3G-SCT Cosmology and Cosmography Report

Oct. 1, 2018

3GSCT Meeting, Potsdam

Subsections Leads

- Dani Figueroa: inflationary and early universe models
- Chiara Caprini: phase transitions models
- Mairi Sakellariadou: cosmic strings
- Andrew Matas, Jan Harms, Eric Thrane: removal of the compact binaries foregrounds
- Giulia Cusin: Correlating SGWB with Large-Scale Structure
- Tania Regimbau: Other astrophysical foregrounds
- Michele Maggiore: Cosmological Parameters and Dark Energy
- Xilong Fan: Strongly lensed GW-EM systems

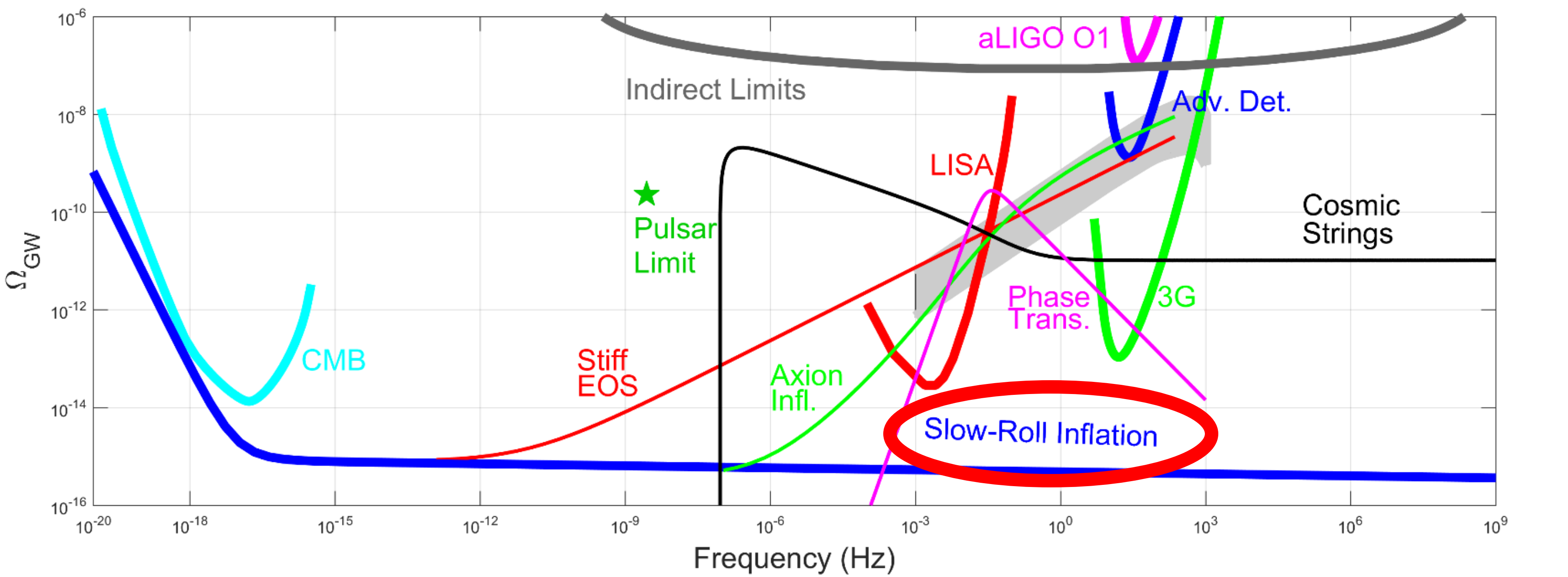
- Vuk Mandic and B. Sathyaprakash: group leads, cheerleading support
- Several others contributed comments/suggestions.

Outline

- Stochastic Gravitational-Wave Background (SGWB)
  - Cosmological models
  - Astrophysical models
    - Subtracting the binary foreground
  - Correlating with EM observations (of large-scale structure)
- GWs and Dark Matter
- Cosmography
  - Standard sirens and Dark Energy
  - Modified GW propagation as a probe of Dark Energy
  - Strongly lensed GW-EM Systems

