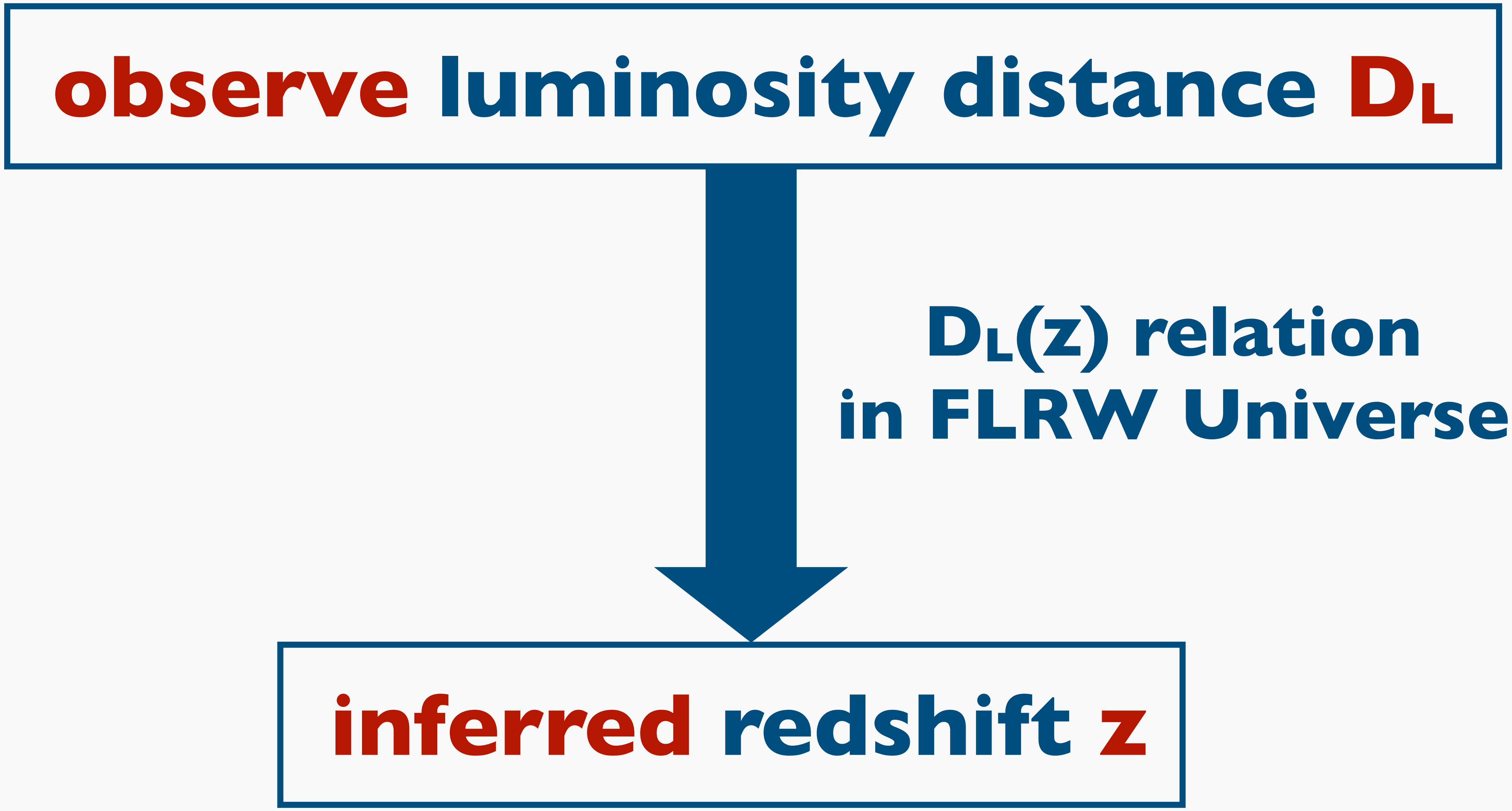



accessible by
3rd generation
GW experiments

**$z_{max}$ ~ 40 for astrophysical origin**

# “High-z” events?



# "High-z" events?

**observe luminosity distance $D_L$**

~~**$D_L(z)$ relation**~~
~~**in FLRW Universe**~~

