Testing Primordial Black Holes Dark Matter with Gravitational Waves and Large Scale Structures cross-correlations

Based on Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020), ArXiv: 2002.02466

Alessandro Cuoco

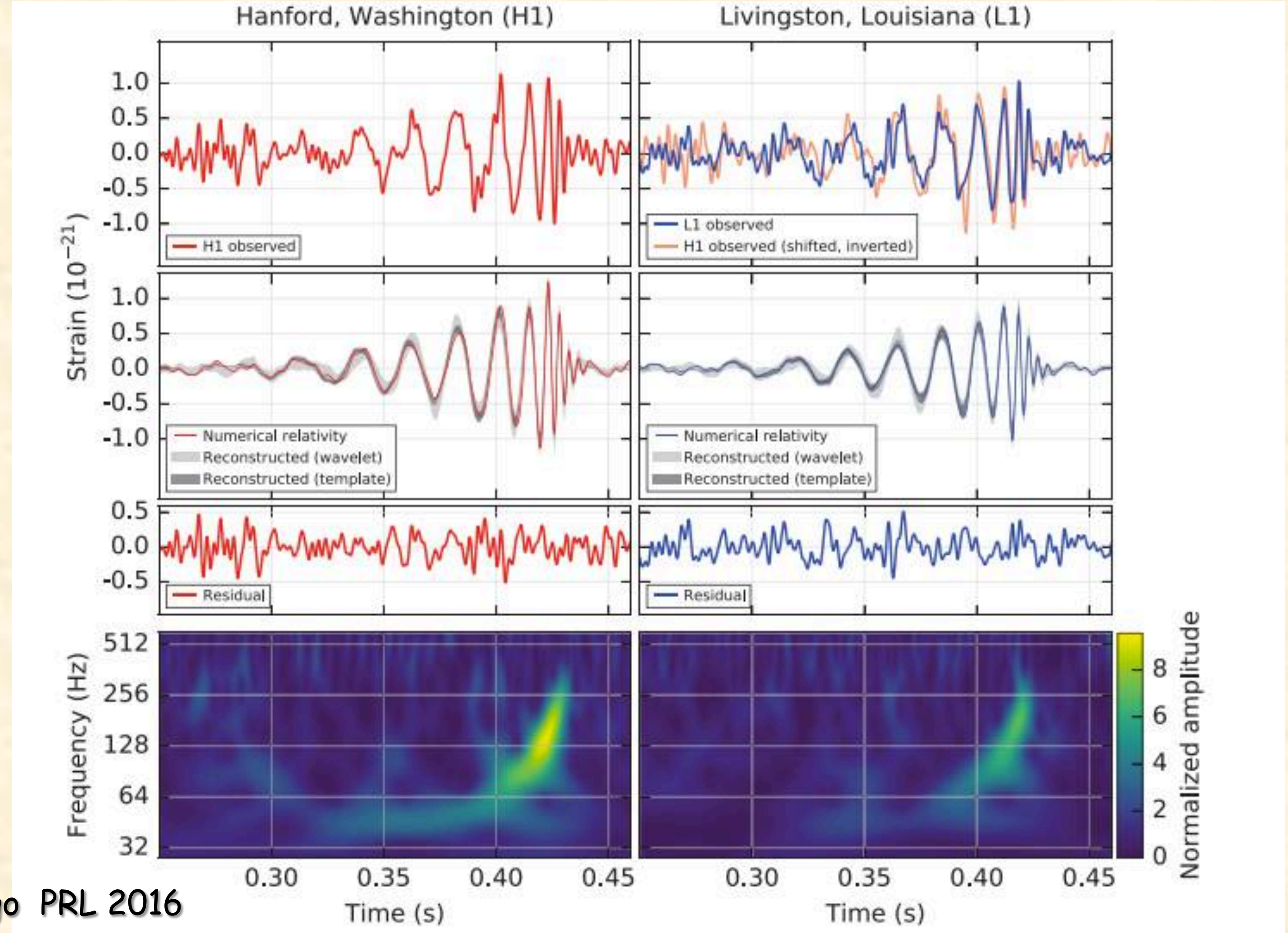
L'Aquila,
Identification of DM (IDM 2024)
July. 8th 2024

