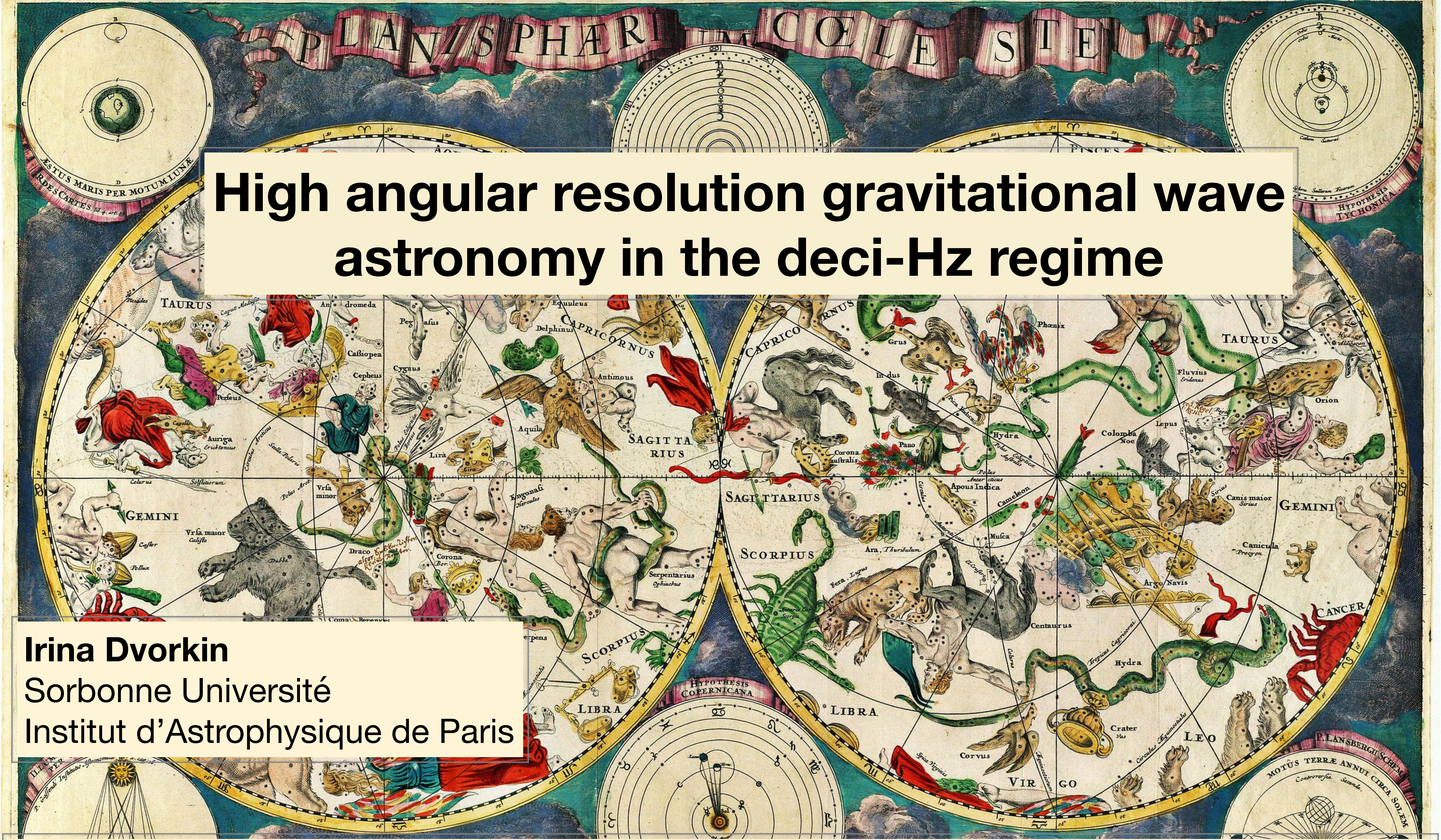


High angular resolution gravitational wave astronomy in the deci-Hz regime

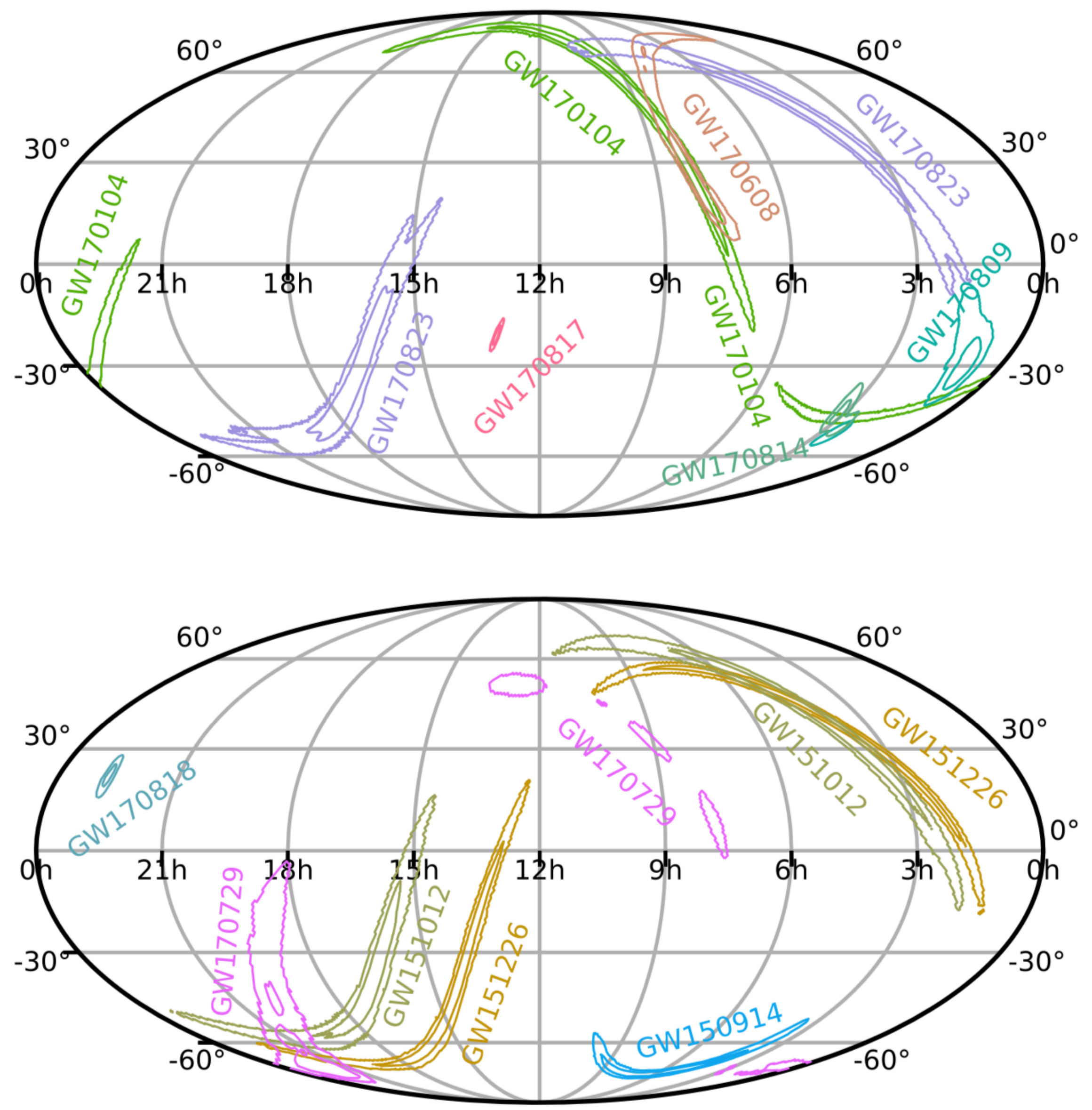
Irina Dvorkin
Sorbonne Université
Institut d’Astrophysique de Paris

On behalf of the writing teams:
«High-resolution gravitational-wave astronomy» coordinated by J. Baker, I. Dvorkin, J. Gair, A. Renzini
«The missing link in gravitational-wave astronomy» coordinated by M. Arca Sedda, C. Berry, K. Jani

ESA Voyage2050 Workshop, Madrid 31 October 2019

Resolution of point sources with ground-based detectors

- LIGO/Virgo O1/O2/O3a:
- Best localization of 16 sq. deg. for the binary neutron star GW170817
- O(100) - O(1000) sq. deg. for most events



From: LIGO/Virgo GWTC-1 (2018)

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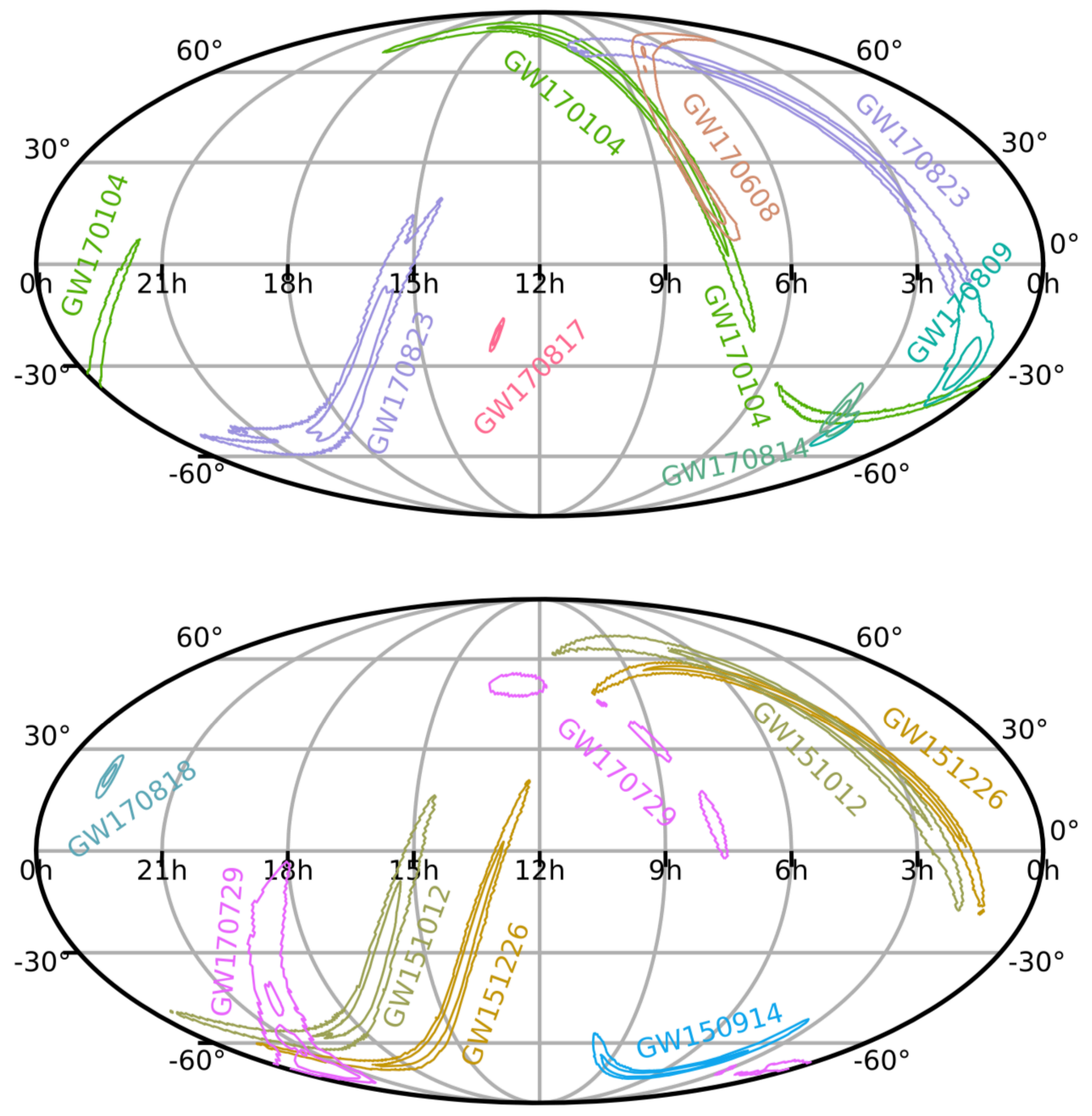
- Up to 1 sq. deg. for a small subset of sources
- Median of O(10) sq. deg. for Voyager



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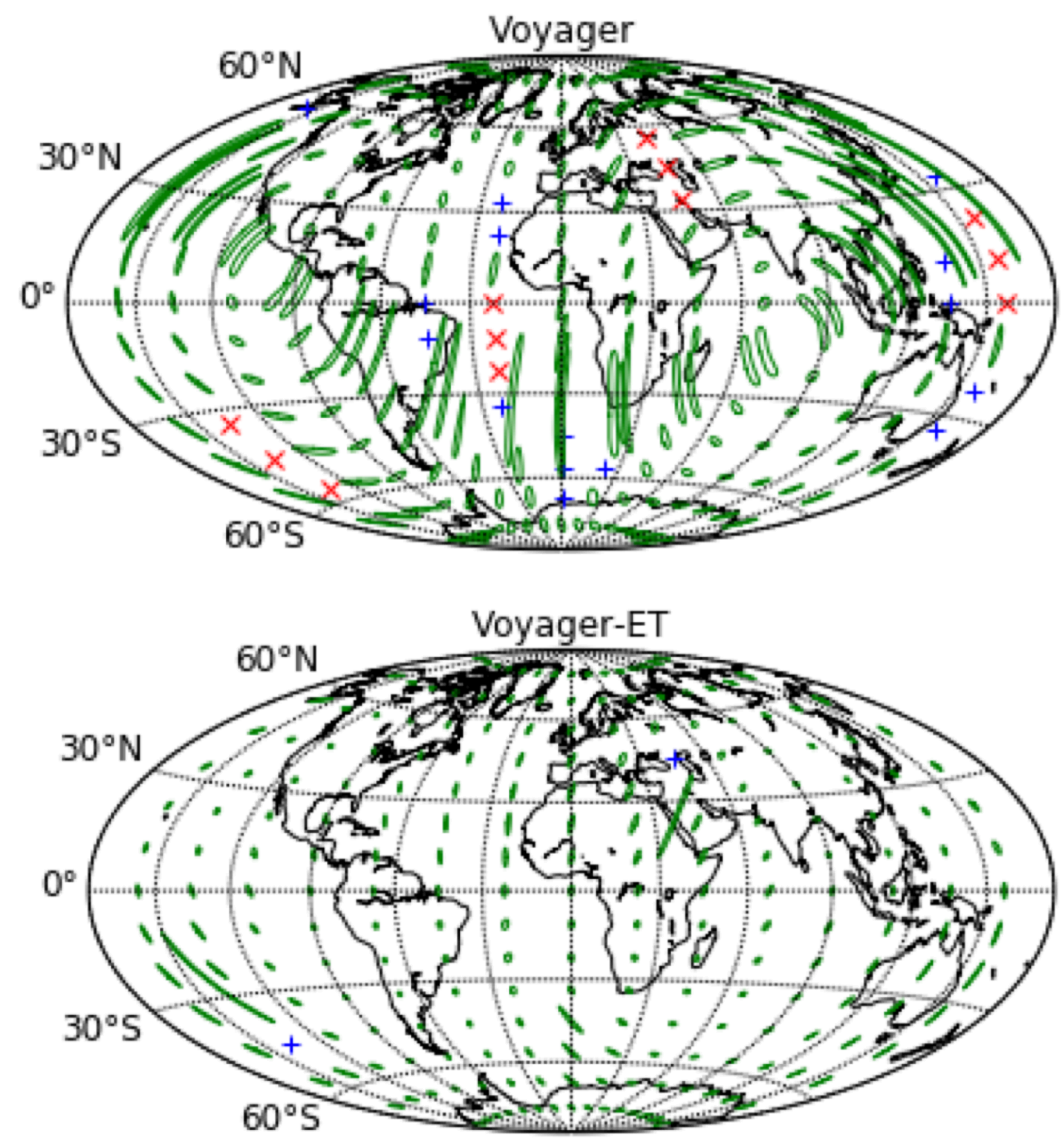

