Title: Cross-correlation technique in GW cosmology

Speakers: Ben Wandelt

Collection: Gravitational Waves Beyond the Boxes II

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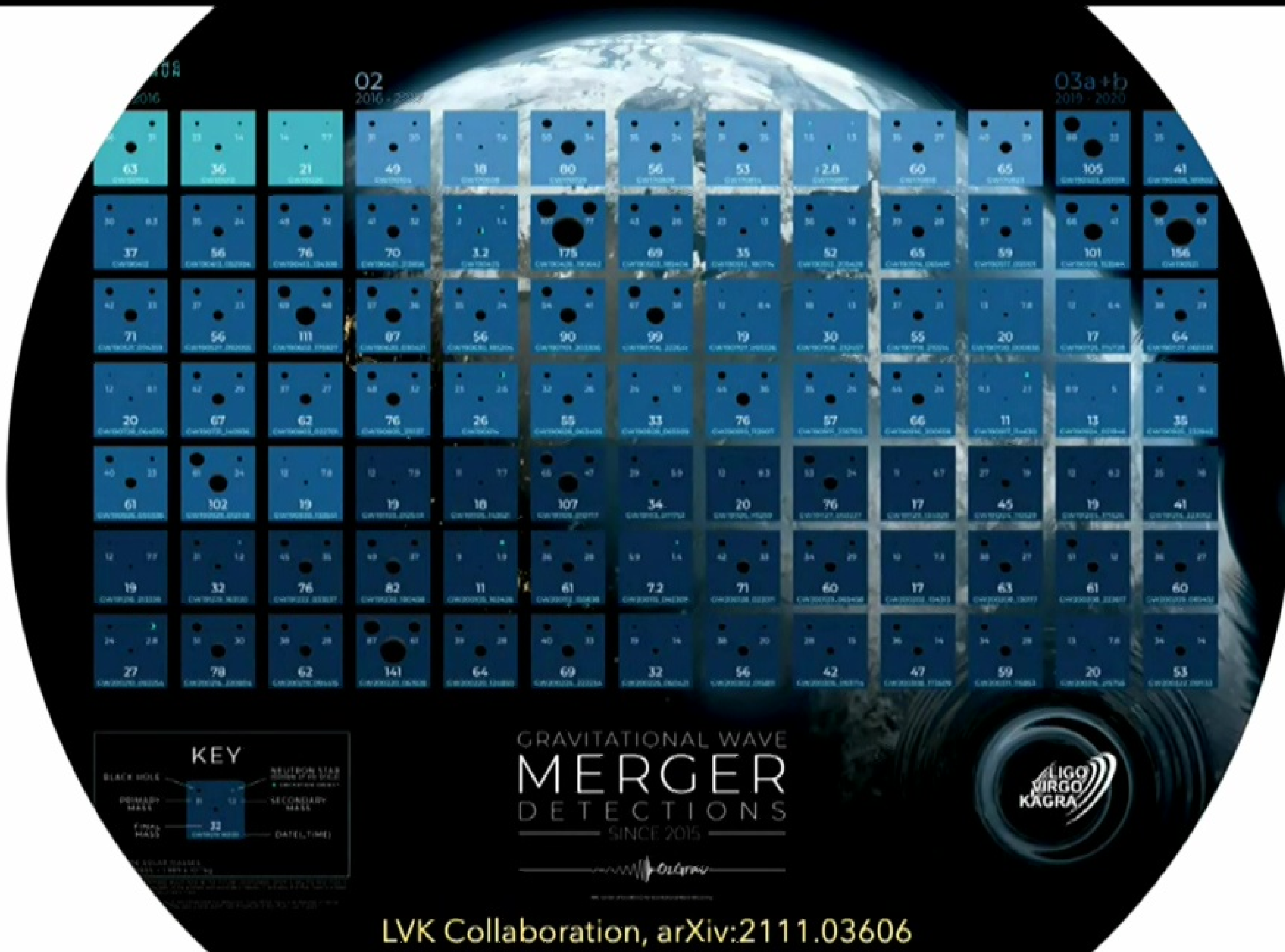
IAP

Cross-correlation methods in GW cosmology

Benjamin Wandelt

with **Suvodip Mukherjee**, Alex Krolewski, Joe Silk, Samaya Nissanke, Alessandra Silvestri, Guilhem Lavaux, Jens Jasche, Gergely Dálya, R. Díaz, François Bouchet, Florent Leclercq, Kenta Hotokezaka, and Doogesh Kodi-Ramanah

FLATIRON INSTITUTE



LVK Collaboration, arXiv:2111.03606

Cosmology 101

- Chapter 1: Homogeneous and isotropic universe
  - 1.1 FLRW metric
  - 1.2 RW equation
  - ...
- Chapter 2: Classical cosmological tests
  - 2.1 Luminosity-distance redshift test

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    "Observe an object's luminosity distance and redshift and plot them against each other"

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Cosmology 101

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"Observe an object's luminosity distance and redshift and plot them against each other"

But there are no objects in a homogeneous and isotropic universe!

Clearly need to consider *structure*.

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A new way to think about cosmological tests

- Consider two types of tracers
  - A luminosity distance tracer *sn*
  - A redshift tracer *g*
- Let's write down the simplest possible model for their density contrasts:
  - Gaussian random field

$$-2\mathcal{L}_{\text{full}}(\boldsymbol{\delta}_g, \boldsymbol{\delta}_{sn}|\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{\delta}_g \\ \boldsymbol{\delta}_{sn} \end{pmatrix}^T \boldsymbol{\Xi}^{-1} \begin{pmatrix} \boldsymbol{\delta}_g \\ \boldsymbol{\delta}_{sn} \end{pmatrix} + \ln |\boldsymbol{\Xi}|$$

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Assume both cluster and are mapped from comoving coordinates into luminosity distance and redshift space. Then

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

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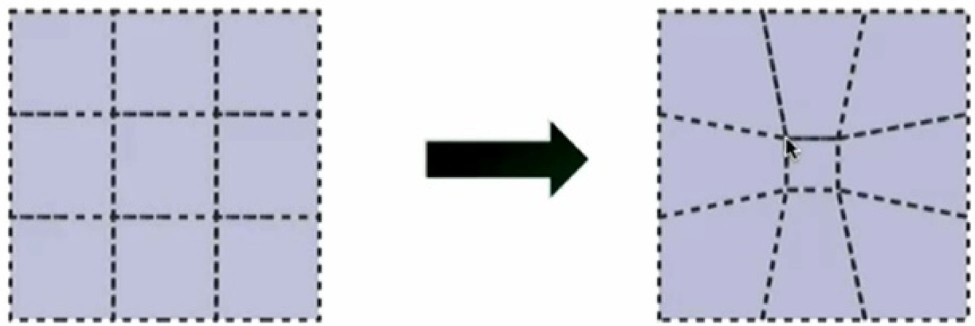
The transformation matrix *Z*



Comoving coordinates	**Scaled redshift coordinates**
$\vec{x}$	$\vec{\mathfrak{z}}_i = \frac{c}{H_0} z_i \hat{u}_i$

D is the analogous transformation to distance space.

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A new way to think about cosmological tests

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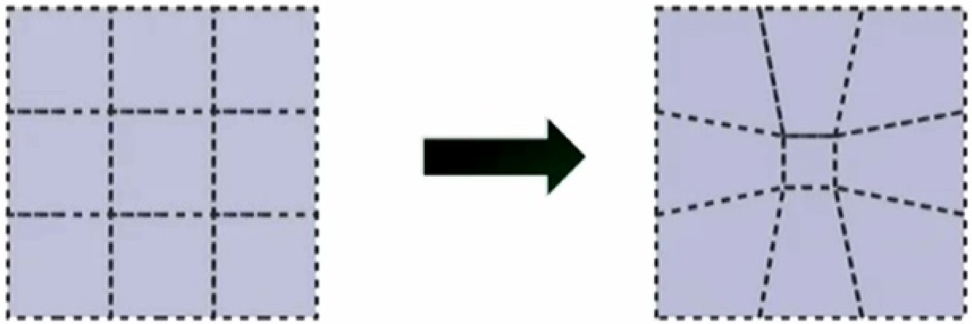
What are the ***Z*** and ***D***?

The transformation matrix *Z*



Comoving coordinates

$$\vec{x}$$

Scaled redshift coordinates

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A new way to think about cosmological tests

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Light-cone generalization of Alcock Paczyński test

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

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A new light-cone AP-test in D_L-space

A new way to think about cosmological tests

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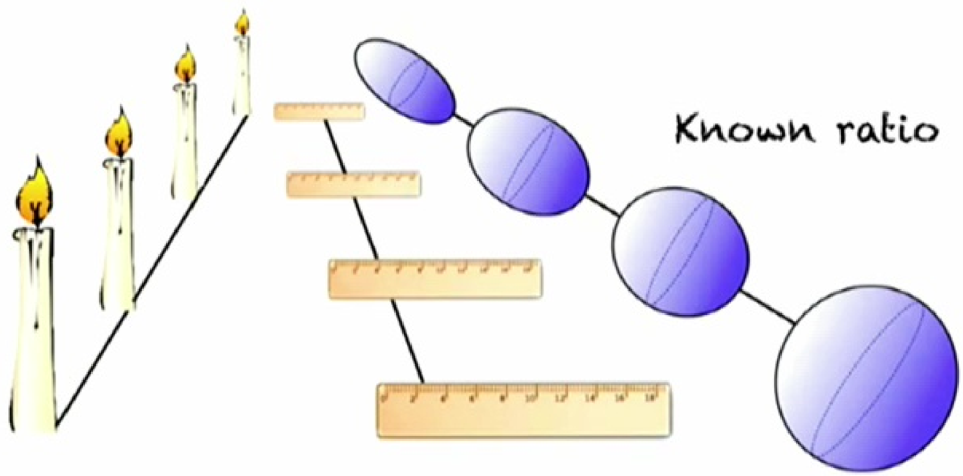
Light-cone generalization of Alcock Paczyński test

A new multi-tracer, global, lightcone AP test!

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

A new light-cone AP-test in D_L-space

Reminder: cosmology with the Alcock-Paczyński test



Known ratio $\frac{\text{radial size}}{\text{angular size}}$

Known luminosity

Standard "candles"

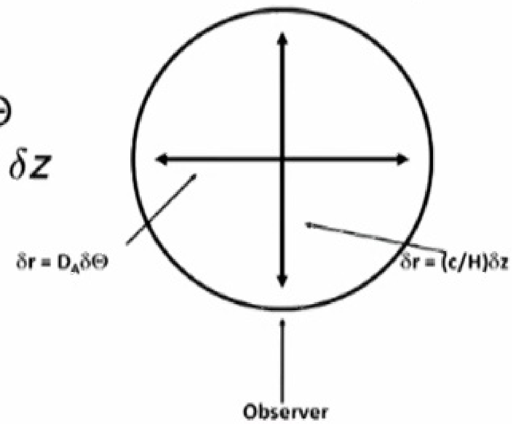
Known length

Standard "rulers"

Standard "spheres" – e.g. isotropic correlation function

Reminder: cosmology with the Alcock-Paczyński test

- Angular separation $\delta r_\perp = D_A(z)\,\delta\Theta$
- Radial separation $\delta r_\parallel = cH^{-1}(z)\,\delta z$



ANGULAR DIAMETER DISTANCE & HUBBLE RATE

$$D_A(z) = c\int_0^z H^{-1}(z')\,\mathrm{d}z' \quad , \quad H(z) = H_0\sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda}$$

Any deviation from the fiducial cosmology causes geometric distortions. $\Rightarrow$ Determine ellipticity ε via

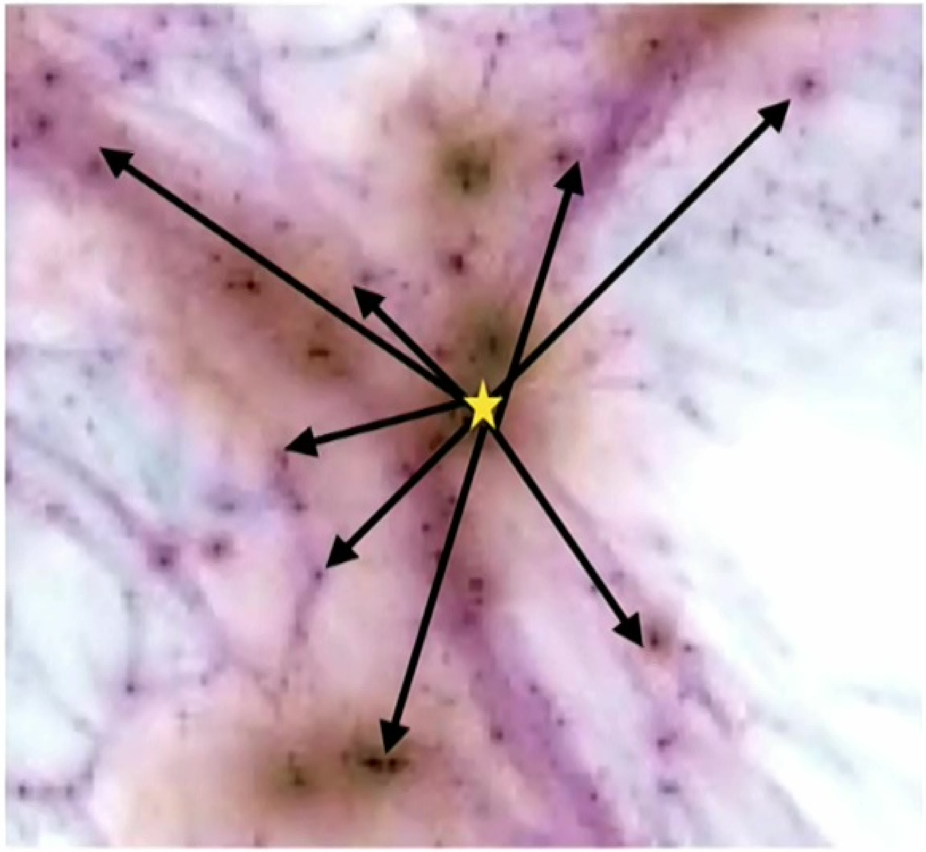
$$\varepsilon = \frac{\delta r_\parallel}{\delta r_\perp} = \frac{D_A^{\mathrm{true}}(z)H^{\mathrm{true}}(z)}{D_A^{\mathrm{fid}}(z)H^{\mathrm{fid}}(z)}$$