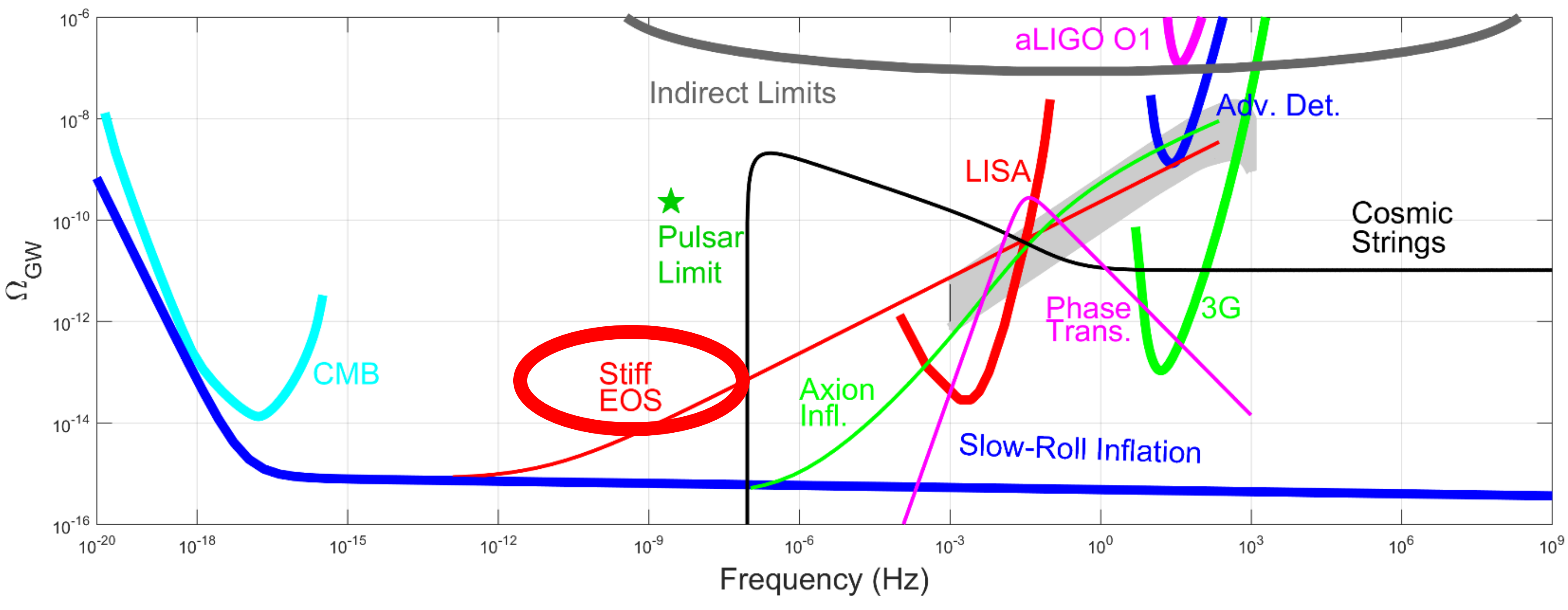
Inflationary Models

- Amplification of primordial tensor vacuum modes.
- In simplest inflationary models, flat and weak.
- Not accessible to 3G, as currently designed.
- But could be a target of follow-up detectors in the same facilities (3G+).



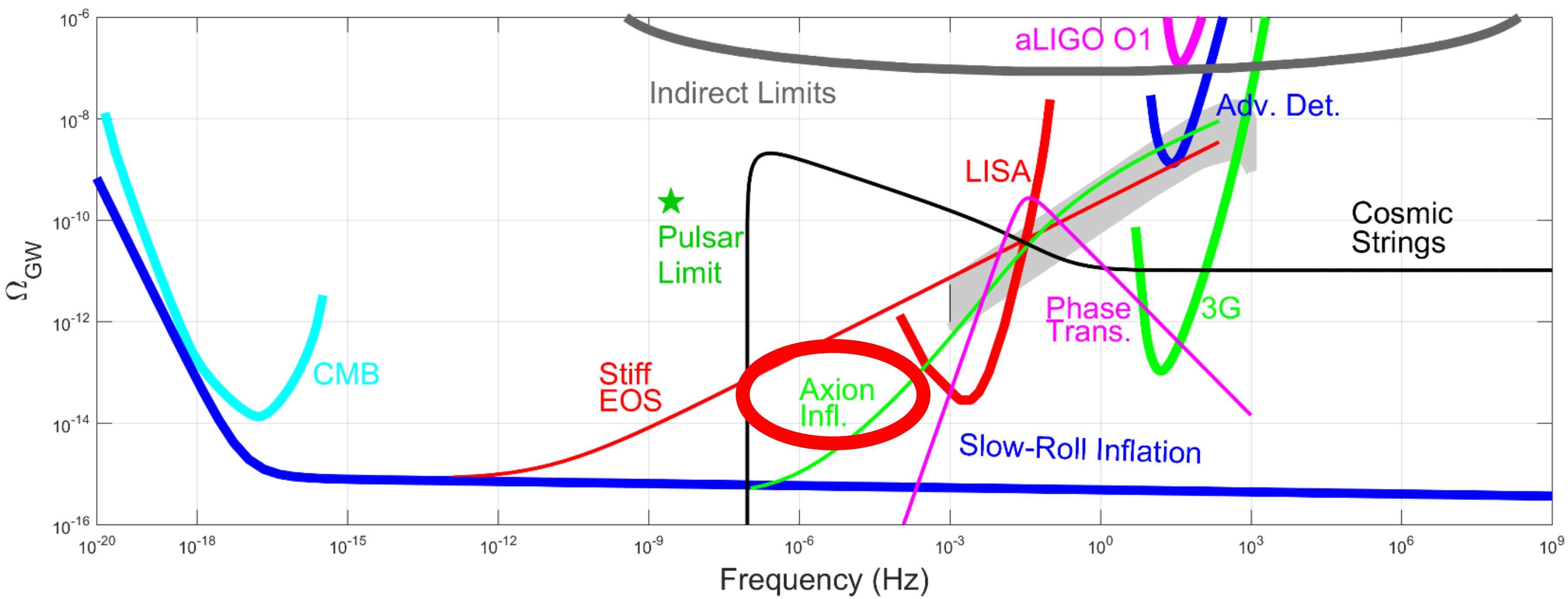
Stiff EOS Phase

- Test a potential new phase in the evolution of the universe.
  - After inflation, before radiation domination.
  - Stiff EOS, w > 1/3.
- Could have a detectable boost at high frequencies.
- No other way to test for presence of such phases.



