Gravitational waves in the inhomogeneous Universe

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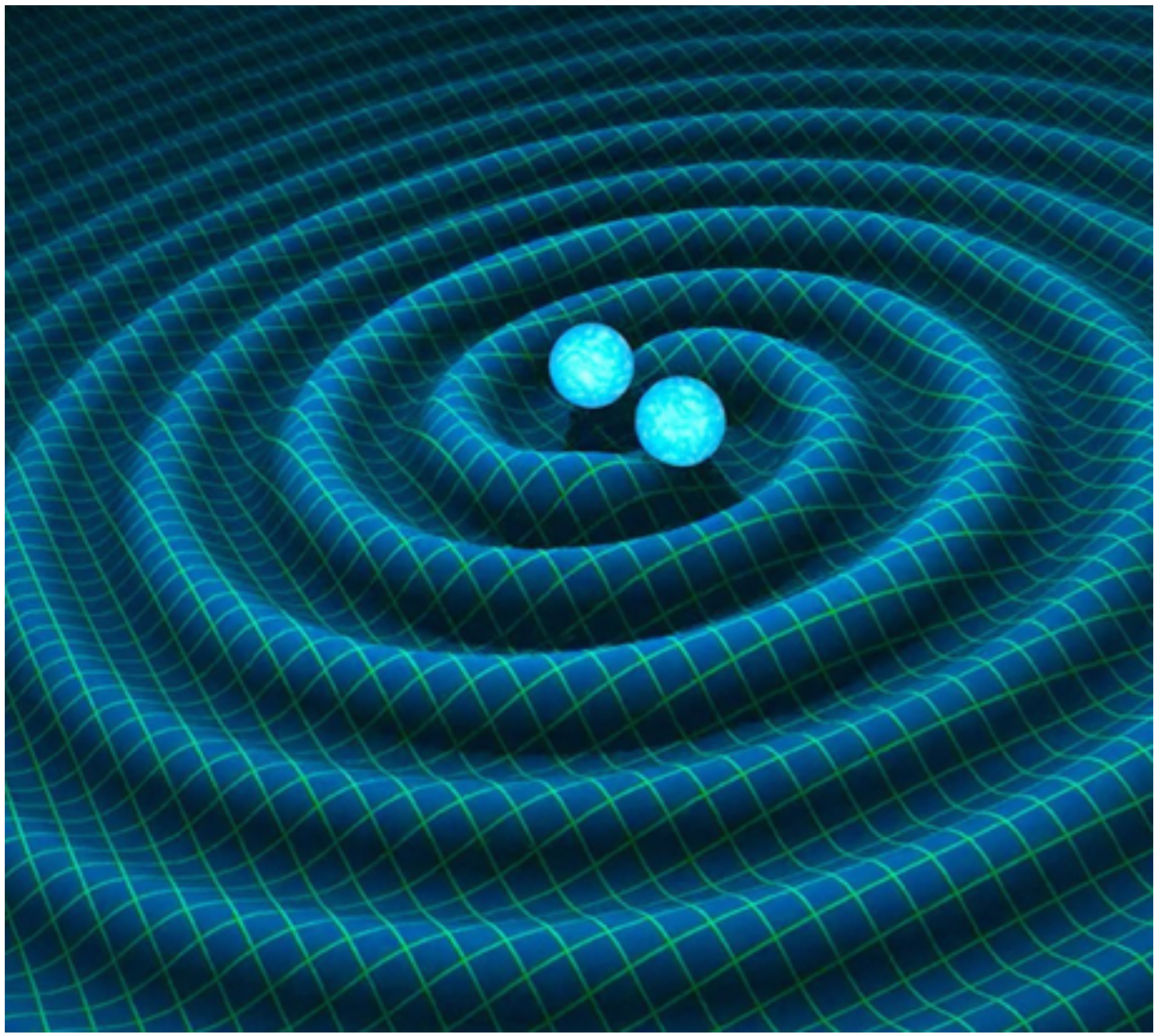
2019/9/3 Cosmological Frontiers in Fundamental Physics@Perimeter

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 waves (GW)

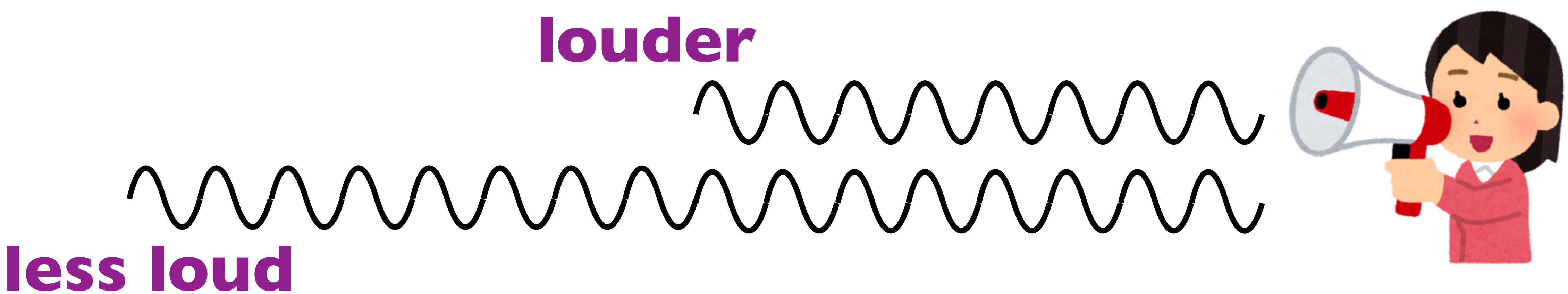


R. Hurt/Caltech-JPL/EPA

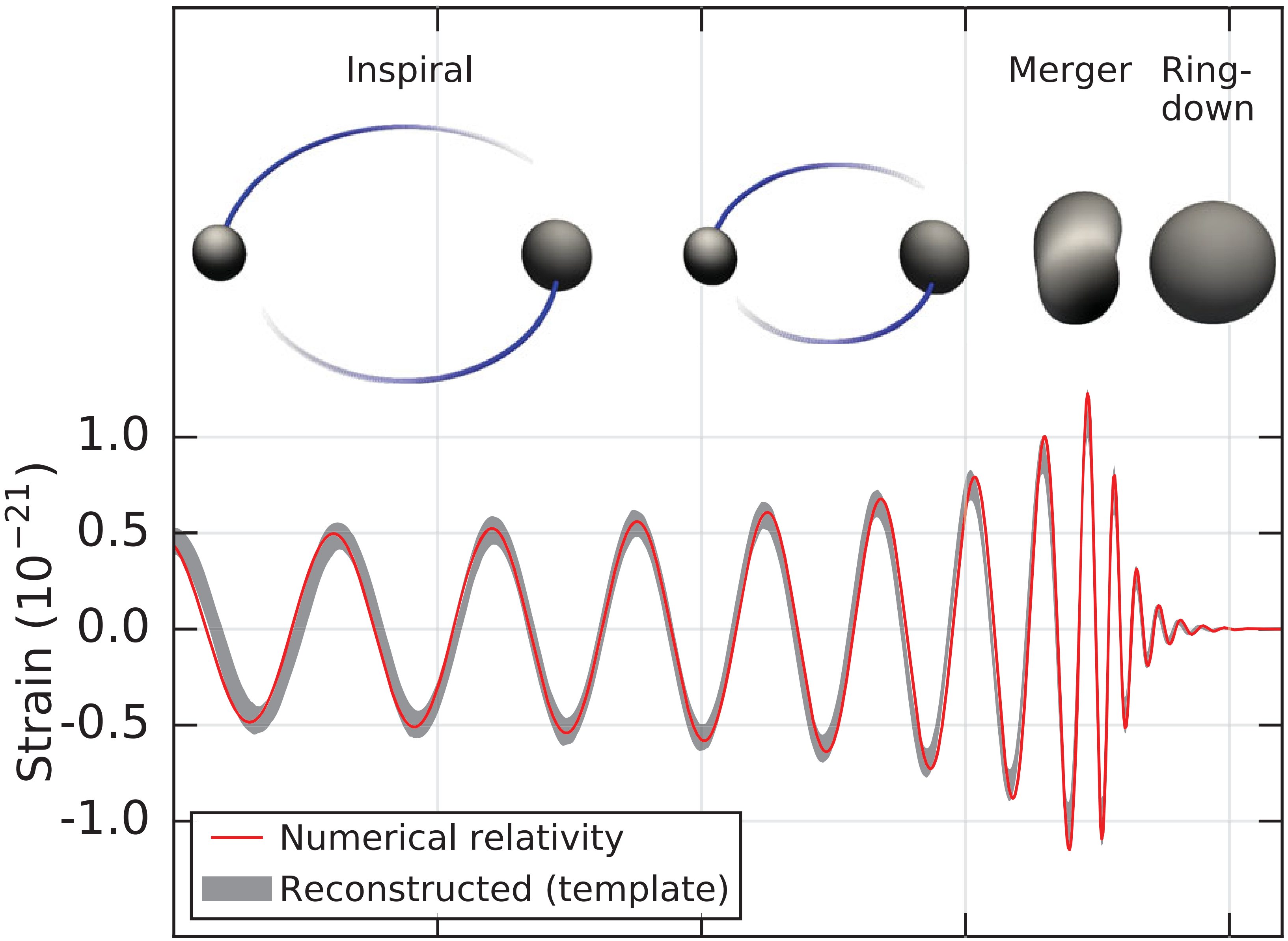
- observed for the first time in 2015
- mergers of compact binaries such as black hole (BH) and neutron star (NS)
- **very useful probe of cosmology and astrophysics!**

Gravitational wave standard sirens

- we can infer mass (→GW amplitude) of inspiraling compact binary from the waveform
- by comparing with observed amplitude, we can measure **luminosity distance** (incl. $\mathbf{H_0}$) directly (Schutz 1986)



Abbott+2016



analytic (post-Newtonian)

numerical relativity

analytic (QNM)

Inspiral

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

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

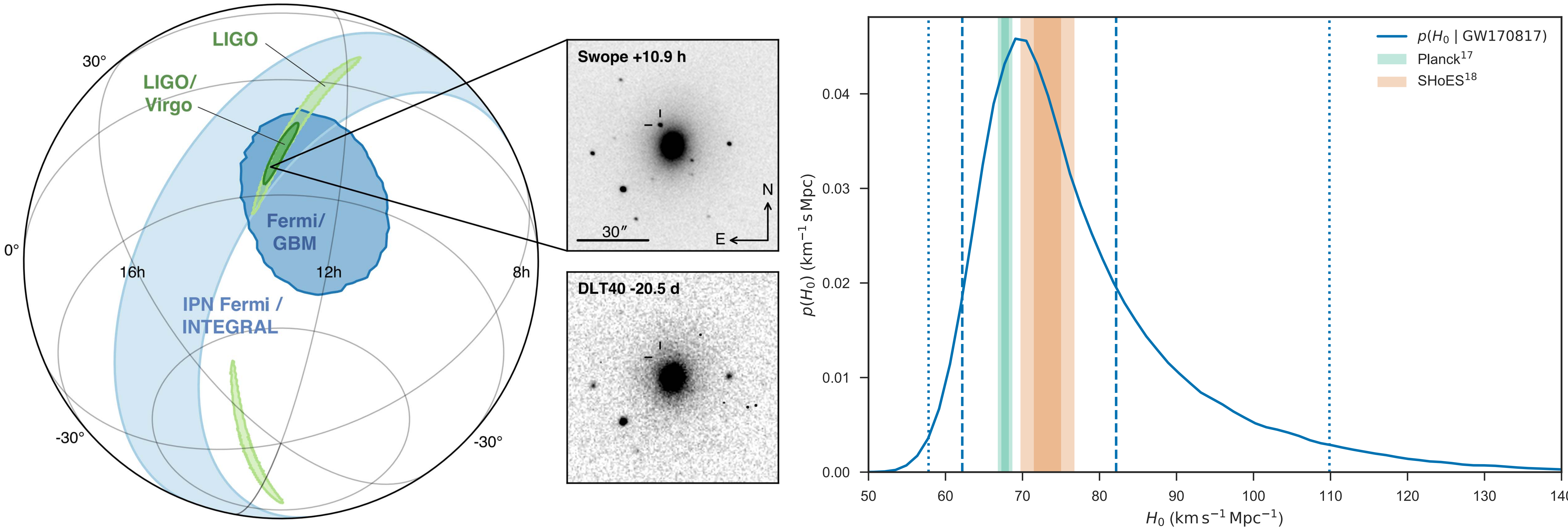
→ **chirp mass M_z** and **distance D_L**

Redshift information

- standard siren can constrain H_0 and other cosmological parameters *if* the **redshift** is known
- usually detection of **EM counterpart** and/or **host galaxy** is needed for the redshift
- this is challenging because of the poor localization accuracy (currently >10−100 deg^2)

Abbott+2017

GW170817 (NS-NS merger)



- GRB and kilonova detected, host galaxy identified
- first constraint on H_0 from gravitational waves

Future?

- kilonova is faint (~24 mag @ 400 Mpc)
- short GRB observed only on-axis
  (e.g., Dalal+2006, Nissanke+2010)
- what about BH-BH mergers?

standard siren without redshift?

