Searching for the Stochastic Gravitational-Wave Background in Light of the Recent BICEP-2 Result

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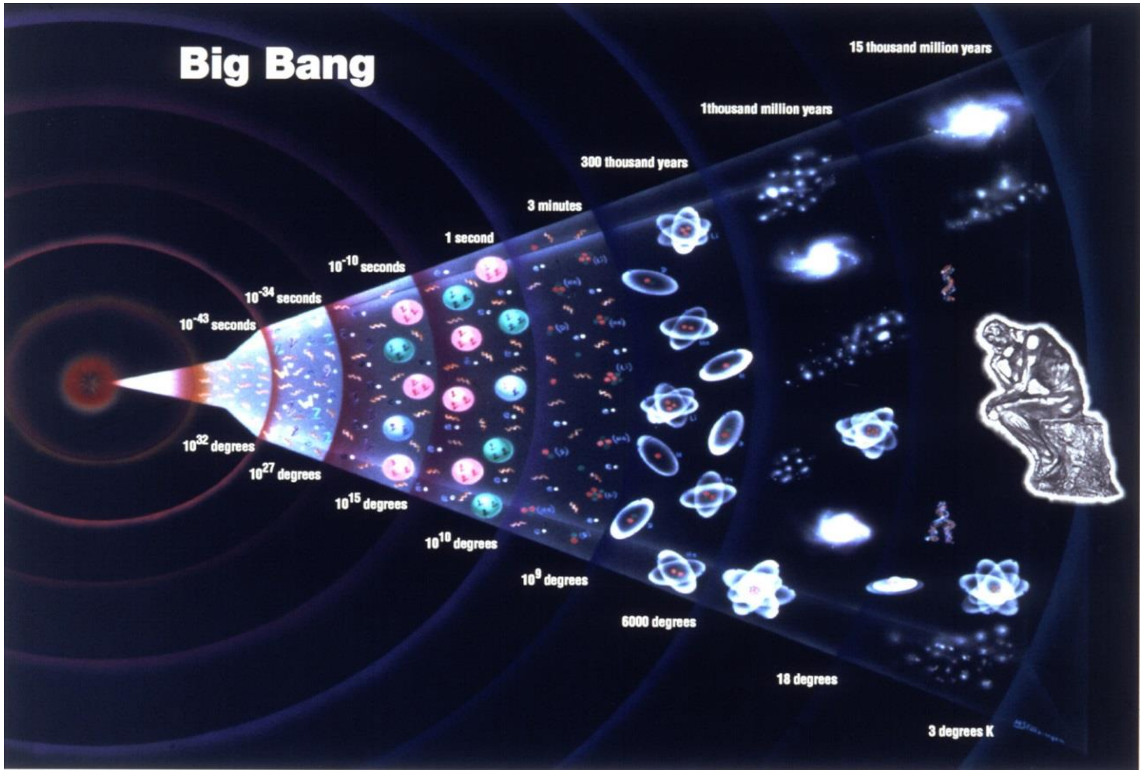
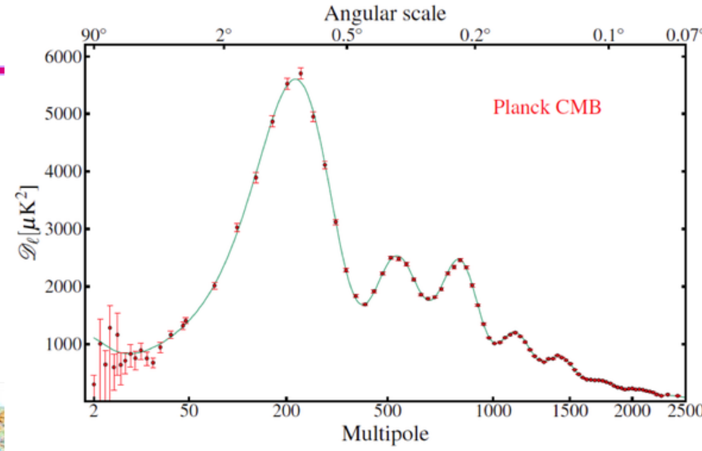
What is CMB?

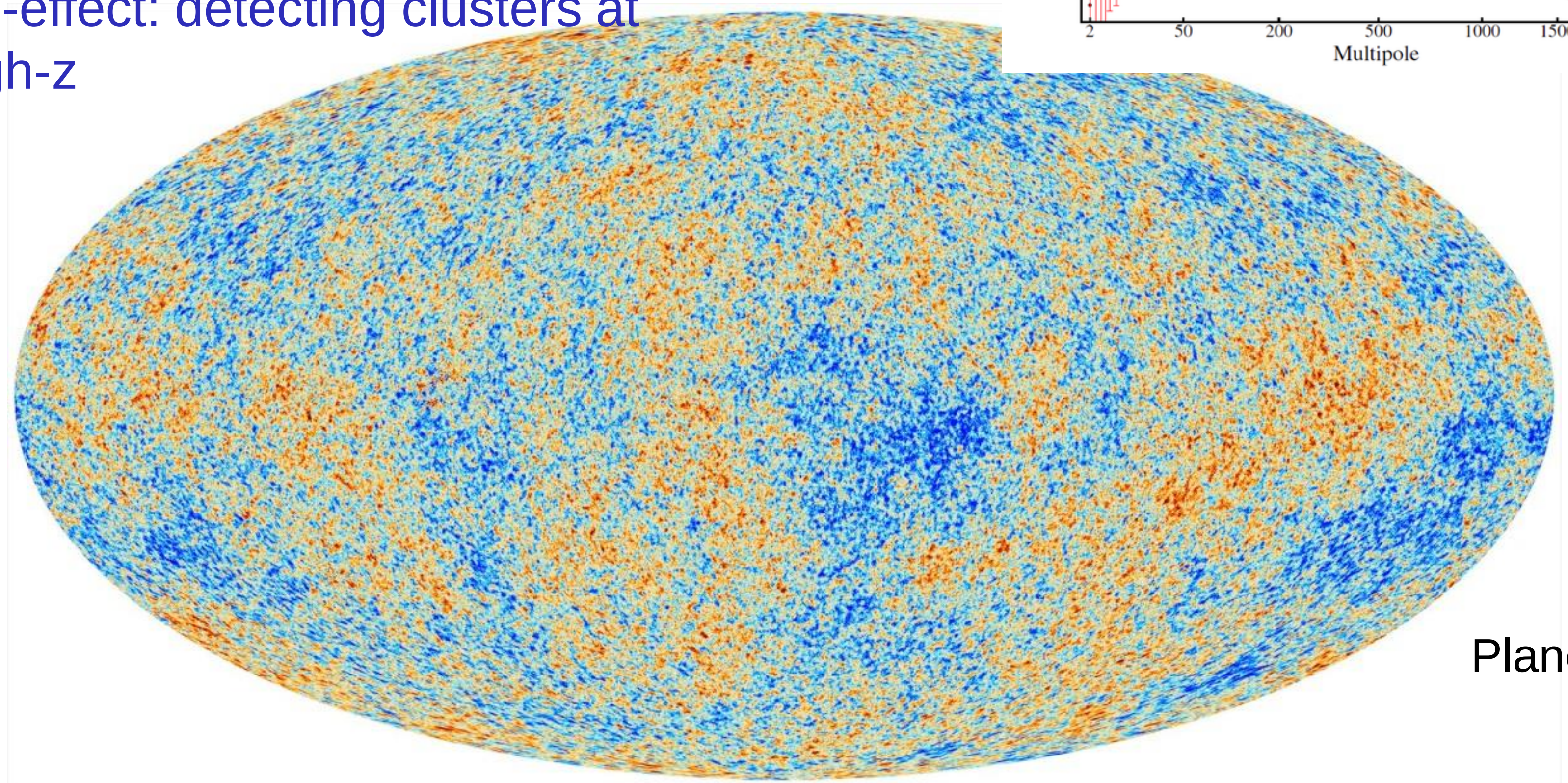
- About 380,000 years after big bang (redshift ~1100), photons decouple from protons/electrons.
  - Temperature falls well below 13.6 eV, photons cannot ionize hydrogen.
- Photons travel freely until today.
  - Temperature today is ~2.7K.
  - Remarkably uniform across the sky, fluctuations at the level of 10^{-5}.
- Measured by a series of experiments, at various angular scales.



CMB Anisotropy

- Remarkably rich measurements.
  - Geometry of the Universe.
  - Energy content of the Universe.
  - SZ-effect: detecting clusters at high-z

