Title: Gravitational waves in the inhomogeneous Universe

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Abstract: The discovery of gravitational waves from a binary black hole merger in
2015 opened up a new window to study the Universe, including the origin of black holes, the nature of dark matter, and the expansion history of the Universe. However, gravitational waves emitted from binary mergers propagate through the inhomogeneous Universe, which can have a considerable impact on observations of gravitational waves, in good or bad ways. I will highlight some examples of the effects of the inhomogeneity on gravitational wave observations, including their possible applications and implications.

Gravitational waves in the inhomogeneous Universe

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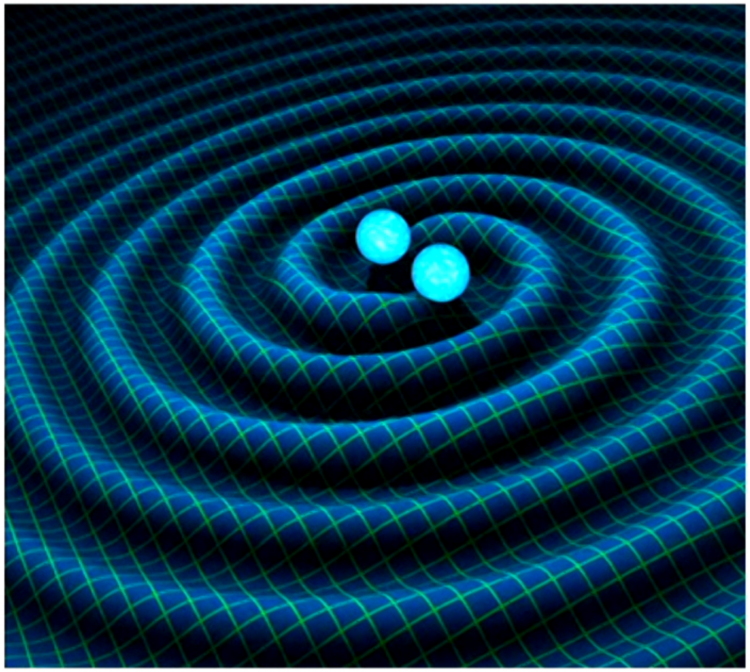
2019/9/3 Cosmological Frontiers in Fundamental Physics@Perimeter

Plan of this talk

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

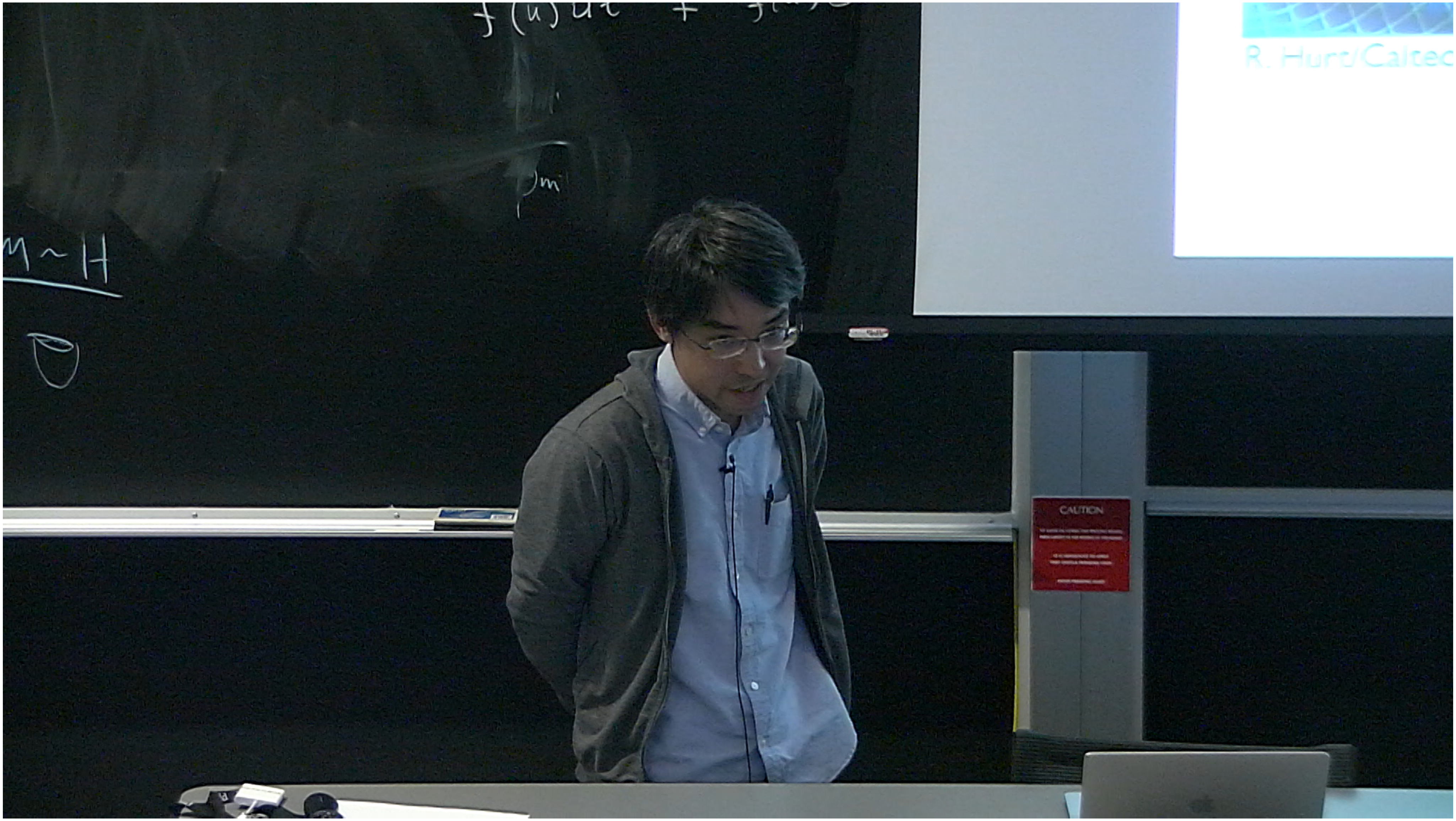
- effect of gravitational lensing on the distribution of binary black hole mergers
  [MO MNRAS **480**(2018)3842]