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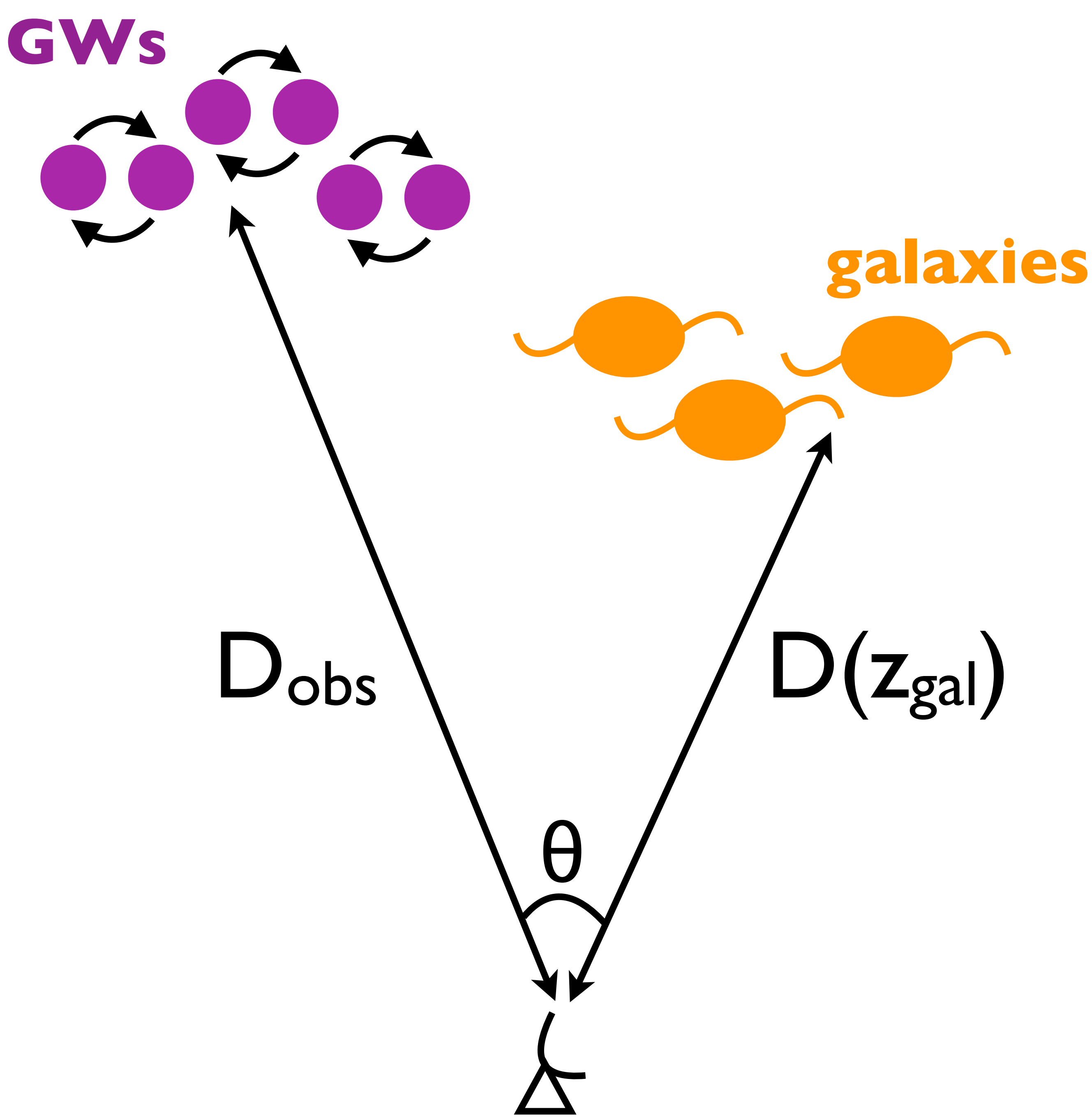
Cross-correlation approach

- **idea**: constrain distance-redshift relation with **cross-correlation** of GW sources (**known D_L**) and galaxies (**known z**)
- similar to "clustering redshift" (e.g., Newman 2008)
- no follow-up of GW sources needed

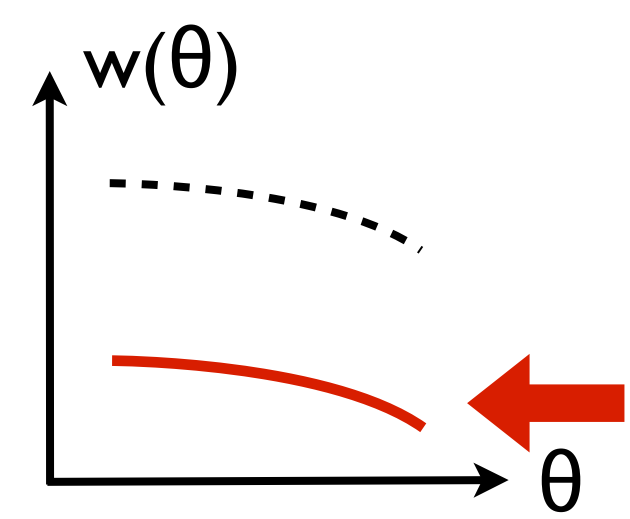
Cross-correlation approach



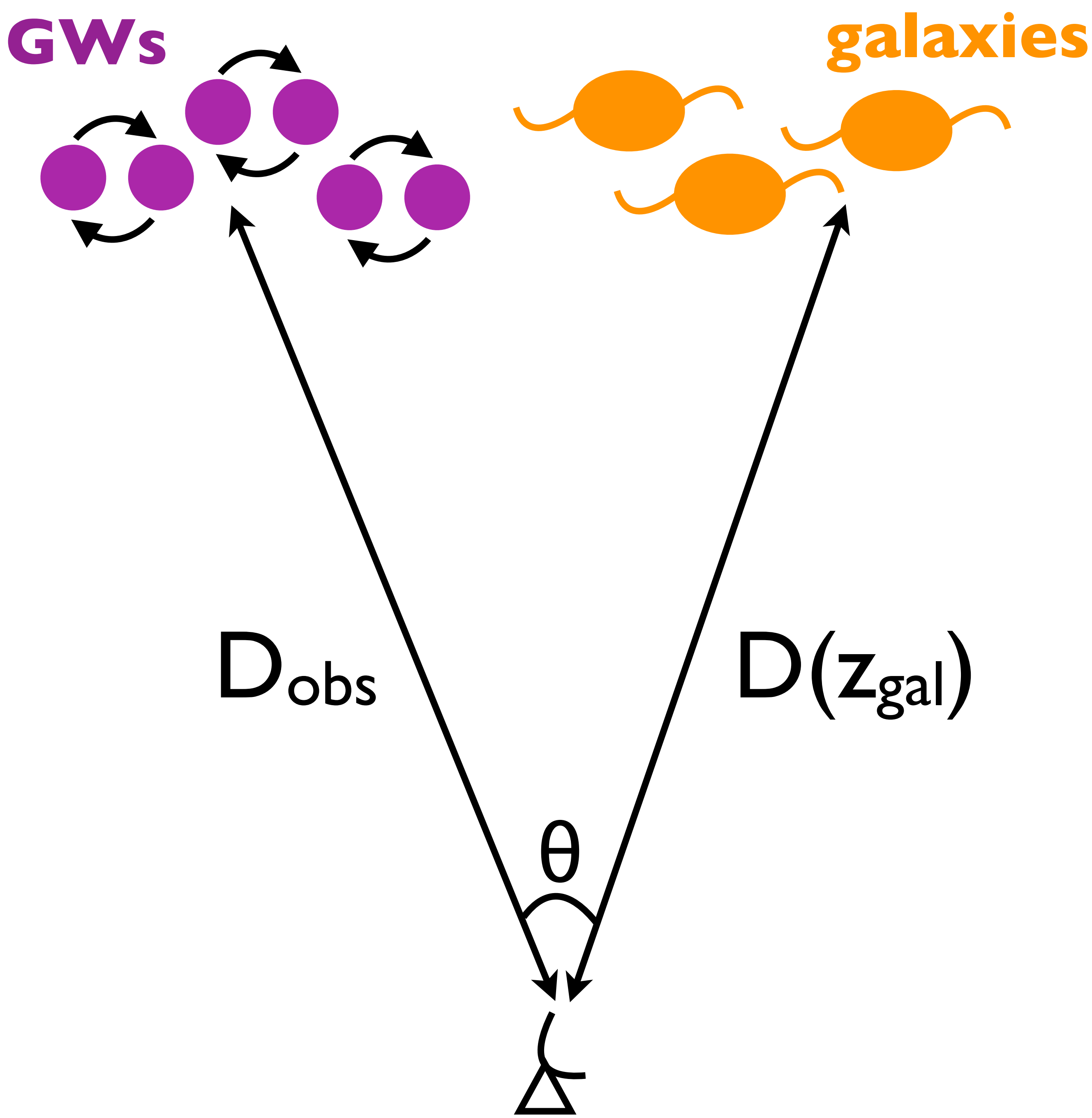
- cross-correlation of spatial distributions

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

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



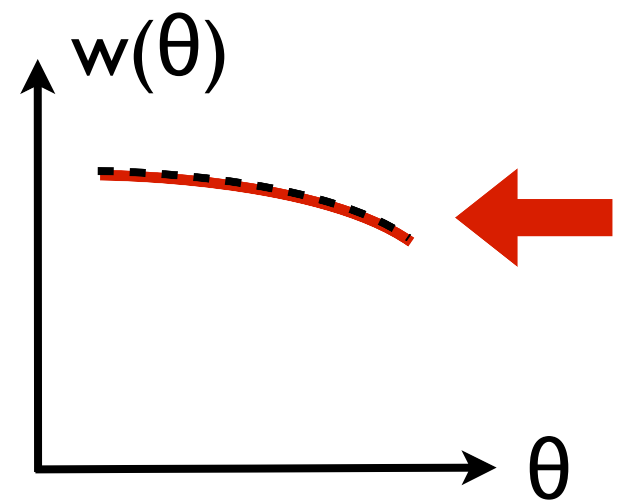
Cross-correlation approach



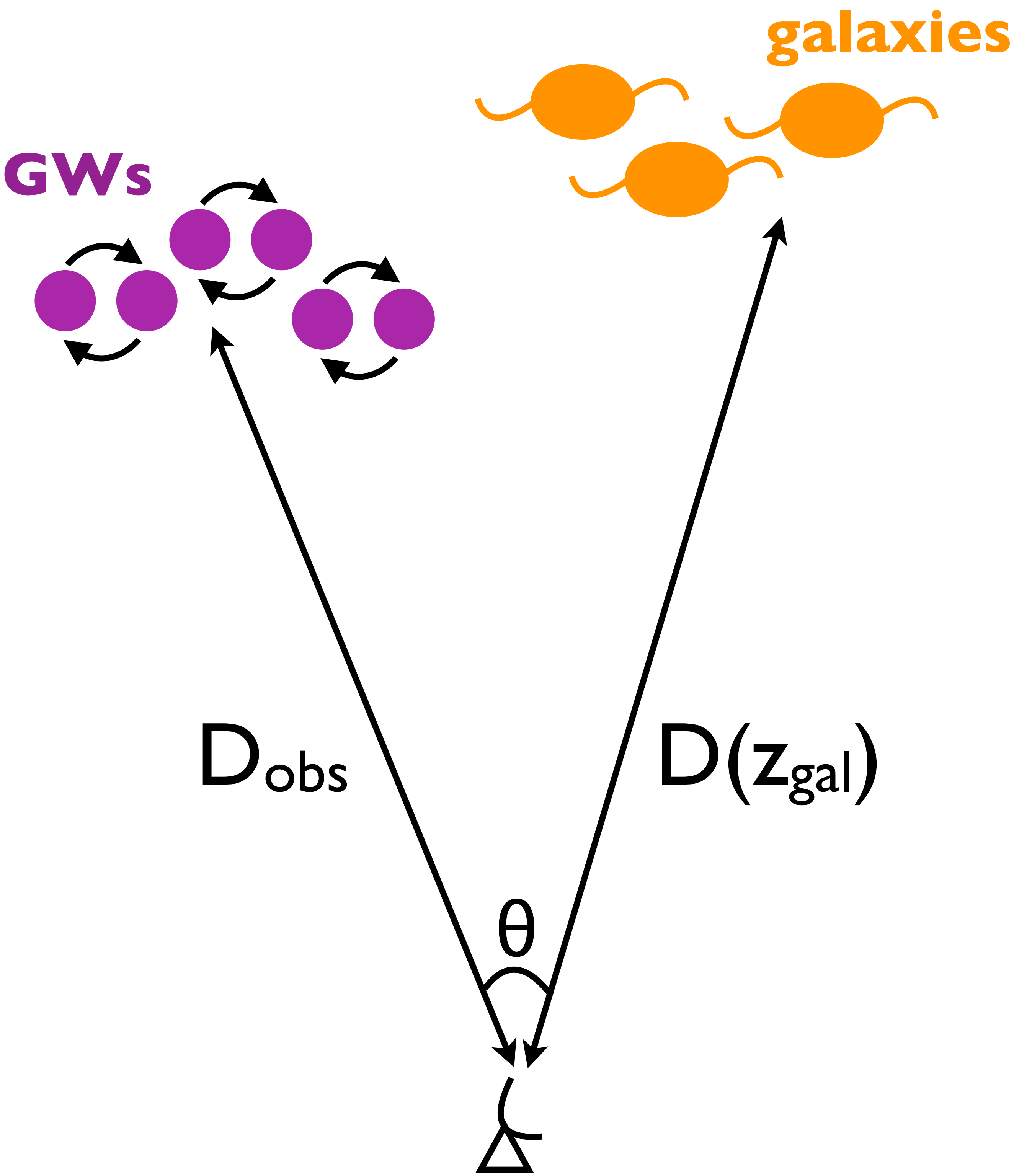
- cross-correlation of spatial distributions

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

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



Cross-correlation approach



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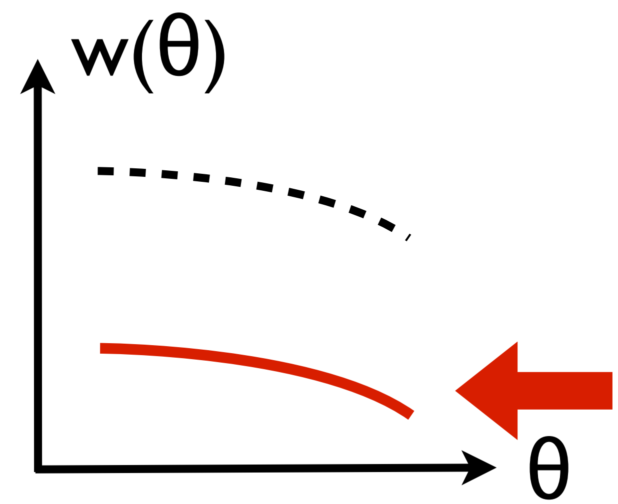
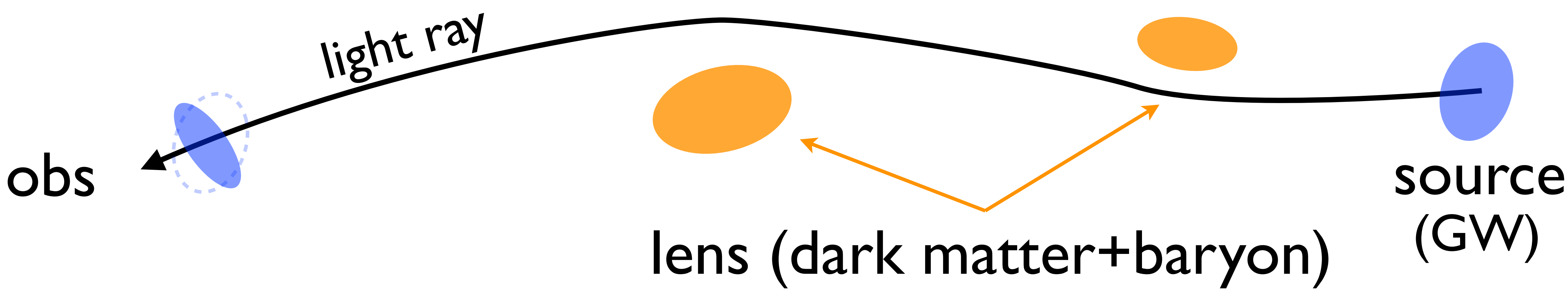


