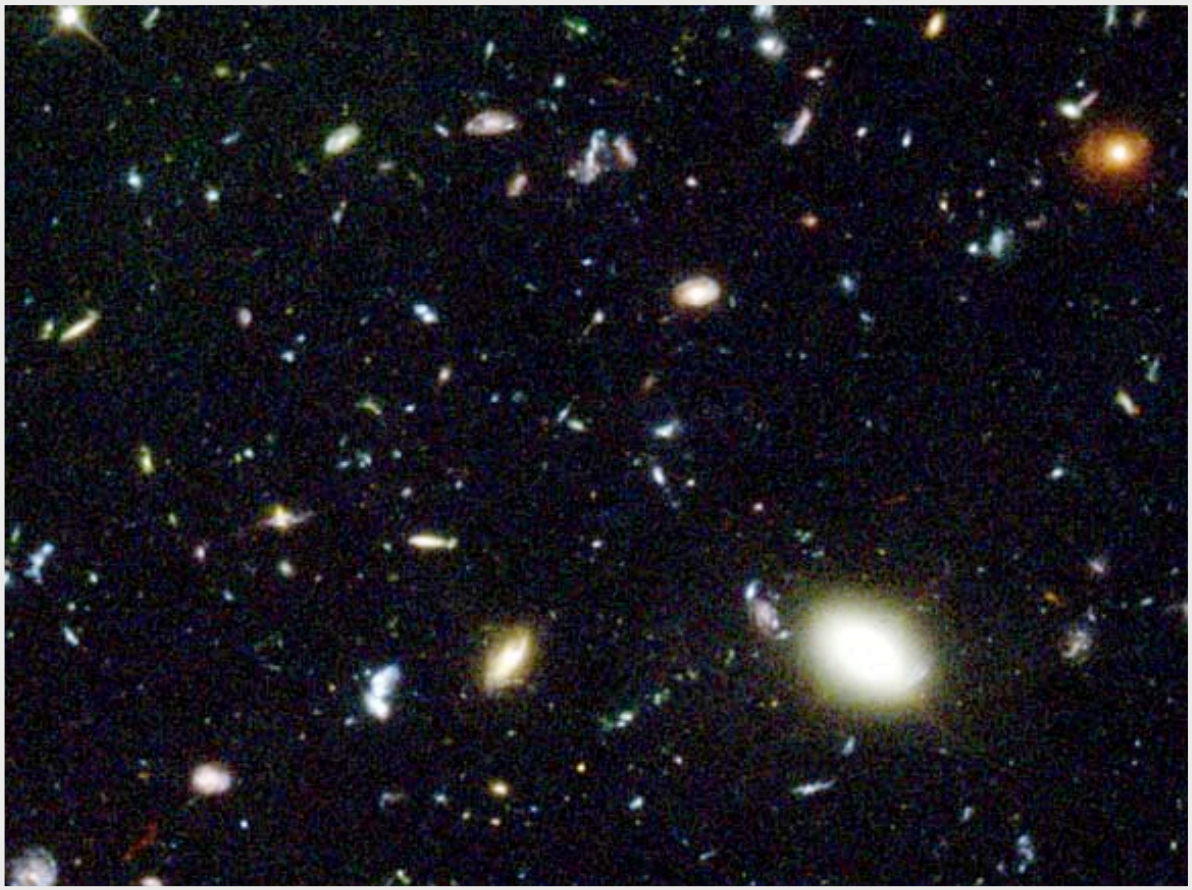
GRAVITATIONAL WAVES AND THE END OF INFLATION



Richard Easther (Yale)

OUTLINE

- Inflation: a reminder
- Ending inflation: Parametric resonance / preheating
  - [SKIP: technical calculation]
  - Gravitational wave generation
- Generic properties of gravitational wave signal
- Implications for future experiments