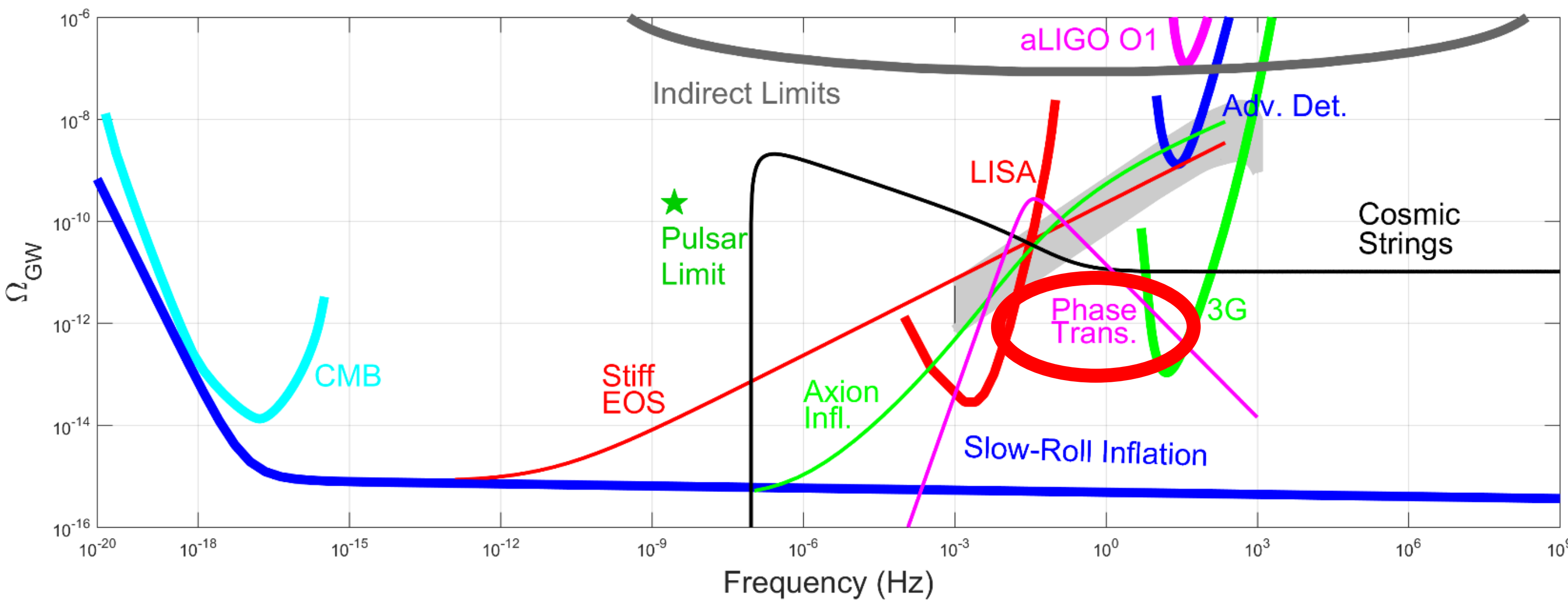
Inflation and Gauge Fields

- Test presence of particle production or symmetries in inflation.
- Example: axion inflation with coupling to a gauge field.
  - Boost at high frequencies.
  - Non-Gaussian.
  - Polarized!



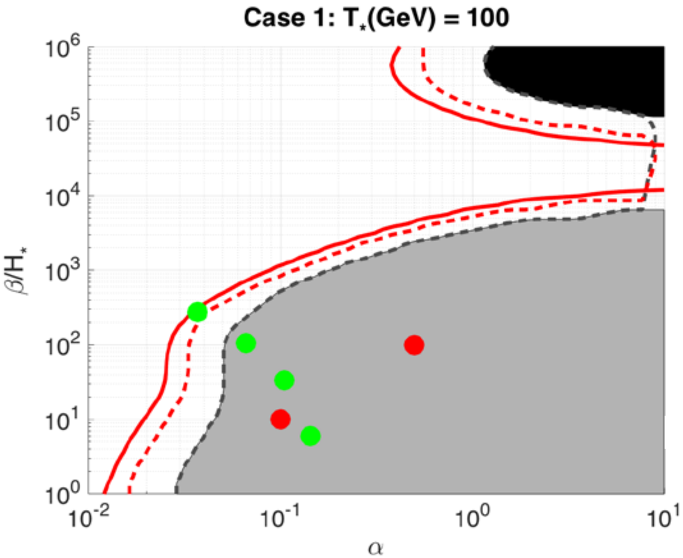
Phase Transitions

- First-order phase transition, results in expanding bubbles of the new vacuum.
- Several mechanisms for GW production:
  - Bubble wall collisions.
  - Sound shock waves propagating through plasma.
  - Magnetohydrodynamic turbulence.

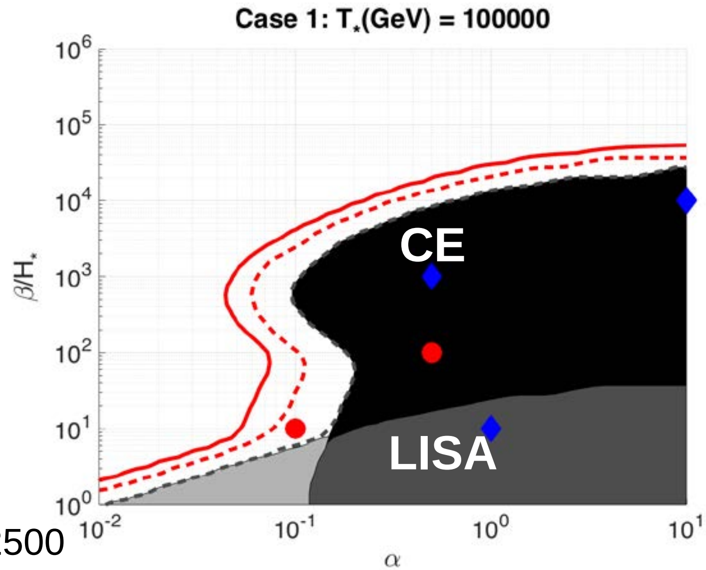


Phase Transitions

- Peak of the spectrum depends on the energy scale of the phase transition.
- Electroweak transition ~ 1 TeV, peaks in the LISA band.
  - Not first order, unless there is new physics.
  - Spectrum is broad and can be accessed by 3G detectors.
- Higher energy transitions would peak in 3G band.
- Complementarity with LISA!



