Signatures from Preheating

KITP Seminar
UC Santa Barbara
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Inst. Física Teórica

Gravitational waves and Magnetic fields: A new window into the early Universe

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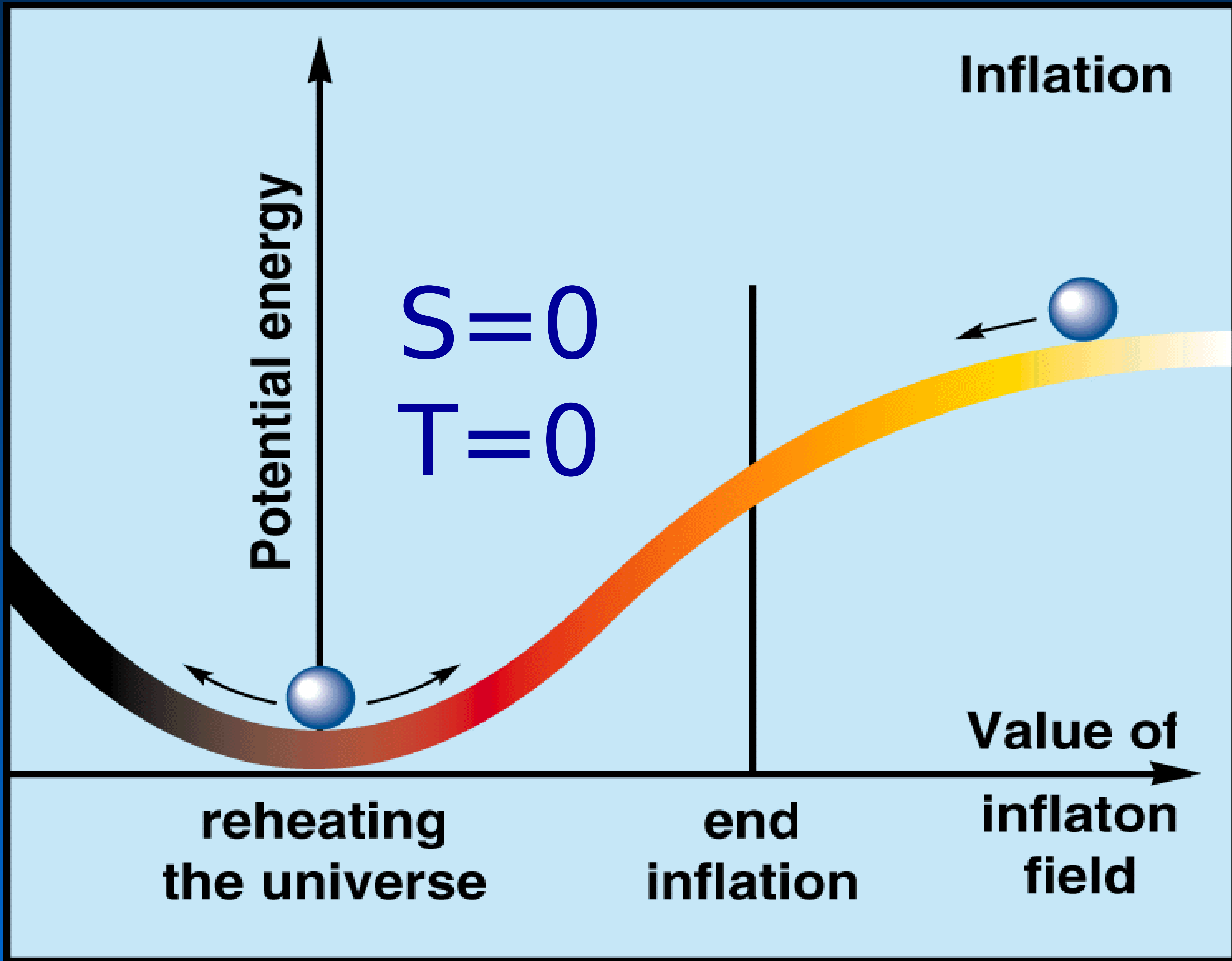
PRL98, 061302 (2007) [astro-ph/0701014] + arXiv:0707.0839 [hep-ph]

Andres Diaz-Gil, J. G.-B.
Margarita Garcia Perez

hep-lat/0509094
arXiv:0710.0580 [hep-lat]

The origin of matter and radiation


Inflation
Potential energy
S=0
T=0
Value of
inflaton
field
reheating
the universe
end
inflation

Preheating

ery rich phenomenology after inflatio

- Non-thermal production of particles (CDM)
- Production of topological defects (strings)
- EW baryogenesis & leptogenesis
- Production of gravitational waves
- Production of primordial magnetic fields
- etc.

Tachyonic preheating

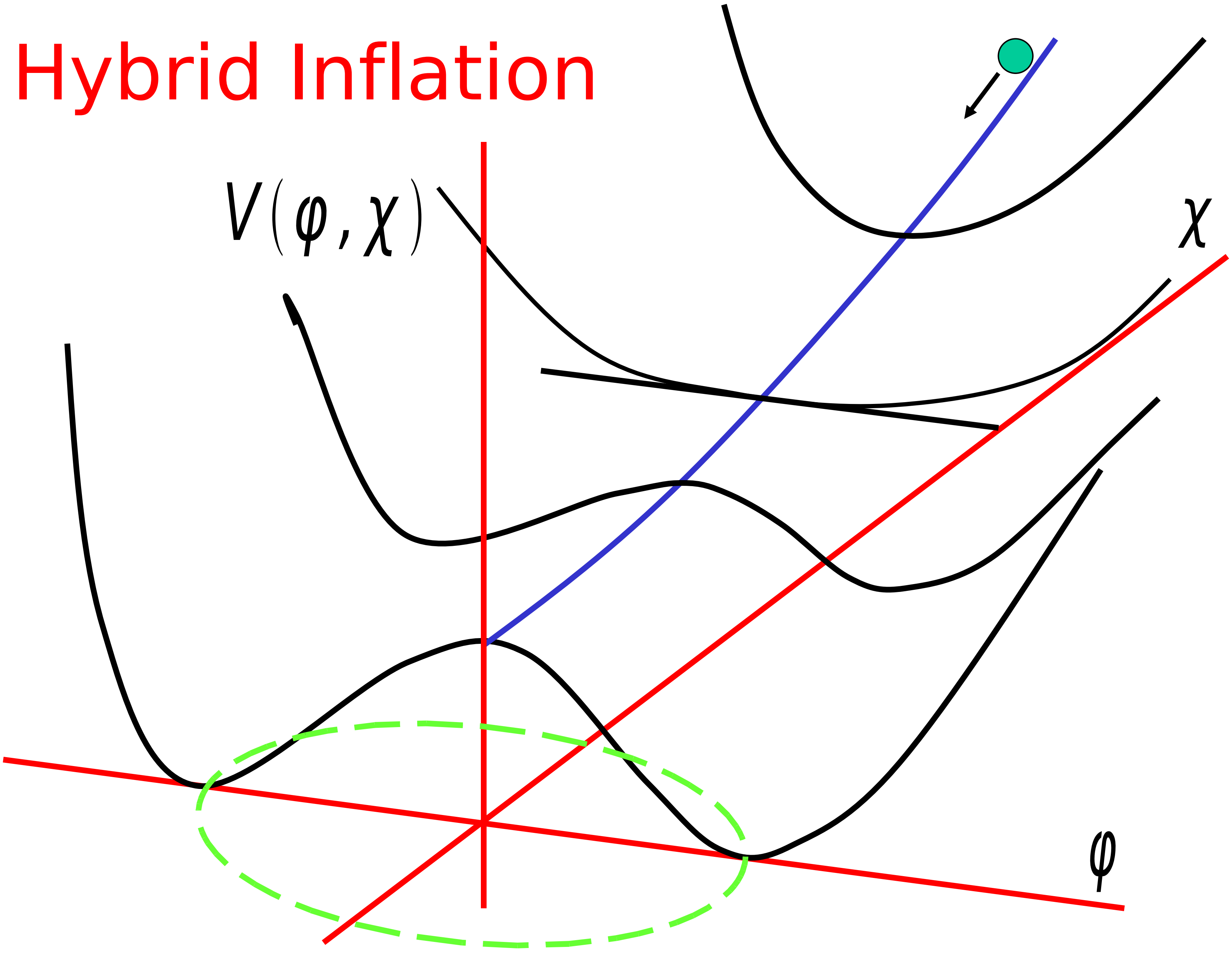
JGB, Linde	PRD57, 6075 (1998)
Felder, JGB, Kofman, Linde, Tkachev	PRL87, 011601 (2001) PRD64, 123517 (2001)
JGB, García-Perez, González-Arroyo	PRD67, 103501 (2003) PRD69