**gravitational lensing**
change the relation!

**inferred redshift z**

# Observed redshift and mass

- “**observed redshift**” $z_{obs}$

$$D_L(z_{obs}) = \frac{D_L(z)}{\sqrt{\mu}}$$

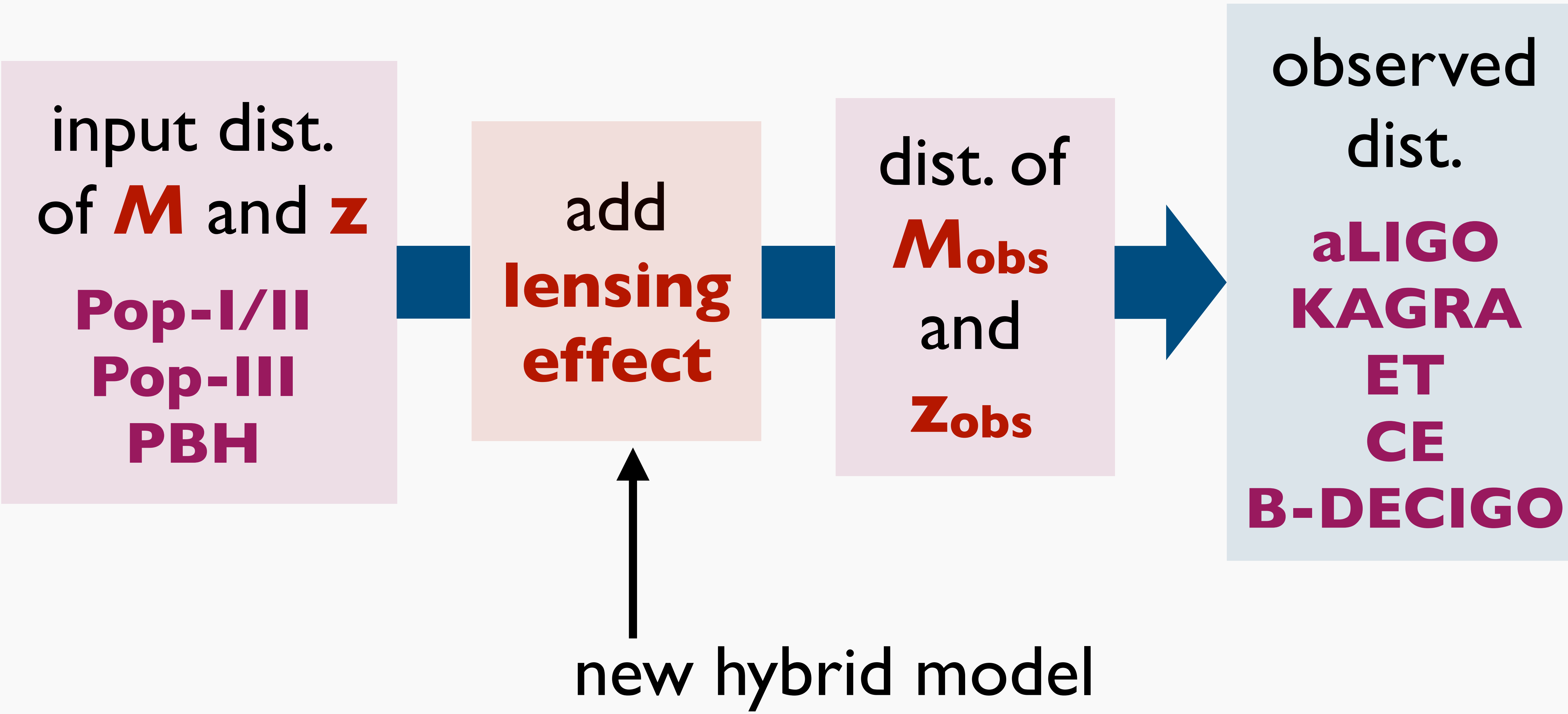