Gravitational waves (GW)



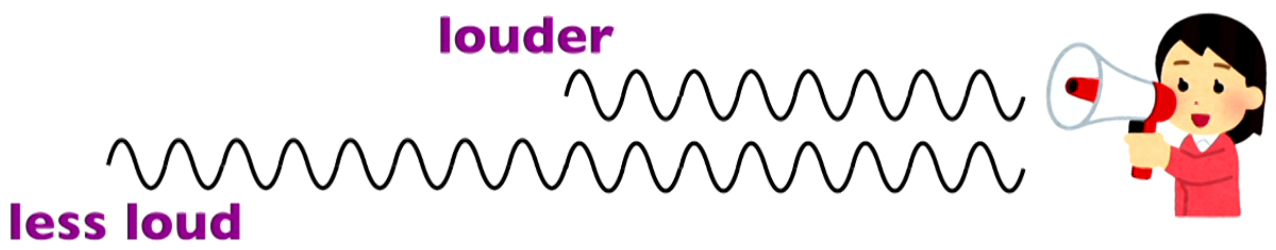
R. Hurt/Caltech-JPL/EPA

- 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!**

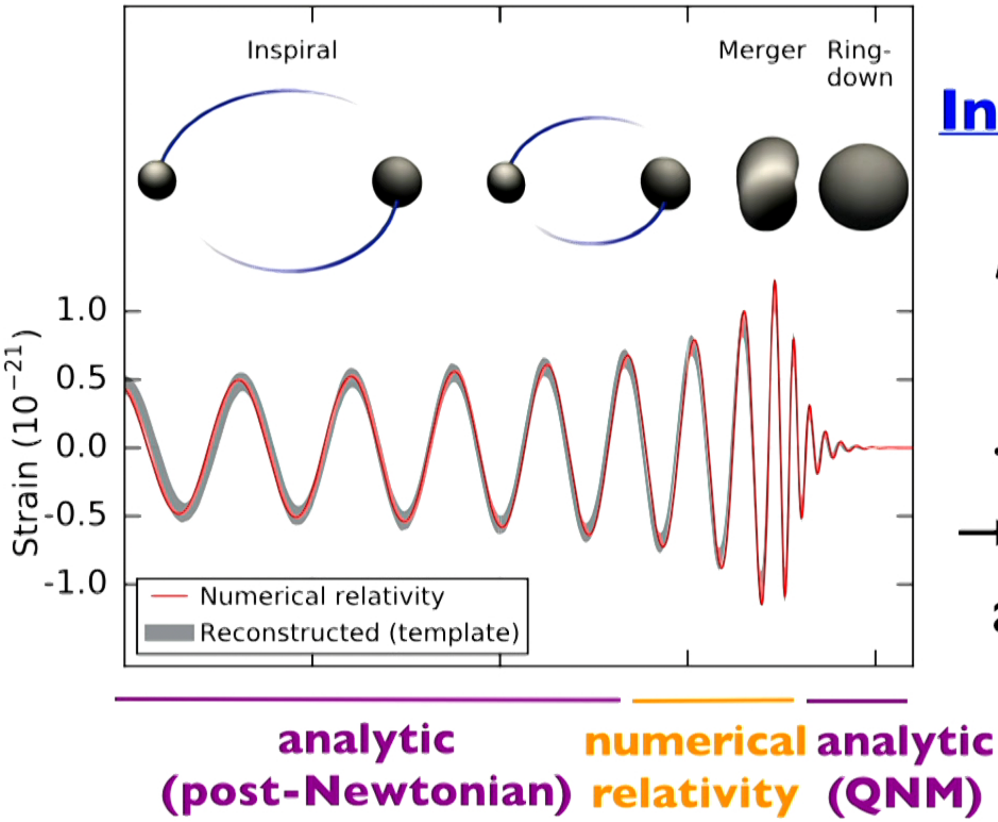

CAUTION

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



Inspiral

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

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

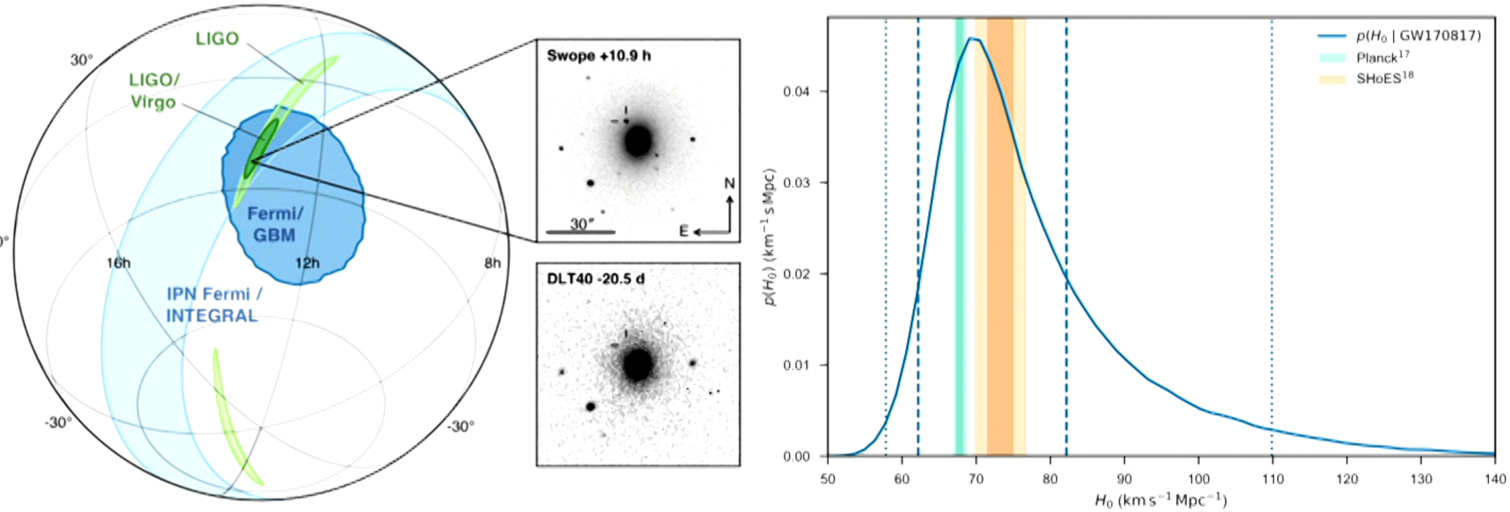
→ **chirp mass M_z** and **distance D_L**