From cross-correlation Alcock-Paczyński test to luminosity distances!

$$\Xi(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

- The multi-tracer AP test involves summing over all pairs of distance and redshift tracers.
- If we (incorrectly) ignore spatial clustering by forcing the covariance to be diagonal, we get a single sum with those objects that trace both D_L and z. This is the D_L-z test!
- But galaxies *are* clustered so we can use all pairs -> can get better performance with *no need* of host identification.
- *Can exploit this in GW and SN cosmology*

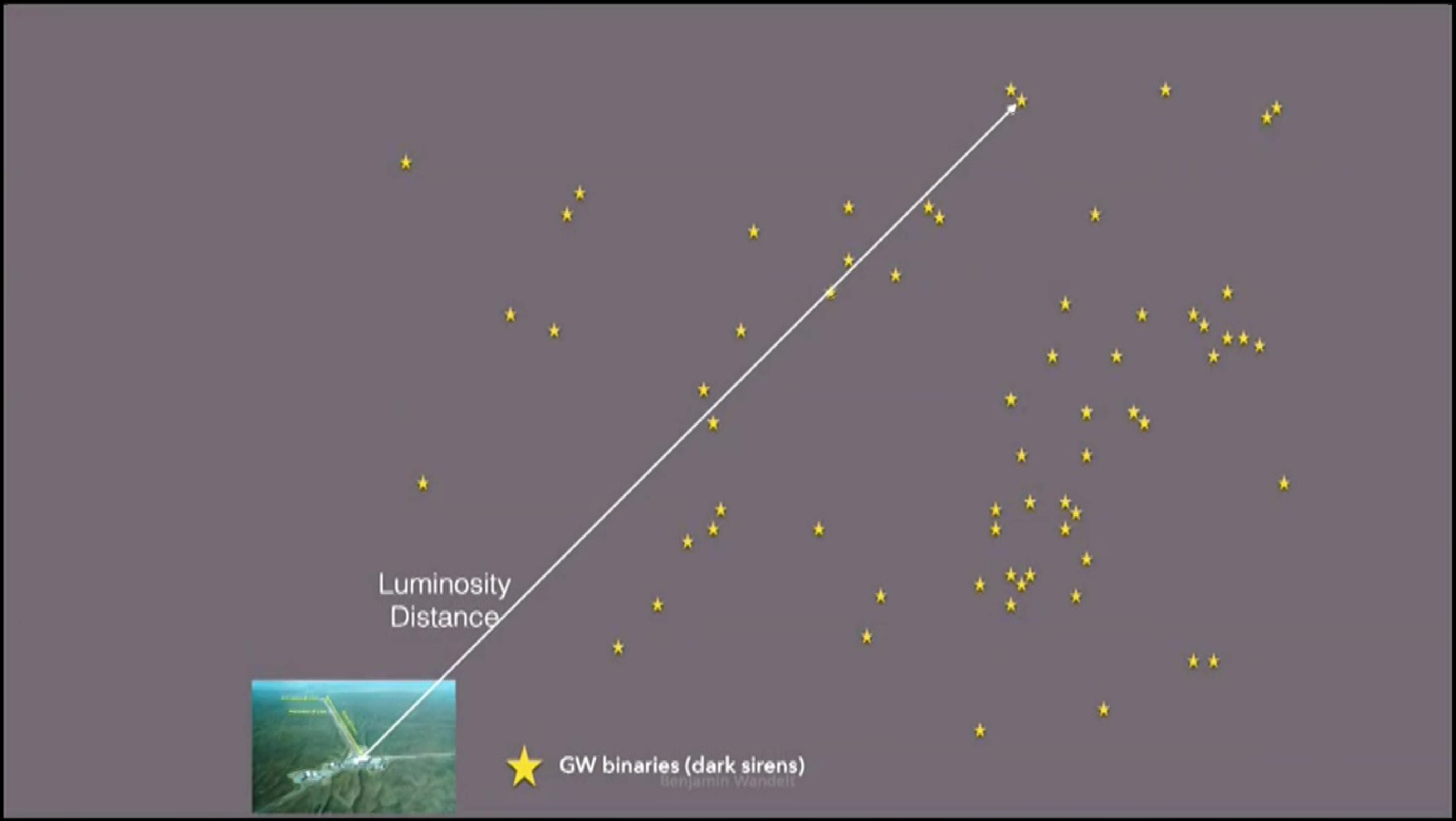
Spatial clustering with galaxies can be used to measure the redshift of the GW source even in the absence of an EM counterpart!

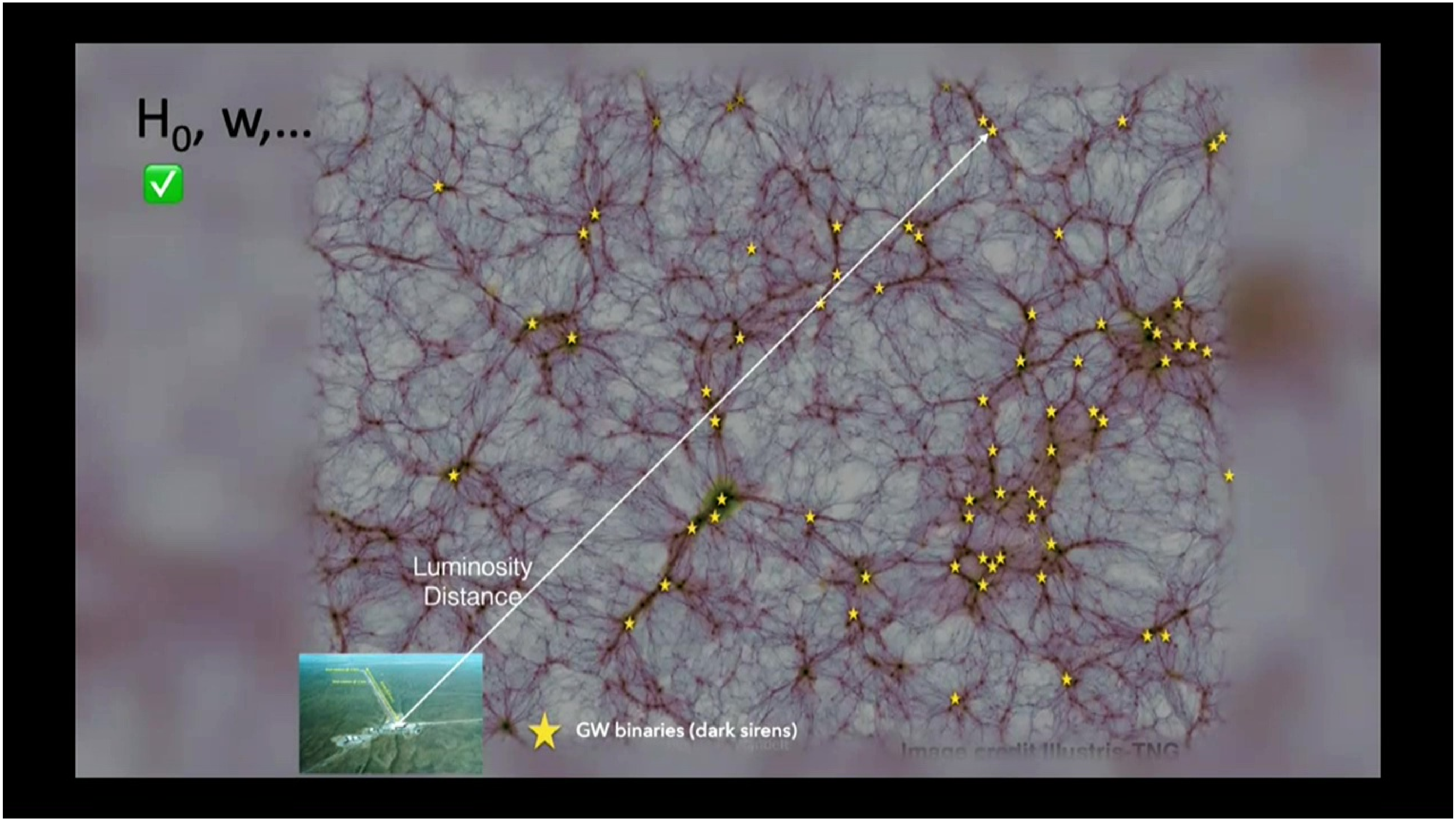


Schutz 1986: Statistical Host ID

Oguri arXiv:1603.02356: Clustering redshift

Mukherjee & Wandelt arXiv:1808.06615: Generalized light-cone AP-test. and simplified approach


Luminosity
Distance
GW binaries (dark sirens)
Benjamin Wandelt


H_0, w,...
Luminosity Distance
GW binaries (dark sirens)

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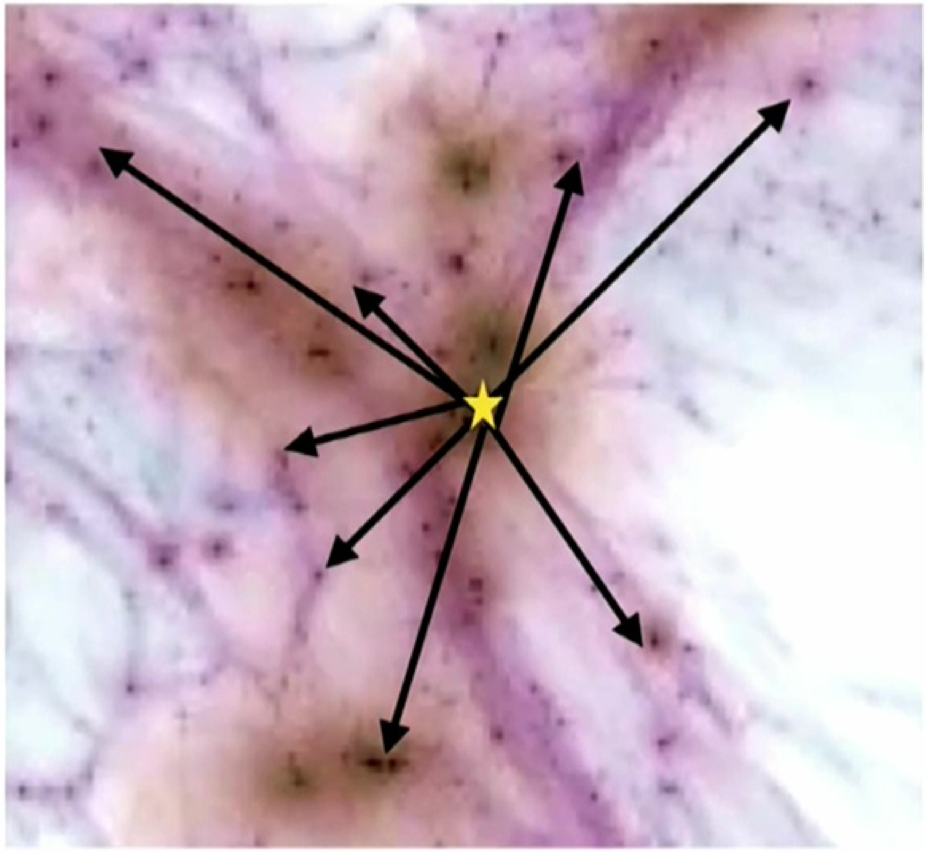
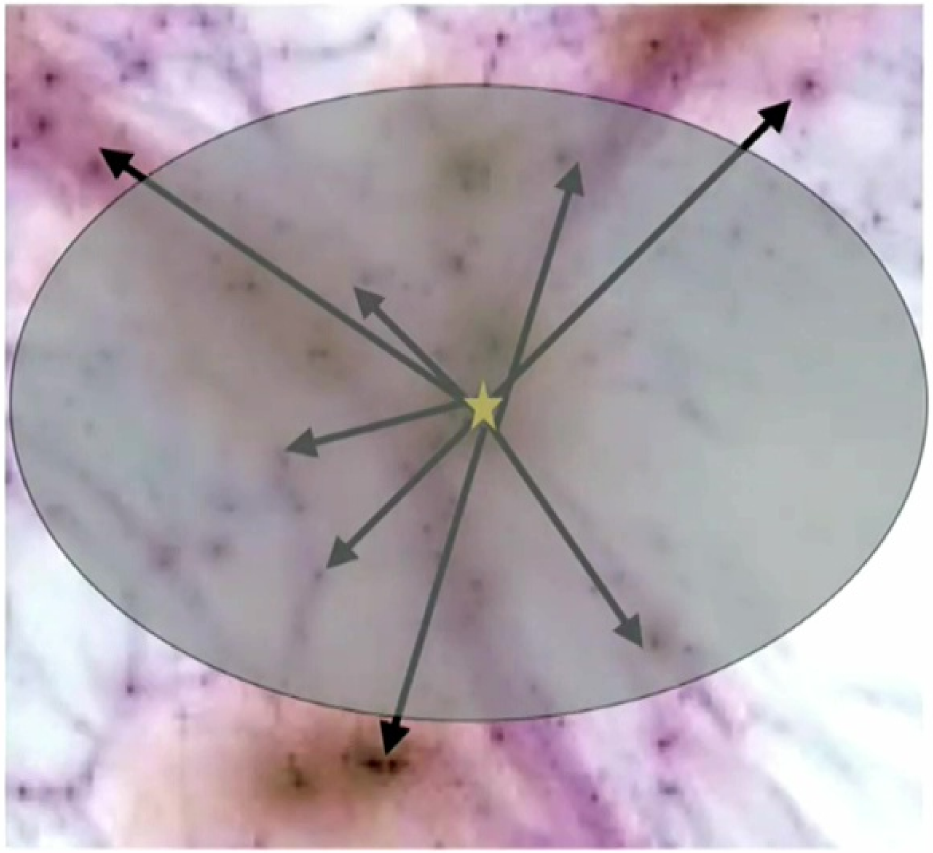


