GW × HI intensity mapping: cosmological and astrophysical applications.

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HITS 2022 - HI Intensity Mapping in Trieste

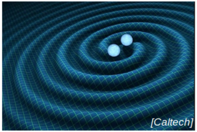
May 24$^{\rm th}$ 2022

Based on:

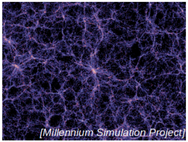
GS, Spinelli, Raccanelli, Boco, Lapi, Viel (JCAP, 2022)

Multi-tracing

Multi-tracing approach can enhance the amount of information from given surveys, leading to new synergies and opening new scientific paths.


[Caltech]

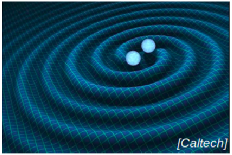
GW × LSS


[Millennium Simulation Project]

- **GW** × **LSS** (e.g. Ogouri+2013, Camera+2013, Raccanelli+2016, Scelfo+2018, Calore+2020, Alonso+2020, Scelfo+2020, Cañas-Herrera+(2020), Libanore+(2021)...)
- **LSS** × **IM** (e.g. Alonso+2015, Kovetz+2016, Pourtsidou+2017...)
- **LSS** × **CMB** (e.g. Ho+2008, Hirata+2008, Raccanelli+2008, Bianchini+2015, Bianchini+2016...)
- **LSS** × $\boldsymbol{\nu}$ (e.g. Fang+2020...)
- **LSS** × **LSS** (e.g. Martinez+1999, Jain+2003, Yang2005, Menard+2014, Paech+2017...)
- and so on...

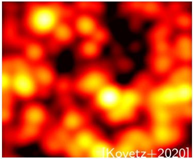
GW × IM

GW



- New and unique way to observe the cosmos
- High z uncertainty without EM counterparts

IM



- Observe large volumes within reasonable time (individual objects are not resolved)
- Allows us to perform very fine tomography

GW resolved signals from **BHBH mergers** - **Einstein Telescope (ET)**

×

21 cm line IM - **SKAO-MID**

GW $\times$ IM

We present **3 applications** for GW $\times$ IM:

- **Can we calibrate the redshift distribution of GW events by looking at GW $\times$ IM?**
- **Can we use GW $\times$ IM to investigate Dark Energy?**
- **Can we use GW $\times$ IM to detect imprints from a population of merging Primordial Black Hole binaries?**

We need some formalism before...

GW × IM formalism: angular power spectrum

- **Number counts angular power spectrum** $C_\ell^{XY}(z_i, z_j)$ for tracer X in bin z_i × tracer Y in bin z_j:

$$C_\ell^{XY}(z_i, z_j) = \frac{2}{\pi}\int \frac{dk}{k}\mathcal{P}(k)\Delta_\ell^{X,z_i}(k)\Delta_\ell^{Y,z_j}(k),$$

where $\mathcal{P}(k)$ is the primordial power spectrum and

$$\Delta_\ell^{X,z_i}(k) = \int_{z_i-\Delta z}^{z_i+\Delta z} dz\,\frac{dN_X}{dz} W(z, z_i)\Delta_\ell^X(k, z),$$

  - $\frac{dN_X}{dz}$: *observed* source number density per redshift interval
  - $W(z, z_i)$: window function

- $\Delta_\ell^X(k, z)$: angular **number counts fluctuations**

$$\Delta_\ell(k, z) = \Delta_\ell^{\mathrm{den}}(k, z) + \Delta_\ell^{\mathrm{vel}}(k, z) + \Delta_\ell^{\mathrm{len}}(k, z) + \Delta_\ell^{\mathrm{gr}}(k, z).$$

- You can compute it with **Multi_CLASS** [Bellomo+(2020), Bernal+(2020)]).