UNIVERSITÀ DEGLI STUDI DI TORINO

INFN
Istituto Nazionale di Fisica Nucleare

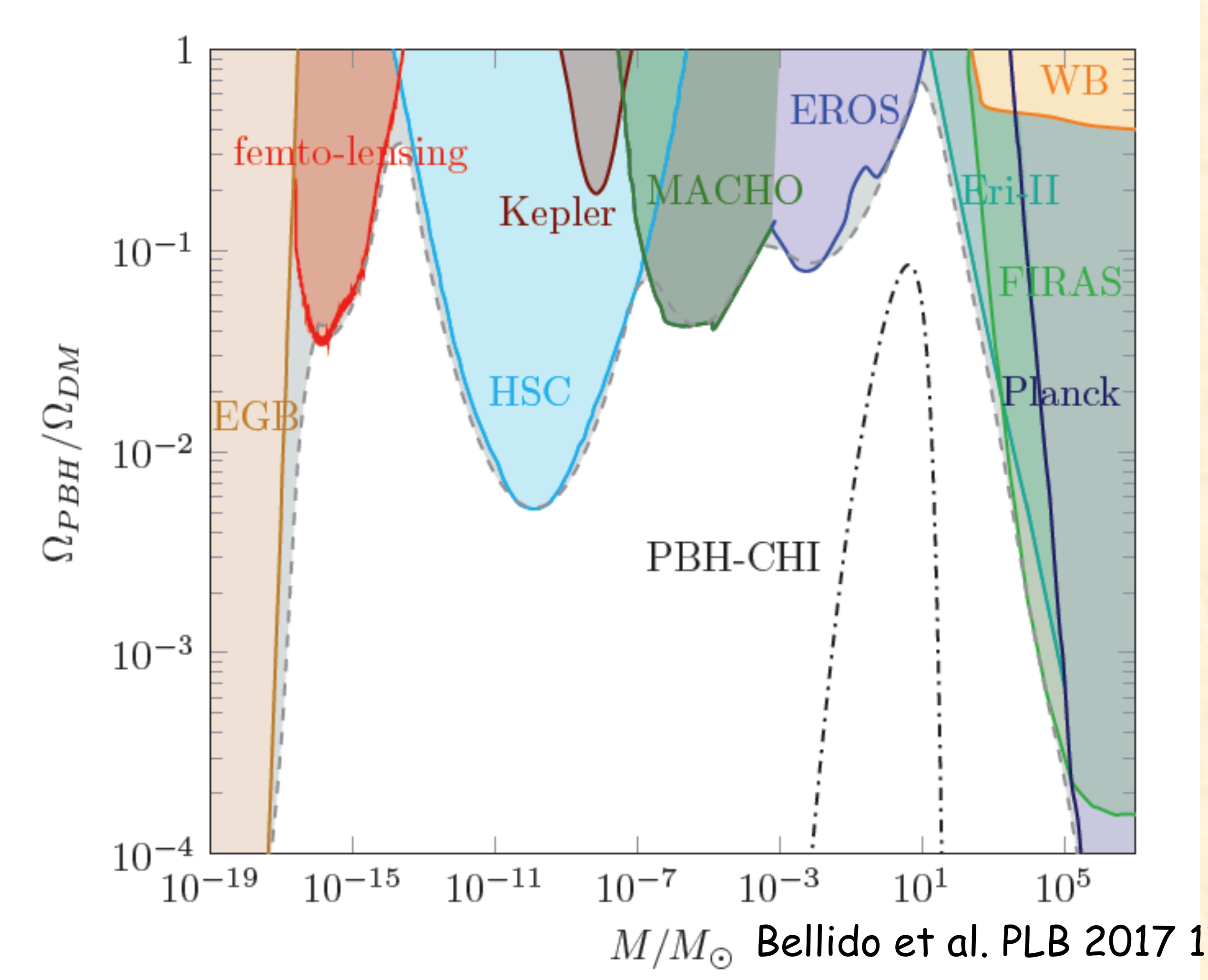
Gravitational Waves

- The detection of GWs by Ligo-Virgo opened a new window on the Universe



Ligo –Virgo PRL 2016

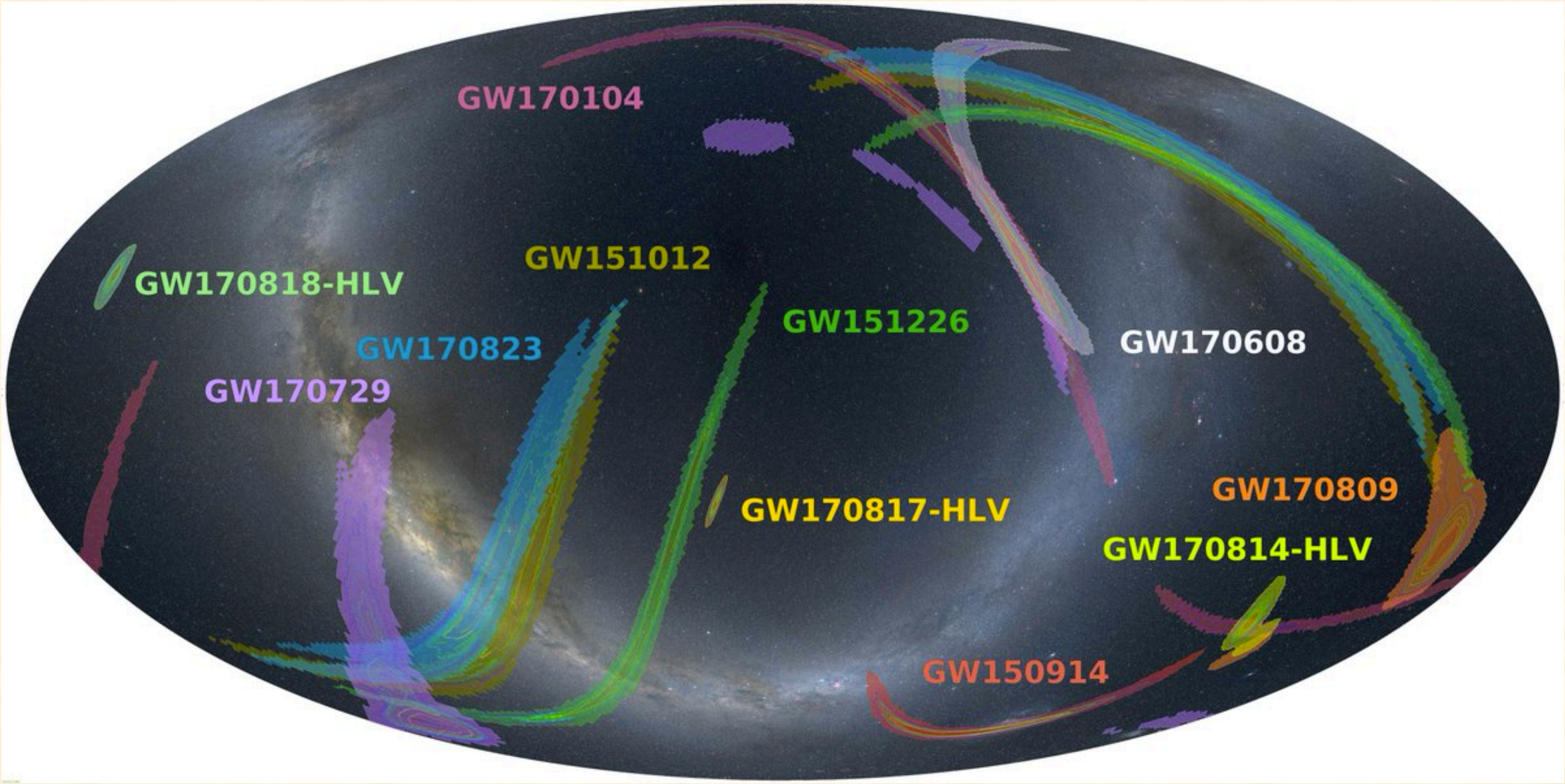
Primordial black holes DM



Bellido et al. PLB 2017 1705.04861

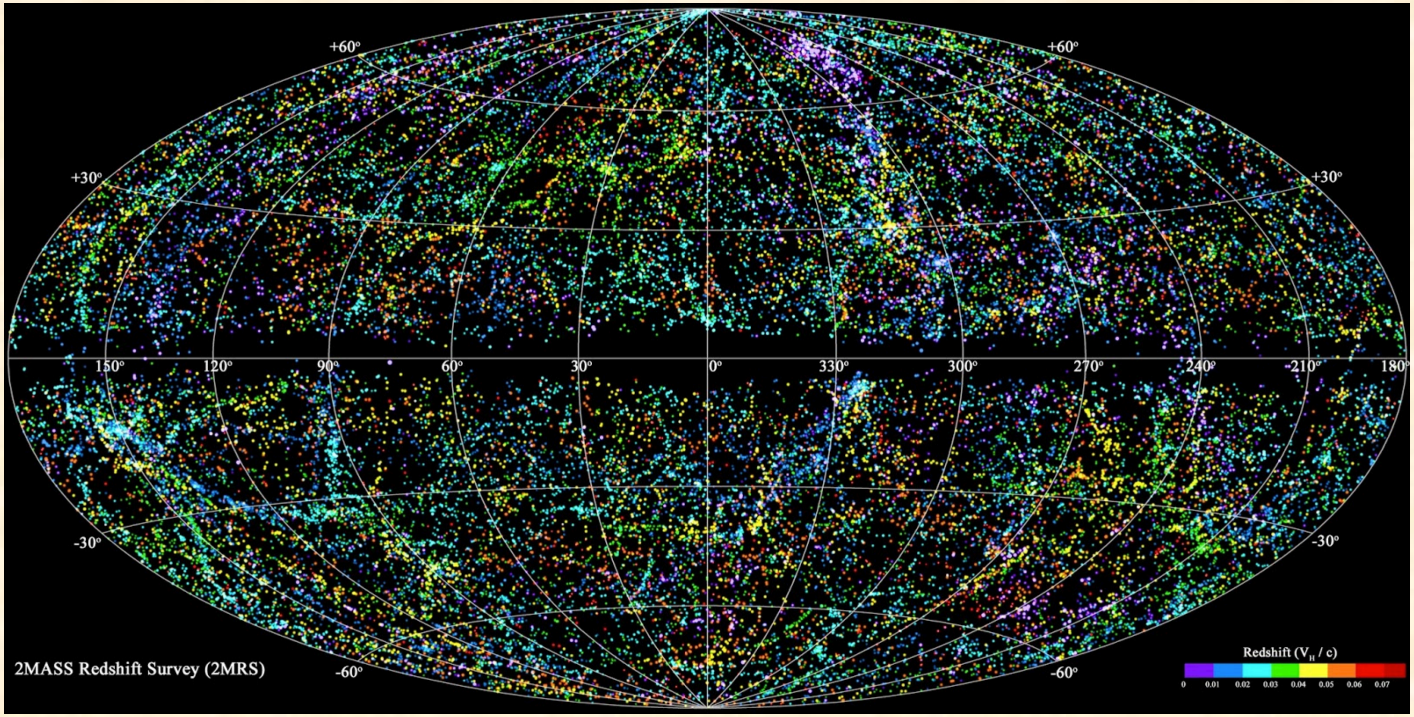
- Some fraction of the BBH seen by LIGO-Virgo could be primordial in origin
- Again, cross-correlations with LSS can help tackle the problem
- Primordial BHs and astro BHs have in general different biases w.r.t. LSS

Map of GWs



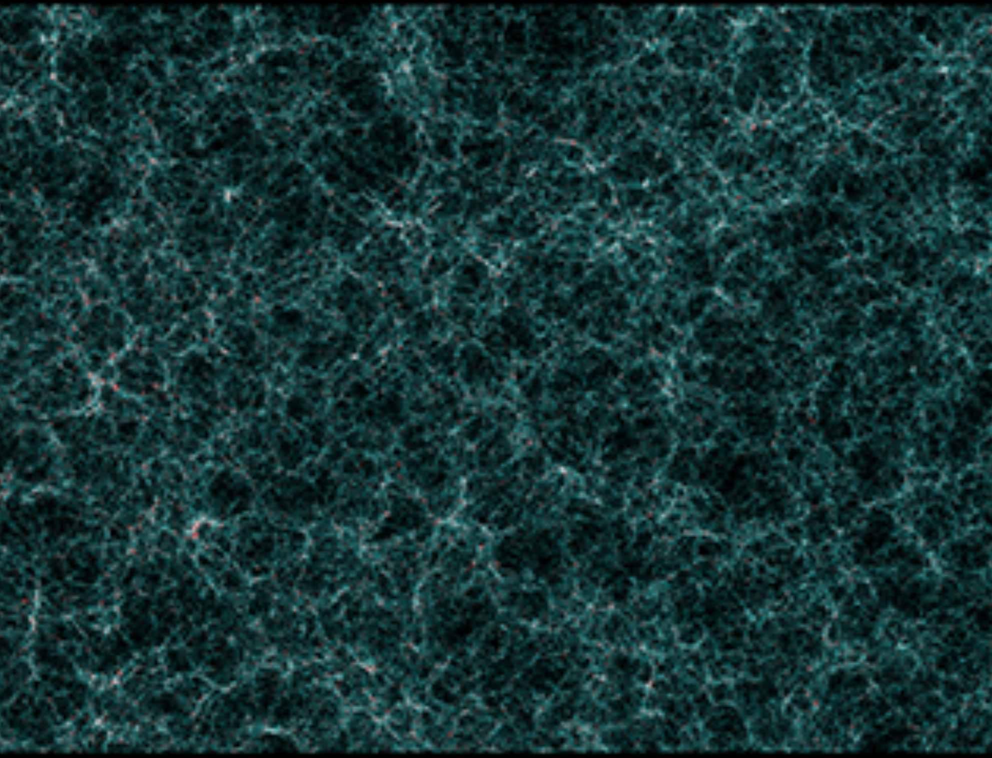
- In the next years number of detections and precision of localization will grow
- Auto-correlation statistics: performances very sensitive to the statistic available and angular precision
- Cross-correlation: exploit information from galaxy catalogs. More robust. Also less sensitive to the statistics and angular resolution