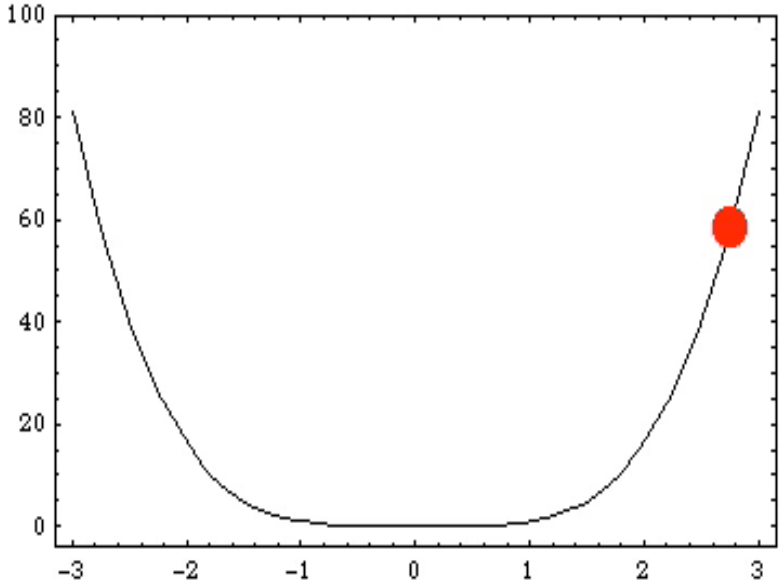
Khlebnikov and Tkachev (1997); RE with Giblin, Lim, Finkel, Swanson, Roth

INFLATION: A REMINDER

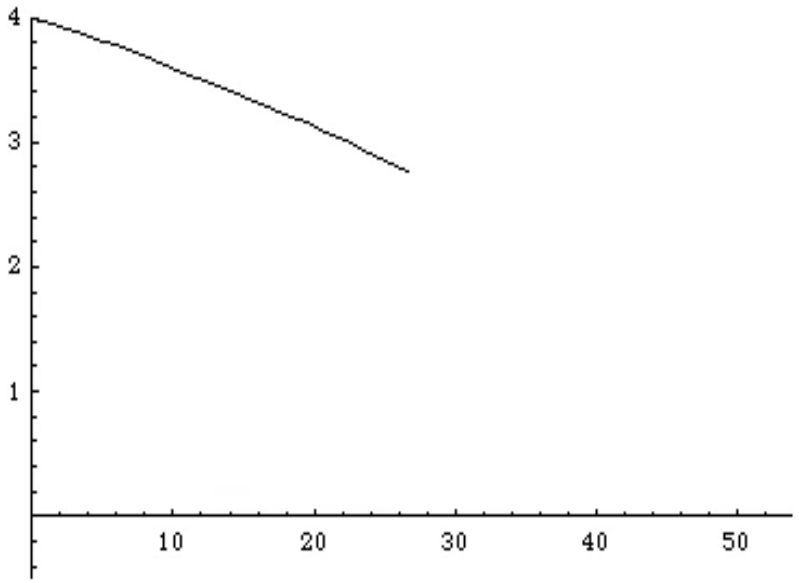
- Period of (quasi)-exponential expansion
  - Driven by slowly evolving scalar field
  - Dynamics fixed by field's potential
  - Solves "standard" cosmological problems
- Sets initial conditions for hot big bang
  - Thermalized universe, with small perturbations