GW × IM formalism: bias parameters for tracers

- **Bias b_X**: it quantifies the mismatch between the distribution of matter and that of tracer X:

$$\delta_X(x) \simeq b_X \delta(x)$$

- **Magnification bias s_X**: quantifies the change in the observed surface density of sources of tracer X induced by gravitational lensing:

$$s_X(z) = -\frac{2}{5} \left. \frac{d \log_{10} \frac{d^2 N_X(z, L > L_{\rm lim})}{dz d\Omega}}{d \log_{10} L} \right|_{L_{\rm lim}}$$

- **Evolution bias f_X^{evo}**: accounts for possible formation of new objects:

$$f_{\rm X}^{\rm evo}(z) = \frac{d \ln \left(a^3 \frac{d^2 N_X}{dz d\Omega} \right)}{d \ln a}$$

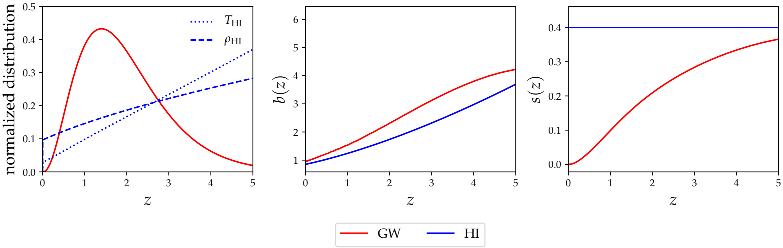
a: scale factor.

Tracers prescriptions and noise sources

GW resolved signals from **BHBH mergers** - **Einstein Telescope (ET)**

×

21 cm line IM - **SKAO-MID**



GW

- shot noise
- localization/cosmology errors "absorbed" if considering large redshift bins
- $\ell_{\max} = 100$

IM

- beam effects
- instrumental noise
- foregrounds removal noise

Fisher formalism

Organize observed data in (symmetric) matrix $\mathcal{C}_\ell$:

$$\mathcal{C}_\ell = \begin{bmatrix} \tilde{C}_\ell^{\rm IM\,IM}(z_1^{\rm IM}, z_1^{\rm IM}) & \dots & \tilde{C}_\ell^{\rm IM\,IM}(z_1^{\rm IM}, z_N^{\rm IM}) & \tilde{C}_\ell^{\rm IM\,GW}(z_1^{\rm IM}, z_1^{\rm GW}) & \dots & \tilde{C}_\ell^{\rm IM\,GW}(z_1^{\rm IM}, z_N^{\rm GW}) \\ & \dots & \tilde{C}_\ell^{\rm IM\,IM}(z_2^{\rm IM}, z_N^{\rm IM}) & \tilde{C}_\ell^{\rm IM\,GW}(z_2^{\rm IM}, z_1^{\rm GW}) & \dots & \tilde{C}_\ell^{\rm IM\,GW}(z_2^{\rm IM}, z_N^{\rm GW}) \\ & \dots & \vdots & \vdots & \dots & \vdots \\ & & \tilde{C}_\ell^{\rm IM\,IM}(z_N^{\rm IM}, z_N^{\rm IM}) & \tilde{C}_\ell^{\rm IM\,GW}(z_N^{\rm IM}, z_1^{\rm GW}) & \dots & \tilde{C}_\ell^{\rm IM\,GW}(z_N^{\rm IM}, z_N^{\rm GW}) \\ & & & \tilde{C}_\ell^{\rm GW\,GW}(z_1^{\rm GW}, z_1^{\rm GW}) & \dots & \tilde{C}_\ell^{\rm GW\,GW}(z_1^{\rm GW}, z_N^{\rm GW}) \\ & & & & \dots & \vdots \\ & & & & & \tilde{C}_\ell^{\rm GW\,GW}(z_N^{\rm GW}, z_N^{\rm GW}) \end{bmatrix}$$

Dimensions: $(N_{\rm bins}^{\rm IM} + N_{\rm bins}^{\rm GW}) \times (N_{\rm bins}^{\rm IM} + N_{\rm bins}^{\rm GW})$.