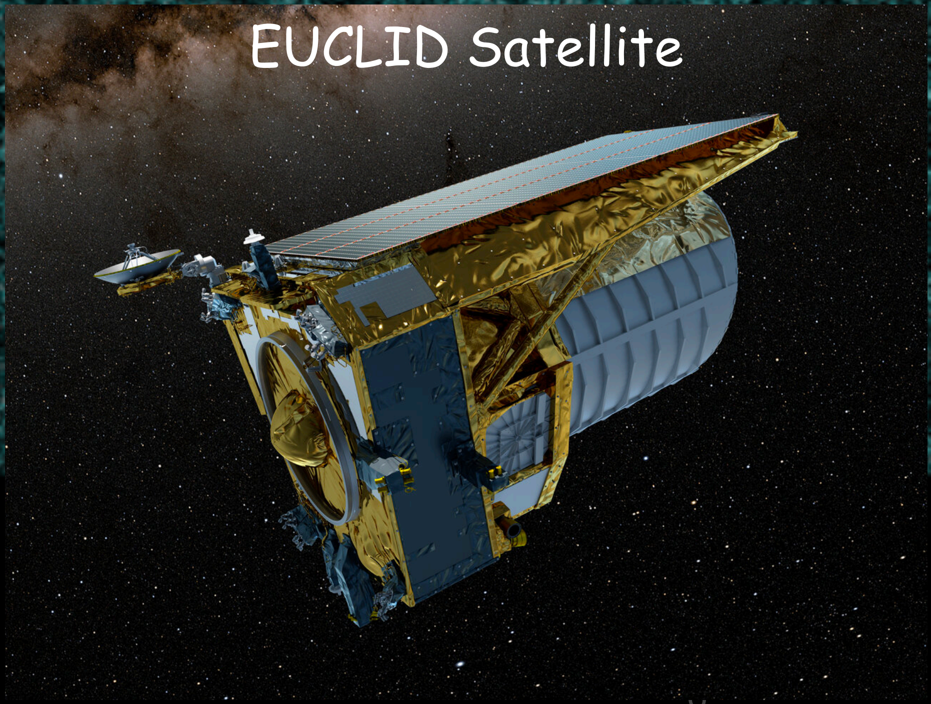
Large Scale Structures



2MASS Galaxy Catalog

Large Scale Structures

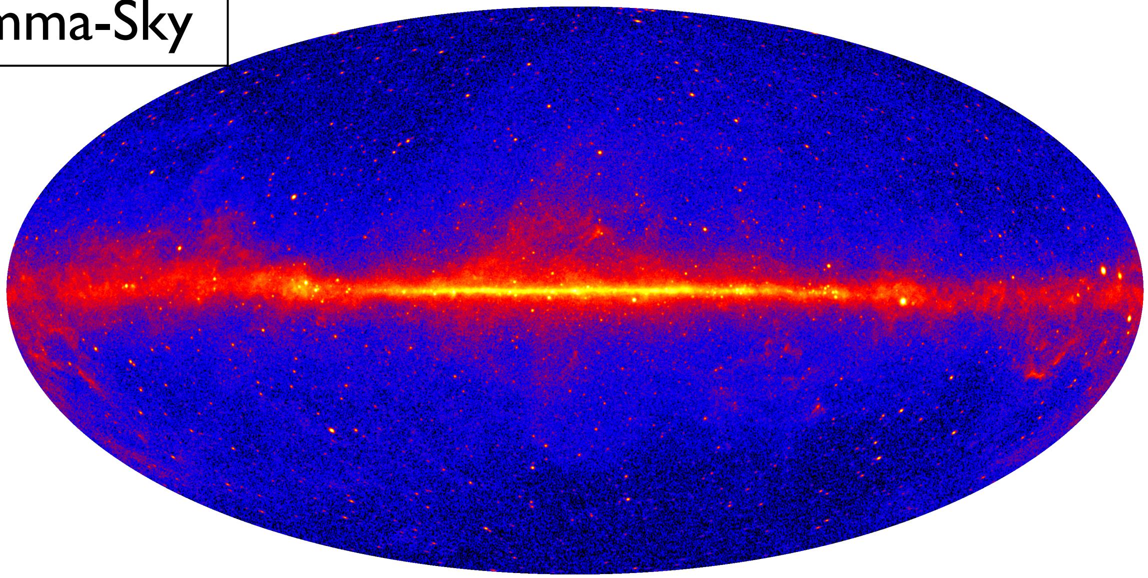




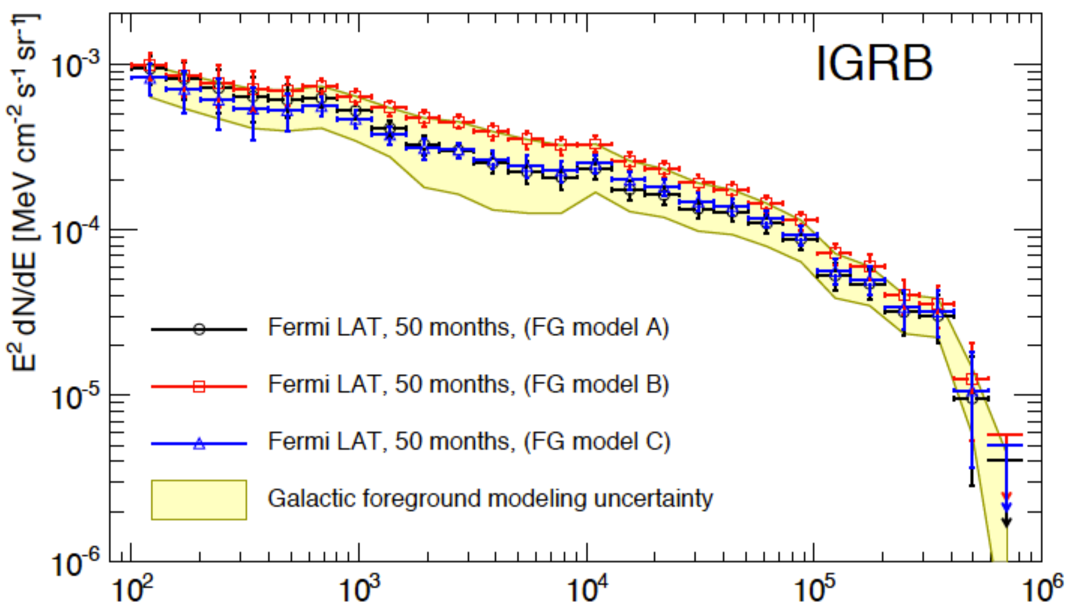
Credits ESA

DM and Gamma rays: EGB

Fermi-LAT Gamma-Sky



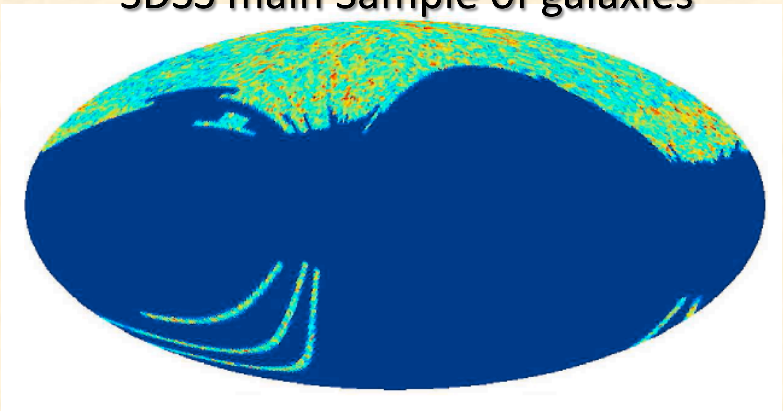
EGB Energy Spectrum



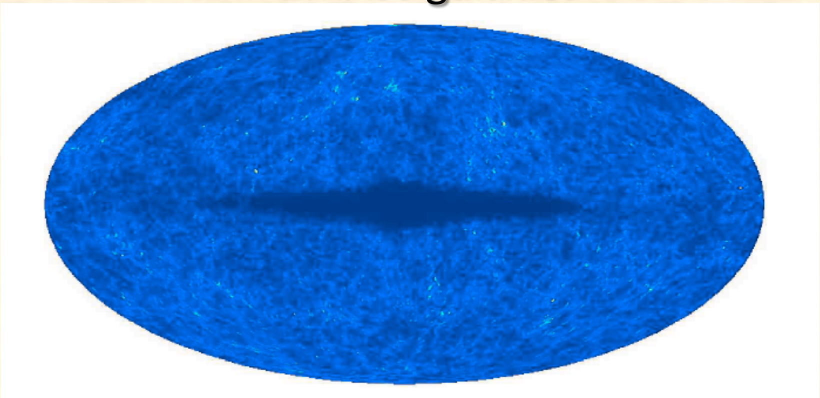
Fermi LAT collaboration, Astrophys.J. 799 (2015) 1, 86

cross-correlation with LSS: catalogues

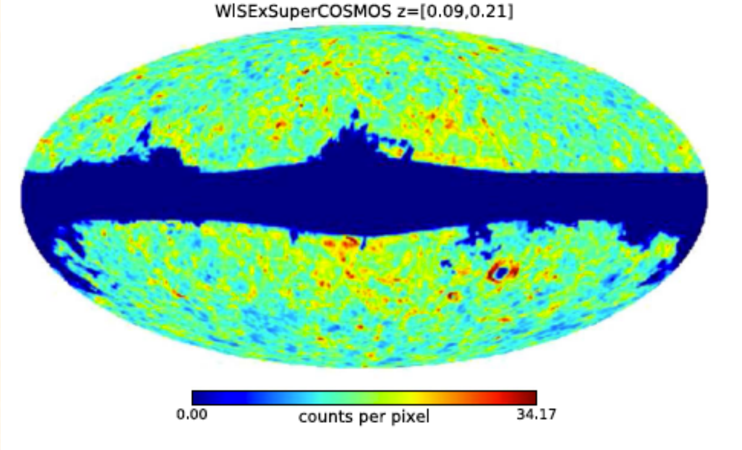
SDSS main Sample of galaxies



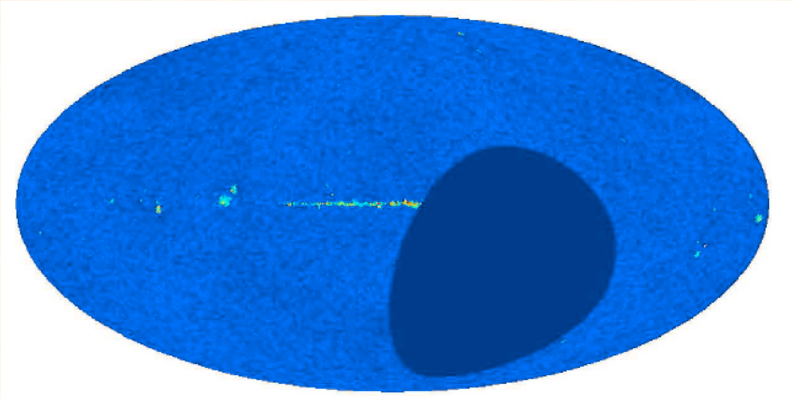
2MASS galaxies



WISE x SC



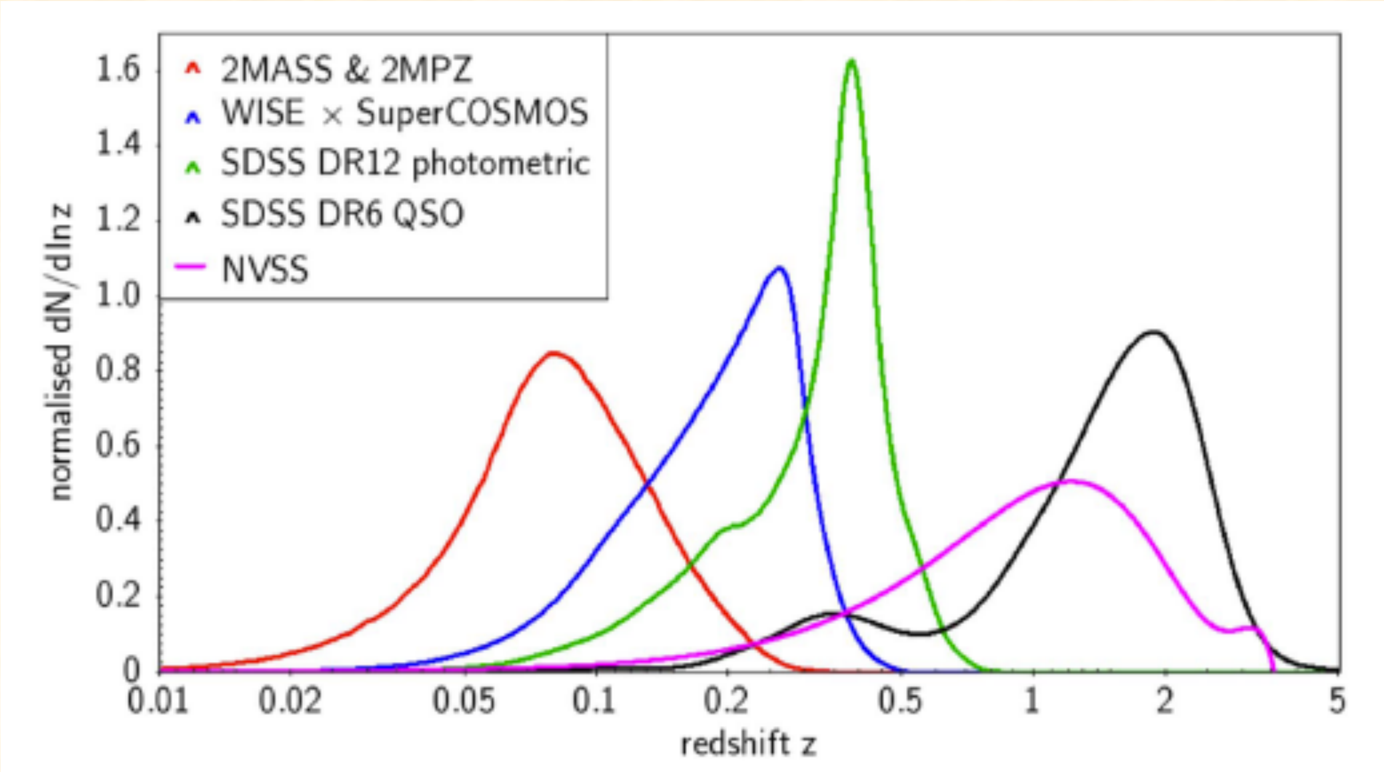
NVSS radio sources



- DM emission in the IGRB should trace the Large Scale Structures of the Universe.
- Galaxy Catalogues can be used as LSS template to cross-correlate with

Xia, Cuoco, Branchini, Viel, ApJS, 2015
Regis, Xia, Cuoco+ PRL 2015
Cuoco, Xia, Regis,+ ApJS, 2015
Cuoco, Bilicki, Xia, Branchini, ApJS, 2017

Tomography of the IGRB via x-correlation with LSS

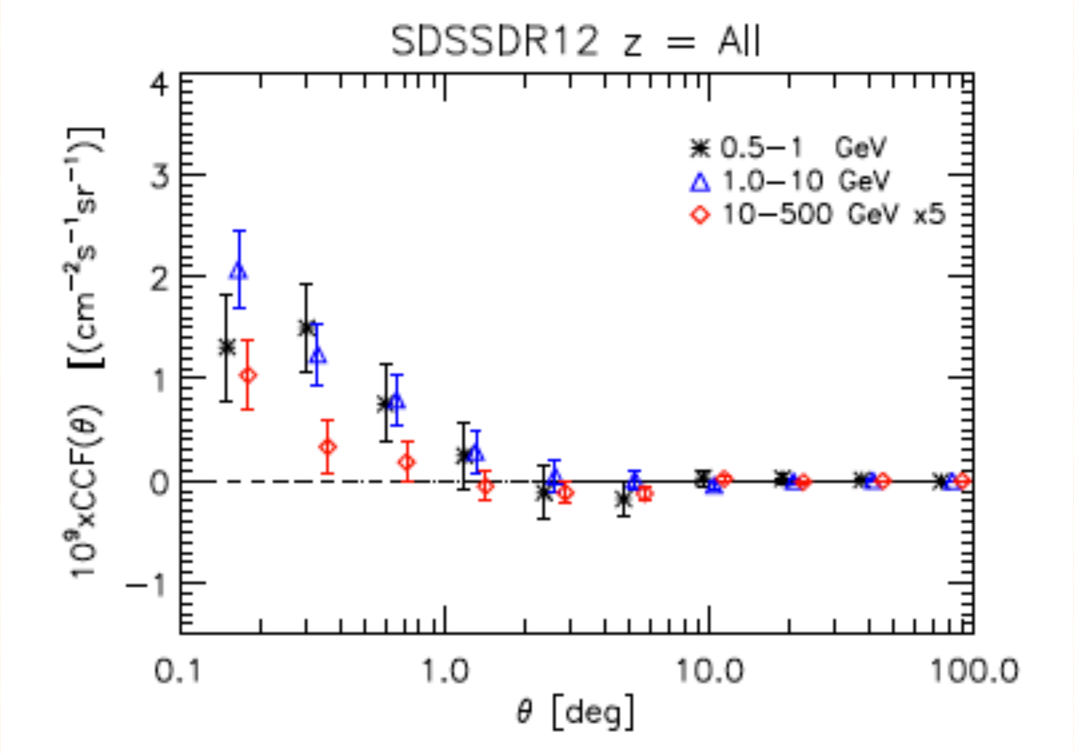


See also:
Xia et al. MNRAS 2011,
Ando, JCAP 2014,
Ando, Benoit-Levy,
Komatsu PRD 2014