From: Mills, Tiwari, Fairhurst (2017)

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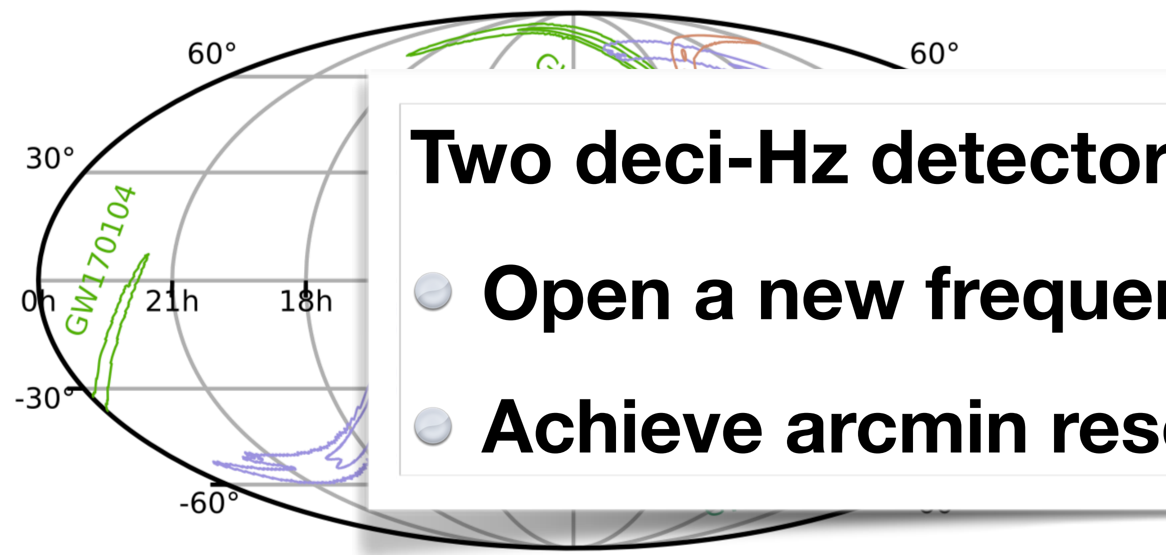
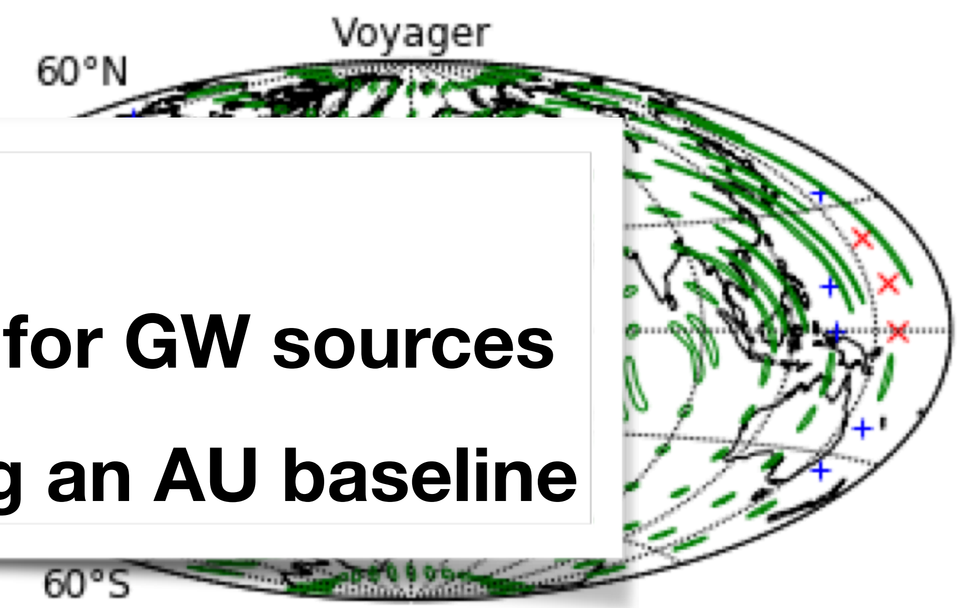
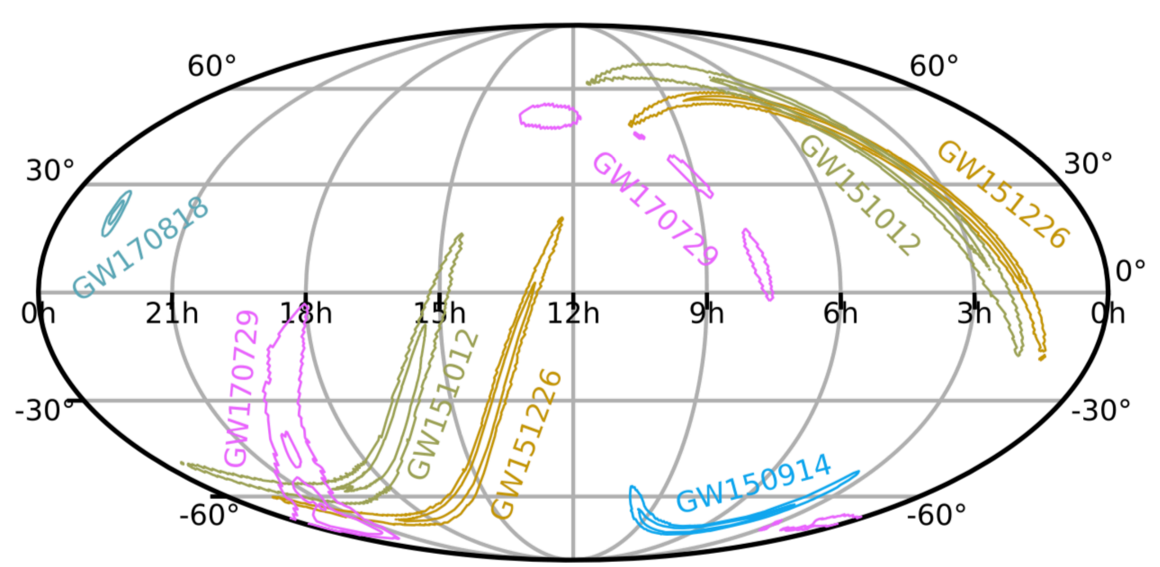




Two deci-Hz detectors in space:

- **Open a new frequency window for GW sources**
- **Achieve arcmin resolution using an AU baseline**



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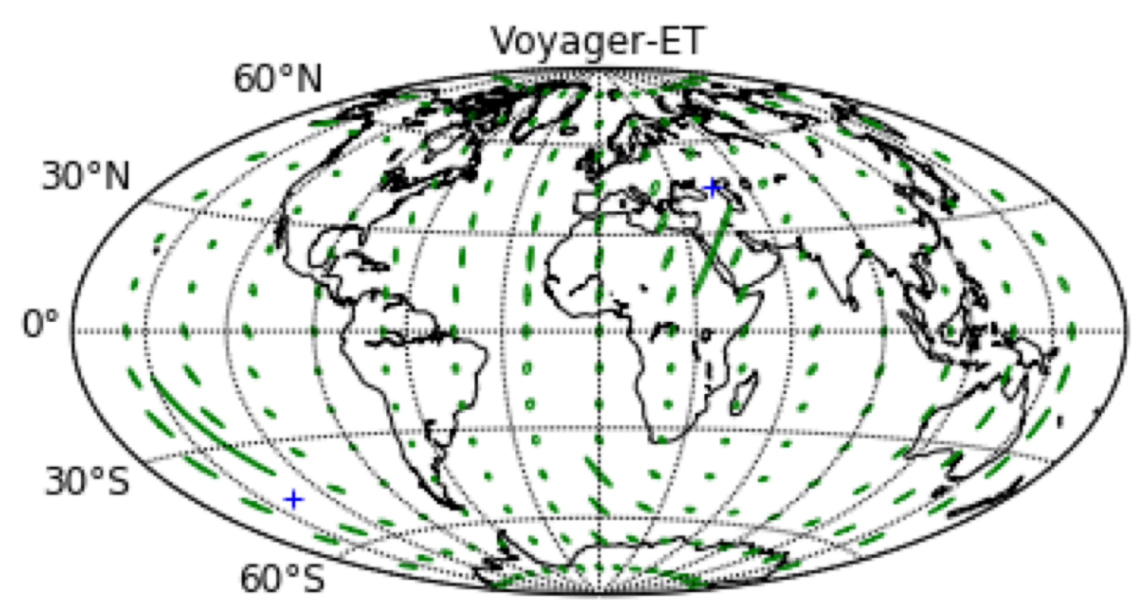

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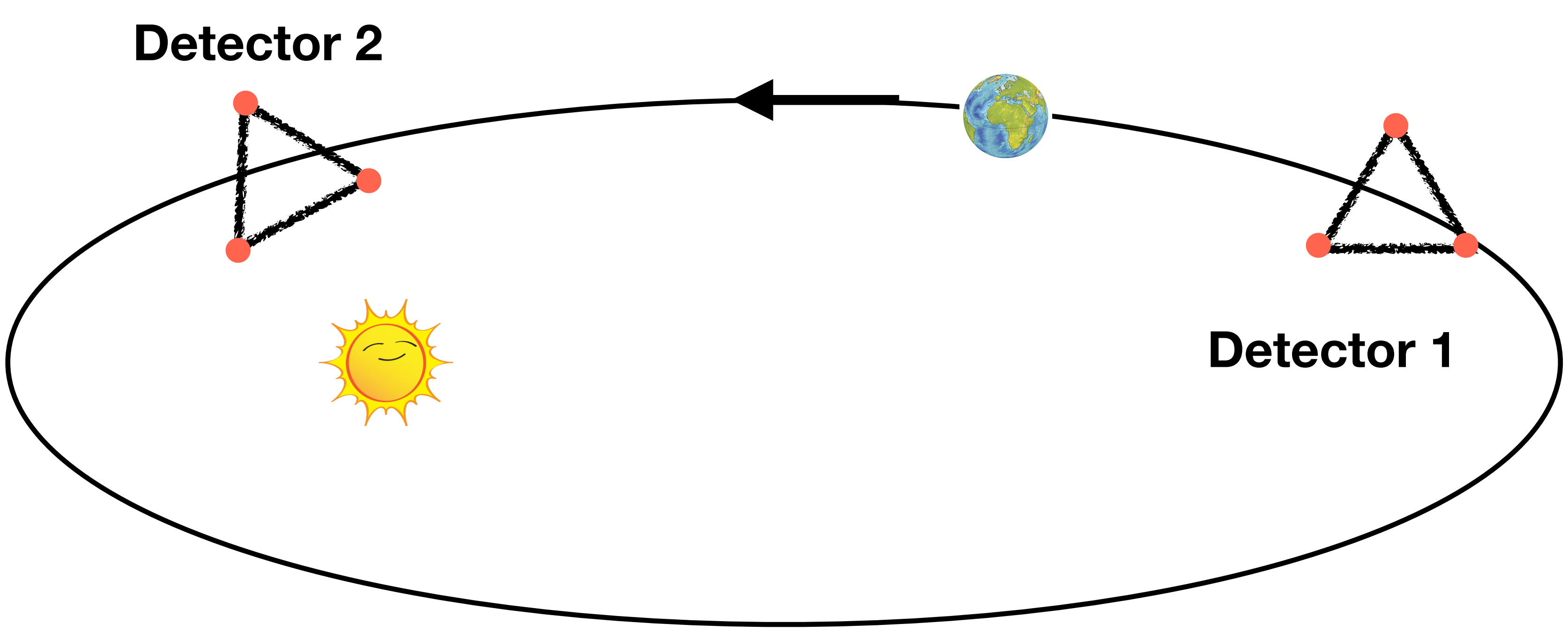
High angular resolution in the deci-Hz regime



- 10^5 km arm length for each detector
- Order of AU separation between detectors
- 1-2 meter telescope diameter
- Peak sensitivity at 0.1 Hz
- Improved sensitivity relative to LISA
- Aim at arcmin^2 resolution for point sources