Fisher matrix elements: $F_{\alpha\beta} = f_{\rm sky} \sum_\ell \frac{2\ell+1}{2} {\rm Tr}\left[\mathcal{C}_\ell^{-1}(\partial_\alpha \mathcal{C}_\ell)\mathcal{C}_\ell^{-1}(\partial_\beta \mathcal{C}_\ell)\right]$

∂_α: partial derivative wrt parameter; **Fisher-estimated marginal error:** $\sqrt{F_{\alpha\alpha}^{-1}}$

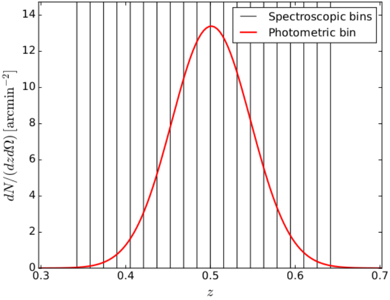
We take: $\mathbf{z} \in [0.5 - 3.5]$, with $\mathbf{N}_{\rm bins}^{\rm GW} = 3$; $\mathbf{N}_{\rm bins}^{\rm IM} = 30$ **equally spaced**.

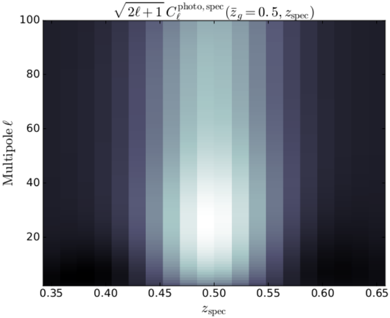
GW × IM: 1) GWs redshift calibration

Exploit the fine tomographic information of IM to constrain z of another tracer!

Already done to calibrate photometric samples of galaxies
(e.g. Menard+2014, Alonso+2017, etc.)
but never applied to GWs!

z-unknown tracer in a larger bin × **IM in many thin internal bins**

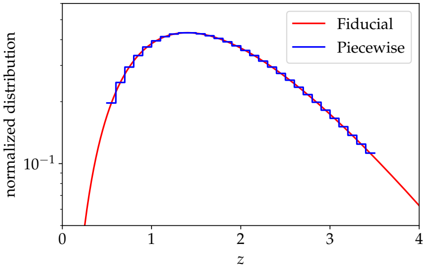




(Alonso+2017)

GW × IM: 1) GWs redshift calibration

- Take the **fiducial GWs redshift distribution**;
- Model it as a **piece-wise function** made of $N = 30\ (= N^{\rm IM}_{\rm bins})$ parts;
- Each $i^{\rm th}$ piece has a **fiducial amplitude** $\rm A_i$;
- Take the following 35 parameters: $\{A_i\} + \{\ln 10^{10} A_s, n_s, \bar{b}_{\rm GW}, \bar{b}_{\rm HI}, K^{\rm fg}\}$;
- Perform Fisher analysis;
- Determine errors σ_{A_i}.



Constraining GWs z distribution

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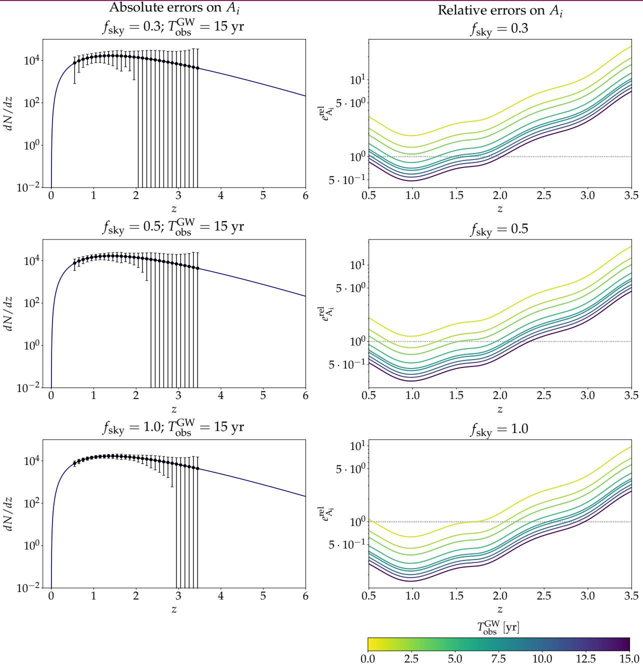
constraining astrophysical or cosmological models (e.g. PBHs)


