NATURE OF BINARY BLACKHOLES PROBED BY CROSS-CORRELATION OF GW AND GALAXIES

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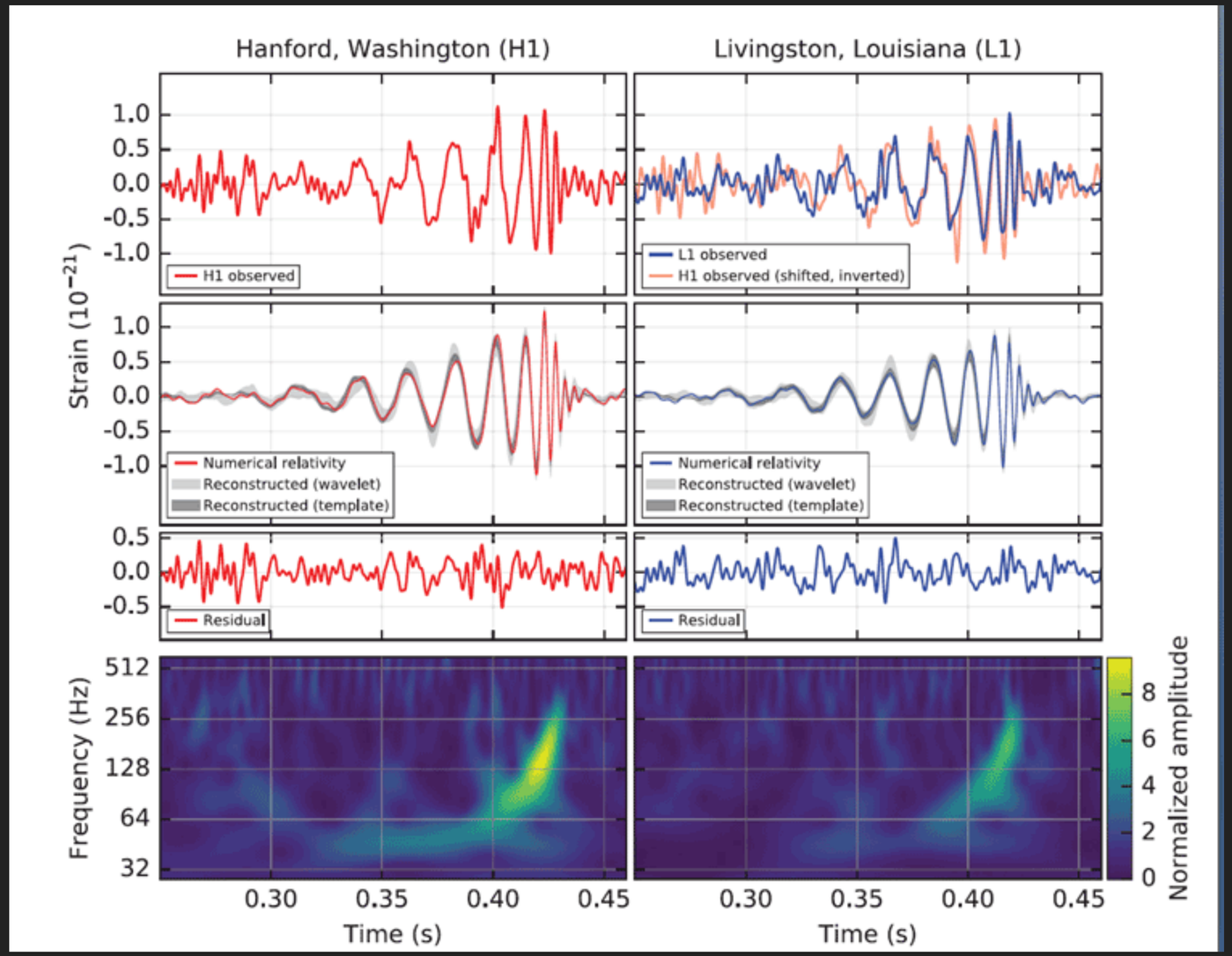
THE FIRST DETECTION OF GRAVITATIONAL WAVE

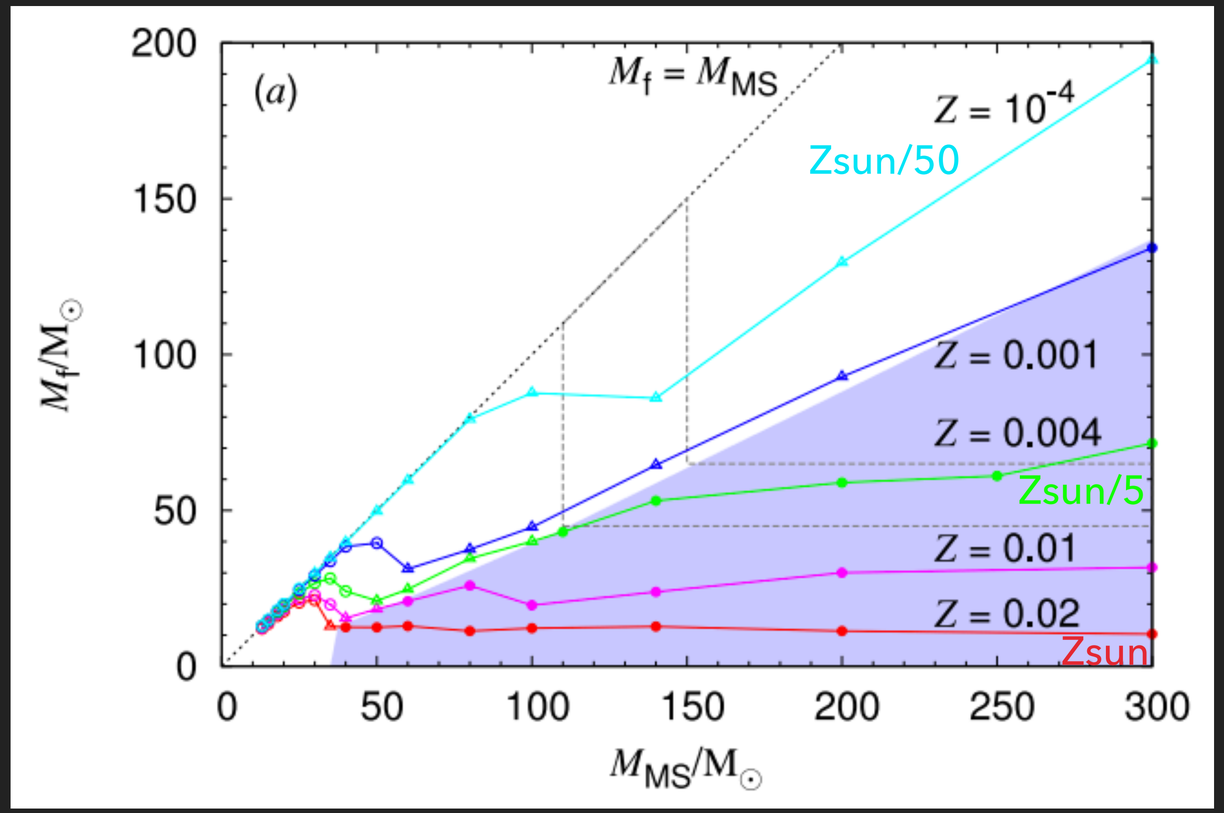
- First detection of GW with LIGO in Sep. 2015
- Four GW events so far detected
- Let's forget about the fourth event (NS-NS binary)
- Two BHs rotating each other merged
- What strikes people in addition to the first GW detection was …