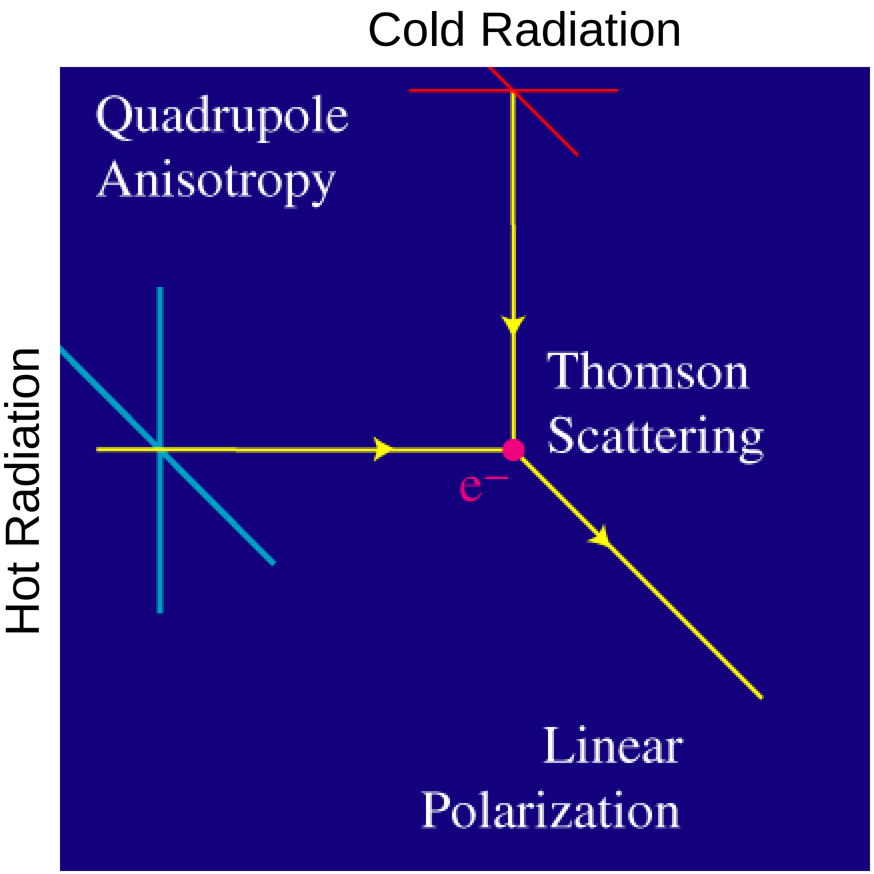




Planck

CMB Polarization

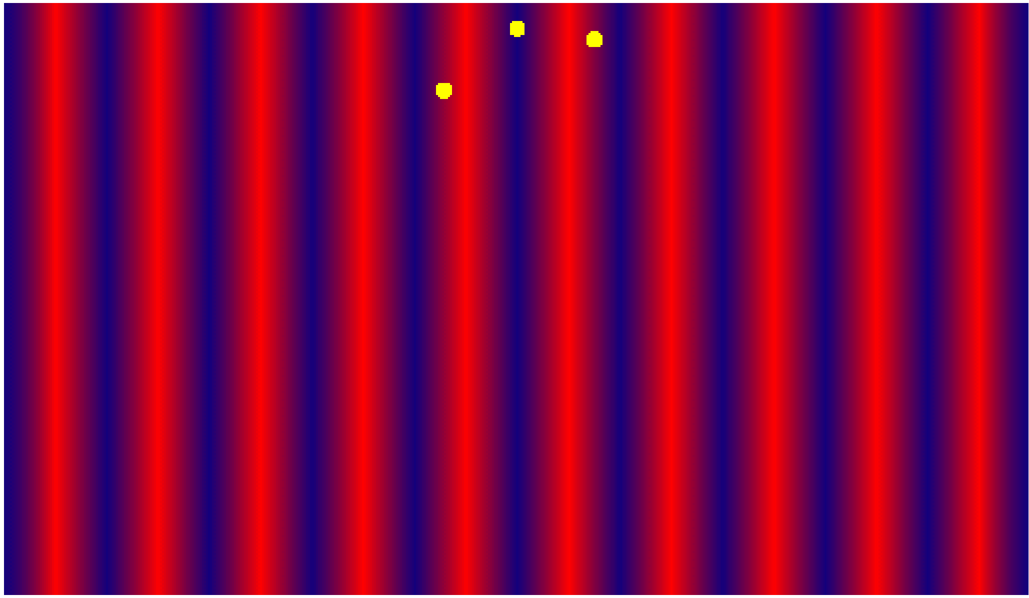
- Thomson scattering of EM radiation off of free electrons.
- If incident light on a free electron is isotropic, the resulting scattered photons will be unpolarized.
- If incident directions separated by 90 degrees had different intensities, net polarization in the scattered light results.
- Quadrupole anisotropy.



http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm

Quadrupole Anisotropy

- Temperature inhomogeneity: red/blue pattern.
- The resulting polarization direction depends on where the electron is.
- Polarization only after the plasma is optically thin AND there are still free electrons around.
  - Short time window, so only a small fraction of CMB is polarized.



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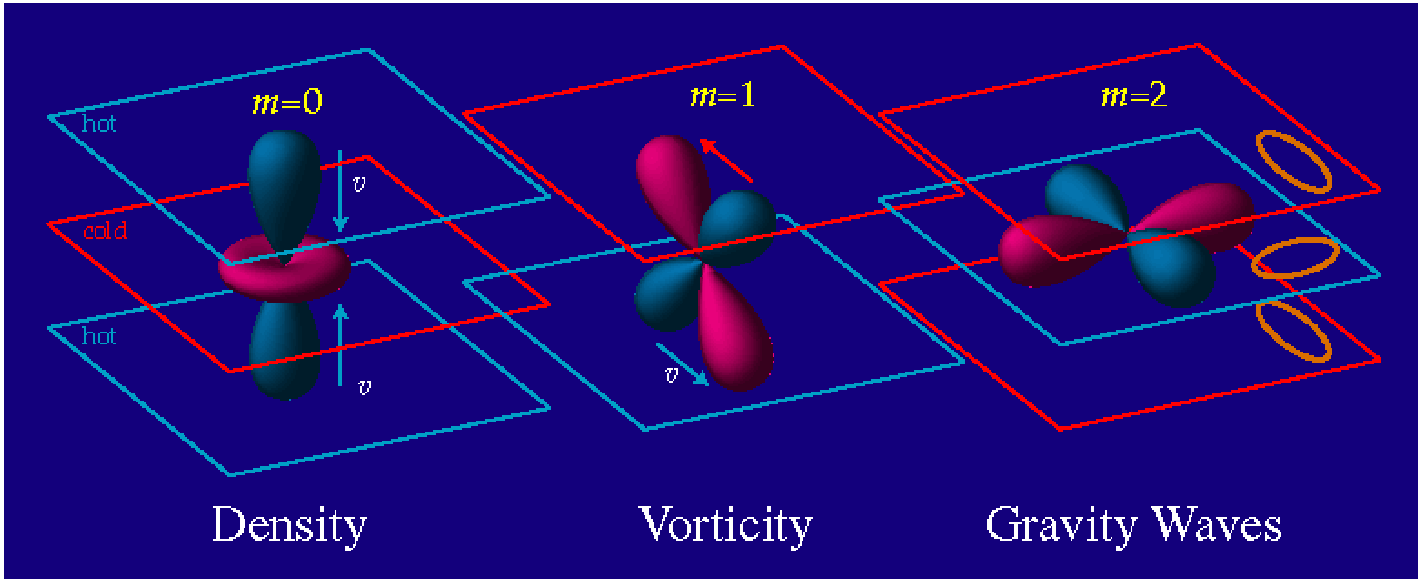
Sources of Quadrupole Anisotropy

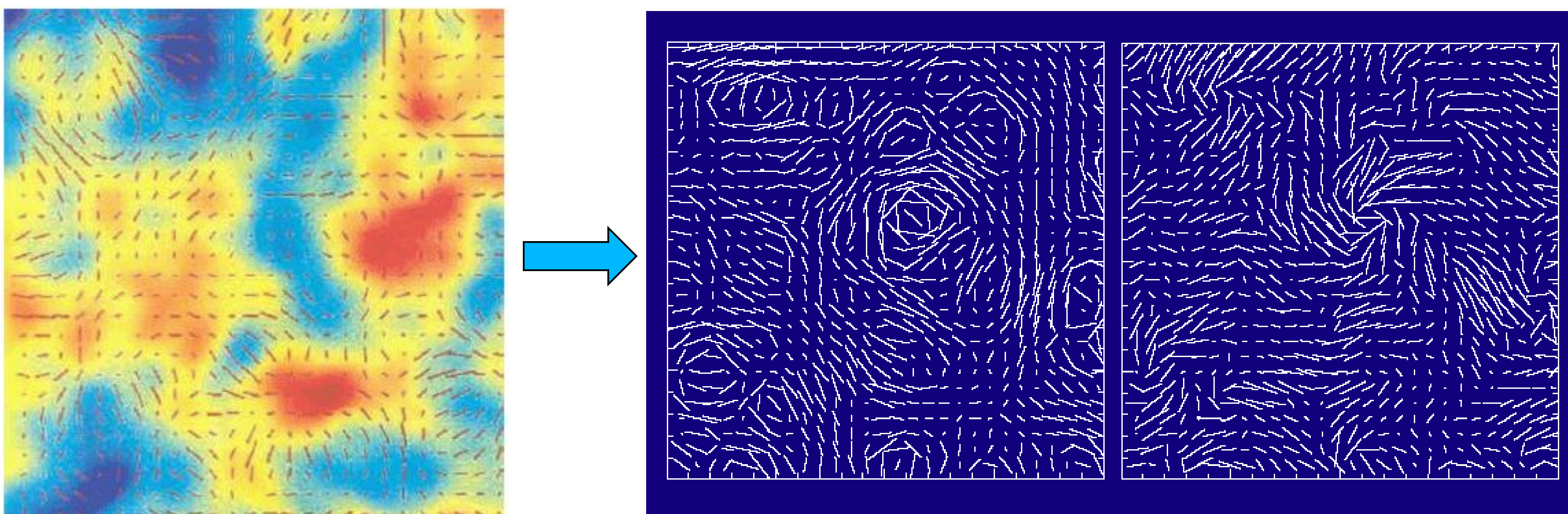
- Scalar: density fluctuations lead to plasma velocity fluctuations that red/blue shift the photons.
- Vector: vorticity in the plasma can also lead to Doppler shift of photons. Expected to be suppressed by inflation.
- Tensor: GWs cause stretching/shrinking of space, and therefore of photon wavelength.



E vs B Modes

- Similarly to EM field, can separate polarization into two components:
  - Curl-free, no handedness, like E-field.
    - Scalar and tensor sources.
  - Grad-free: with handedness, like B-field.
    - Only tensor sources.
- E-mode can be converted into B-mode with gravitational lensing, but only at small scales (high-*l*).