Absolute errors on A_i
$f_{\rm sky} = 0.3$; $T_{\rm obs}^{\rm GW} = 15$ yr
$f_{\rm sky} = 0.5$; $T_{\rm obs}^{\rm GW} = 15$ yr
$f_{\rm sky} = 1.0$; $T_{\rm obs}^{\rm GW} = 15$ yr
dN/dz
z
Relative errors on A_i
$f_{\rm sky} = 0.3$
$f_{\rm sky} = 0.5$
$f_{\rm sky} = 1.0$
$e^{\rm rel}_{\rm A_i}$
z
$T_{\rm obs}^{\rm GW}$ [yr]

GW × IM: 2) constraining dark energy

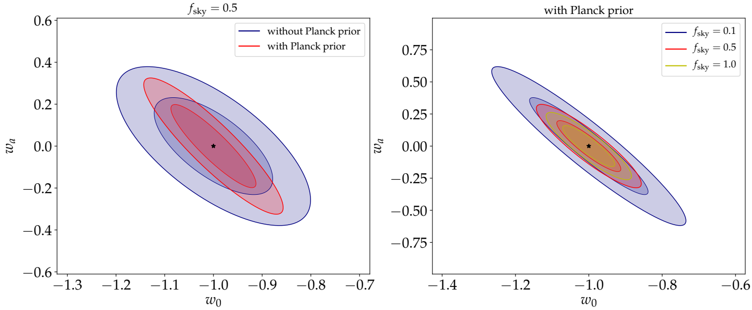
- Can we investigate **cosmological models** through GW × IM?
- Let's focus on **Dark Energy**.
- Possible **time evolution** described by:

$$w(a) = w_0 + w_a(1 - a).$$

- How well can GW × IM constrain $\{w_0, w_a\}$?

GW × IM: 2) constraining dark energy

- Fisher parameters: $\{w_0, w_a, \omega_{\rm cdm}, \omega_{\rm b}, 100\theta_s, \ln 10^{10}A_s, n_s, \bar{b}_{\rm GW}, \bar{b}_{\rm HI}, K^{\rm fg}\}$



- Constraints in agreement with IM only experiments [e.g. Bull+(2015)]
- Still, cross-correlating information from different observation channels, such as GW × IM, can help in overcoming systematics limitations.

GW × IM: 3) Could merging BBHs be primordial?

THE HYPOTHESIS OF CORES RETARDED DURING EXPANSION AND THE HOT COSMOLOGICAL MODEL
Ya. B. Zel'dovich and I. D. Novikov

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS
Stephen Hawking

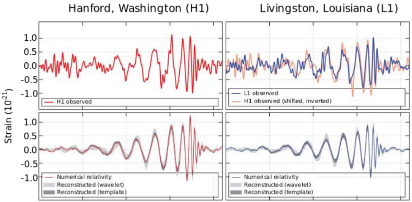
BLACK HOLES IN THE EARLY UNIVERSE
B. J. Carr and S. W. Hawking

- **Highly overdense regions** in the primordial Universe can directly undergo **gravitational collapse** to **form BHs** [Zeldovich,Novikov(1966); Hawking(1970); Hawking,Carr(1974)].

↓

- **MACHOS constraints** + **WIMP**: "**PBHs as DM**" hypothesis lost interest.

↓

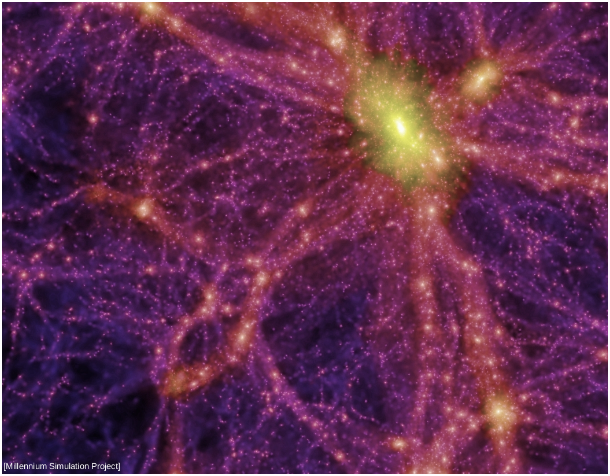


- **GW150914** [Abbott+(2016)]: BBH merger of $\mathcal{O}(30M_\odot)$. Interest revived!