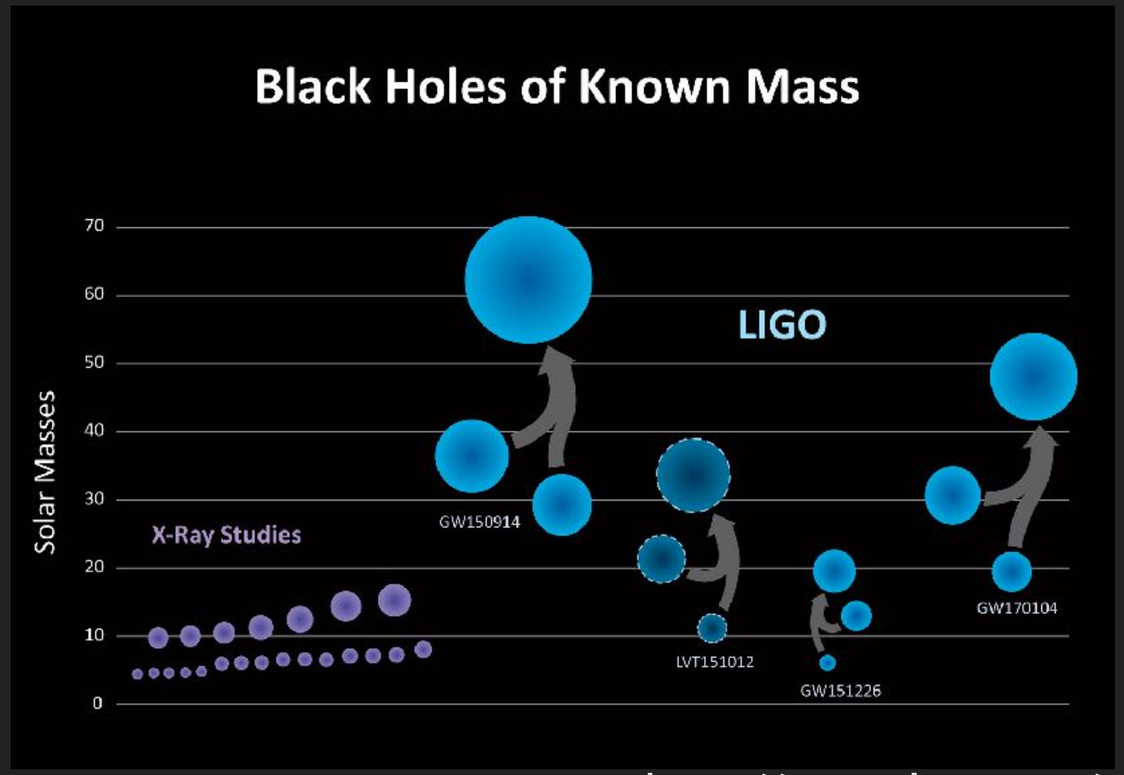
Abbott+ 2016, PRL 116, 6

SURPRISINGLY MASSIVE BLACK HOLES EVER DETECTED!!

- The most massive stellar BH ever detected!
- Need to form super massive progenitor



