Gravitational Waves from Cosmological Phase Transitions

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Phase transitions occur at a characteristic temperature and release energy into primordial plasma (latent heat)

Electroweak phase transition: T=100 GeV, t= 1/H = 1.e-12 seconds

QCD phase transition: T=100 MeV, t= 1/H= 1.e-6 seconds

At any time in the early universe, 1/H is the only length / time scale

This scale sets the gravitational wave frequency today, typically 0.01/H

This frequency for EW phase transition is around 1.e-3 Hz (LISA!)

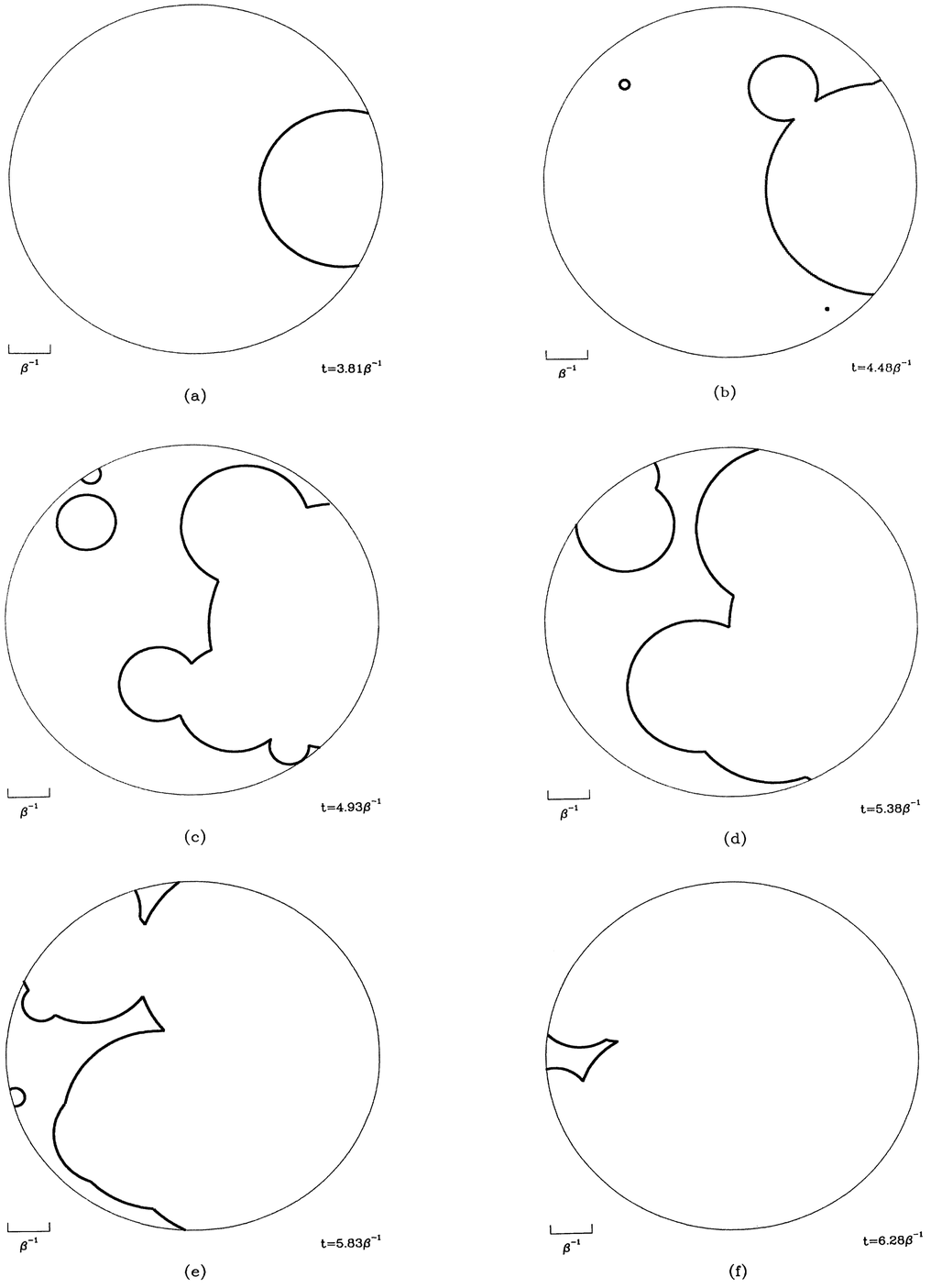
This frequency for QCD phase transition is around 1.e-6 Hz

First-Order: proceeds via nucleation of lower-energy phase bubbles which expand and merge. Latent heat into kinetic plus thermal energy

Continuous: latent heat into thermal energy, little kinetic energy

What is the temperature of the phase transition?
How much energy density goes into the plasma?
What fraction of that energy goes into kinetic energy?
On what length scale is the kinetic energy injected?
How long does the plasma motion last?