Note that correlation is not just through combined tracing of large scale structure, but grows to very small scales, since GW mergers presumably go off in galaxies – so it includes the "host galaxy ID" information!

Mukherjee & Wandelt arXiv:1808.06615: Generalized light-cone AP-test

A simplified approach suffices for current data



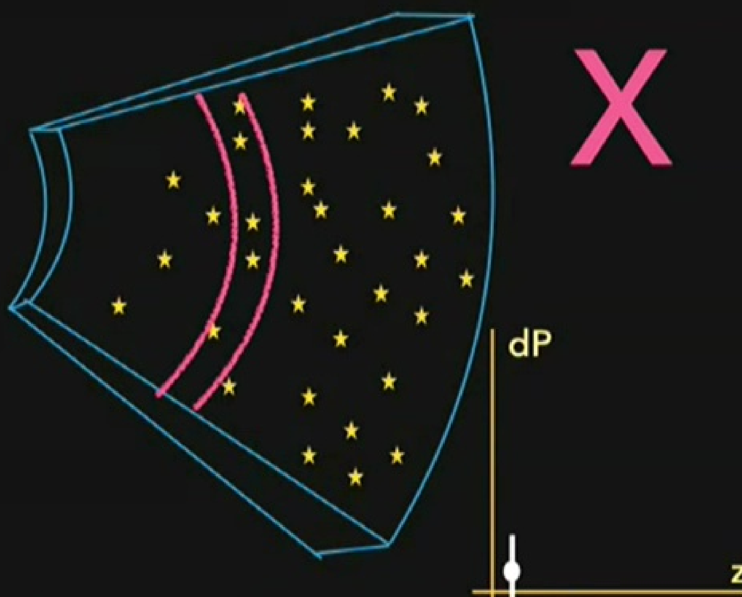
With current data, photo-z redshifts and sky localization error reduce clustering information

In every z-shell fit cross-correlation to model based on auto-correlation and bias

Oguri arXiv:1603.02356
Mukherjee & Wandelt arXiv:1808.06615
Mukherjee, Wandelt, Nissanke & Silvestri: arXiv:2007.02943

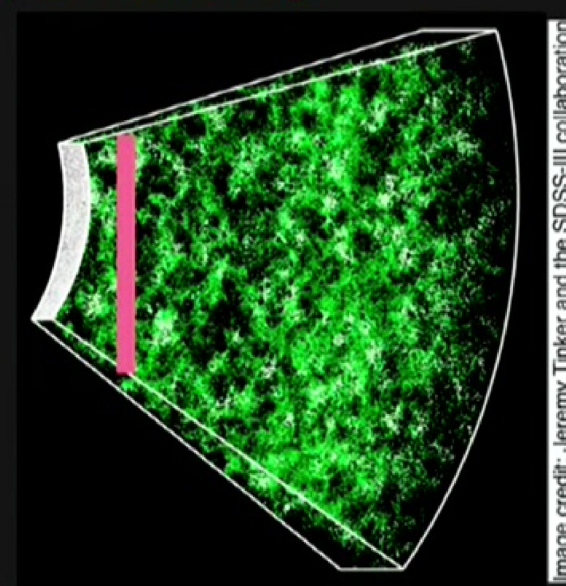
CROSS-CORRELATION OF GW SOURCES WITH GALAXIES

$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$



Dark sirens observed in luminosity distance space

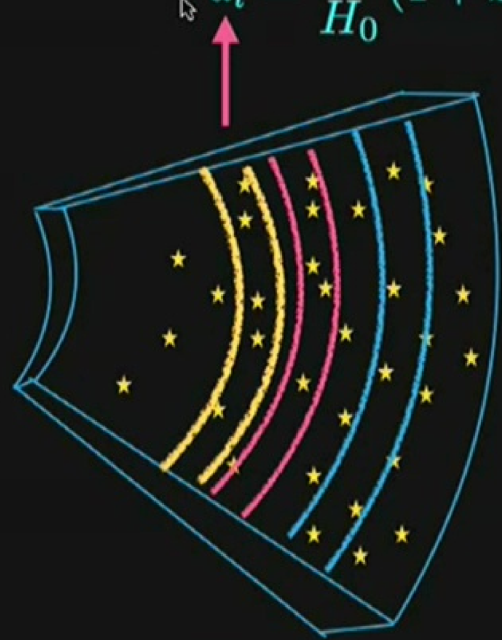
X



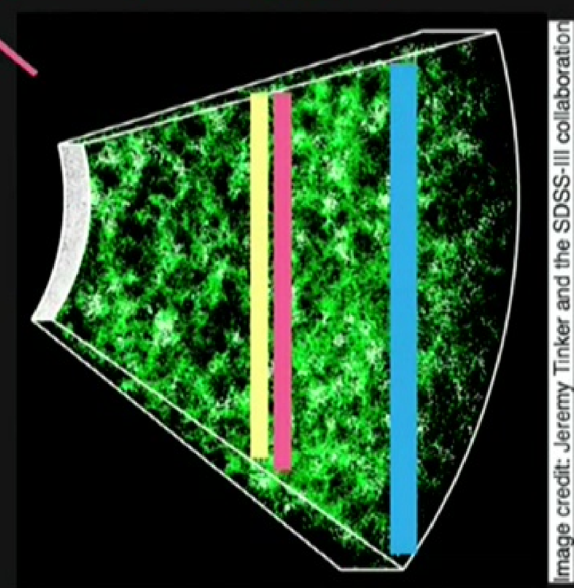
Galaxy samples observed in redshift space

EXPANSION HISTORY USING DARK SIRENS THROUGH CROSS-CORRELATION

$$d_l = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_{DE}(z')}}$$



Dark sirens observed in luminosity distance space

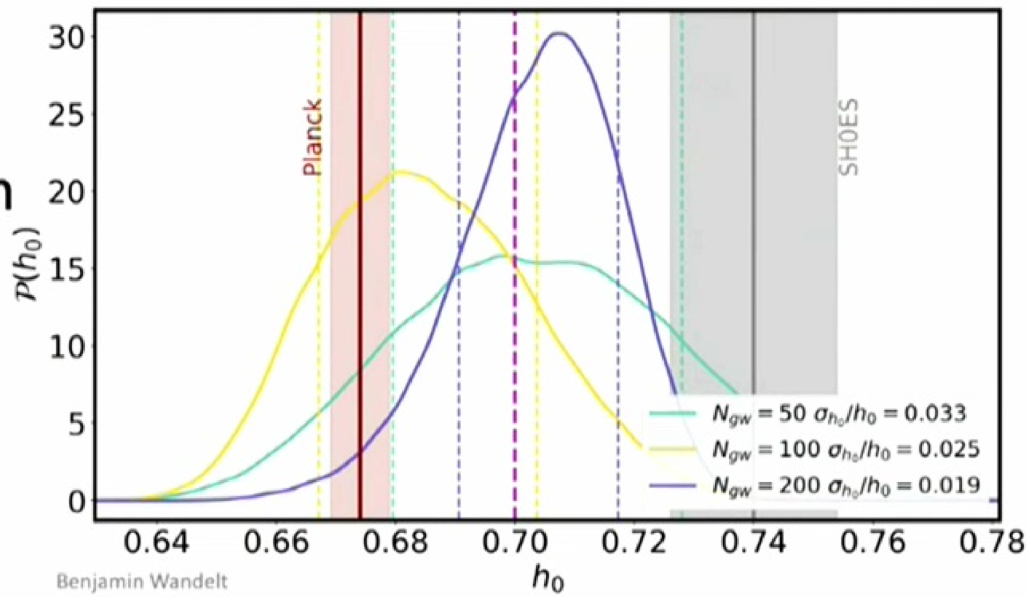


Galaxy samples observed in redshift space

Dark Sirens

- The technique applies to any distance tracer, including dark gravitational wave sirens.
- ~200 GW events *without EM counterpart* suffice to reach the similar precision on H0 as the SH0ES measurement

Mukherjee, BDW, Nissanke & Silvestri arXiv:2007.02943



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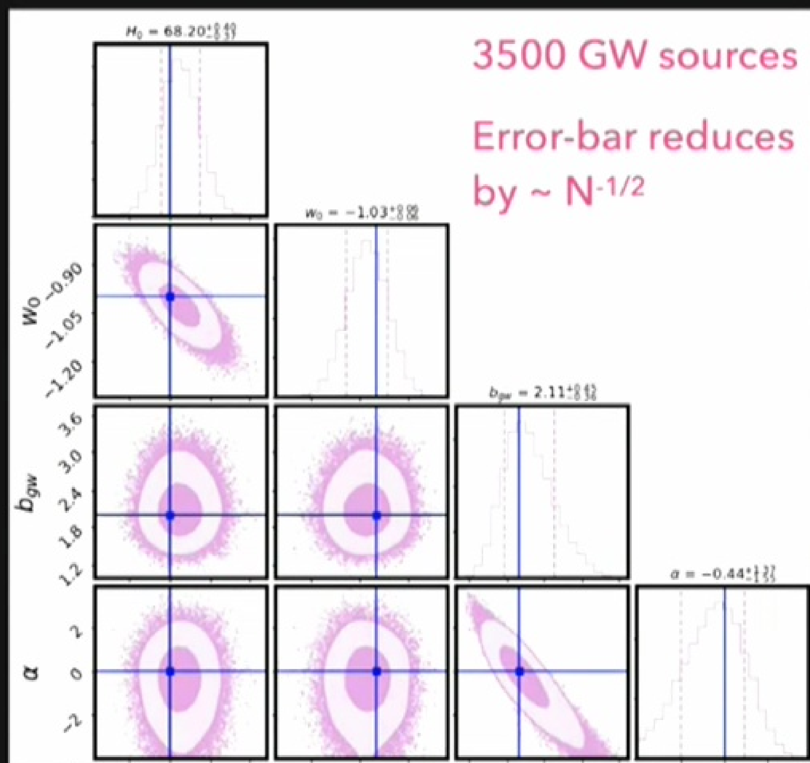
INFERRING THE EXPANSION HISTORY WITH DARK GW SOURCES