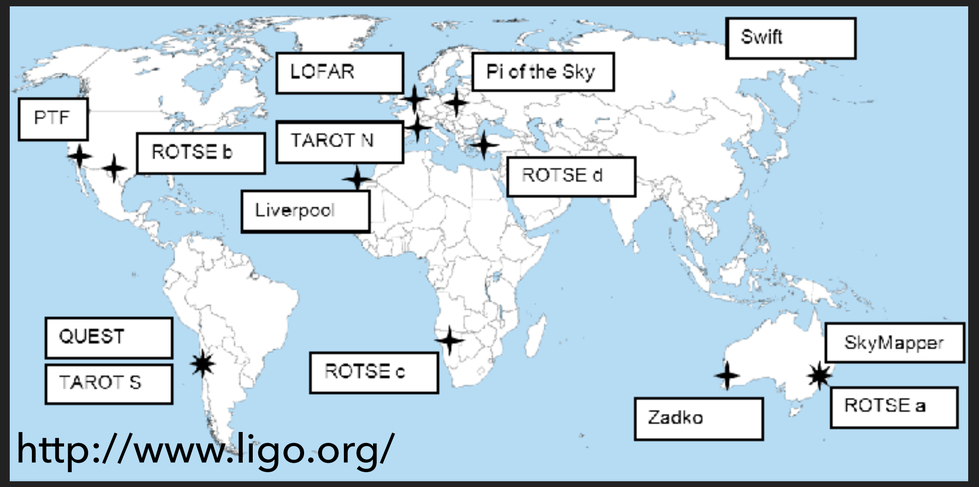
T.Yoshida+ 2014

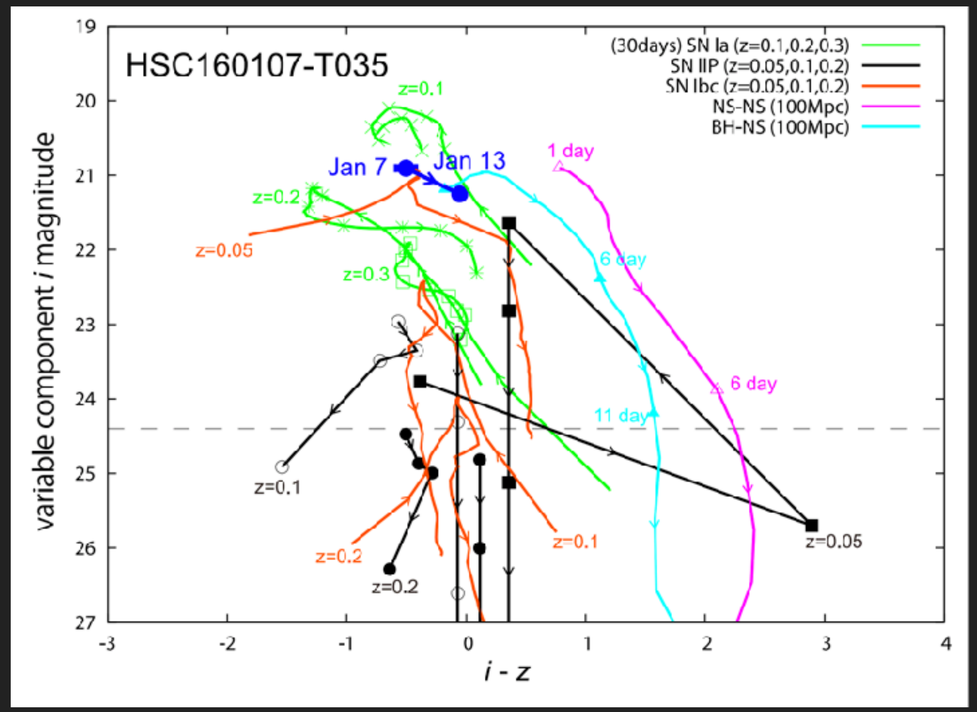


http://www.ligo.org/

OPTICAL / X-RAY / RADIO FOLLOWUP OBSERVATIONS

- EM counterpart -> redshift -> cosmology thru dL(z) relation (standard siren)
- identifying host galaxy -> BH formation
- no detection so far due to large positional uncertainty
- few candidates (sGRB, Kilo-nova, but for NS binary)
- immediate follow-up required (hours, days)
- more observations (HSC, DECam, PS1, …) but none of them claims detection.
- ToO observation in HSC, a week behind the GW151226 but variable object HSC160107-T035 fits none of the known transient templates.