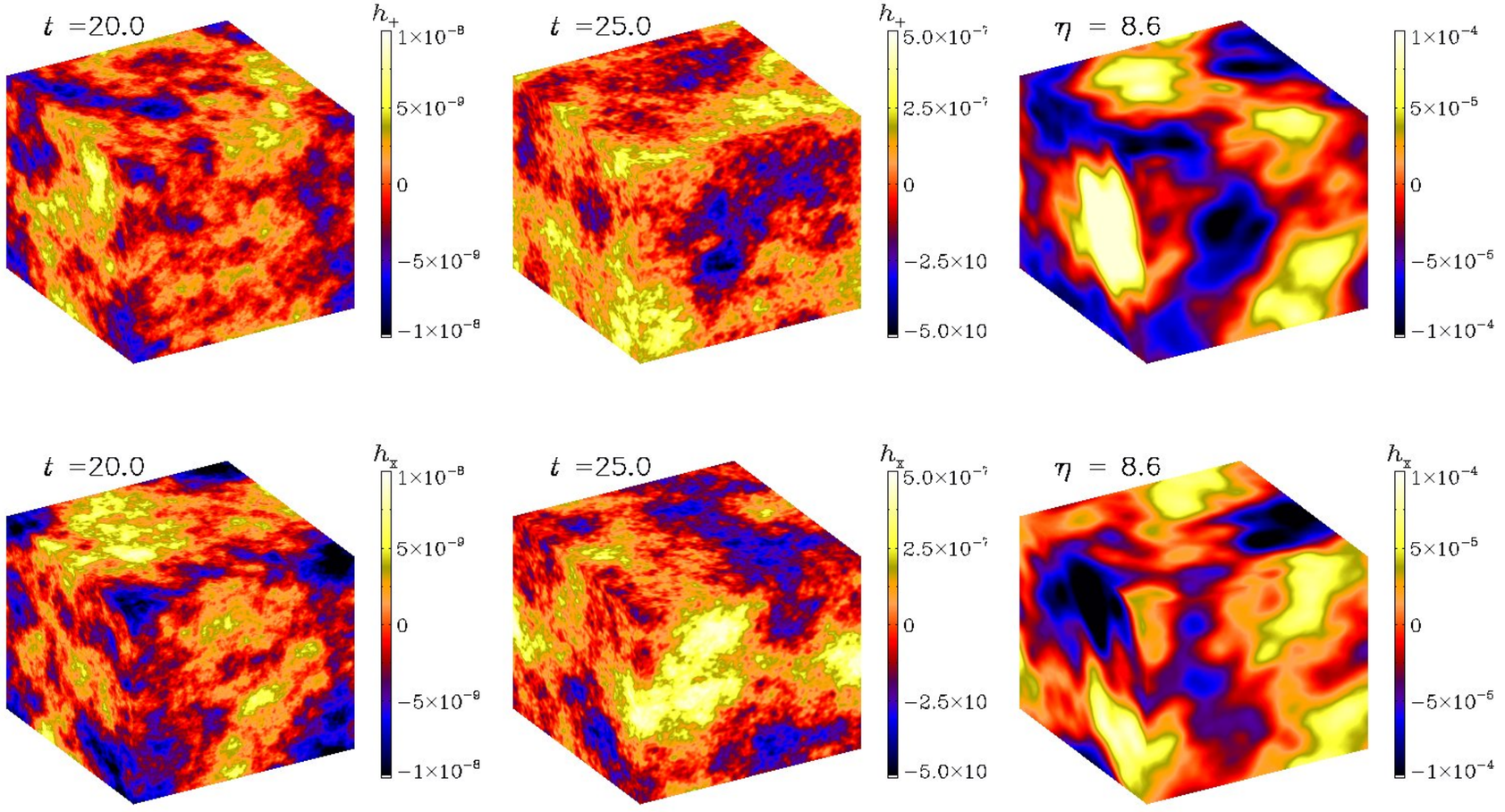
(Details of the plasma motion)



Nucleation rate per unit volume

$$\Gamma(t) = \Gamma_0 e^{\beta t}$$

Kosowsky and Turner 1993


t =20.0
h_+
1×10^{-8}
5×10^{-9}
0
-5×10^{-9}
-1×10^{-8}
t =25.0
h_+
5.0×10^{-7}
2.5×10^{-7}
0
-2.5×10
-5.0×10
η = 8.6
1×10^{-4}
5×10^{-5}
0
-5×10^{-5}
-1×10^{-4}
t =20.0
$h_\times$
1×10^{-8}
5×10^{-9}
0
-5×10^{-9}
-1×10^{-8}
t =25.0
$h_\times$
5.0×10^{-7}
2.5×10^{-7}
0
-2.5×10
-5.0×10
η = 8.6
$h_\times$
1×10^{-4}
5×10^{-5}
0
-5×10^{-5}
-1×10^{-4}