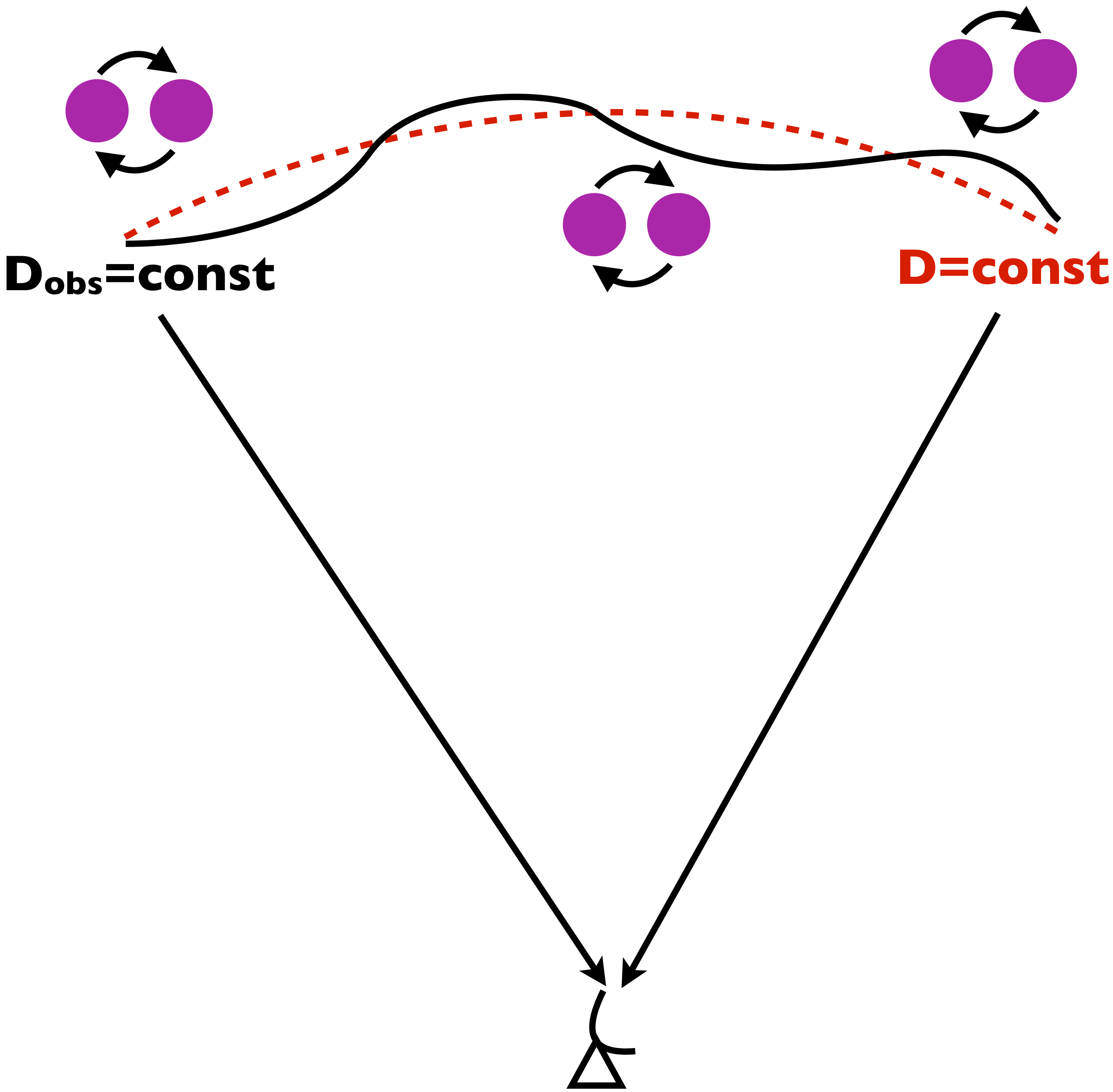
Gravitational lensing as noise



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

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

Apparent clustering due to lensing



- lensing depends on sky position
- induces additional clustering pattern on the sky

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Cross-correlation signals

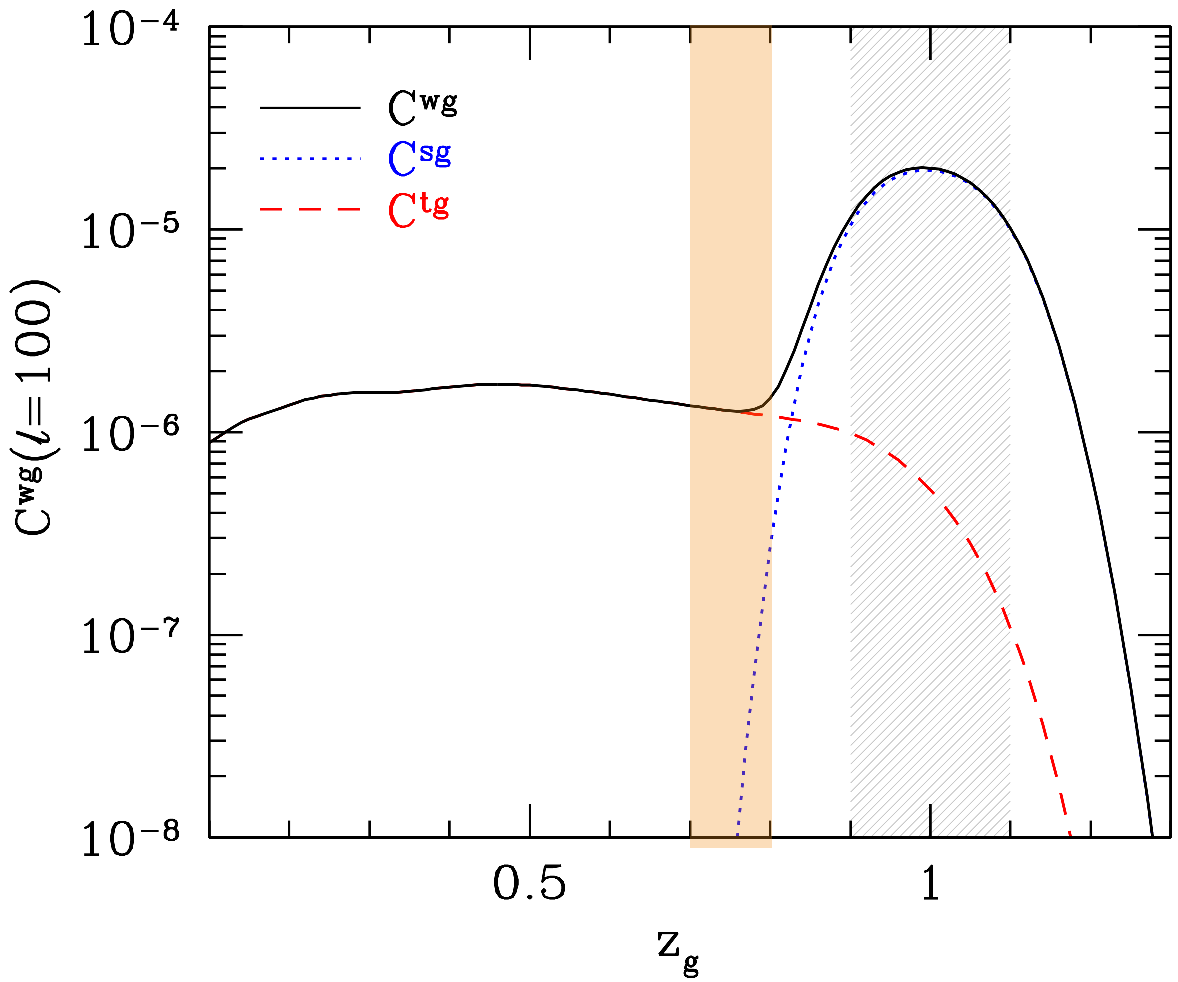
$$C^{\mathrm{w}_i\mathrm{g}_j}(\ell) = C^{\mathrm{s}_i\mathrm{g}_j}(\ell) + C^{\mathrm{t}_i\mathrm{g}_j}(\ell)$$

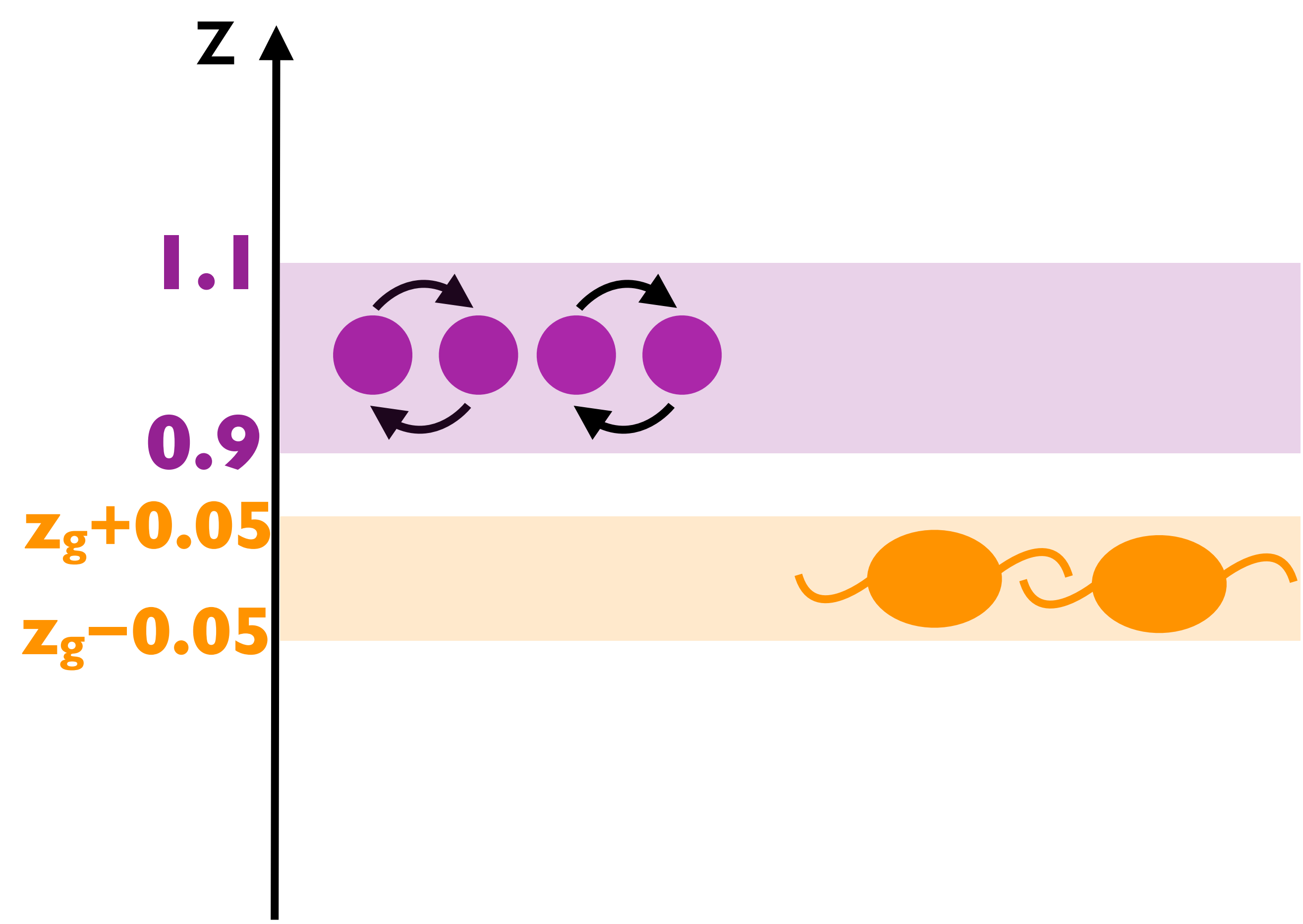
$$C^{\mathrm{s}_i\mathrm{g}_j}(\ell) = \int_0^\infty dz\, W_i^{\mathrm{s}}(z) W_j^{\mathrm{g}}(z) \frac{H(z)}{\chi^2} b_{\mathrm{GW}} b_{\mathrm{g}} P_{\mathrm{m}} \left(\frac{\ell + 1/2}{\chi}; z \right)$$