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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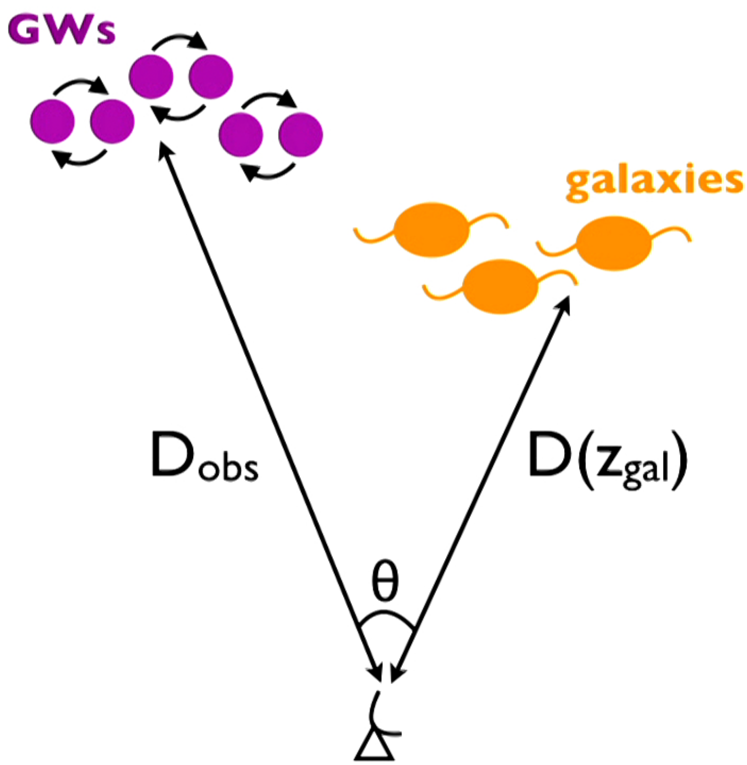
Cross-correlation approach

- **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

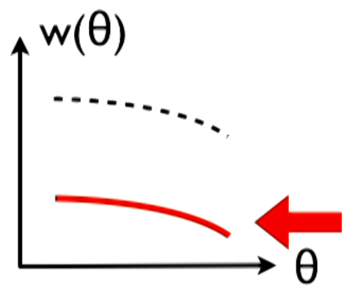
Cross-correlation approach



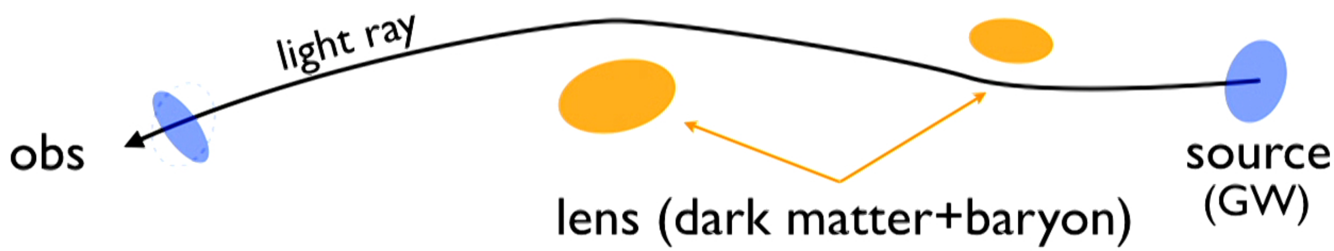
- cross-correlation of spatial distributions