LVK DETECTOR NETWORK WILL RECONSTRUCT THE DARK ENERGY EQUATION OF STATE USING BINARY BLACK HOLES



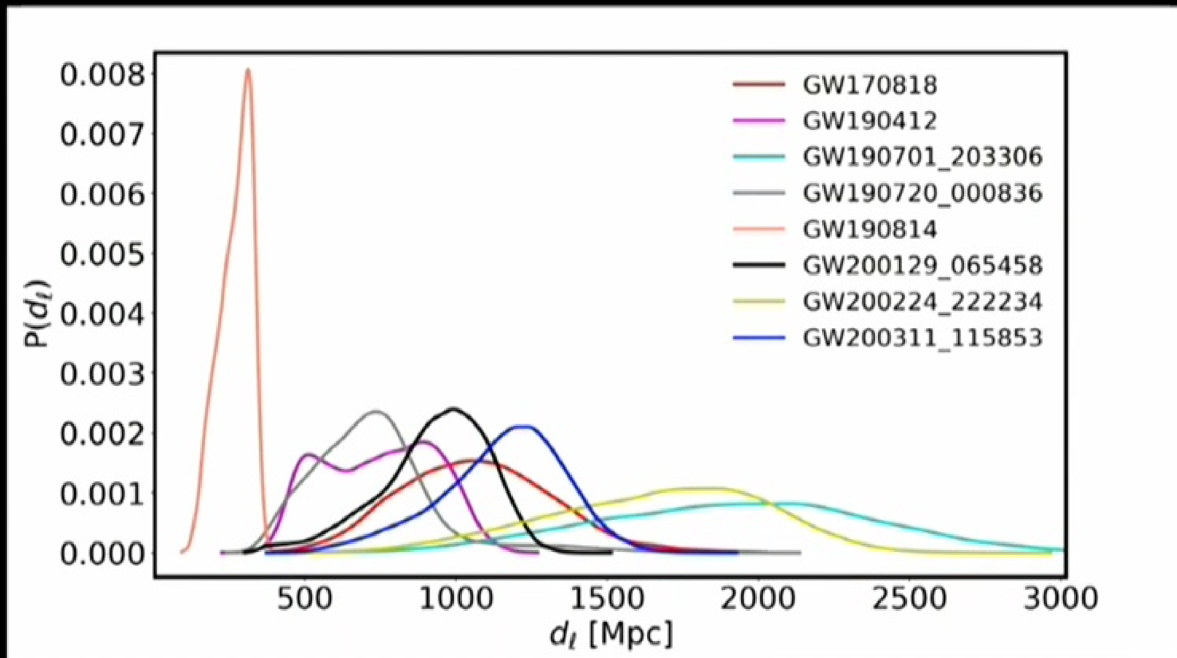
Suvodip Mukherjee,JBCA, 2021

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

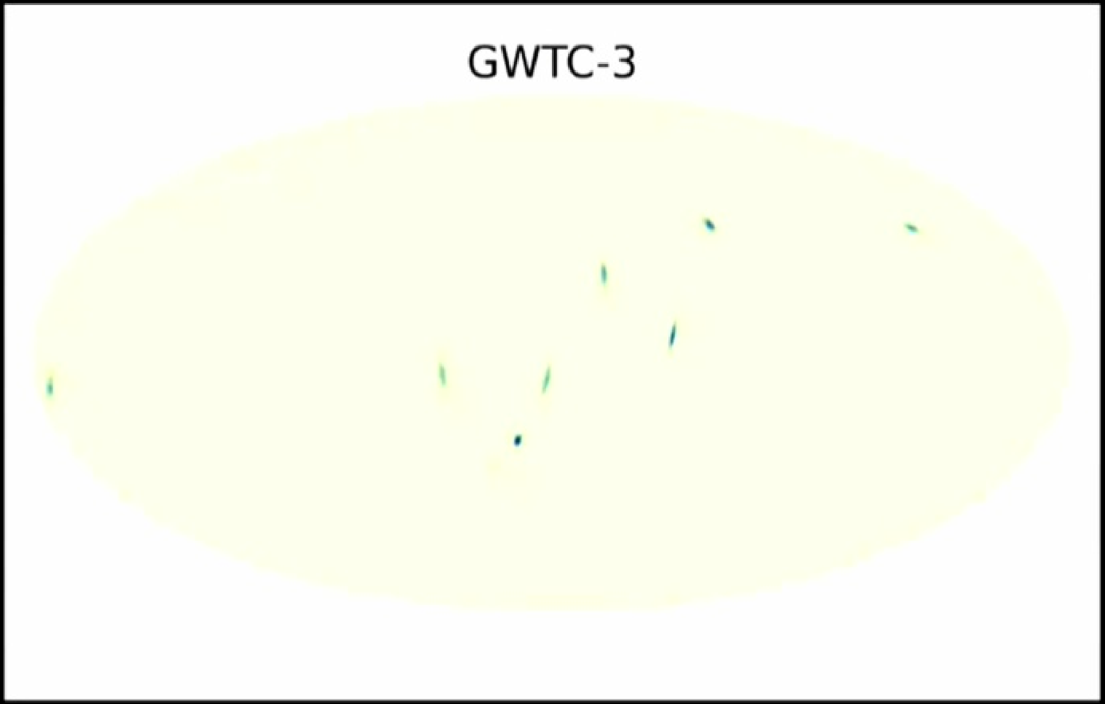
$$b(z) = b_{GW}(1+z)^{\alpha}$$

Mukherjee, Wandelt, Nissanke, Silvestri
(Phys. Rev. D 103, 043520, 2021)
(2007.02943)

Luminosity distance posterior of the selected sources



Eight sources from GWTC-3



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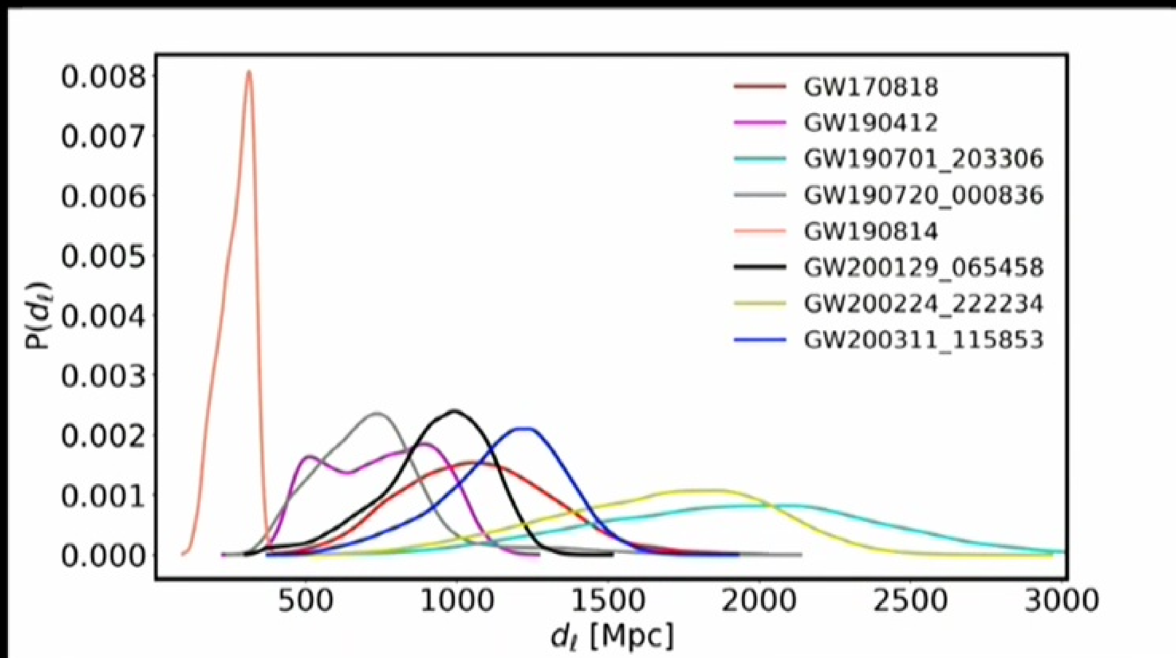
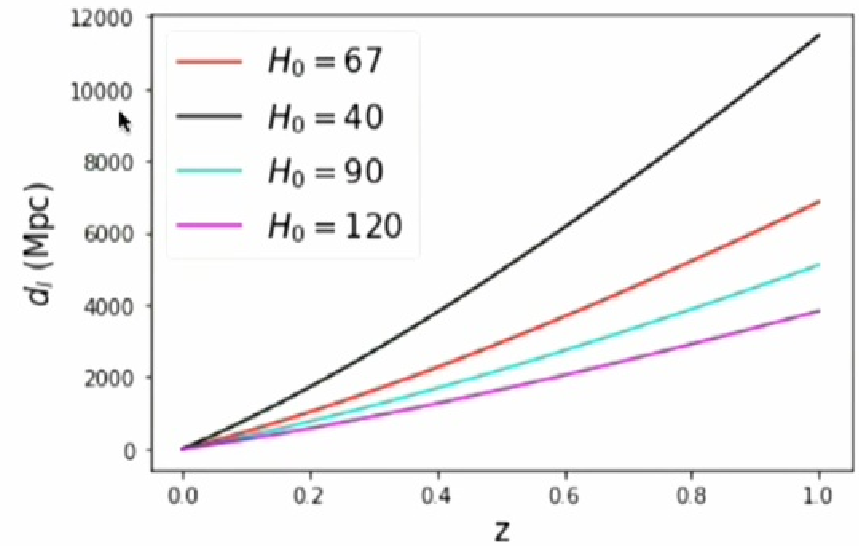


Luminosity distance

$$d_l = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_{DE}(z')}}$$



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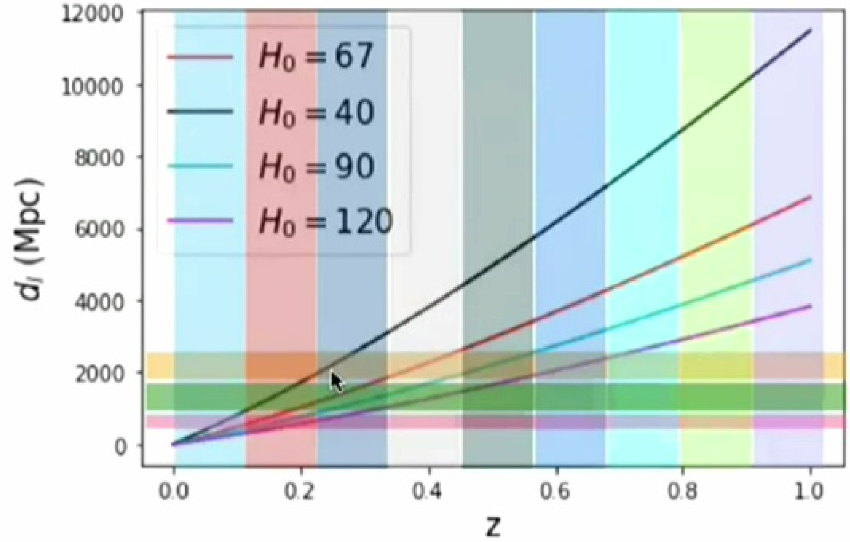
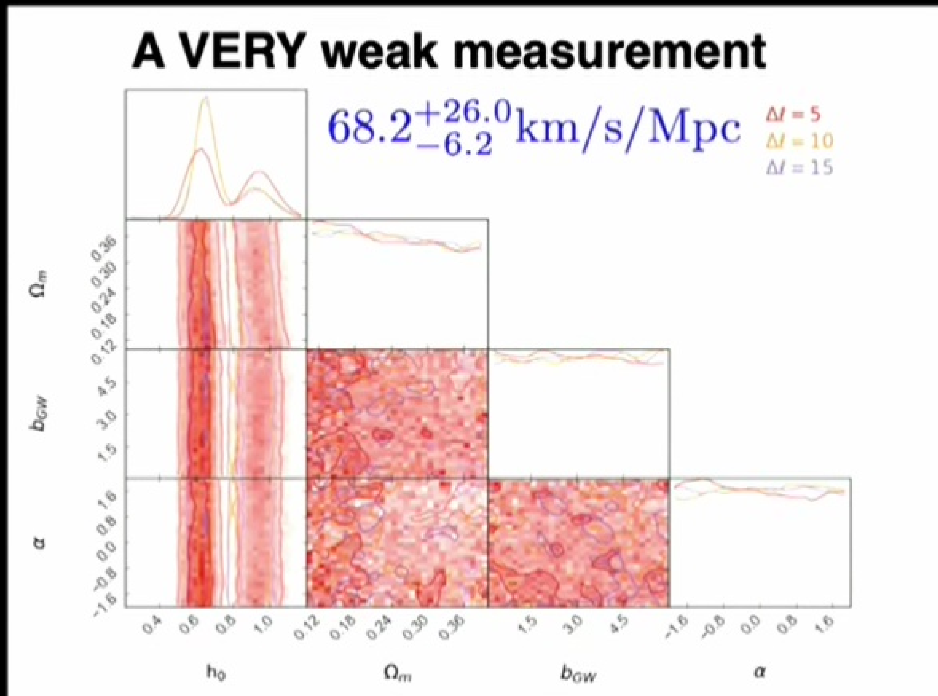