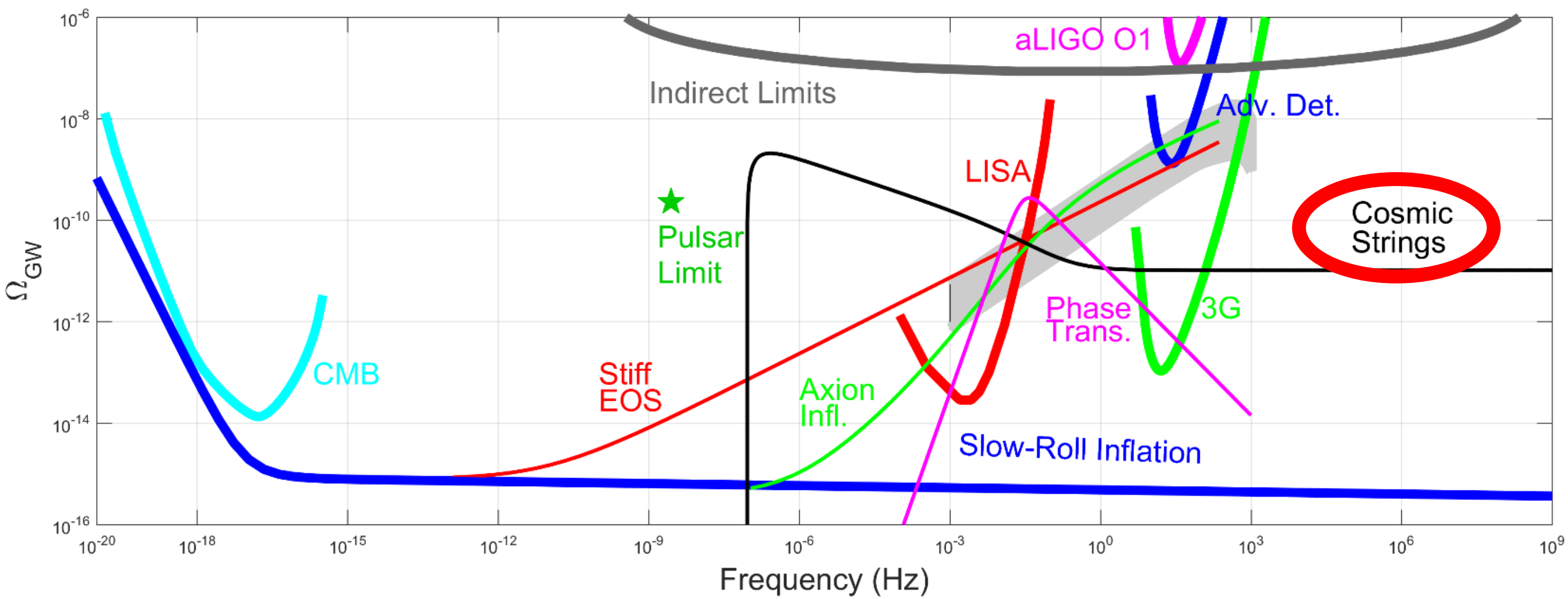
Example: non-runaway bubbles: Bubbles propagate through plasma, speed << c



Fitz Axen et al., arxiv:1806.02500

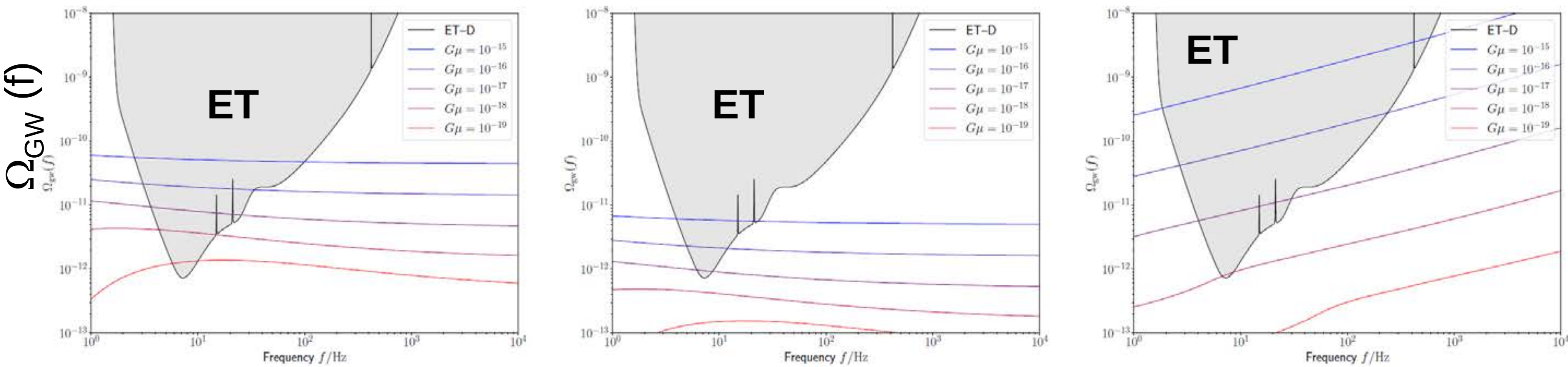
Cosmic Strings

- Topological defects created in phase transitions.
  - Could be fundamental too (string theory).
- GWs emitted in a variety of processes.
- Dominant contributions are from cusps and kinks.
  - Individual bursts, or integrated across the cosmic strings network to form a stochastic background.



Cosmic Strings

- Several models are considered in the literature, based on different assumptions or simulations of the cosmic string network.
- In all models, strong constraints can be made on the string tension (Gμ).
- May also result in small spatial anisotropies.