**μ: magnification factor**

- “**observed chirp mass**” $\mathcal{M}_{obs}$

$$\mathcal{M}_{obs} = \frac{1+z}{1+z_{obs}}\mathcal{M}$$

MO MNRAS **480**(2018)3842

# Distribution with lensing effects

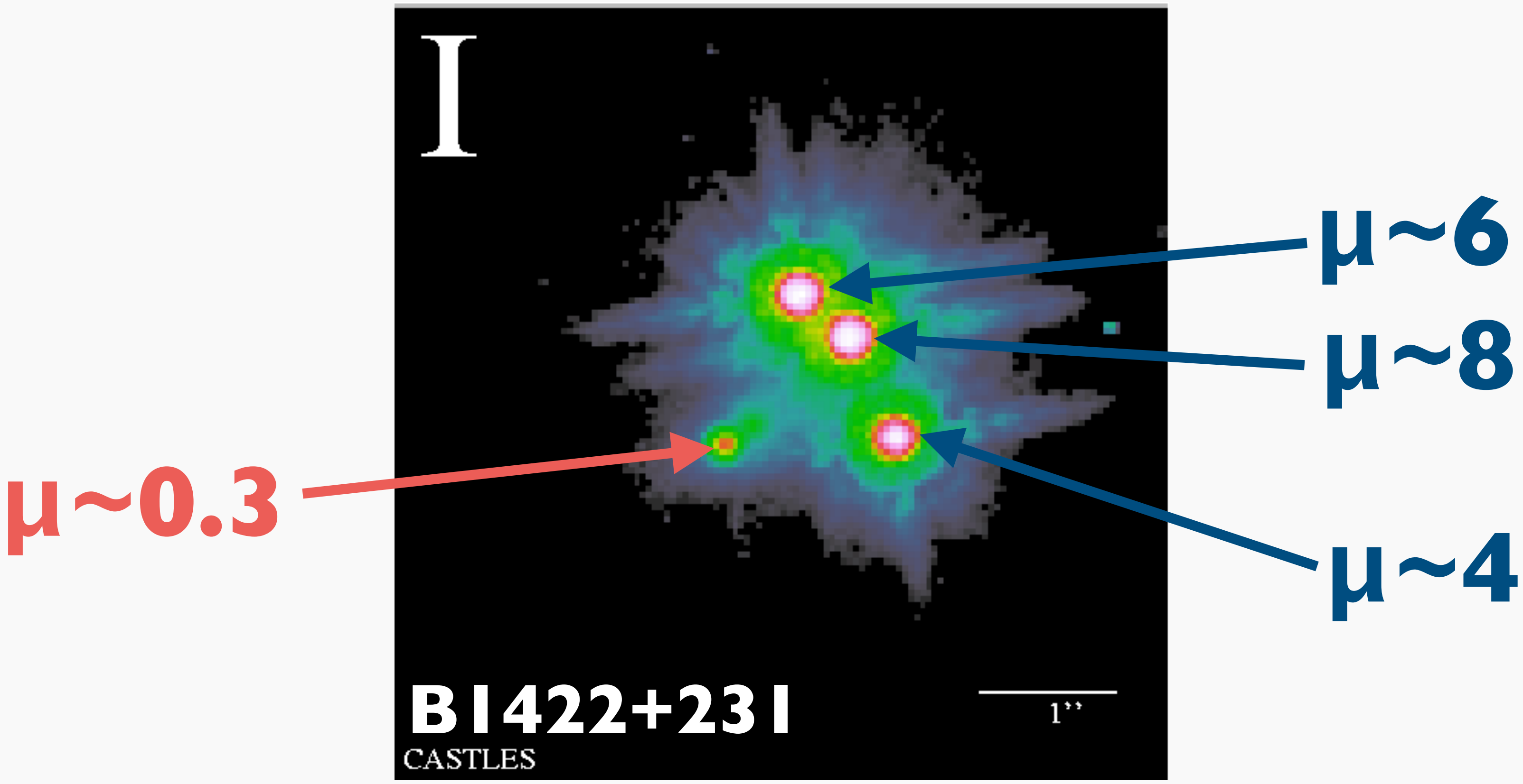


# Strong lensing of BH mergers

- hard to identify **multiple images**