Joint estimation of H_0, matter density and GW bias parameter

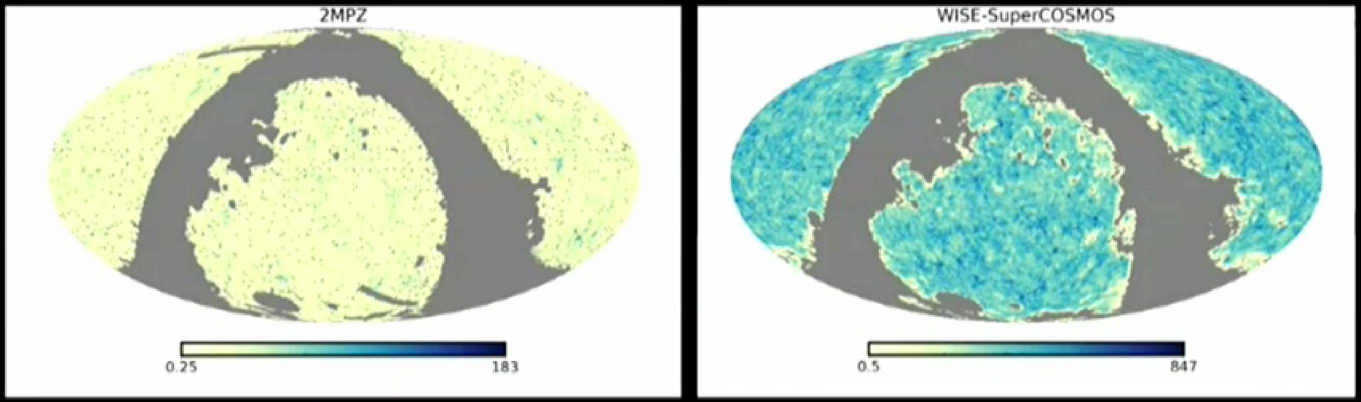


$$b(z) = b_{GW}(1+z)^{\alpha}$$

GW bias parameter

Mukherjee, Krolewski, Wandelt & Silk arXiv:2203.03643

Galaxy catalogs



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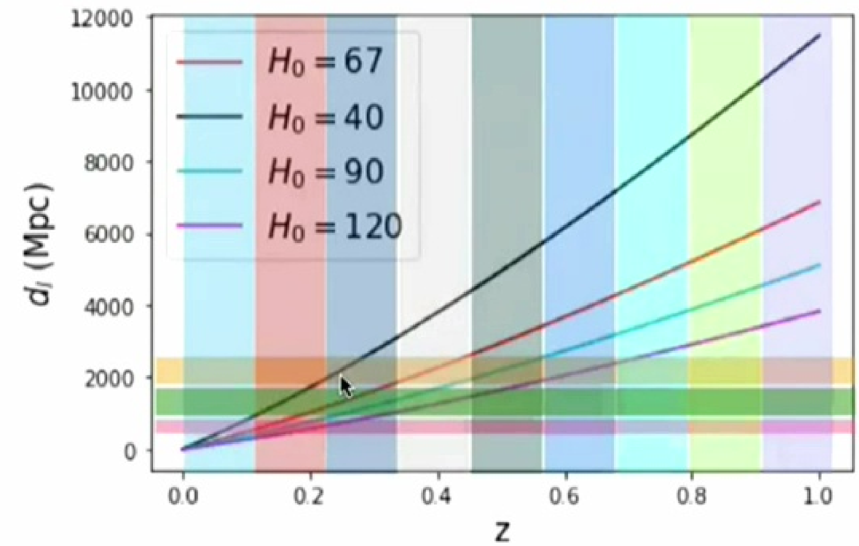
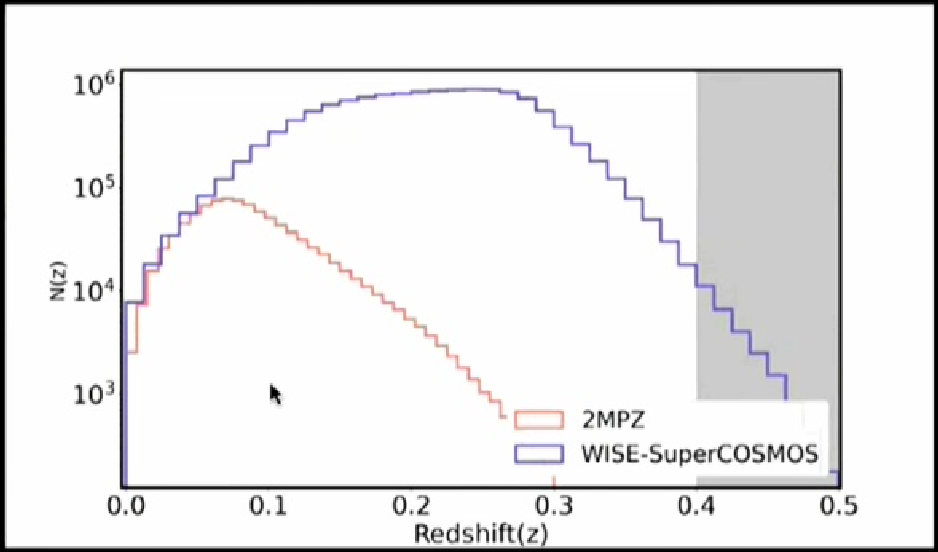


Redshift distribution of the galaxy catalogs



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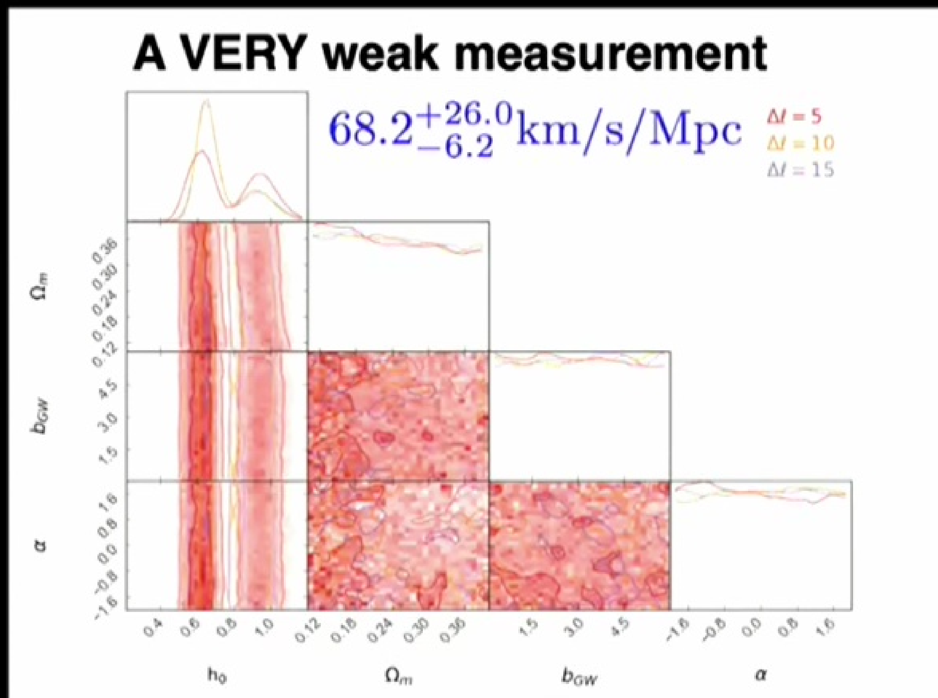

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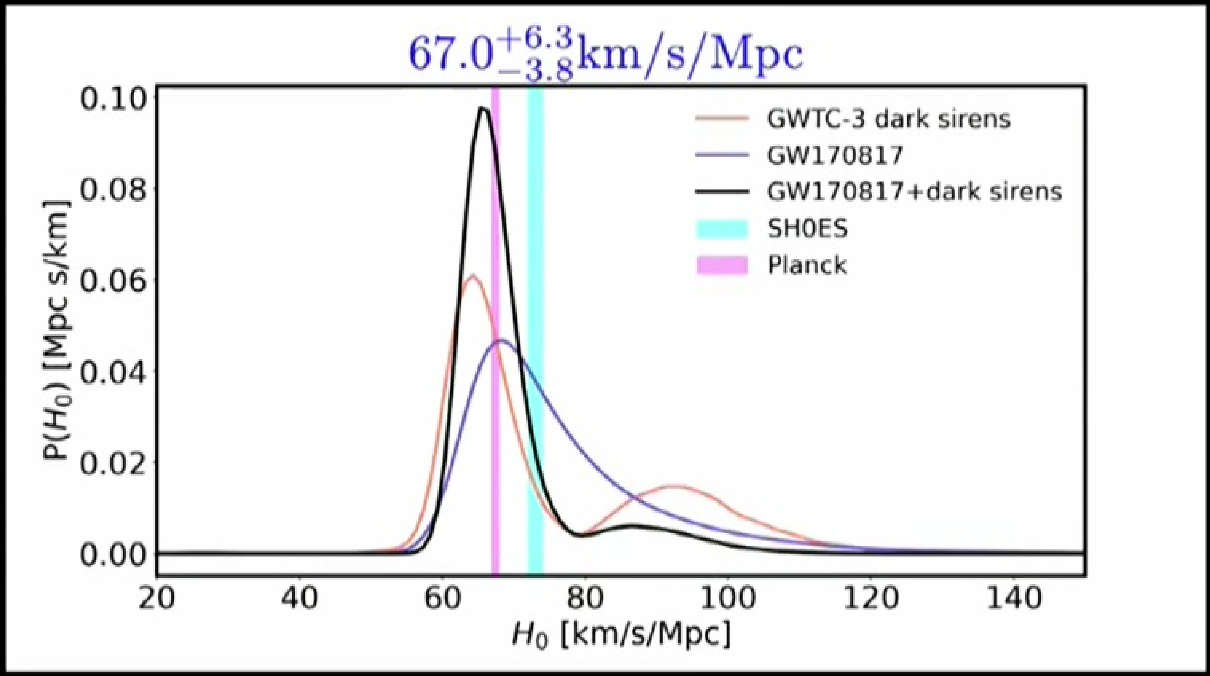
GW bias parameter

Mukherjee, Krolewski, Wandelt & Silk arXiv:2203.03643

Dark sirens+ GW170817



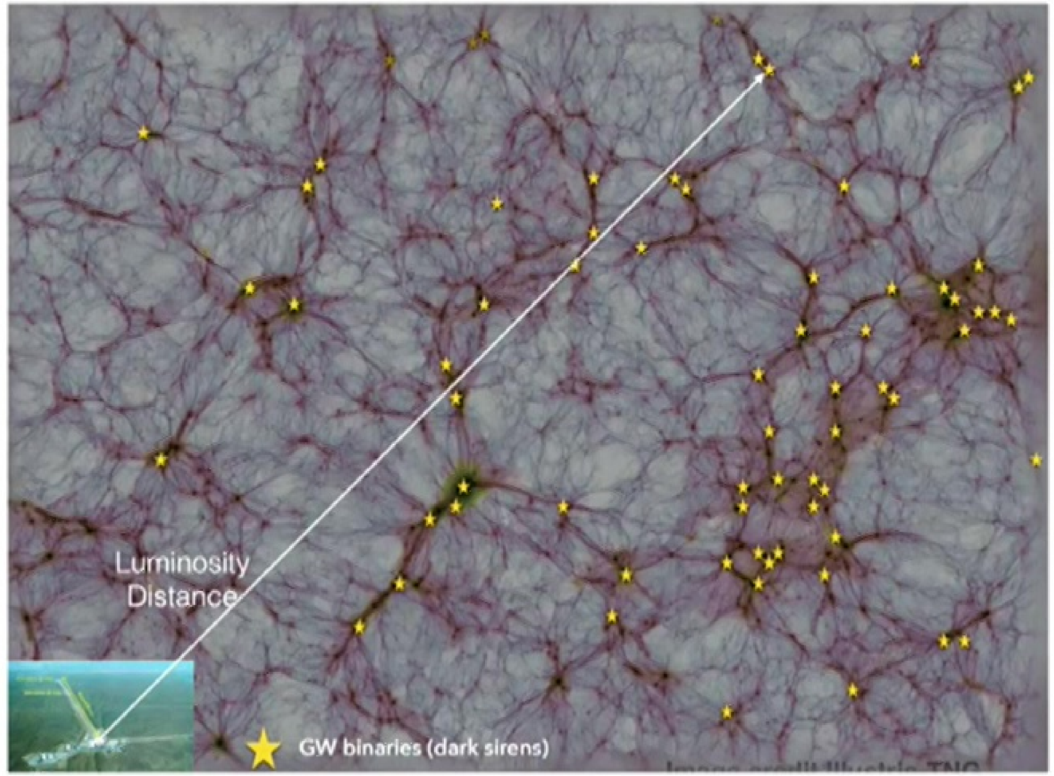
Mukherjee, Krolewski, Wandelt & Silk arXiv:2203.03643

Proof of principle application on public GWTC-3 data

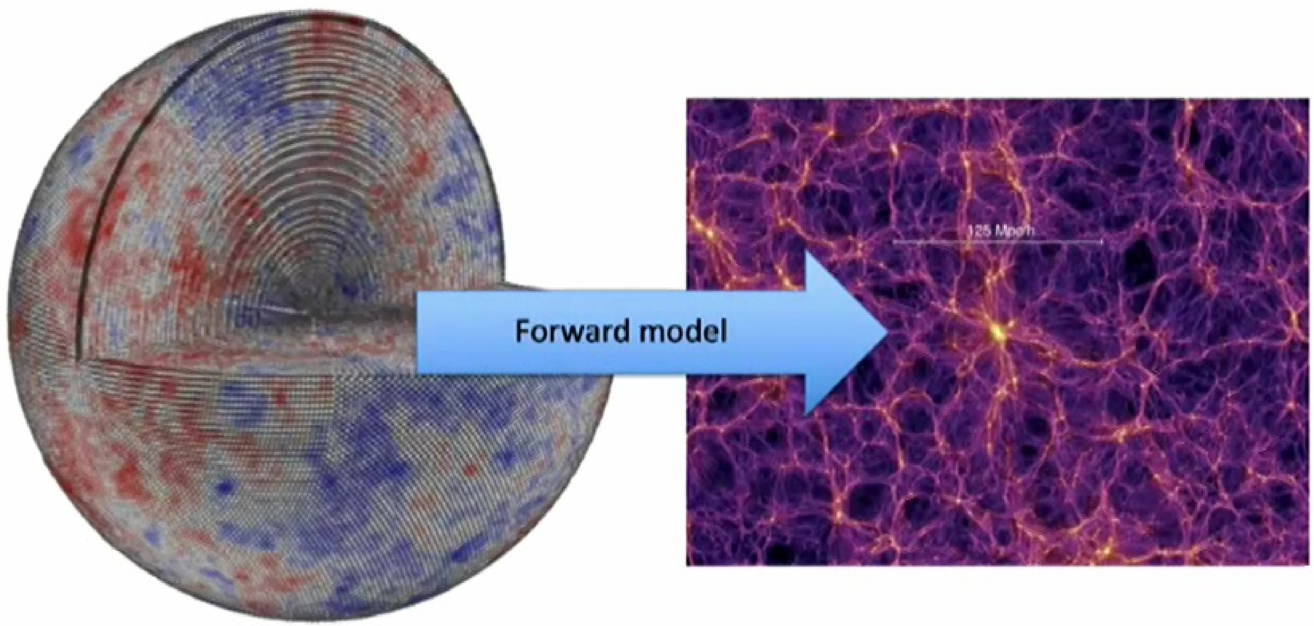
- Measurement of H0 using cross-correlation technique
- This measurement is not influenced by a population model (such as Gaussian + power law)
- The results are obtained after marginalising over the GW bias parameter
- The largest systematic effect arise from the redshift bins comparable to the photo-z errors.
- Results are consistent with the measurement in the LVK O3 cosmology paper.