Cartoon Version

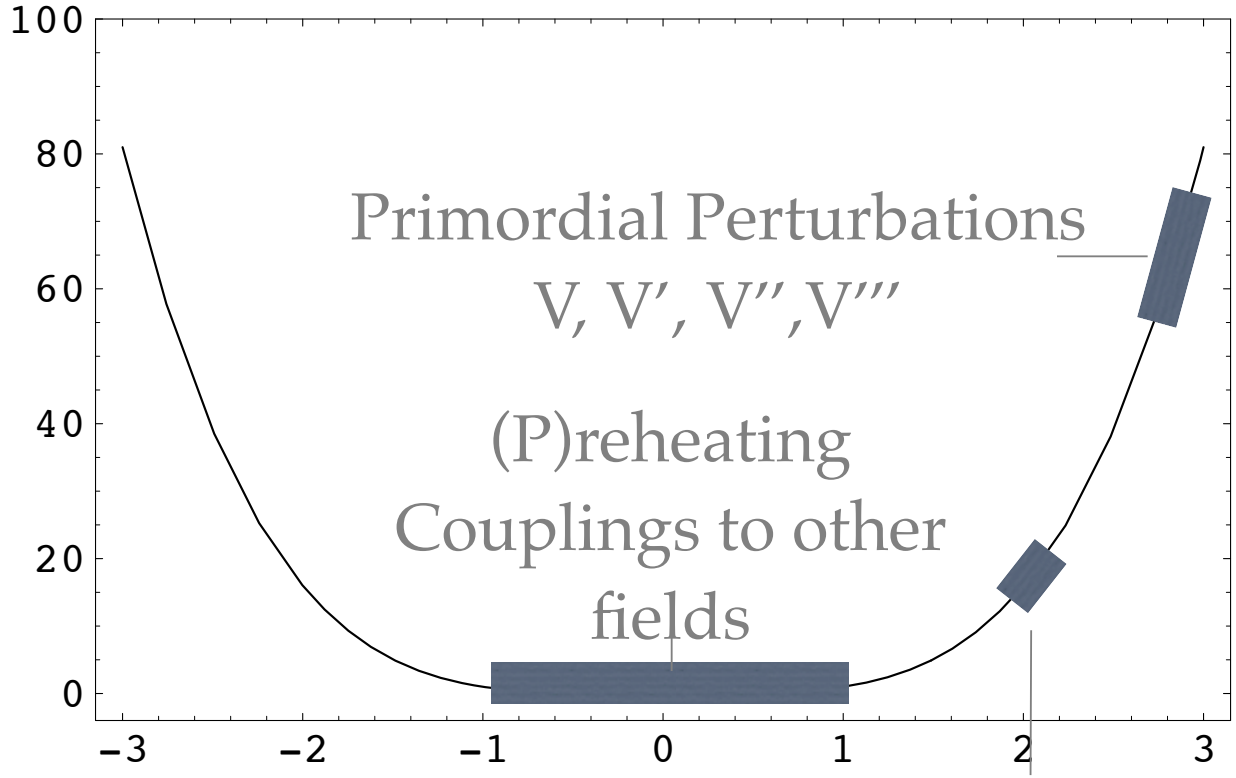
Field Evolution



Field v. log(scale factor)



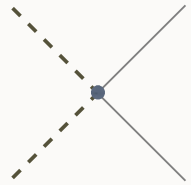
INFLATIONARY OBSERVABLES



Direct detection: BBO
V and V′

ENDING INFLATION

- Inflationary universe cold and empty
  - "Reheat" universe to set up hot big bang
- Originally: tree level couplings to inflaton
  - Couplings necessarily weak
- Parametric resonance / preheating
  - Non-perturbative; "stimulated emission"



PARAMETRIC RESONANCE: A QUICK SKETCH

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - \frac{1}{2} m^2 \phi^2 - \frac{g}{2} \phi^2 \chi^2$$

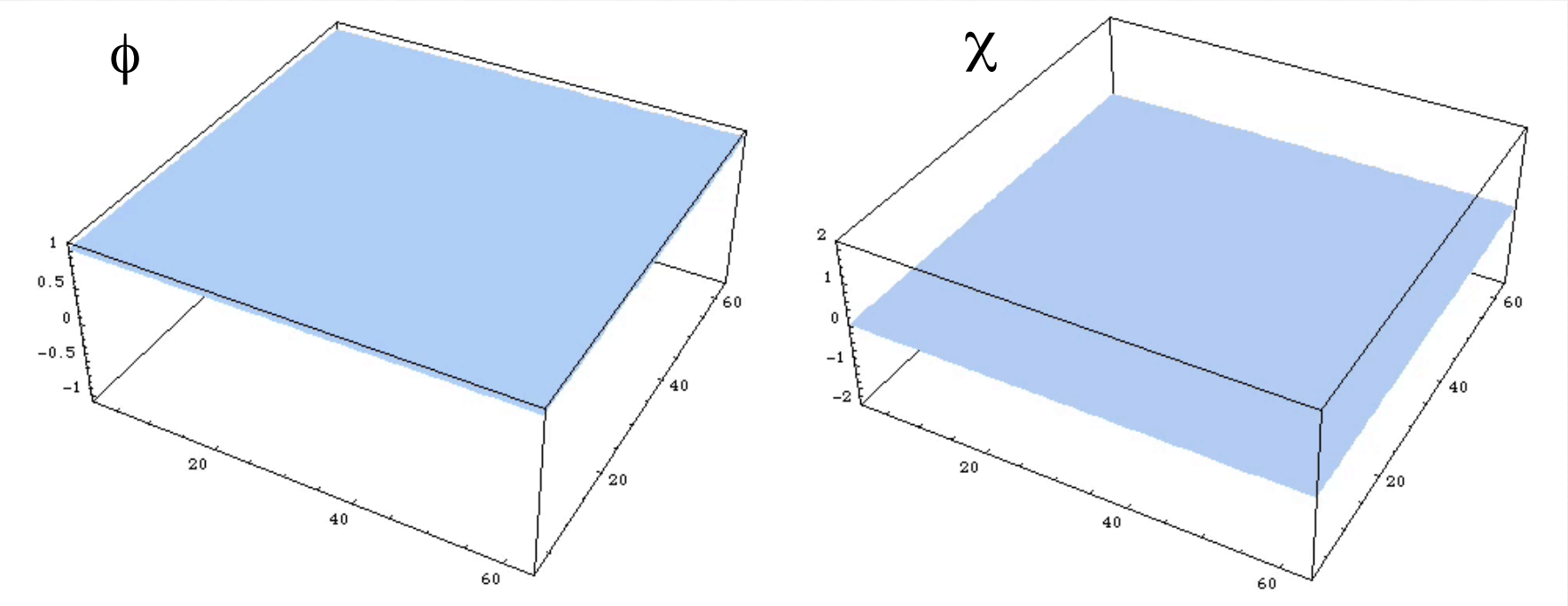
- ϕ is the inflaton field, χ coupled to inflaton
  - Perturbations in χ; canonically quantize χ_k