Numerical Computations of Gravitational Waves from Turbulence

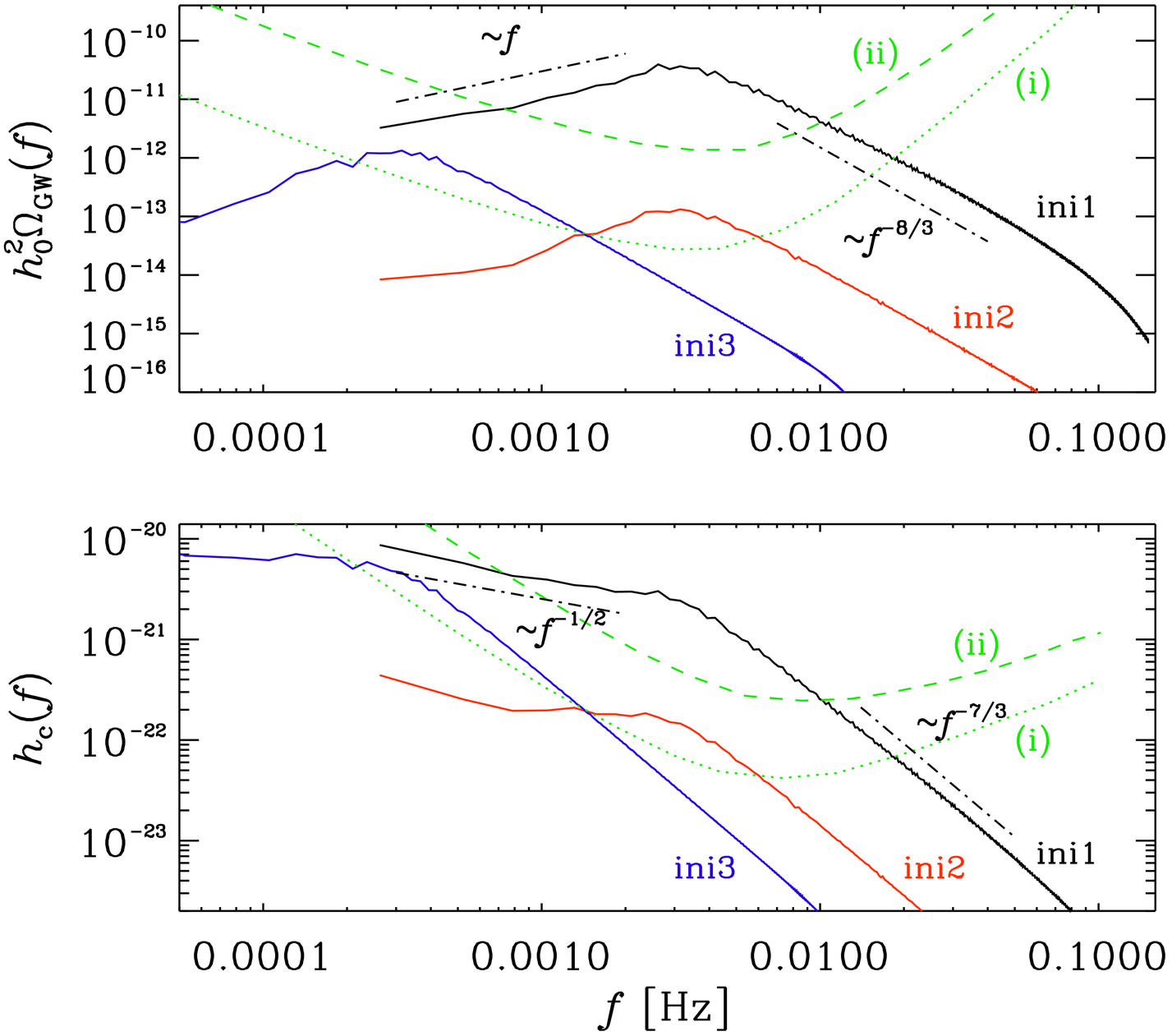
A. Roper Pol, A. Brandenburg, T. Kahniashvili,
A. Kosowsky, and S. Mandal, GeoAstFD 2020,
arXiv:1807.05479

A. Roper Pol, S. Mandal, A. Brandenburg,
T. Kahniashvili, and A. Kosowsky, PRD 2020
arXiv:1903.08585

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 h_{ij}(\mathbf{x}, t) = \frac{16\pi G}{c^4} S_{ij}(\mathbf{x}, t)$$

$$S_{ij}(\mathbf{x}, t) \equiv T_{ij}(\mathbf{x}, t) - \frac{1}{3}\delta_{ij} T^k{}_k(\mathbf{x}, t)$$


$h_0^2\Omega_{GW}(f)$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$\sim f$
(ii)
(i)
ini1
$\sim f^{-8/3}$
ini2
ini3
0.0001
0.0010
0.0100
0.1000
$h_c(f)$
10^{-20}
10^{-21}
10^{-22}
10^{-23}
$\sim f^{-1/2}$
(ii)
$\sim f^{-7/3}$
(i)
ini1
ini3
ini2
0.0001
0.0010
0.0100
0.1000
f [Hz]

Gravitational wave amplitude depends on form of initial conditions: turbulence versus acoustic waves

Need realistic numerical initial conditions