  ➡ treat as **distinct events**

- some images are **magnified** and
  some images are **demagnified**



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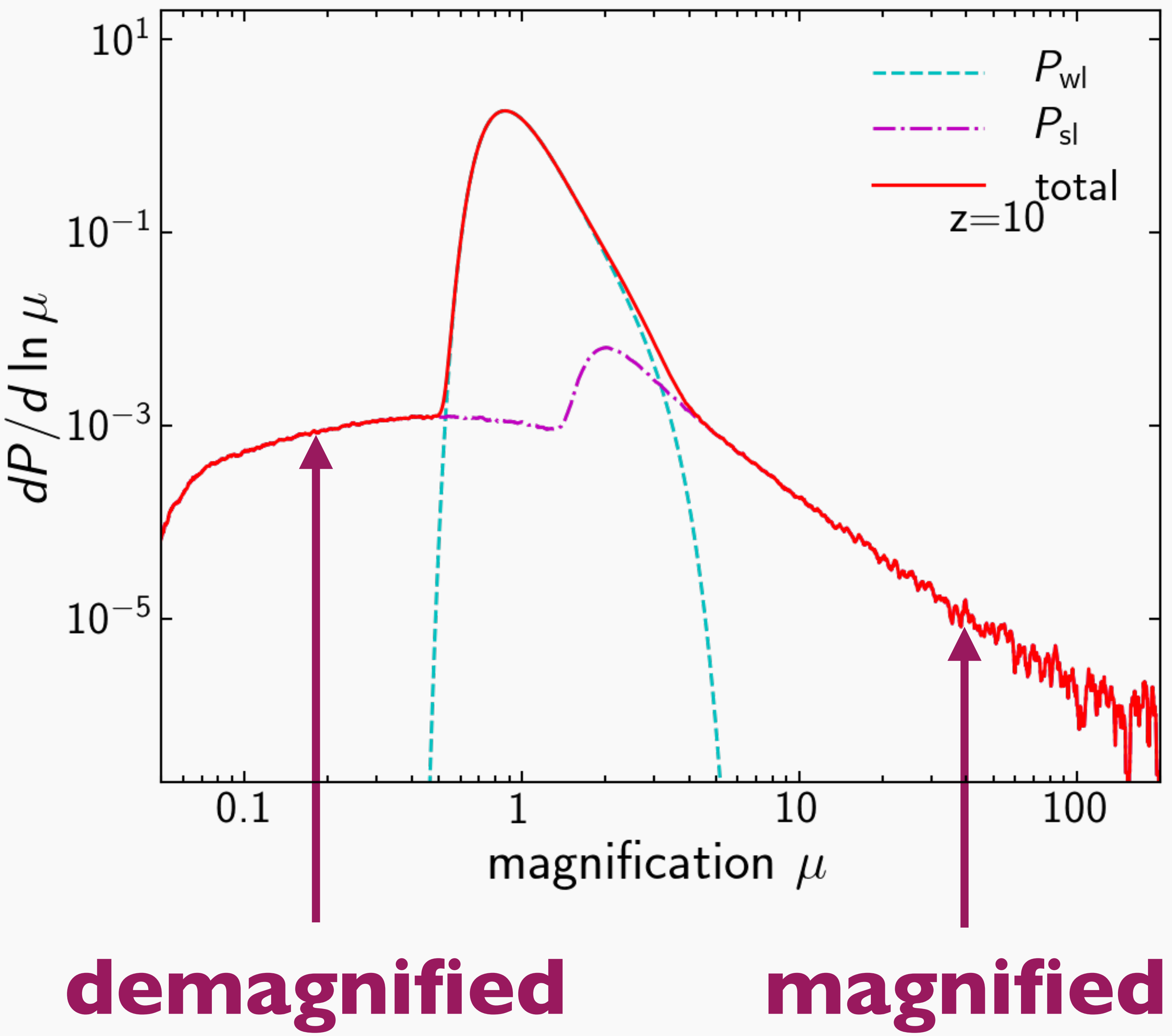
# New model of magnification PDF