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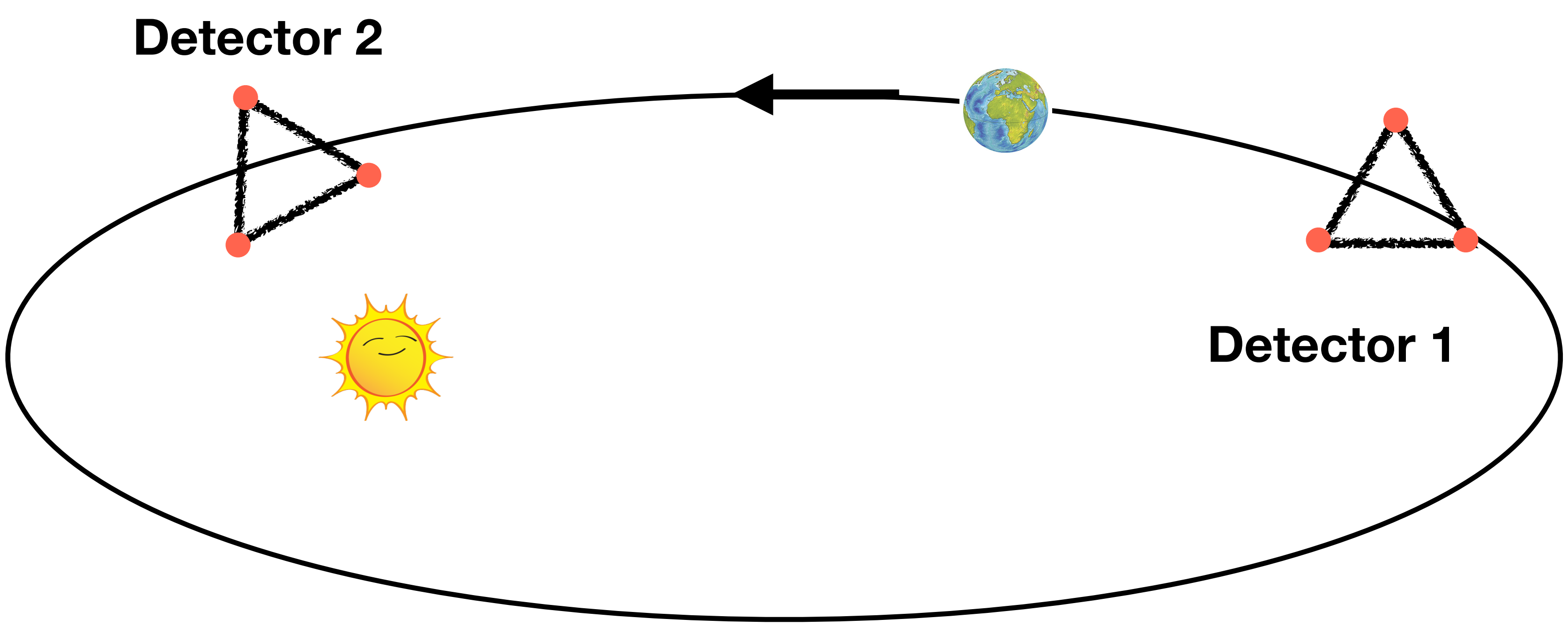

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New classes of gravitational-wave sources in the deci-Hz regime:

✱ Intermediate-mass black hole binaries: seeds of massive black holes?

✱ Gravitational-wave background from the early Universe

New tools for cosmology and fundamental physics:

✱ Multi-messenger observations of stellar-mass binaries and high-precision determination of cosmological parameters

✱ Exploration of new gravity theories

Intermediate-mass black holes: the bridge between two known populations?

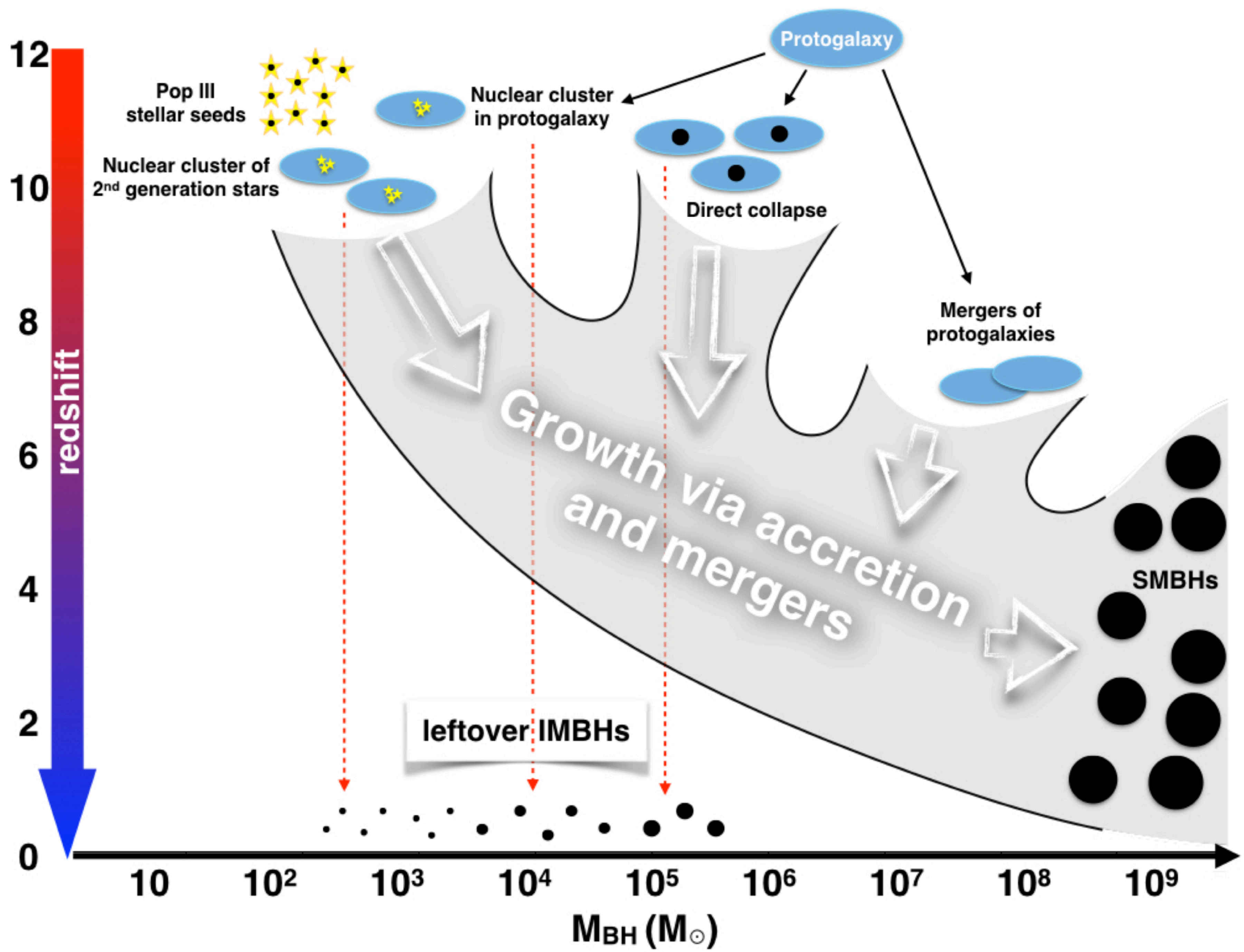

Figure from Mezcua 2017

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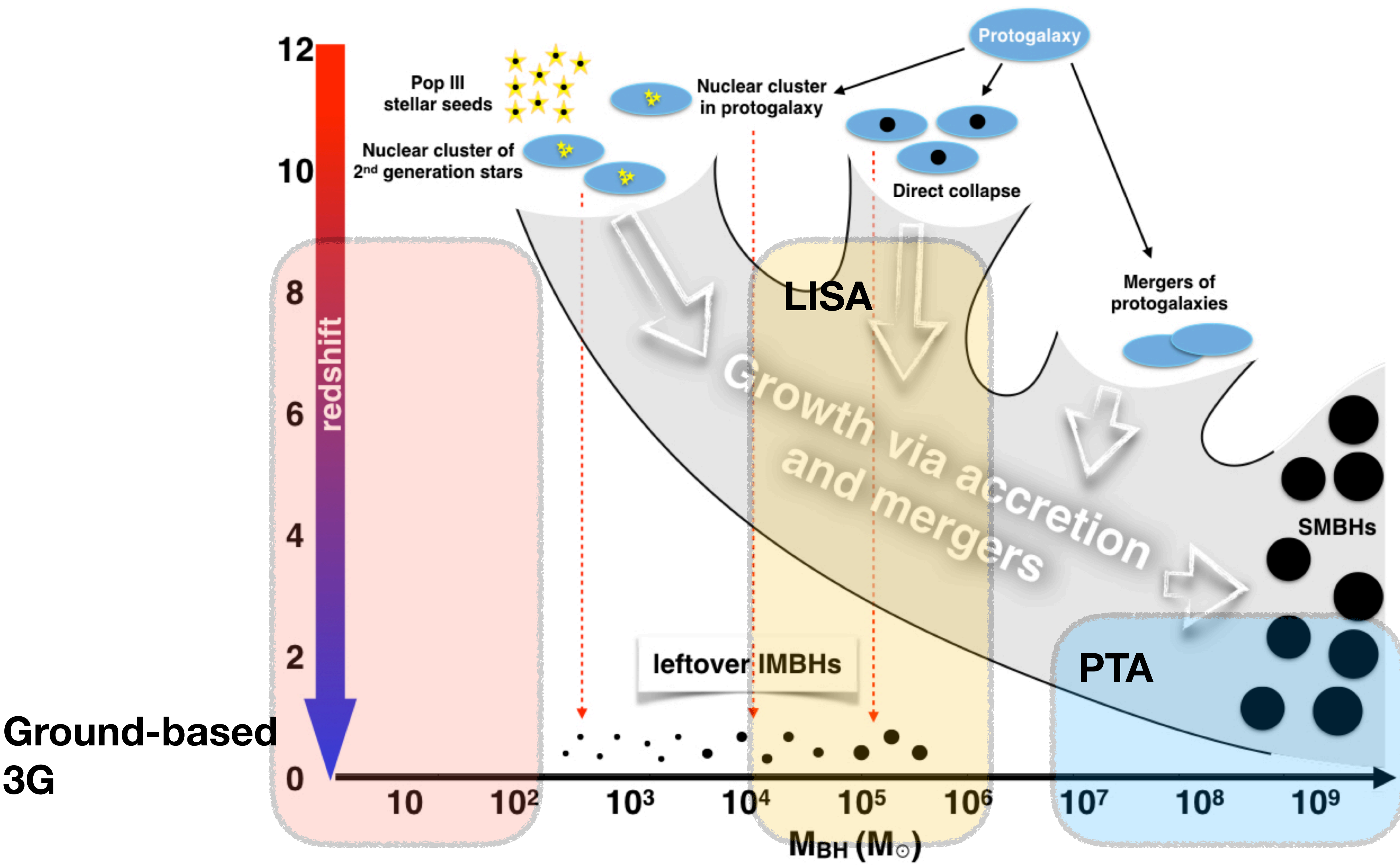

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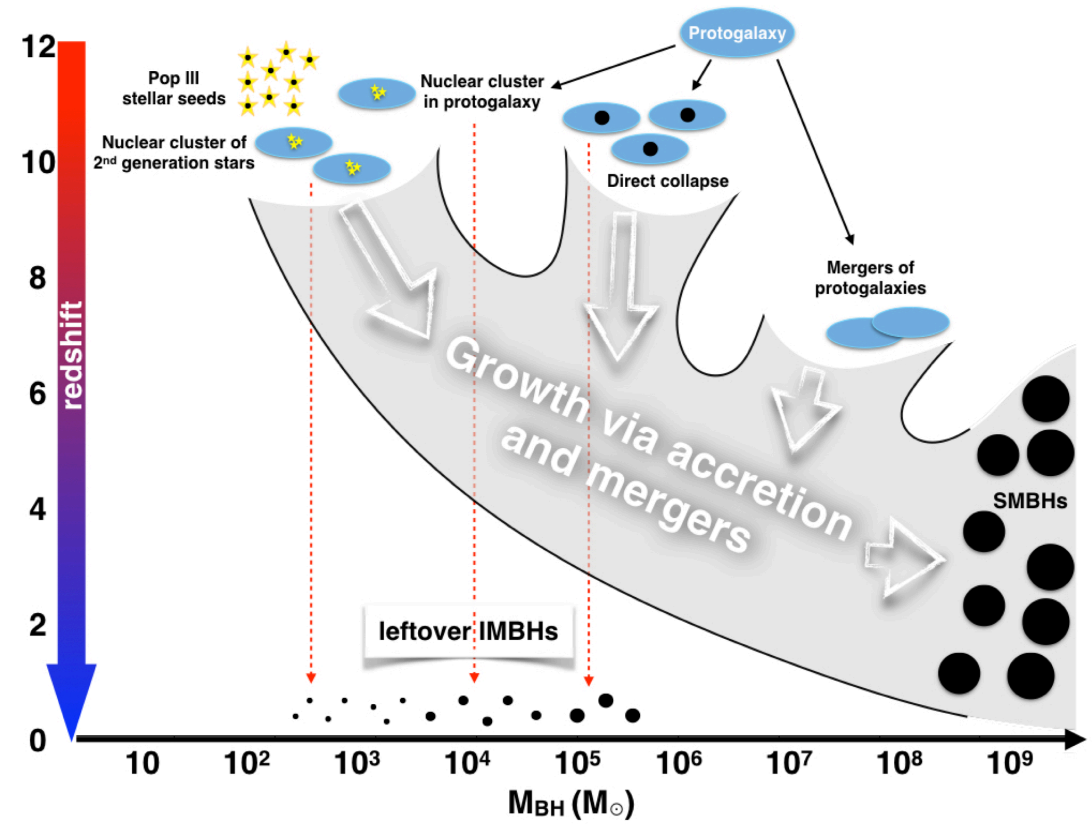
Intermediate-mass black holes: the bridge between two known populations?

- Are these the seeds of super-massive BHs?
- What is their effect on the formation of the first galaxies?
- How do they interact with the surrounding stellar populations?
- Do they form intermediate-mass-ratio inspirals (IMBH + stellar-mass object)?