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

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



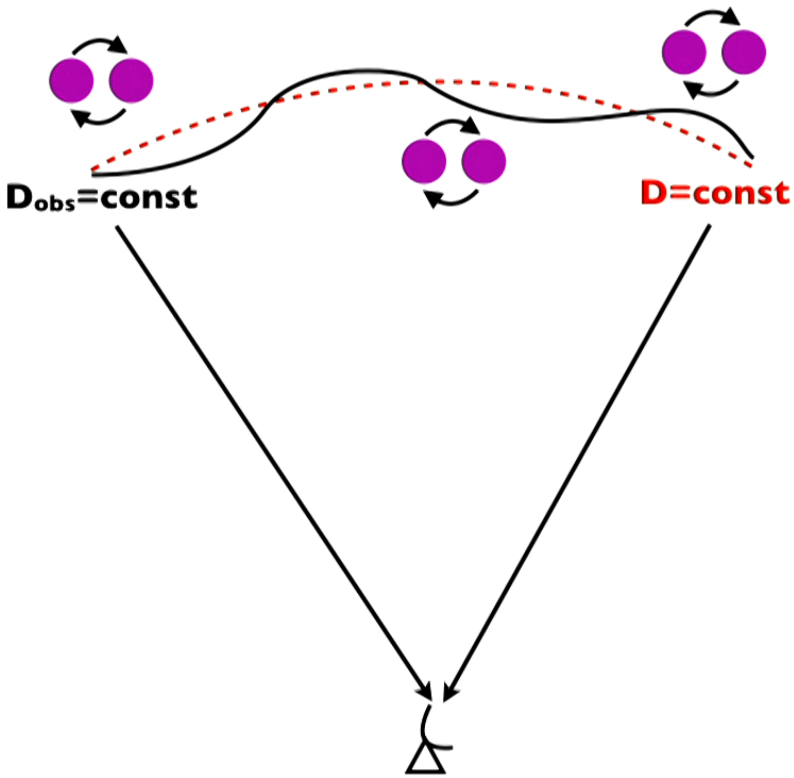
Gravitational lensing as noise



- 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

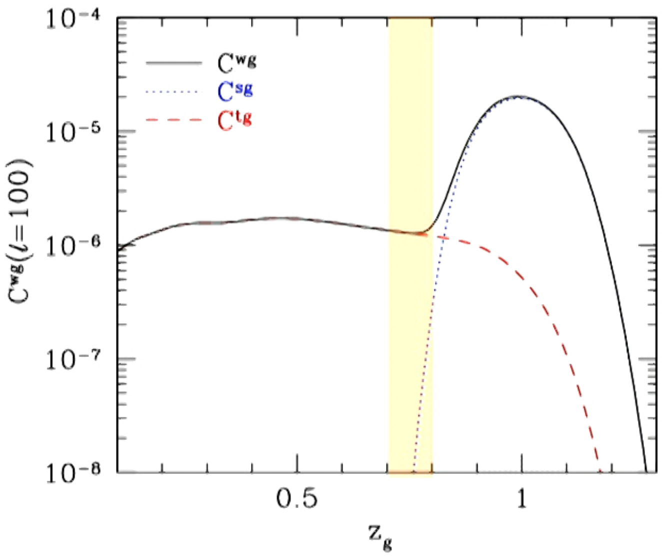
$$C^{\mathrm{w}_i\mathrm{g}_j}(\ell) = C^{\mathrm{s}_i\mathrm{g}_j}(\ell) + C^{\mathrm{t}_i\mathrm{g}_j}(\ell)$$

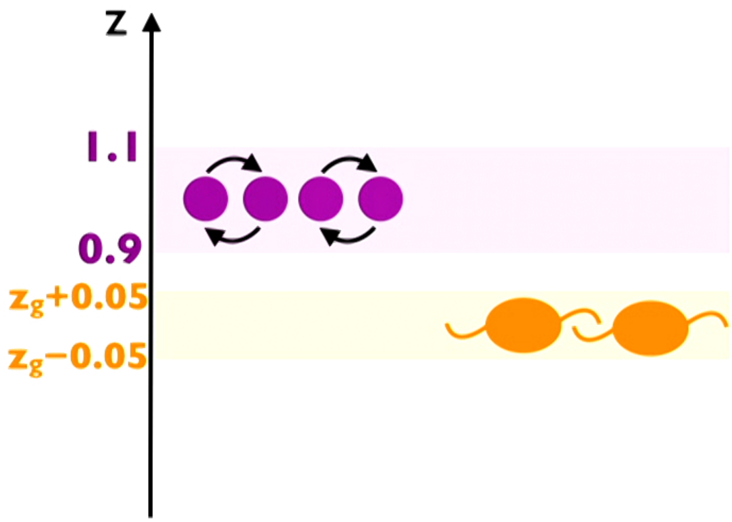
$$C^{\mathrm{s}_i\mathrm{g}_j}(\ell) = \int_0^\infty dz\, W_i^{\mathrm{s}}(z) W_j^{\mathrm{g}}(z) \frac{H(z)}{\chi^2} b_{\mathrm{GW}} b_{\mathrm{g}} P_{\mathrm{m}}\left(\frac{\ell+1/2}{\chi}; z\right)$$

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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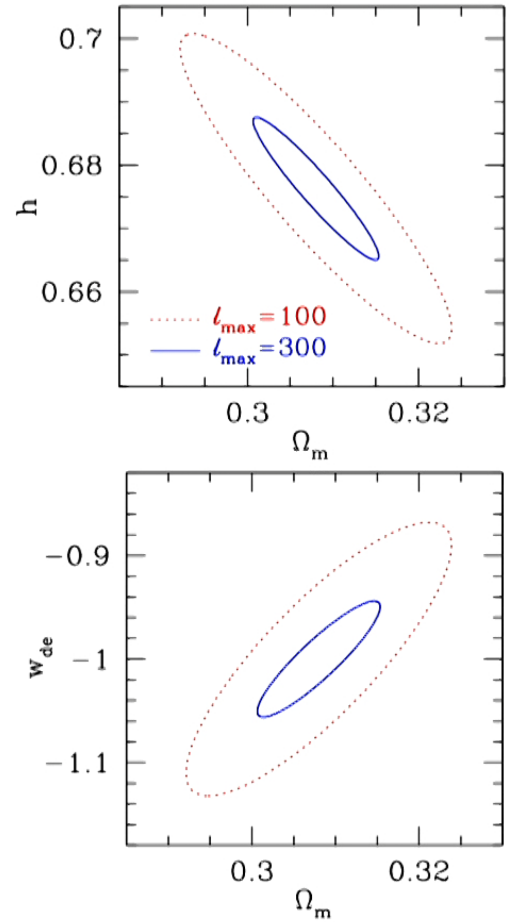
Forecast

- 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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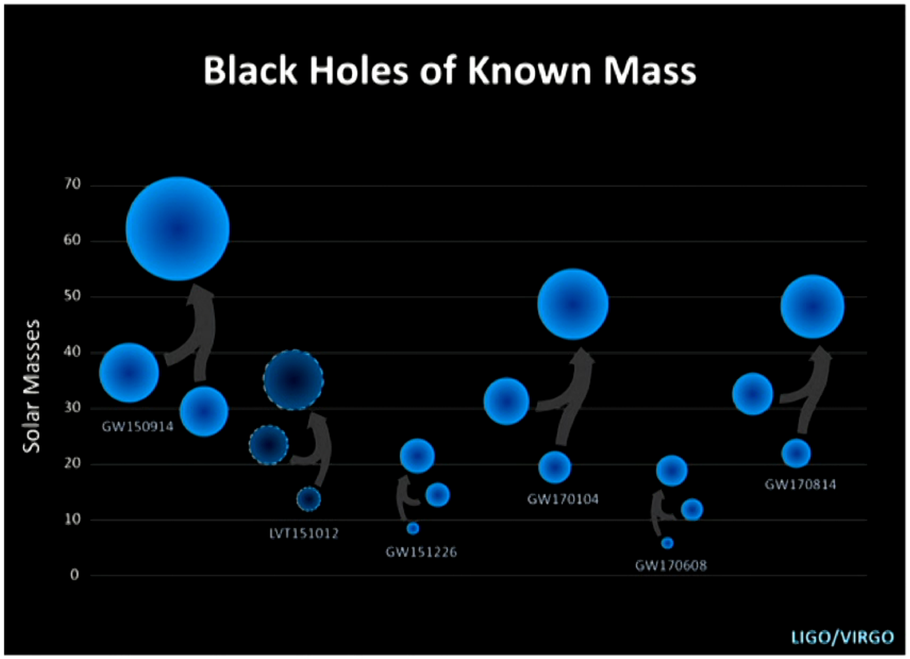
Cross-correlation: Summary

- **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!