E-mode B-mode

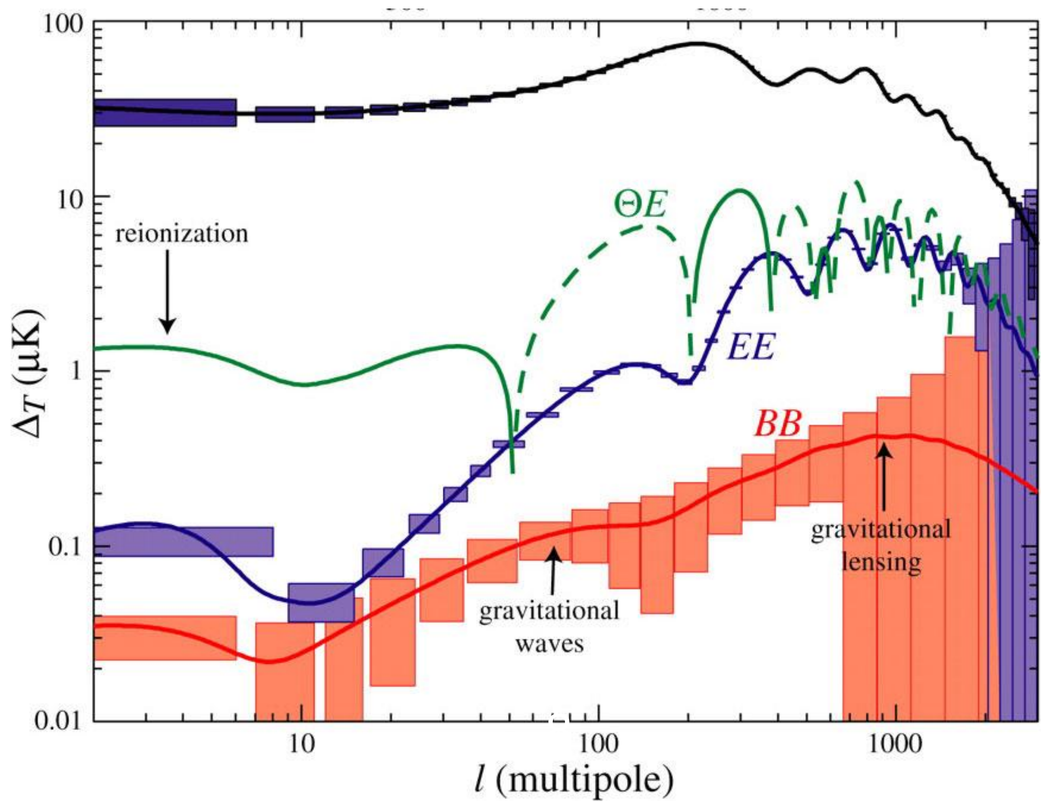


Expected CMB Spectra

- Cross-correlate temperature, E-mode, and B-mode between different directions on the sky.
  - Actually, between different spherical harmonics.
  - Similar to the anisotropic stochastic GW search.

- BB spectrum has a strong astrophysical foreground due to gravitational lensing (at small scales, large *l*'s).

$$
\begin{aligned}
\langle E^*_{\ell m} E_{\ell' m'} \rangle &= \delta_{\ell\ell'}\delta_{mm'} C_\ell^{EE} , \\
\langle B^*_{\ell m} B_{\ell' m'} \rangle &= \delta_{\ell\ell'}\delta_{mm'} C_\ell^{BB} , \\
\langle \Theta^*_{\ell m} E_{\ell' m'} \rangle &= \delta_{\ell\ell'}\delta_{mm'} C_\ell^{\Theta E} .
\end{aligned}
$$

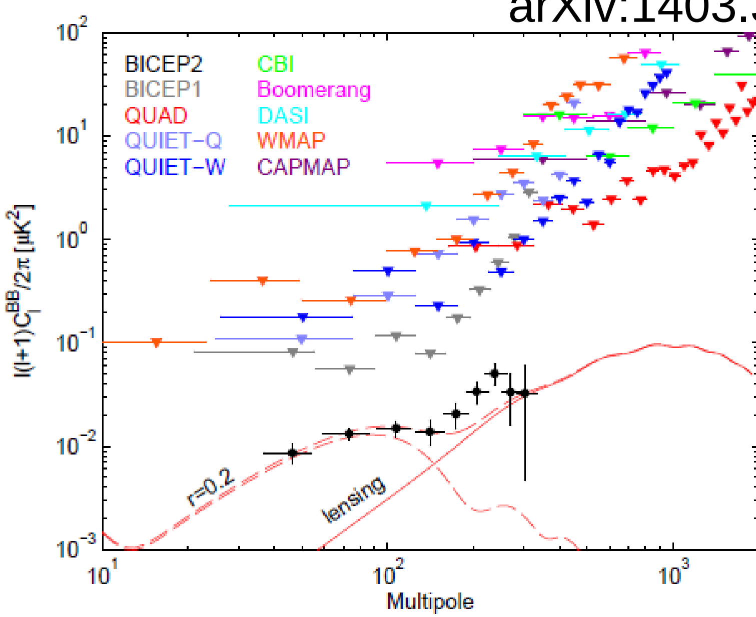


Past Measurements

- E-mode first measured in 2002 by DASI, confirmed by several experiments.
  - Nature 420, 772 (2002).
- First hint of B-mode at high-*l* by SPT:
  - Correlations with Herschel observations of high-redshift galaxies.
  - Phys. Rev. Lett. 111, 141301 (2013).
- POLARBEAR claims B-mode signal at small scales (high-*l*, due to grav. lensing) .
  - arXiv:1403.2369
- BICEP-2 claims detection of primordial B-mode signal at large scales (low-*l*).
  $r = 0.20 + 0.07 – 0.05$
  $r = 0$ excluded at 7σ.
- Scale of inflation: GUT scale!

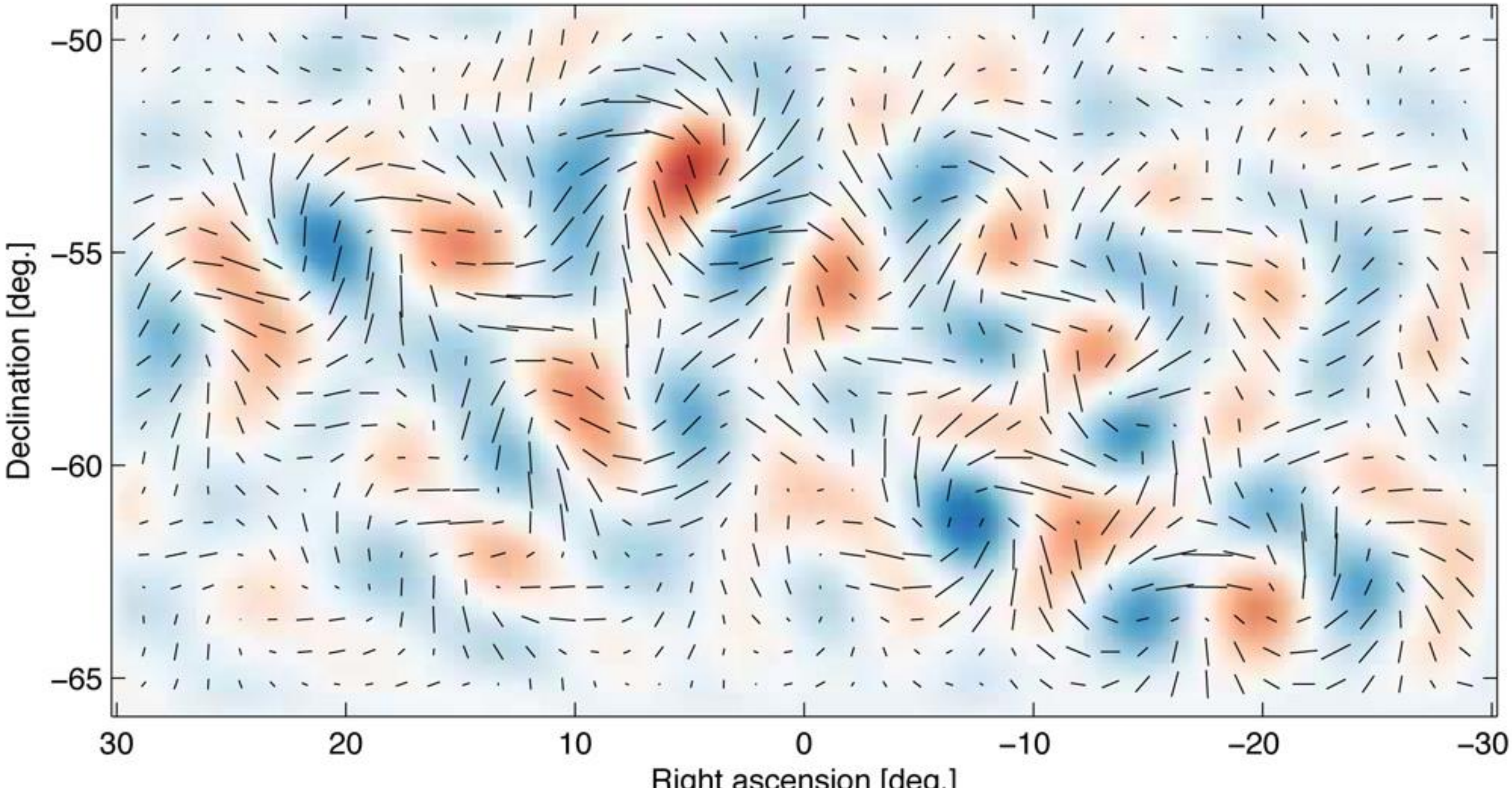
$$V_* = \frac{3\pi^2 A_s}{2} r M_{\rm pl}^4 = (1.94 \times 10^{16}\ \mathrm{GeV})^4 \frac{r_*}{0.12}$$