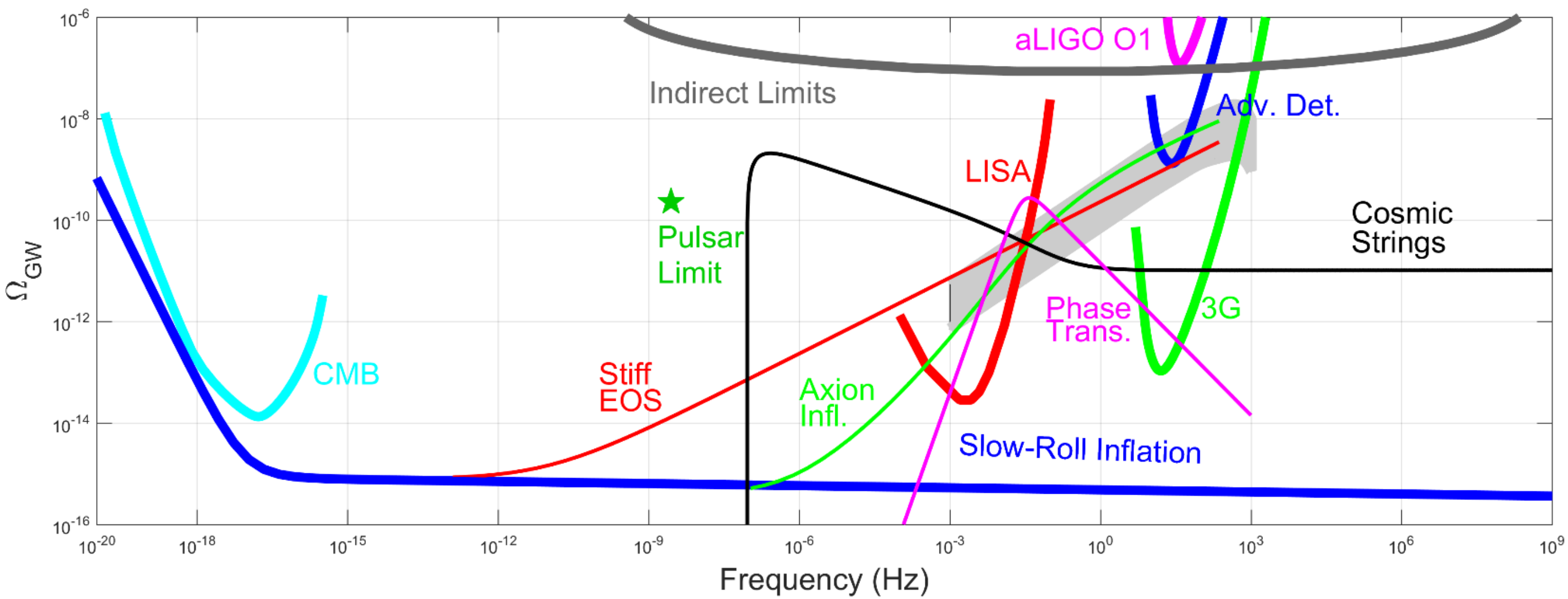


Frequency (Hz)

A. Jenkins and M. Sakellariadou
Phys. Rev. D 98, 063509 (2018)

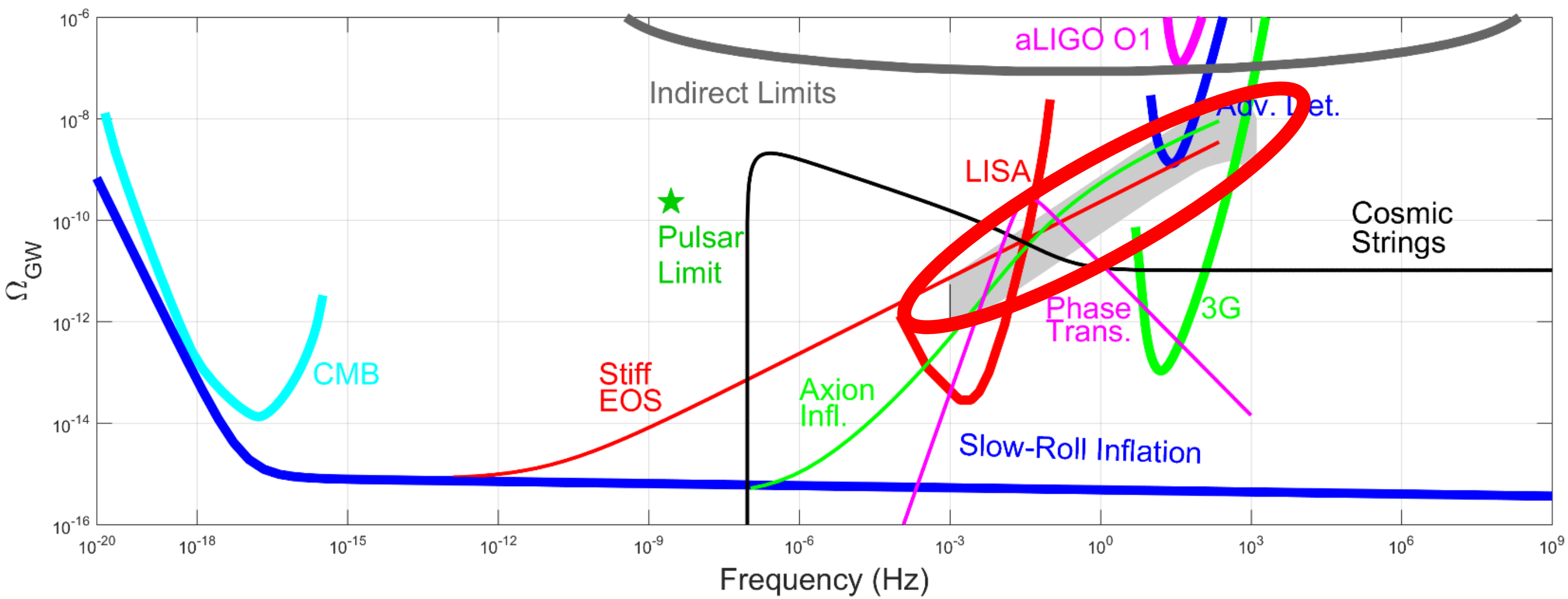
LISA + 3G Interplay

- Note that many cosmological models cross both LISA and 3G frequency bands.
  - Different frequency and angular spectra, even polarization!
- Offers the possibility of distinguishing among different models.
  - Estimate the SGWB energy budget!