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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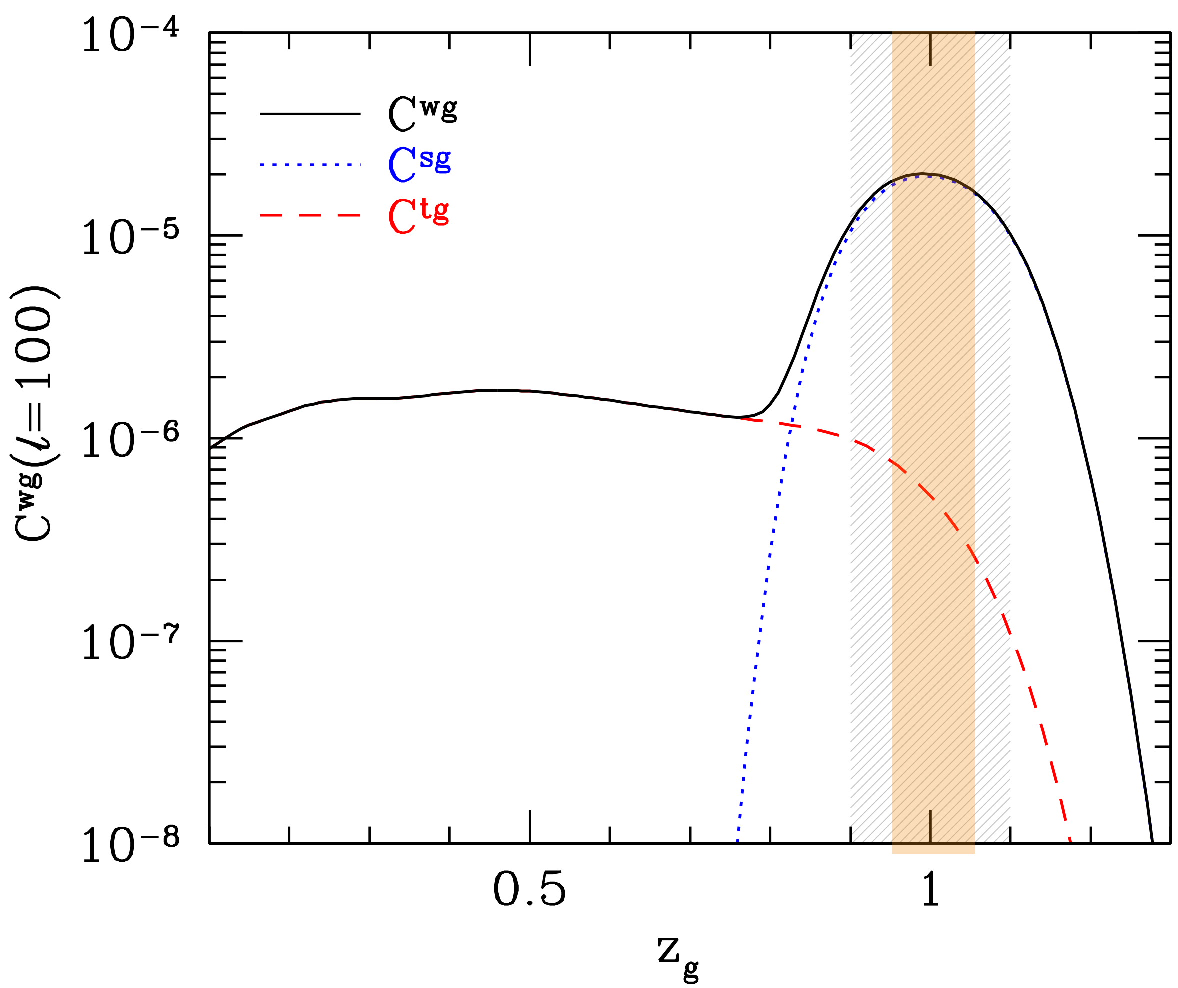
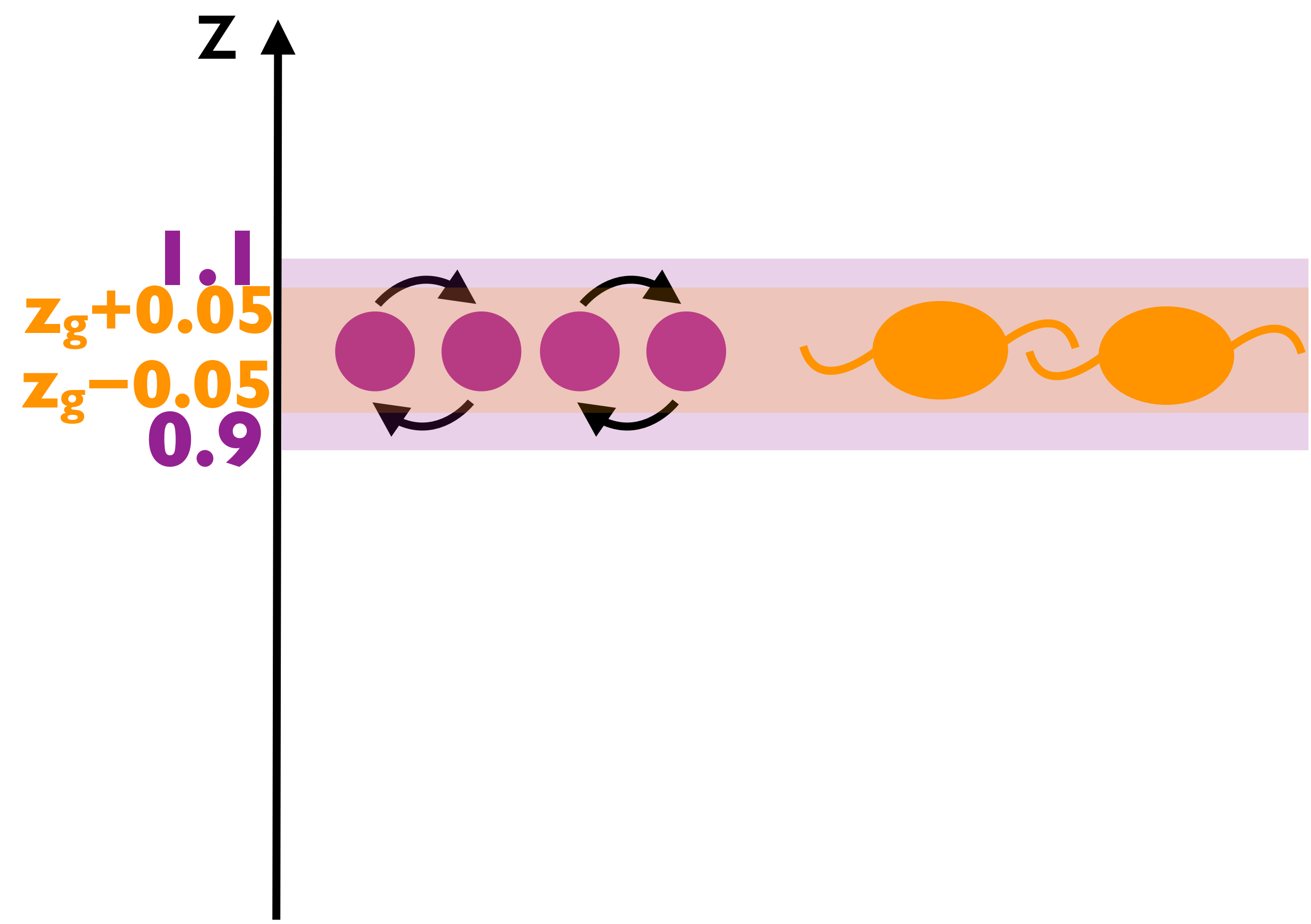
apparent clustering due to weak lensing





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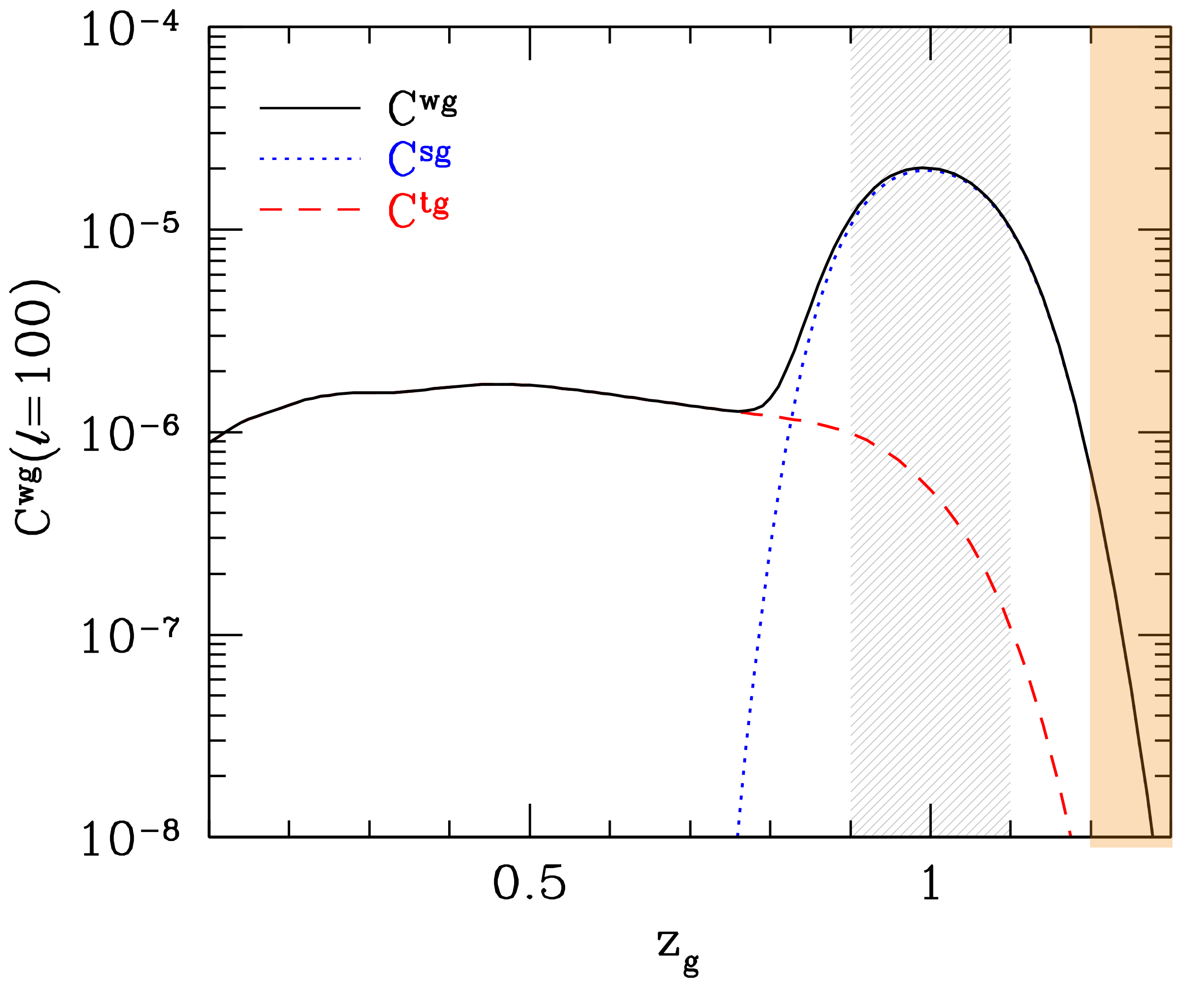