Xia et al. ApJS, 2015
Cuoco et al. ApJS, 2017

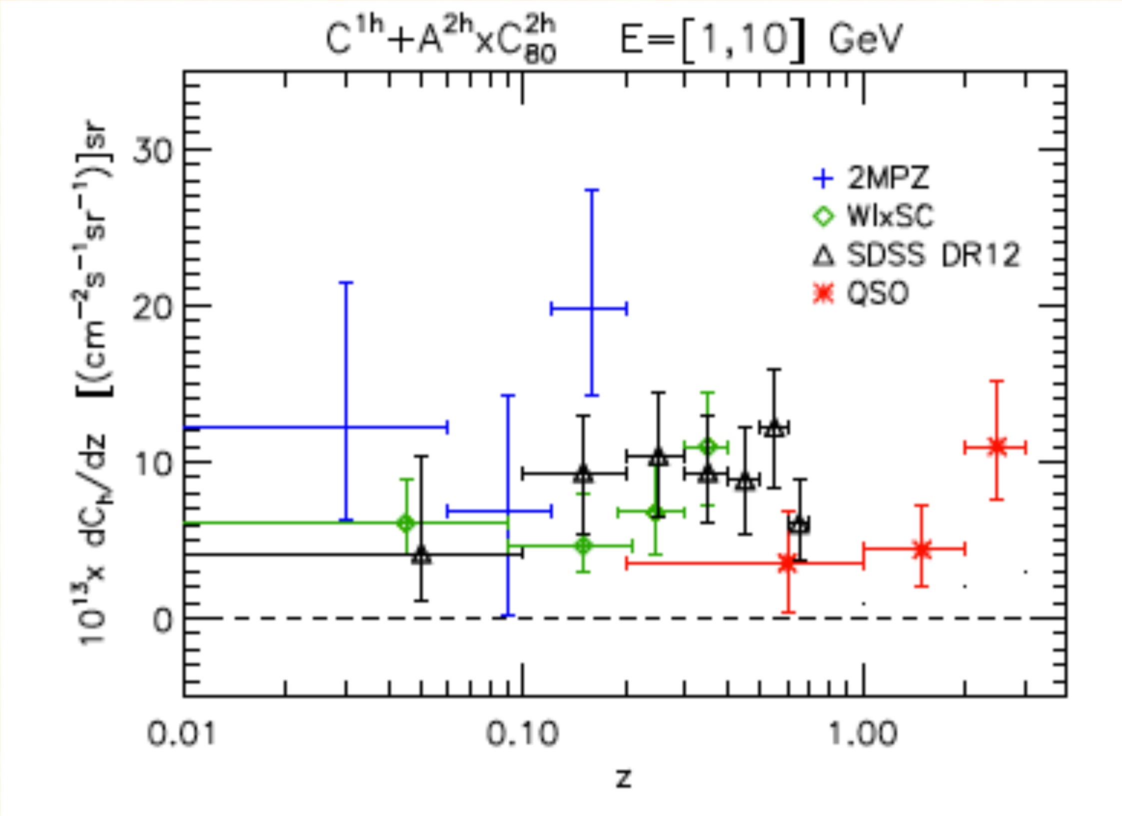
- The different z-coverage of each catalogue allows to isolate the IGRB at different z effectively performing a Tomography of the IGRB
- This provides a strong handle to better separate components and eventually DM

Fermi- SDSS X-Correlation



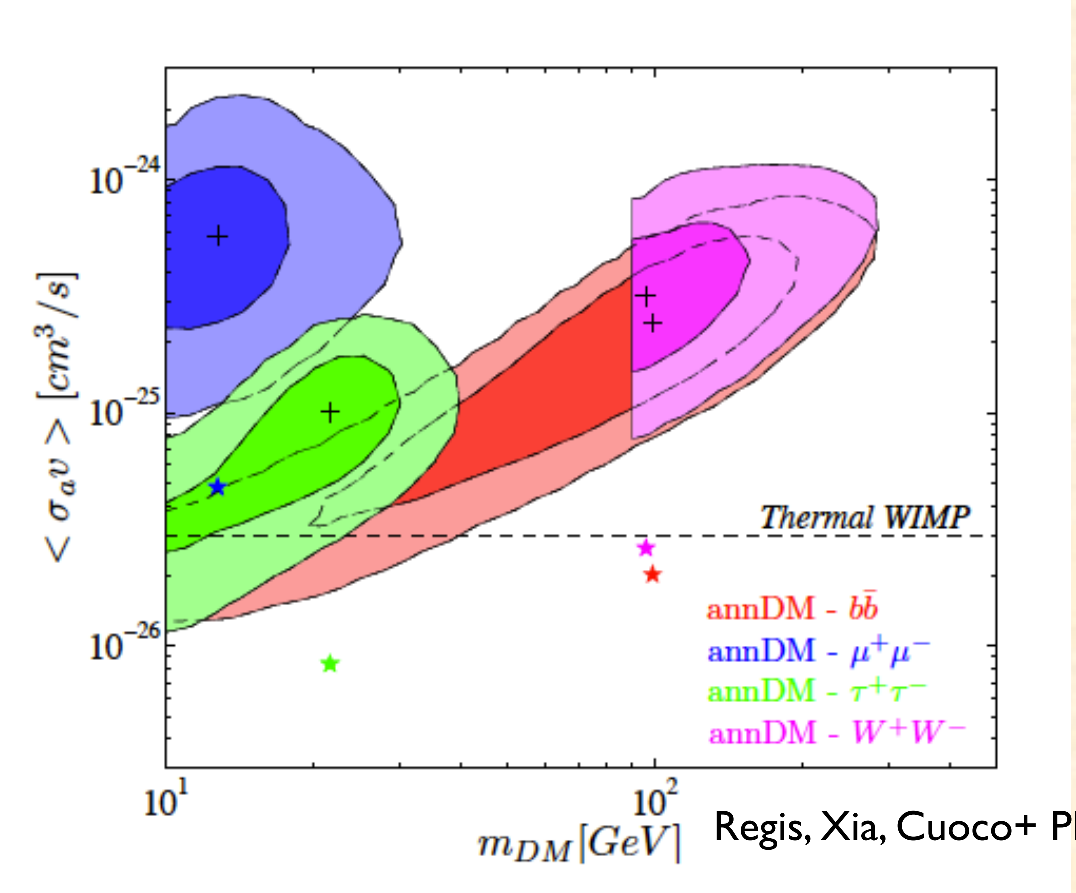
- Cross-correlation detected with a high significance (> 5 sigma)

Measured IGRB redshift distribution



- Exploiting the redshift information of the catalogs, a fine-binning tomography of the IGRB can be performed and the redshift distribution can be reconstructed

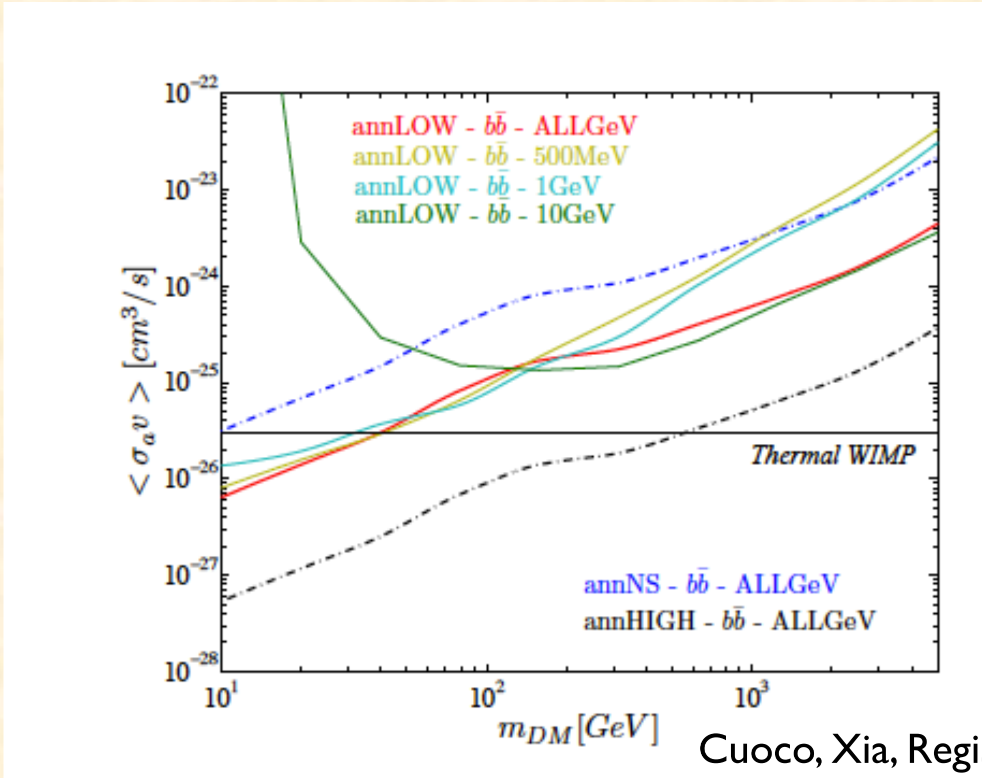
Dark Matter Interpretation



Regis, Xia, Cuoco+ PRL 2015

- A large DM contribution to the 2MASS correlation cannot be excluded, since, due to the peaking at low z, an high 2MASS correlation does not affect the correlations at higher z.