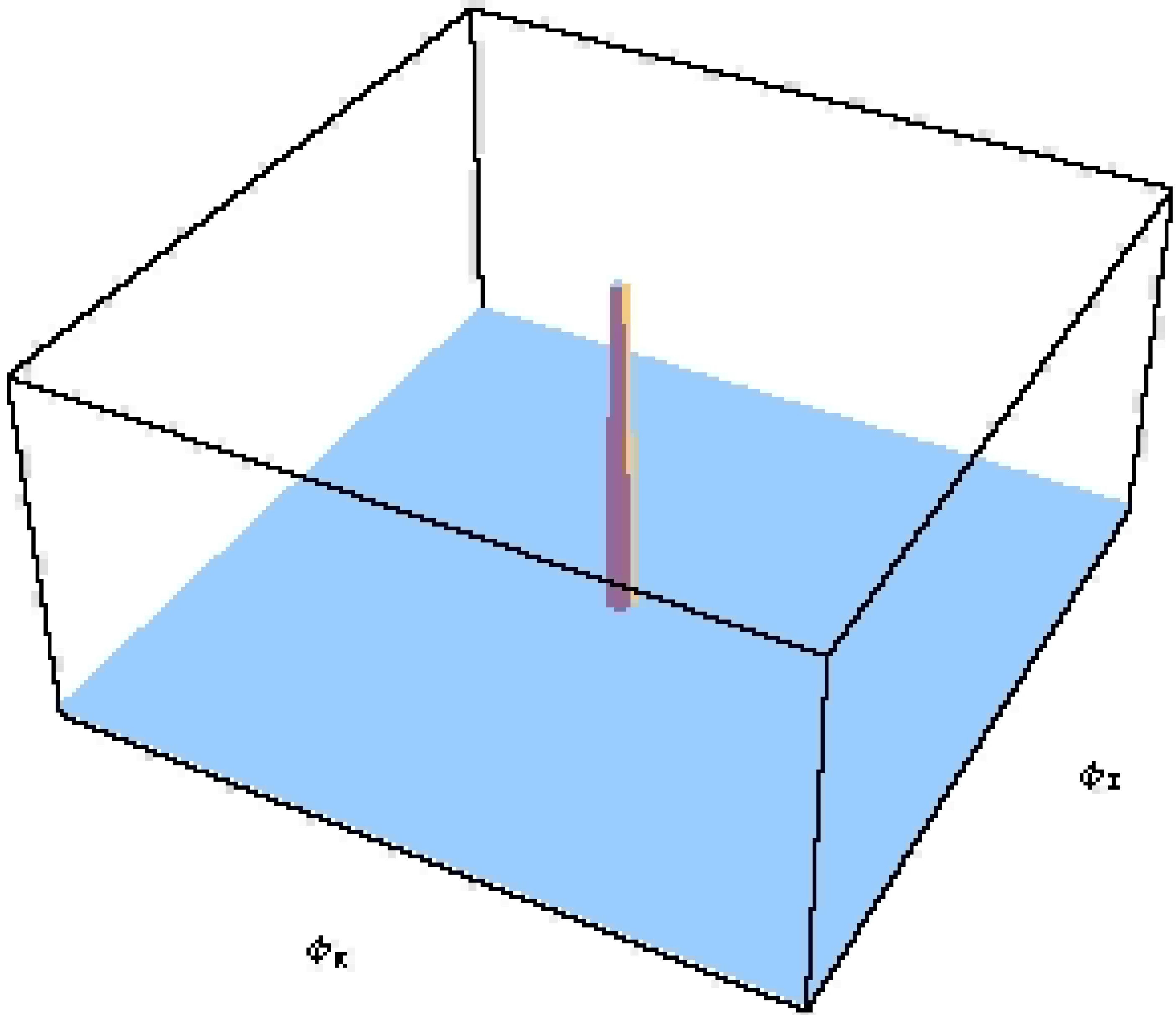
Tachyonic preheating

Spinodal growth of long wave Higgs modes

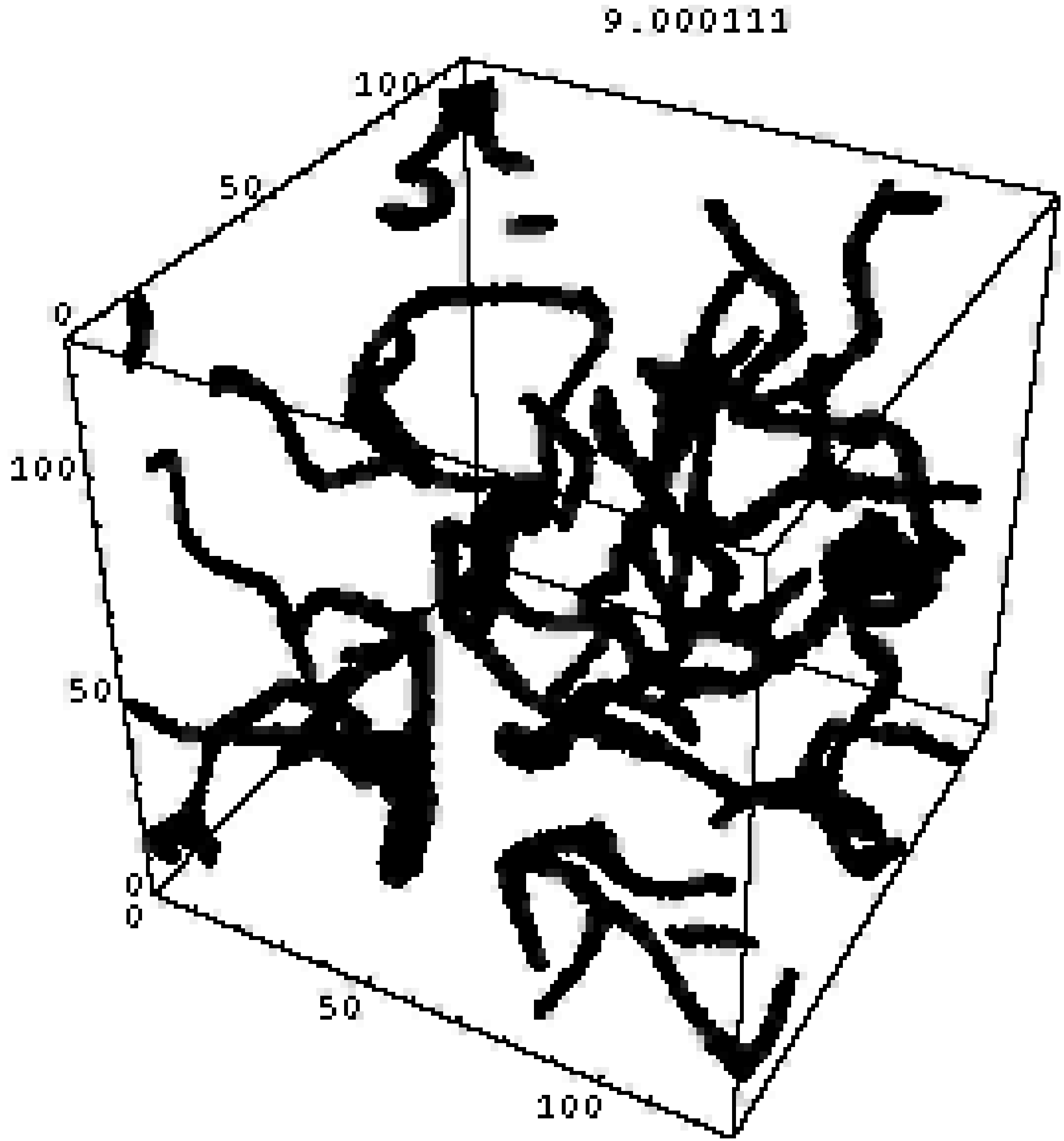
- At the end of Hybrid Inflation
- Higgs couples to gauge fields
- Strong production of fermions
- Production of cosmic strings

Hybrid Inflation



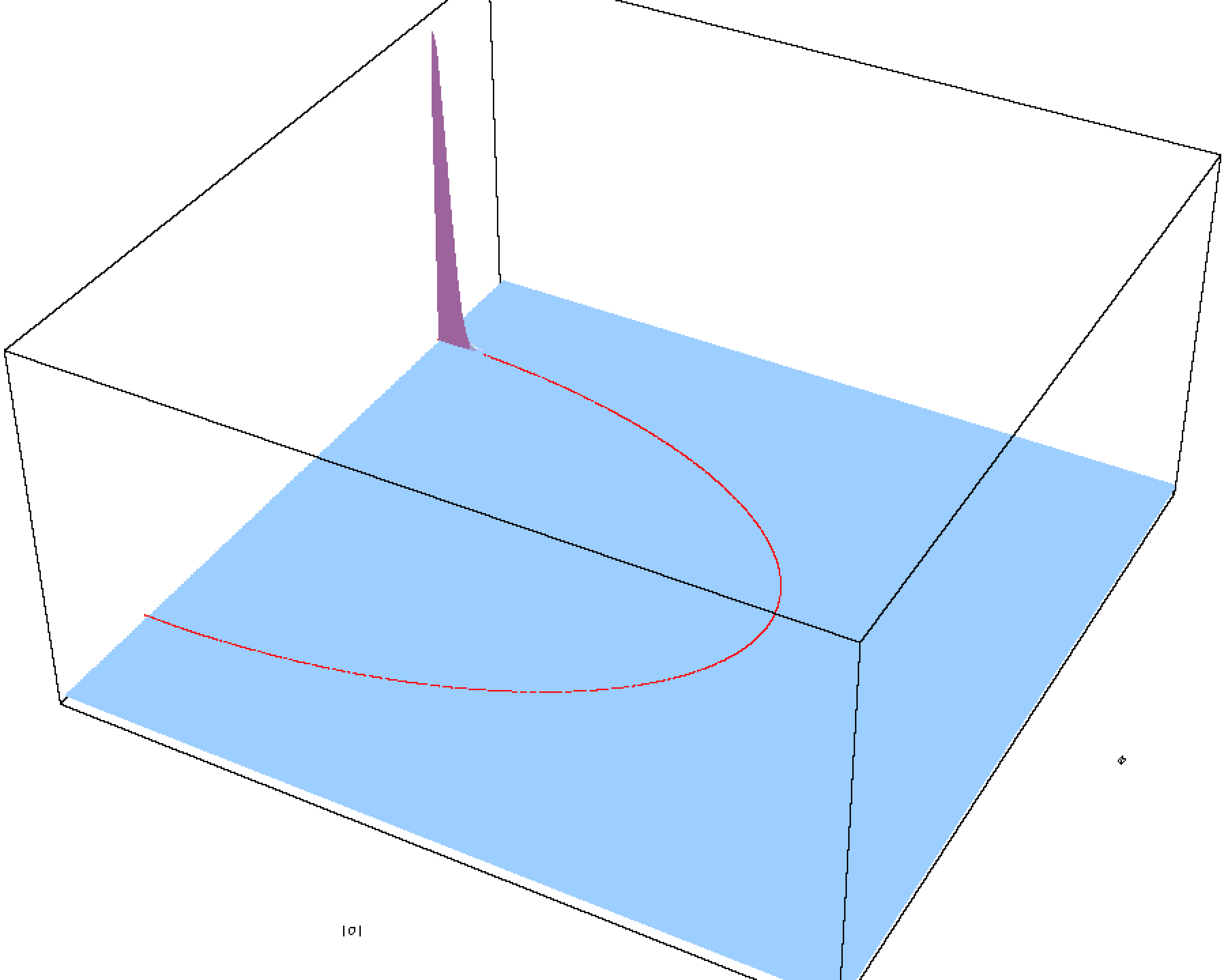


ϕ_R
ϕ_I



$\varphi \in U(1)$

String production @ end hybrid inflation


|σ|
φ

The Higgs Evolution

$$m_\varphi^2 = m^2\left(\frac{\chi^2}{\chi_c^2} - 1\right) \approx -2Vm^3(t - t_c)$$

$$= -M^3(t - t_c) = -M^2\tau$$

$$H = \frac{1}{2}\int d^3k\left[p_k(\tau)p_k^+(\tau) + (k^2 - \tau)y_k(\tau)y_k^+(\tau)\right]$$

$$\left[y_k(\tau), p_{k'}(\tau)\right] = i\hbar\,\delta^3(k - k')$$

Higgs Quantum Field

$$y_k(\tau)=f_k(\tau)a_k(\tau_0)+f_k^{¿}(\tau)a^{+}_{-k}(\tau_0)$$

$$p_k(\tau)=-i\left[g_k(\tau)a_k(\tau_0)-g_k^{¿}(\tau)a^{+}_{-k}(\tau_0)\right]$$

$$f''_k+(k^2-\tau)f_k=0 \qquad\qquad g_k=if'_k$$

Airy function

$$\Omega_k(\tau)=\frac{g_k^{¿}(\tau)}{f_k^{¿}(\tau)}=\frac{1-2iF_k(\tau)}{2|f_k(\tau)|^2}$$

$$F_k(\tau)=\mathrm{Im}(f_k^{¿}g_k)$$

Quantum Initial Conditions

$$\forall k \;\; a_k(\tau_0)|0,\tau_0\rangle = 0 \Rightarrow \Psi_0(\tau_0) = N_0 e^{-k|y_k^0|^2}$$