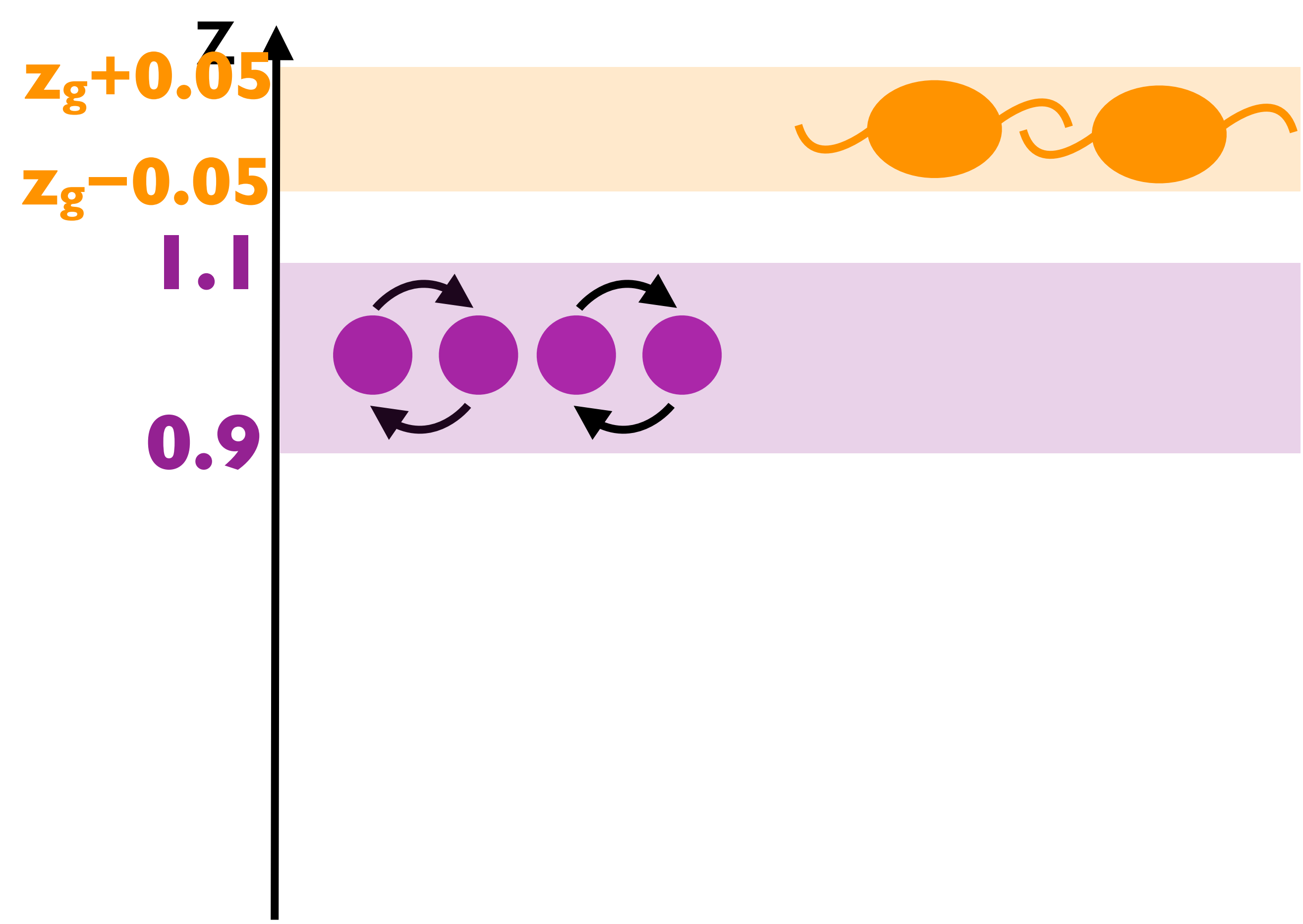

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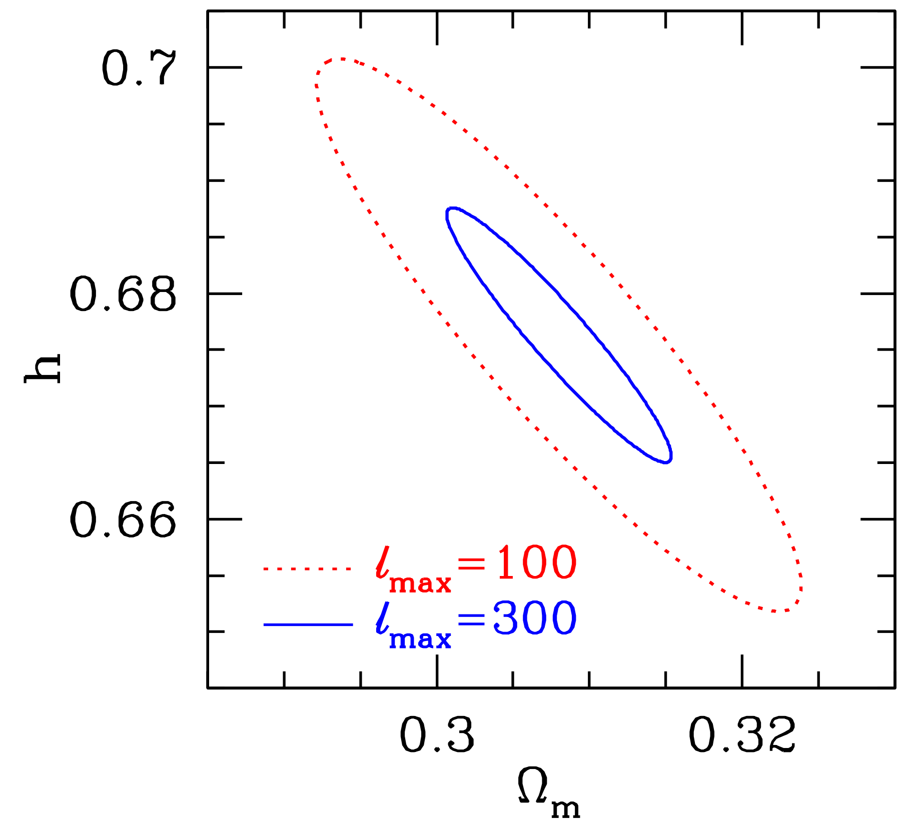
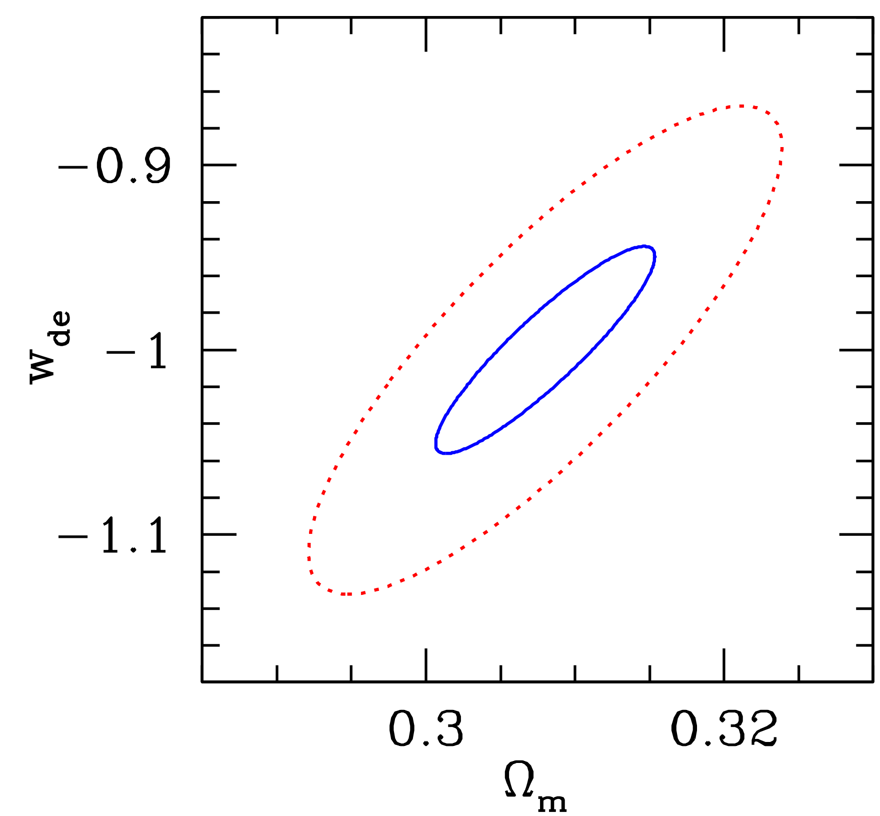
Forecast

- GWs from 3rd-generation exp. + galaxies from Euclid (0.3<z<1.5)
- l_{max} is related with accuracy of GW localizations
- **tight constraints on H_0 and w possible with the cross-correlation!**





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Cross-correlation: Summary

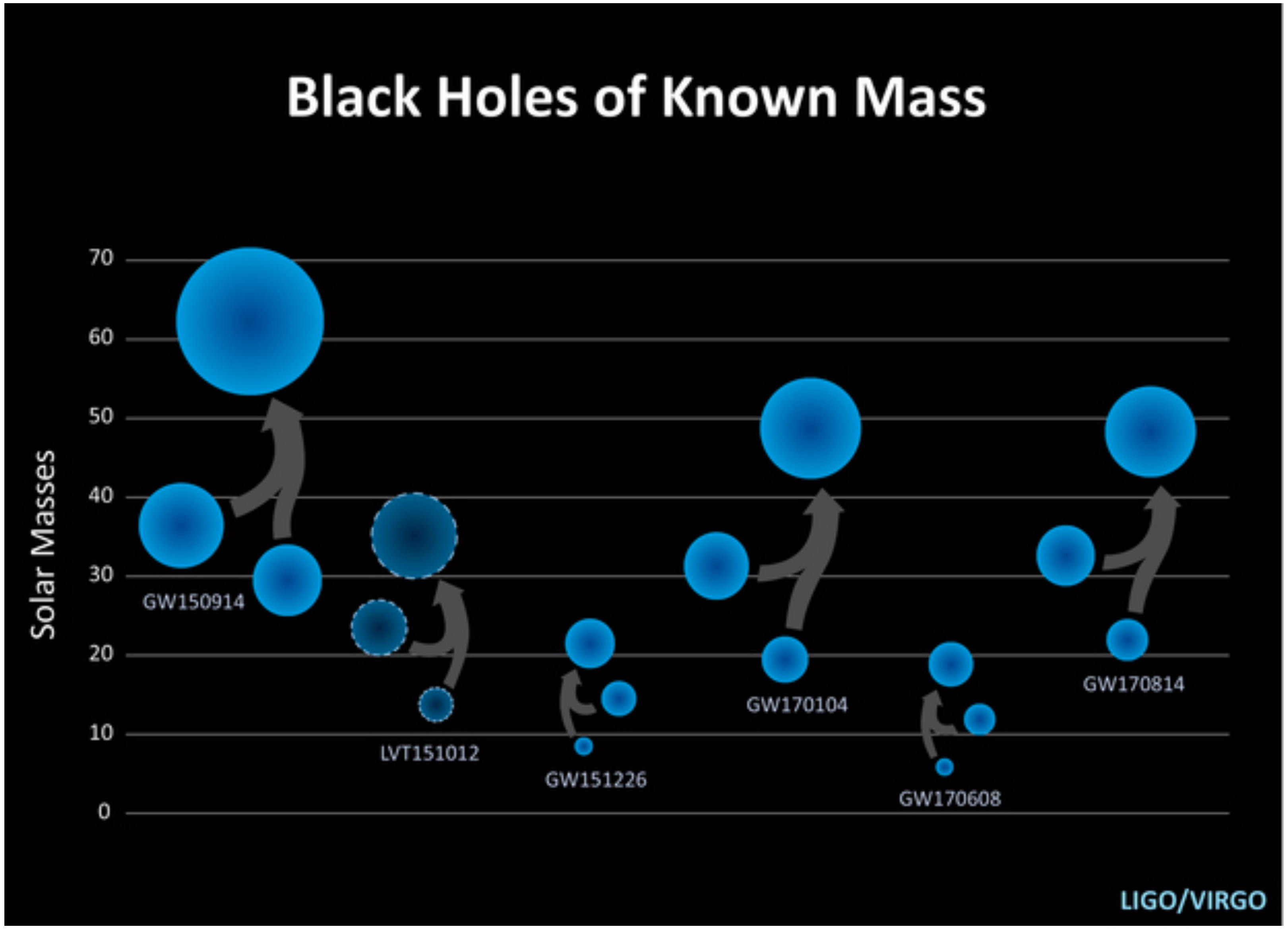
- **proposed cross-correlation of GW sources and galaxies with known z** to constrain H_0 and other cosmological parameters

- standard siren cosmology without redshift and even at high-z

- other applications of cross-correlation?
  - infer progenitor from bias (e.g., Raccanelli+2016)
  - 3D clustering in distance space (e.g., Zhang 2018)

a lot of room to explore!

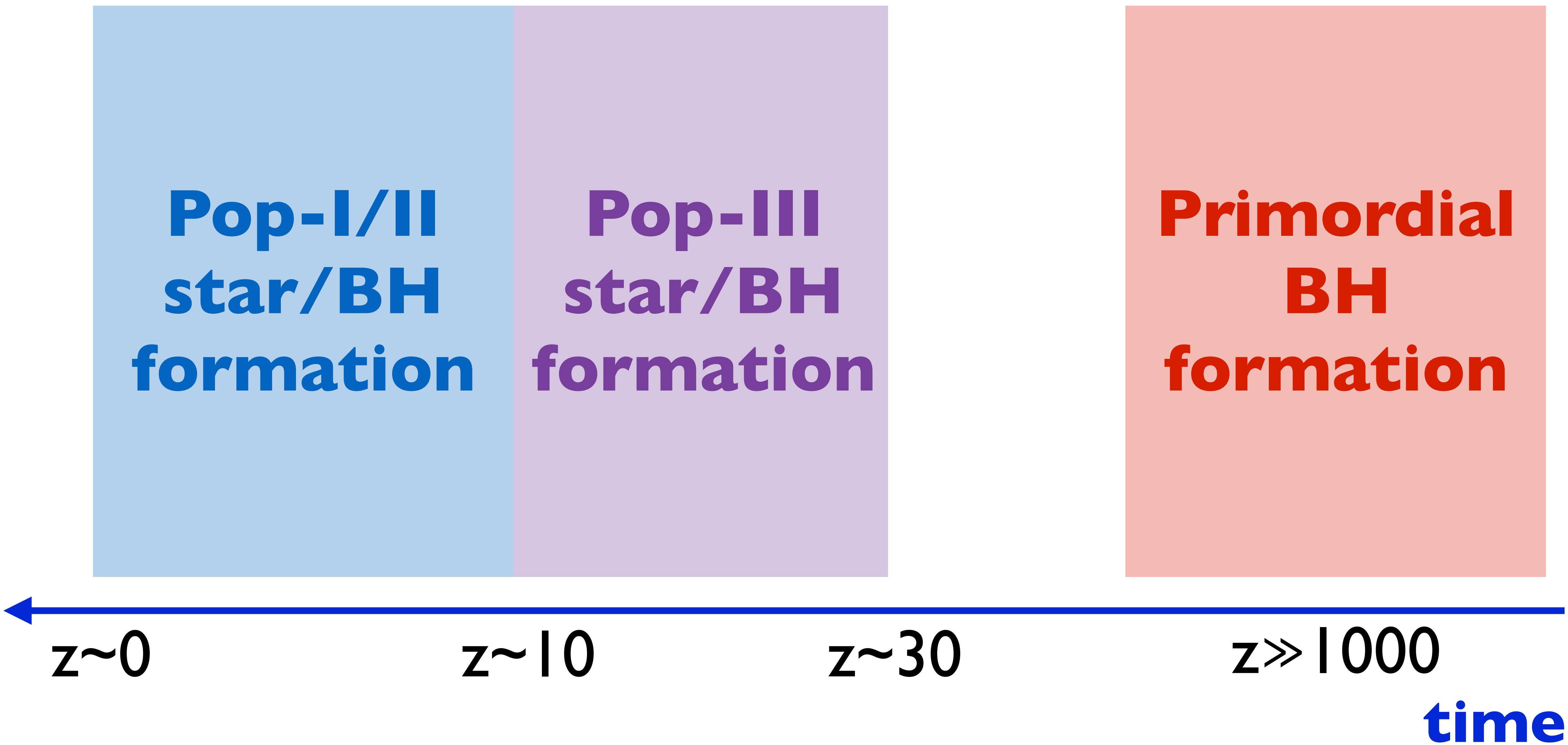
Origin of binary BHs?



https://www.ligo.caltech.edu

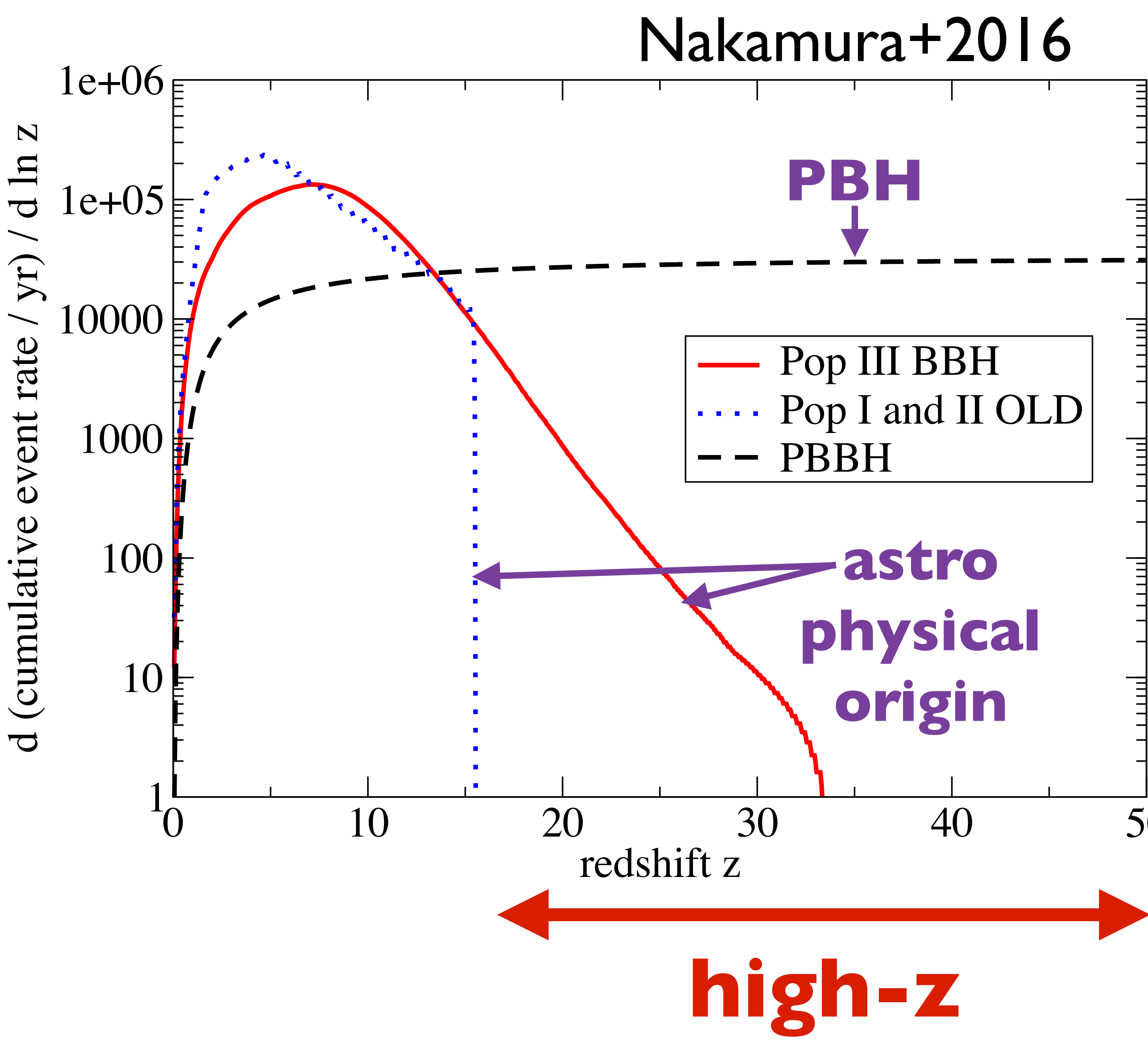
- ~10-30 $M_\odot$ BHs discovered by LIGO/VIRGO
- their origin still unknown
  - **Pop-I/II?**
  - **Pop-III?**
  - **PBH?**