Dark Matter Constraints



Cuoco, Xia, Regis,+ ApJS, 2015

- Limits on the DM contribution can be placed, although they depend on the DM Halo substructure modeling.
- They are, however, competitive even in the most conservative substructure boost scenario (i.e. no boost)

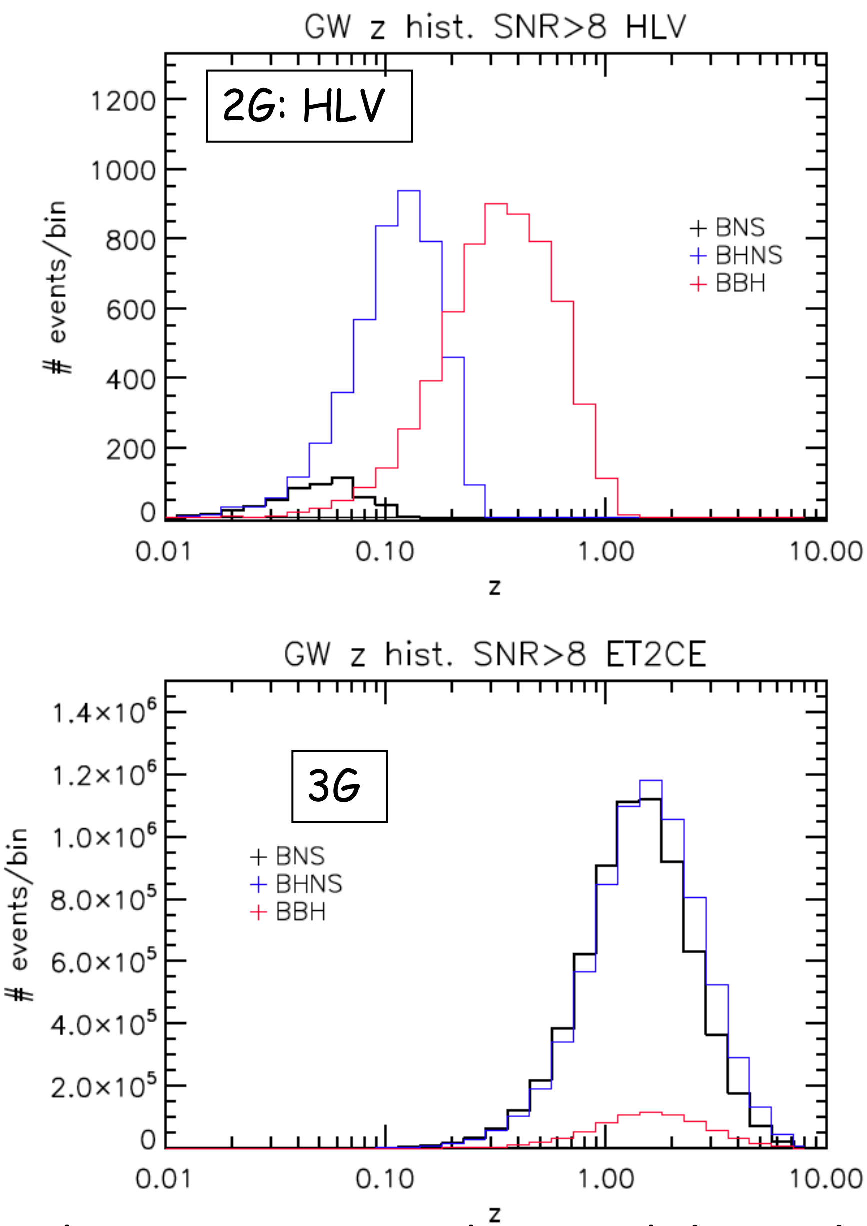
GW-LSS forecast

- Considering 3 cases:
  - HLV design sensitivity (~4000 BBH Events in 10 yr)
  - HLVIK design sensitivity (~20000 BBH Events in 10 yr)
  - 3G: Einstein Telescope+ 2xCosmic Explorer (1M BBH events up to z~5)

- Expected angular resolutions of the order ~0.1-1 deg

Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020), ArXiv: 2002.02466

GW-LSS forecast



- The simulation gives the z-distribution for the observed GW events and for the 3 sub-classes BBHs, BNS, BH-NSs

- 2G will detect events up to z~0.6, while 3G up z~5

Calore, Cuoco, Regimbau, Sachdev and Serpico, Phys.Rev.Res. 2 (2020)

Theoretical predictions

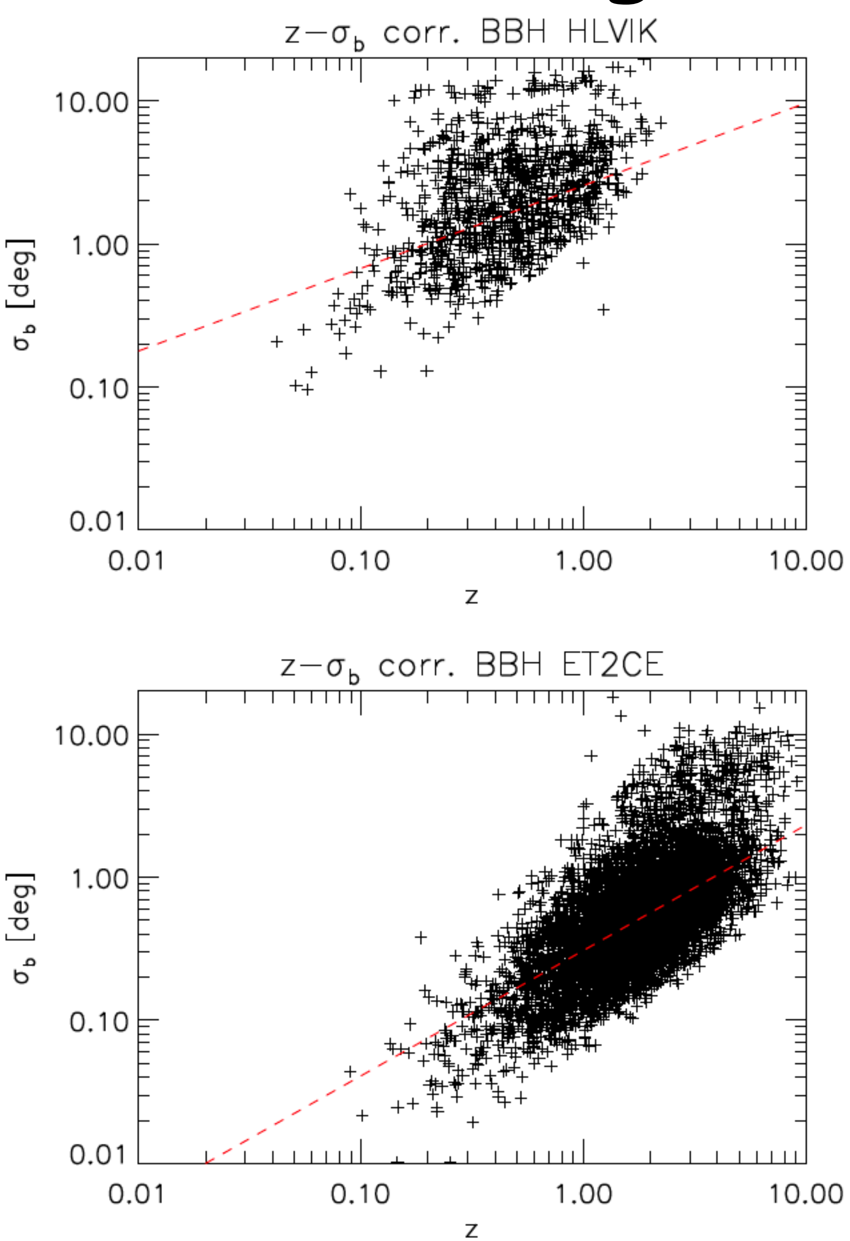
Angular Power Spectrum of GW-LSS cross-correlation

$$C_\ell^{ab} = \int \frac{\mathrm{d}\chi}{\chi^2} W_a(\chi) W_b(\chi) b^a(z(\chi)) b^b(z(\chi)) P\left(k = \frac{\ell}{\chi}, z(\chi)\right)$$

Expected Error on the Angular Power Spectrum

$$\left(\frac{\delta C_\ell^{ab}}{C_\ell^{ab}}\right)^2 = \frac{1}{(2\ell+1)\Delta\ell f_{\mathrm{fov}}} \left[1 + \frac{C_\ell^{aa} C_\ell^{bb}}{(C_\ell^{ab})^2} \times \right.$$
$$\left. \times \left(1 + \frac{C_N^{aa}}{W_{\ell,a}^2 C_\ell^{aa}}\right)\left(1 + \frac{C_N^{bb}}{W_{\ell,b}^2 C_\ell^{bb}}\right)\right]$$

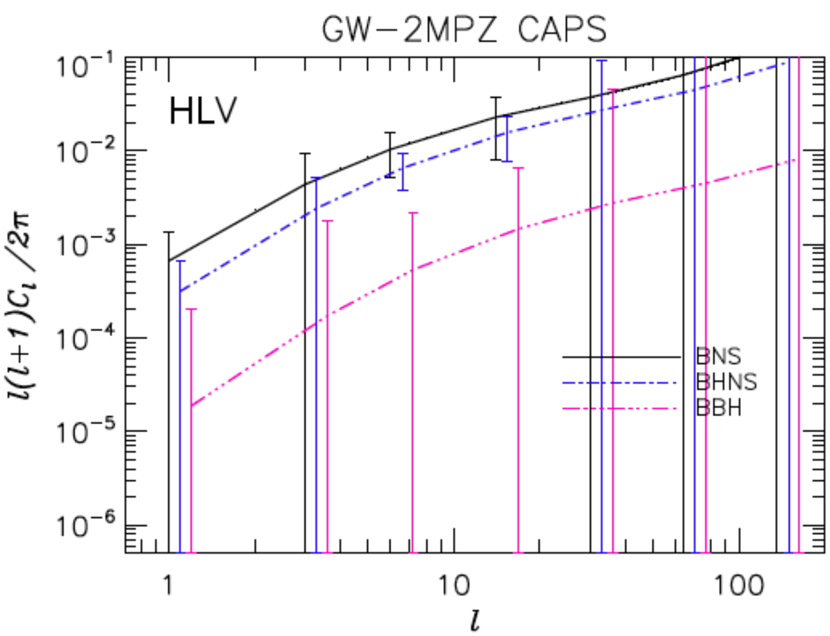
Angular resolution



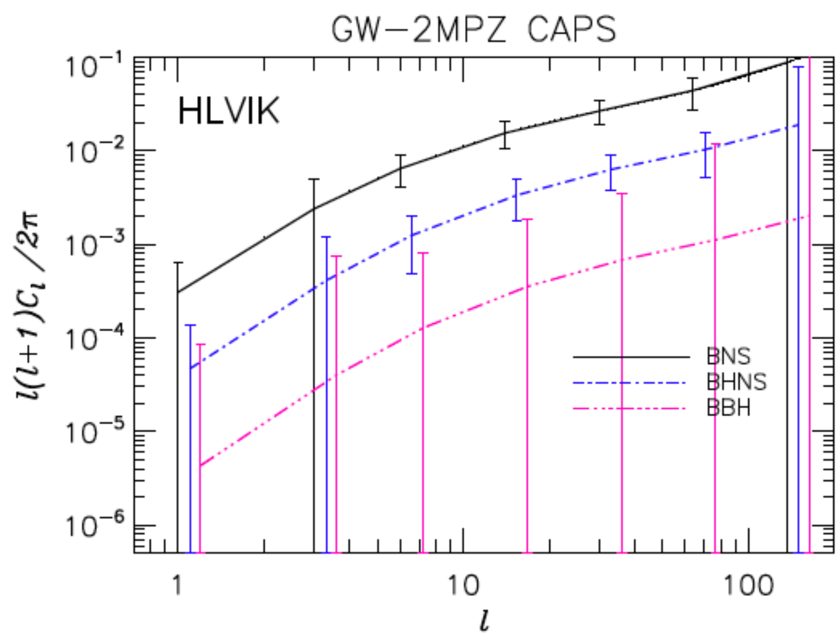
- We performed a series of simulations of reconstruction of GW events to determine the angular resolution.
- There is a strong correlation between SNR and angular resolution which translates into a correlation with z.
- For large SNR resolutions up to 0.1 deg are achieved. Resolutions of ~1 deg are typical.