Detector	Detection rate		
	$\Gamma_{\mathrm{WD}}/\mathrm{yr}^{-1}$	$\Gamma_{\mathrm{NS}}/\mathrm{yr}^{-1}$	$\Gamma_{\mathrm{BH}}/\mathrm{yr}^{-1}$
LISA	6×10^{-3}	7×10^{-5}	8×10^{-3}
DO-Conservative	4	4×10^{-2}	4
DO-Optimal	24	3×10^{-1}	5
ALIA	8	9×10^{-2}	5
DECIGO	32	4×10^{-1}	5

Source: Voyage2050 White Paper: « The missing link in gravitational-wave astronomy »

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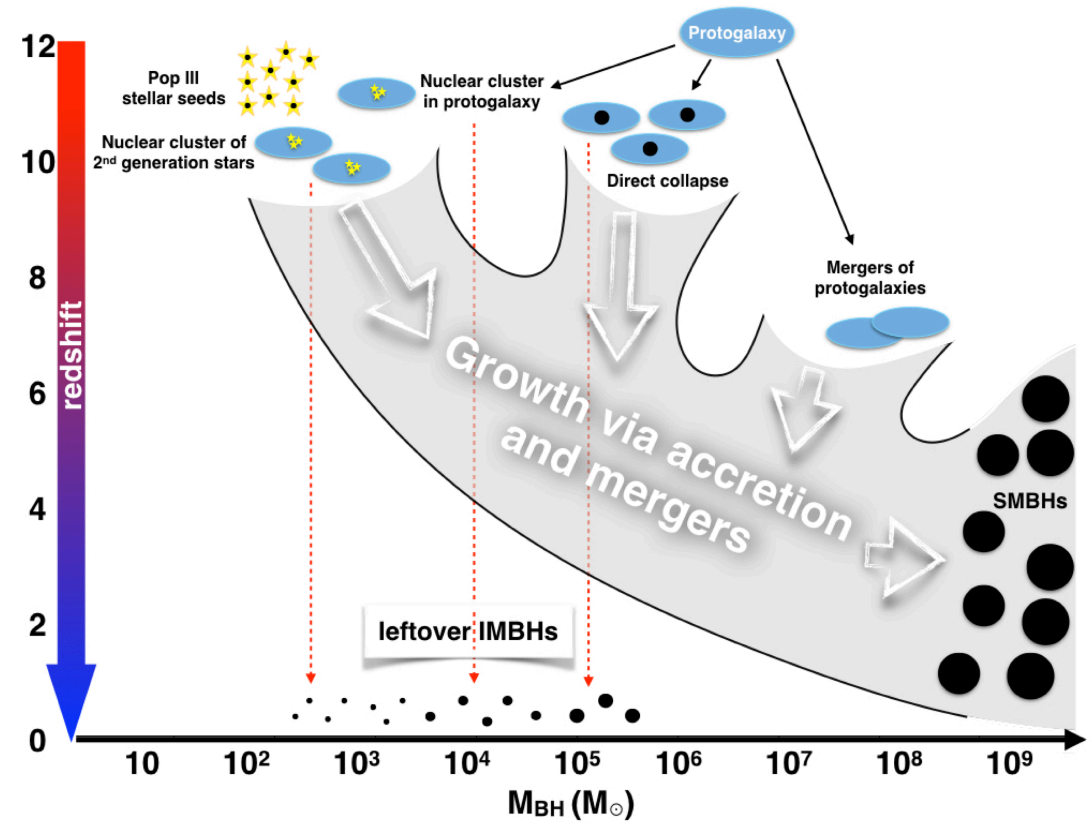

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Galaxy mergers create binaries of massive black holes

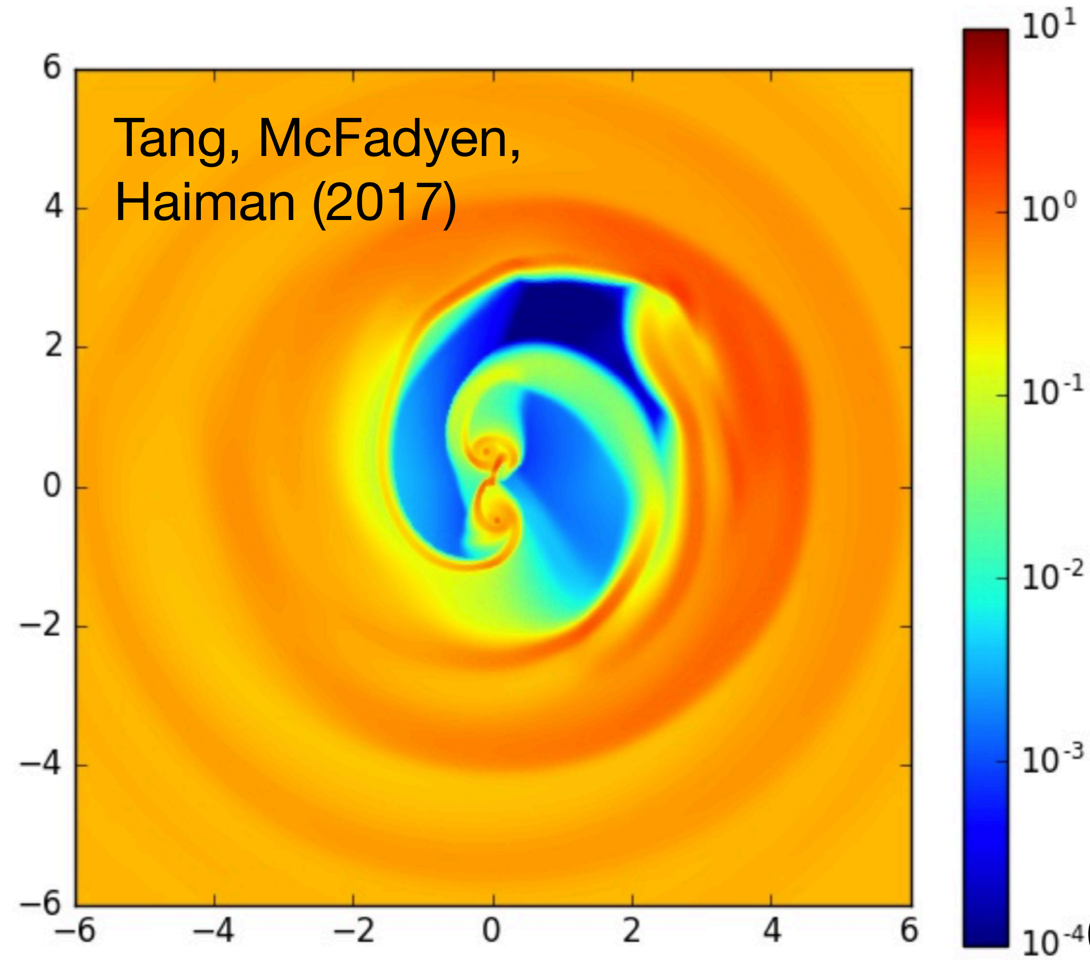
When these binaries coalesce, they emit gravitational waves, which could be observed with LISA and Pulsar Timing Array networks

What if we could identify the host galaxies of these mergers?

Circumbinary accretion disks: a multi-messenger approach

Dense gas in the nuclei of merged galaxies creates a circumbinary accretion disk

Disk-binary interactions modify the electromagnetic and the gravitational-wave signals



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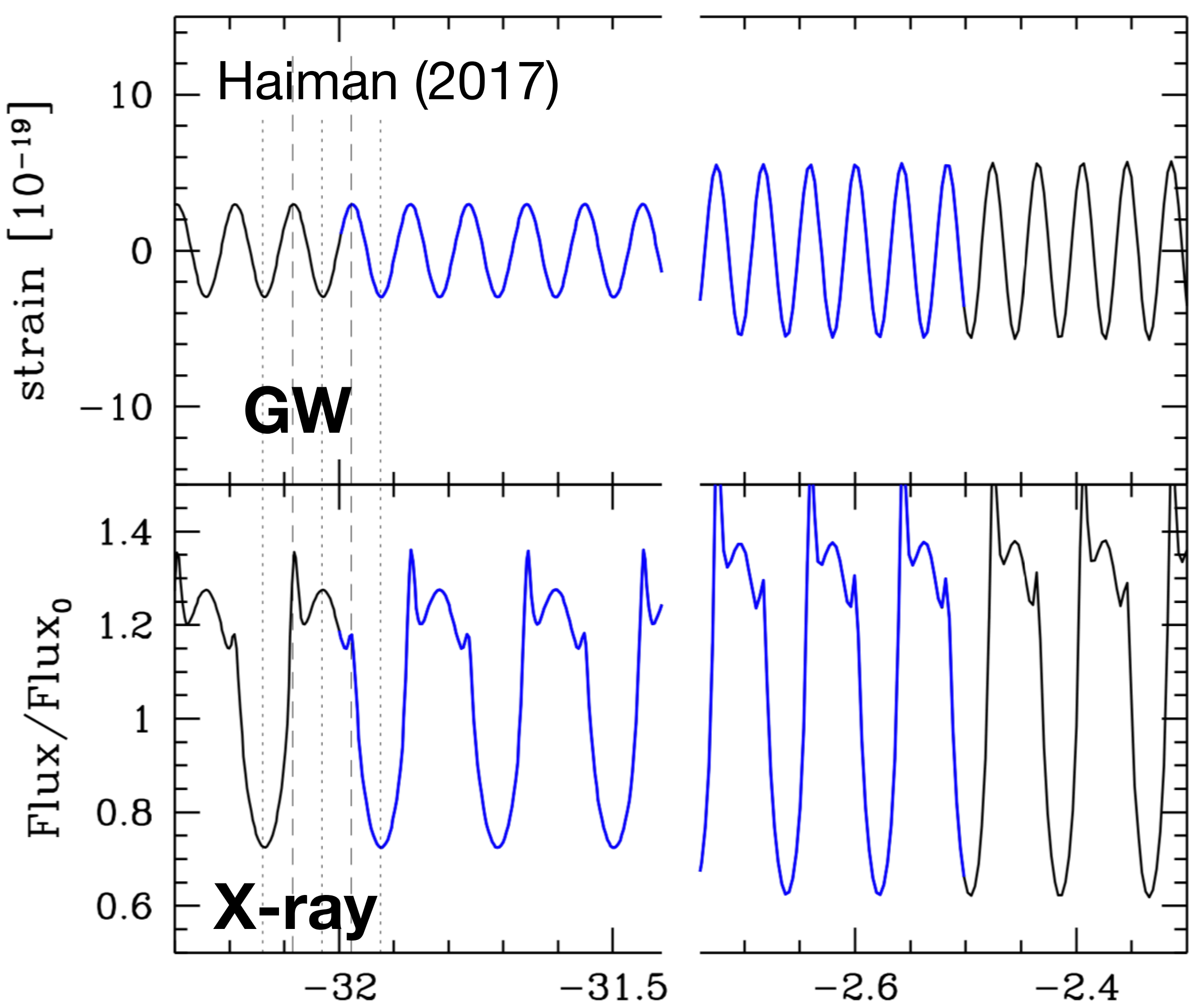
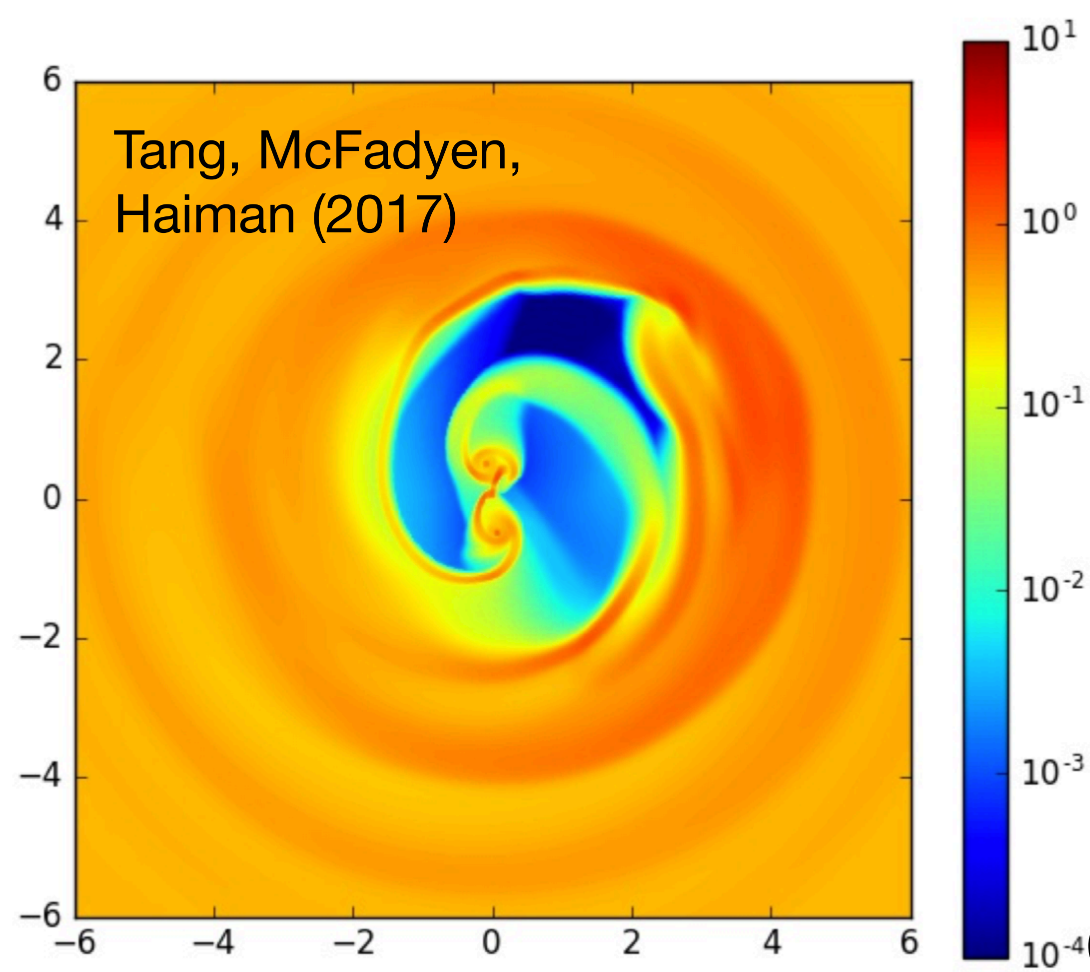
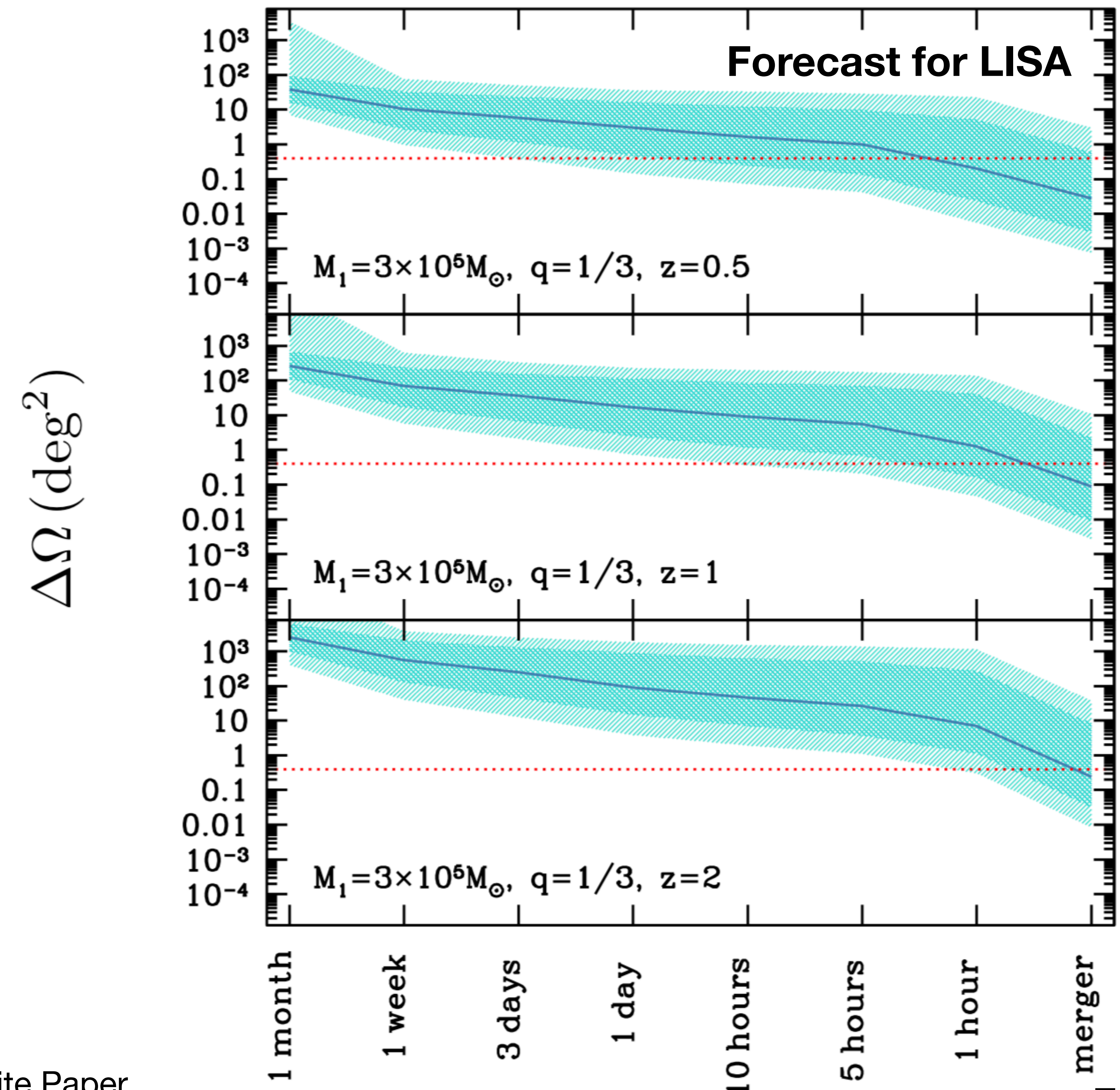
- ✱ Modifications in the gravitational waveform
- ✱ Electromagnetic 'chirp' which tracks the phase of the gravitational waves
- ✱ Modulation of the electromagnetic lightcurve