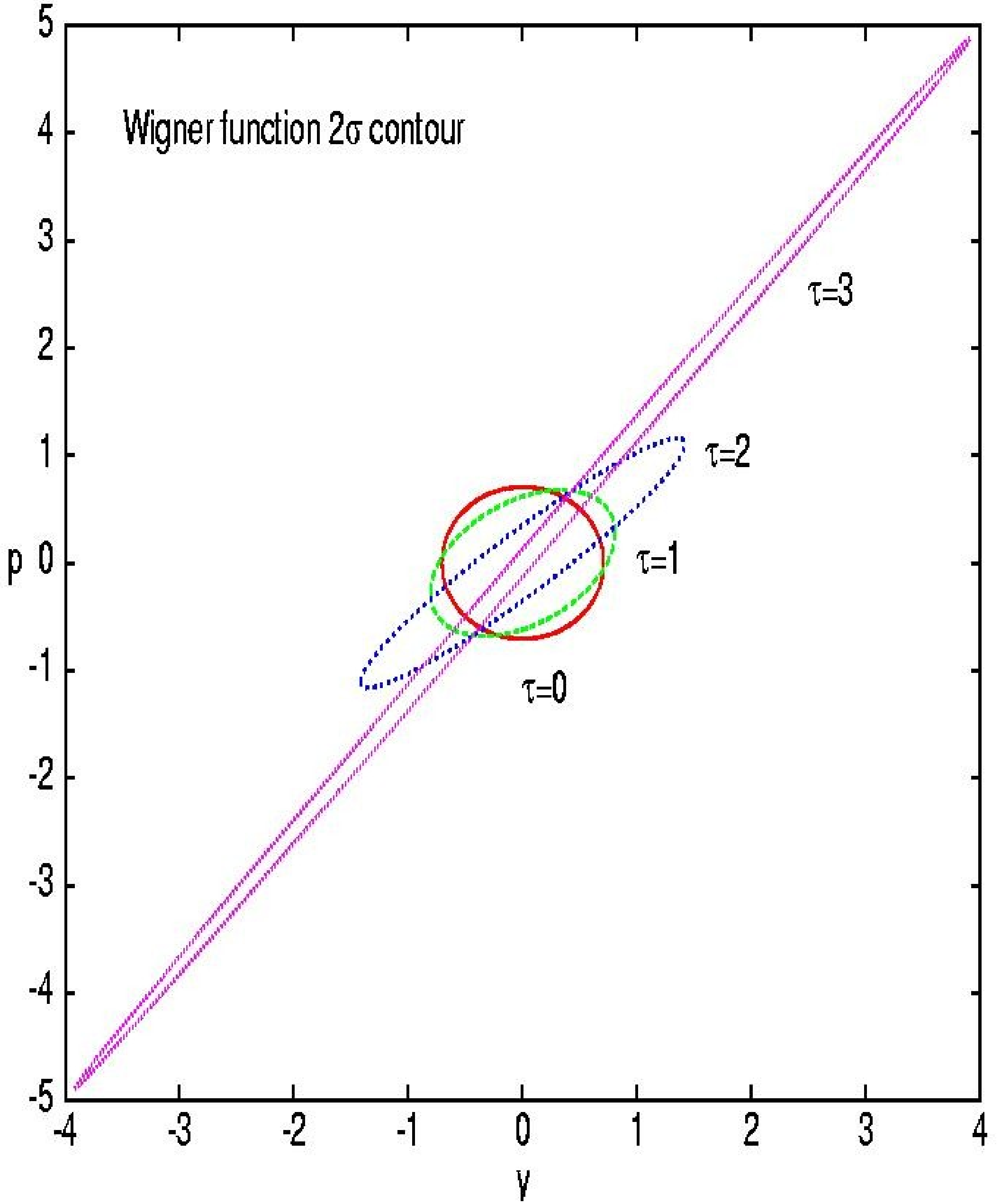
Unitary Evolution

$$|0,\tau\rangle = U|0,\tau_0\rangle \Rightarrow \Psi_0(\tau) = \frac{1}{\sqrt{\pi}|f_k|} e^{-\Omega_k(\tau)|y_k^0|^2}$$

Occupation number of mode k

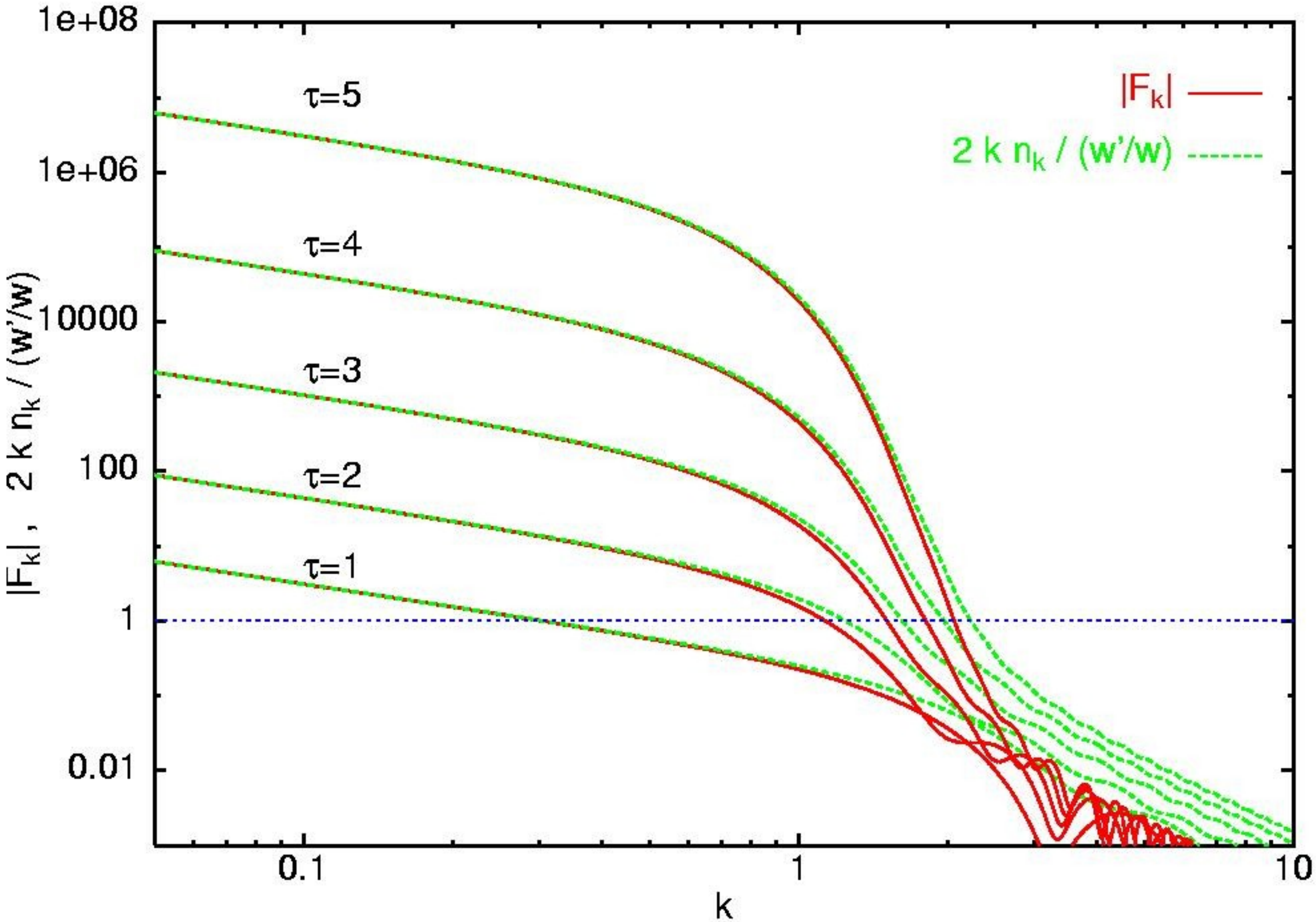
$$n_k(\tau) = \langle 0,\tau|N_k(\tau_0)|0,\tau\rangle = \frac{1}{2k}|g_k|^2 + \frac{k}{2}|f_k|^2 - \frac{1}{2}$$

Wigner function



Quantum to Classical Transition

$$\langle 0,\tau | G(\hat{y},\hat{p}) | 0,\tau \rangle \approx \langle G_0(y,p) \rangle_{gaussian}$$



$$|F_k(\tau)| \gg 1$$

Semiclassical (diagonal density functional)

Quantum to Classical Transition

For $k < \sqrt{\tau}$ (longwave modes)

Power spectrum (approximation):