Results

2MPZ-HLV

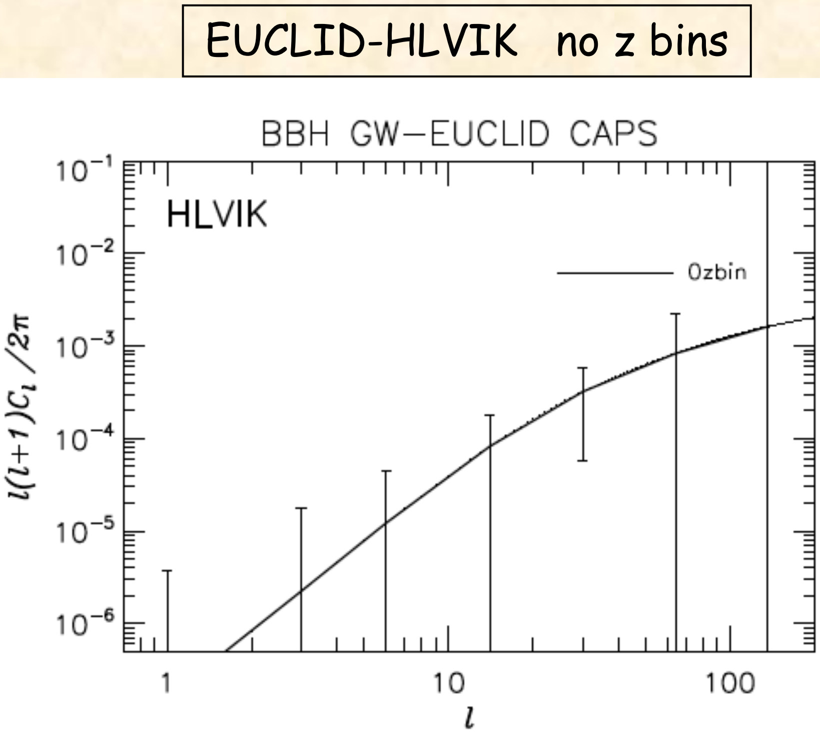


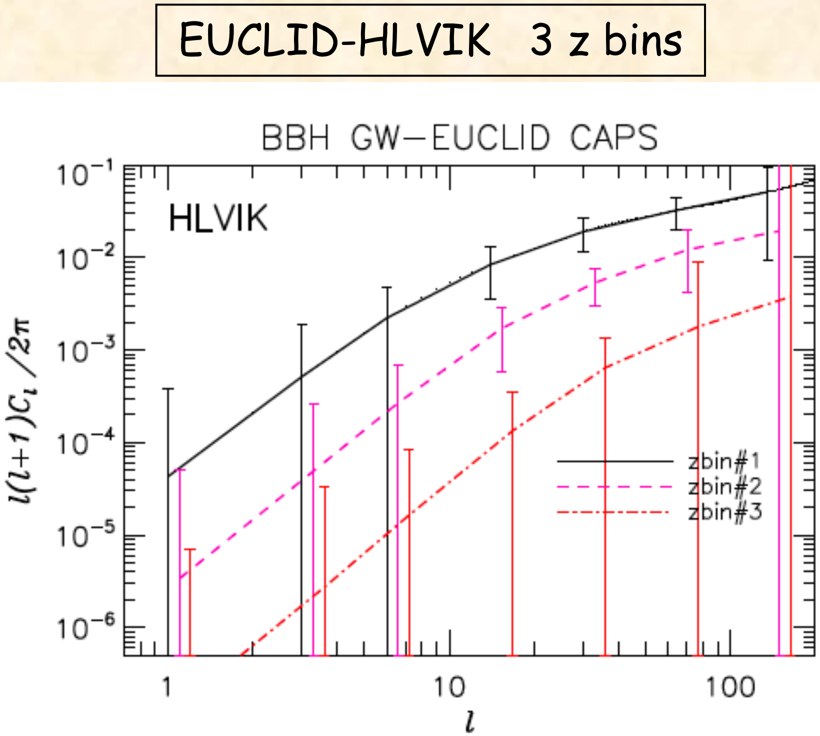
2MPZ-HLVIK



- Prospects for the detection of the cross-correlation are good already with the current generation, especially with 5 detectors

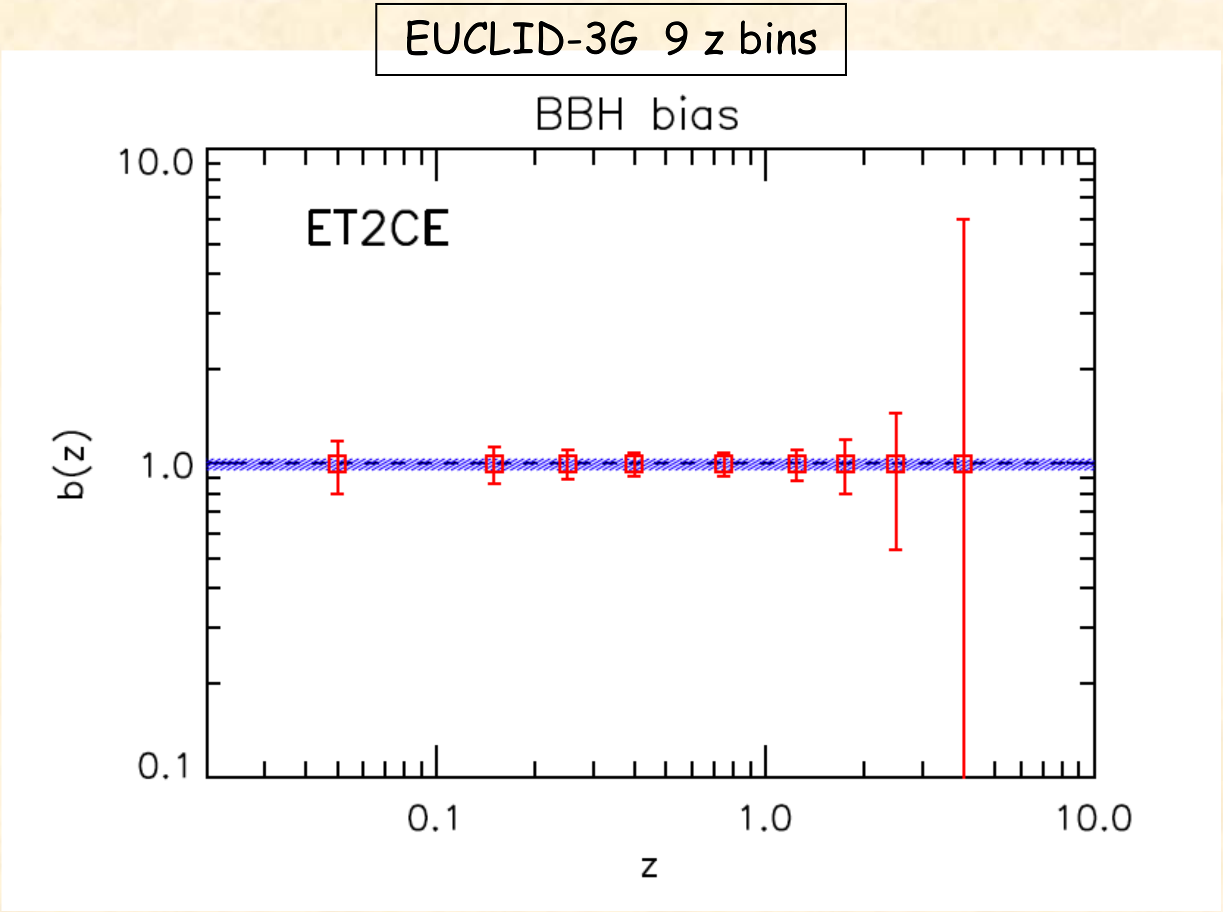
Results





- With future Galaxy surveys like Euclid is also possible to perform redshift tomography
- Tomography is particularly convenient and enhances the signal

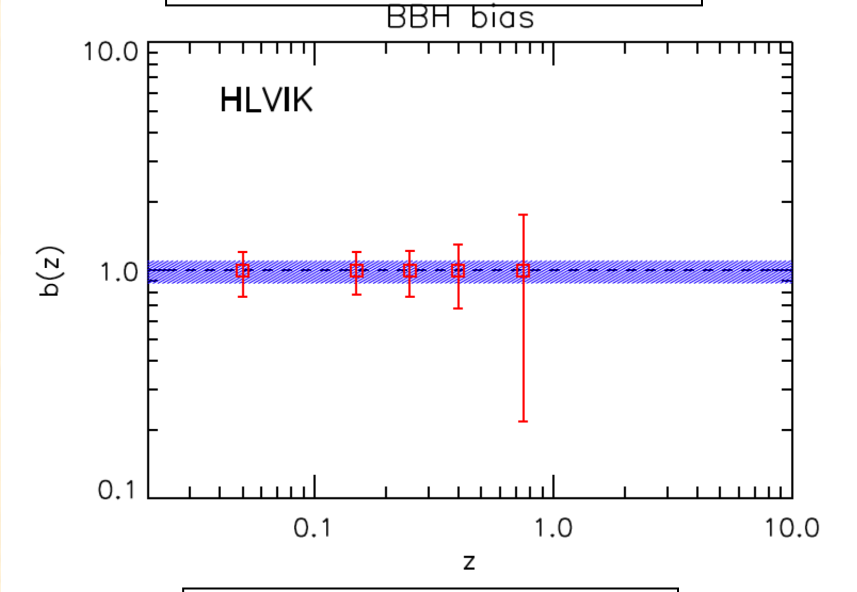
Results: bias



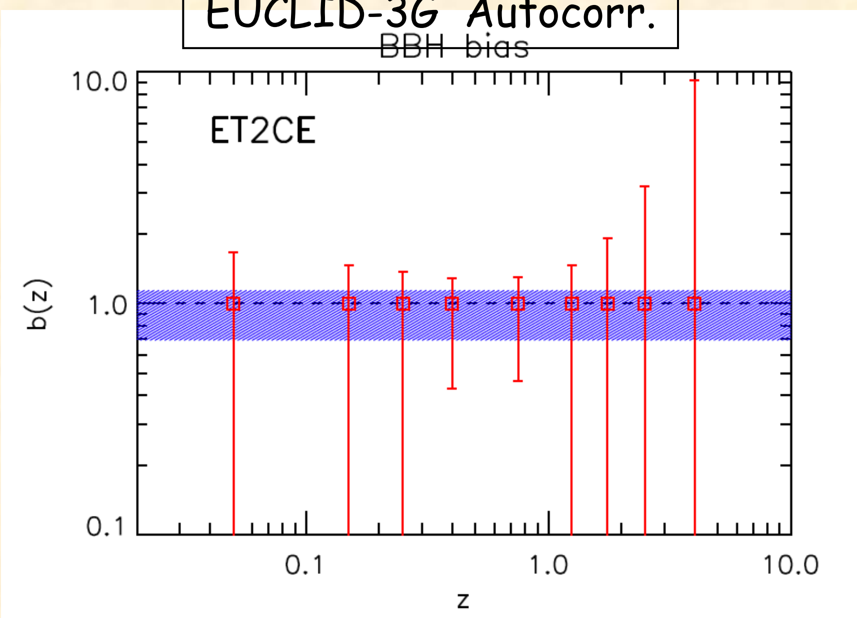
- Combining 3G and future galaxy surveys it possible to determine the bias as function of z at about 10% precision, which should be enough to distinguish the primordial BHs case from the astro BHs case

