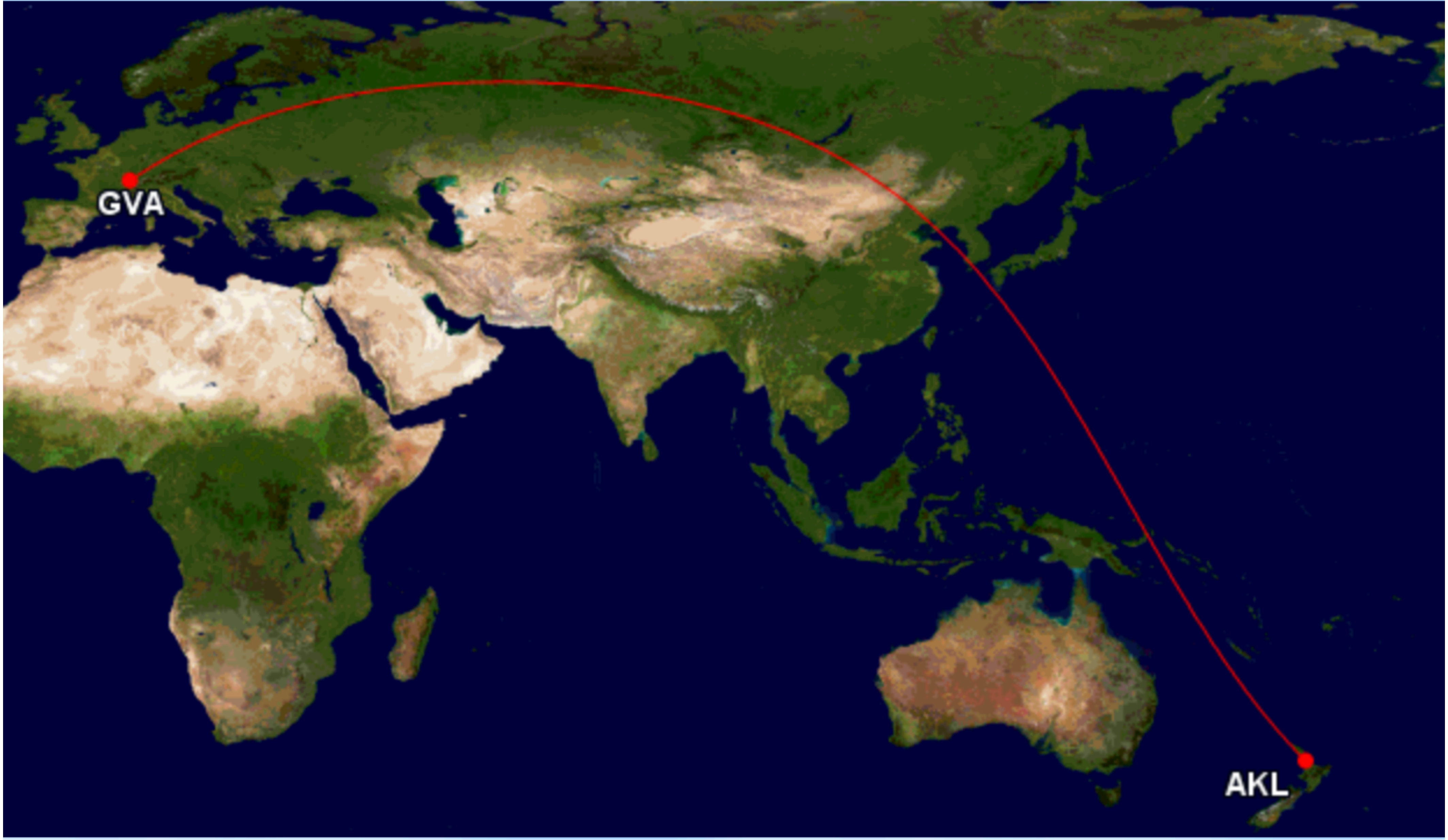
Early Universe Sources

Richard Easther [University of Auckland]