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + \cancel{m_\chi^2} + g^2 \phi^2 \right) \chi_k = 0$$

- Forced, damped oscillator (~Mathieu equation)
  - Exponetially growing solutions

PARAMETRIC RESONANCE: FOR BEGINNERS

SIMULATION

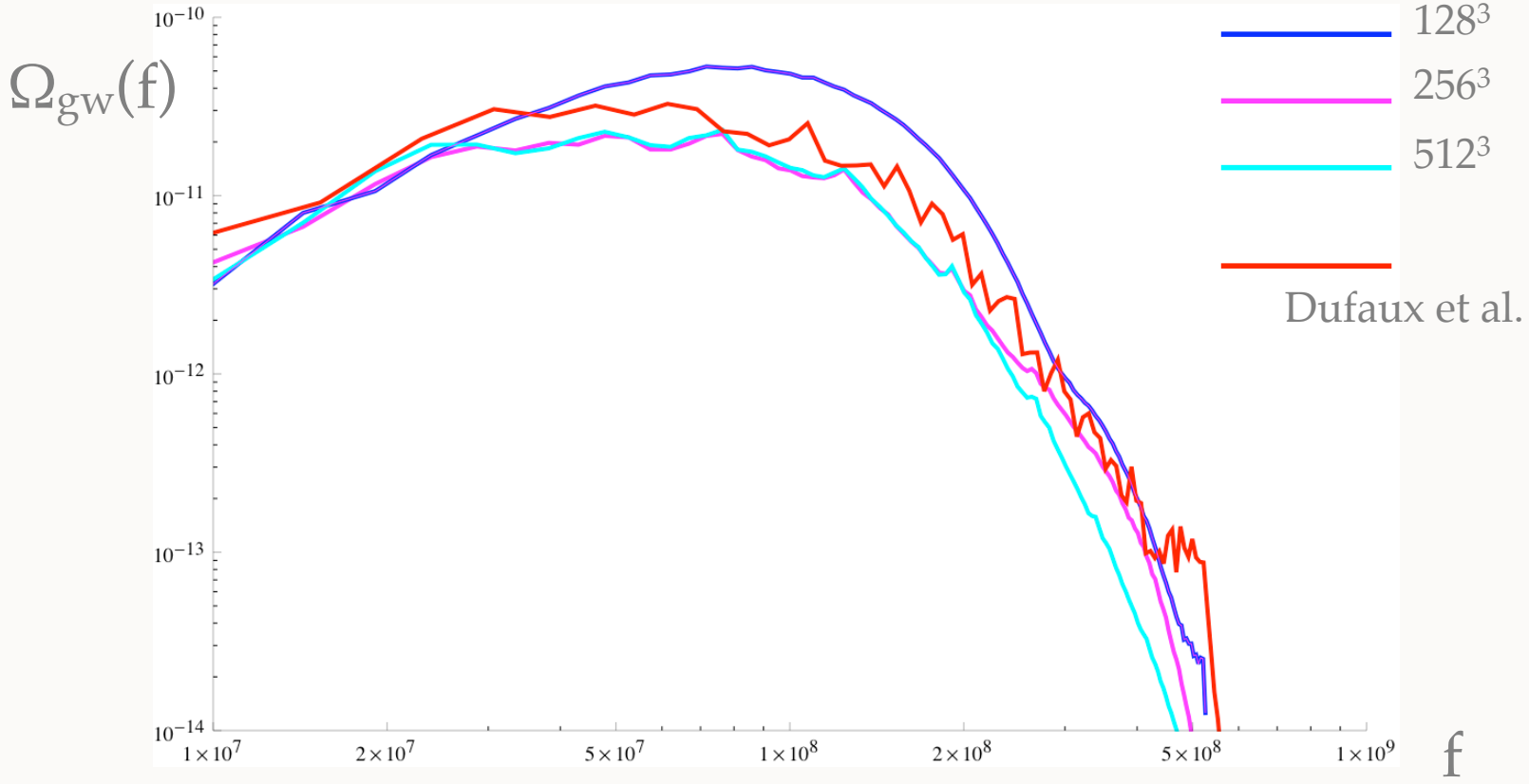


- Fields rescaled.

PRODUCTION OF GRAVITATIONAL WAVES

- Inhomogeneous universe; non-zero quadrupole