Results: bias

EUCLID-HLVIK 5 z bins



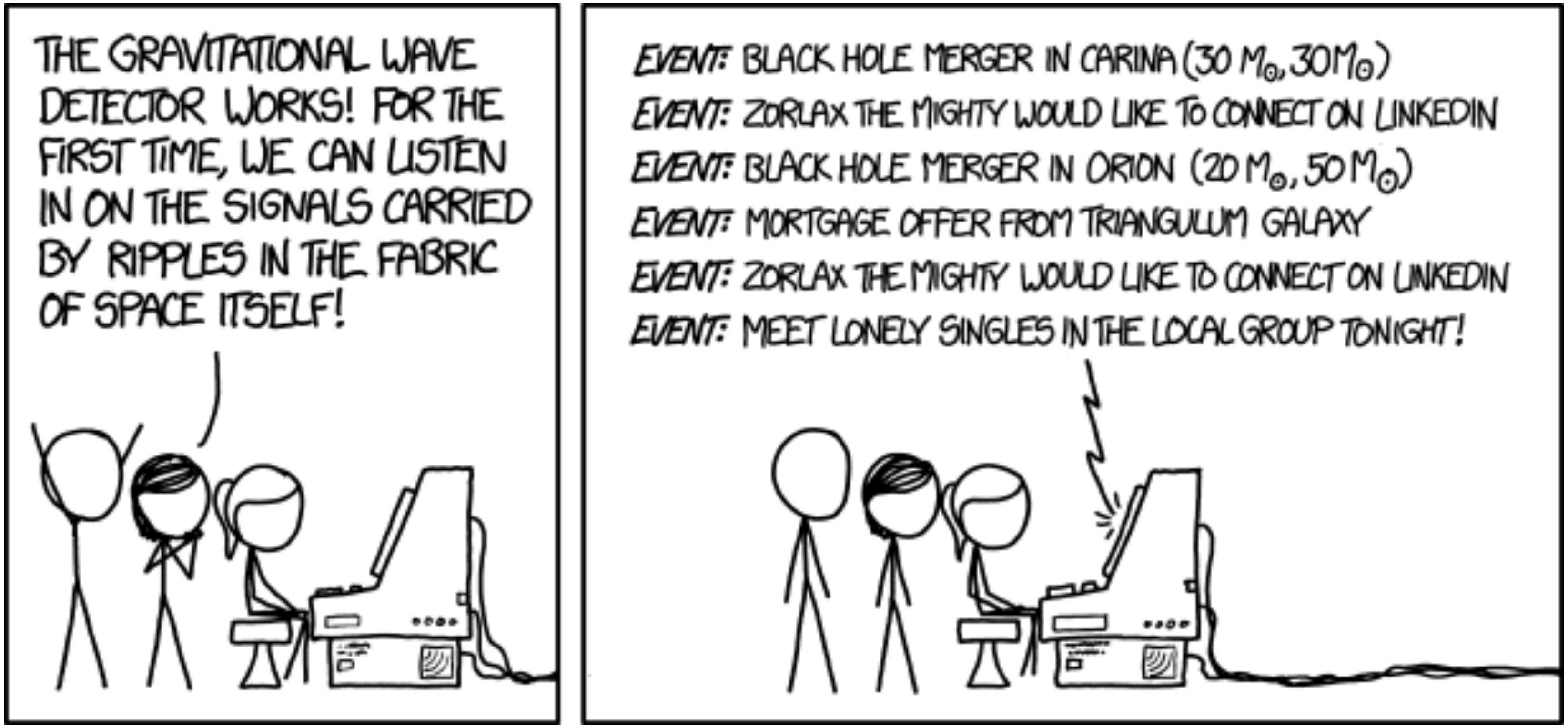
EUCLID-3G Autocorr.



- Already with the current generation the bias can be measured reasonable well giving discrimination capabilities
- Results from GW autocorrelation only are poor. The extra information from correlation with galaxies dramatically enhance the discrimination power.

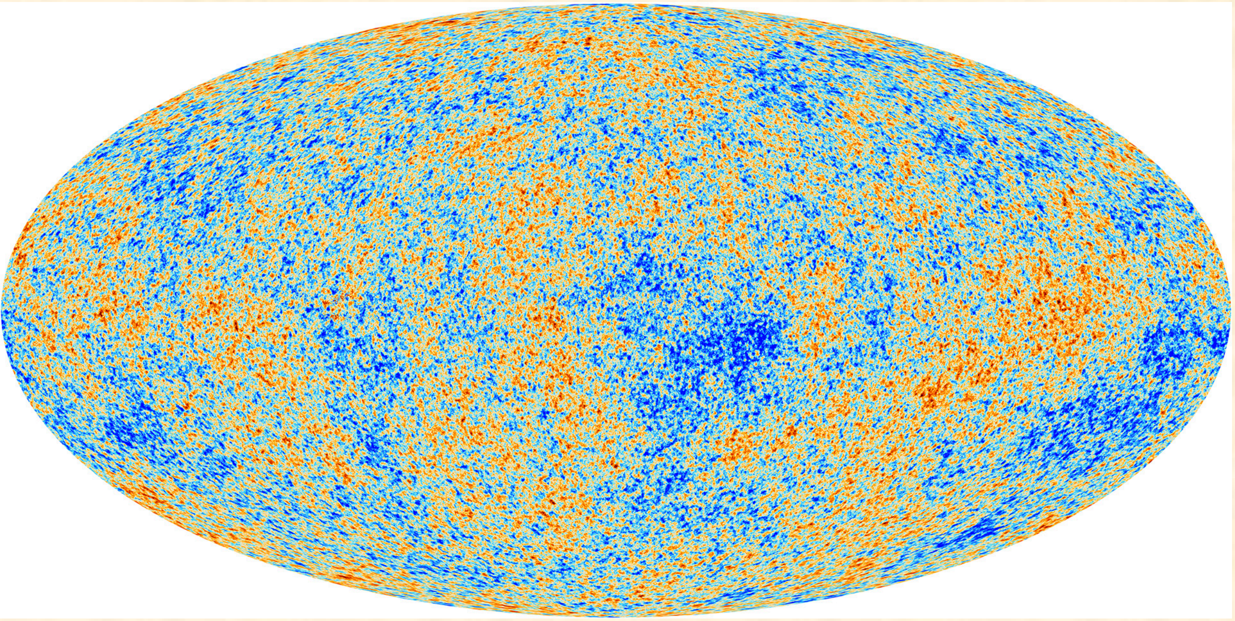
Conclusions

- Cross-correlation with LSS is a promising tool to test the primordial BH DM scenario
- Cross-correlation is detectable with 10yr data taking of the current (2G) generation instruments
- Next generation (3G) should allow to perform precision studies (~ few %)



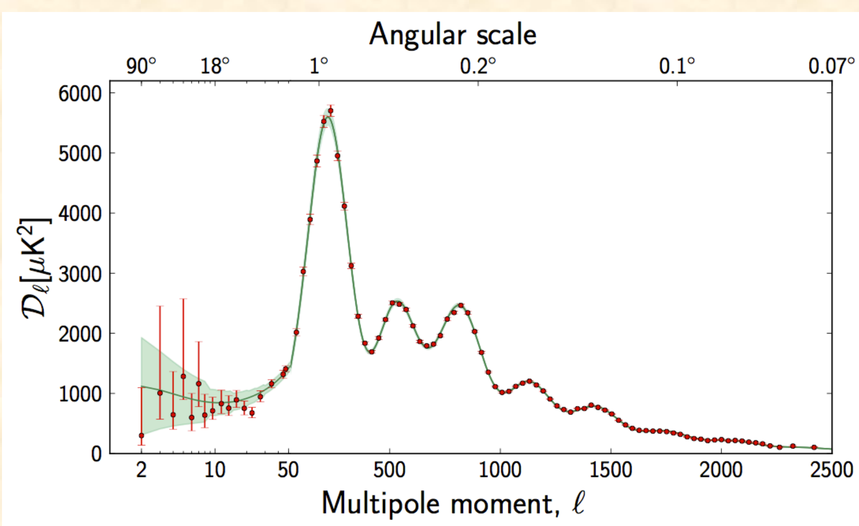
Credits: xkdc

Auto-Correlation of the CMB

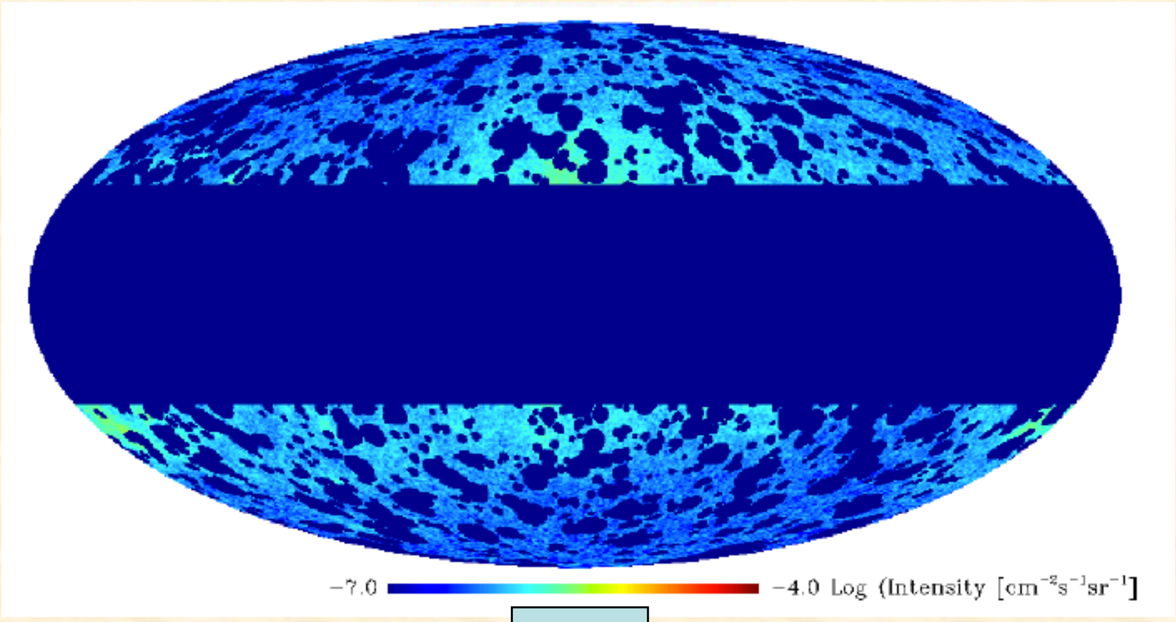


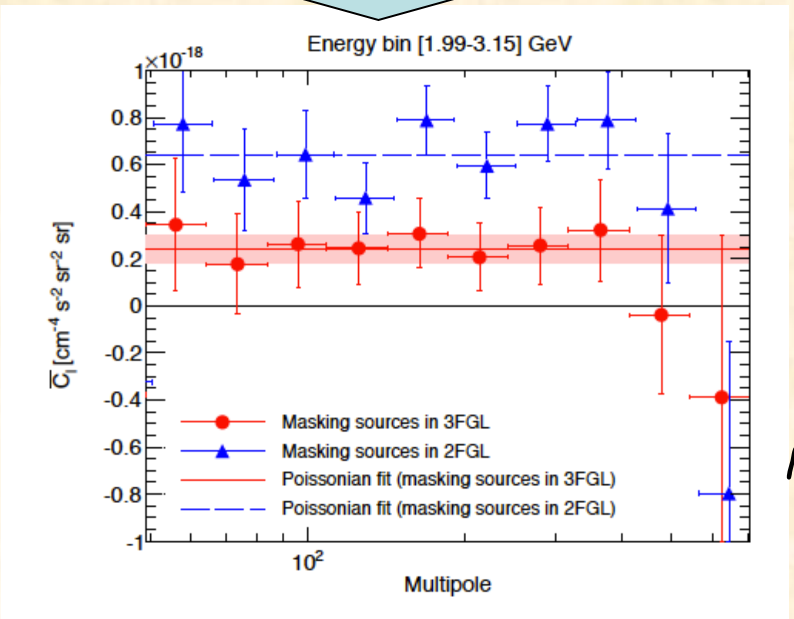
$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$