The full approach is more powerful and more robust

- Explicit cosmic variance cancellation
- Less sensitive to bias model since both distance and redshift mapping are adjusted together as a function of cosmological model parameters
- Can go beyond 2-point correlations ➔ field-based cosmology with GW and EM tracers of the LSS.



Complementary approach: full forward model modeling of LSS



Initial conditions of the universe

The universe today

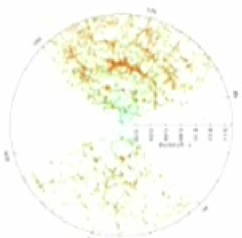
A fully generative *probabilistic* model of galaxy surveys with $O(10^7)$ parameters

BORG: *Bayesian Origin Reconstruction from Galaxies*

- Gaussian prior + **Gravity** + likelihood for galaxies

  (includes survey model, bias model, automatic noise level calibration, selection function, mask, ...)

- Hamiltonian Markov Chain Monte Carlo in $O(10^7)$-D

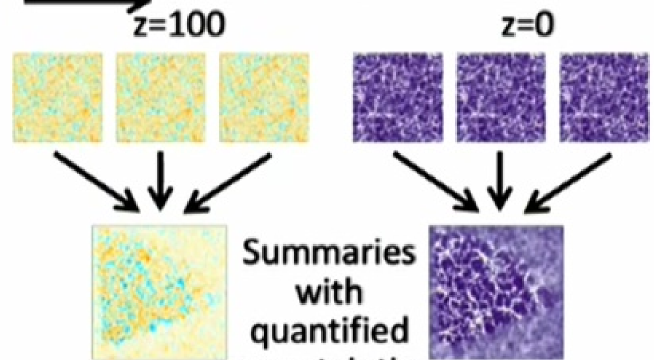


Observations

(galaxy catalog + meta-data: selection functions, completeness...)

→ **BORG** →

E.g. inferred dark matter densities

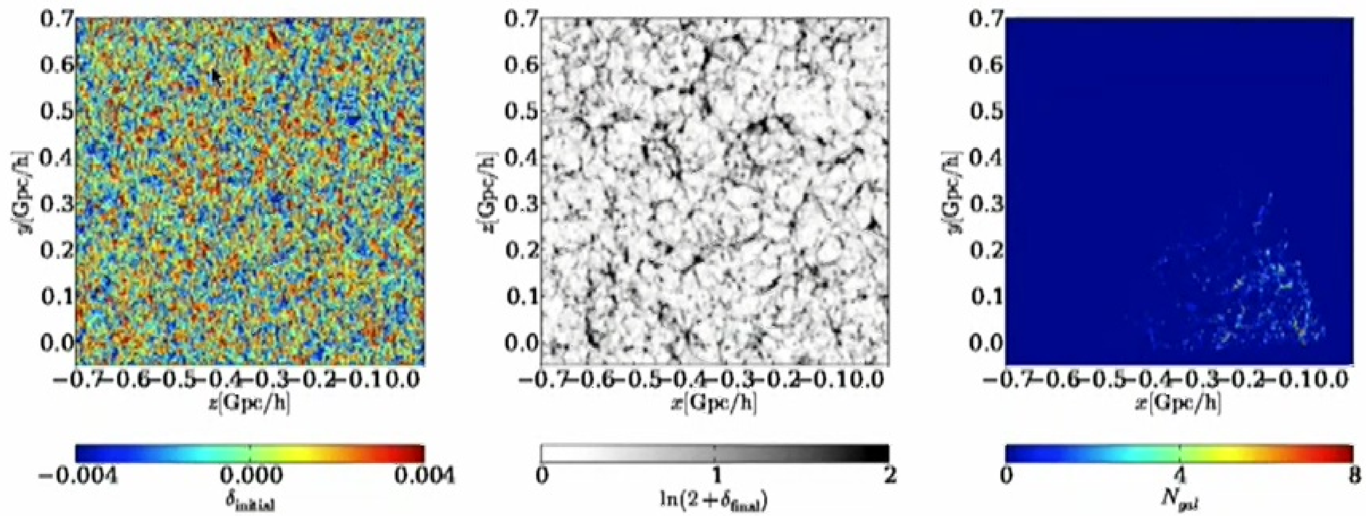


Jasche & Wandelt 2013, arXiv:1203.3639

Jasche, Leclercq & Wandelt 2015, arXiv:1409.6308

Lavaux & Jasche 2017

Bayesian LSS sampling with BORG



Initial conditions | Final conditions | Observations

Jasche, Leclercq & Wandelt 2014, arXiv:1409.6308

SDSS main survey

How to do cosmology with BORG?

- Tons of statistical power! How to make it robust?
- Want to decouple bias model from cosmological parameters
- Do (generalized, global) “Alcock-Paczyński” (AP) test *only keeping parameter dependence in coordinate mapping*

Alcock Paczynski test

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boxed{\boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta})} & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}^T\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

AP test with all moments of the density field

Coordinate Transformation

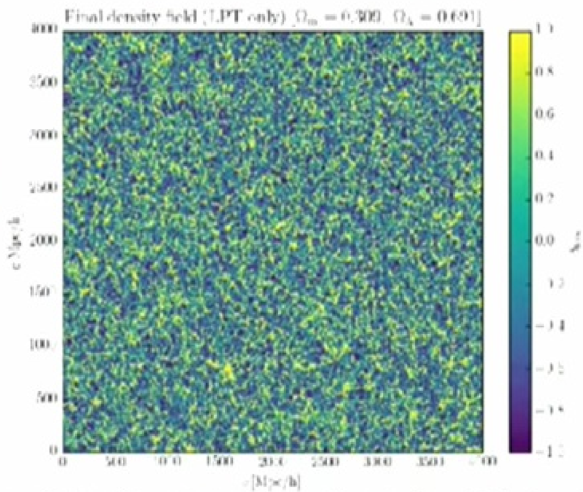
(Alcock & Paczyński 1979)

$(z, \vec{u})$ $\{\Omega_m, \Omega_\Lambda, \Omega_k, \omega, H_0\}$ $(d, \vec{u})$

Redshift space ⟷ **Comoving space**

- Distortions due to assumption of incorrect cosmological parameters
- Structure: **Spherical → Ellipsoidal**
- Statistical distribution: **Isotropic → Anisotropic**

comoving space



$$d = \int_{z_1}^{z_2} \frac{1}{cH(z)}$$

$$H(z) = H_0(\Omega_\mathrm{m}(1+z)^3 + \Omega_\mathrm{k}(1+z)^2 + \Omega_\Lambda)^{\frac{1}{2}}$$

Doogesh Kodi Ramanah et al., arXiv 1808.07496

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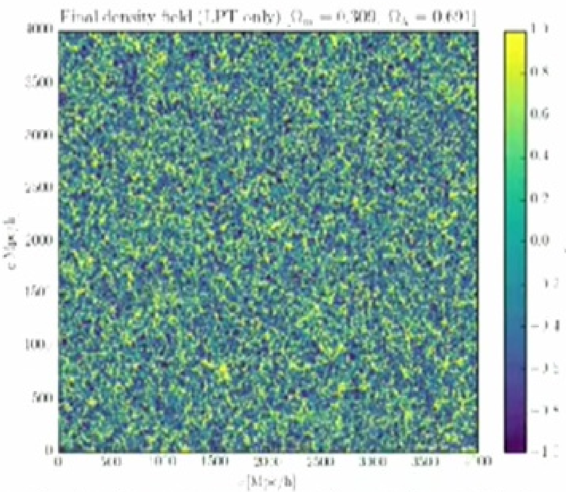

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Doogesh Kodi Ramanah et al., arXiv 1808.07496

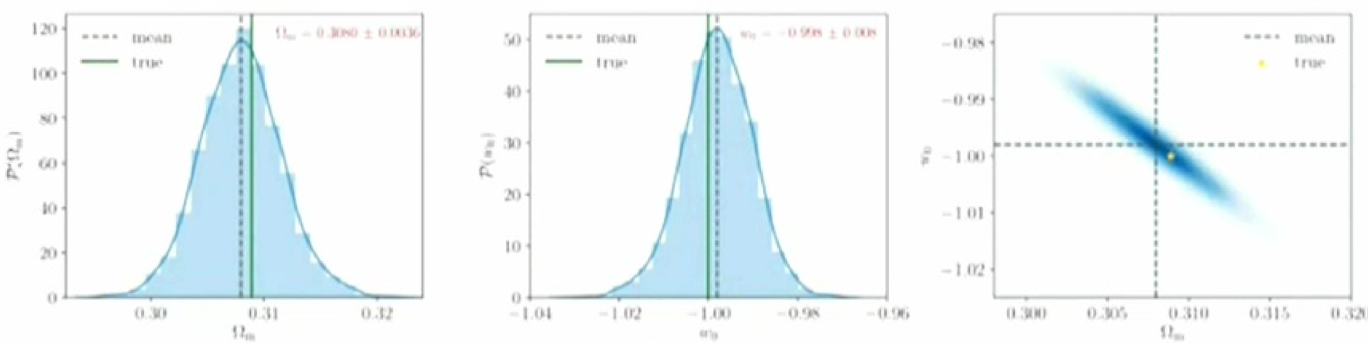
High precision inferences

- Probing deep redshift range; geometric distortion due to cosmic expansion is highly informative

$$\{\Omega_{\rm m} = 0.3080 \pm 0.0036, \quad w_0 = -0.998 \pm 0.008\}$$

- **CPL parameterization**: $w = w_0 + (1-a)w_a$ (set $w_a = 0$)
- **Impose flatness**: $\Omega_{\rm k} = 0, \; \Omega_{\rm de} = 1 - \Omega_{\rm m}$

Marginal & joint posteriors



Doogesh Kodi Ramanah et al., arXiv 1808.07496

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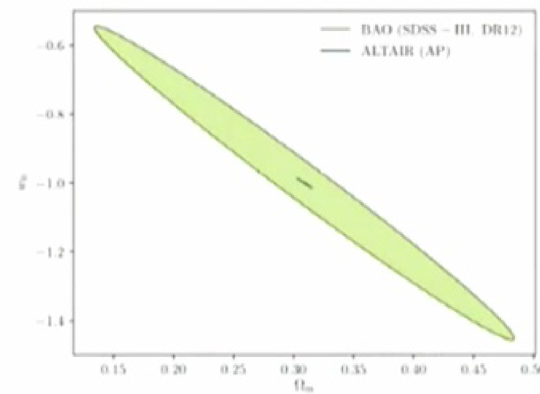

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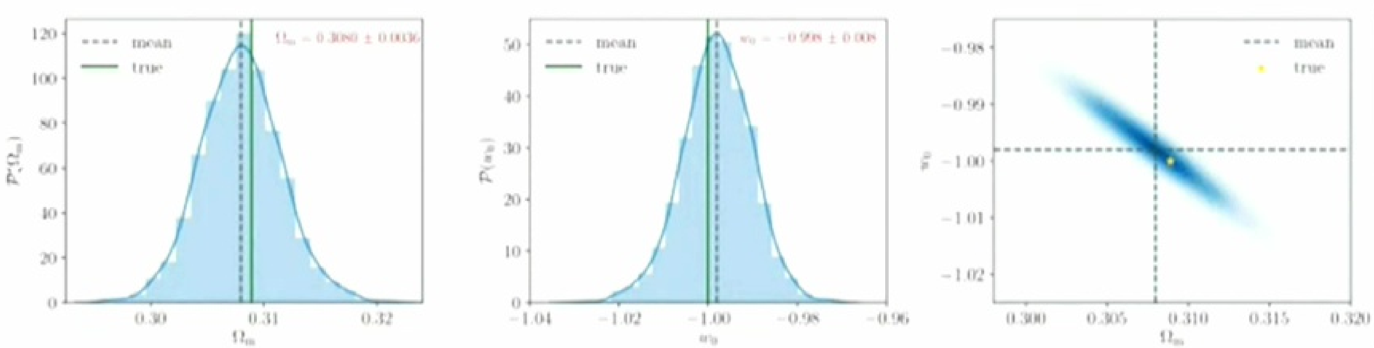