  - Sourced by gradient terms in fields (look at $T_{\mu\nu}$)
  - cf. Early universe phase transitions (first order EW)
- Assume spacetime rigid (ignore backreaction)
  - Need full nonlinear equations for scalar fields
  - Evolve transverse-traceless $h_{\mu\nu}$ (sourced by $T_{\mu\nu}$)
  - Solve alongside evolution of φ and χ

QUARTIC POTENTIAL (TOY MODEL)



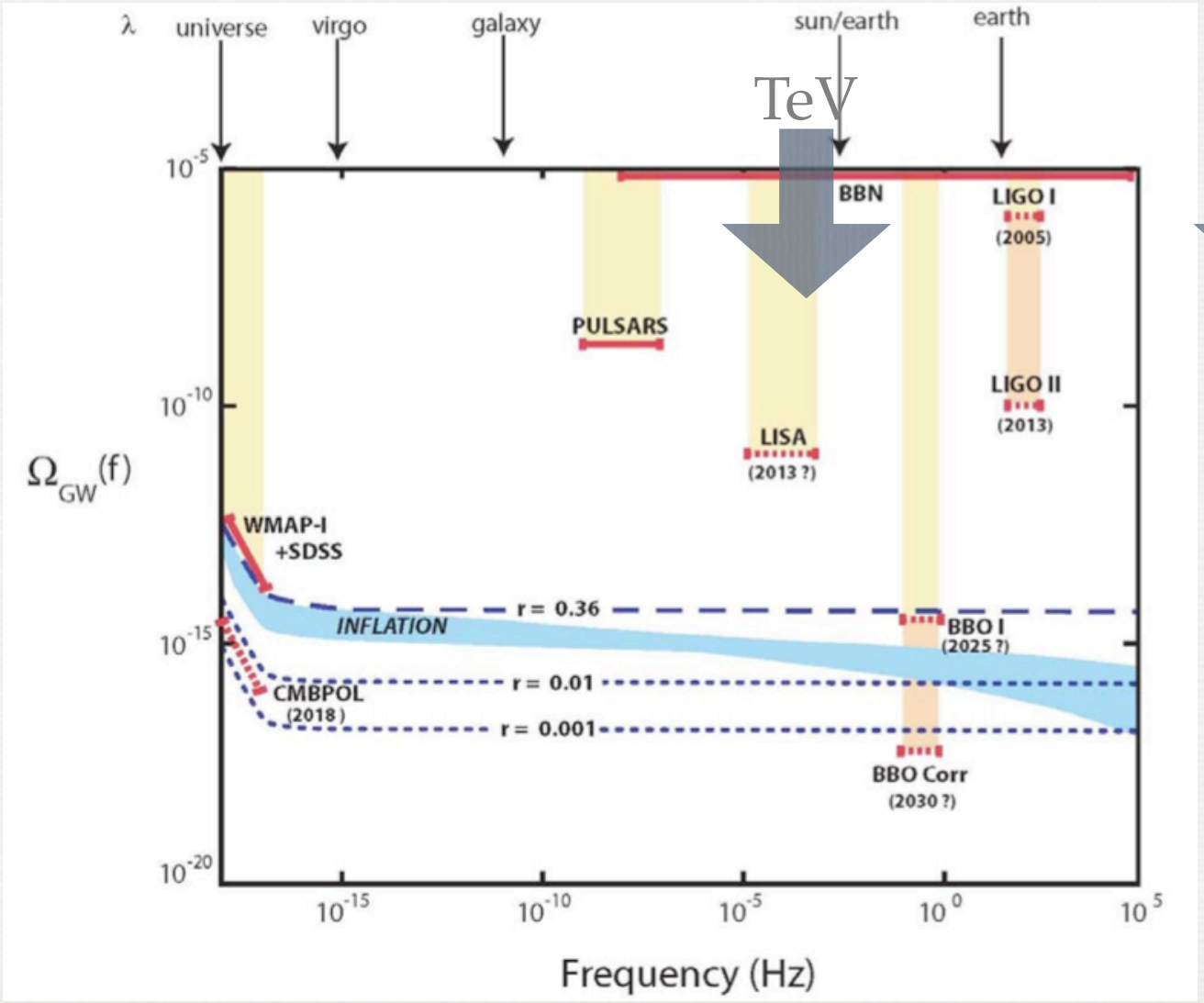
COMMENTS...