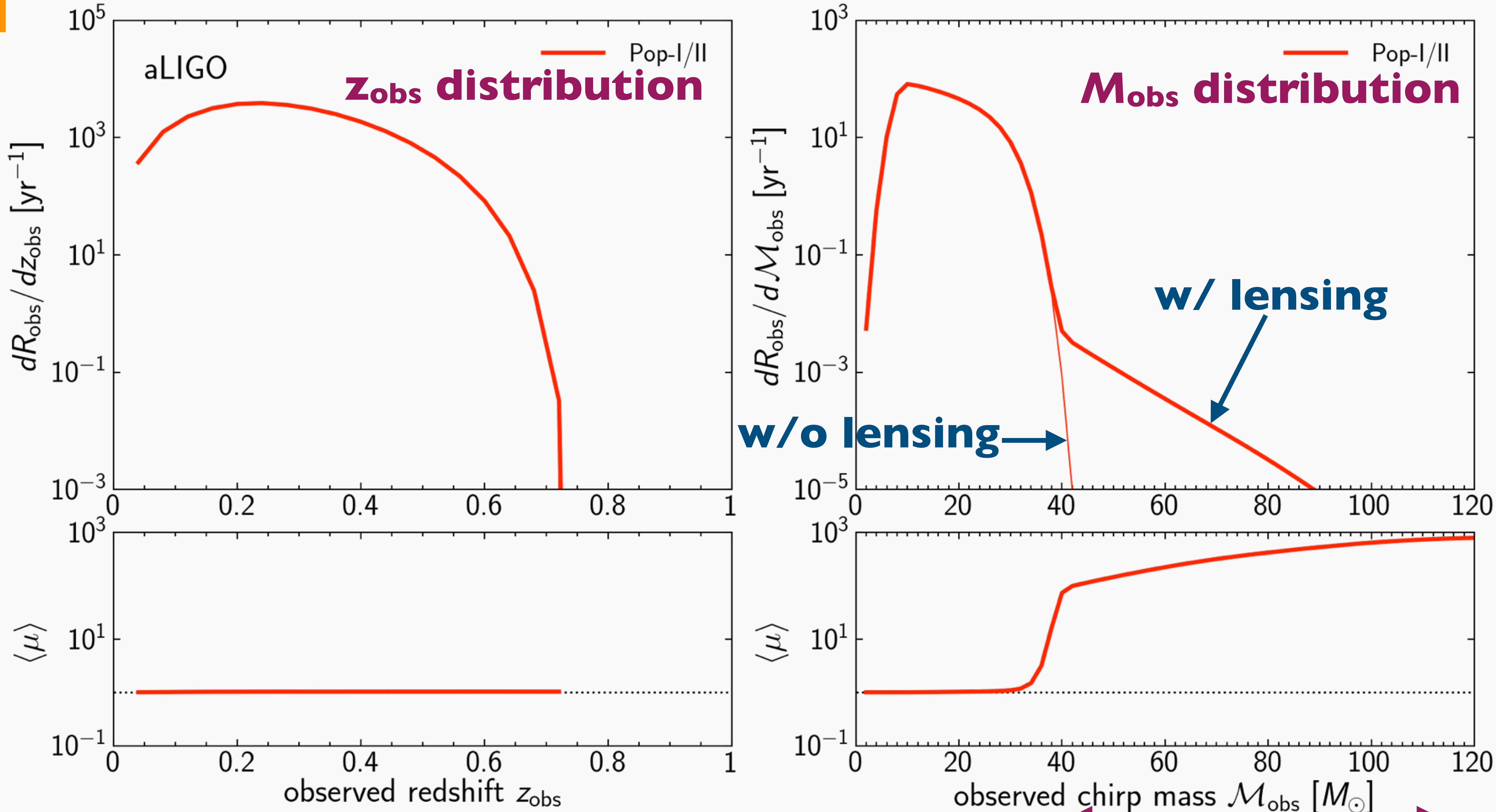

combine

**strong lensing**
(Monte Carlo)