arXiv:1403.3985



BICEP-2 B-mode Polarization Map

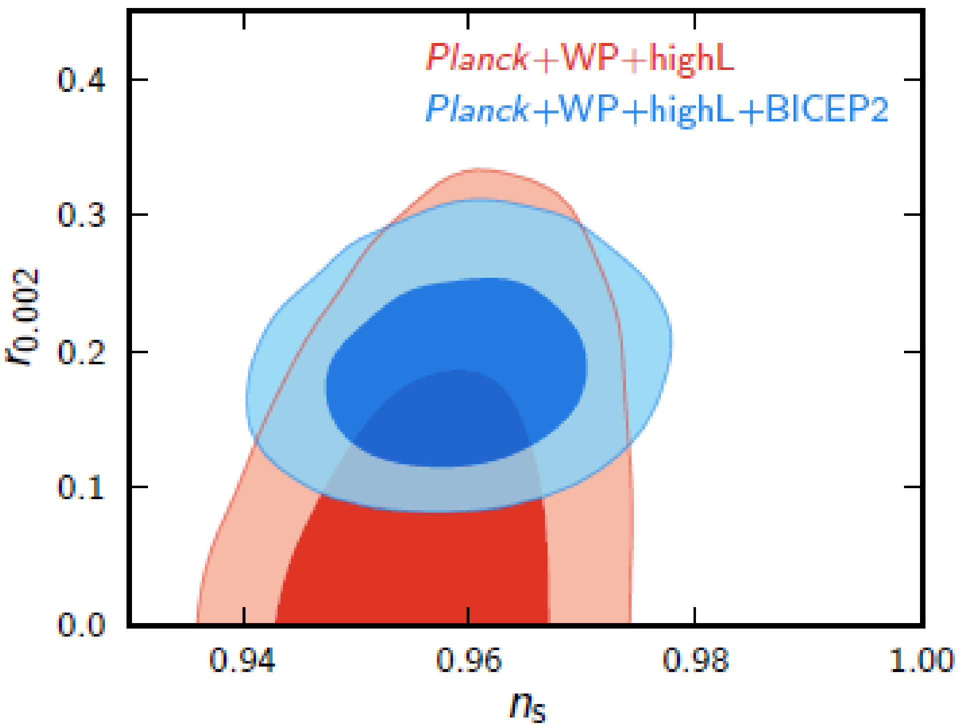
arXiv:1403.3985



Tension with Past Results?

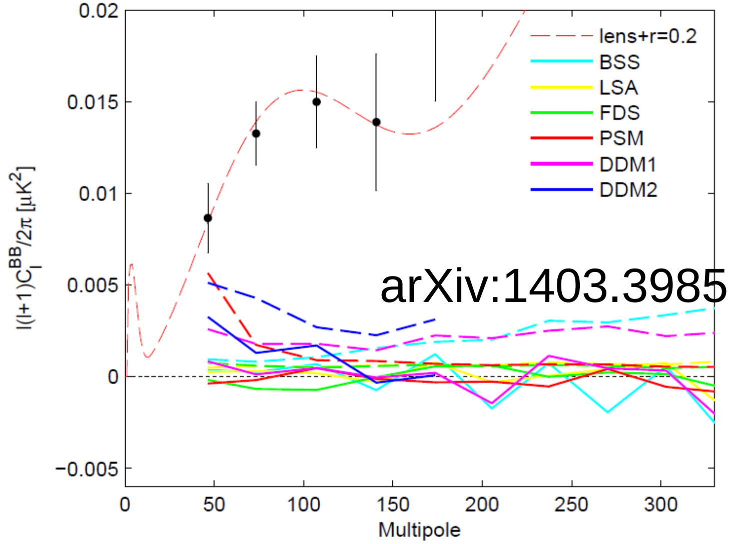
- WMAP/Planck/SPT: r < 0.11
  - So, some tension exists with past results.
- Subtracting dust models also reduces the BICEP *r* value (to about 0.16).
- Also, past measurements did not allow for running of the spectral index.
  - Running relaxes the past upper limits.

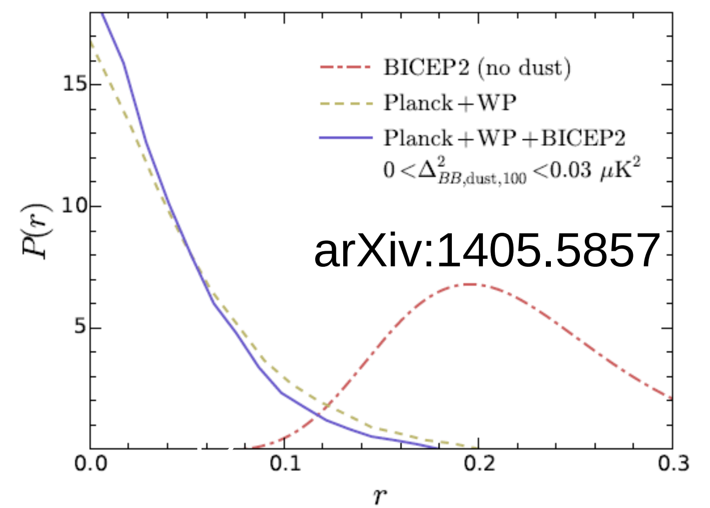
arXiv:1403.3985



Criticism

- Largest uncertainty: galactic dust foreground.
- BICEP2:
  - Considered 6 models, consistent with what was known in March 2014.
  - Minor effect on the result.
- Planck:
  - Recently published new dust polarization maps.
  - Suggests significantly larger (~3x) dust polarization spectrum.
  - But, does not include the BICEP2 region, due to remaining uncertainties.
- Mortonson & Seljak, arXiv:1405.5857:
  - More conservative analysis, assume little prior knowledge on the dust.
  - Dust models preferred over gravitational-waves.





Relating to SGWB

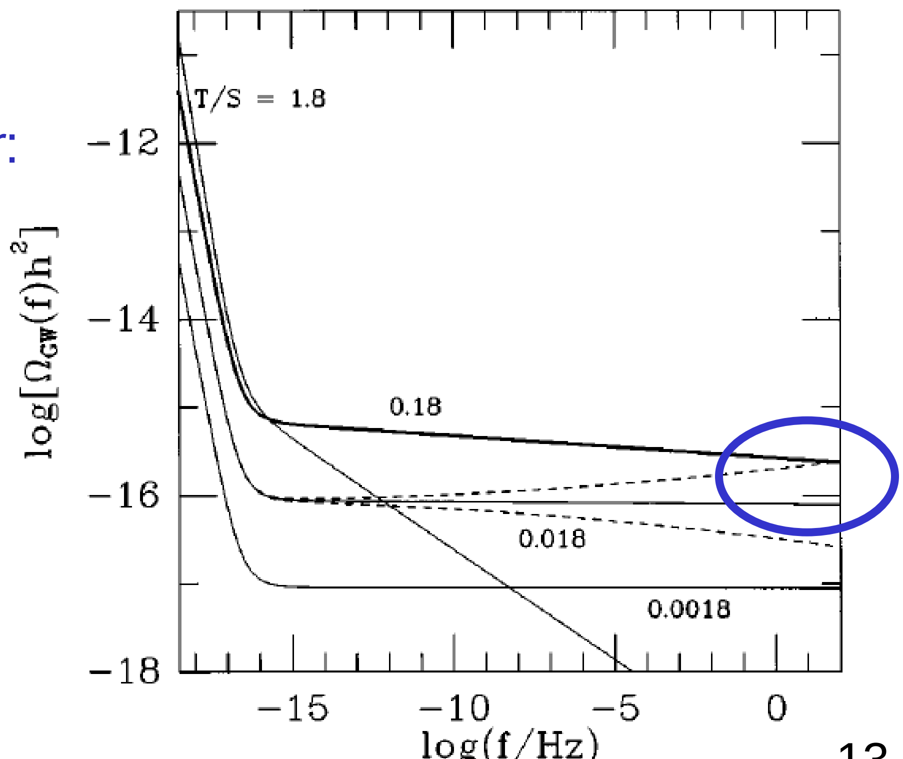
- Past constraint based on temperature anisotropy:

$$\Omega_{GW} = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d(\ln f)} \sim \left(\frac{H_0}{f}\right)^2 \left(\frac{\delta T}{T}\right)^2 < 10^{-10}\left(\frac{H_0}{f}\right)^2$$

(3×10^{-18} Hz < f < 10^{-16} Hz)

  - At 10^{-16} Hz, $\Omega_{GW} < 10^{-14}$

Turner, PRD 55, R435 (1997)