Circumbinary accretion disks: a multi-messenger approach

Precise localization a few months (weeks) ahead of the merger to allow for joint EM/GW observations for a few hundreds of cycles is beyond LISA capabilities



From: Athena-LISA Synergy White Paper

Stochastic background: new window into the early Universe

- GW from the early Universe: manifestation of **physics beyond the Standard Model**
- Main processes that can generate GW: **inflation**, **primordial phase transitions**

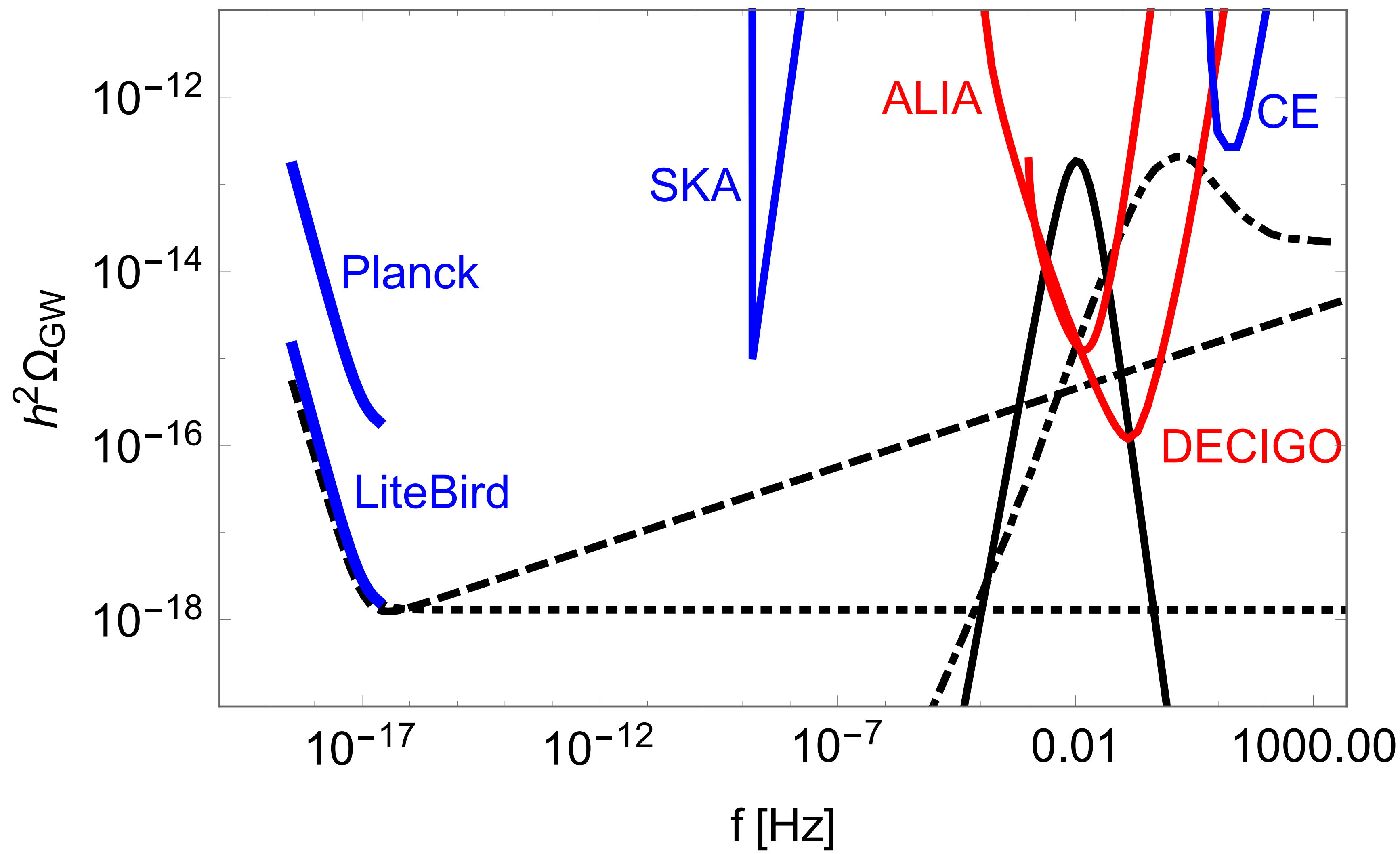


Figure: C. Caprini, G. Nardini

Astrophysical foregrounds will be detected and characterized by 3G ground-based experiments

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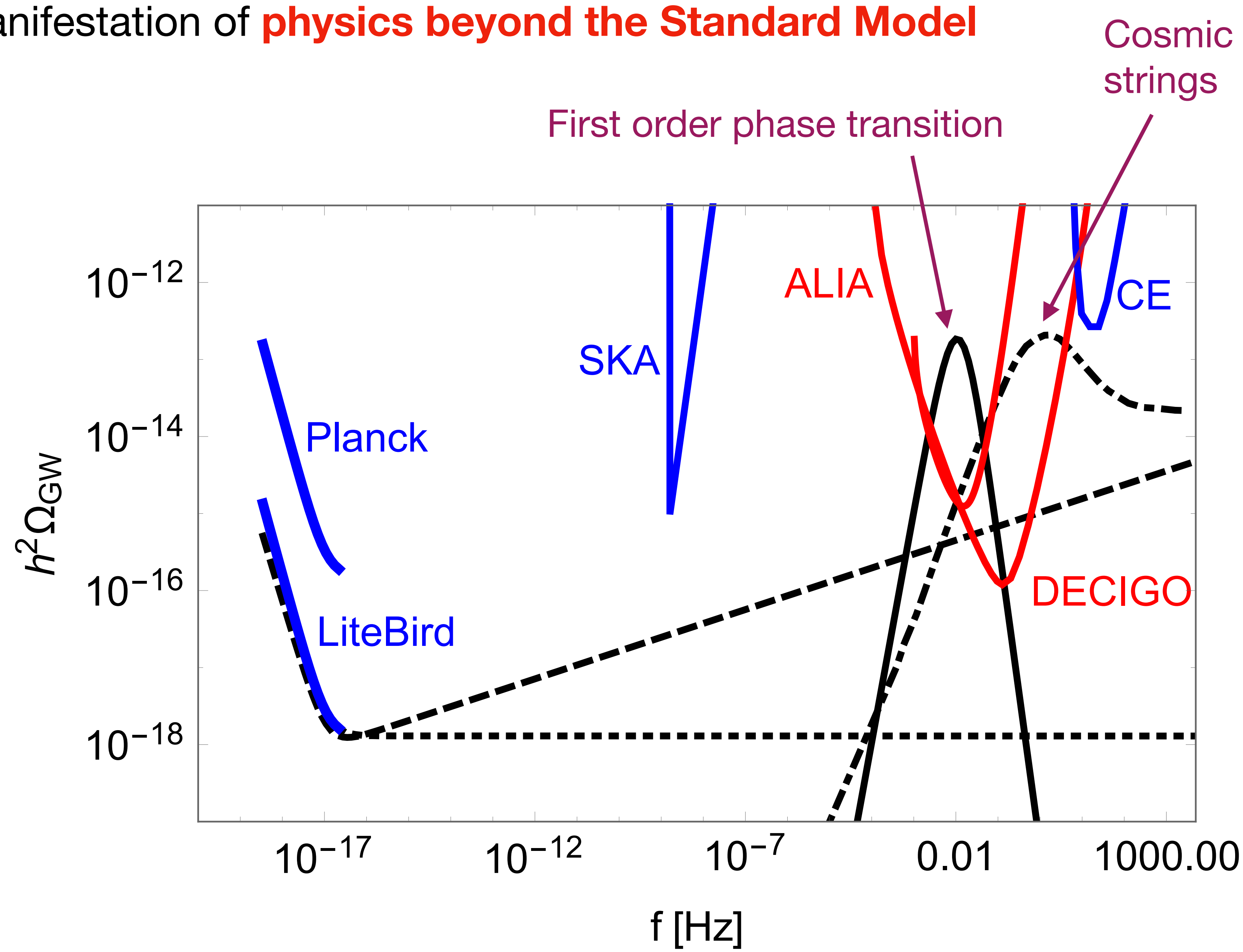

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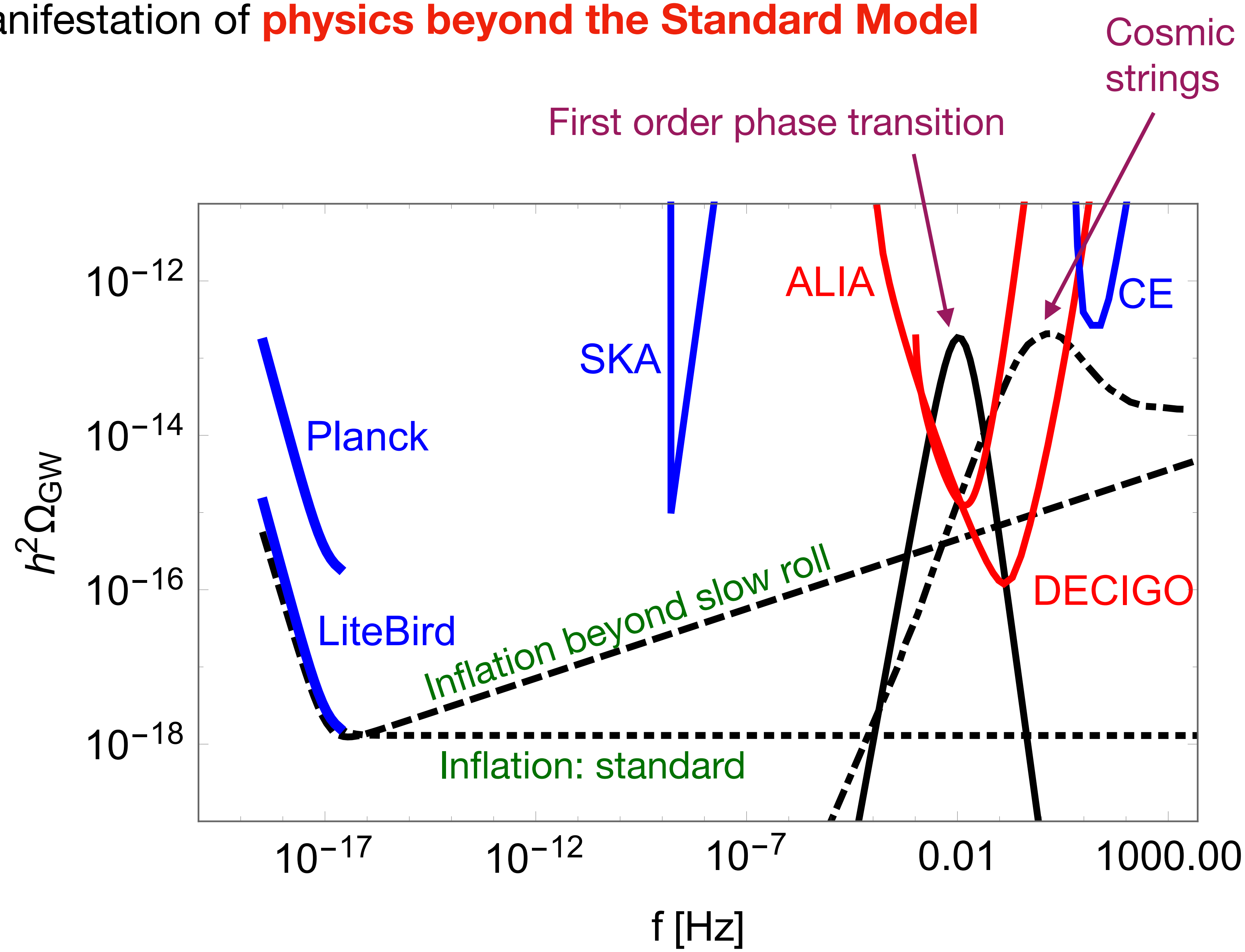
- Signal from inflation at higher frequencies than CMB experiments: study models beyond the standard slow roll scenario