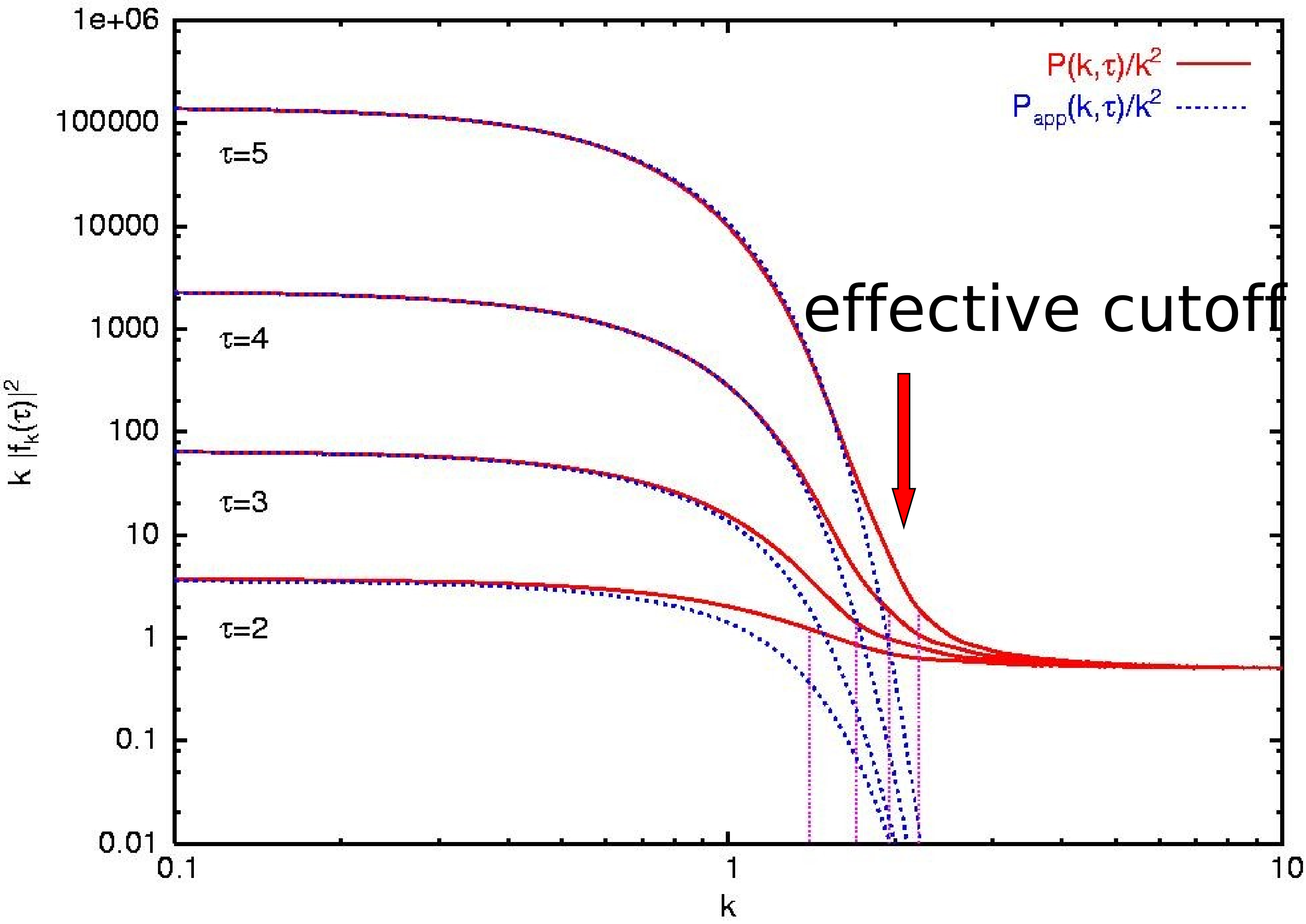
$$P_{app}(k,\tau) = k^3 |f_k(\tau)|^2 \approx A(\tau) k^2 e^{-B(\tau)k^2}$$

$$A(\tau) = A_0 Bi^2(\tau) \approx \frac{A_0}{\pi\sqrt{\tau}} e^{\frac{4}{3}\tau^{3/2}}$$

$$B(\tau) = 2\sqrt{\tau}$$

Airy function

Power spectrum of longwave modes



Lattice Simulations

Quantum averages = Gaussian ensemble averages

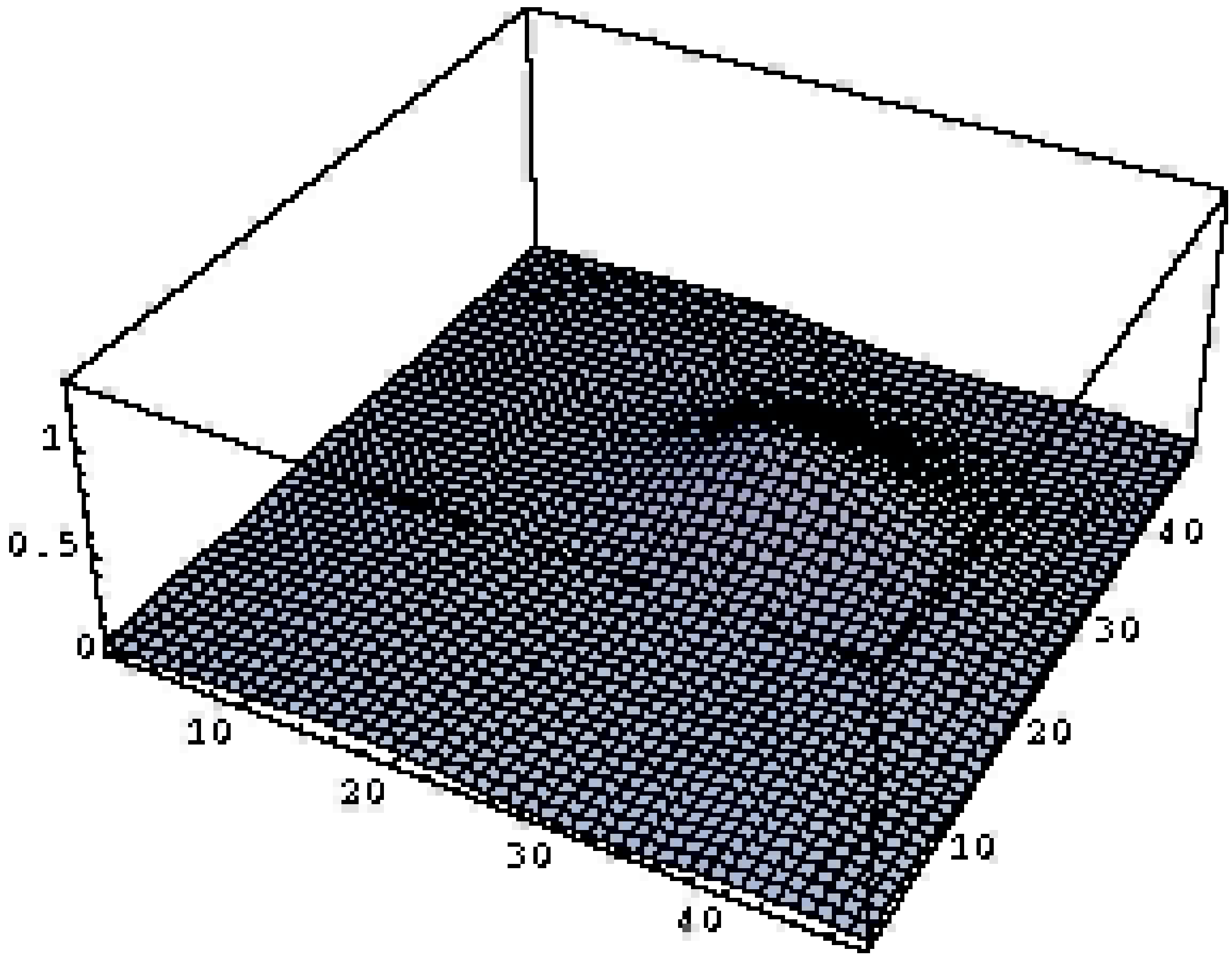
Initial conditions: Highly occupied modes

$$|0,\tau\rangle = U|0,\tau_0\rangle \Rightarrow \Psi_0(\tau) = \frac{1}{\sqrt{\pi}|f_k|} e^{-\Omega_k(\tau)|y_k^0|^2}$$

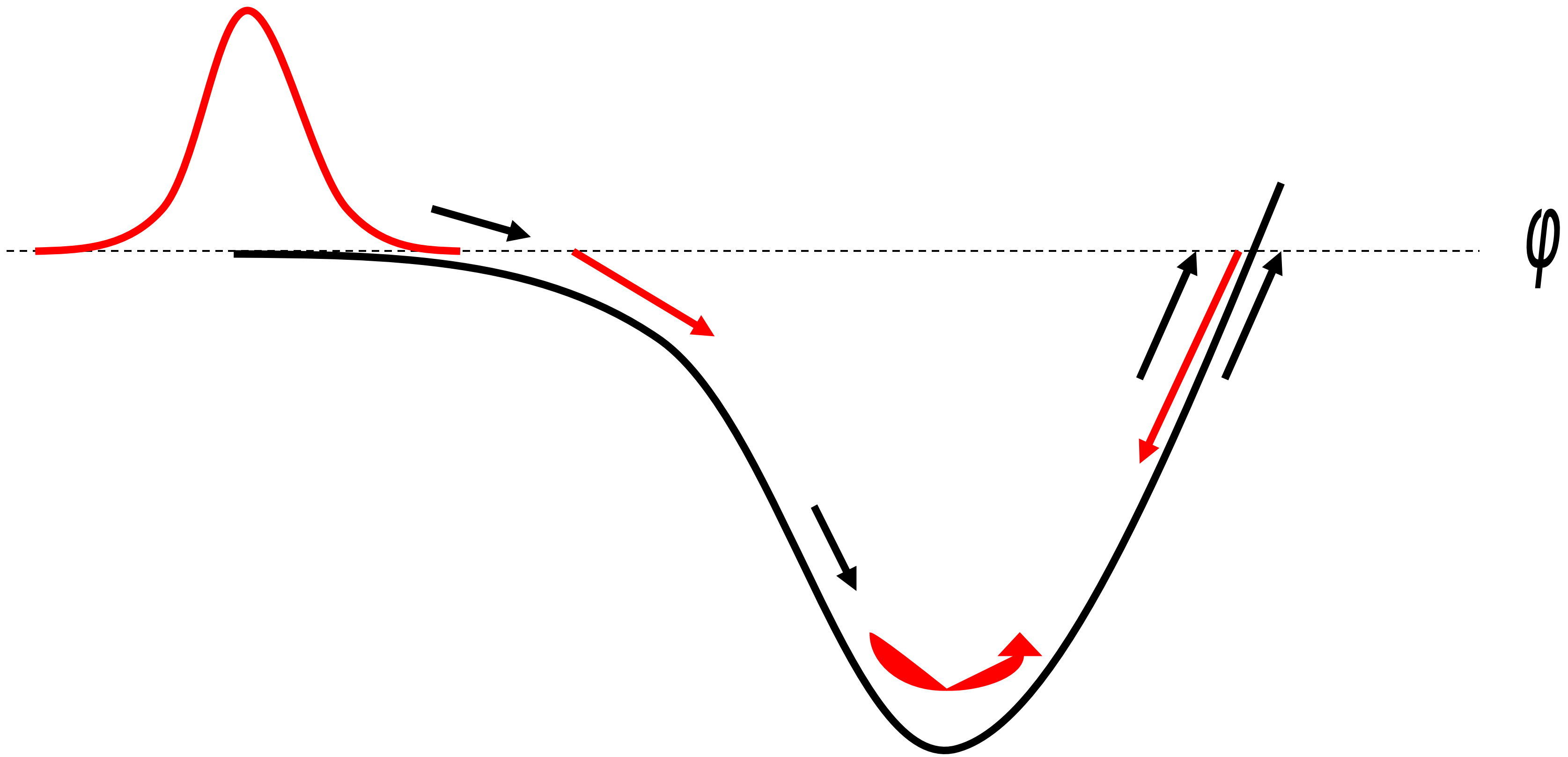
Rayleigh distribution:

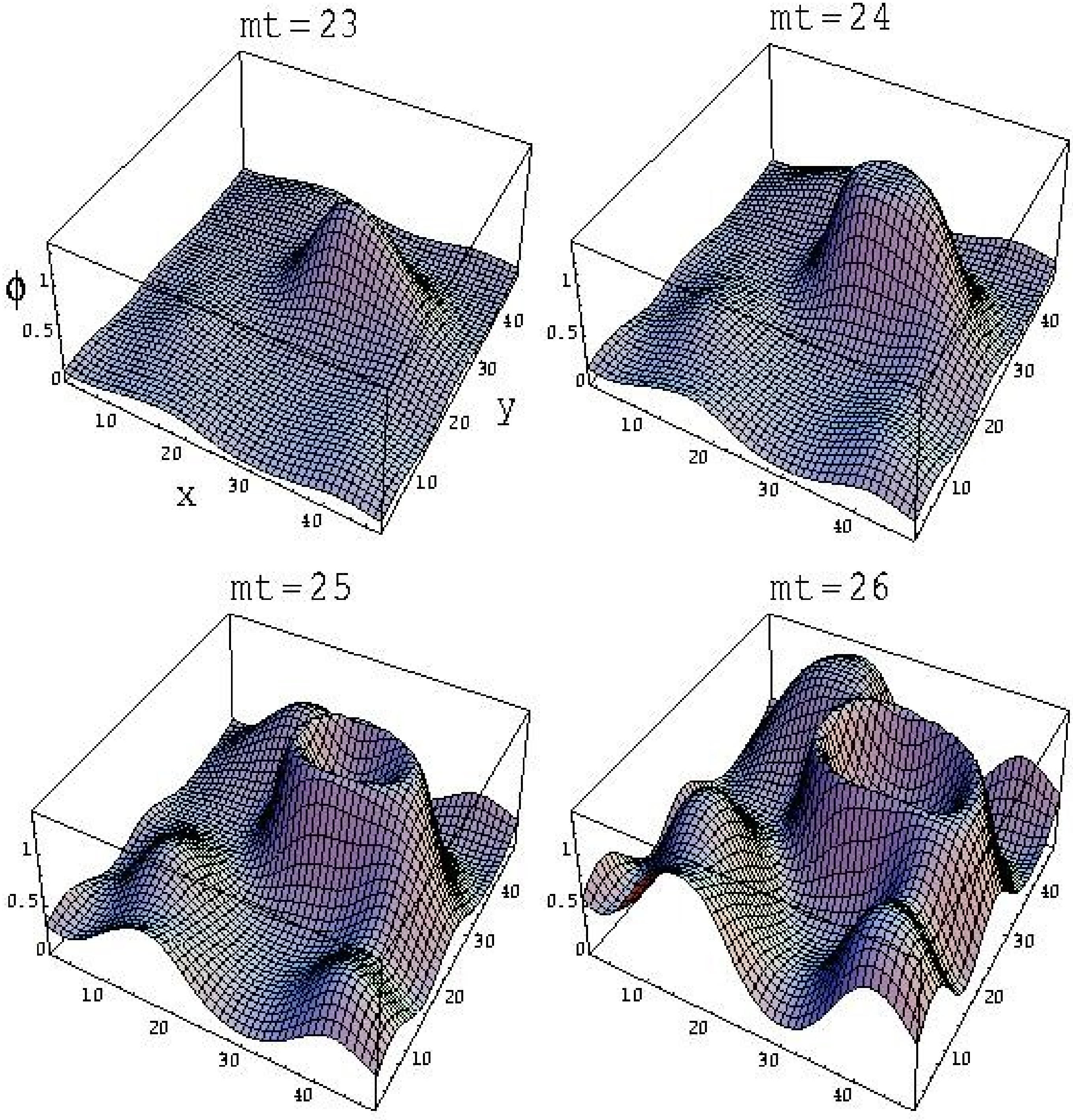
$$P_\psi(|\varphi_k|)d|\varphi_k|d\theta_k = e^{-\frac{|\varphi_k|^2}{|f_k|^2}} \frac{d|\varphi_k|^2}{|f_k|^2} \frac{d\theta_k}{2\pi}$$