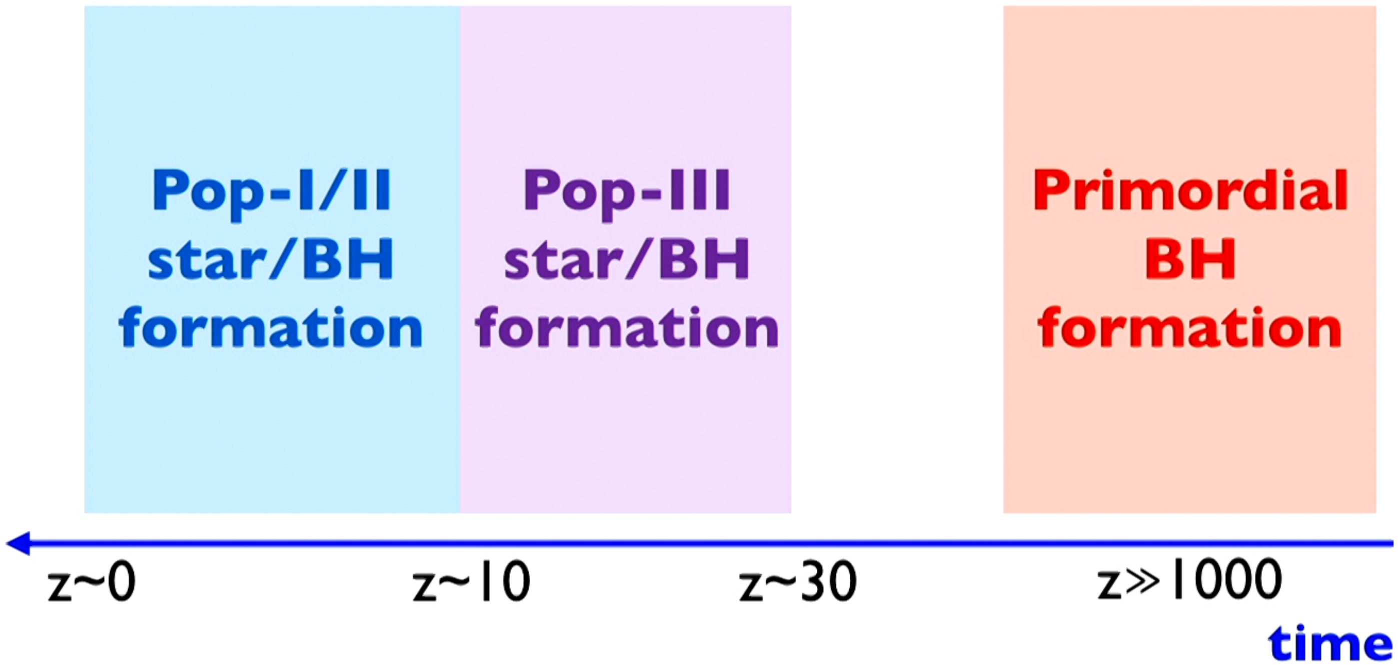
Origin of binary BHs?