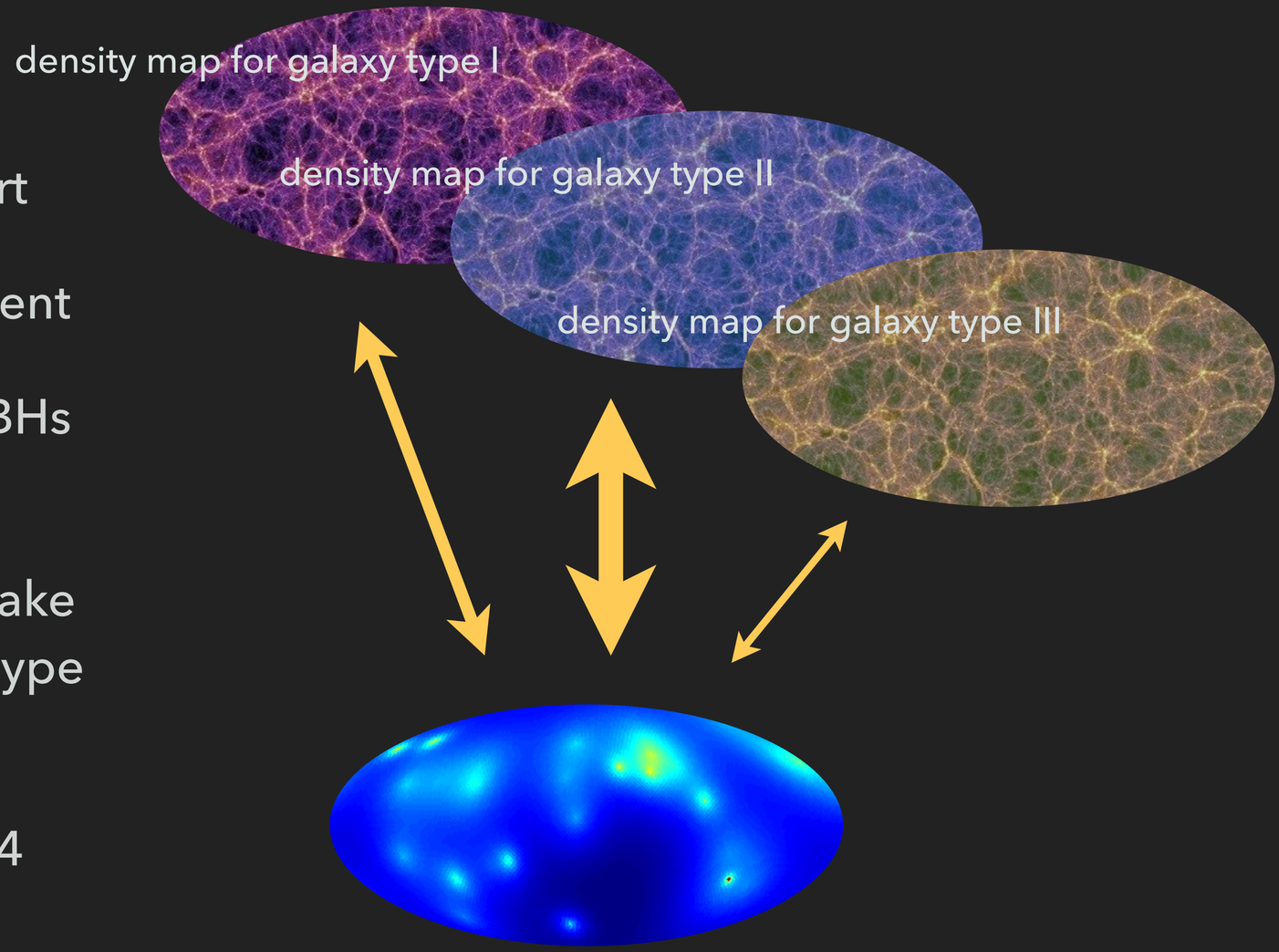




M. Yoshida+ 2016

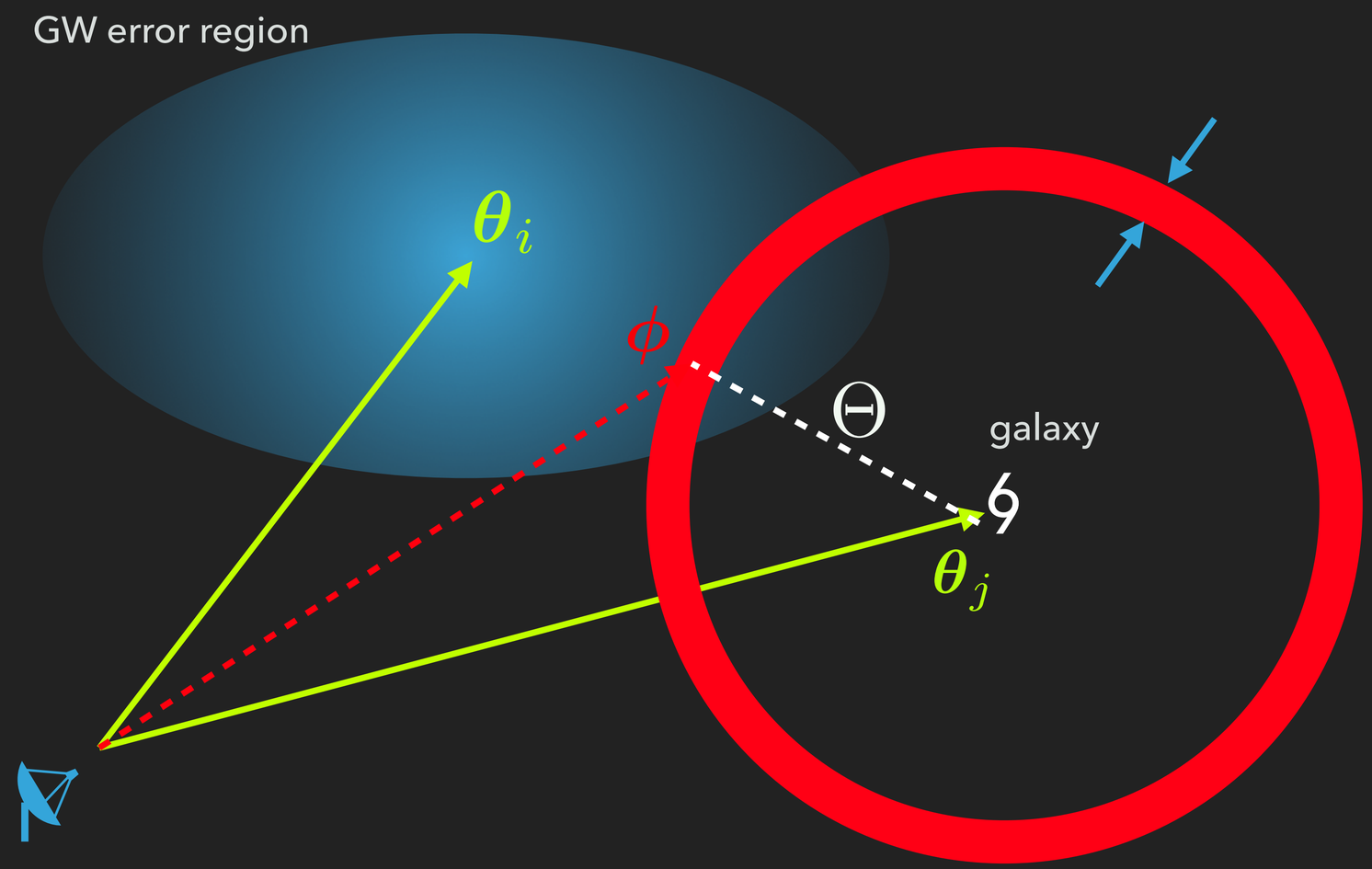
CROSS-CORRELATION OF GW AND GALAXY

- no need to identify individual counterpart
- can also be applied well after the GW event
- may give a hint to the origin of massive BHs in galaxy
- using real galaxy data, we can naturally take into account the clustering of particular type of galaxies
- Originally proposed by Namikawa+ 2014



CROSS-CORRELATION FORMULAE

$$w^{\rm cross}(\Theta) = \langle \delta_{\rm GW}(\boldsymbol{\theta}_0)\delta^{\rm P}_{\rm gal}(\boldsymbol{\theta}_0+\boldsymbol{\theta})\rangle$$
$$\propto \sum_{i,j}\int_{|\boldsymbol{\phi}-\boldsymbol{\theta}_j|=\Theta} \exp\left[-\frac{1}{2}(\boldsymbol{\phi}-\boldsymbol{\theta}_i){\rm Cov}_i^{-1}(\boldsymbol{\phi}-\boldsymbol{\theta}_i)^{\rm T}\right] d^2\boldsymbol{\phi}$$



- Cross-correlation of GW is subject to positional uncertainties
- Here we consider 2D angular correlation function but it can easily be extended to 3D CCF.
- Integration for all the pairs would be highly time consuming
- Replace integral with MC integral

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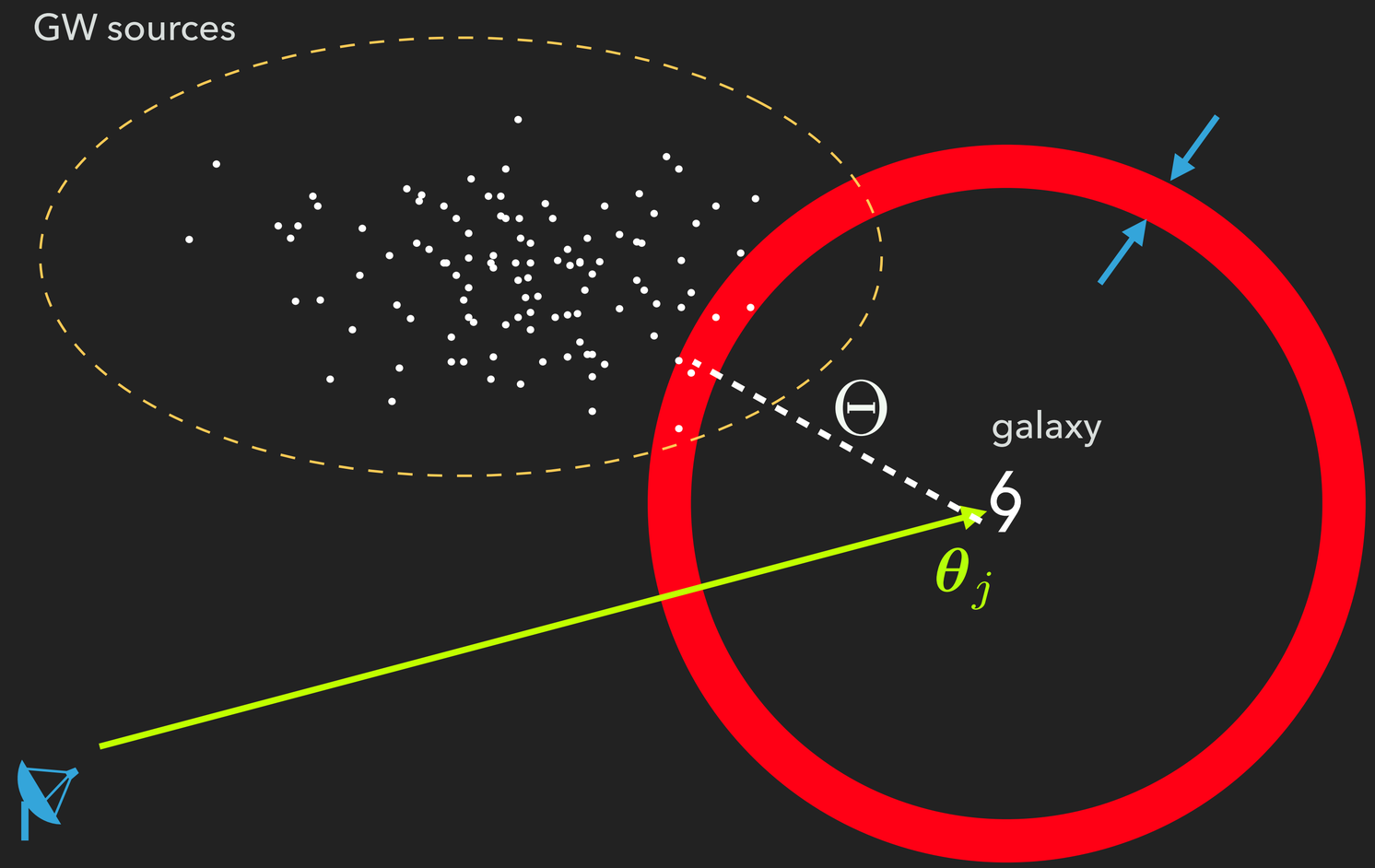