Doogesh Kodi Ramanah et al., arXiv 1808.07496

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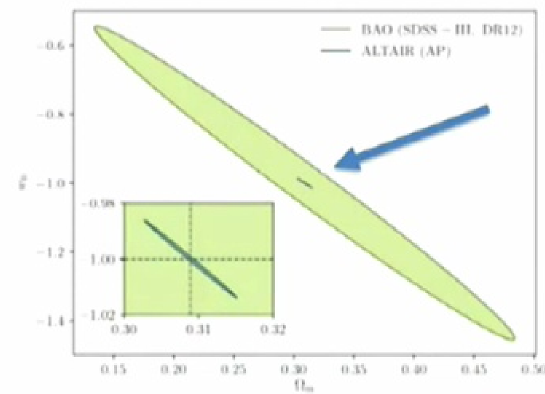

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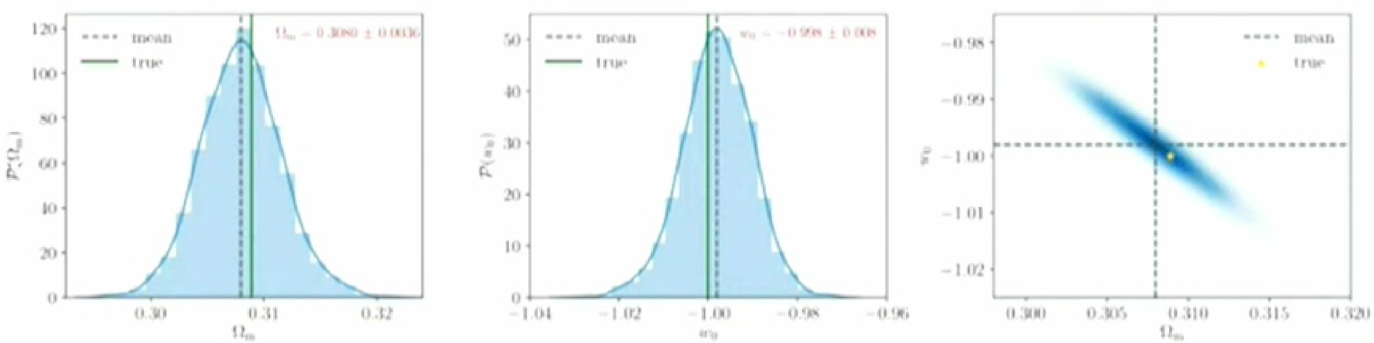
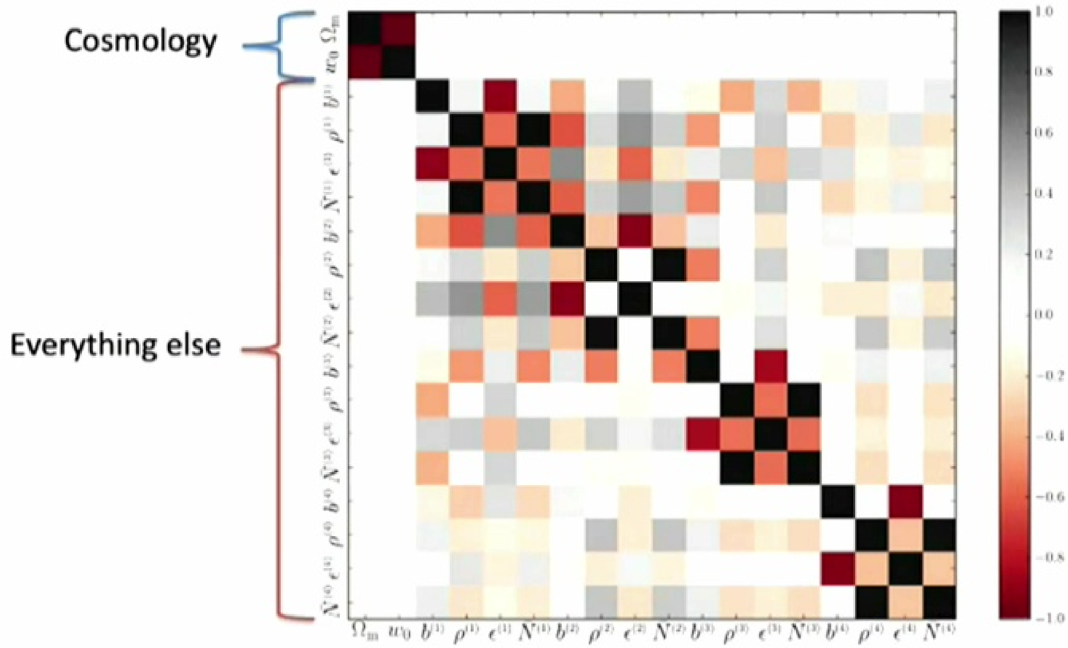


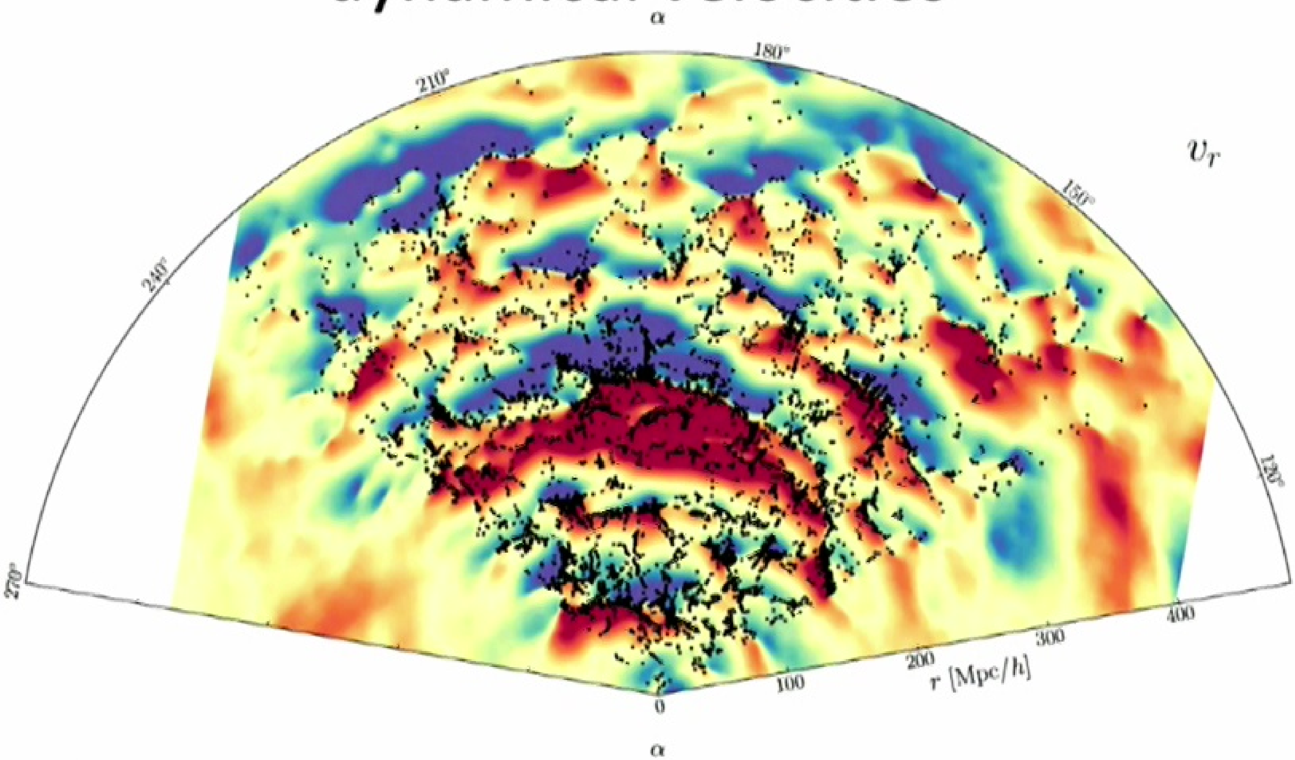
Doogesh Kodi Ramanah et al., arXiv 1808.07496

Inferred cosmology is robust to bias and model misspecification



Doogesh Kodi Ramanah et al., arXiv 1808.07496

Bayesian LCDM predictions: dynamical velocities



Leclercq et al. 2017

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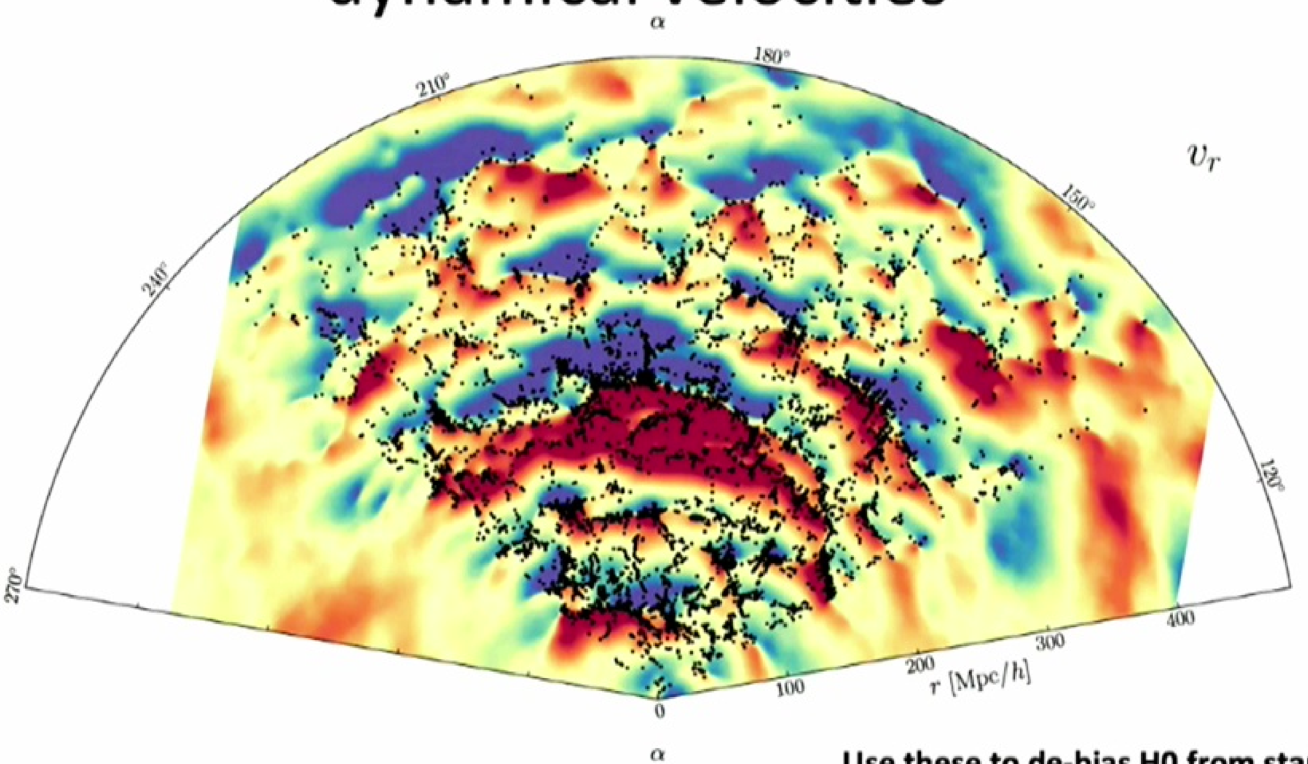
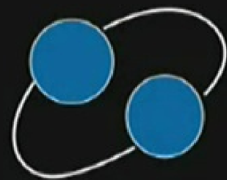


Leclercq et al. 2017

Use these to de-bias H0 from standard sirens!
Mukherjee et al arXiv:1909.08627

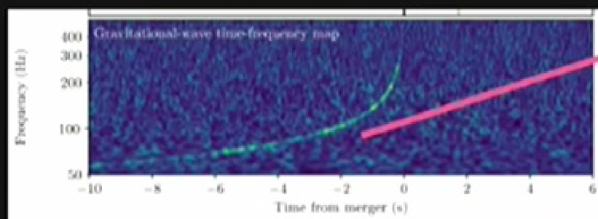
MEASUREMENT OF THE HUBBLE CONSTANT FROM GW170817