https://www.ligo.caltech.edu

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

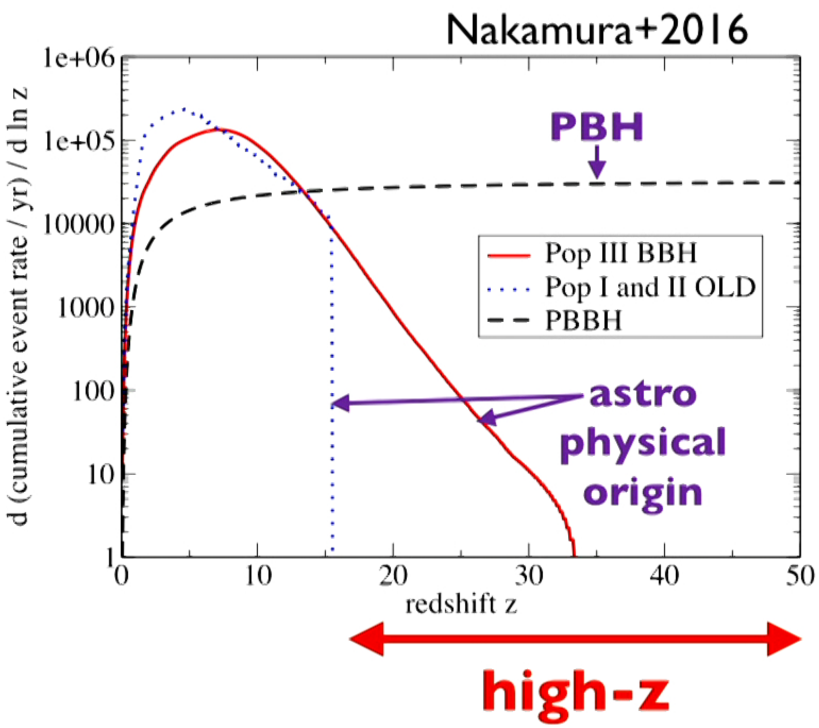
Models of BH formation



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

Nakamura+2016; Koushiappas & Loeb 2017

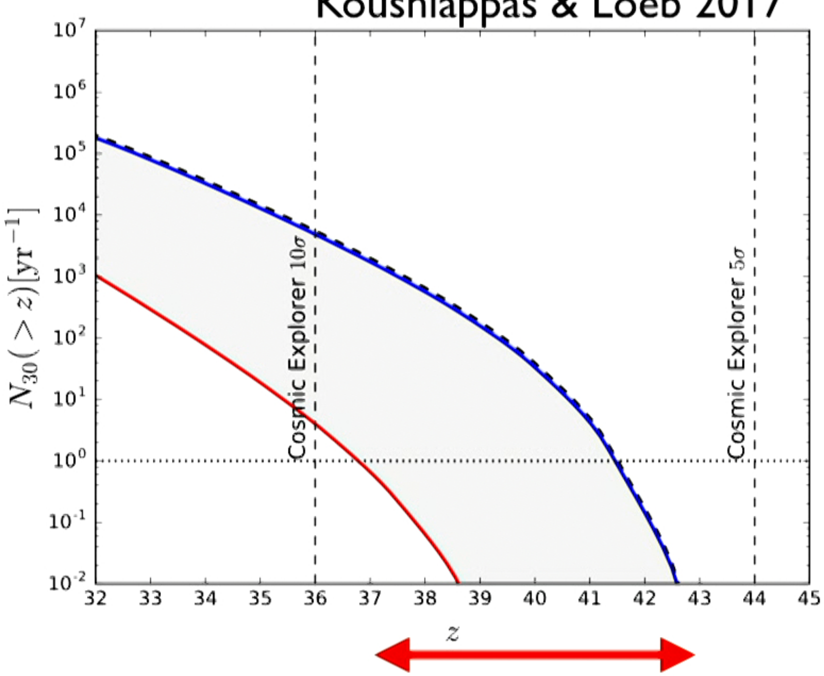
Key observation: high-z events



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

Nakamura+2016; Koushiappas & Loeb 2017

Key observation: high-z events



maximum z ~ 40
for astrophysical origin

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

“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

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

μ: magnification factor

- "**observed chirp mass**" M_{obs} defined as

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

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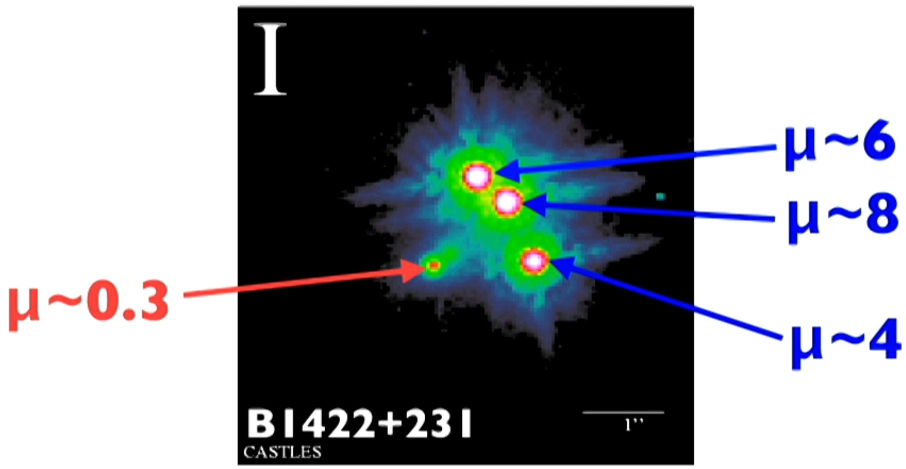
Distributions with lensing effects

- 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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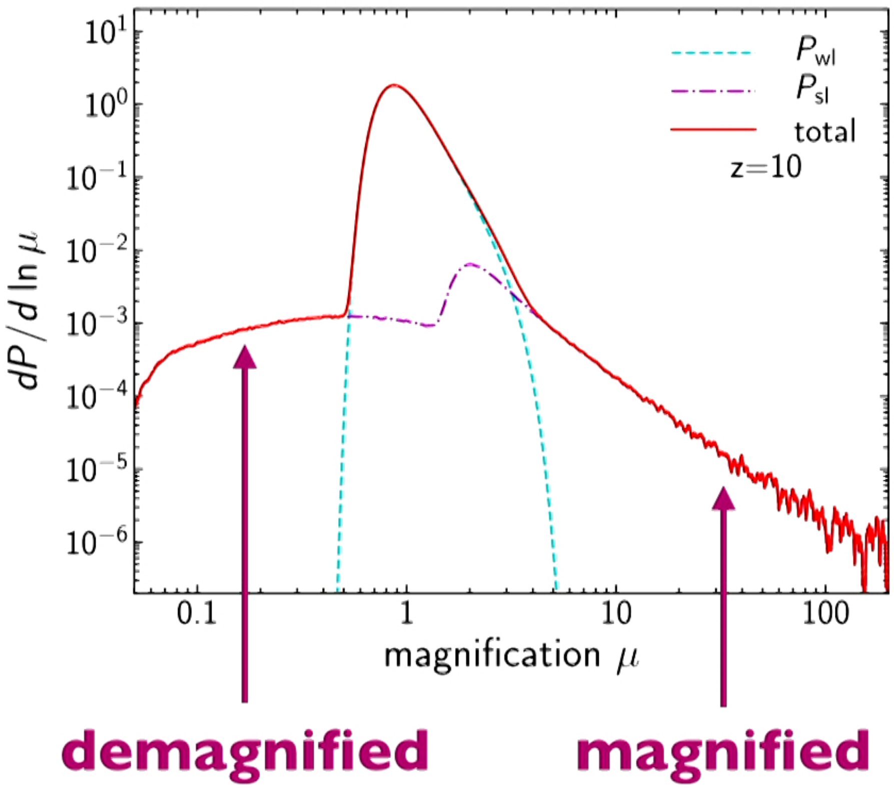
Magnification PDF