Auto-Correlation of the Gamma-ray sky



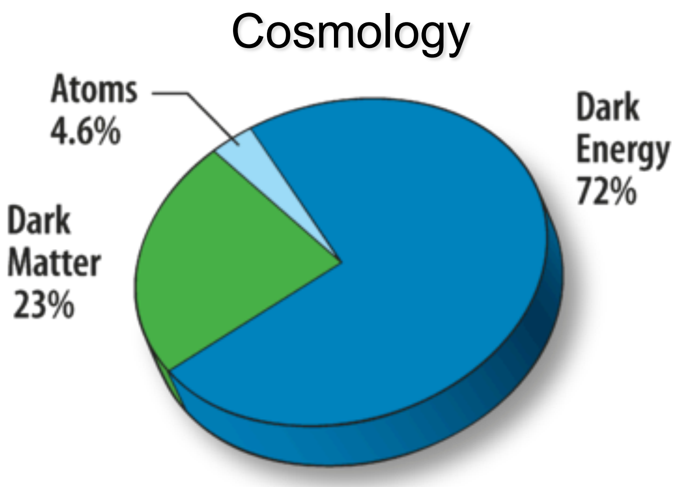


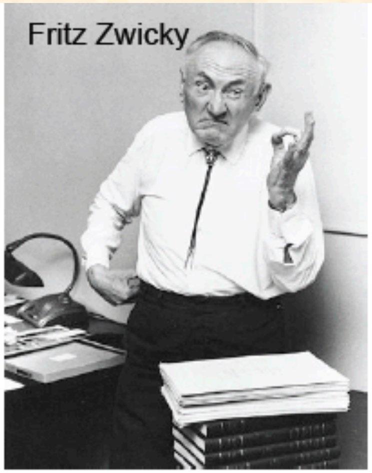
$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

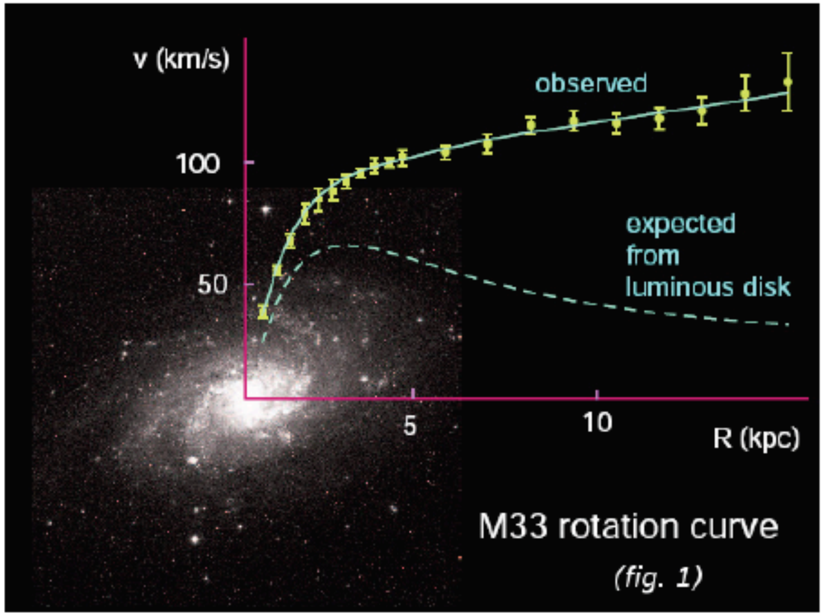
$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

M.Fornasa, AC, et al. PRD 2016

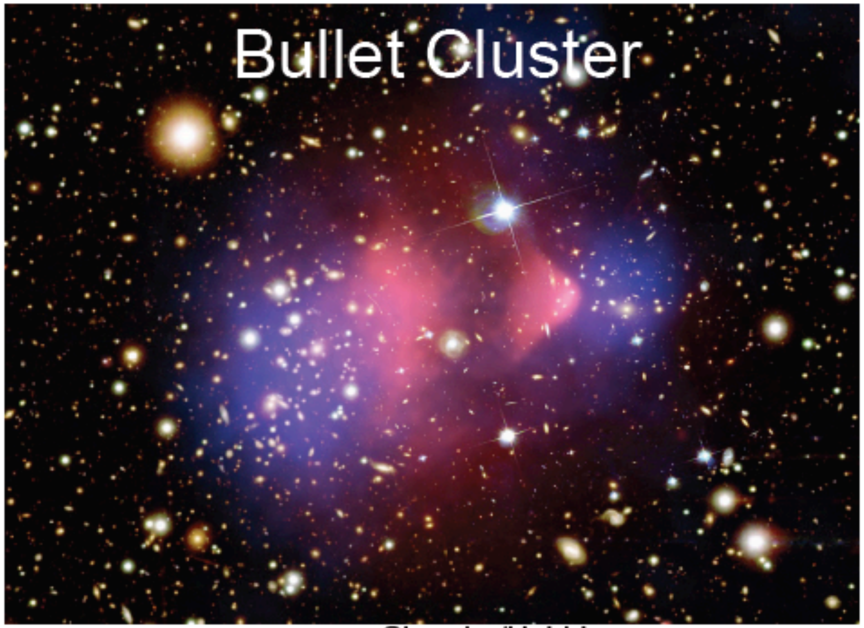
Dark Matter





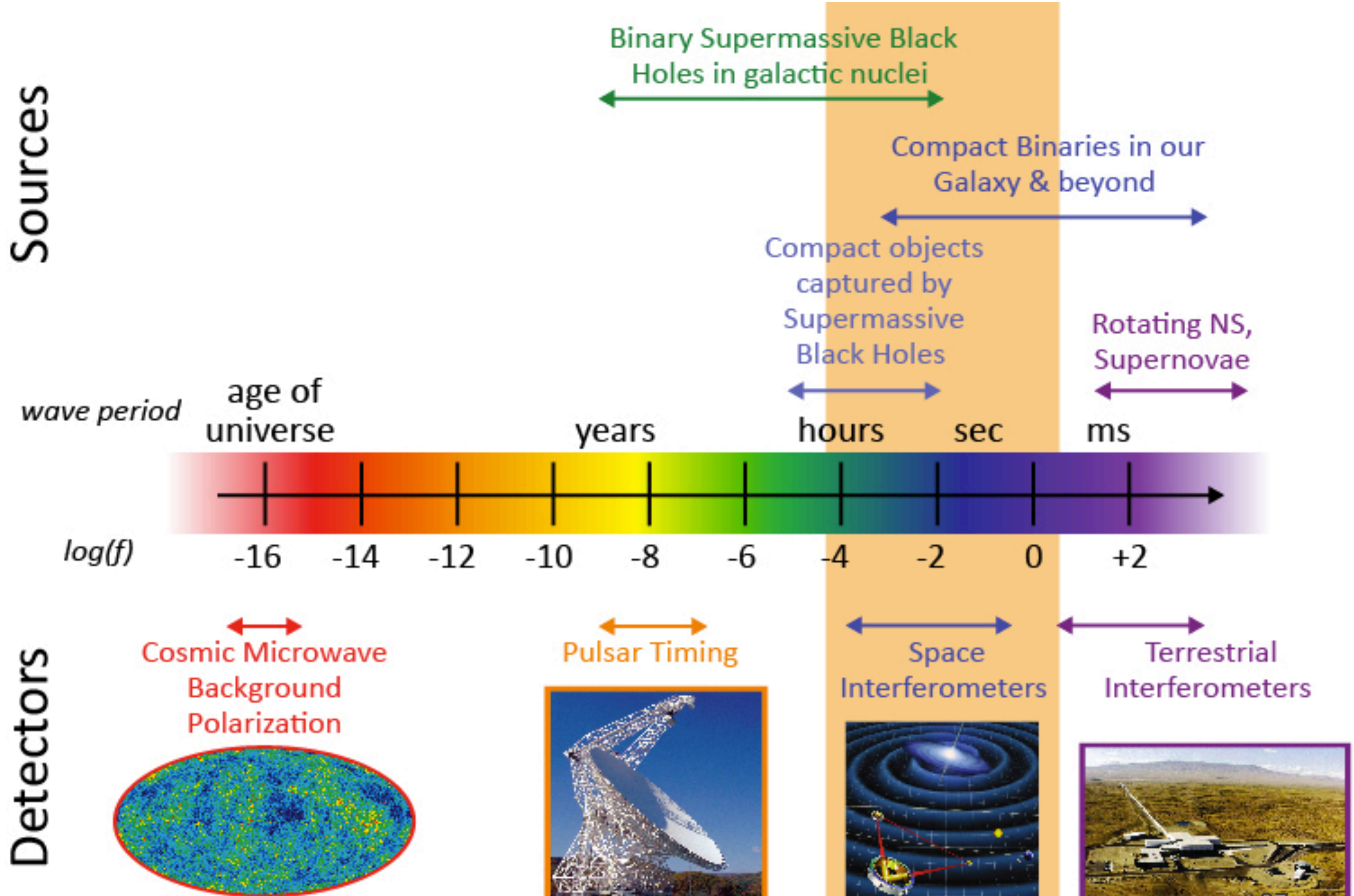


www4.nau.edu/



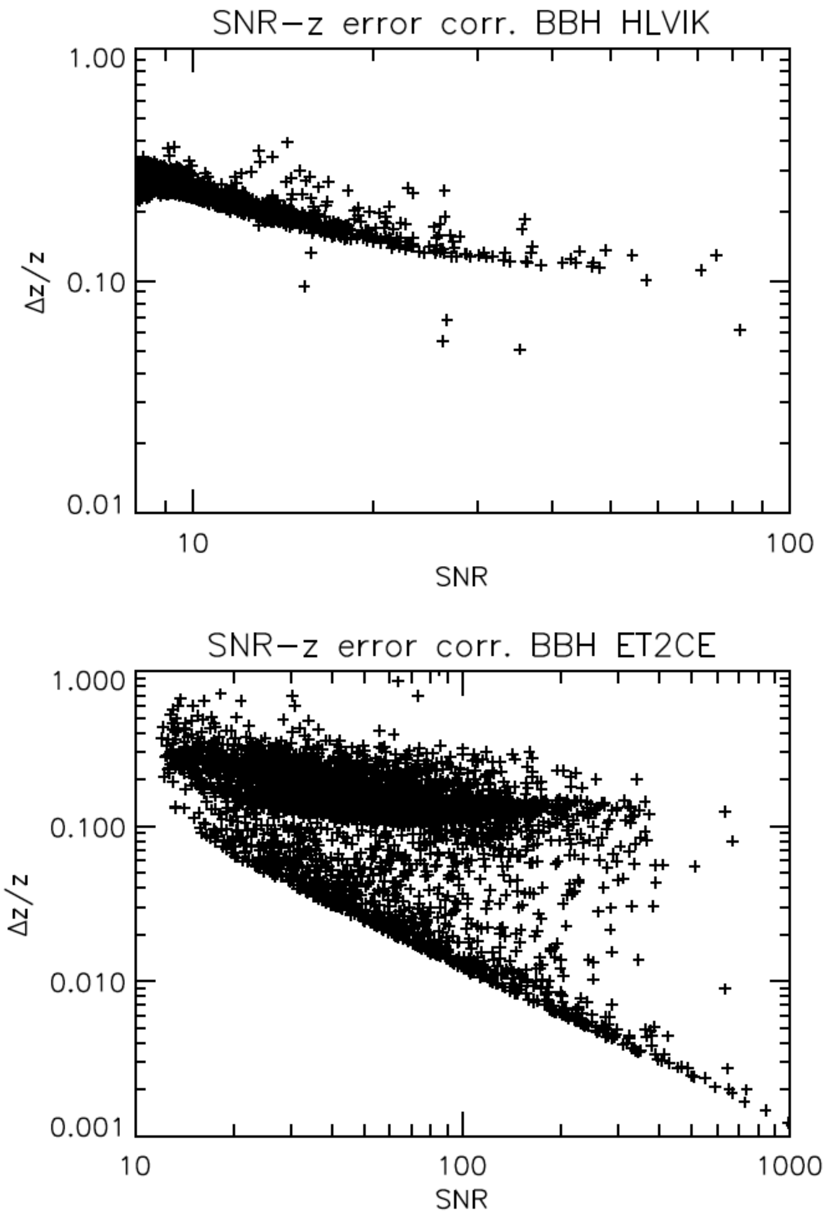
Chandra/Hubble

The Gravitational Wave Spectrum



Credits: lisa.nasa.gov

Redshift resolution



- Redshift resolution typically of the order of 20%
- For some very well reconstructed event can go down to 1% or 0.1%

Catalogs z-distributions