Early Universe Gravitational Waves and Fundamental Physics

Vuk Mandic
University of Minnesota

February 3, 2022

Contributors

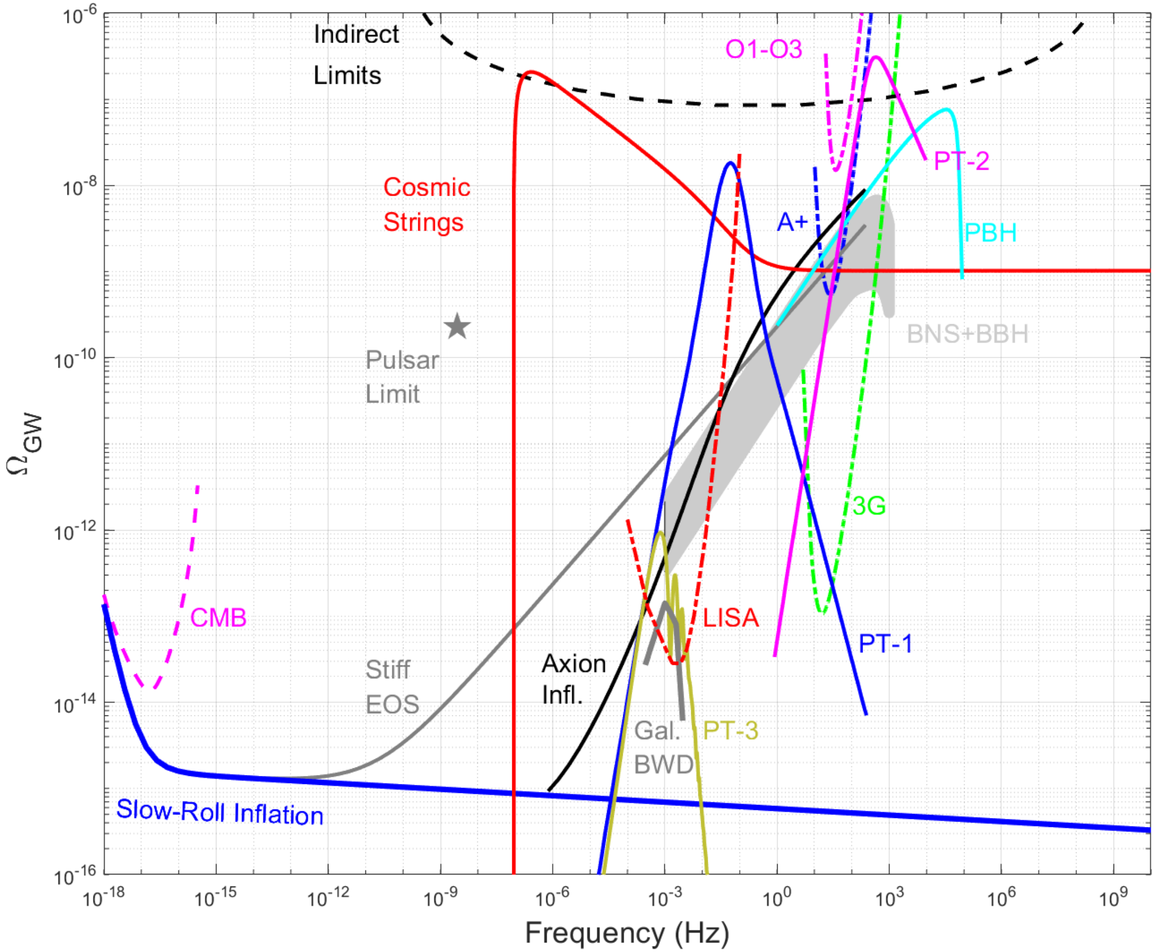
Haipeng An, Robert Caldwell, Chiara Caprini, Marcela Carena, Sebastien Clesse, Jim Cline, Nathaniel Craig, Yanou Cui, Giulia Cusin, Noam Dan, Barmak Es Haghi, Archisman Ghosh, Huaike Guo, Anson Hook, Alexander Jenkins, Ryusuke Jinno, Ashutosh Kotwal, Jonathan Kozaczuk, Benoit Laurent, Da Liu, Kunfeng Lyu, Vuk Mandic, Alberto Mariotti, Mario Martinez, Andrew Miller, Jose Miguel No Redondo, Nicholas Radulesco, Michael Ramsey-Musolf, Diego Redigolo, Mairi Sakellariadou, Claudia Scarlata, Alexandre Sevrin, Ashish Sharma, Xavier Siemens, Kuver Sinha, Tristan Smith, Lorenzo Sorbo, Daniele Steer, Raman Sundrum, Carlos Tamarit, LianTao Wang, David Weir, Graham White, Kepan Xie, Fengwei Yang, Yue Zhao, Siyi Zhou

Paper Leads
Section Leads

Motivation

- Gravitational waves are likely emitted in the early universe, at energies beyond those accessible to accelerators.
  - Stochastic GW background: frequency spectrum, polarization, angular power spectrum
- Connects with open questions in Cosmology:
  - Inflation and early phases (before BBN)
  - Dark Matter
- Connects with fundamental questions in particle physics:
  - Phase transitions, EW (and other) symmetry breaking, topological defects.
- Complementarity with accelerator-based experiments
- GW-EM anisotropy correlations