Using BORG to infer peculiar velocity correction

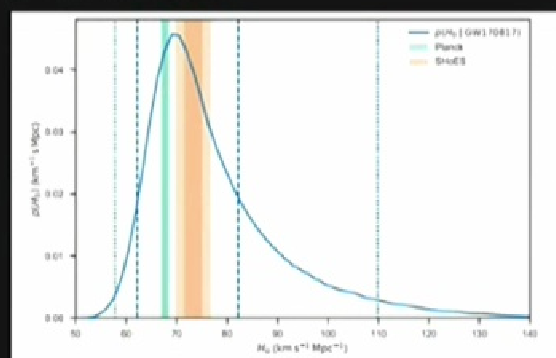


$$H_0 = \frac{cz + v_p}{D_l}$$

Independent measurement of the host of the GW source



LIGO-Virgo Collaboration



LIGO Virgo Collaboration Nature **551**, 85, 2017

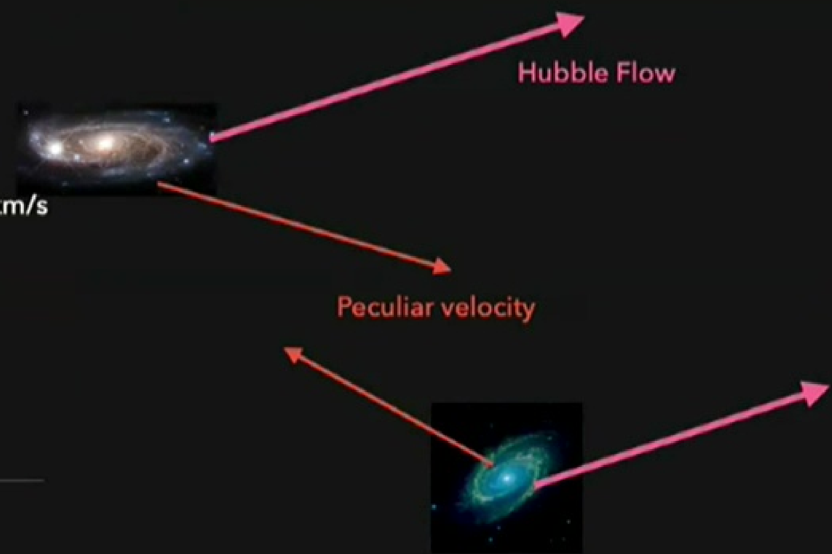
MEASUREMENT OF HUBBLE CONSTANT REQUIRES PECULIAR VELOCITY CORRECTION

PECULIAR VELOCITY CORRECTION IS IMPORTANT AT LOW REDSHIFT

$$cz + v_p$$

Typical values around 300 km/s

For sources with z <0.05, the peculiar velocity effect is > 2%

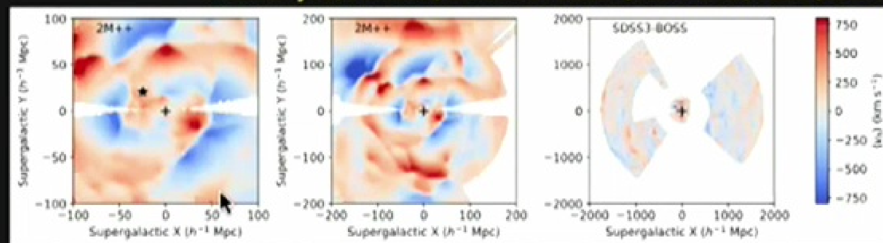


Nearby sources have smaller luminosity distance error but larger peculiar velocity error

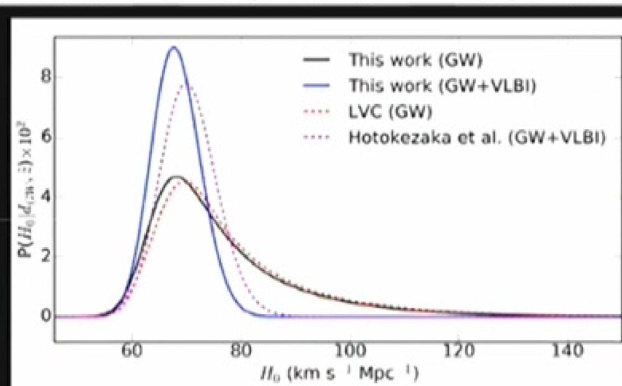
PECULIAR VELOCITY CORRECTION ESSENTIAL FOR PRECISION COSMOLOGY

PAVES: PECULIAR VELOCITY ESTIMATES FOR SIRENS

Mukherjee, Lavaux, Bouchet et al. (A&A 646, A65 (2021), 1909.08627)



BORG
(Jasche & Wandelt 2013; Jasche et al. 2015; Lavaux & Jasche 2016)



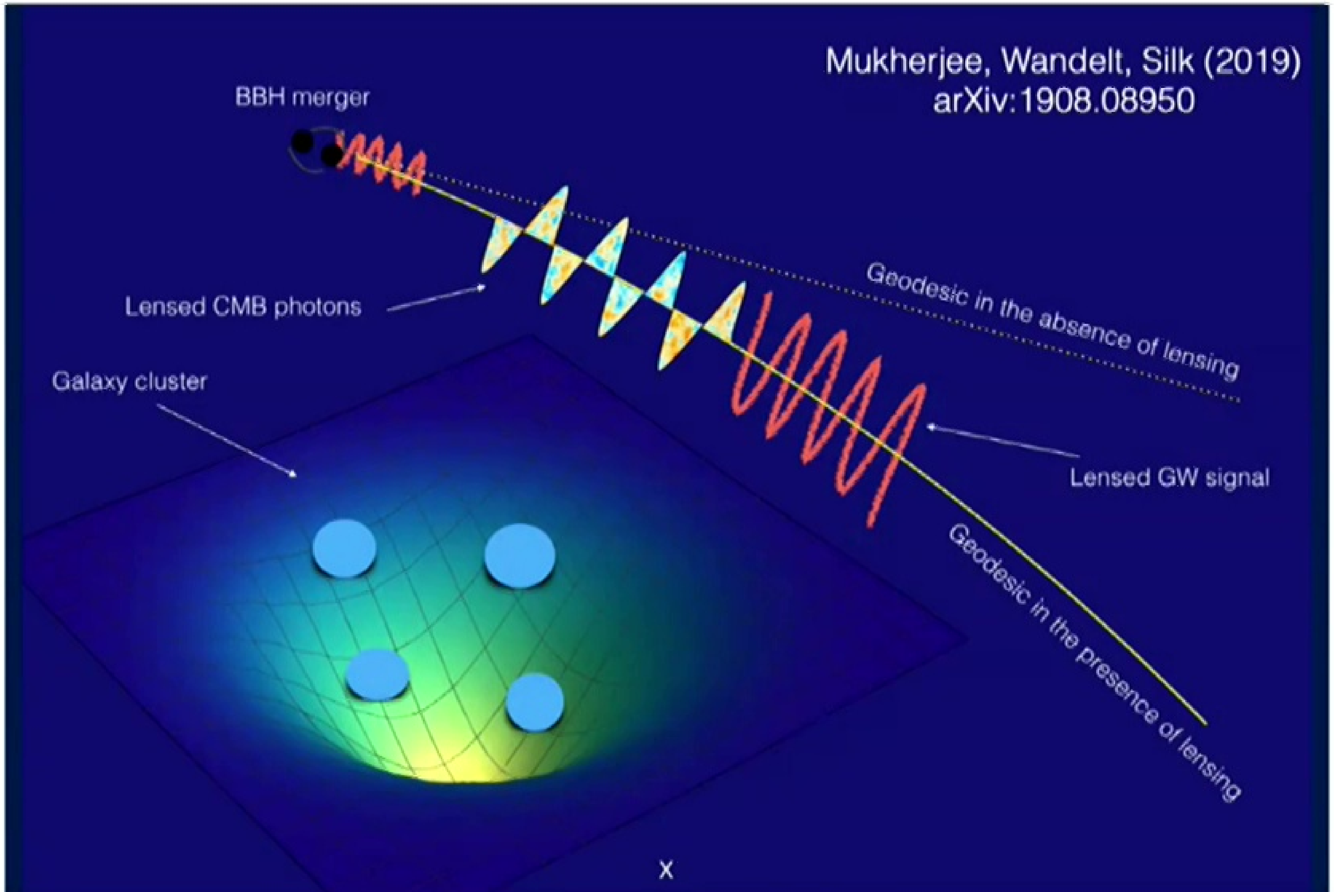
Impacts both mean value and the error-bar of the Hubble constant

New catalog for multi-messenger data analysis GLADE+ (Dalya, ..., S.M, et al (2110.06184))

Testing gravity with EM-GW cross-correlations

with Suvodip Mukherjee, Joe Silk

Lensing of GW waves



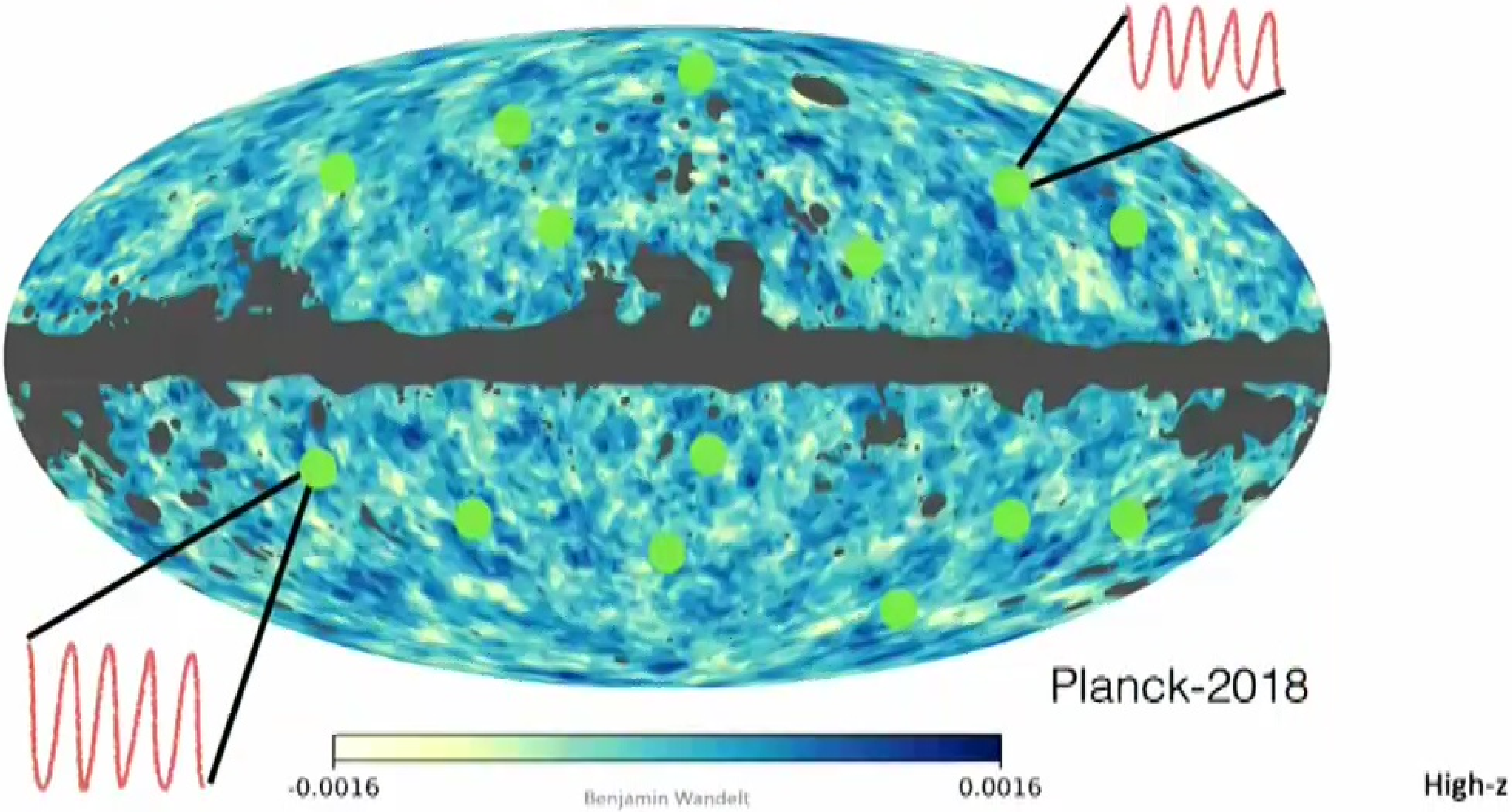
Effects on the gravitational waves signal

$$\tilde{\nu} = \nu\left(1 - \left(\Phi|_e^r - (\vec{n}.\vec{v})|_e^r - \int_{\lambda_e}^{\lambda_r} \partial_\eta(\Psi + \Phi)d\lambda'\right)\right),$$

$$\tilde{h}(\tilde{\nu}, \hat{n}) = h(\tilde{\nu}, \hat{n})[1 + \kappa_{gw}(\hat{n})],$$

$$\kappa_{gw}(\hat{n}) = \int_0^{z_s} dz \frac{3}{2}\frac{\Omega_m H_0^2(1+z)\chi(z)}{cH(z)} \int_z^{\infty} dz' \frac{dn_{gw}(z')}{dz'} \frac{(\chi(z_s) - \chi(z'))}{(\chi(z_s))} \delta(\chi(z)\hat{n}, z).$$

Can use CMB lensing template to trace mass



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Luminosity distance posterior of the selected sources