High peaks of Higgs field

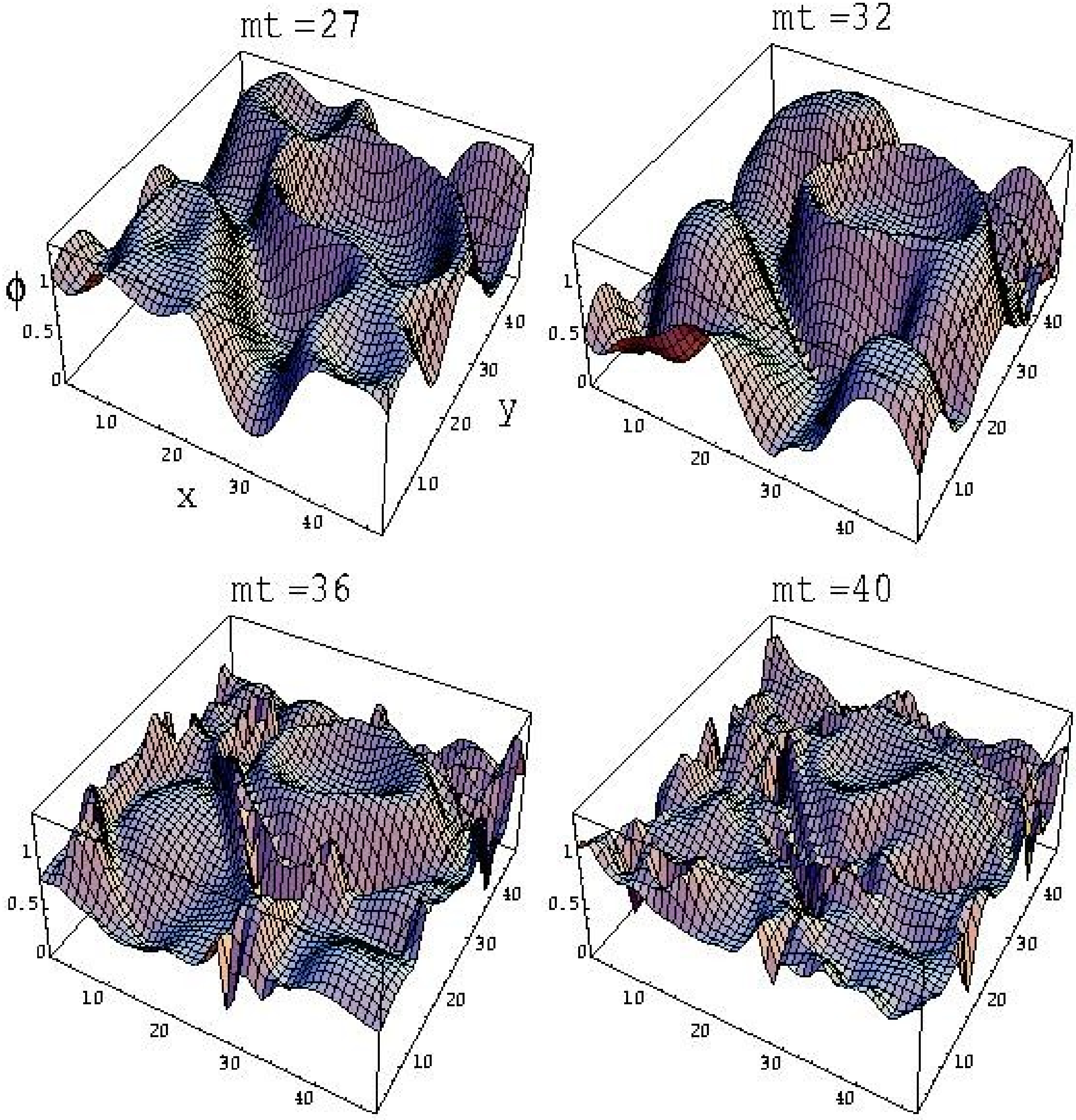


High peaks





mt = 23
mt = 24
mt = 25
mt = 26
ϕ
x
y
0
0.5
1
10
20
30
40



mt =27
mt =32
mt =36
mt =40
ϕ
1
0.5
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x
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10
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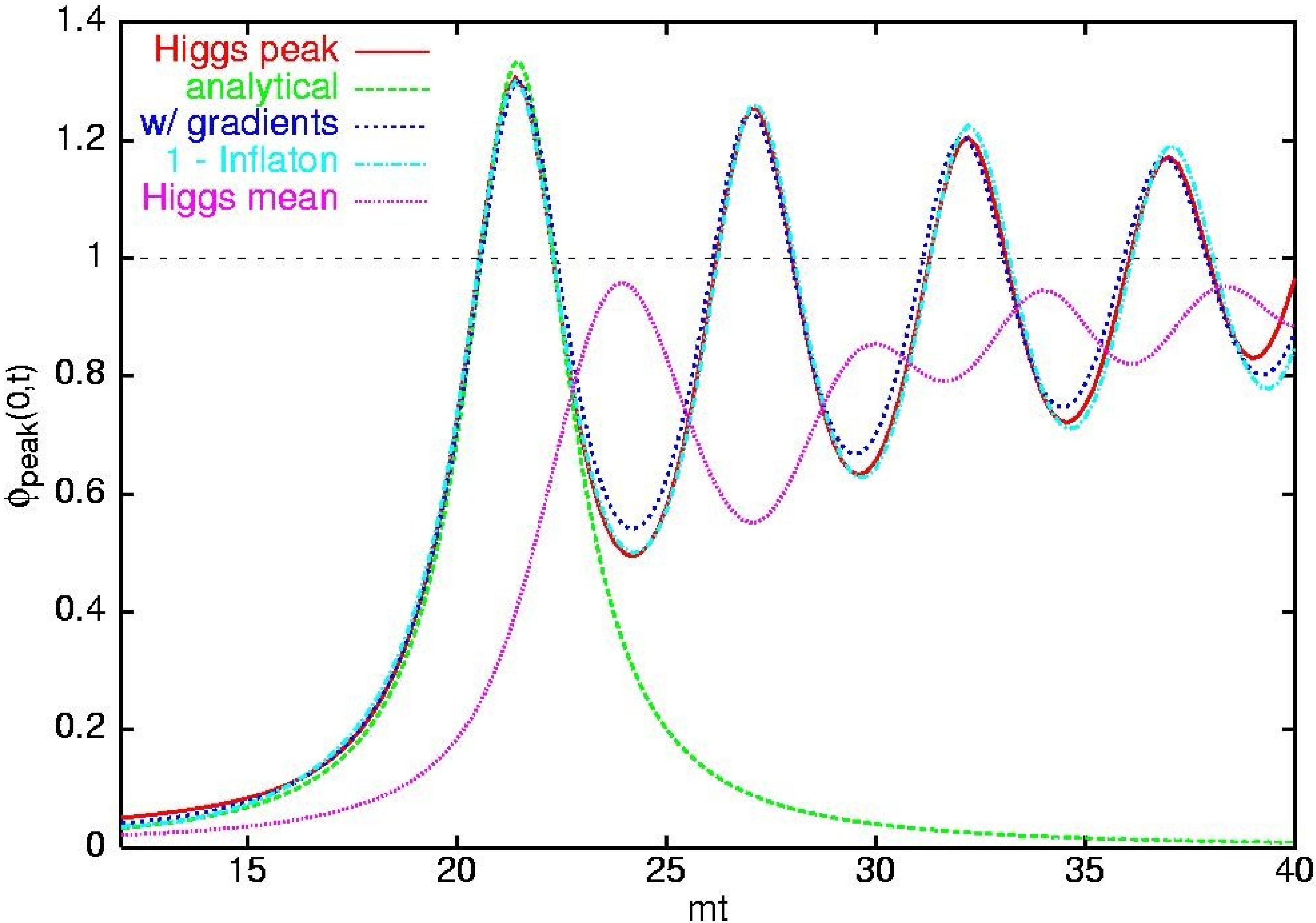
High peaks and mean of Higgs field



stochastic background gravitational waves

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PRL98, 061302 (2007)

arXiv:0707.0839 [hepph]

The Higgs-Inflaton model

$$L = Tr\left[(\partial_\mu \Phi)^+ \partial^\mu \Phi\right] + \frac{1}{2}(\partial_\mu \chi)^2 - V(\Phi, \chi)$$

$$Tr\left[\Phi^+ \Phi\right] = \frac{1}{2}(\varphi_0^2 + \varphi^a \varphi_a) \equiv \frac{1}{2}\varphi^2$$

$$V(\varphi, \chi) = \frac{\lambda}{4}(\varphi^2 - v^2) + \frac{g^2}{2}\varphi^2 \chi^2 + \frac{1}{2} m^2 \chi^2$$

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

backreaction

$$g^{\mu\nu} \partial_\mu \varphi\, \partial_\nu \varphi = (\partial_0 \varphi)^2 - (\nabla \varphi)^2 \quad - h^{ij} \nabla_i \varphi \nabla_j \varphi$$

Gravity waves evolution equation

$$\partial_0^2 h_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$ anisotropic stress tensor

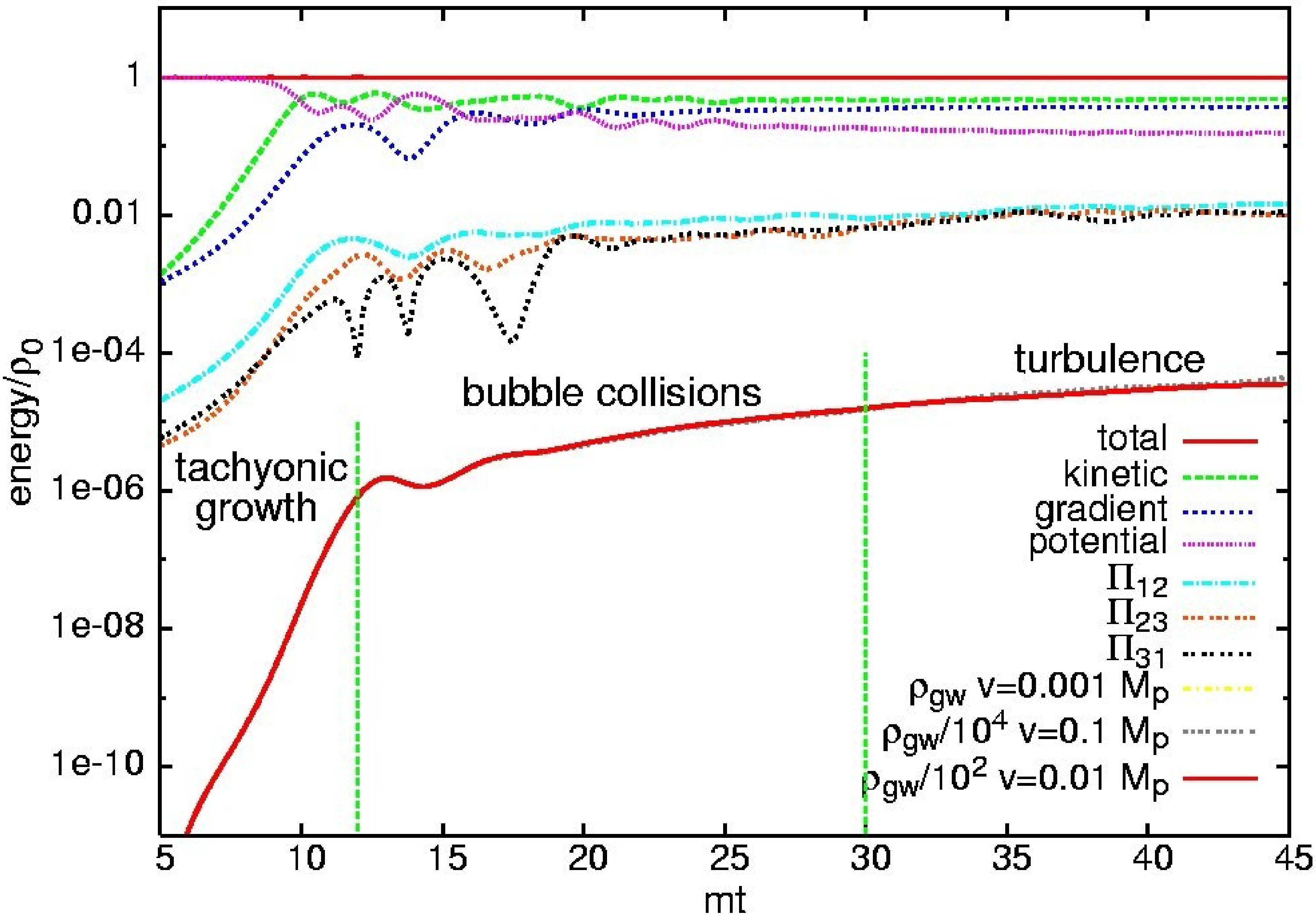
$$\Pi_{ij} = \nabla_i \varphi \nabla_j \varphi - \frac{1}{3}\delta_{ij}(\nabla\varphi)^2 + \nabla_i \chi \nabla_j \chi - \frac{1}{3}\delta_{ij}(\nabla\chi)^2$$

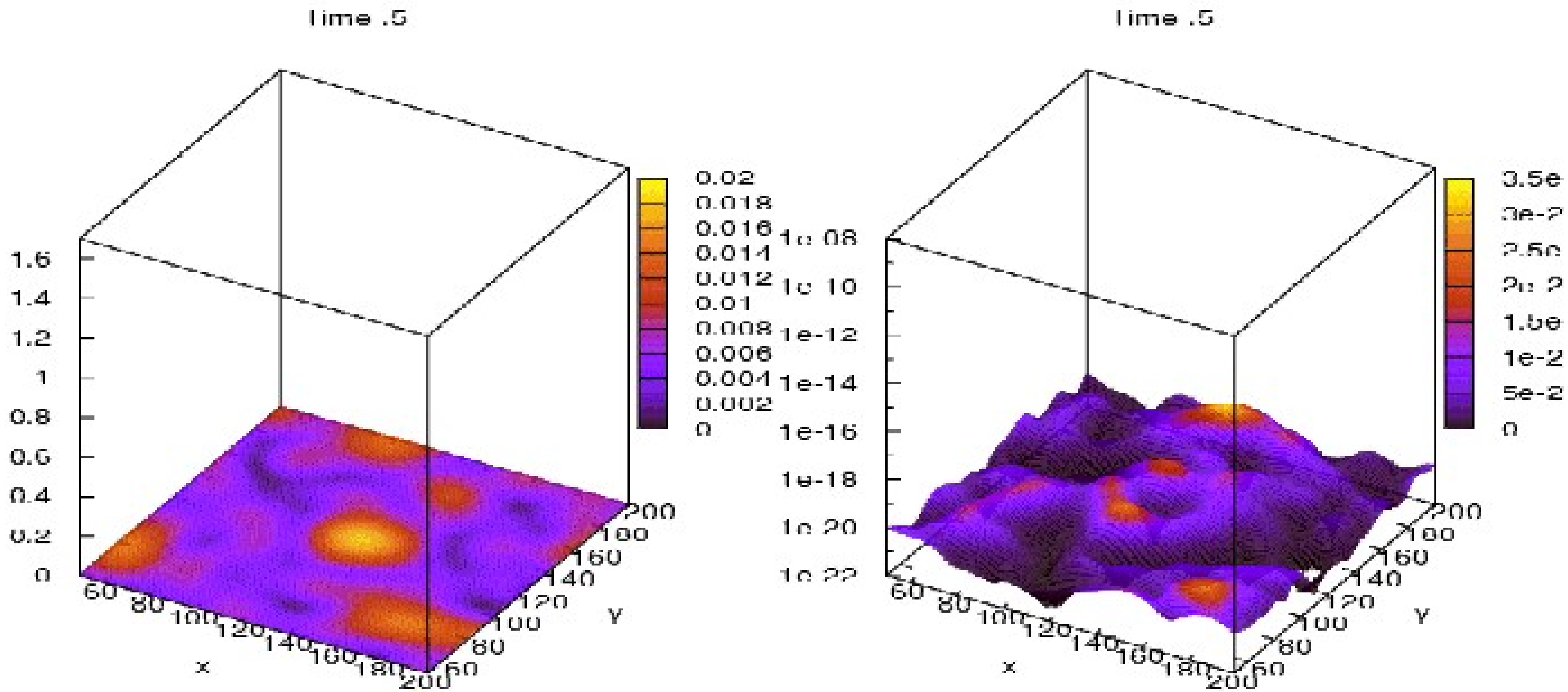
$$t_{\mu\nu} = \frac{1}{32\pi G}\langle \partial_\mu h_{ij}^{TT} \partial_\nu h_{ij}^{TT} \rangle$$ energy density