Models of BH formation



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

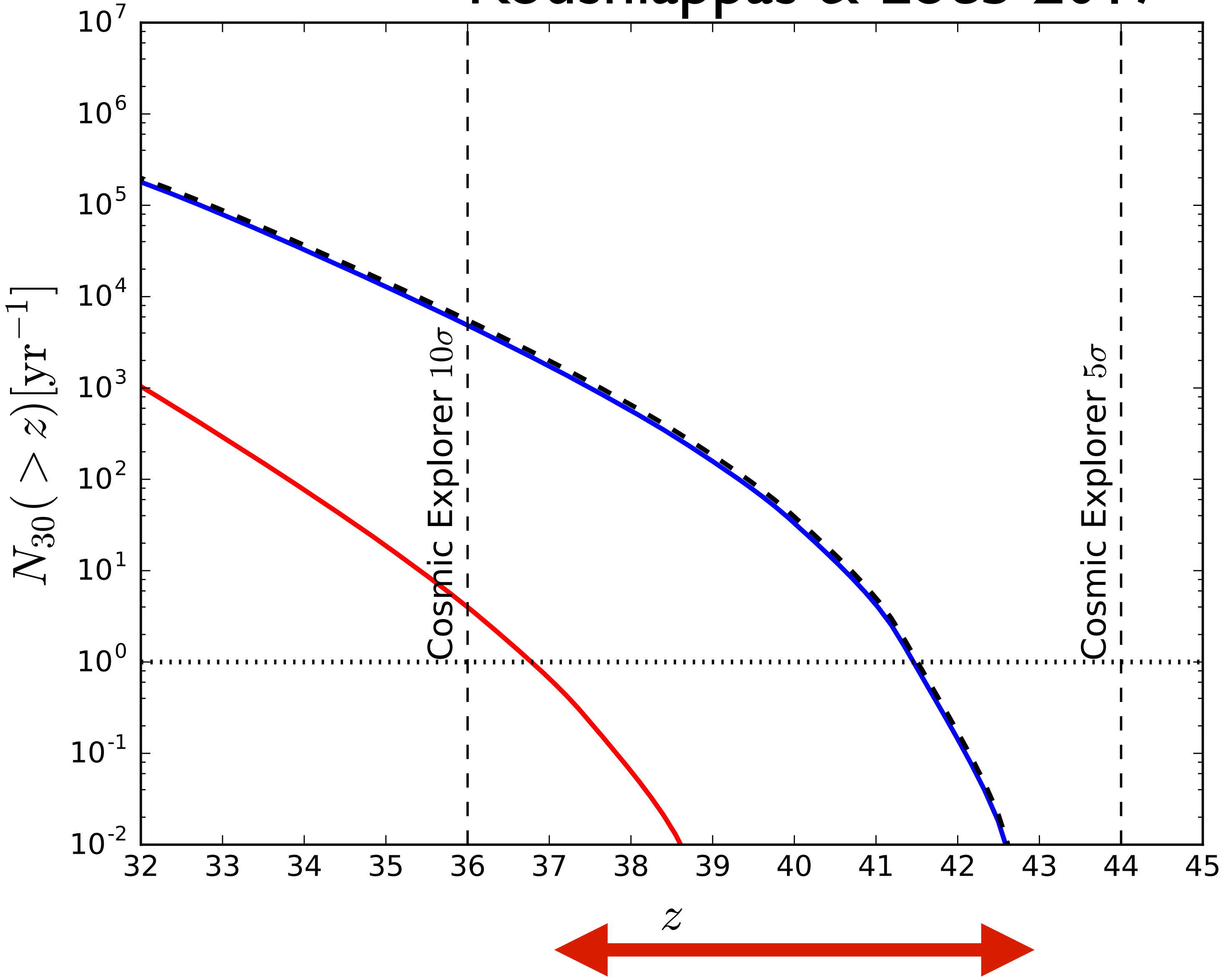
Key observation: high-z events



- different scenarios predict different event rates at z≳15
- accessible in 3rd-gen. experiments

Key observation: high-z events

Koushiappas & Loeb 2017



- different scenarios predict different event rates at z≳15
- accessible in 3rd-gen. experiments

maximum z ~ 40
for astrophysical origin

“High-z” events?

- from GW observations we do not directly measure their redshifts
- we measure **luminosity distance**, which is affected by gravitational lensing
- **lensing magnification μ** can bias redshift inferred from the luminosity distance, and also chirp mass

Observed redshift and mass

- "**observed redshift**" z_{obs} defined as

$$D_{\mathrm{L}}(z_{\mathrm{obs}}) = \frac{D_{\mathrm{L}}(z)}{\sqrt{\mu}}$$

μ: magnification factor

- "**observed chirp mass**" $\mathcal{M}_{obs}$ defined as

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

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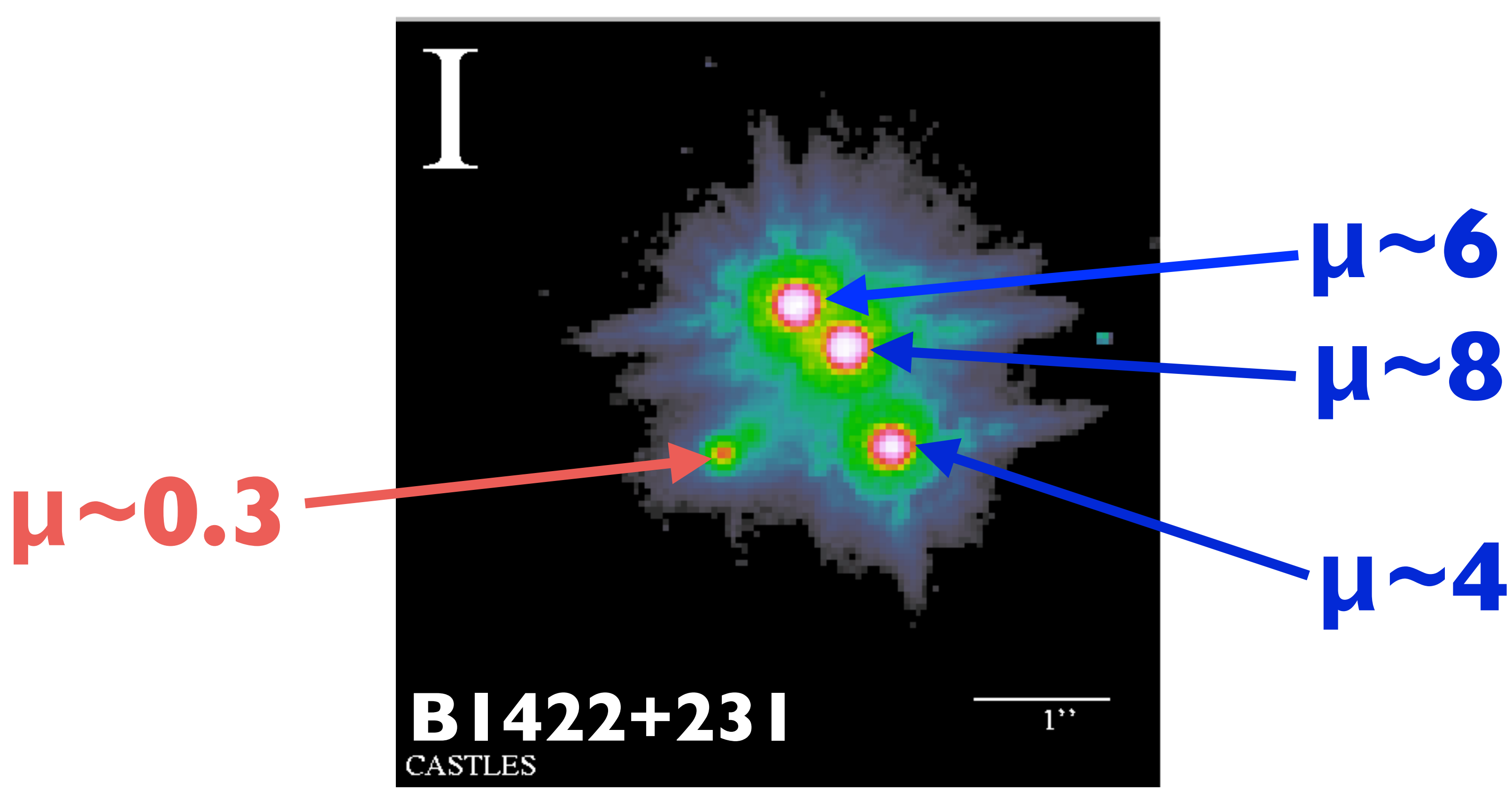
Distributions with lensing effects

- redshift and mass dist. of binary BH mergers taking full account of gravitational lensing
- various scenarios: **PopI/II**, **Pop-III**, **PBH**
- various experiments: **aLIGO**, **KAGRA**, **ET**, **CE**, **B-DECIGO**
- check how lensing (de-)magnification modify these distributions

Strong lensing of BH mergers

- difficult to identify multiple images given the poor localization on the sky
  → **treat multiple images as distinct events**