- **Can we determine the progenitors of BBHs through GW × LSS?** [Raccanelli+(2016); Scelfo+(2018)]

GW × IM: 3) How would GWs trace the LSS in different scenarios?

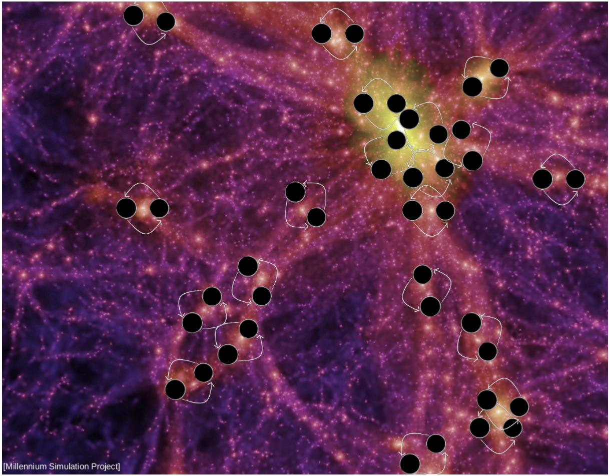
LSS:



Depending on the origin of the merging BBHs (astrophysical or primordial), **GWs events trace the underlying LSS in different ways**.

GW × IM: 3) How would GWs trace the LSS in different scenarios?

Astrophysical scenario:

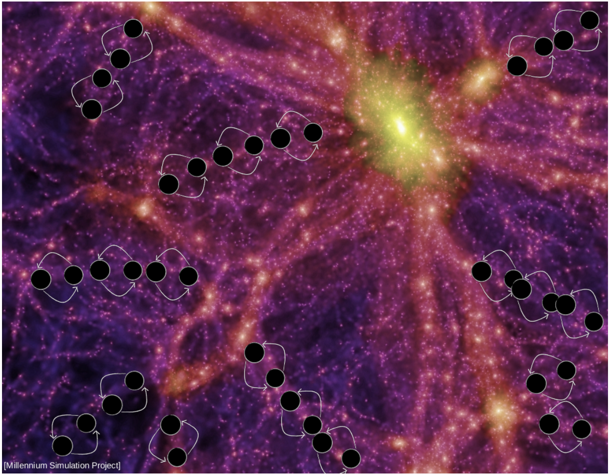


Luminous, massive halos
(highly star-forming)
↓
Astrophysical BHs

Bias parameter
$b_{\rm GW} > 1$
($\sim$ host bias)

GW × IM: 3) How would GWs trace the LSS in different scenarios?

"Late" primordial scenario:



PBHs binaries form in the late universe.

Dark, low-mass halos tracing the LSS filaments have **lower typical velocities**

↓

PBHs binaries are more likely to form here

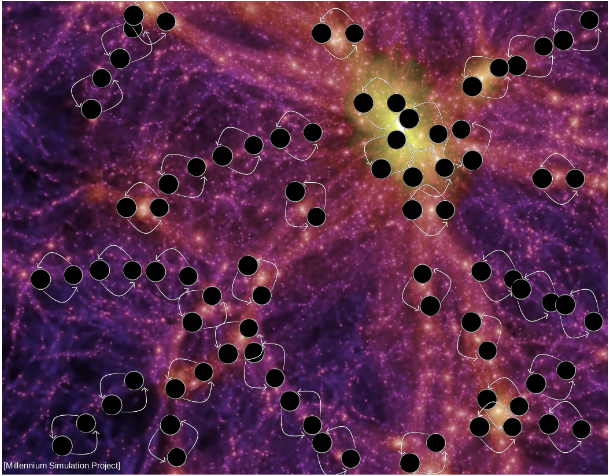
Bias parameter

$b_{\rm GW} \sim 0.5$

(∼ host bias)

GW × IM: 3) How would GWs trace the LSS in different scenarios?