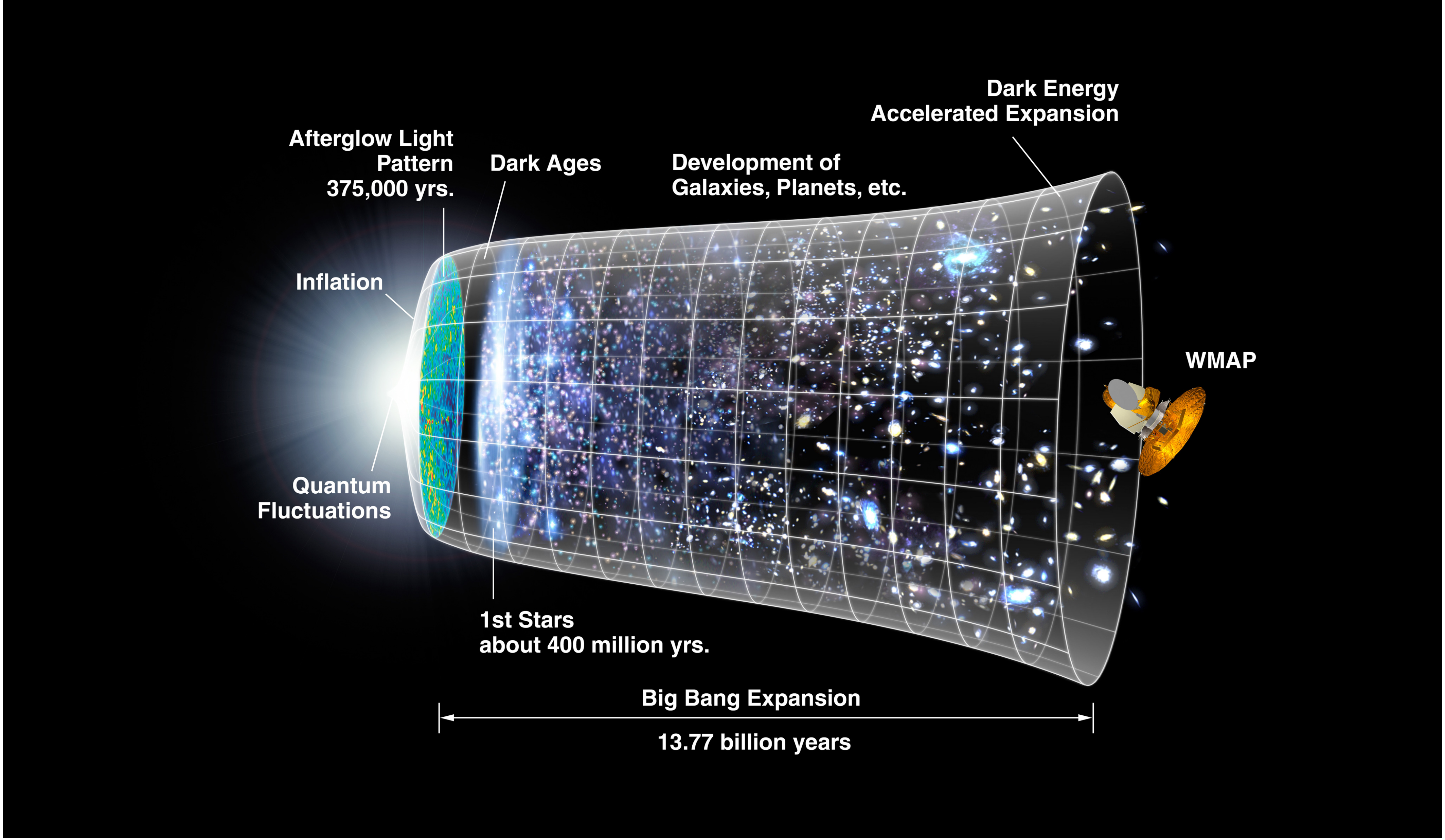


Where I am…

[~7 tons of carbon]

Opening thoughts

- Early universe — above electroweak scales
    - Temperatures in excess of 1 TeV
    - Beyond the LHC
- Immediately playing for high stakes
    - High energy physics we don't understand
    - Very early universe cosmology we have not explored
- Distinguish between *what we think* and *what we know*



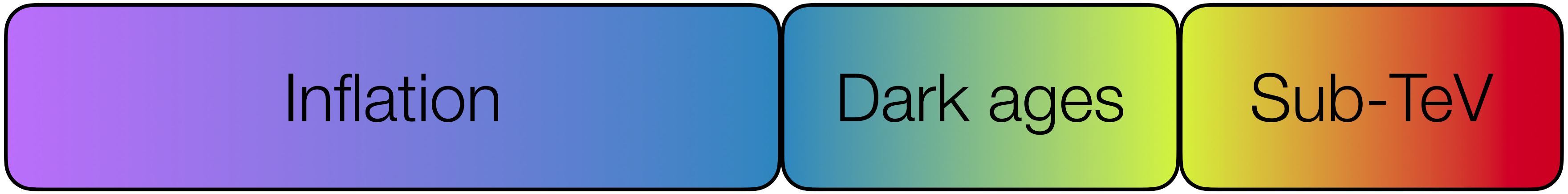
NASA “funnel diagram”

What we think…

Sizes and Temperatures [Stuff we know]