$$\frac{\rho_{gw}}{\rho_0} = \frac{1}{8\pi G v^2 m^2}\langle \partial_0 h_{ij}^{TT} \partial_0 h_{ij}^{TT} \rangle = \frac{2}{5}\frac{1}{8\pi G v^2 m^2}\langle \partial_0 h_{ij} \partial_0 h_{ij} \rangle$$

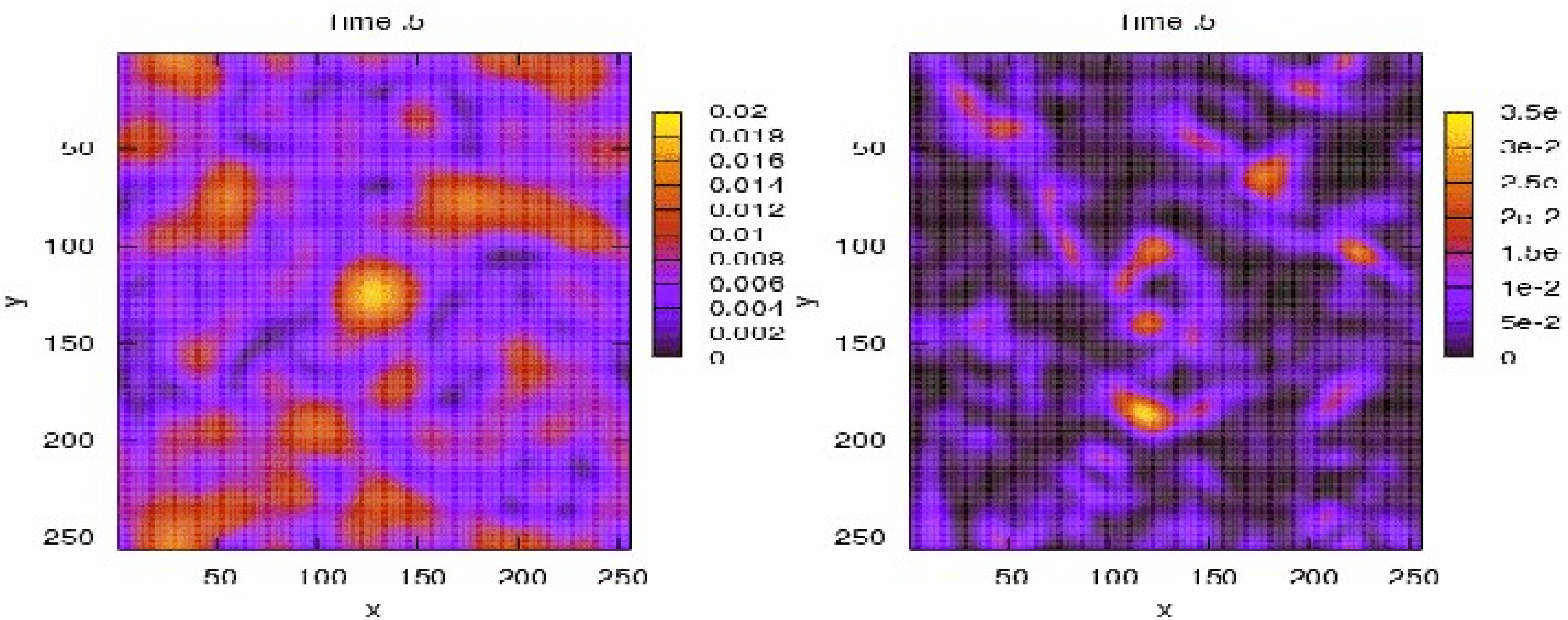
$$\Omega_{gw} = \int \frac{df}{f}\Omega_{gw}(f) = \int \frac{dk}{k}\frac{k^3}{2\pi^2}\frac{\rho_{gw}(k)}{\rho_0}\frac{\rho_{rad}}{\rho_c}$$