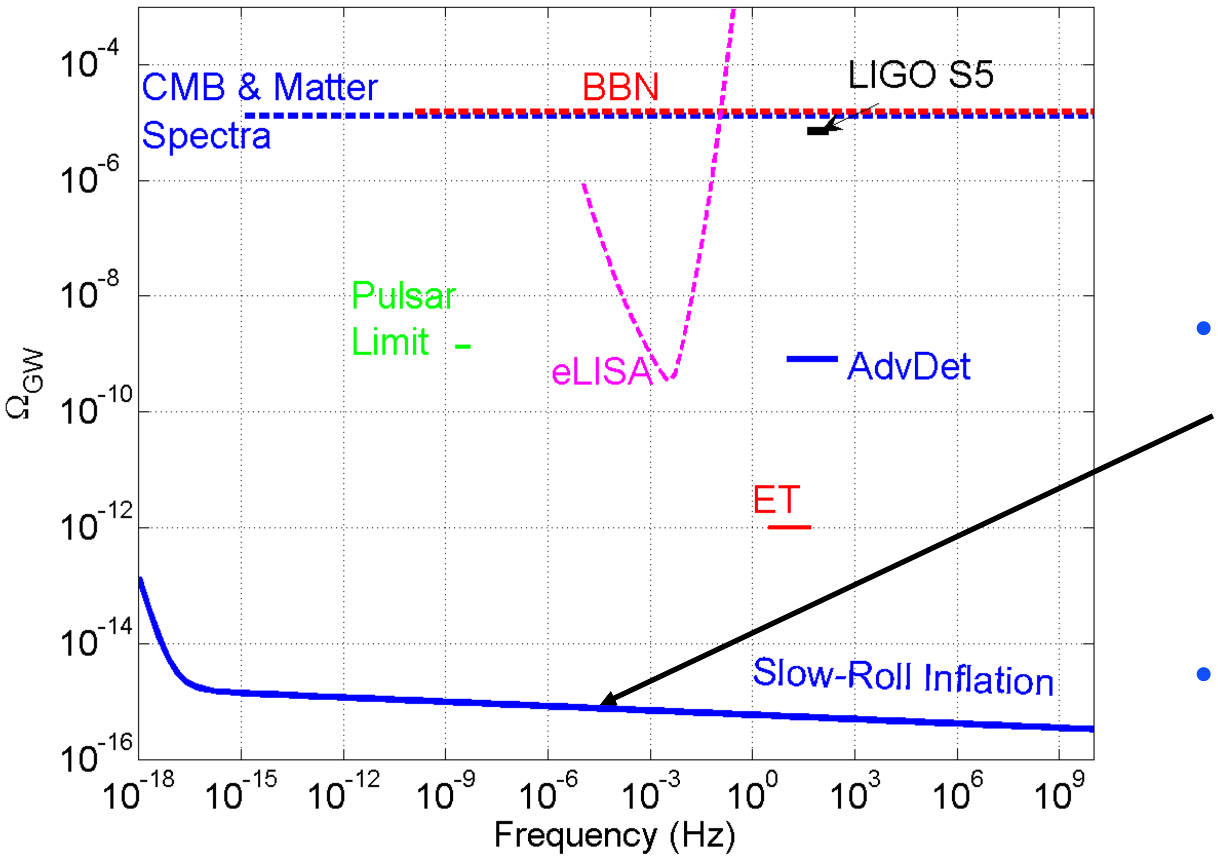
- CMB measuring tensor-to-scalar ratio *r*:
  - Ω_{GW} roughly scales with *r*.
  - Spectral shape also dependent on r:

$$\Omega_{GW} \sim f^{n_t}$$

$$n_t = -r/8$$

(consistency relation for many, but not all inflationary models)

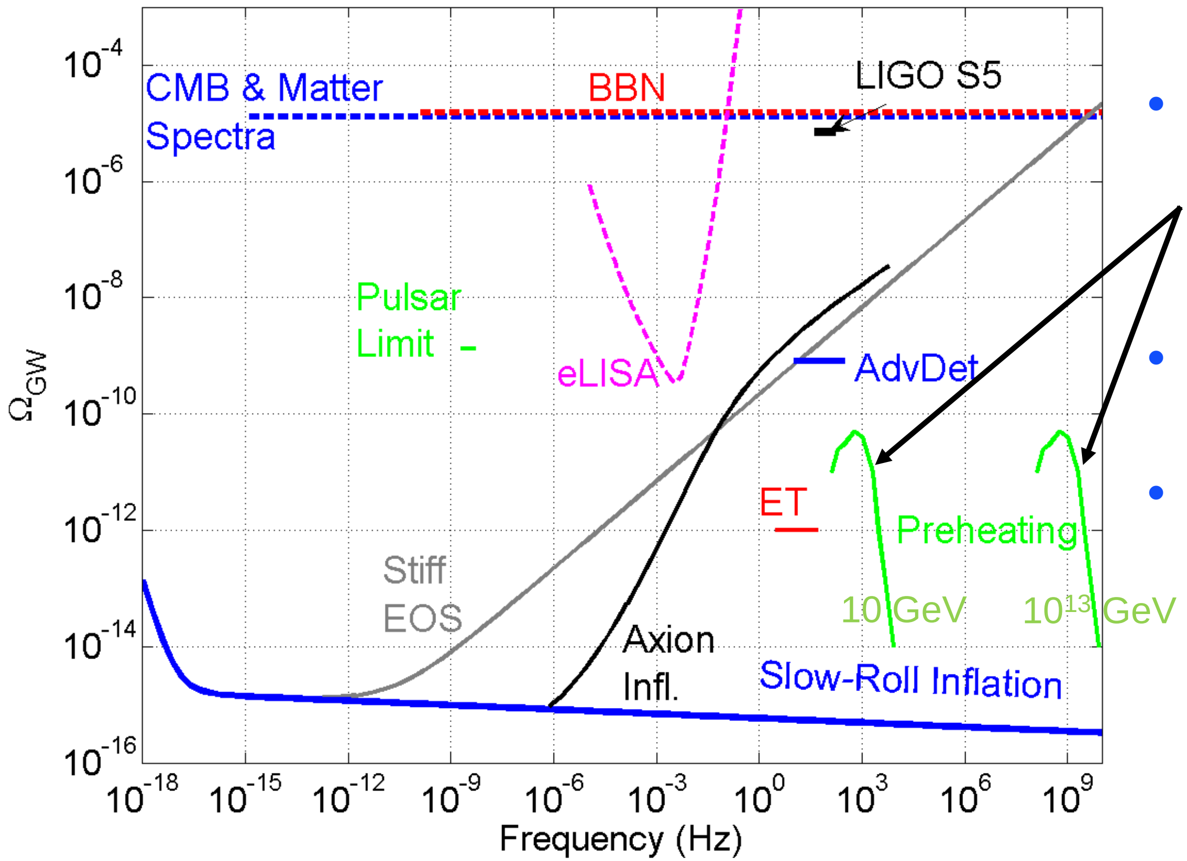
Standard Inflationary Model



- Inflationary spectrum corresponding to r = 0.2.
  - Slow-roll.
  - Amplification of vacuum modes.
- Out of reach by at least 6-7 orders of magnitude at most frequencies.

Catalog of models:
http://homepages.spa.umn.edu/~gwplotter/

Other Inflationary Physics



- If inflation ends with a preheating resonant phase, inflaton energy is efficiently transferred to other particles.
- Can have significant increase in GW background.
- Peak depends on energy scale.
  - » Easther & Lim, JCAP 0604, 010 (2006).
  - » Easther et al, PRL 99, 221301 (2007).
  - » Easther, Nucl. Phys. Proc. Suppl. 194, 33 (2009).

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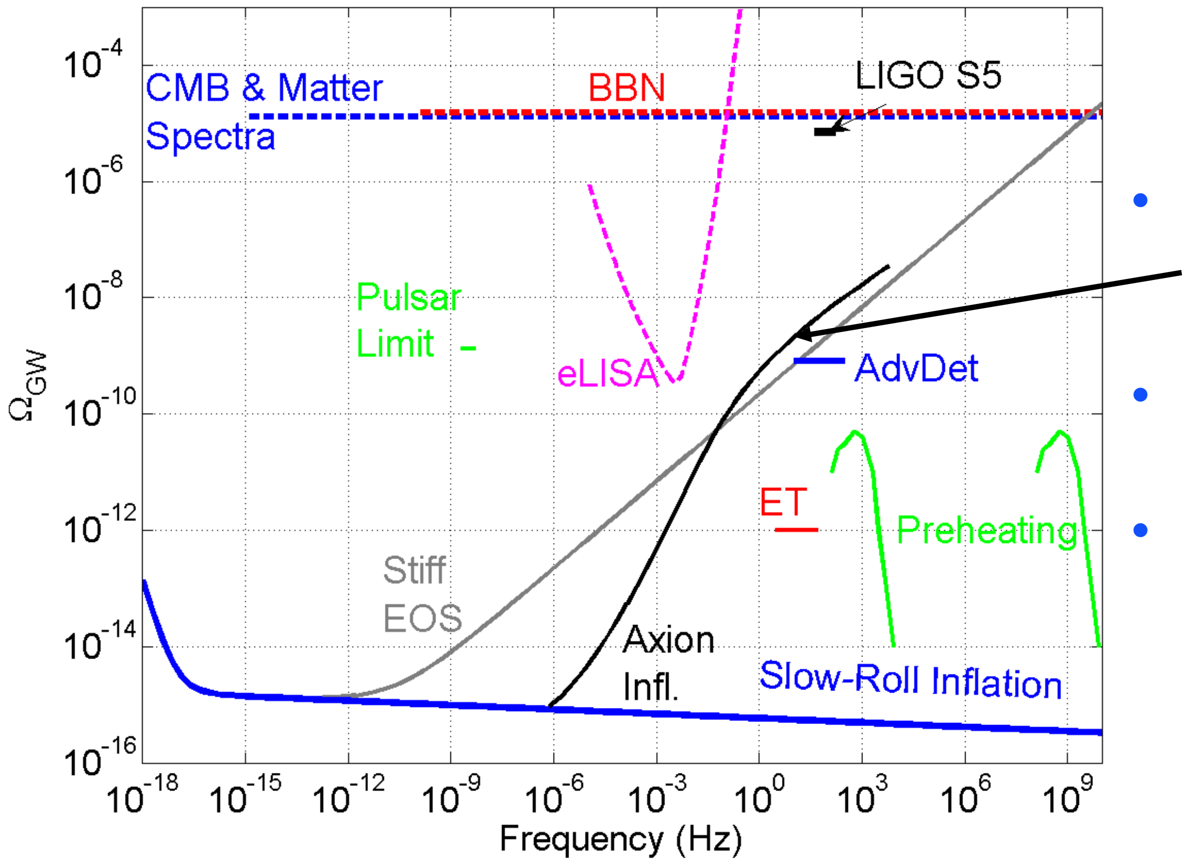
Other Inflationary Physics



- Axion-based inflation models include axion-gauge couplings.
- Gauge backreaction on the inflaton extends inflation.
- This late inflationary phase increases GW production at high frequencies.
  - » Barnaby et al, Phys. Rev. D. 85, 023525 (2012).
  - » Cook & Sorbo, Phys. Rev. D85, 023534 (2012).