- Statements about General Relativity and causality (so safe at a GW meeting)
- Horizon size today
  - 40×10^9 light years
  - 3.26×10^{26} m
  - 2.3×10^{61} Planck lengths…
- Scale factor describes the growth of the universe: a(t)
  - When $a(t) \sim 10^{-60} a(t_0)$ everything we now see was sub-Planckian…
- CMB temperature: 6×10^{-4} eV; Planck scale 10^{19} GeV
  - Temperature ~ 1/a: Planck temperature reached when $a(t) \sim 10^{-30} a(t_0)$

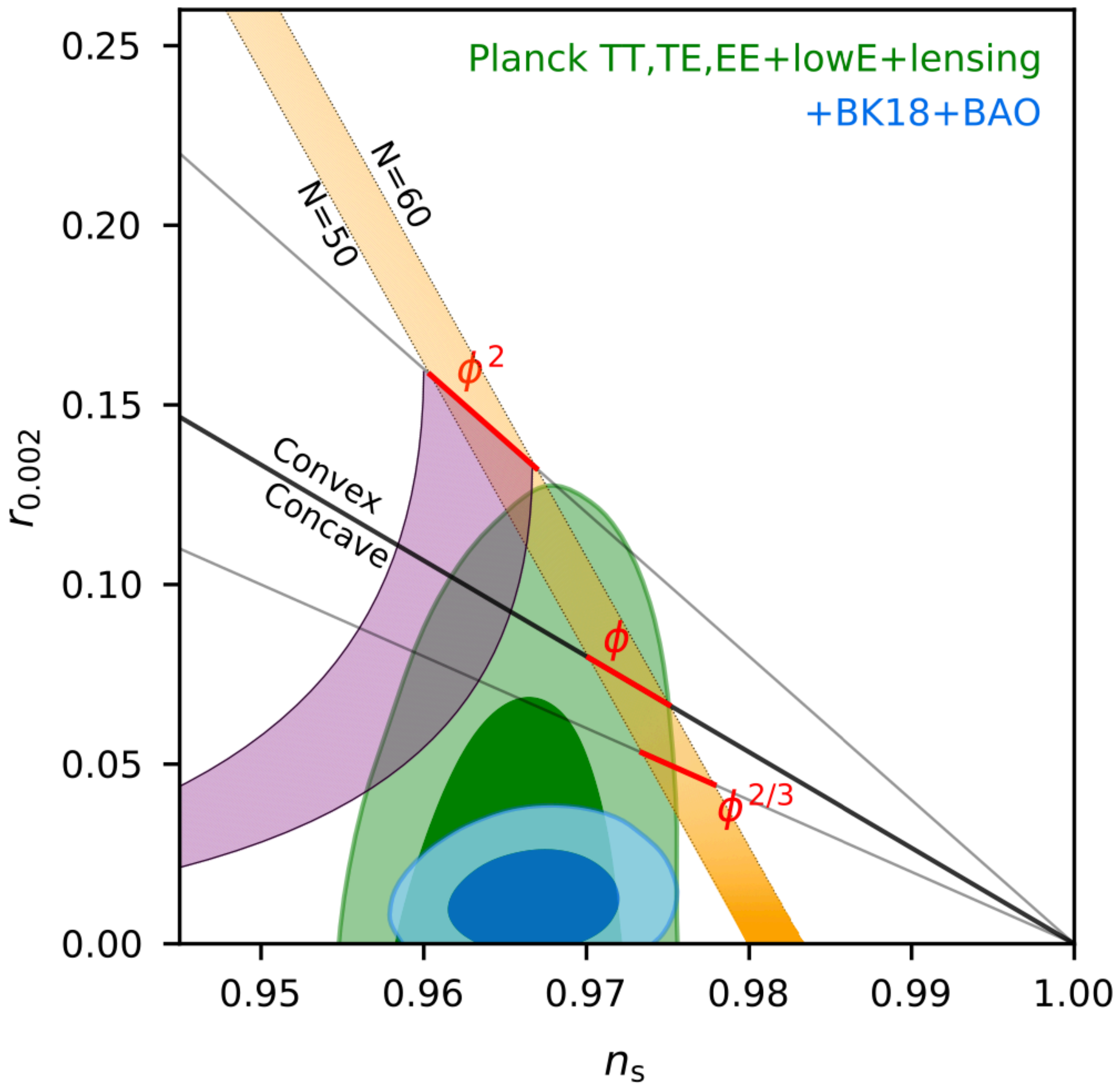
Primordial Dark Age [Stuff we think]



- CMB temperature: 6×10^{-4} eV
  - Scale factor a(t) when T~1 TeV; 10^{-15}
  - Inflation, maybe a factor of 10^{30}
  - "Primordial dark age" maybe a factor of 10^{15} [Term: Boyle and Steinhardt]
- Dark age: about a quarter of the growth of the universe (in logarithmic terms)
  - And half of the post-inflationary growth.