CBC Foregrounds

- BBH, BNS, and BHNS binaries across the universe combine to form a SGWB foreground.
  - Much stronger than most cosmological models.
- Currently large uncertainties:
  - Poisson errors due to small statistics.
  - Stellar vs primordial origin etc…



CBC Subtraction

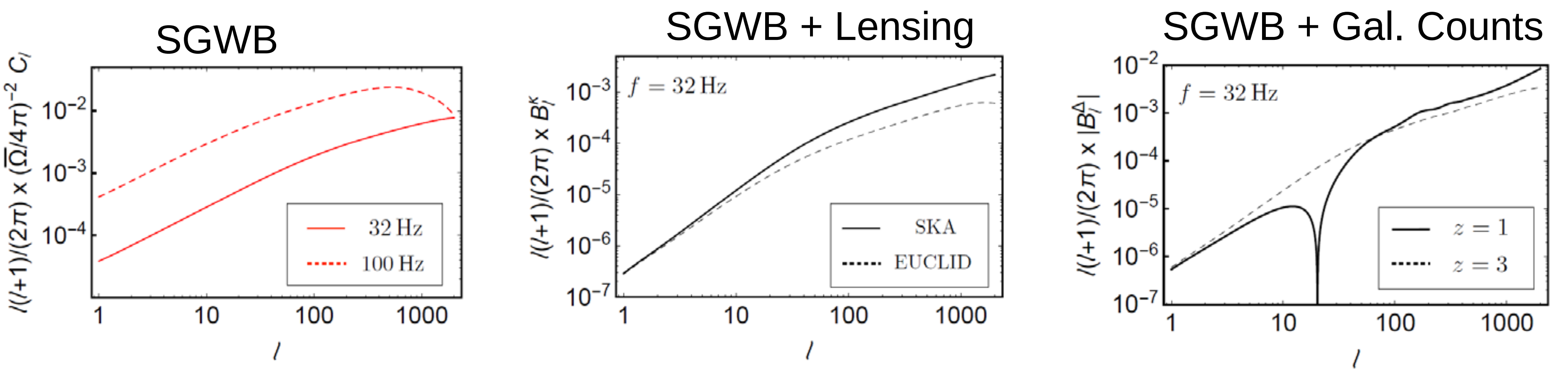
- Individually detected CBC's can be subtracted.
  - How well can this be done?
- Several approaches under way, simulations being pursued.
- Time-domain subtraction:
  - Measure CBC parameters, compute waveform, subtract in time-domain data.
  - Residuals due to detector noise.
    - Projections in the space of templates to minimize residuals.
- Time-Frequency domain subtraction:
  - Compute spectrograms, notch chirps for detected waveforms.
  - Widen the notch to account for detector noise, as needed.
    - Price: loss in sensitivity due to removed data.
- The Bayesian Search:
  - Simultaneously estimate all CBC's *and* the cosmological SGWB.

Other Astrophysical Foregrounds

- Other astrophysical processes could also give rise to astrophysical SGWB.
  - Stellar core collapse events to neutron stars or black holes.
  - Distortions or instabilities in rotating neutron stars (eg magnetars).
- Significant uncertainties exist in these models.
  - E.g. equation of state in NS determines its deformability.
- If sufficiently strong, these signals could probe the NS EOS, or provide information on the mechanism of stellar core collapse.
- But they could also be subdominant to other (eg cosmological) models.
  - Tend to peak at high frequencies, ~1 kHz, with a steep spectrum.

SGWB-EM Correlations

- If SGWB is dominated by CBC's, there should be a spatial correlation between the SGWB and the large-scale structure.
- Could use different proxies for the large-scale structure:
  - Galaxy counts.
  - Gravitational lensing.
- First computation of these cross-spectra were recently performed.
- Requires correlating SGWB with EM observational (survey) data.



Cusin et al., Phys. Rev. Lett. 120, 231101 (2018)