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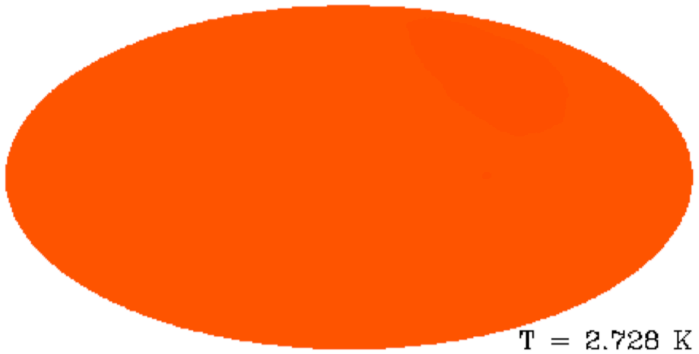
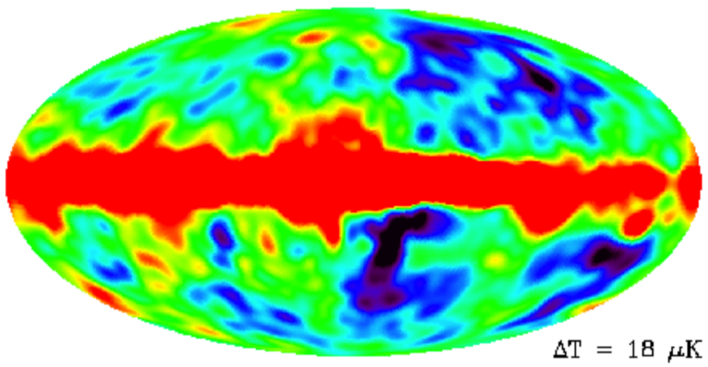
Astrophysical foregrounds will be detected and characterized by 3G ground-based experiments

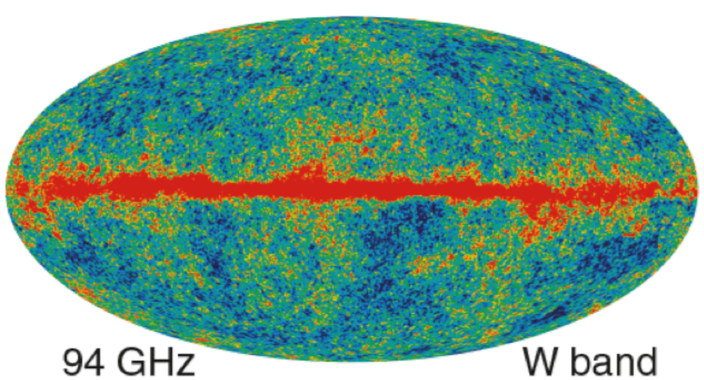
Resolving the stochastic background: how it happened with the CMB…



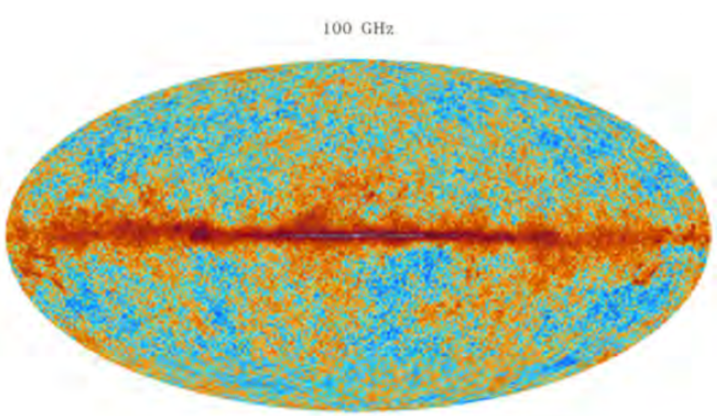
Discovery of the isotropic component (Penzias&Wilson)



COBE: $\ell \leq 10$



WMAP: $\ell \leq 1000$



Planck: $\ell \leq 2500$

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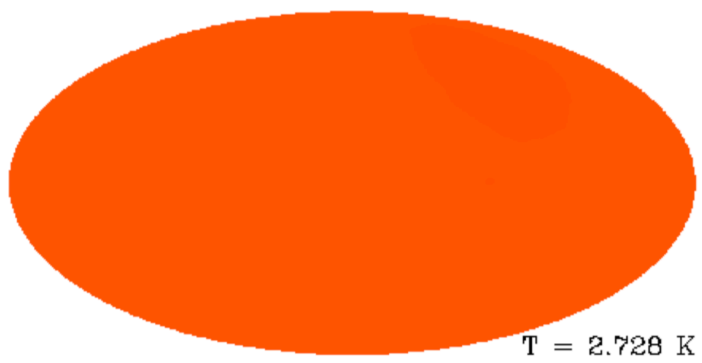

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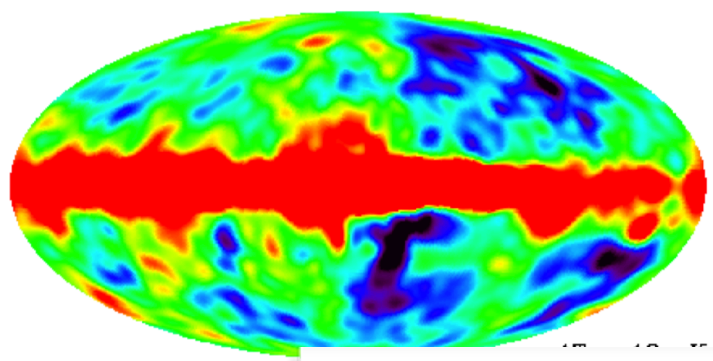

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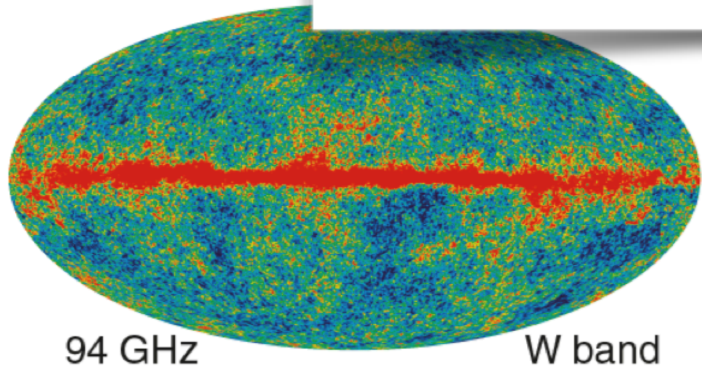
What will we learn from GW background anisotropies?



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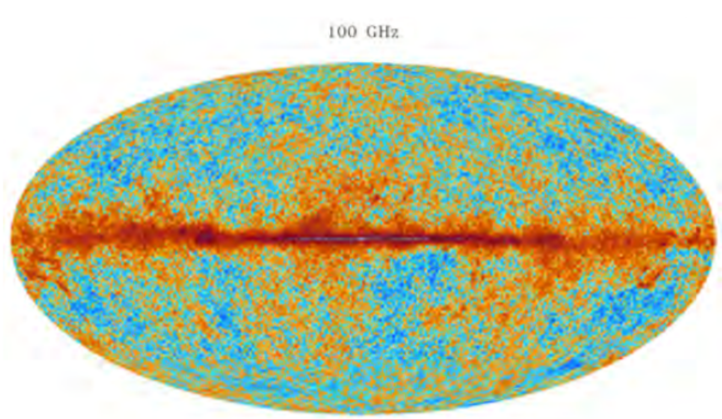

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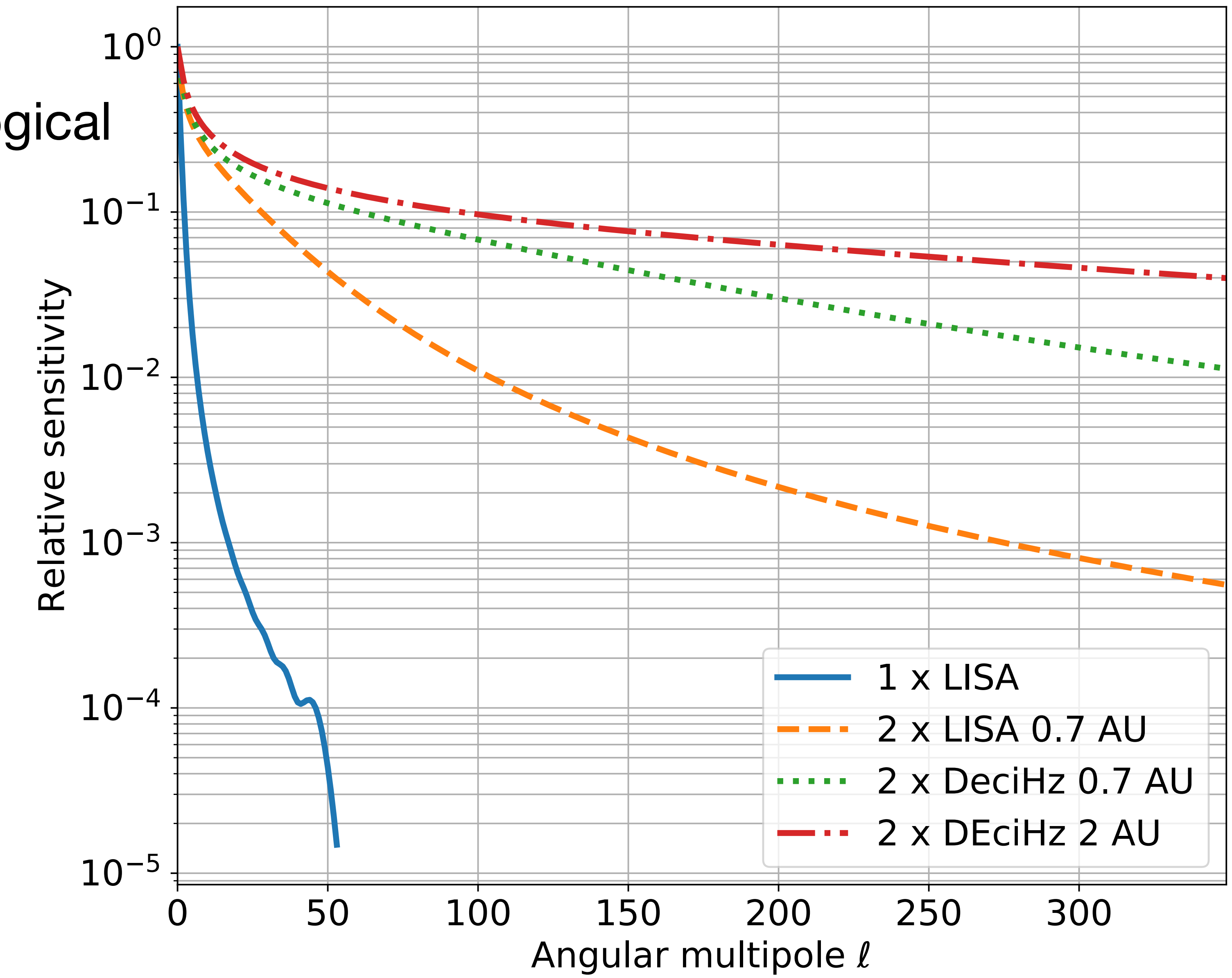
Resolving the gravitational wave background

- Anisotropies of the astrophysical background due to the large scale structure
- Anisotropies of the various cosmological backgrounds



Need a long (order of AU) baseline to resolve the angular features of the stochastic background