Gravitational wave production: quantum

- Quantum mechanical - would vanish if $\hbar \equiv 0$
- Inflationary gravitational wave background
  - Wavelength at formation proportional to Hubble scale
  - Hubble scale ~ energy density; roughly constant during inflation
  - Wavelength then stretched with subsequent expansion of the universe
- Amplitude *constant* while superhorizon
  - Reenters the horizon and scales like radiation
  - Present on “all” scales - table-top though to cosmological
  - But probably not motivating UHF-GW experiments
- cf ekpyrosis / bouncing universe scenarios (blue primordial spectrum)

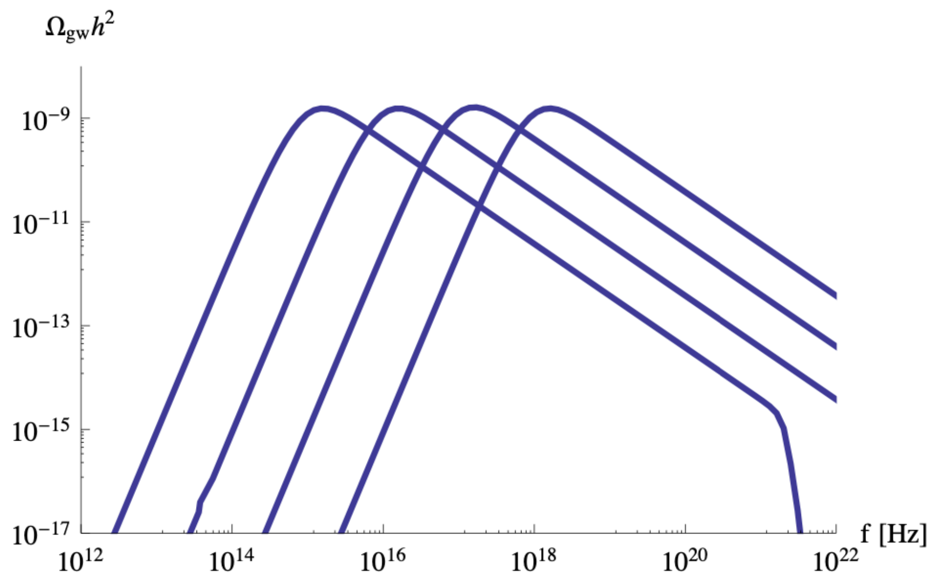


This month: BICEP2/Keck

https://arxiv.org/abs/2110.00483

Gravitational wave production: quantum

- Hawking radiation from PBH
  - Possible the early universe passes through a black hole dominated phase
  - Small black holes Hawking radiate and decay before nucleosynthesis
  - Produce gravitons along with everything else (+grey body factors)
- Anantua, Easther and Giblin
  - ArXiV: 0812.0825



Gravitational wave production: classical

- Driven by “stuff being accelerated” - sourced by T-T parts of $T_{\mu\nu}$
  - May still be “quantum” sources (e.g. phase transitions, string networks)
- Must be in the post-inflationary universe to be observable
  - Inflation will dilute any pre-existing GW background
- Will be associated with periods of high inhomogeneity
  - Plenty of scope for this in the primordial dark age
  - And on scales far smaller than any present-day cosmological structure

Parametric Resonance

- Inflation *must* end eventually, if it happens at all [something we know]
  - Post-inflation: universe filled with cold, coherent inflaton condensate
  - Universe must then thermalise
- Multiple possible mechanisms
  - Self-resonance (production of inflaton particles)
  - Resonant production of scalar particles coupled to inflaton
  - Resonant production of spin$\neq$0 particles coupled to the inflaton
  - No resonant production of anything…
- Inflationary mechanism unclear
  - Inflaton coupling to Standard Model doubly unclear

Not a new idea…

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Particle production during out-of-equilibrium phase transitions