"Early" primordial scenario:



PBHs binaries form in the early universe.

↓

PBHs binaries as good **tracers of the DM**

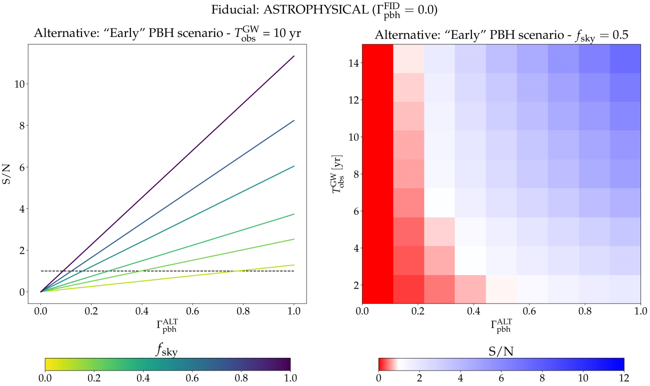
Bias parameter

$b_{\rm GW} \sim 1$

($\sim$ host bias)

GW × IM: 3) Forecasts: Primordial vs Astro BHs

- Fisher parameters: $\{w_0, w_a, \omega_{\rm cdm}, \omega_{\rm b}, 100\theta_s, \ln 10^{10} A_s, n_s, \bar{b}_{\rm GW}, \bar{b}_{\rm HI}, K^{\rm fg}\}$
- **Is the error on $\bar{b}_{\rm GW}$ small enough to distinguish between different scenarios? Yes!**



$\Gamma_{\rm pbh}^{\rm FID/ALT}$ = fraction of detected mergers of primordial origin for the Fiducial/Alternative model

GW × IM: 3) Forecasts: Primordial vs Astro BHs

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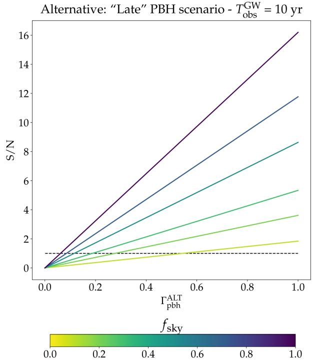

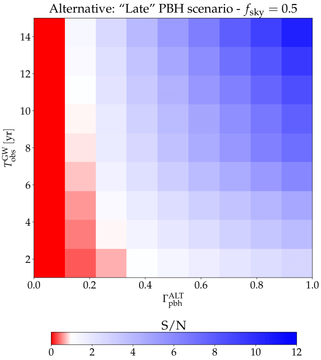

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GW × IM: 3) Forecasts: Primordial vs Astro BHs

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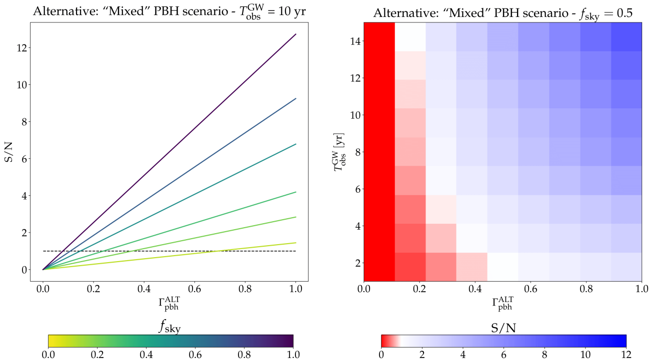

$\Gamma_{\rm pbh}^{\rm FID/ALT}$ = fraction of detected mergers of primordial origin for the Fiducial/Alternative model

GW $\times$ IM: Recap

1. GW $\times$ IM can well **calibrate the redshift distribution of observed GWs** at lower z;
2. **constraints on DE** are not competitive (but systematics are reduced in cross-correlations);
3. Imprints of a **small population of PBHs would be detected** in a reasonable amount of time!

Thank you for your attention!