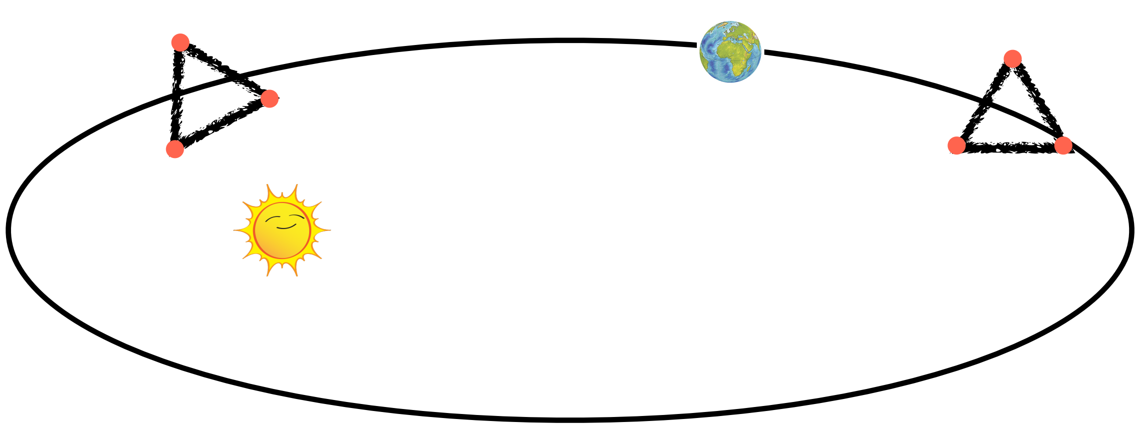
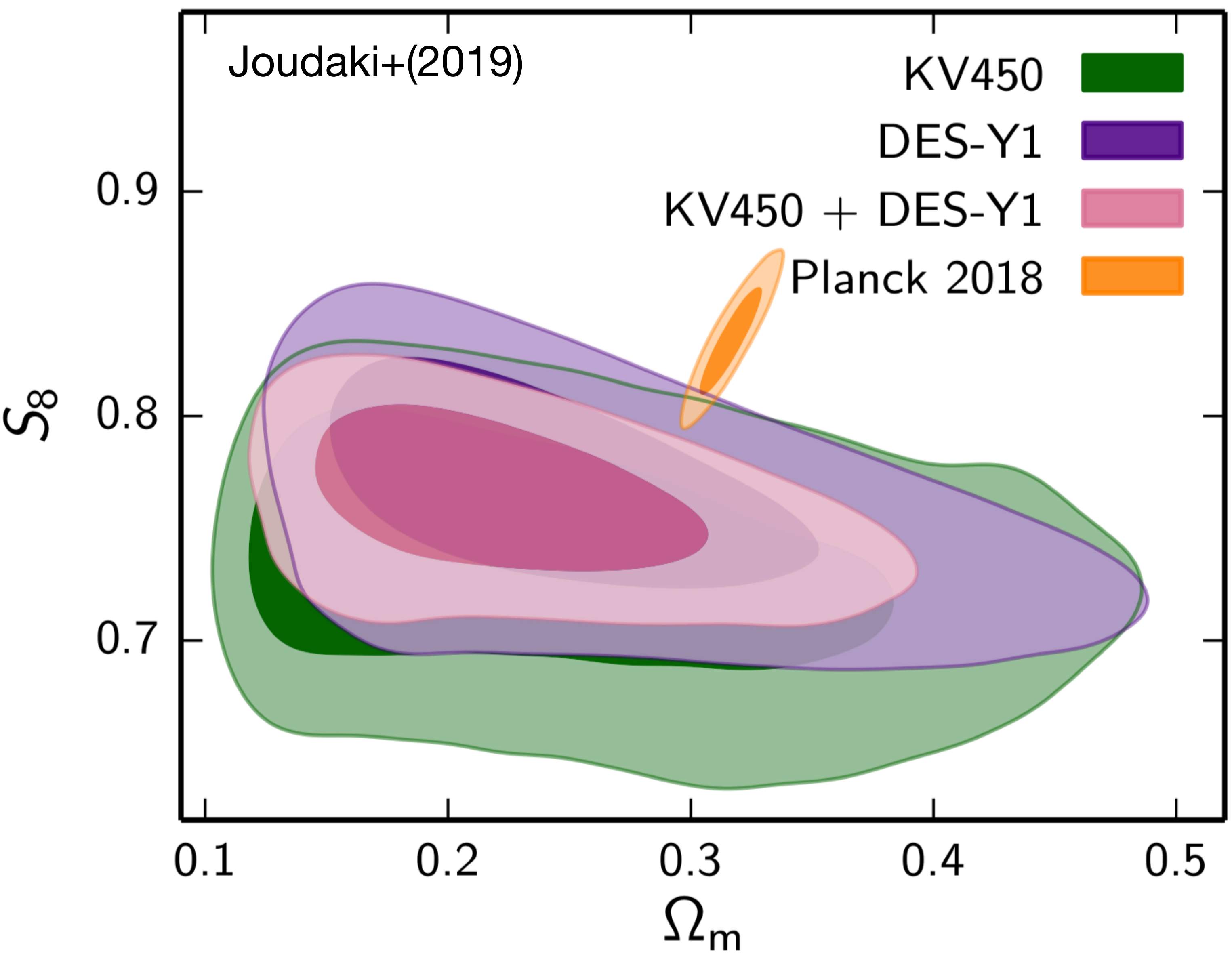
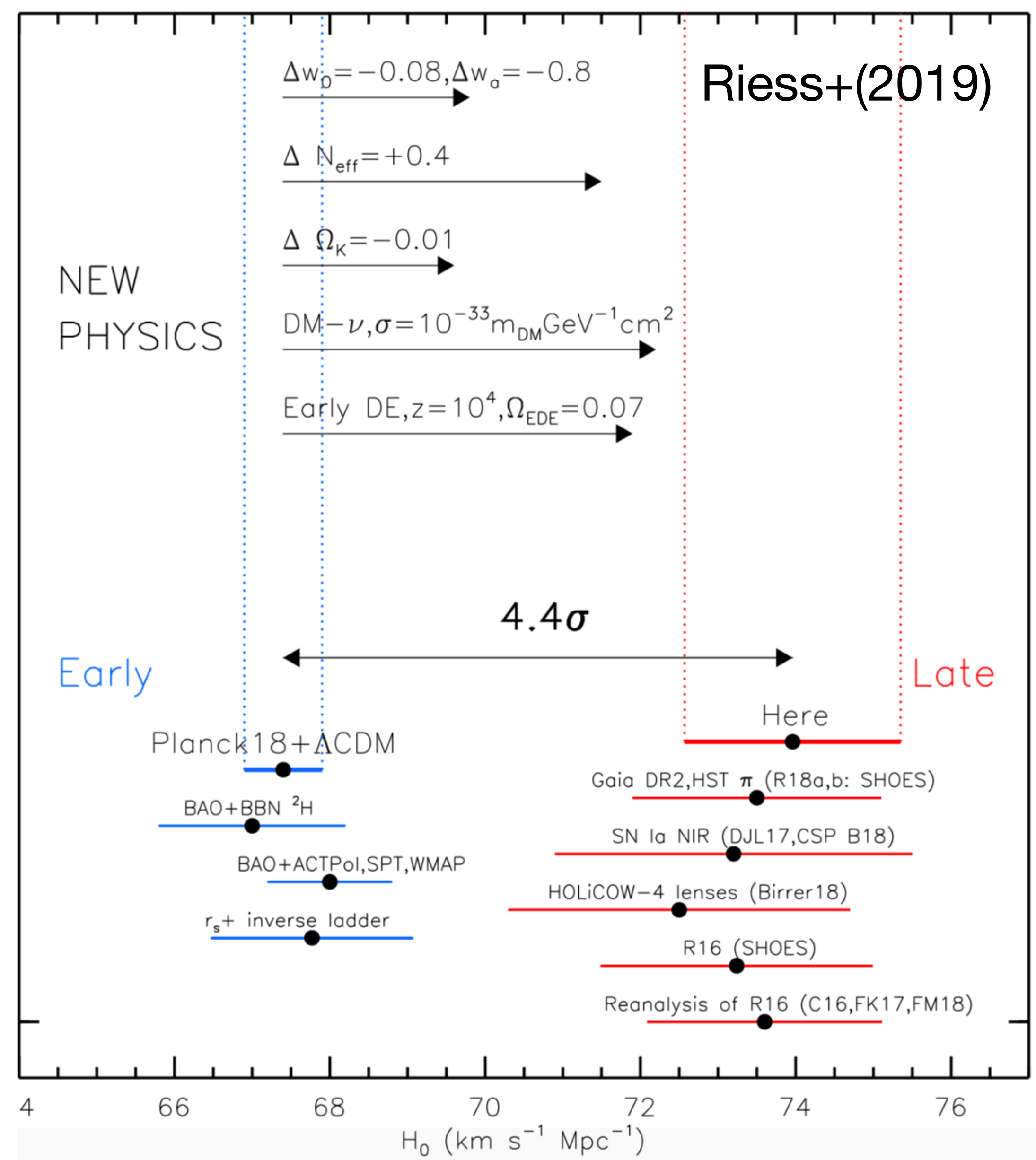


Figure: C. Contaldi (Voyage2050 White Paper: « High angular resolution gravitational-wave astronomy »)

New tools for precision cosmology

- Precision cosmology measurements revealed important discrepancies
  - in the dark matter sector ($\sigma_8 - \Omega_m$)
  - in the geometry sector (H_0)





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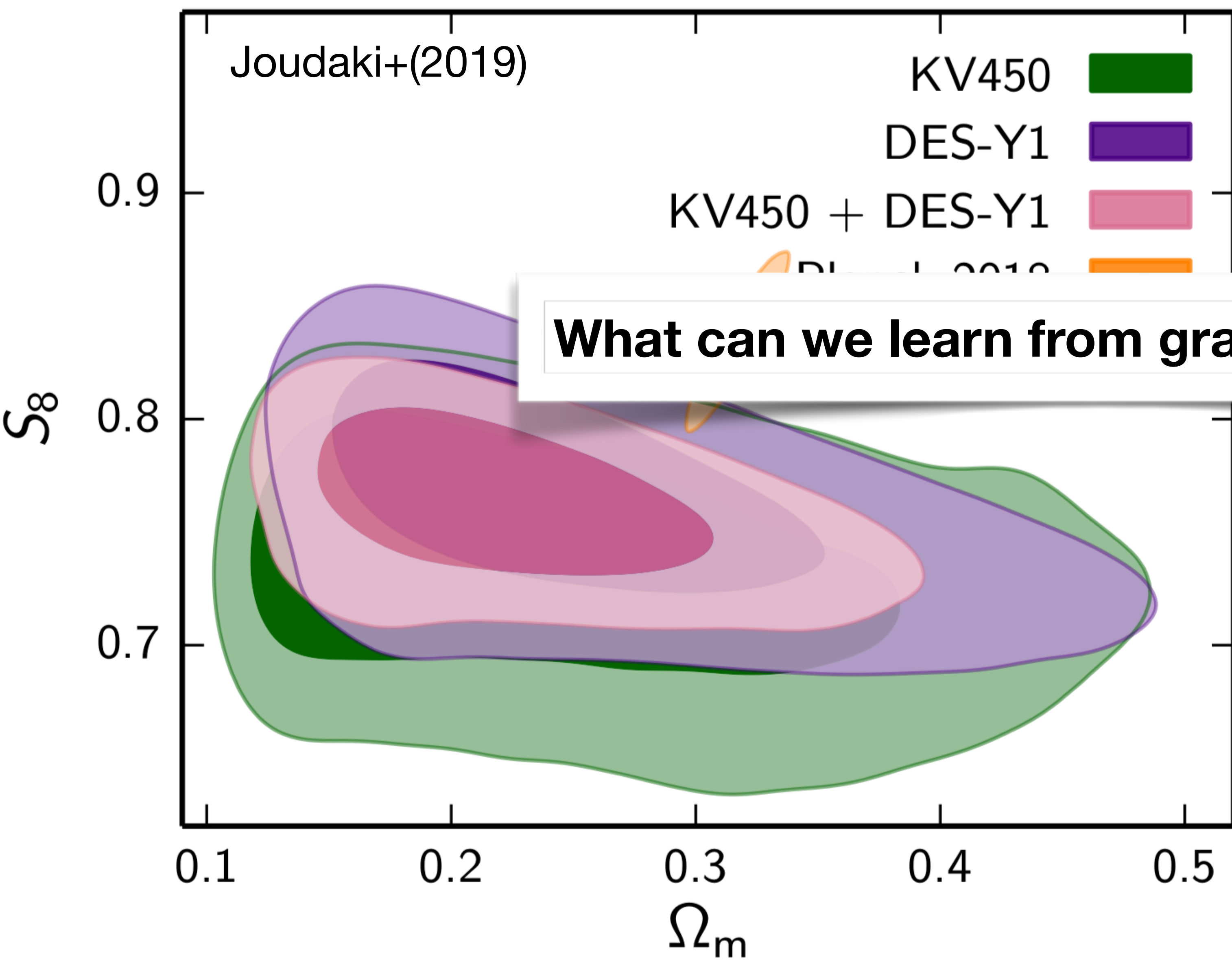
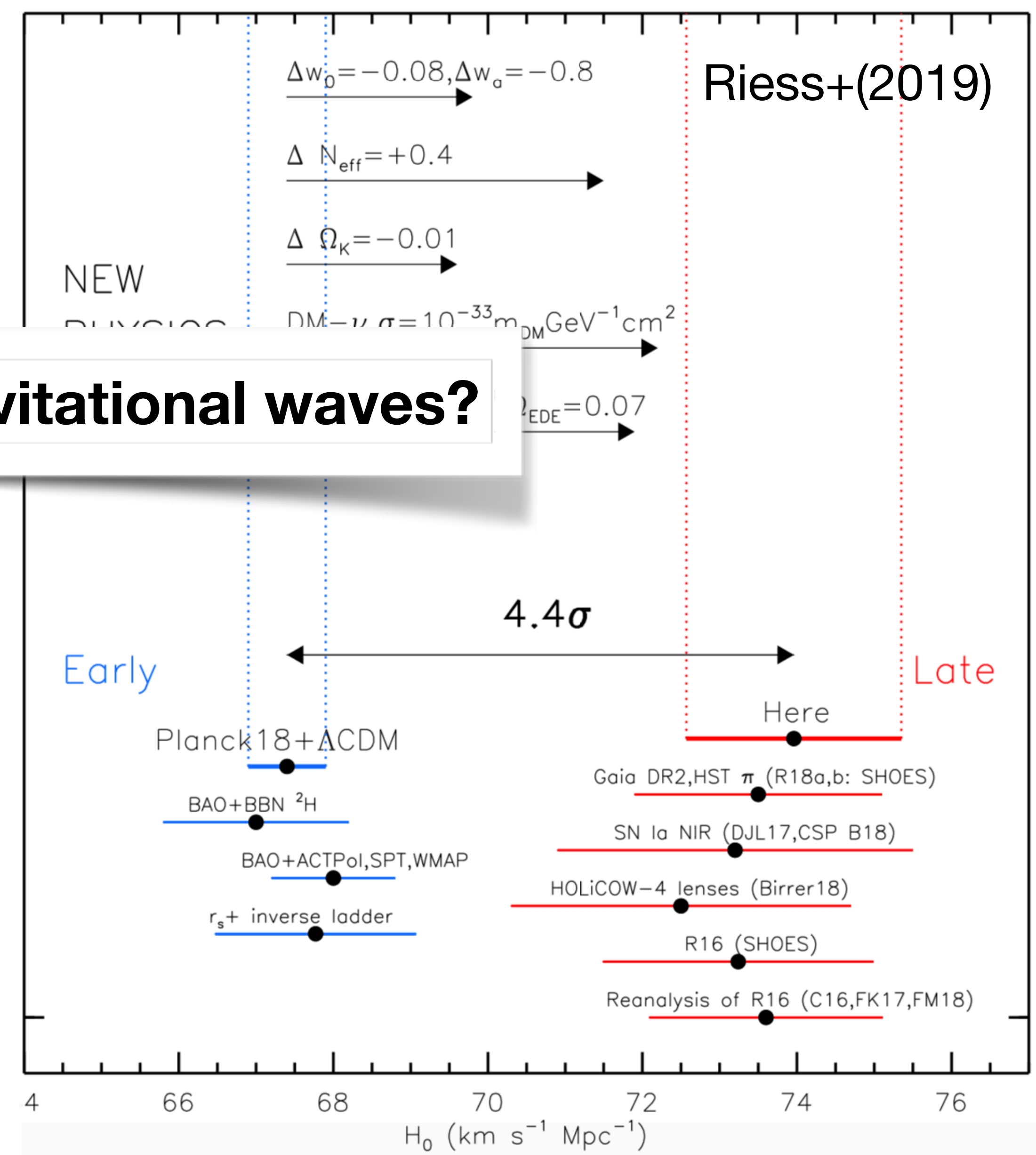
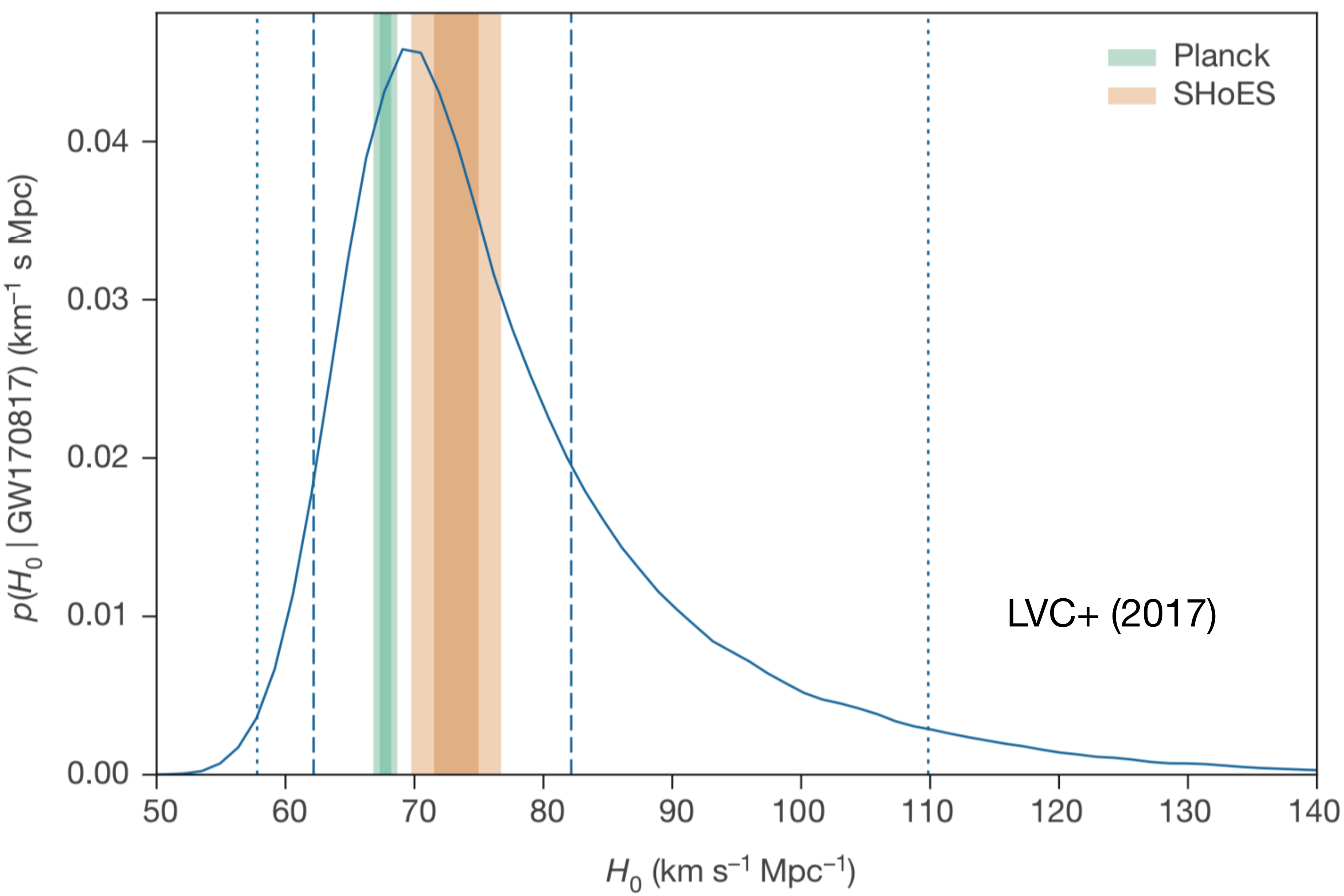