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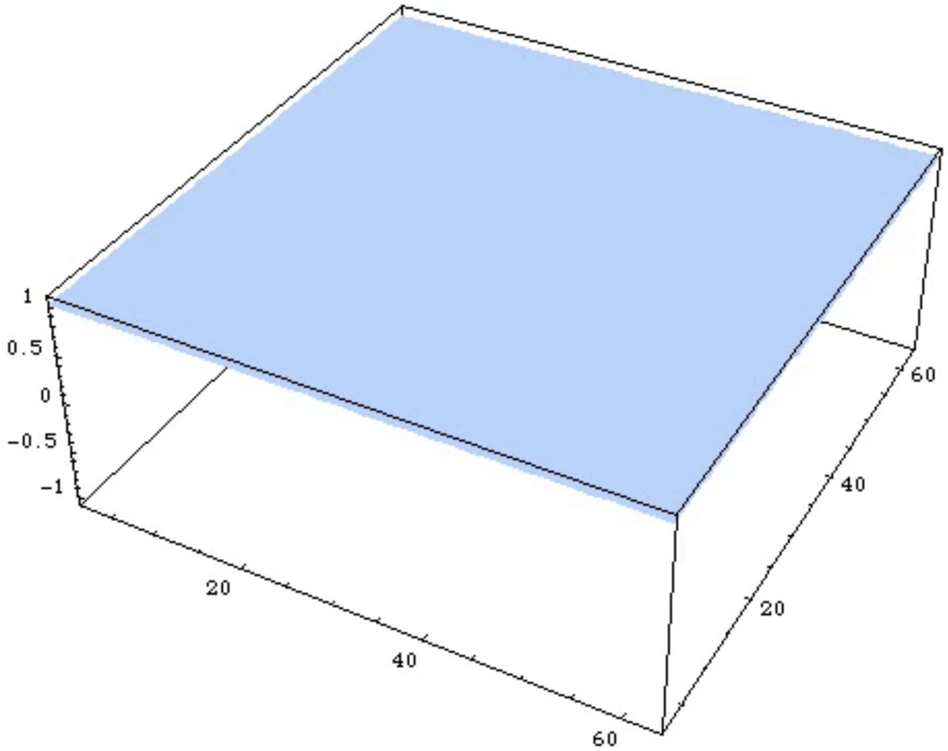
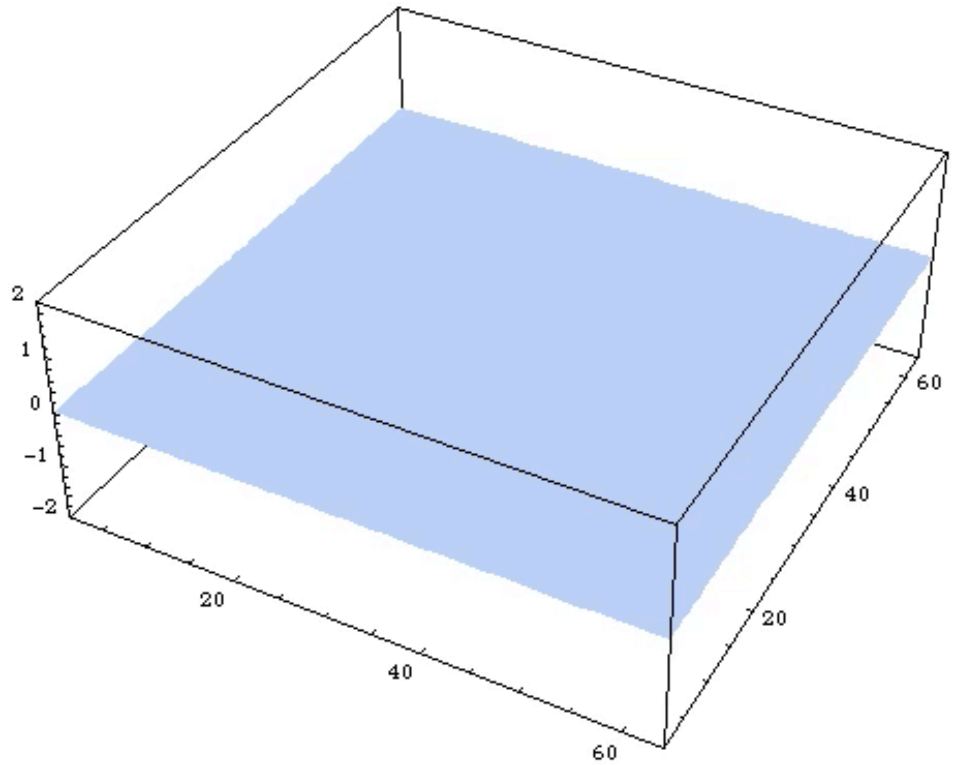
(Received 12 February 1990; revised manuscript received 24 May 1990)