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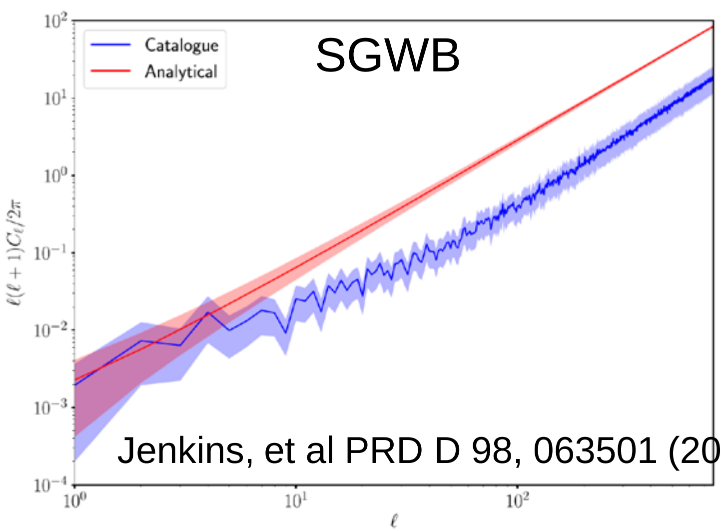
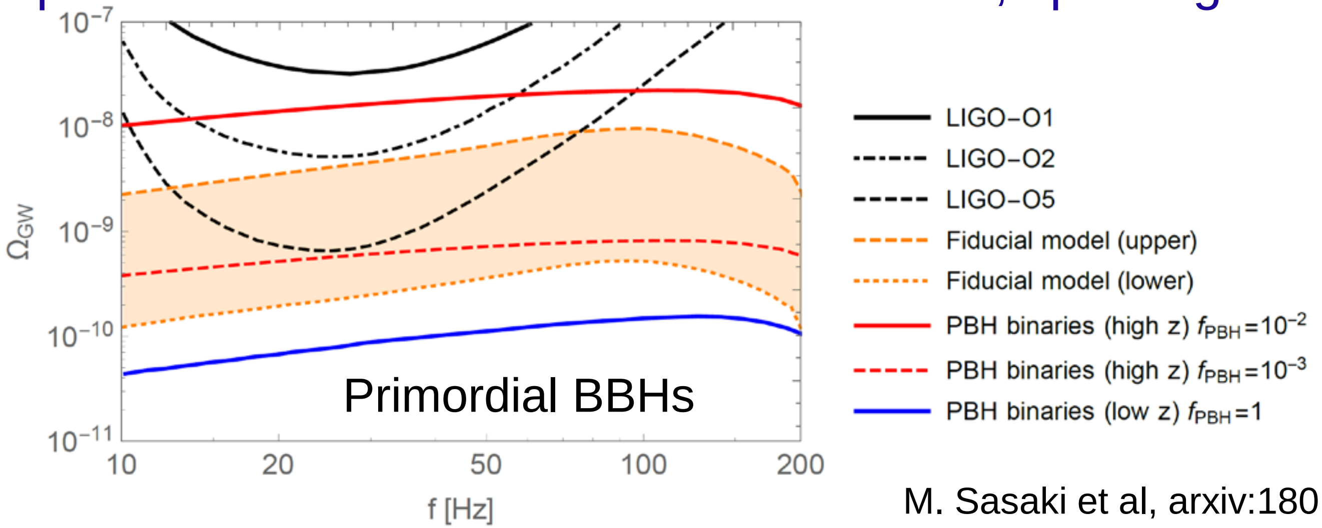


Jenkins, et al PRD D 98, 063501 (2018)

- Multiple approaches exist in the literature.
- Need to compare them and understand systematics.

GWs and Dark Matter

- Numerous Dark Matter candidates have been proposed.
  - Some may leave observable signatures in the SGWB.
- Primordial black holes, 2 mechanisms for binary production:
  - Different redshift distribution of primordial BBH's could result in a smaller SGWB as compared to the stellar origin case.
- Dark Photon: coherent oscillation of a U(1) gauge field, producing oscillating force on U(1) charged objects.
- Ultra-light bosons, including QCD axions.
  - Super-radiance: Cloud of boson around BH, spinning it down.



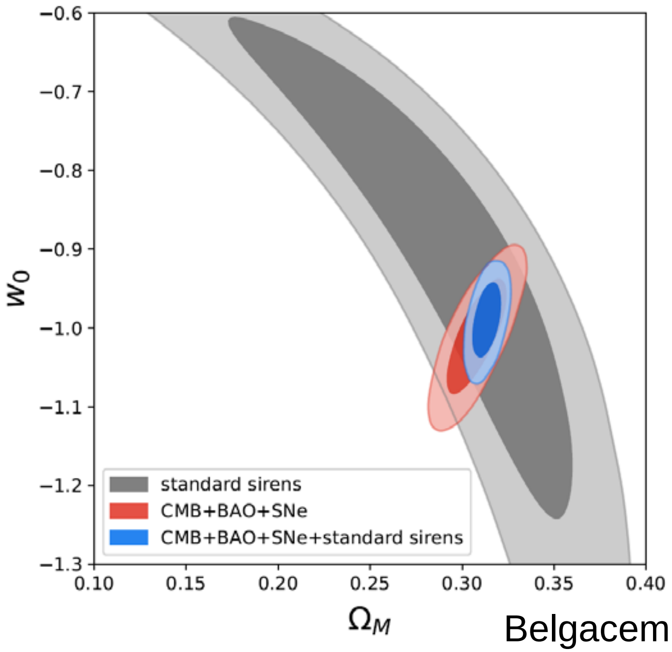
M. Sasaki et al, arxiv:1801.05235

GW and Dark Energy

- Use standard sirens to probe luminosity distance vs redshift.

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}}$$

- Low redshifts, $d_L(z) = H_0^{-1} z$, so measure the Hubble parameter.
- 3G detectors will measure CBC up to z~8, so can probe Dark Energy and Dark Matter.
- Common parametrization of the DE equation of state:



$$w_{\rm DE}(a) = w_0 + (1-a) w_a$$

- Assume 10^3 BNS standard sirens at ET, with EM counterparts.
- Can lead to significant improvements on estimates of cosmological parameters, relative to present CMB+BAO+SNe.