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



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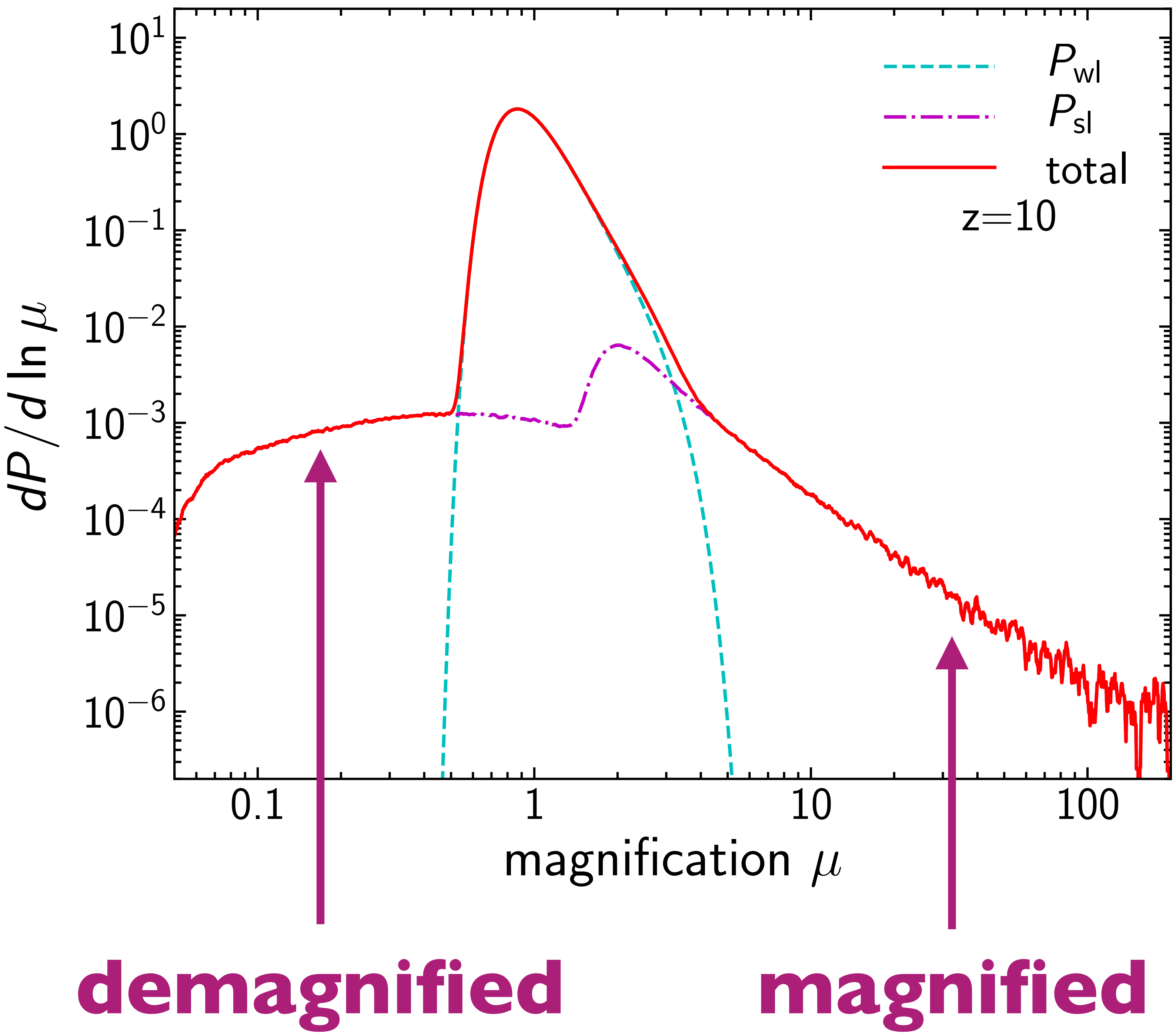
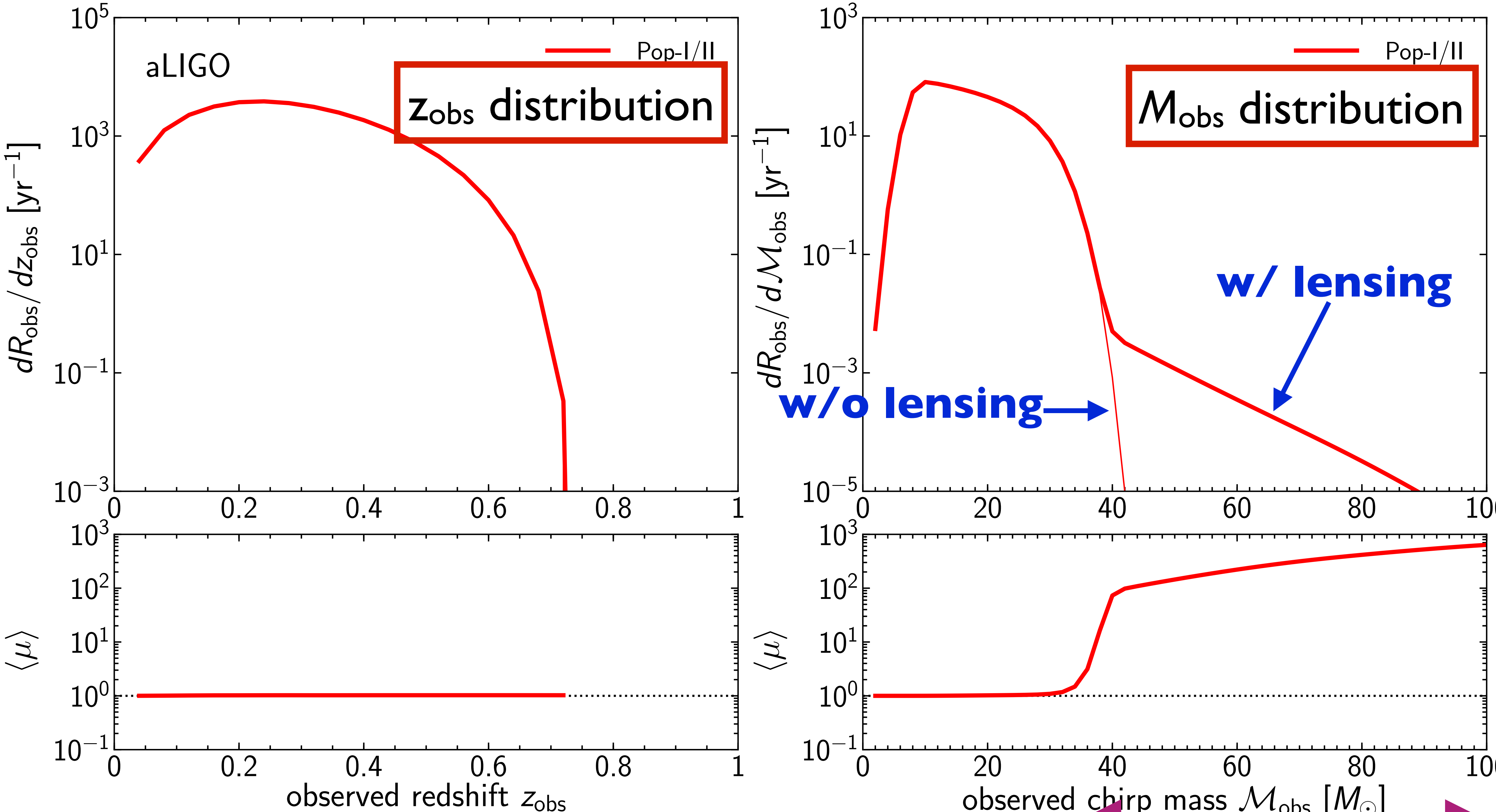
Magnification PDF



- **new hybrid model** combining weak+strong lens
- weak lens from analytic model, strong lens from Monte Carlo
- long tails at high and low μ

Result: advanced LIGO



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

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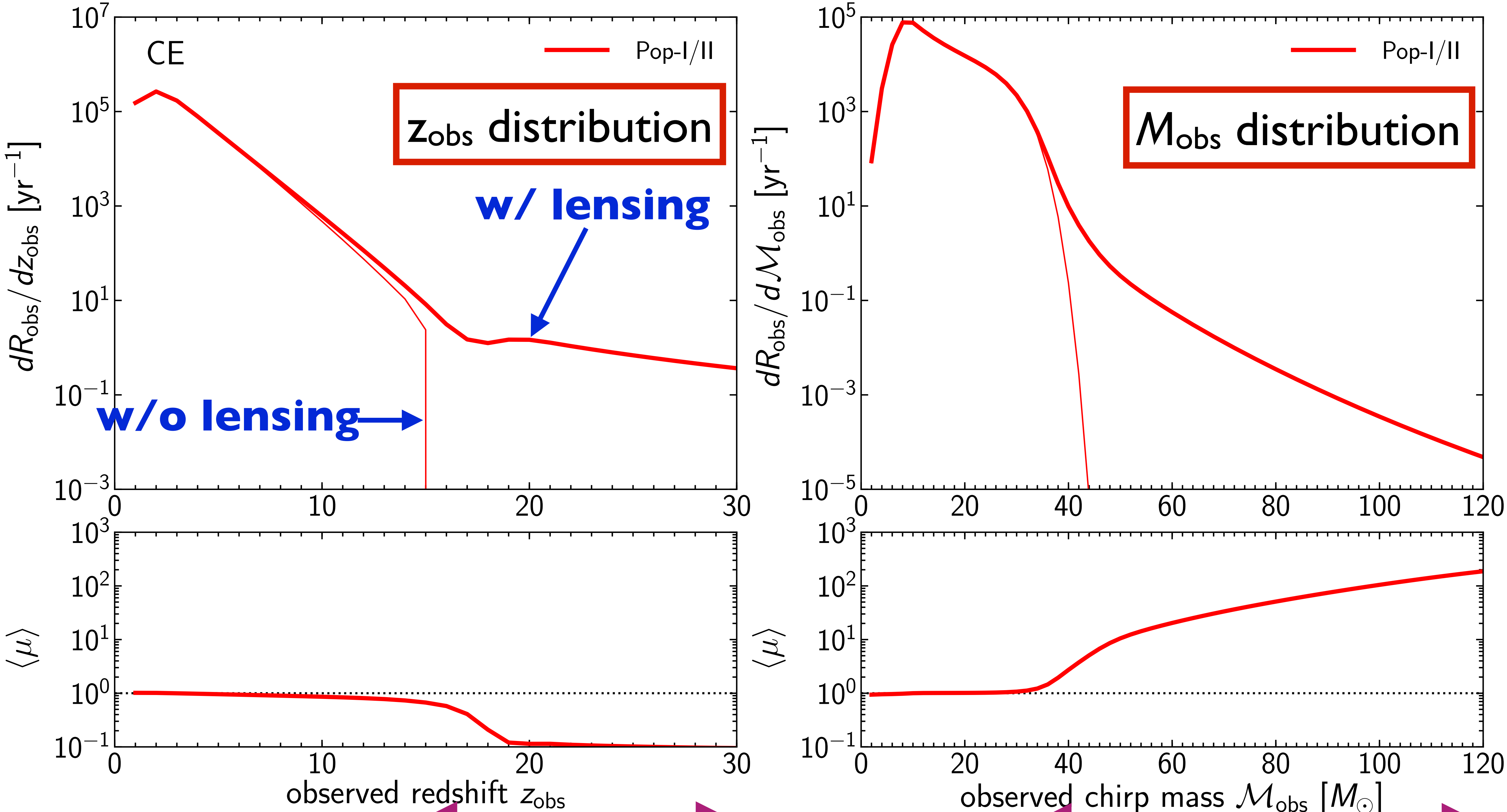
Result: Cosmic Explorer



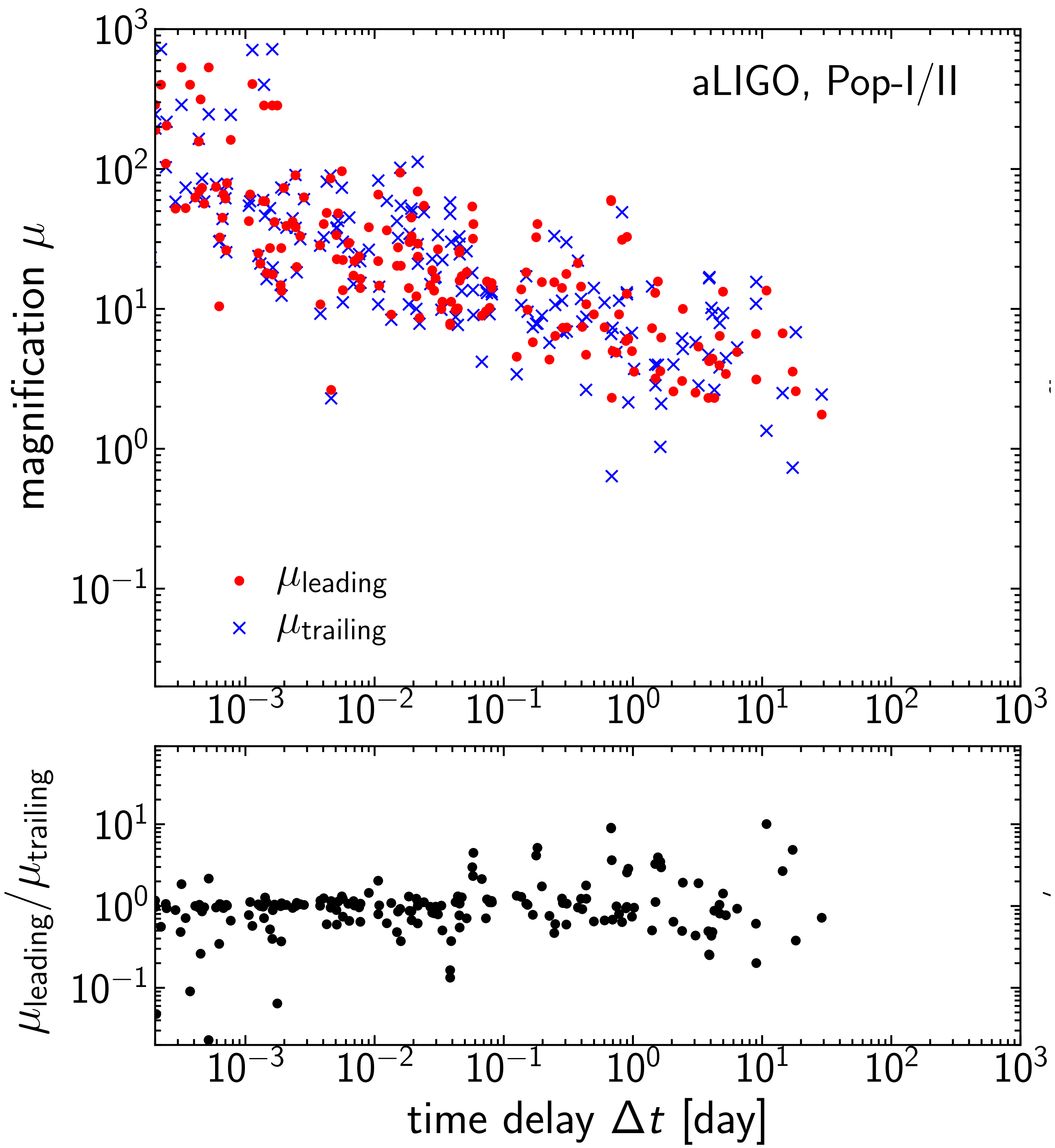
excess due to **demagnified** events

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

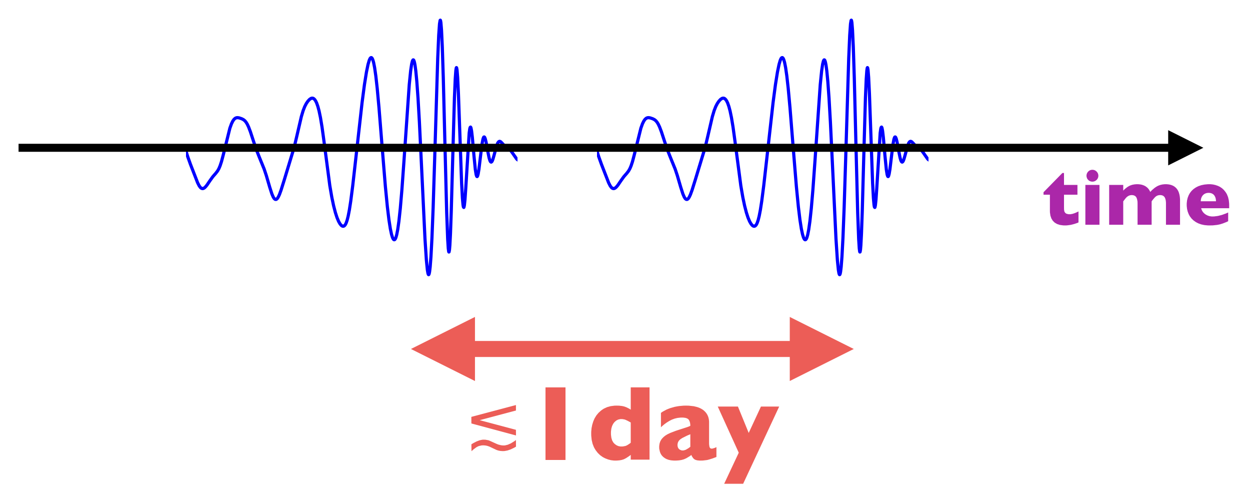
Effect of lensing (de-)magnification

- produce apparently **very high-z** and **very high mass** binary BH merger events
- high-z events due to **demagnification**, and high mass events due to **magnification**
- those events are strongly lensed, so should be accompanied by other **multiple images**