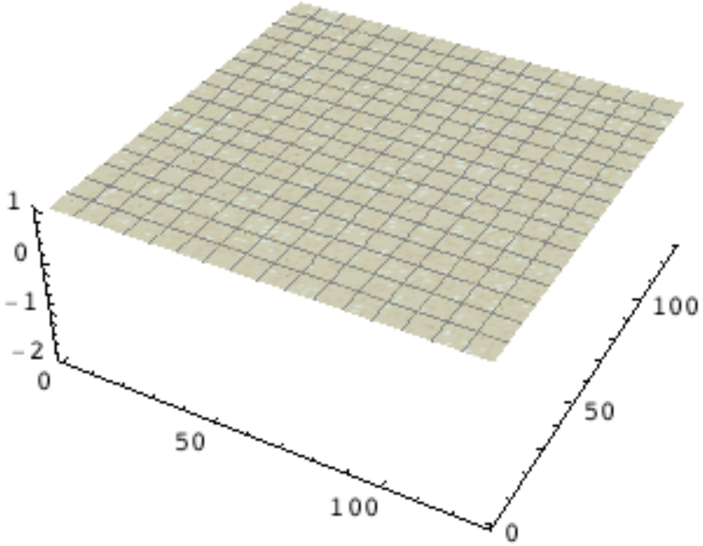
Techniques are developed to calculate the energy production in quantum fields which obtain a mass through the spontaneous symmetry breaking of a second field which is undergoing a phase transition. All fields are assumed to be out of thermal equilibrium and weakly coupled. The energy produced in a field, which is initially in its ground state, is computed for two generic types of time-dependent masses: a roughly monotonic turn on of the mass and an oscillatory mass. The formalism is applied to the questions of particle production and reheating in inflationary universe models. Requirements are found which the couplings in new-inflation-type models must satisfy for efficient reheating to occur.