and

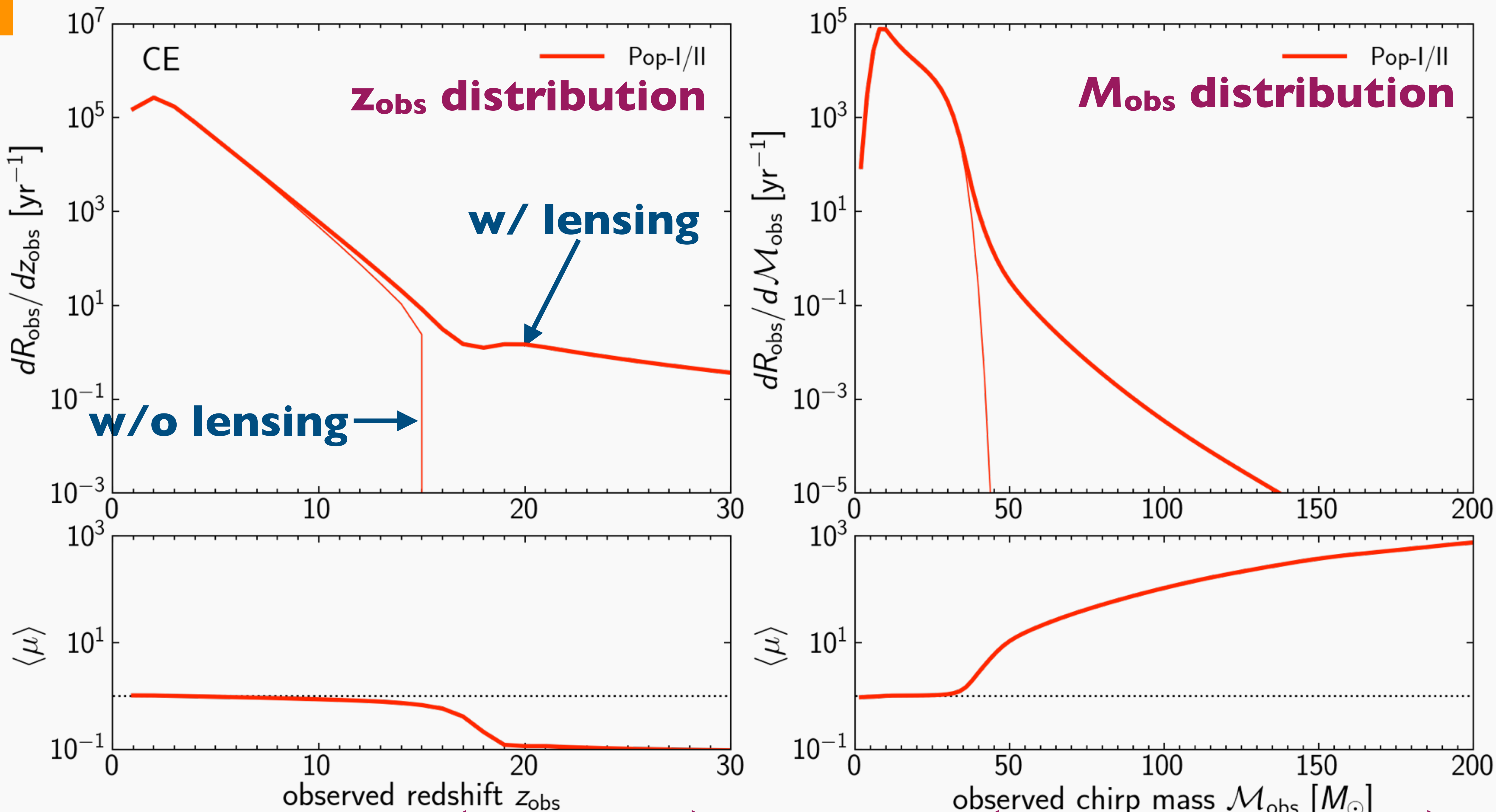
**weak lensing**
(analytic)