Expected multiple image pairs

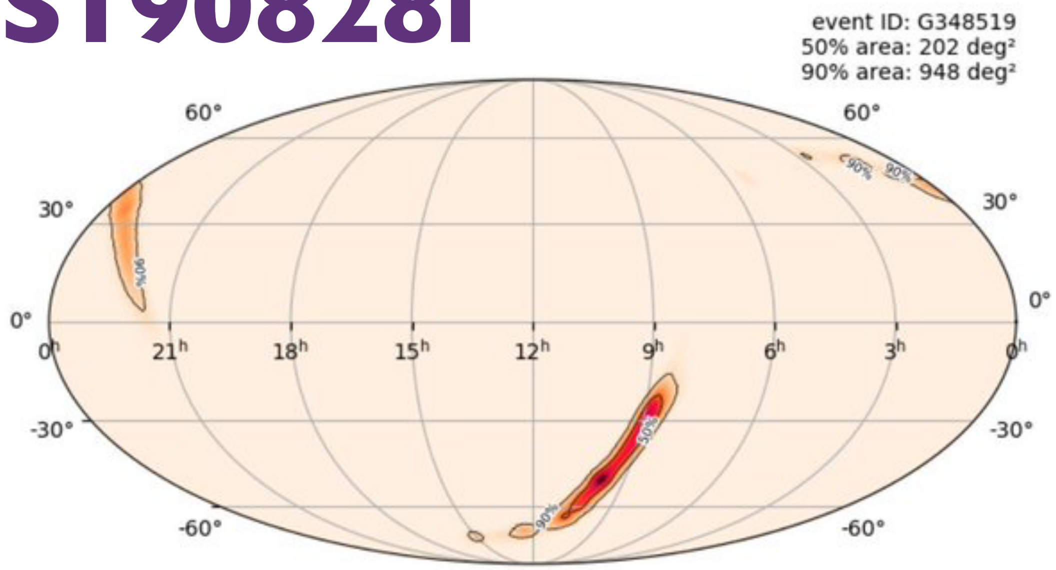


- **advanced LIGO**
  - time delay $\lesssim$ **1 day**
  - high, similar μ
  - $R_{obs} < 1\ yr^{-1}$



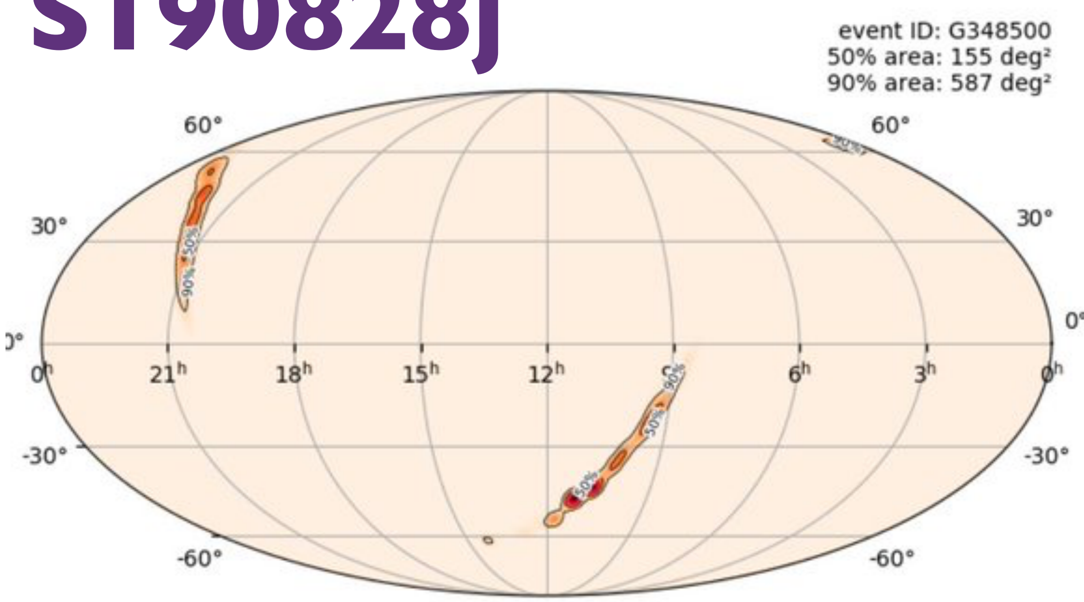
Gravitationally lensed GW??

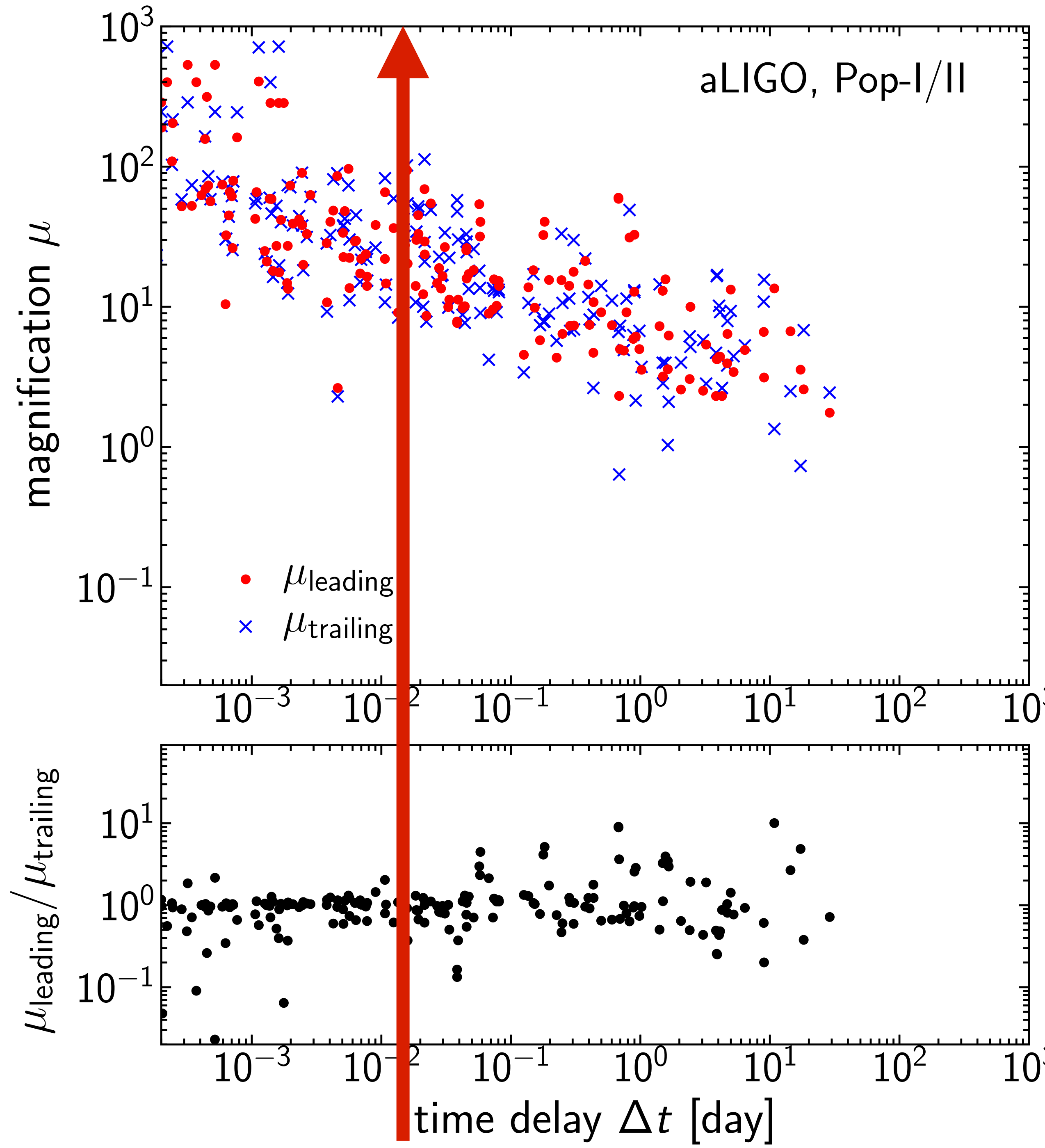
S190828l



separated by 21 min

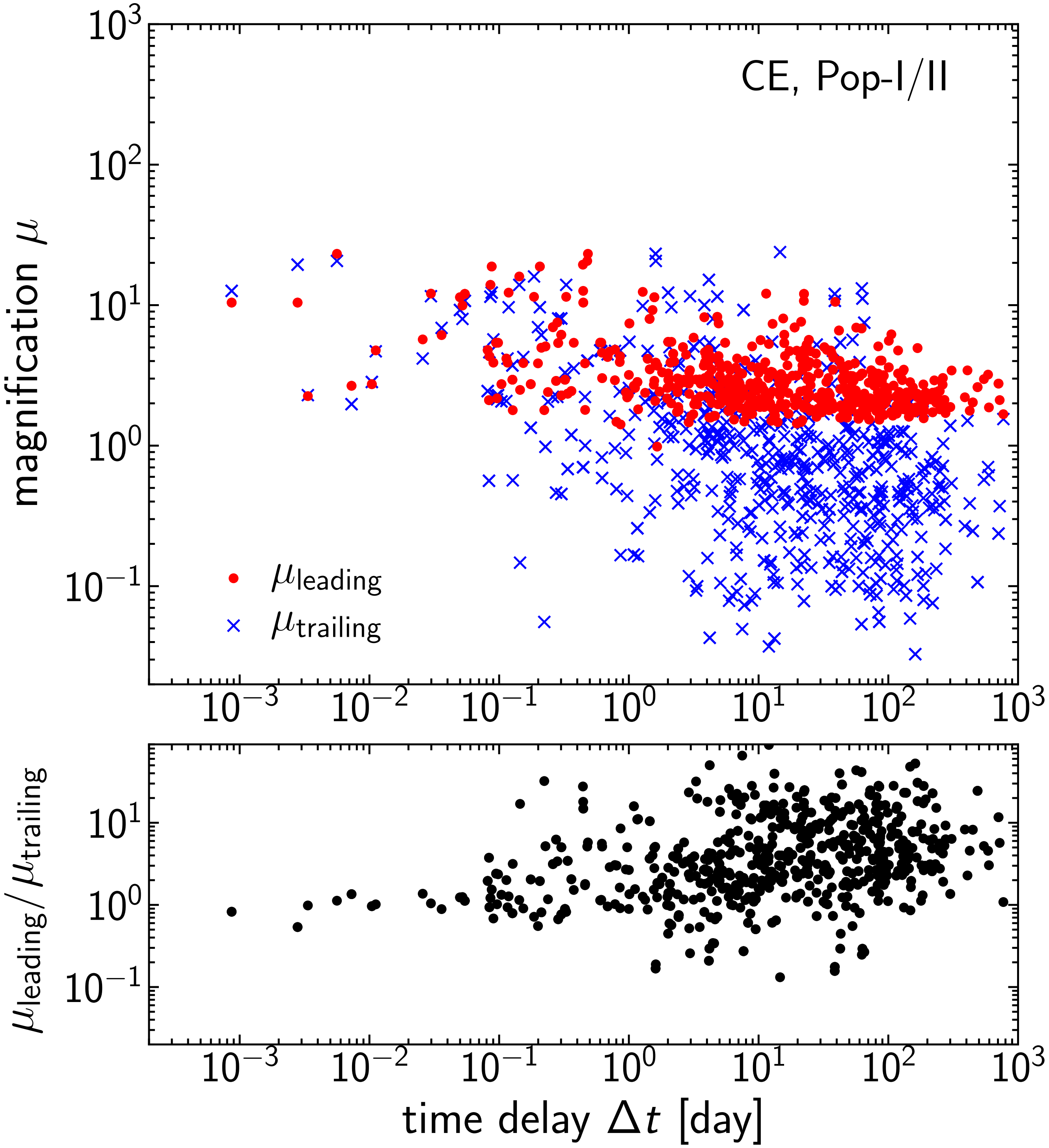
S190828j



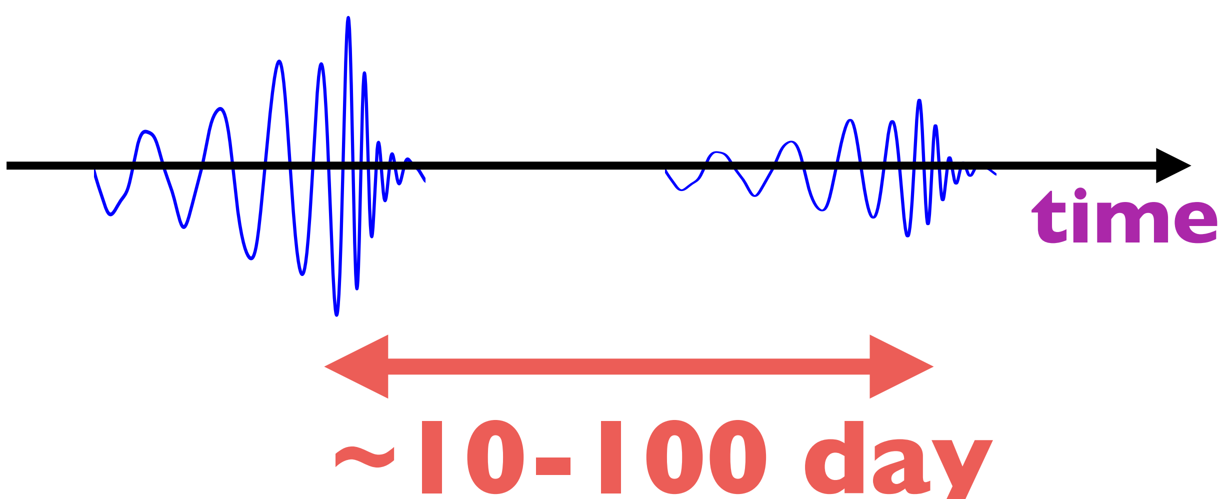


21 min (!)

Expected multiple image pairs



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



Binary BH distribution: Summary

- **pronounced lensing effect at high z_{obs} and M_{obs}**
- the discovery of apparently very high-z events does not necessarily support PBH scenario
- predictions on multiple image pairs
- see the paper for detailed results for different BH merger scenarios and GW experiments

Conclusion

- **interesting synergies** between **GW** and **large-scale structure**/**gravitational lensing**
  - spatial clustering of GW sources
  - observables affected by weak and strong gravitational lensing
- more work needed to fully exploit the potential of GW observations!

Review article arXiv:1907.06830 (covering SN, GRB, FRB, GW)

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