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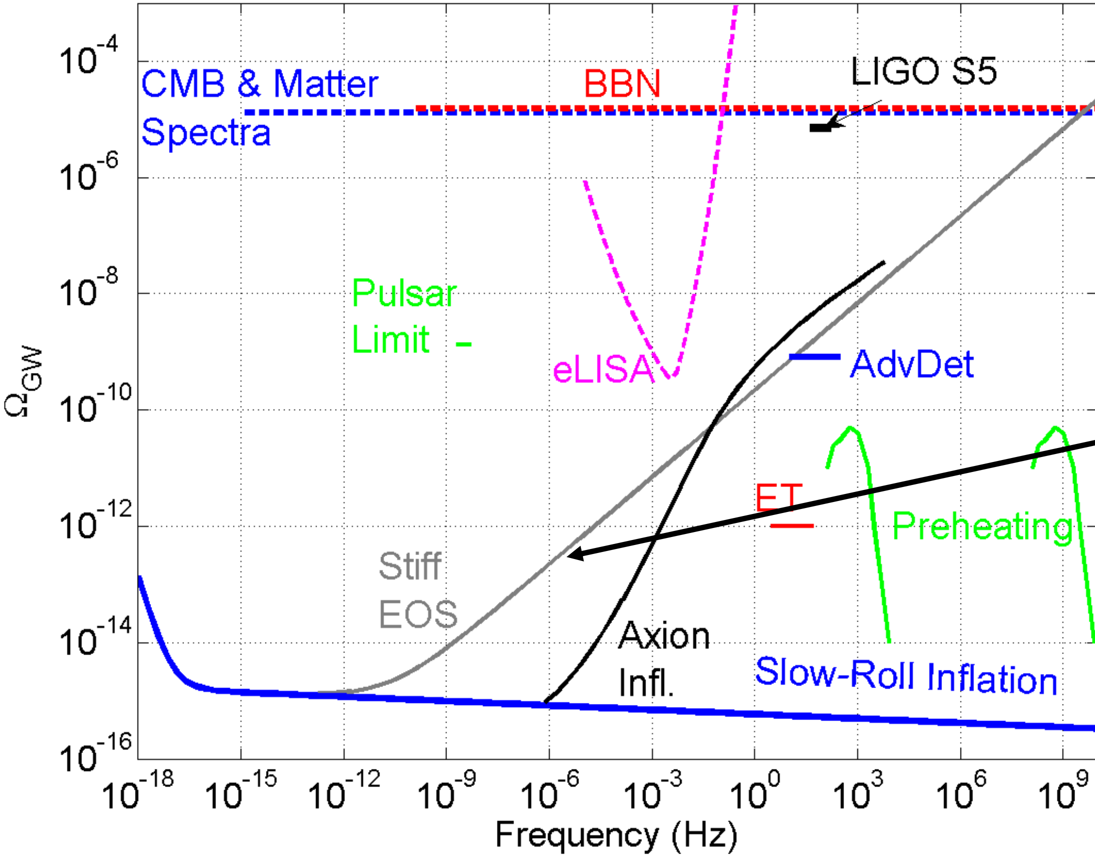
Post-Inflationary Physics



- The consistency relation need not be correct:

$$n_t = -r/8$$

- Should measure it!
- The equation of state between inflation and radiation era could be stiff.
  - If so, Ω_{GW} could increase with frequency.
  - Potentially detectable by advanced detectors.
  - Boyle & Buonanno, PRD 78, 043531 (2008).

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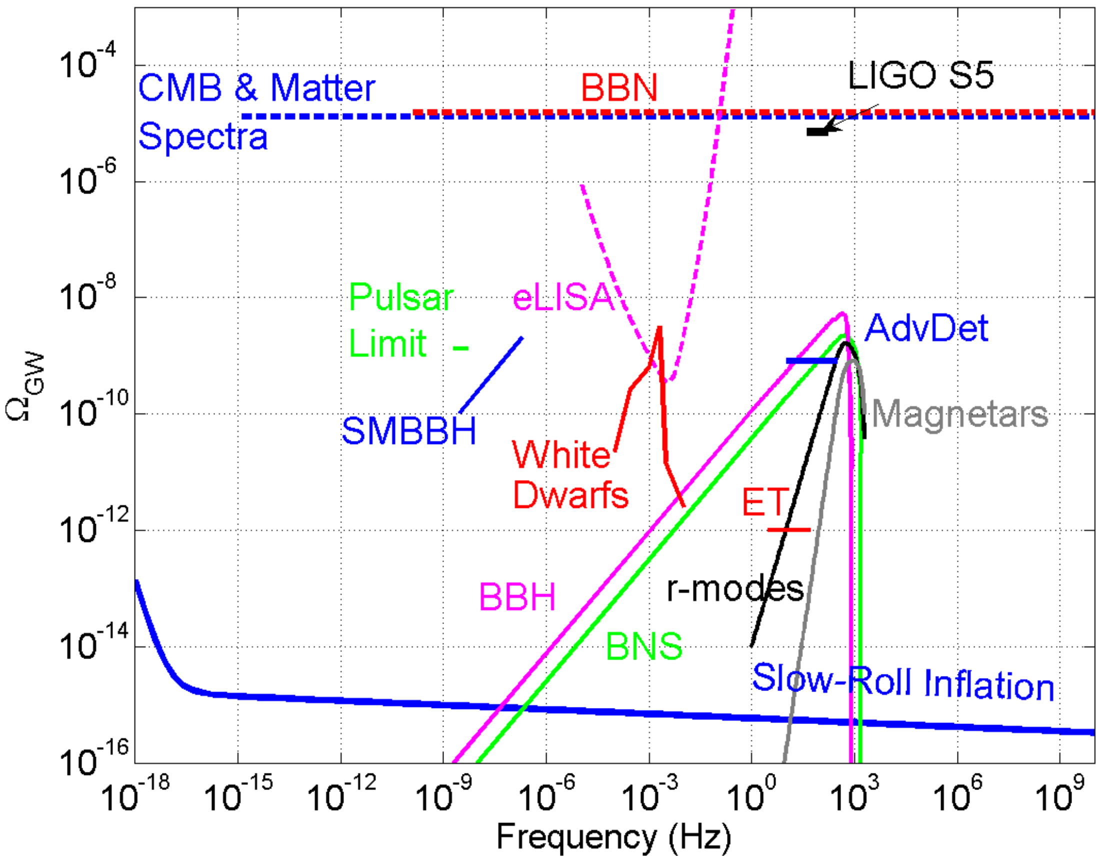
Astrophysical Foregrounds



- Numerous foregrounds have been predicted.
- Neutron stars: instabilities, magnetars…
  - 1 – 10^3 Hz
- White dwarf binaries.
  - 10^{-5} – 10^{-2} Hz
- Neutron star and/or black hole binaries.
  - Span many frequencies, depending on the mass of the binaries.
  - Waveforms better understood, potentially subtractable.

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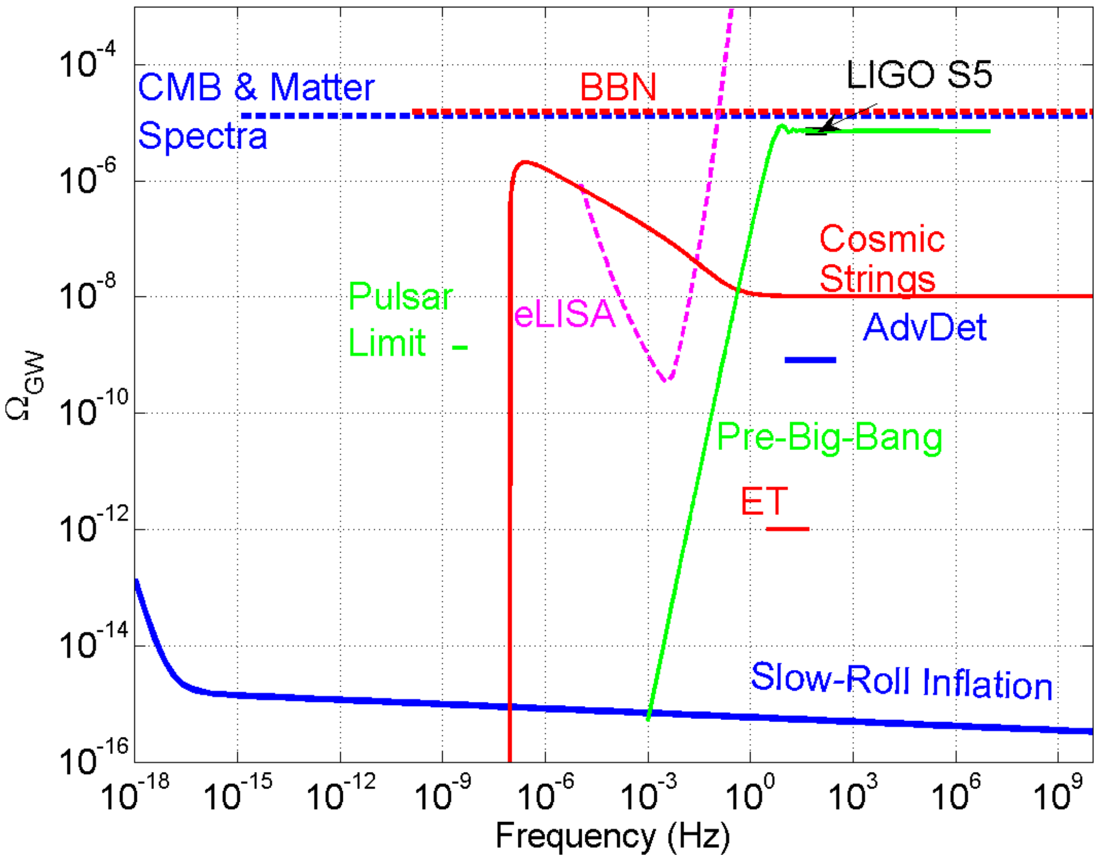
And Potential Surprises



- More exotic models:
  - Cosmic (super)strings.
  - Pre-Big-Bang models (alternative cosmology scenarios).
- Potentially could be stronger than the foregrounds.
- Potentially could span many frequencies.

Catalog of models:
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So, What Does the Future Hold?