# Result: advanced LIGO




excess due to **magnified** events
(see also Dai+2017)

# Result: Cosmic Explorer




excess due to **demagnified** events

excess due to **magnified** events (see also Dai+2017)

# Effect of lensing (de-)magnification

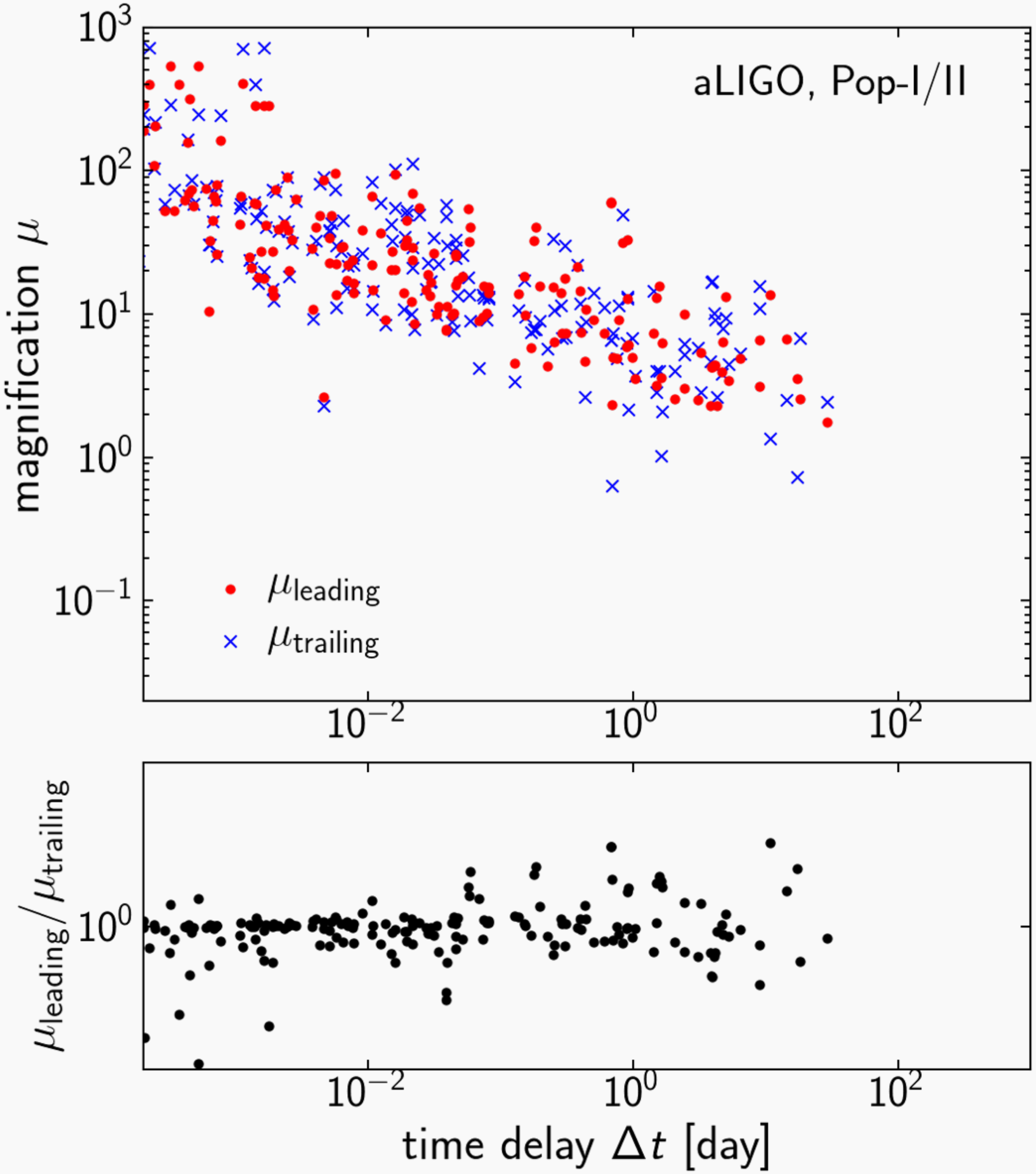
- significant modifications of tails

  **apparently high $M_{obs}$ ⟵ magnification**

  **apparently high $z_{obs}$ ⟵ demagnification**

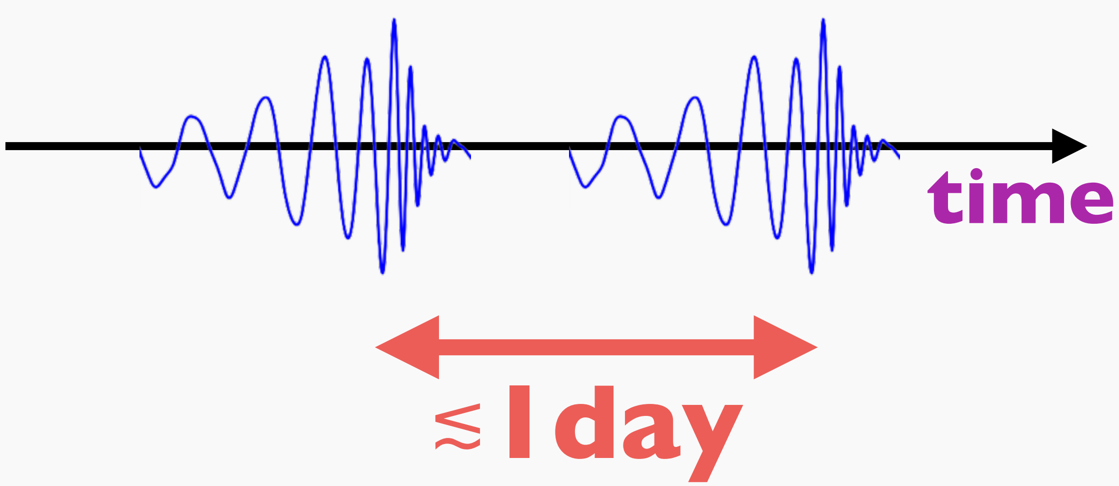
- should be accompanied by multiple images