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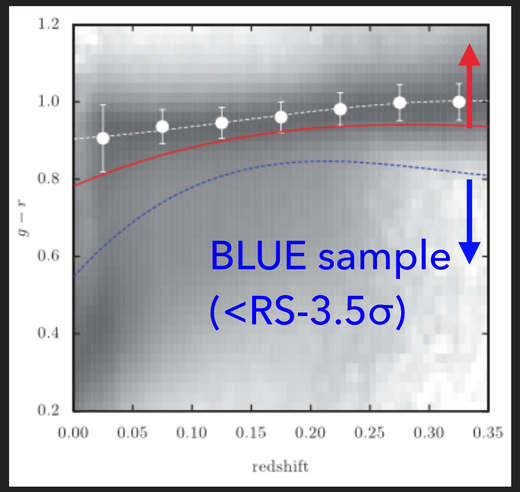
DATA (GALAXY) = REAL SDSS GALAXIES

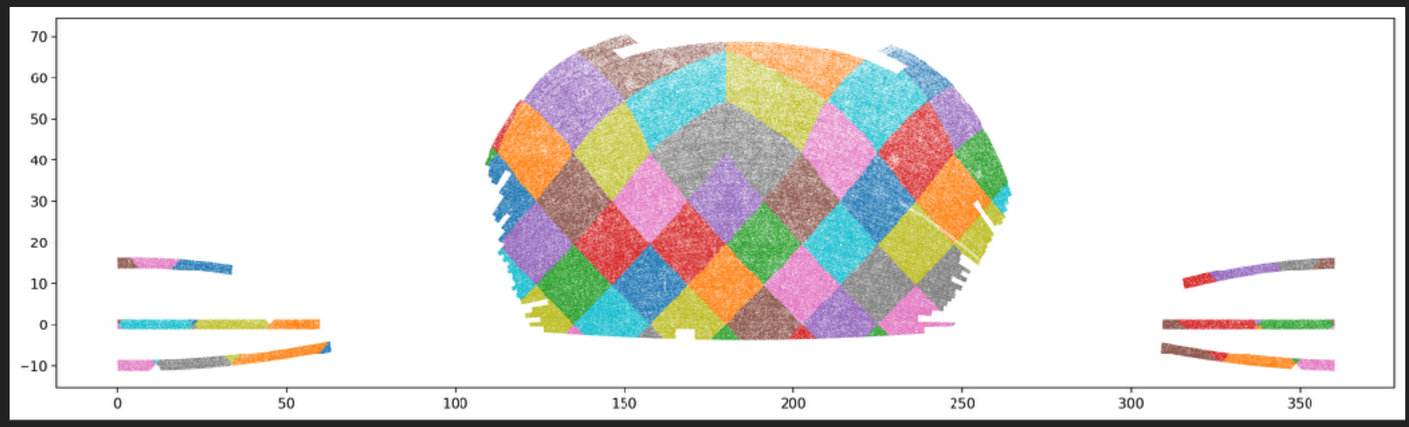
- SDSS DR7 photo-z sample
- subsample by photo-z (red/blue galaxies are classified based on the best fit SEDs)
- each sub-sample further classified based on SF activity (starburst, passive, green, AGN, …)
- JK subsample by Healpix (Nside=16) for error estimation



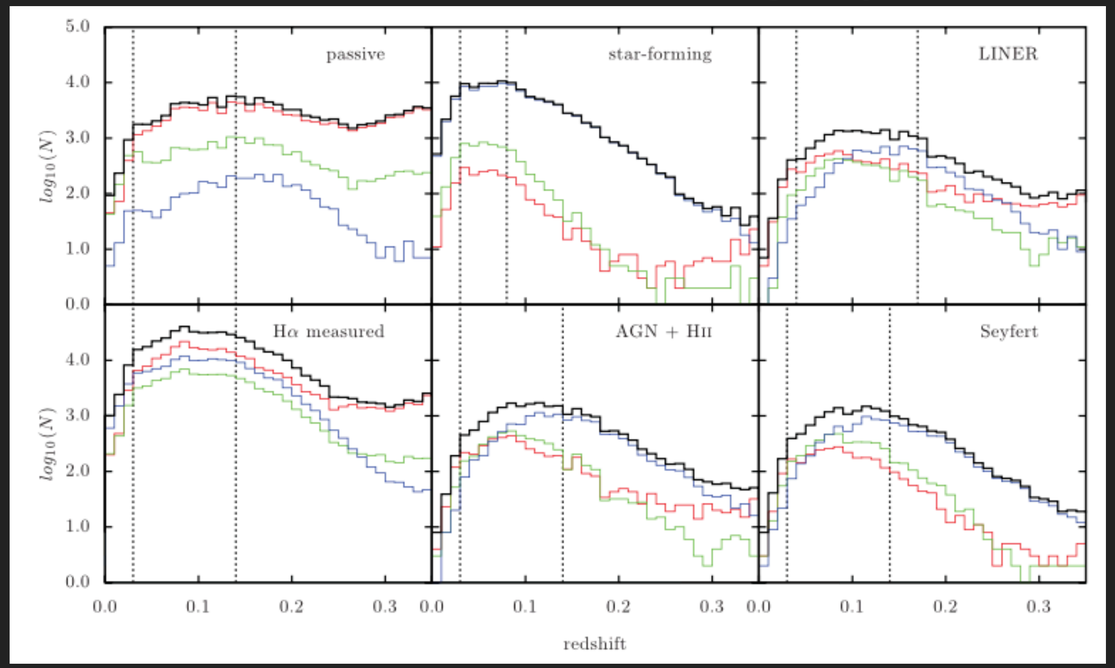
RED sample
(>RS-1.2σ)

Dobos+ 2012

SDSS DR7 galaxy sky-distribution (color : JK patch)

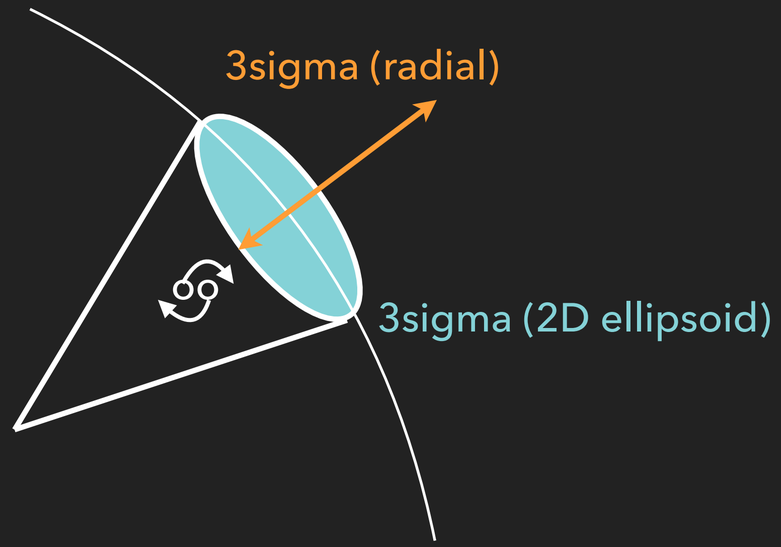


redshift distribution for different class of galaxy (Dobos+ 2012)