What can we learn from gravitational waves?

New tools for precision cosmology

- GW standard sirens: merging binaries
  - Luminosity distance is measured directly
  - Redshift is measured if EM counterpart is observed or host galaxy identified



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  - EM counterparts for binary neutron star mergers
  - Host galaxies for binary black holes
    - Hubble diagram with $10^5 - 10^6$ sources

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    - Hubble diagram with $10^5 - 10^6$ sources
  - Information from gravitational lensing of GW due to intervening large scale structure
    - Precision of 0.1 % on ΛCDM cosmological parameters

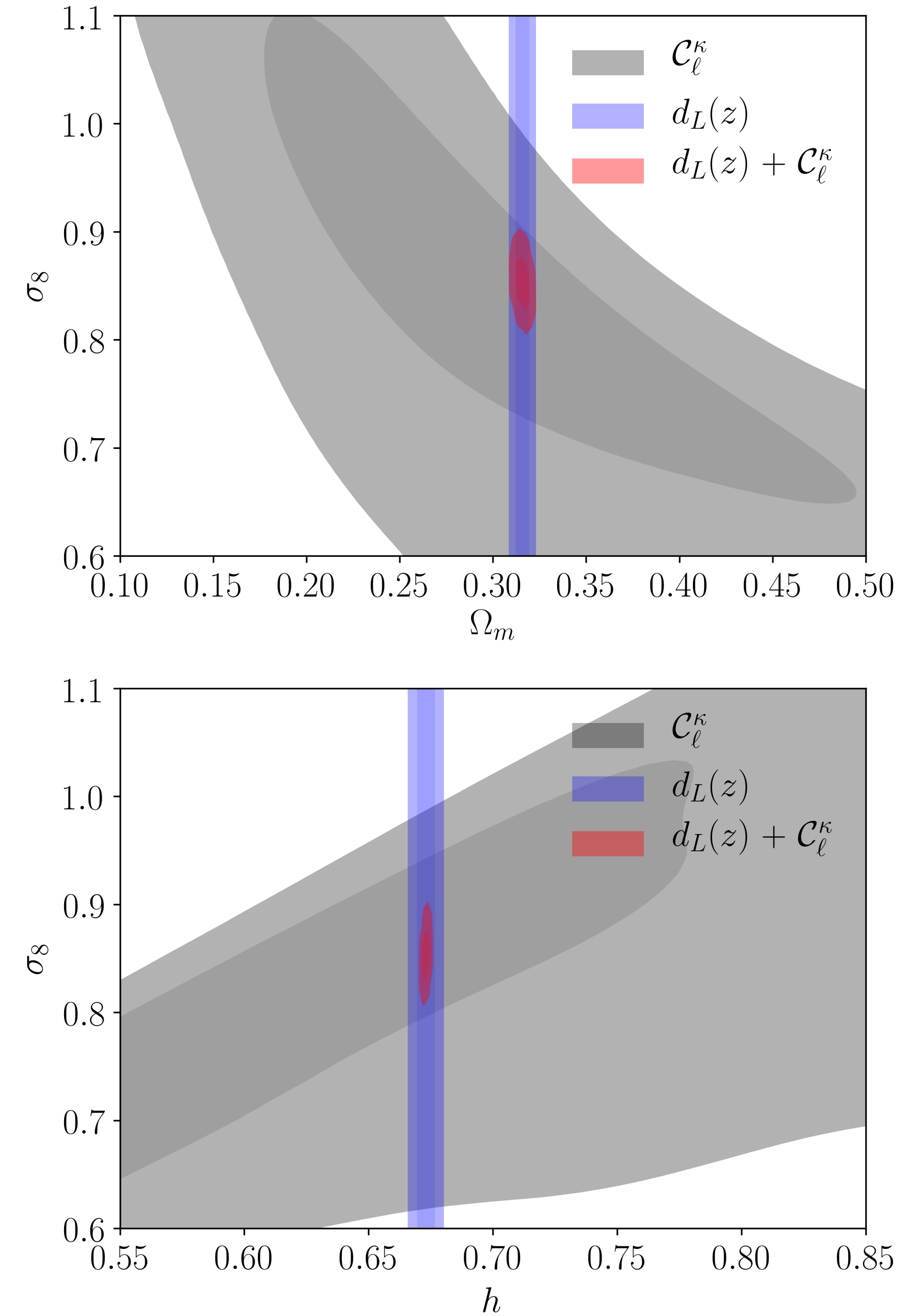
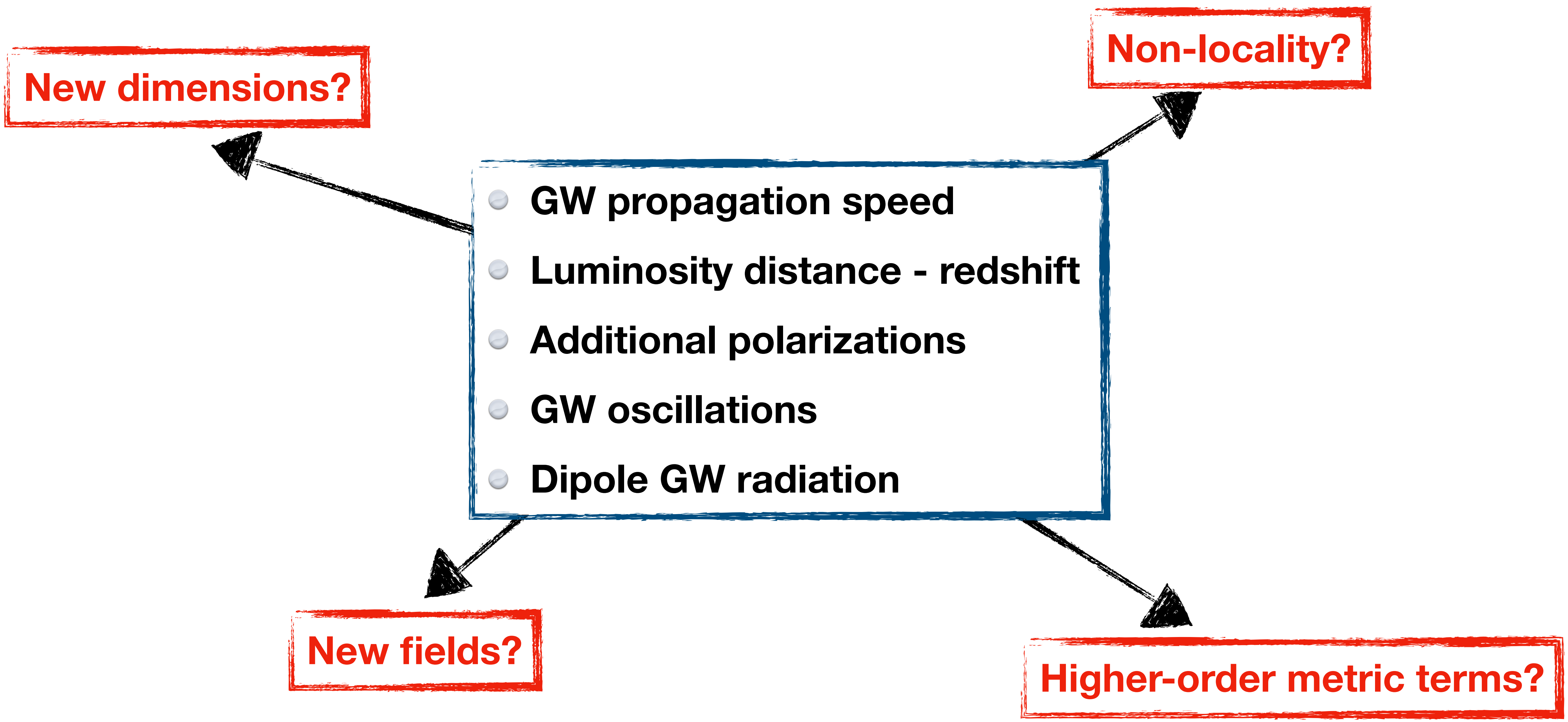


Figure: G. Congedo (Voyage2050 White Paper: « High angular resolution gravitational-wave astronomy »)

New tools for fundamental physics

- Joint GW and EM observations will allow to explore a wide range of new gravity theories
  - New classes of sources in the deci-Hz range - new regime for GR tests



Gravitational-wave detector technologies in 2035-2050

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- LISA is limited by laser shot noise at $f > 0.01$ Hz
- Resolution is limited by detector baseline, bandwidth and SNR

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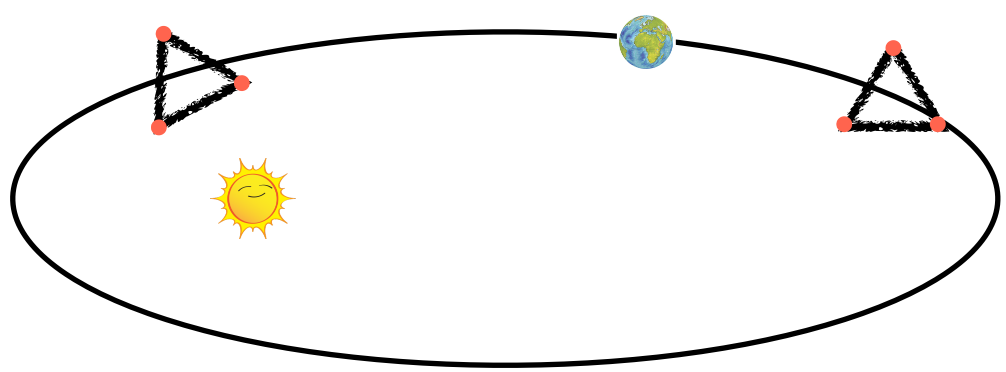
- LISA is limited by laser shot noise at $f > 0.01$ Hz
- Resolution is limited by detector baseline, bandwidth and SNR
- Several proposals from the community based on **laser interferometry** (ALIA, DECIGO, BBO) with improved sensitivity at 0.1 Hz due to shorter arm length
- Developments in **atom interferometry** (MAGIS, AEDGE) will provide alternative designs
- US, Japan, China have expressed interest in a deciHz detector: possibilities for international collaboration

High angular resolution gravitational wave astronomy in the deciHz regime

- New frequency regime: discover **new types of sources** and provide **new tools** for cosmology and fundamental physics
- High-resolution observations will enable efficient **multi-messenger campaigns**
- Many promising technologies will allow to meet the requirements in the 2035-2050 time frame
- Possibility of collaboration with an international partner



High-resolution gravitational wave astronomy: John Baker, Tessa Baker, Carmelita Carbone, Giuseppe Congedo, Carlo Contaldi, Irina Dvorkin, Jonathan Gair, Zoltan Haiman, David F. Mota, Arianna Renzini, Ernst-Jan Buis, Giulia Cusin, Jose Maria Ezquiaga, Guido Mueller, Mauro Pieroni, John Quenby, Angelo Ricciardone, Ippocratis D. Saltas, Lijing Shao, Nicola Tamanini, Gianmassimo Tasinato, Miguel Zumalacárregui

The missing link in gravitational wave astronomy: Manuel Arca Sedda, Christopher Berry, Karan Jani, Pau Amaro-Seoane, Pierre Auclair, Jonathon Baird, Tessa Baker, Emanuele Berti, Katelyn Breivik, Chiara Caprini, Xian Chen, Daniela Doneva, Jose M. Ezquiaga, K.E. Saavik Ford, Michael Katz, Shimon Kolkowitz, Barry McKernan, Guido Mueller, Germano Nardini, Igor Pikovski, Surjeet Rajendran, Alberto Sesana, Lijing Shao, Nicola Tamanini, Niels Warburton, Helvi Witek, Kaze Wong, Michael Zevin