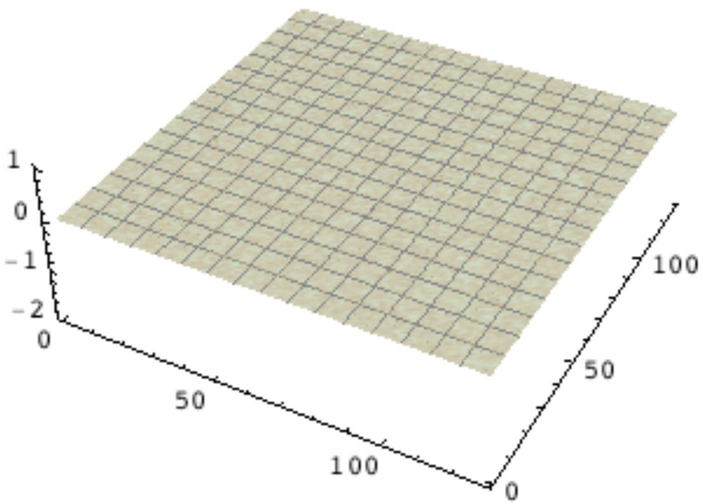


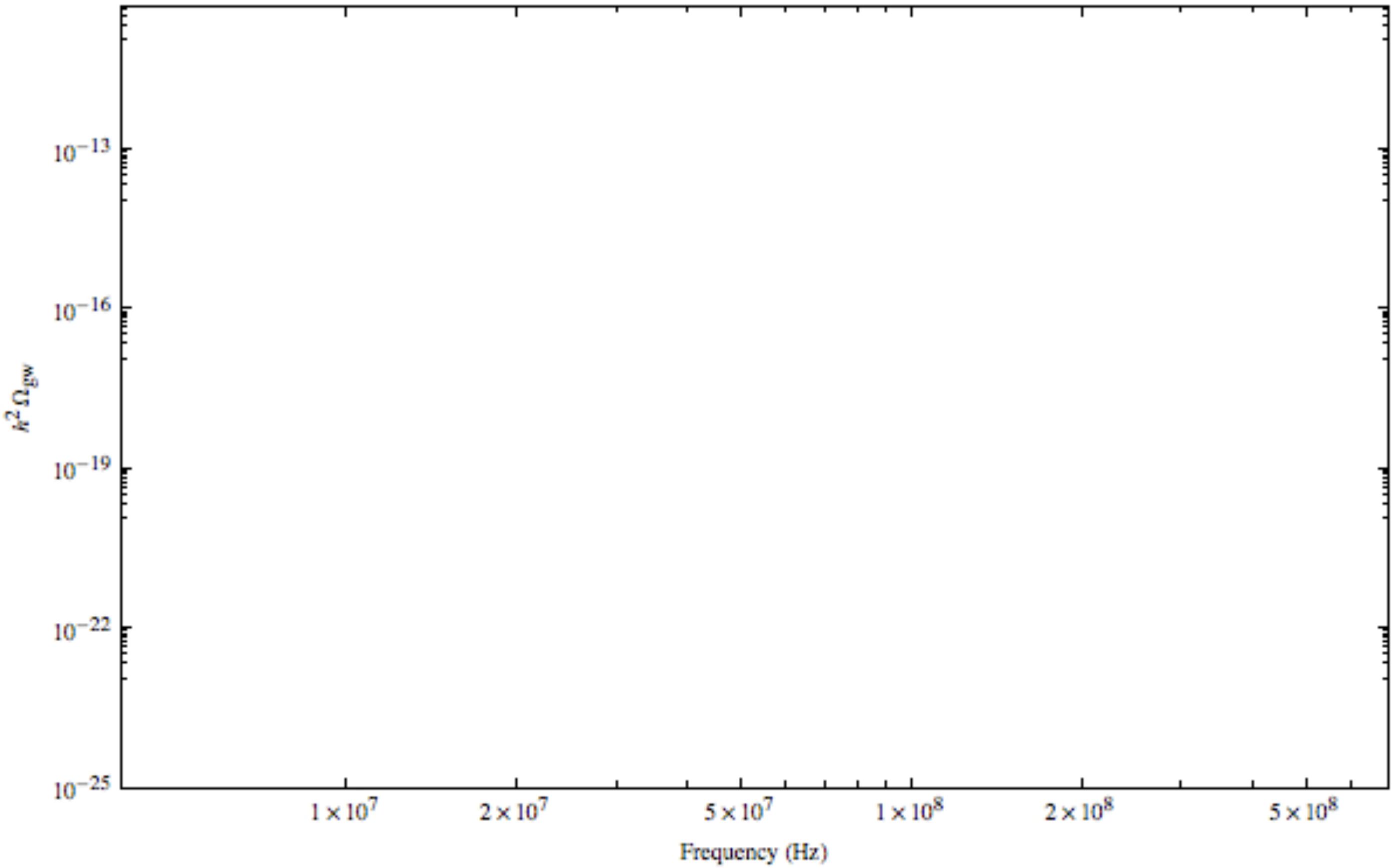


$$V(\phi,\chi) = \frac{m^2}{2}\phi^2 + g^2\phi^2\chi^2$$

Resonance | 2 field







Gravitational Waves

Plot: Giblin

GW and Parametric Resonance: thoughts…

- Original work: Khlebnikov and Tkachev (1997, hep-ph/9701423)
- 2006-10 (and much activity since)
  - RE, Giblin, Lim, Finkel…
  - Garcia-Bellido, Figueroa …
  - Dufaux, Kofman, Felder, Bond …
- Lower bound on wavelength — Hubble length at production
  - Then redshifted by subsequent expansion of the universe
  - Which will be smaller when density is lower; Hubble length larger
  - Laid out in astro-ph/0601617 ("We believe that the time is ripe for revisiting this question.")

GW and Parametric Resonance: thoughts…

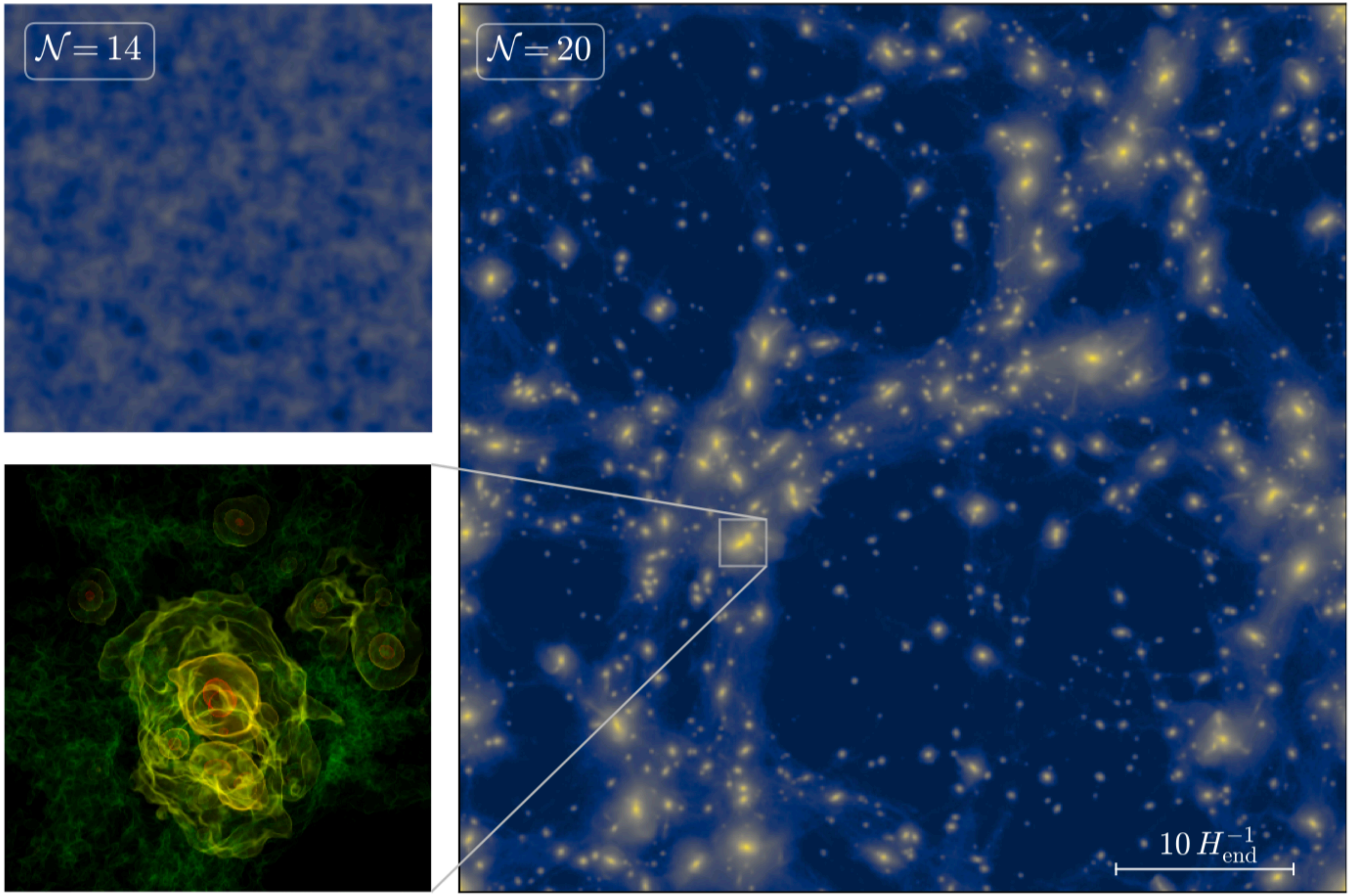
- Production at lower energy
  - Permits gravitational wave background at lower (present-day) frequencies
  - But frequency at production need not be close to limit from Hubble length
- Gravitational wave spectrum reflects detailed mechanism of resonance
- Unknown impact from reheating history
  - Post-resonance universe may still be matter dominated
  - Gravitational wave energy density is diluted until thermalisation
  - Major theoretical unknown
- Also: can have oscillon production; long-lived inflaton bound states
  - Distinctive gravitational wave spectrum