- Case 1: We get lucky!
    - New inflationary or post-inflationary physics detected by advanced detectors.
    - Or, more exotic models, such as cosmic strings.
    - Will want to measure the signal at multiple frequencies to discriminate between models.
    - The “standard” inflationary signal (amplification of vacuum modes) might only be reachable at ~nHz frequencies.

So, What Does the Future Hold?

- Case 2: We don't get so lucky!

  - Standard inflationary model (amplification of vacuum modes) may be the only cosmological signal in GWs.

  - Could go after it at different frequencies:
    - 10^{-9} Hz with future improved pulsar timing measurements?
    - 0.1-1 Hz window might be relatively free of foregrounds.
      - Will require multiple experiments at different frequencies to understand foregrounds and potentially subtract them.
      - But, strain sensitivity of $10^{-23}/\sqrt{\text{Hz}}$ in this band amounts to $\Omega_{GW} \sim 10^{-16}$ (assuming cross-correlated measurement).
    - 10 kHz band seems free of foregrounds.
      - But requires strain sensitivity of $\sim 10^{-30}/\sqrt{\text{Hz}}$ (for cross-correlated measurement).

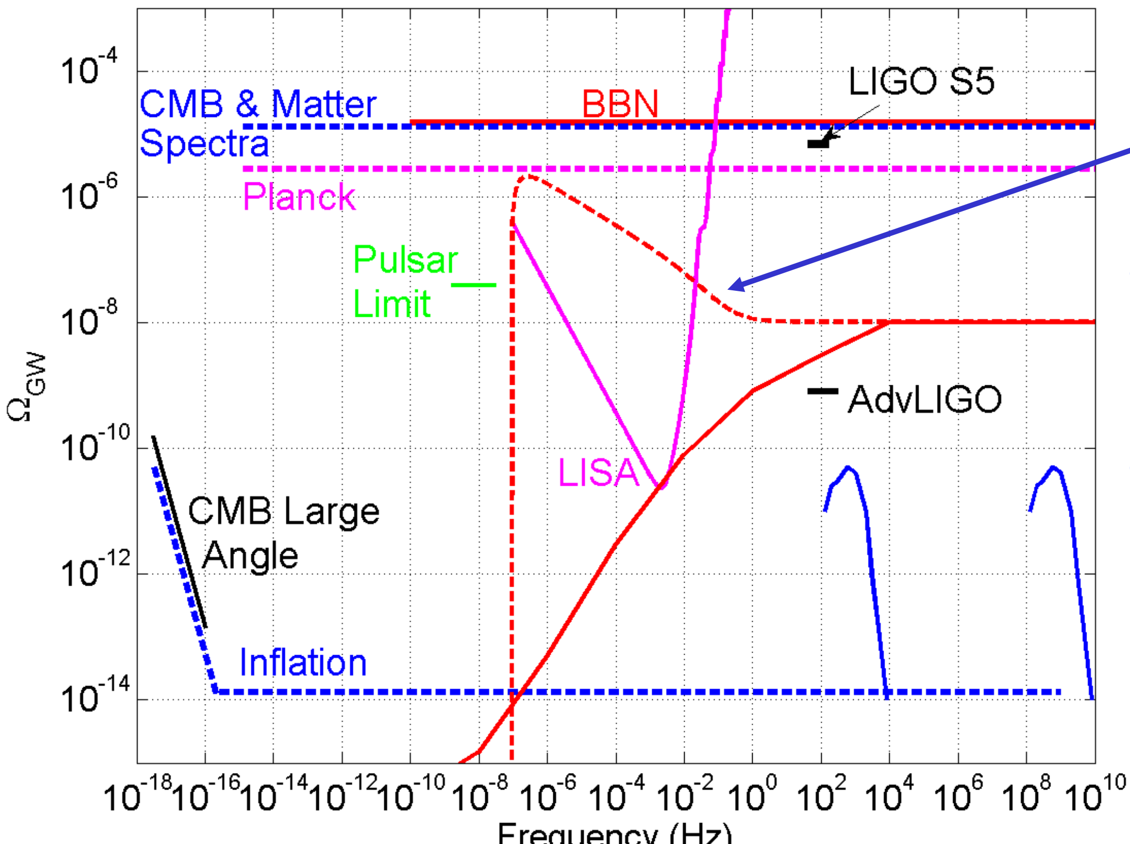
Conclusions

- If BICEP-2 result holds up, this is really good news for our field!
- We would know that it is possible to study the physics of these very early times and high energies.
    - This is not a "given"!
    - Not possible with any lab-based techniques.
- Physics of inflation could be rich.
    - Many processes do not leave signatures in the CMB, but could be detectable by direct GW observations today.
    - Combine CMB B-mode measurements with interferometric SGWB measurements at different frequencies to disentangle different models, and to really study the physics of inflation.
- BICEP-2 result is the strongest argument to build the next-generation GW detector dedicated to searching for SGWB.

- This story is just beginning to unfold, and we have an important role to play!

Back-up Slides

Advanced Detectors and the Stochastic Background



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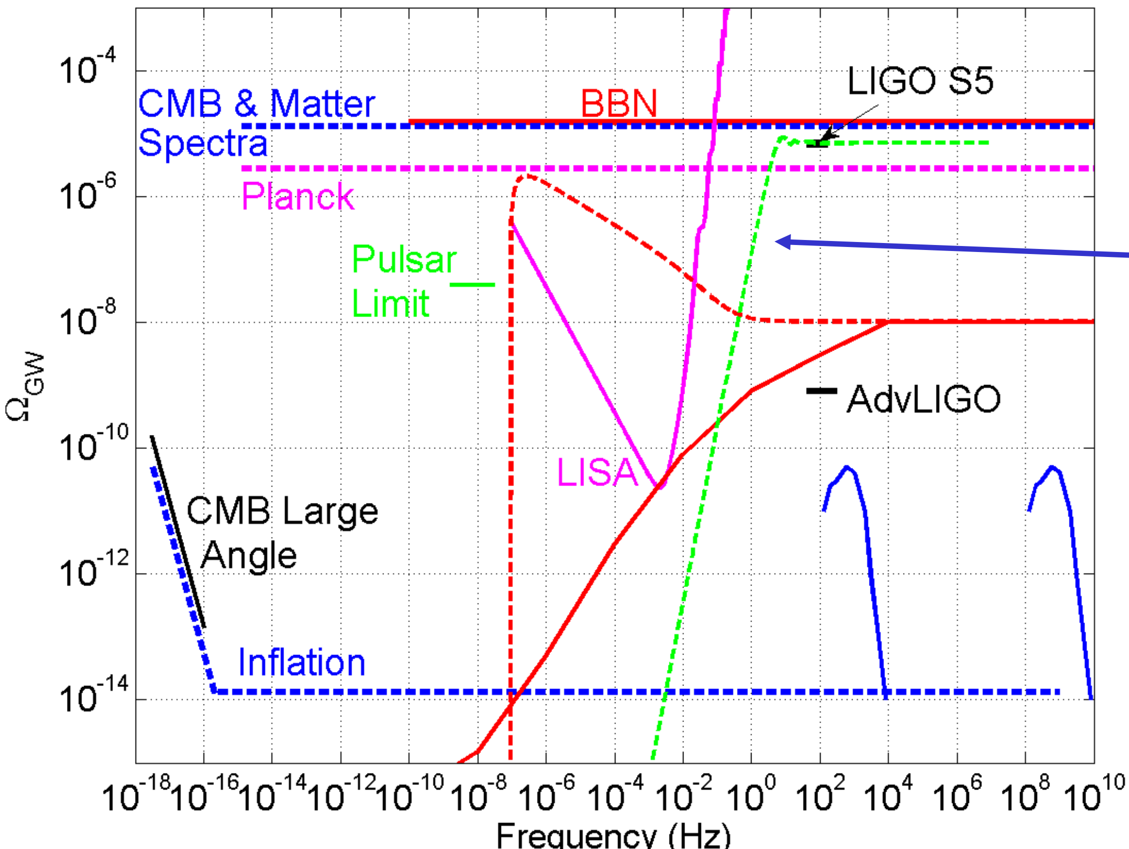
- Cosmic (super)strings models: cusps or kinks moving at relativistic speeds produce bursts of gravitational radiation.
- Integrating over the whole universe leads to a GW background.
- Large parameter space, some of it already probed by initial LIGO.
  - » Damour & Vilenkin, PRL 85, 3761 (2000).
  - » Siemens et al, PRL 98, 111101 (2007).
  - » Olmez et al, PRD 81, 104028 (2010).

Advanced Detectors and the Stochastic Background



- Alternative cosmologies, such as pre-Big-Bang models, can lead to strong GW backgrounds at high frequencies.
  - » Gasperini & Veneziano, Phys. Rep. 373, 1 (2003).
  - » Buonanno et al, PRD 55, 3330 (1997).