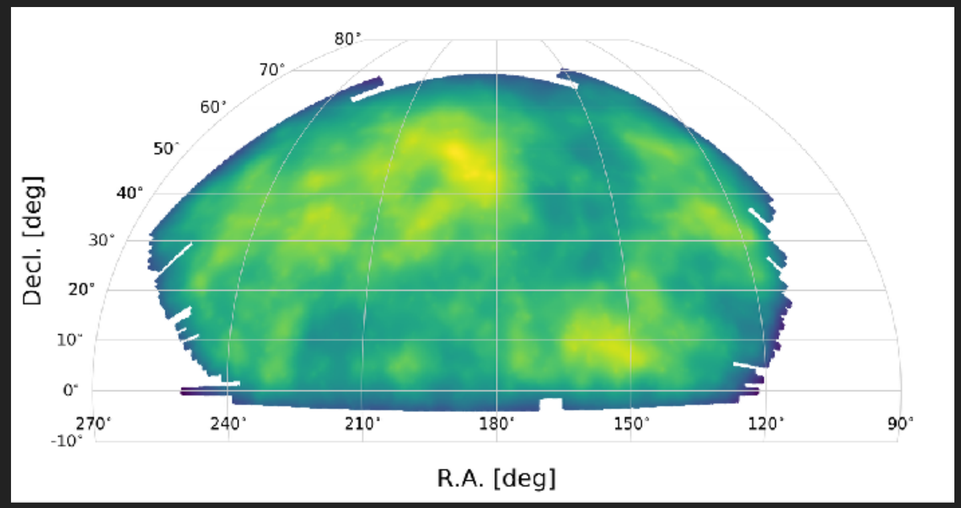


DATA (GW) = MOCK SIMULATED SOURCES

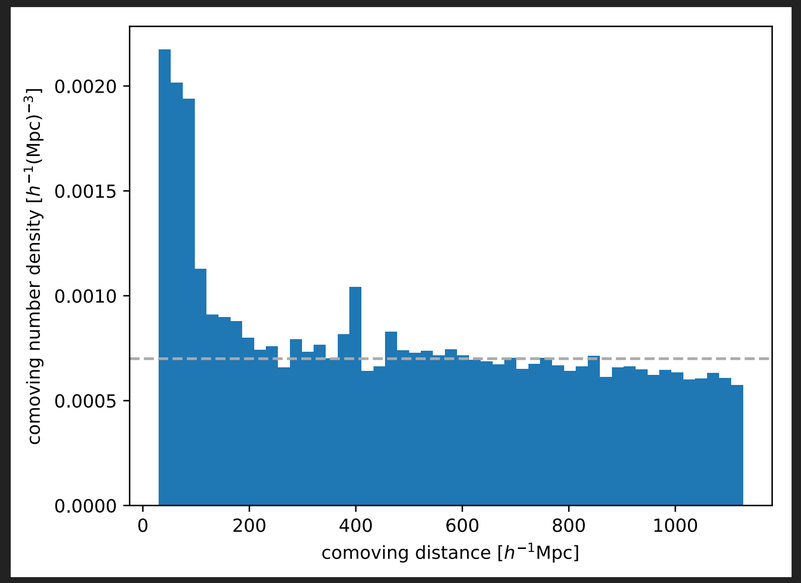
- At the position of selected galaxy (w mass weighted), put GW source
- randomly assign BH binary properties (M_1>5Msun, M_1+M_2<100Msun)
- observed orientation is also random assuming 3 detectors
- generate random 100 points around true position of GW (Gaussian dist.)