- Nontrivial numerical problem
- Four independent calculations; all well-matched!
  - Easther, Giblin & Lim: *astro-ph/0612294*
  - Dufaux et al. *astro-ph/0707.0875*
  - Garcia-Bellido and Figueroa: *astro-ph/0707.0839*
  - Price and Siemens: *astro-ph/0805.3570*

PEAK FREQUENCY (LOCATION)

- Hubble size at end of inflation: $1/H_{end} \sim (V_{end})^{-1/2}$
  - $H^2 \sim \rho \sim V_{inflation} \sim T_{max}^4$ (0-0 Einstein equation)
  - Growth since thermalization: $\sim T_{max}/T_{CMB}$
- Overall scaling: Peak location $\sim 1/T_{max}$ 
  - GUT scale inflation: cm - m today; MHz - GHz
  - Inflation at 10 TeV: $\sim 10^7$ km $\sim 10^{-2}$ Hz

EXPERIMENTS



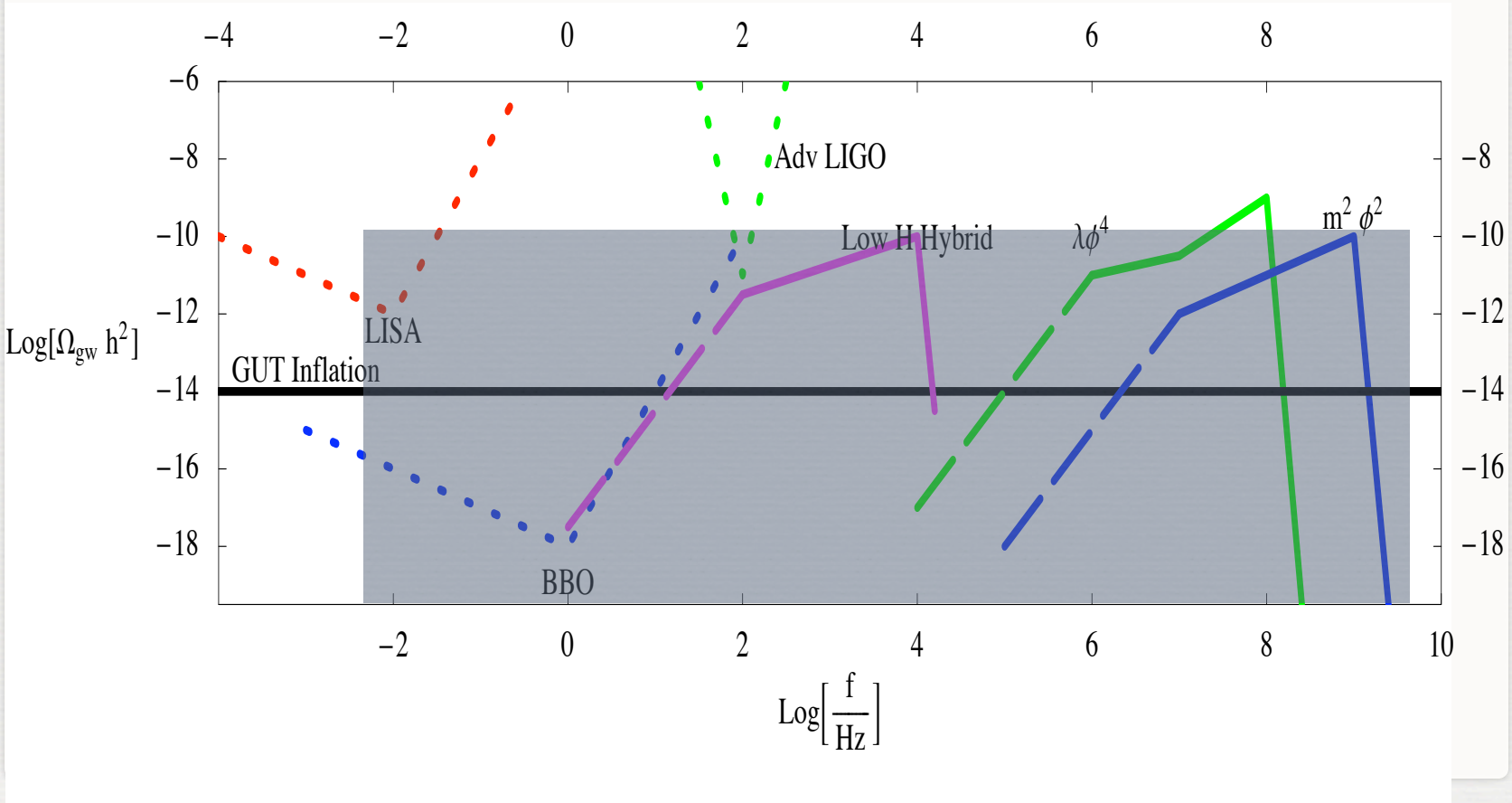
HEIGHT OF PEAK

- Upper bound: ~25% of total in *gradient* energy
  - GW background scales like radiation
  - Ω_{gw} fixed until matter domination
  - Independent of inflationary scale!!
  - Maximal $\Omega_{gw} \sim 10^{-10}$ today (large signal)
- Very model dependent (upper bound, verified by explicit calculations)

STRUCTURE OF PEAK

- Depends on underlying resonance structure
  - Many possibilities available
  - Including *broad* resonance (hard numerically)
- Sharp cutoff possible at high frequency
- Potential for long ~k^3 tail at low frequencies
- Also bubble collisions, vector and fermionic modes

SUMMARY PLOT



GRAVITATIONAL WAVE BACKGROUNDS

Primordial	Preheating
Quantum source	Classical source