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

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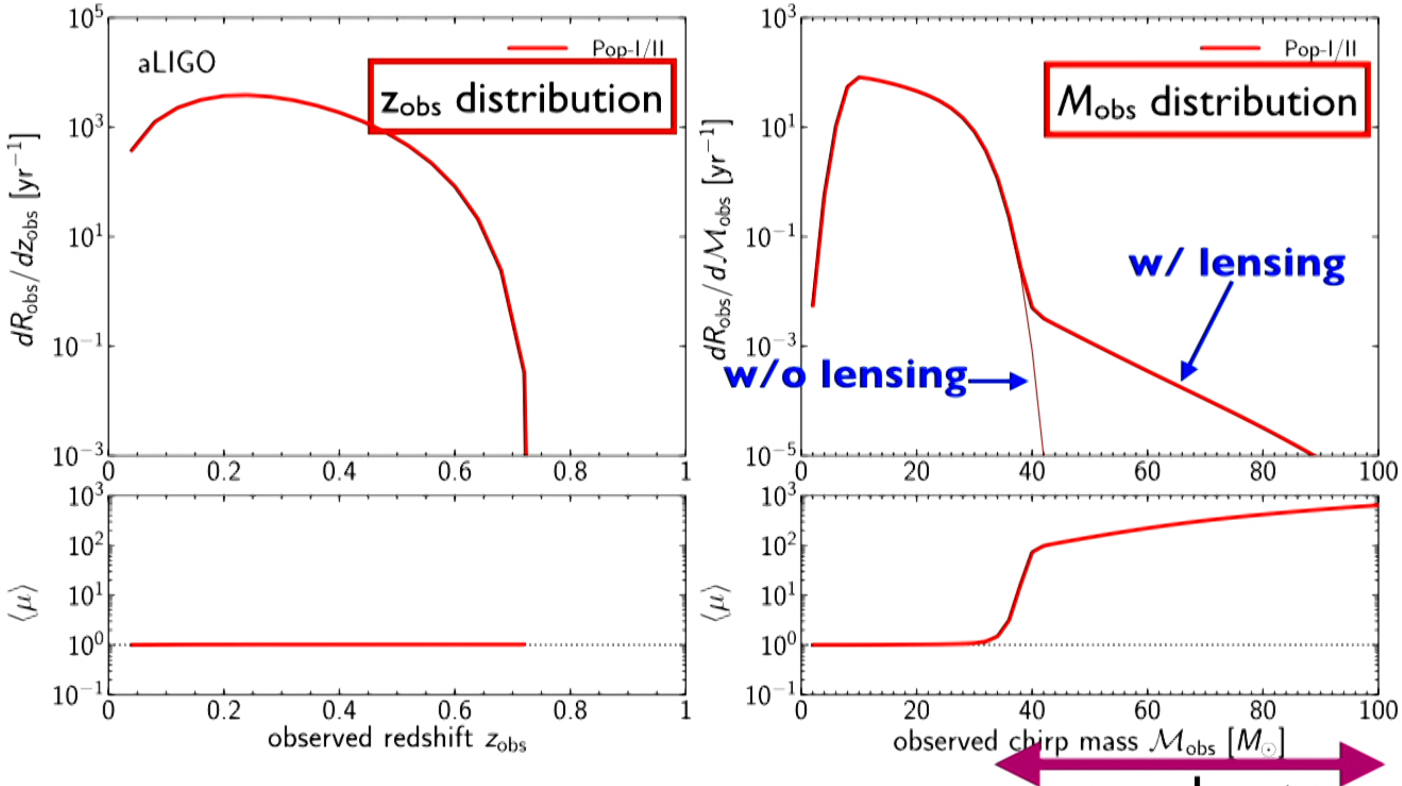
Result: advanced LIGO



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

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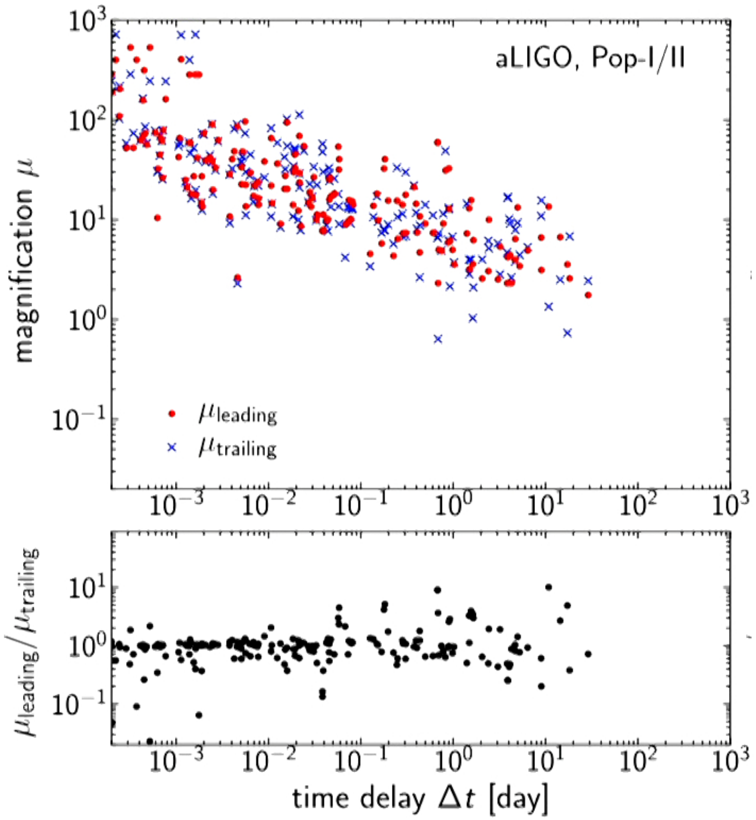
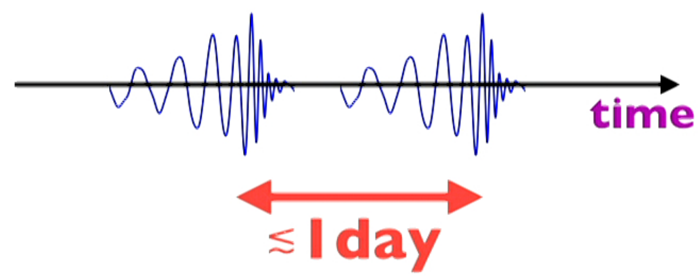
Expected multiple image pairs