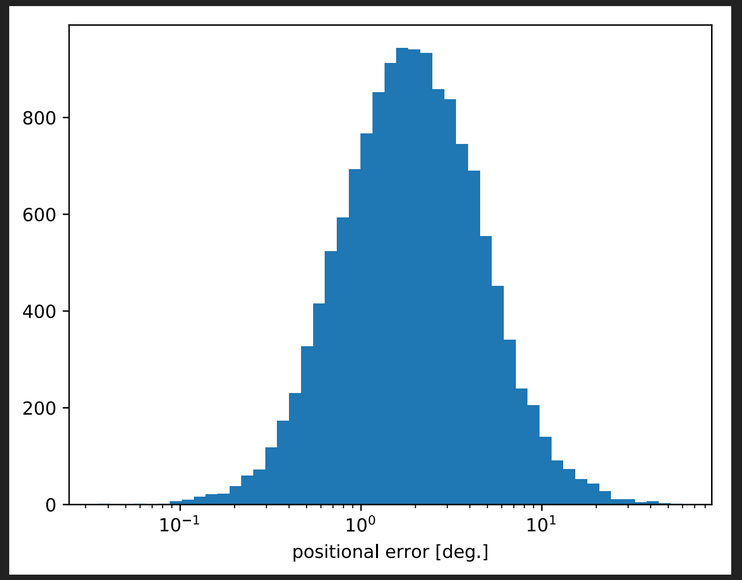
Probabilistic sampling of GW sources



comoving number density

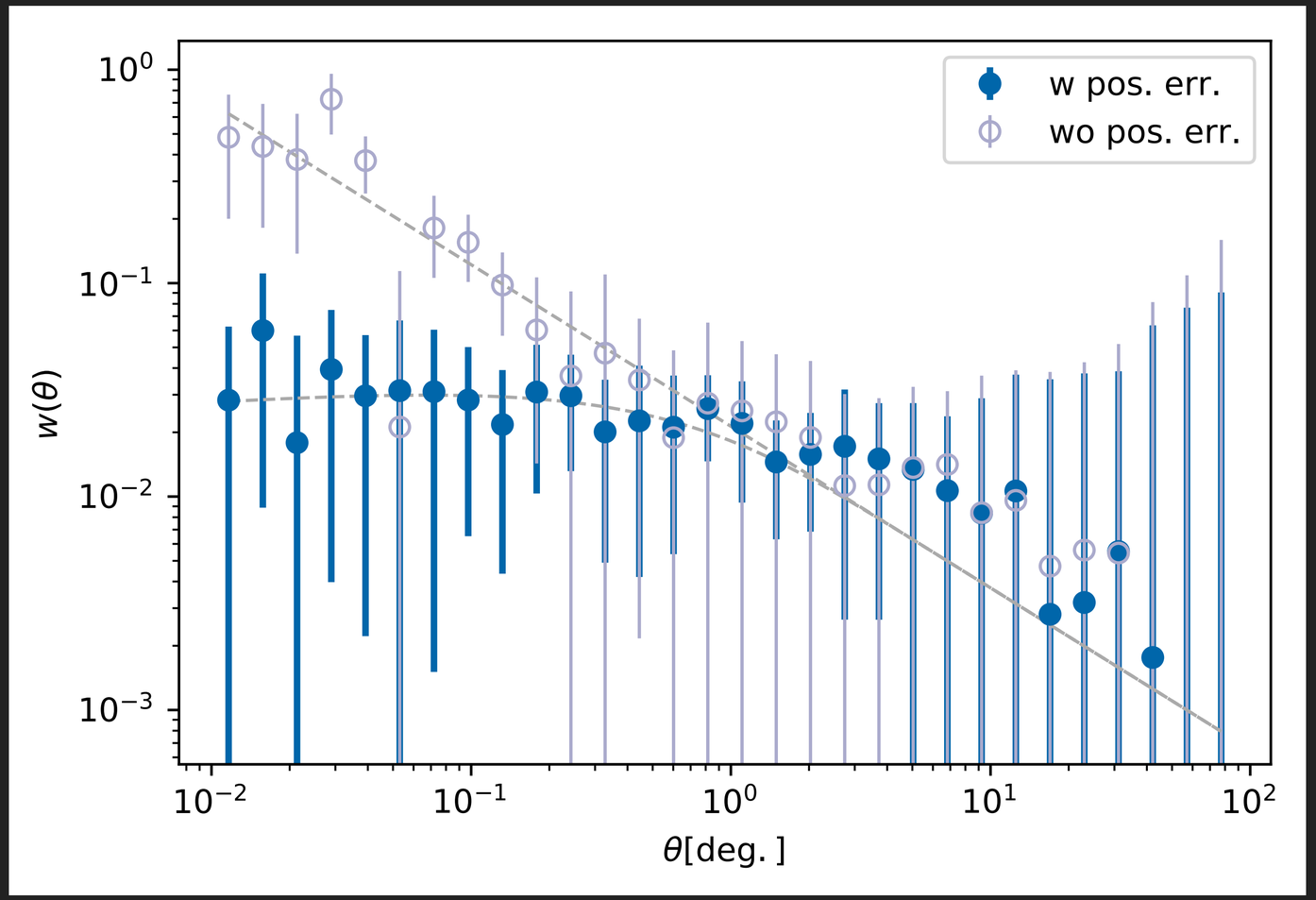


positional error distribution



ANGULAR CORR. FUNC. – EFFECT OF POSITIONAL UNCERTAINTY –

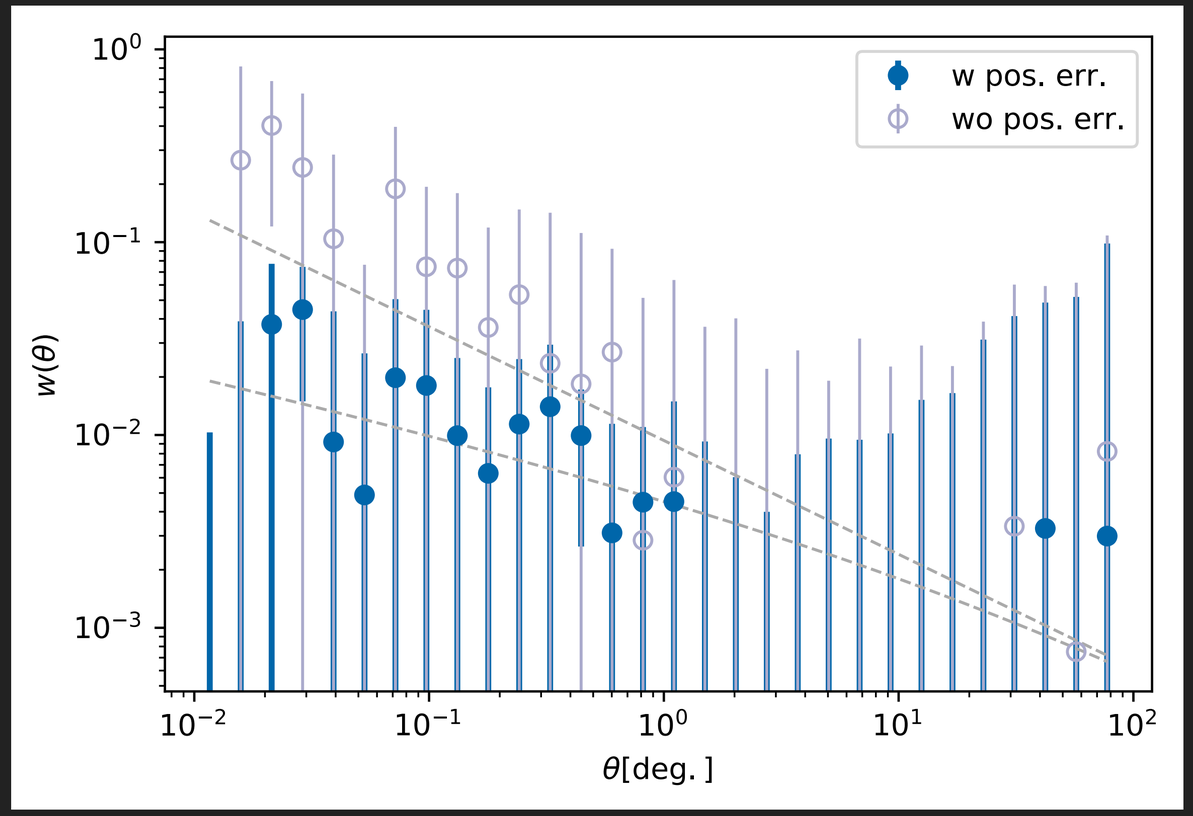
- wo positional error, the angular power spectrum is well fitted by power-law ($w \propto \theta^{-0.7}$)
- positional error suppress the power on small scales ($\theta < 1$)
- errorbar includes sample variance and shot-noise from 30 JK-resampling.