# Expected multiple image pairs




**advanced LIGO**

- time delay $\lesssim$ **1 day**
- high, similar μ
- $R_{obs} < 1\ yr^{-1}$



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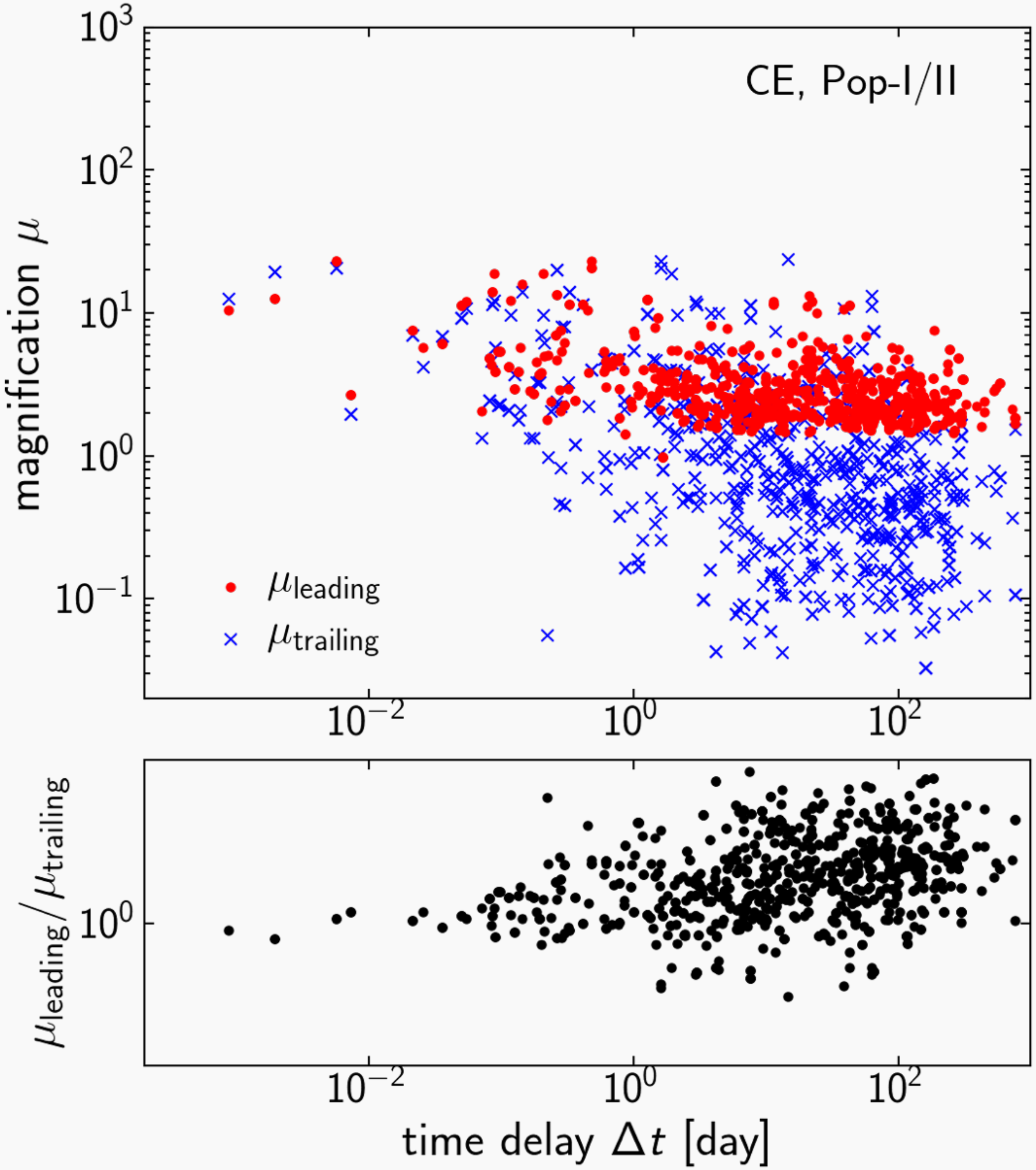
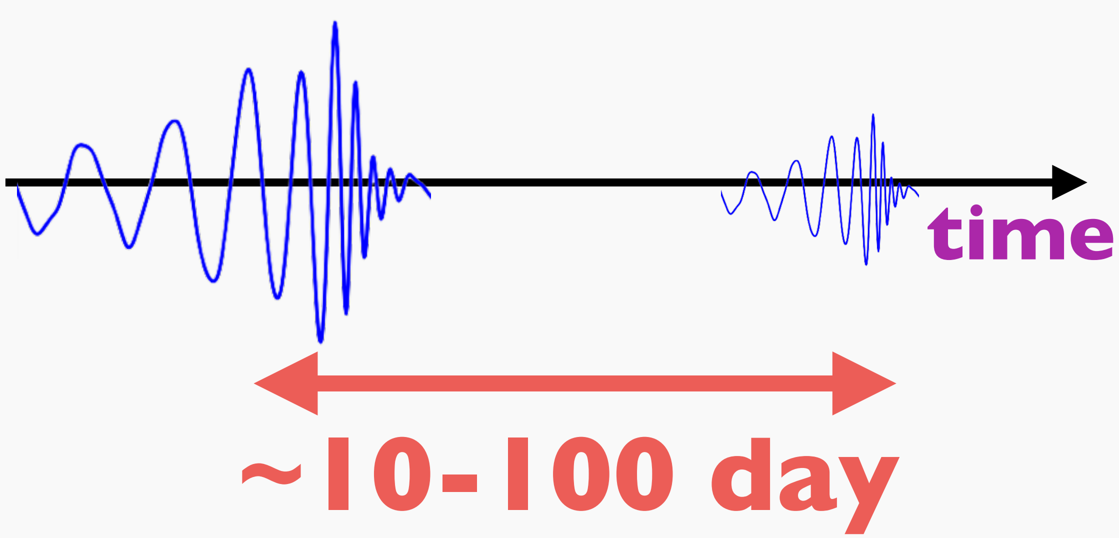



## Cosmic Explorer

- time delay
  **~10-100 days**
- different μ
- $R_{obs}$ ~ O($10^3$) $yr^{-1}$



# Binary BH distribution: summary

- pronounced lensing effects at **high $M_{obs}$** and **high $z_{obs}$**

    ➡ discovery of apparently very high-z event does not necessarily support PBH

- markedly different properties of multiple images for different experiments

# Conclusion

- interesting **synergies** between **GW** and **large/small-scale structure** of Universe
- a lot of room to explore!

# Review article (incl. GW lensing!)

IOP Publishing Reports on Progress in Physics

Rep. Prog. Phys. **82** (2019) 126901 (37pp) https://doi.org/10.1088/1361-6633/ab4fc5

## Review

# 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