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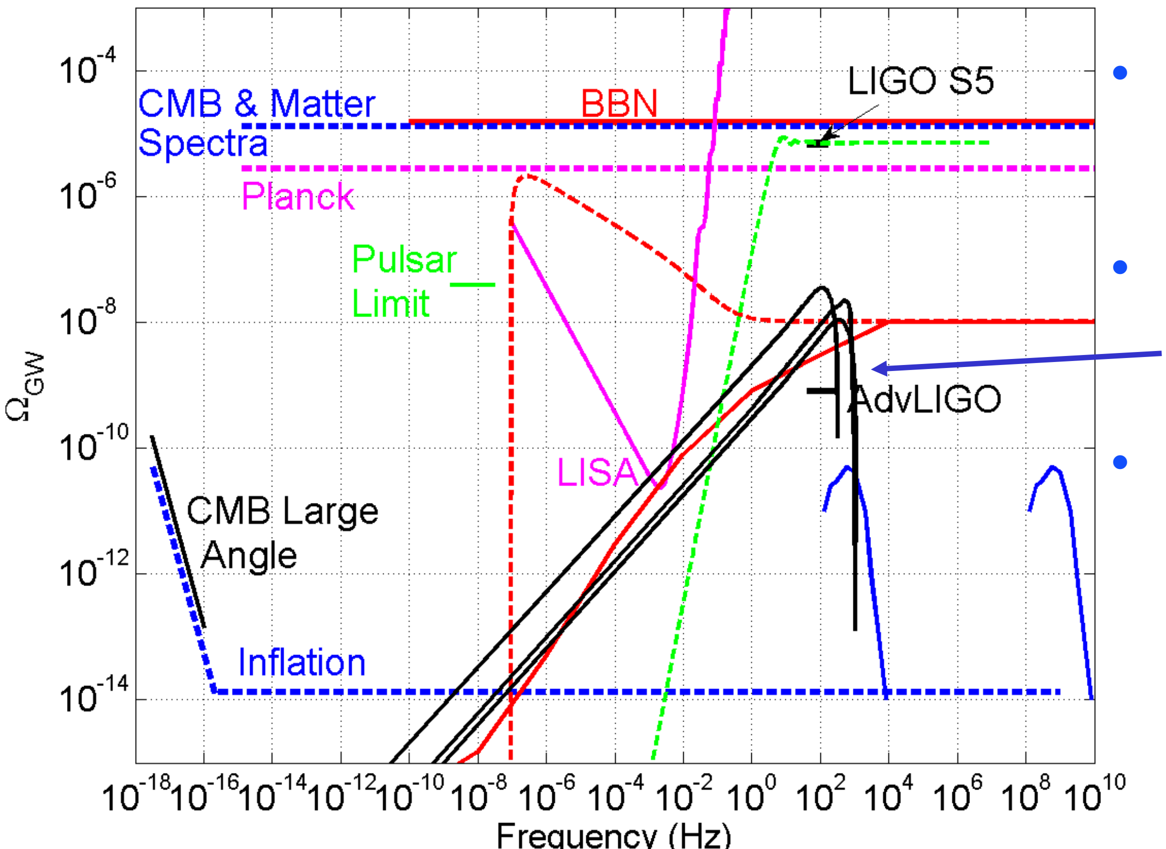

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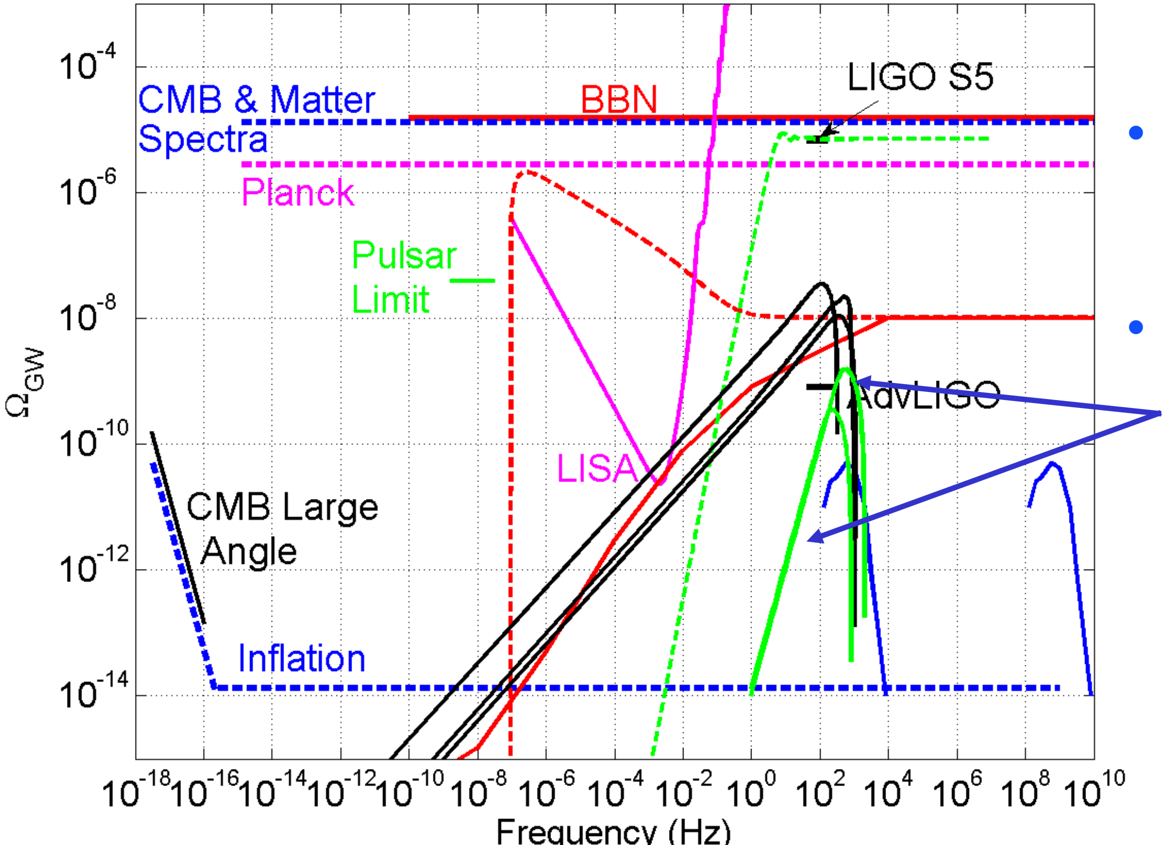
- Individual neutron star and/or black hole pairs generate chirp GW signals.
- Integrating over the whole universe (z<6) leads to a GW background.
- Peak in the LIGO band.
  - » Phinney, ApJ 380, L17 (1991).
  - » Ignatiev et al., MNRAS 327, 531 (2001).
  - » Regimbau & de Freitas Pacheco, ApJ 642, 455 (2006).
  - » Wu et al, Phys. Rev. D 85, 104024 (2012).

Advanced Detectors and the Stochastic Background



- Neutron stars can have a variety of instabilities: r-modes, bar-modes etc.
- Integrating over the entire universe leads to a GW background.
  - » Owen et al, PRD 58, 084020 (1998).
  - » Lai & Shapiro, ApJ 442, 259 (1995).
  - » Regimbau & de Freitas Pacheco,, A&A 376, 381 (2001).

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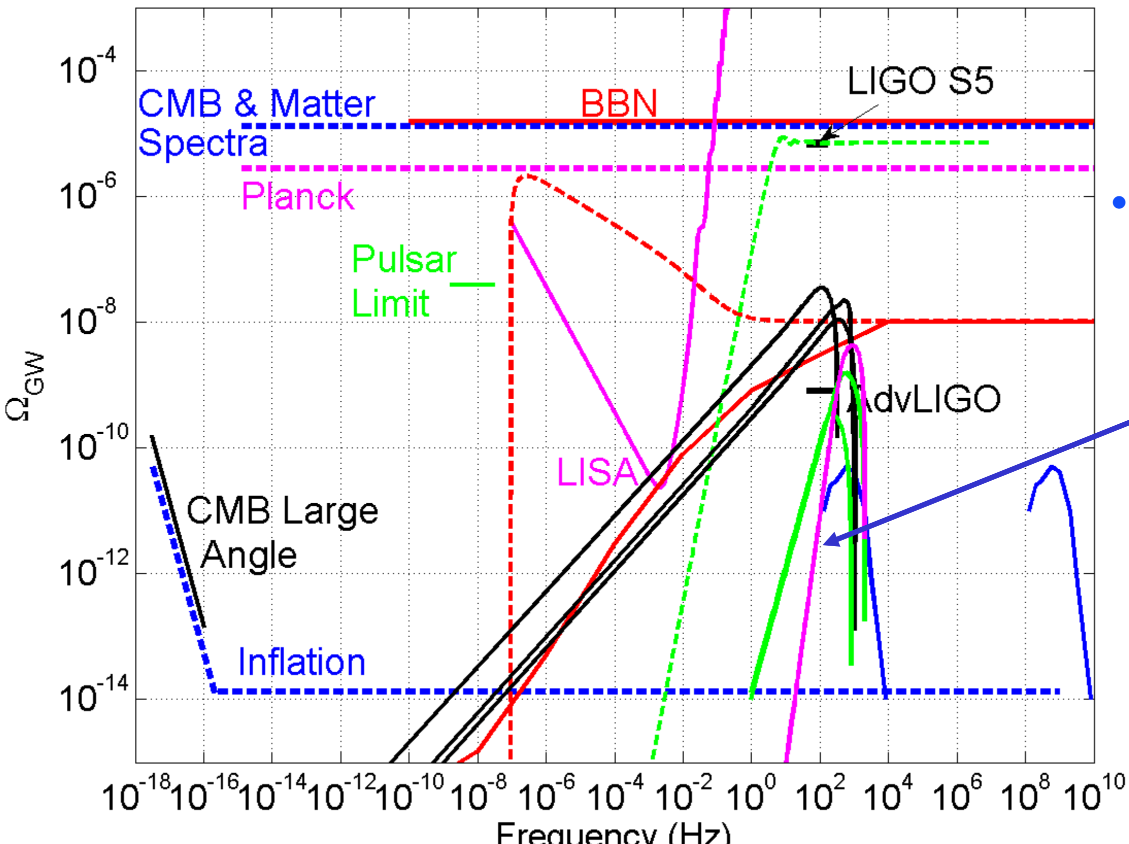
Advanced Detectors and the Stochastic Background



Catalog of models:
http://homepages.spa.umn.edu/~gwplotter/

- Magnetar model: protoneutron stars in very strong magnetic fields (10^{16} G) can be distorted (high ellipticity).
- Integrating over the whole universe leads to a GW background.
  - » Cutler, PRD 66, 084025 (2002).
  - » Regimbau & Mandic, CQG 25, 184018 (2008).
  - » Dall'Osso et al, MNRAS 398, 1869 (2009).
  - » Marassi et al, MNRAS 411, 2549 (2011).
  - » Wu et al, Phys. Rev. D 87, 042002 (2013).