ANGULAR CORR. FUNC. – COMPARISON BTWN RED AND BLUE GALAXIES –

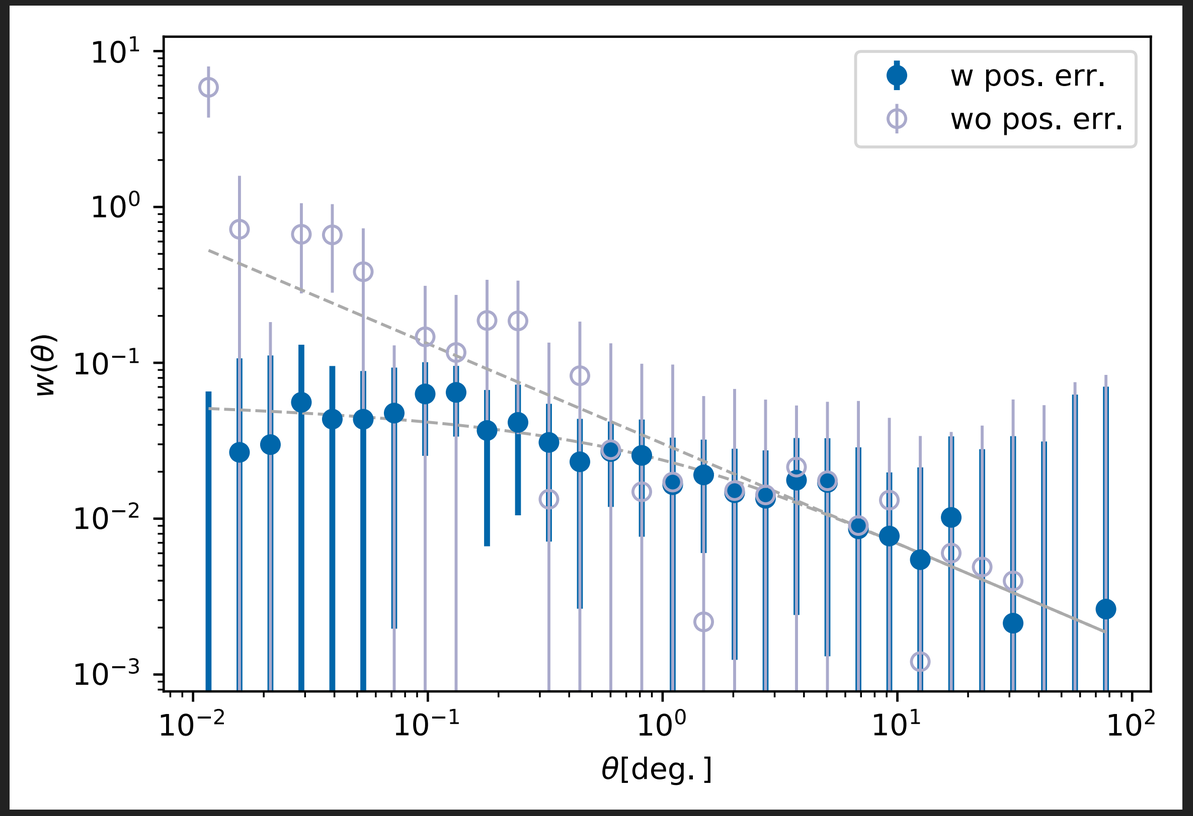
- Let's assume **GWs are associated with RED** galaxies and we find ~1,400 GW sources
- Cross-correlation with RED galaxies clearly has significant signal than that with BLUE

BLUE-GW cross correlation



Not detected

RED-GW cross correlation



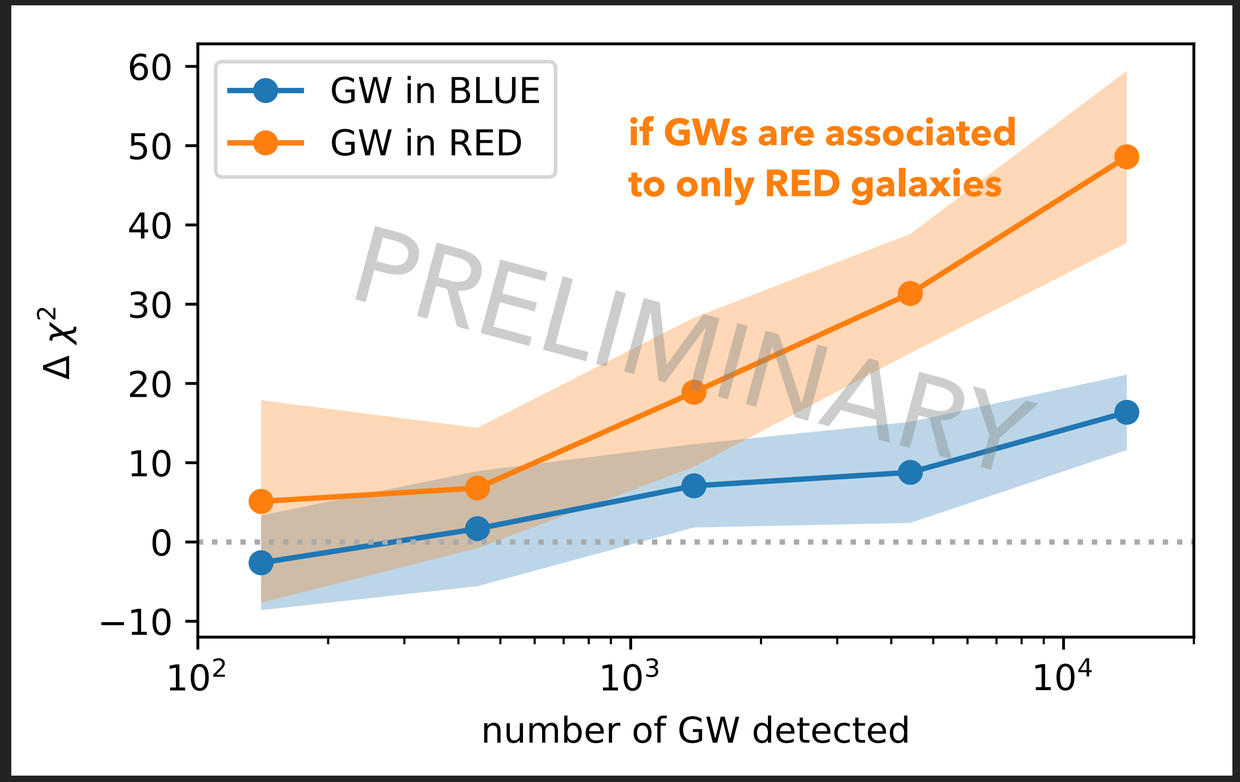
Detected

CAN WE DISTINGUISH THE RED/BLUE GALAXY ASSOCIATION?

$$\chi^2_{\rm null} = \sum_i \left(\frac{w(\theta_i) - 0}{\sigma_i} \right)^2$$

Significance of detecting the clustering

- Now, lets consider the case where GWs are associated with RED/BLUE galaxies.
- number of GWs required to distinguish the associated galaxy population.
- Delta chi^2 gives us how the detection of clustering is significant compared to the other.
- 100 GWs are not sufficient but **a few 100 / 1000 GWs are enough**



SUMMARY

- Gravitational wave has been detected and more is expected in near future.
- The detected GWs are emitted by the binary of anomalously massive stellar blackholes.
- Given that those massive blackholes are only able to be populated in some particular types of galaxies, GWs and galaxies might be spatially correlated.
- We estimate the **cross-correlation between GW-galaxy** for mock GW data based on the SDSS galaxies considering the uncertainty on the positional determination of GW.
- If the GW are populated in RED galaxies, we expect a significant correlation signal with RED galaxies once the number of GWs reaches to **a few 100** but no-signal with BLUE galaxies.
- **Caveat** : the significance of association will depend on the model (GW sources are associated with what types of galaxies actually), i.e. if GWs are associated with the population of weakly clustered galaxies, the significance will decrease.
- **Future** : We will see the significance when GWs are associated with the different types of galaxies, or finer classes of population, like AGN, SBG, etc…, and what happens after KAGURA?