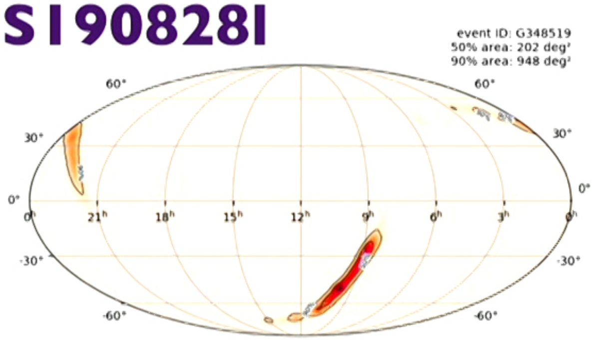


- **advanced LIGO**
  - time delay $\lesssim$ **1 day**
  - high, similar μ
  - $R_{obs} < 1\ yr^{-1}$



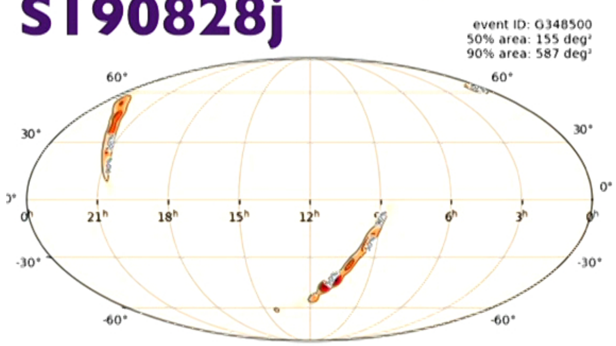
Gravitationally lensed GW??

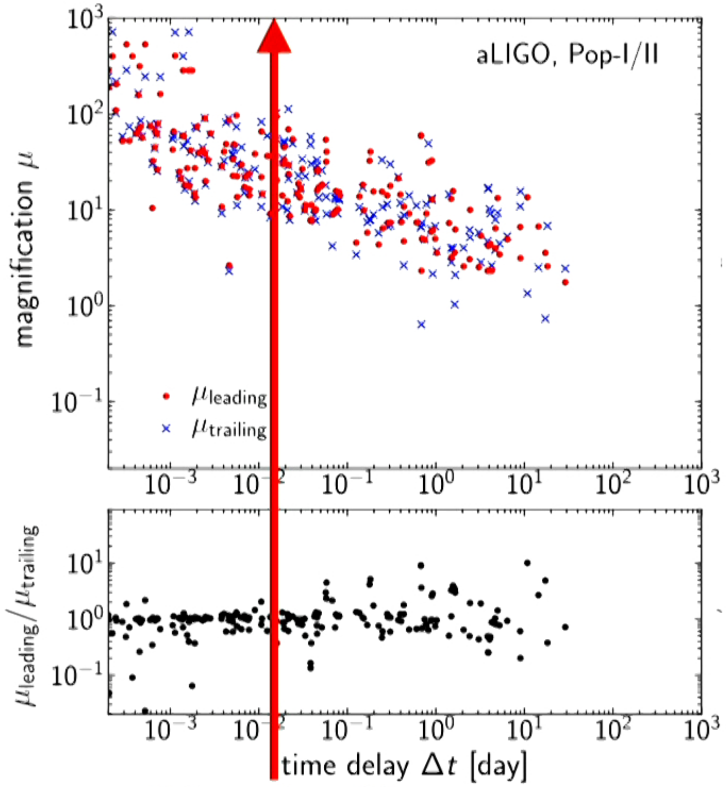
S190828l



separated by 21 min

S190828j





21 min (!)

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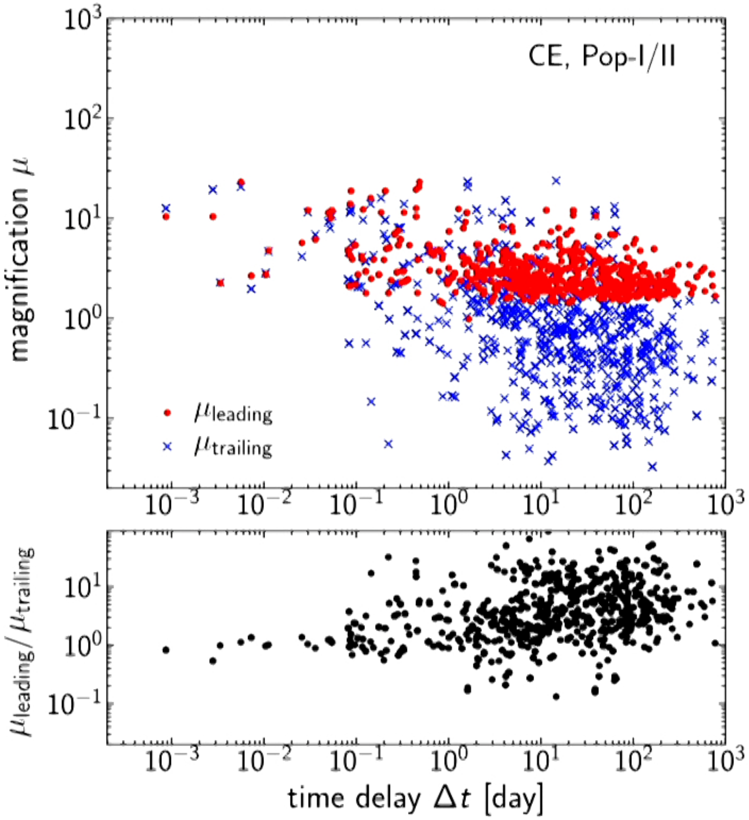
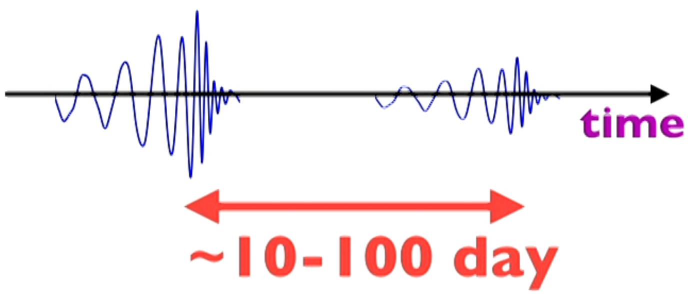
Expected multiple image pairs



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



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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!