Extended Matter Domination

- Schrodinger-Poisson equation
  - Simplest form of the Gross–Pitaevskii equation (includes self-interactions)
  - Effectively a WKB approximation to the Klein-Gordon equation
  - Non-relativistic limit / fixed particle number
- Very trendy equation: describes Axion / Ultralight / Fuzzy Dark Matter
  - Galactic halos are a Bose-Einstein condensate with axion mass 10^{-21} eV
  - Compton wavelength on kiloparsec scales
  - Smooths out purported short-range issues with cold dark matter.
  - Developing solvers (PyUltraLight / Axionyx)

Extended Matter Domination

- Applies in the *absence* of resonance
- Matter dominate phase analogous to present-day structure formation
  - But can last far longer, since there is no analogue of dark energy
  - Convert existing tools and techniques (Press-Schecter, N-body)
- Schrodinger-Poisson formalism, RE, Hotchkiss and Musoke, 1909.11678
  - Musoke, Hotchkiss and RE 1909.11678; Niemeyer and RE 1911.01661
  - Eggemeier, Niemeyer and RE 2011.13333
  - Eggemeier, Niemeyer, Schwabe and RE - next week
- Lots of scope for interesting physics



Biggest blob
20kg/10^{-20} m

2011.13333

Extended matter domination

- Gravitational wave production by second order effects
- Present day gravitational wave amplitude diluted during matter domination
  - Spectrum convolved with expansion history
  - GW produced later in matter dominated phase undergoes less dilution
- No inclusions (thus far) of gauge fields / phase transitions
  - GW from transitions; transient defect networks
- Thermalisation mechanism still unclear

Conclusions

- These are, in many ways, familiar topics for this community
- High-frequency gravitational wave bounds are blind searches for new physics
  - Vast number of *possible* production mechanisms
  - Cheaper than a bigger particle accelerator
- Priors on the plausibility of theoretical ideas are hard to quantify
  - Applying pure reason to the world did not work well for classical Greeks
  - But we get gravitational wave production in *simple* inflationary models
  - And without adding new/additional physics to achieve it
- Long matter dominated phase: vast range of possible consequences
- Quick thermalisation: appears to require resonance, preserves GW amplitude

Conclusions

- Nice inverse correlation with inflationary scale
  - Inflation at lower energies can produce lower frequency GW
- Looks as though if inflation did happen, it did not produce a large SGWB
  - Strong scaling of amplitude with inflationary scale
  - But a topic of heated debate in theory community
- Consequences of “low r” inflation for post-inflationary dynamics
  - Not yet really explored…
  - But could have major implications for priors on GW background