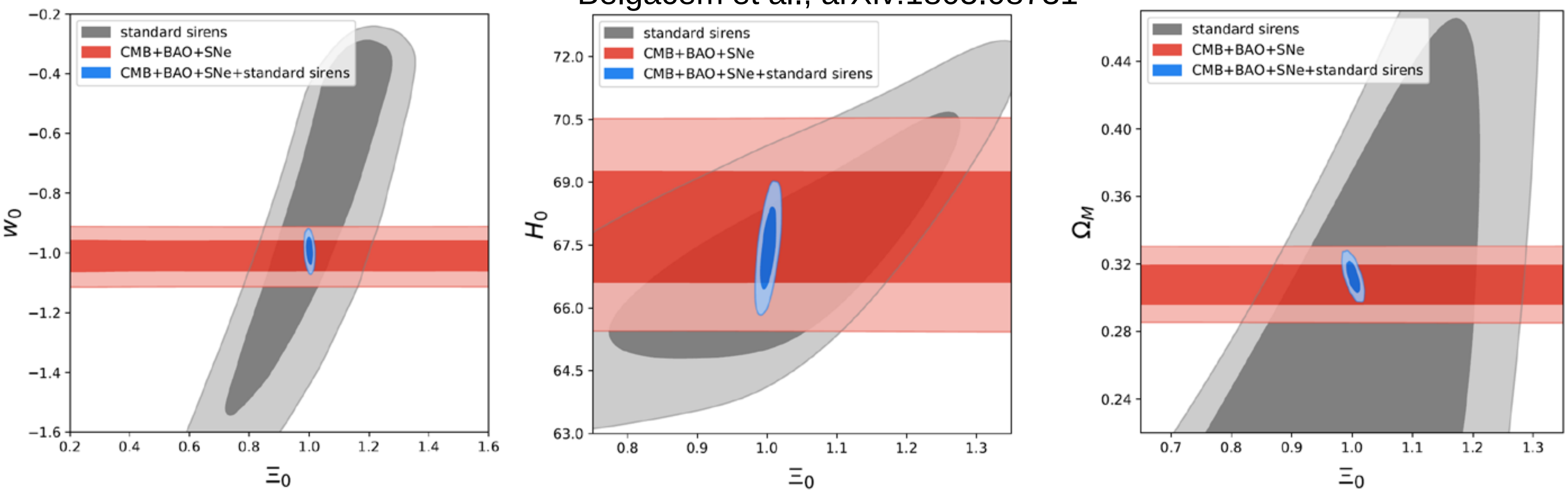
Belgacem et al., arXiv:1805.08731

Modified GW Propagation

- Modified gravity theories lead to modified propagation of GWs.
  - Extra dimensions, Horndeski class of theories (Brans-Dicke), non-local modifications of gravity.
- GW luminosity distance is modified, relative to the EM luminosity distance.
- *Unique probe of the DE sector, that cannot be tested with EM observations.*
- Even ~200 BNS with EM counterparts is enough to probe interesting models.

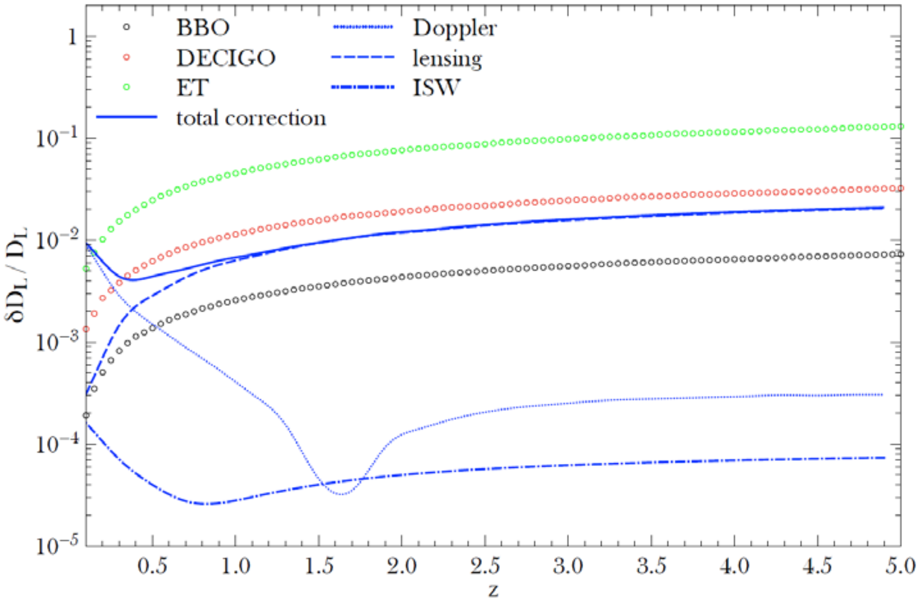
$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

Belgacem et al., arXiv:1805.08731



Cosmological Perturbations and GW Luminosity Distance

- Variety of effects on the GW luminosity distance:
  - Integrated Sachs-Wolfe effect
  - Peculiar velocities
  - Gravitational lensing
- Typically ~1% effects, may be measurable by 3G.



Bertacca et al., arXiv:1702.01750

Strongly Lensed Systems

- Analogous to the Refsdal supernova.
  - Lensed image reappeared, at the predicted time and location.
- Search for echoes of GW signals.
- Expect ET to detect 50-100 strongly lensed inspirals per year, dominated by BBHs.
- Joint GW-EM observation would facilitate source identification and estimate lensing time-delays better than was done in the past.
- Applications:
  - Test modified theories of gravity.
  - Constrain cosmology parameters independently of the standard siren approach.
  - Probe galaxy structure: mass density slope and its evolution with redshift, dark matter substructures etc.

Some Questions

- Are we missing anything important?
- Do we need to prioritize? If so, how?
  - Do we remove some models/sources? Which ones?
  - Note that the section is already too long…
- Should we emphasize the 3G-LISA connection?
  - Much science could be done using the two!
  - Arguments to pursue both types of detectors.
- Do we need to be more quantitative about CBC subtraction?
  - BNS detectability may well limit the 3G SGWB sensitivity.
- Do we need to emphasize reaching the standard inflationary models, $\Omega_{GW} \sim 3 \times 10^{-16}$?
  - Will not reach it with 3G, but maybe with 3G+.
  - Should the facility be designed with a possible upgrade in mind?