Scale Invariant	Peaked at “human” scales
Low H : Low amplitude	Low H : redder peak
Always generated	Strongly model dependent
Amplitude bounded by CMB	Amplitude possibly large
$\Omega_{gw,inf}\, h^2 < 10^{-14}$	$\Omega_{gw}\, h^2 \lesssim 10^{-10}$

REMARKS

- Still work in progress
  - But opens new window on inflationary physics
  - Link between inflation and “everything else”
- Present status: “Existence proof”
  - Preheating *can* generate background
  - Need to understand if this signal is generic
  - Preheating “free” in most (?) models of inflation

REMARKS

- Preheating involves tough physics
  - Nonlinear, nonequilibrium, in expanding universe.
  - But code(s) now mature and well-tested
- Other early universe gravitational wave sources
  - Bubble formation, phase transitions
  - Code will work for any stochastic background

QUANTUM TO COSMOS: TAKE-HOME MESSAGES

- Signal depends on energy scale of inflation
  - GUT scale inflation: ~GHz GW signal
  - Also be visible in CMB B-mode / BBO
  - Hard to find good models of GUT scale inflation
- *Most* string models at lower scales?
  - This signal gets easier to see

QUANTUM TO COSMOS: TAKE-HOME MESSAGES

- Need to understand whether preheating is *generic*
  - But not "cooked up" for gravitational waves
- Any gravitational waves are exciting
- Learn /confirm energy scale of inflation (huge!)
- Connect inflation to "rest of physics" (string/GUT?)