Landscape



Indirect Limits
O1-O3
PT-2
Cosmic Strings
A+
PBH
BNS+BBH
Pulsar Limit
3G
CMB
LISA
PT-1
Stiff EOS
Axion Infl.
Gal. BWD
PT-3
Slow-Roll Inflation
Ω_{GW}
Frequency (Hz)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}

Early Phases

- Inflation:
  - Amplification of vacuum fluctuations at transitions to RD and MD.
  - Weak, scale invariant GW spectrum.
  - Alternatives: pre-big-bang scenarios, ekpyrotic models…
- Knowledge of the pre-BBN universe is limited, SGWB serves as a *cosmic witness* recording evolution of the EoS in the universe.
  - Temperatures between 10^{16} GeV and 1 MeV are effectively unprobed.
  - Additional phases are possible, with non-standard EoS. Could lead to blue or red tilts in GW spectrum.
  - Interplay of evolution and phase transitions: PT GW spectrum depends on evolution when modes re-enter the horizon.
  - Inflationary reheating and preheating – a variety of scenarios, but likely out of reach.

Phase Transitions

- First order PTs produce stochastic GWs through multiple mechanisms:
  - Bubble collisions, sound shock waves, magnetohydrodynamic turbulence.
- GW spectrum is sensitive to the effective potential, which is related to the symmetry breaking process and the particle content.
- EWPT in the Standard Model is a smooth cross-over. But new physics near TeV scale could change this into a FOPT.
- Other examples: QCD, SUSY, axions, B-L symmetry breaking…
  - Can happen at many energies, corresponding to peaks at different GW frequencies.
- Different energy scales are accessible to different detectors (e.g. EWPT @ LISA, higher energies at terrestrial GW detectors).
- Much theoretical work also remains to be done: perturbative and numerical approaches, bubble nucleation rate, bubble wall velocity, sound wave modeling/propagation…

Topological Defects

- Formed at symmetry breaking transitions.
  - Domain walls, textures, cosmic strings.
  - Considering all possible symmetry breaking patterns from GUT to SM, cosmic string formation is unavoidable.
- Local cosmic strings: GW production by string loops.
  - Depends on spectrum per loop, and the number of loops.
- Global/axion strings and domain walls.
  - New development, potentially detectable, logarithmically declining spectrum.
- GW from superstrings, potential to probe string theory.
- Non-standard cosmology: spanning wide frequency range.
  - Probe new EoS in early universe, sensitive to g_* (and new particle species)…
- GW spectrum amplitude grows with symmetry breaking scale, potentially sensitive to new particle physics – e.g. associated with PQ symmetry breaking or dark matter.
- Accessible to NANOGrav, LISA, terrestrial detectors.
  - Across wide frequency range, complementary observations.

Dark Matter

- DM problem still open, with extremely broad range of candidates: 10^{-22} eV – M_{solar} .
  - GWs can probe much of this range
- Primordial BHs:
  - Subsolar BH mergers: terrestrial detectors.
  - BH in the NS mass range and low mass gap: MMA.
  - High redshift BBH: CE/ET.
  - Statistical methods: PBH vs stellar BH population differences (spin, redshift etc)
  - SGWB spectral shape differs for PBH vs stellar BHs.
- Dark Photon DM: push interferometer mirrors in quasi-monochromatic way at frequency near photon mass (LIGO~10^{-13} eV).
- Dilaton: ultralight, appears in extra dimension models.
  - Changes fundamental constants, affects mirror size and refraction index. GEO600 already used to search.
- Axions:
  - Black hole superradiance: BH spin measurements, GW from superradiance cloud.
  - Sourced by NS, changes BNS waveform: GW170817 constrained axion mass below 10^{11} eV.

Complementarity with Accelerometers

- PT at 100 GeV – 100 TeV is in 1 mHz – 1 Hz range: LISA, BBO, DECIGO.
- Also accessible to HL LHC, ILC, CLIC, FCC…
- New physics near TeV scale can make EW transition first-order.
  - New particle states
  - Deviations of the Higgs couplings to SM particles:
    - Higgs trilinear self-coupling: 5-10% measurement at FCC-hh, SppC…
    - Coupling to Z: 0.1% measurement at ILC, FCC-ee...
  - Combining with LISA, can explore large fractions of parameter space.
- Other PT:
  - SUSY particles could make EWPT first-order.
  - R-symmetry breaking can be first-order and yield SGWB.
  - Additional phase transitions possible, at different energy scales.

GW-EM Anisotropy Correlations

- Techniques for measuring SGWB anisotropy now exist: LIGO/Virgo, LISA, NANOGrav.
- Potential to correlate with EM anisotropies of different types.
- BBH SGWB correlation with galaxy catalog (visible matter) or with gravitational weak lensing (dark matter).
  - Potentially discern primordial vs stellar populations.
- PT SGWB may or may not be correlated with the CMB.
  - If PT happens after inflation, both SGWB and CMB should have signatures of the same primordial fluctuations and be correlated.
  - SGWB my have simpler angular spectrum (no Silk damping, BAO).
- Cosmic string SGWB may also be correlated with the CMB.

Conclusion

- All sections have mature drafts, expect completion by March 2.
  - Update the landscape plot, connect the section to it, reduce repetitions, improve flow.
- Significant theoretical work is needed: PT processes, topological defect production mechanisms…
- Experiments needed:
  - GW: Voyager, CE/ET, LISA, BBO, DECIGO, NANOGrav
  - Colliders: HL LHC, ILC, CLIC, FCC…
  - CMB: CMB-S4, LiteBIRD, CORE…
  - EM Surveys: EUCLID, SPHEREx, DESI, SKA…