Time evolution after inflation





Time .5
Time .5
x
y
x
y


Time .5
y
x
50
100
150
200
250
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Time .5
y
x
50
100
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2e-2
1.5e
1e-2
5e-2
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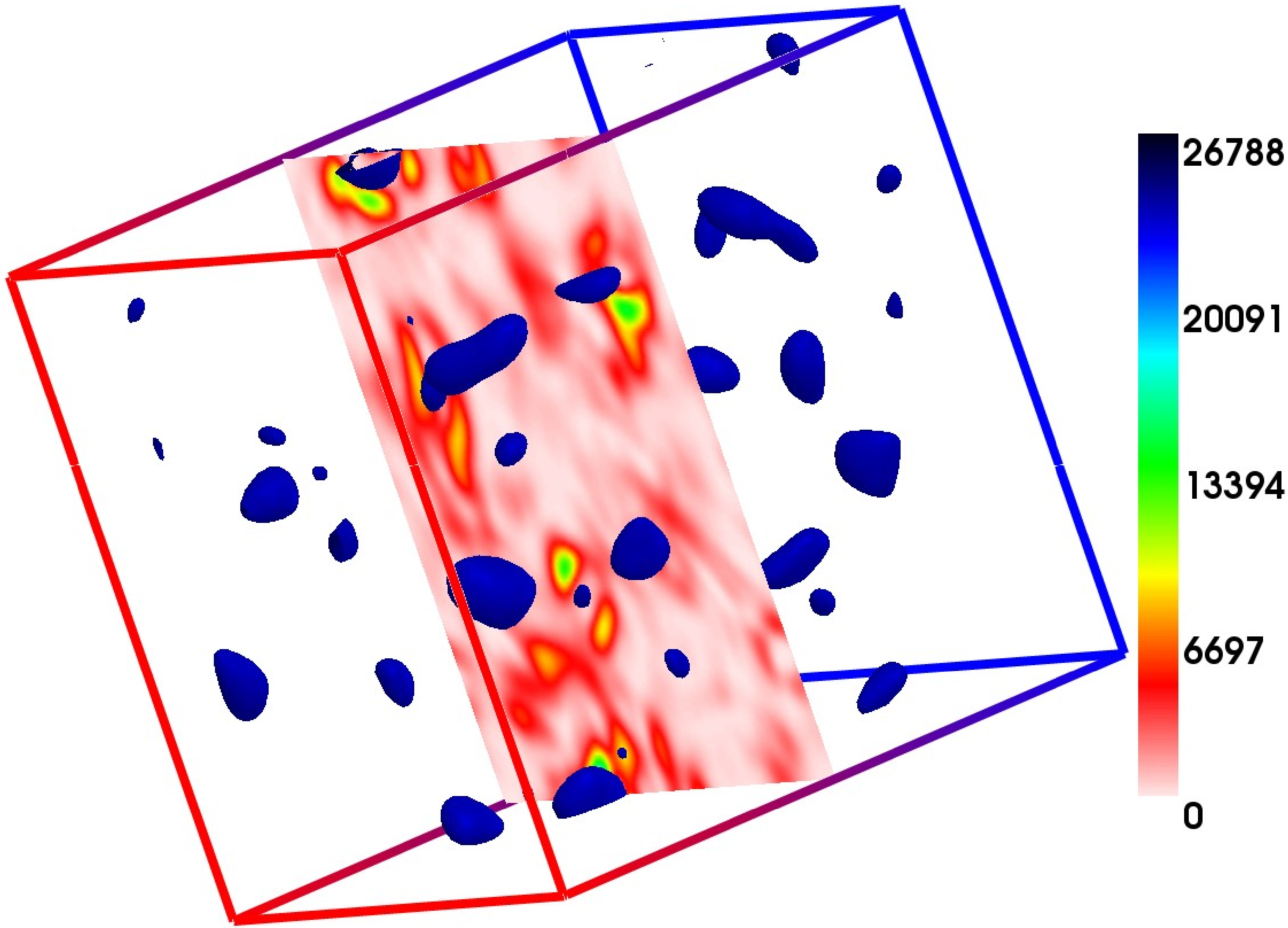
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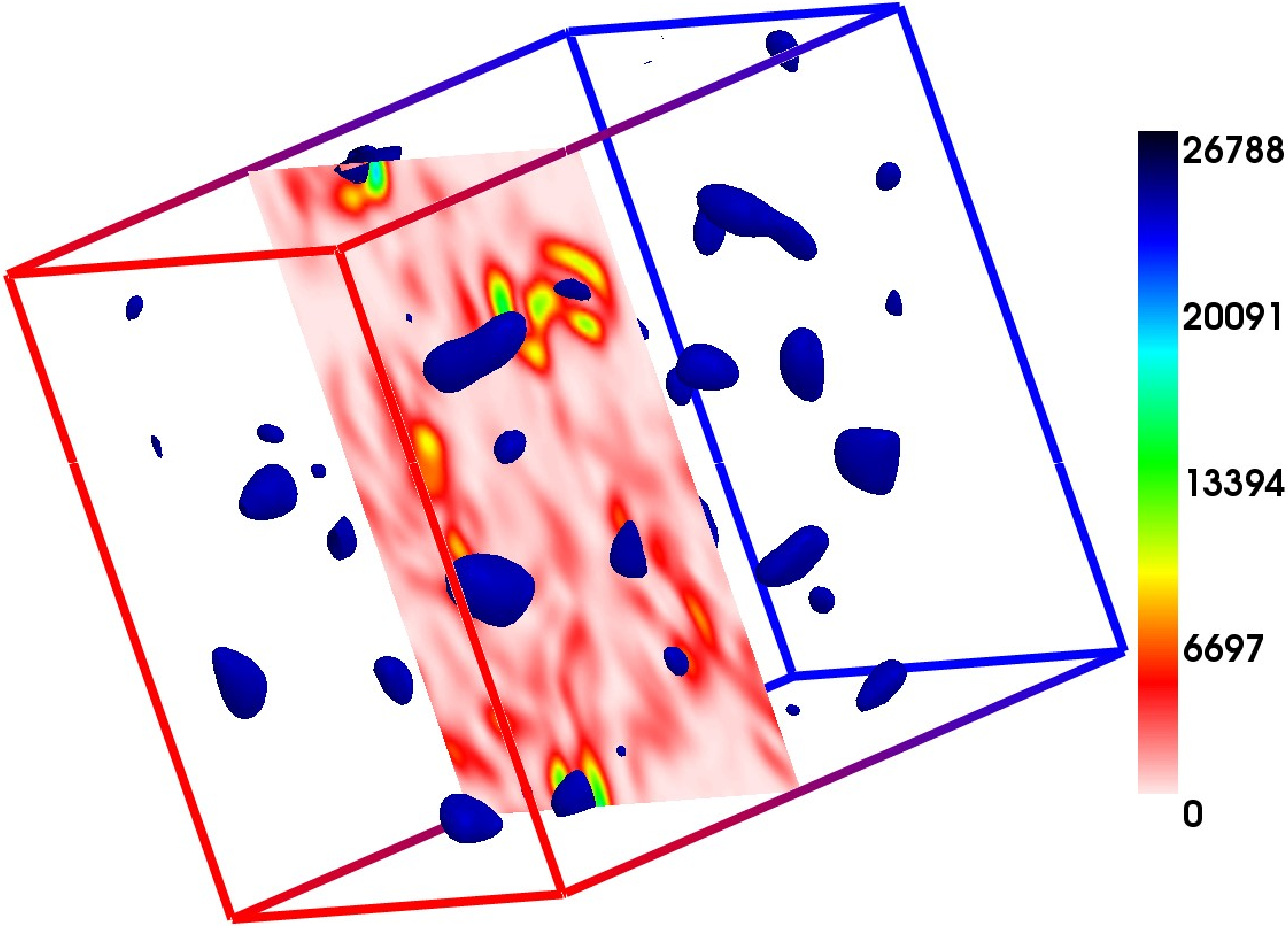
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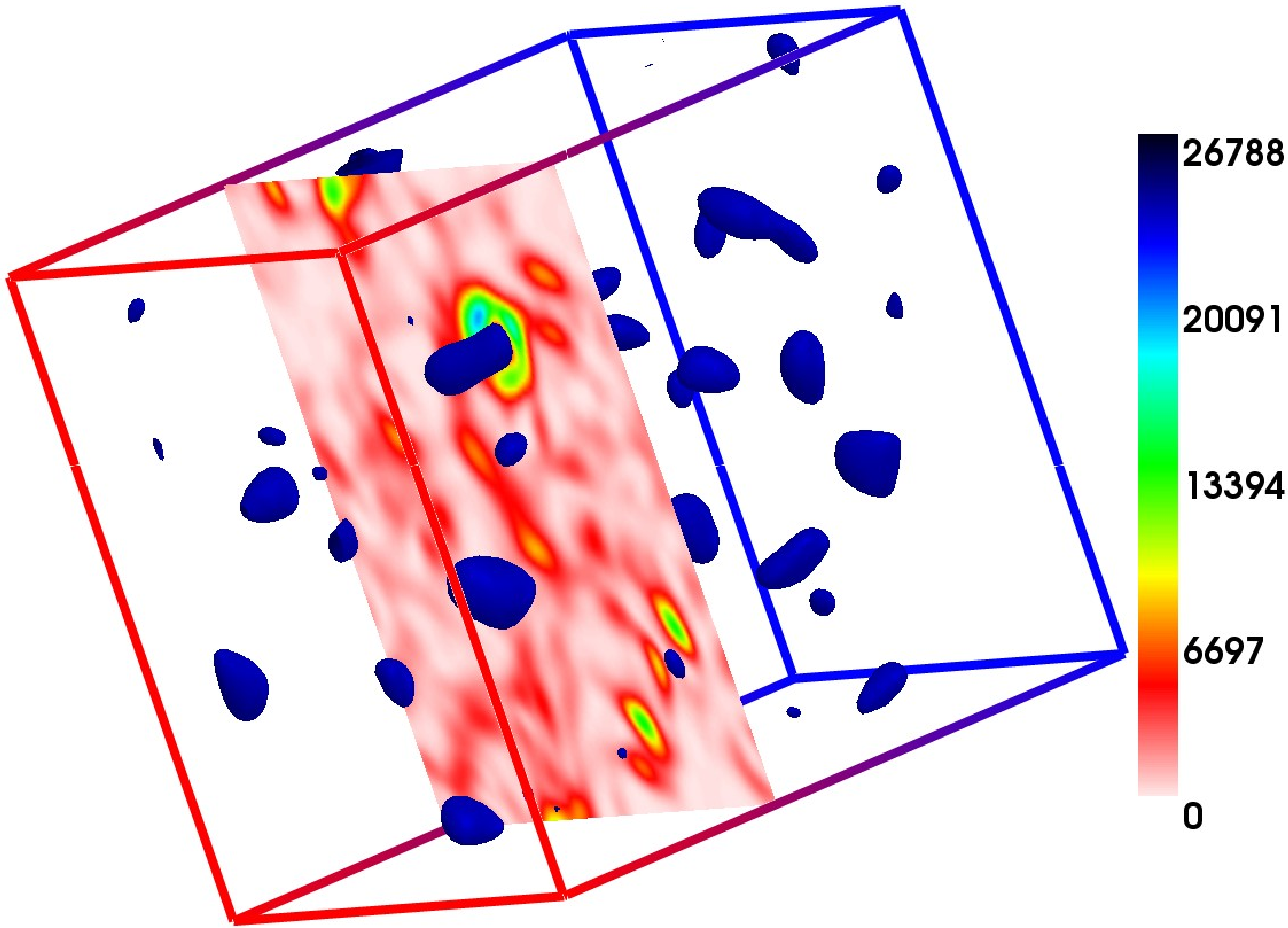
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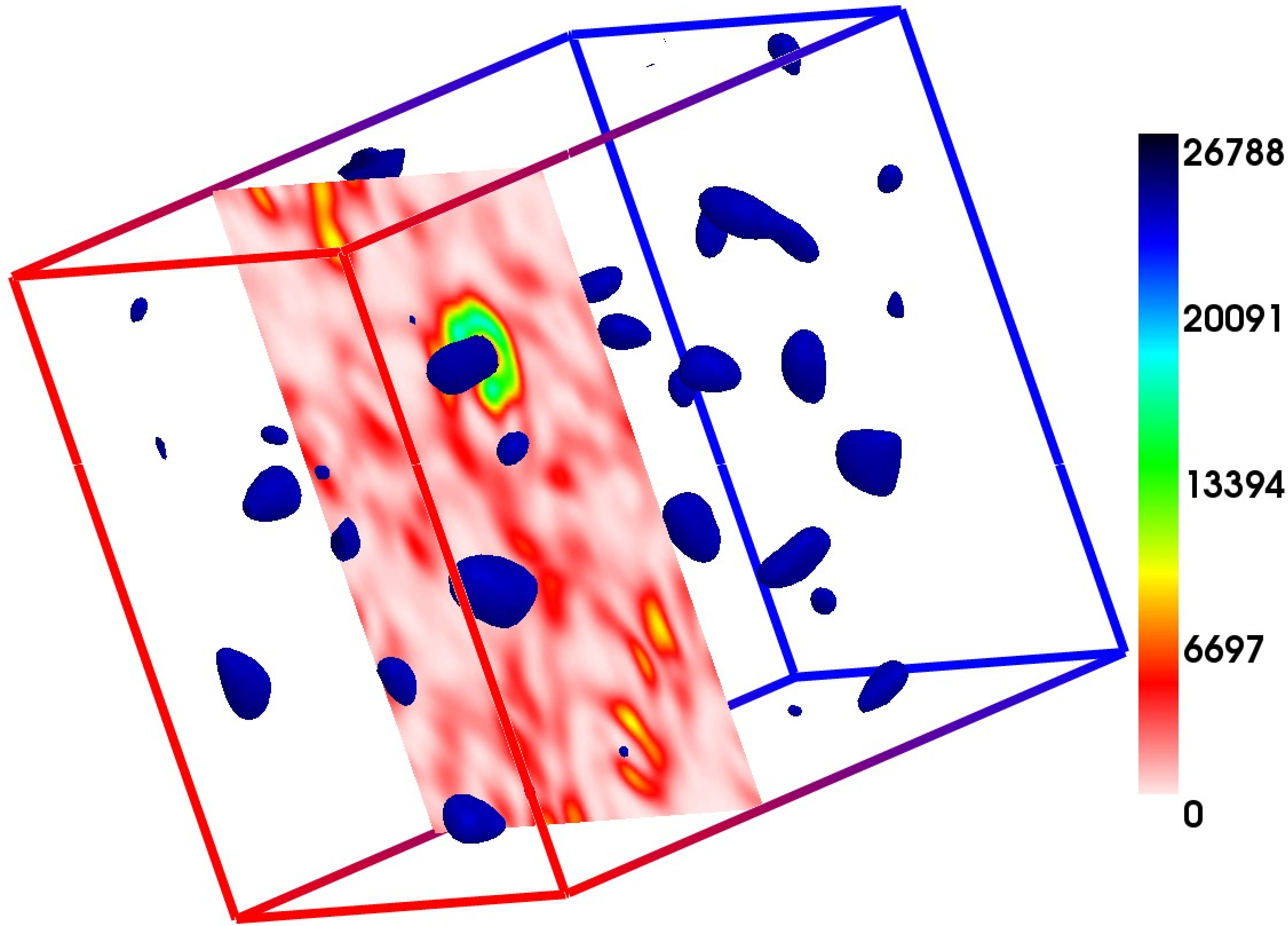
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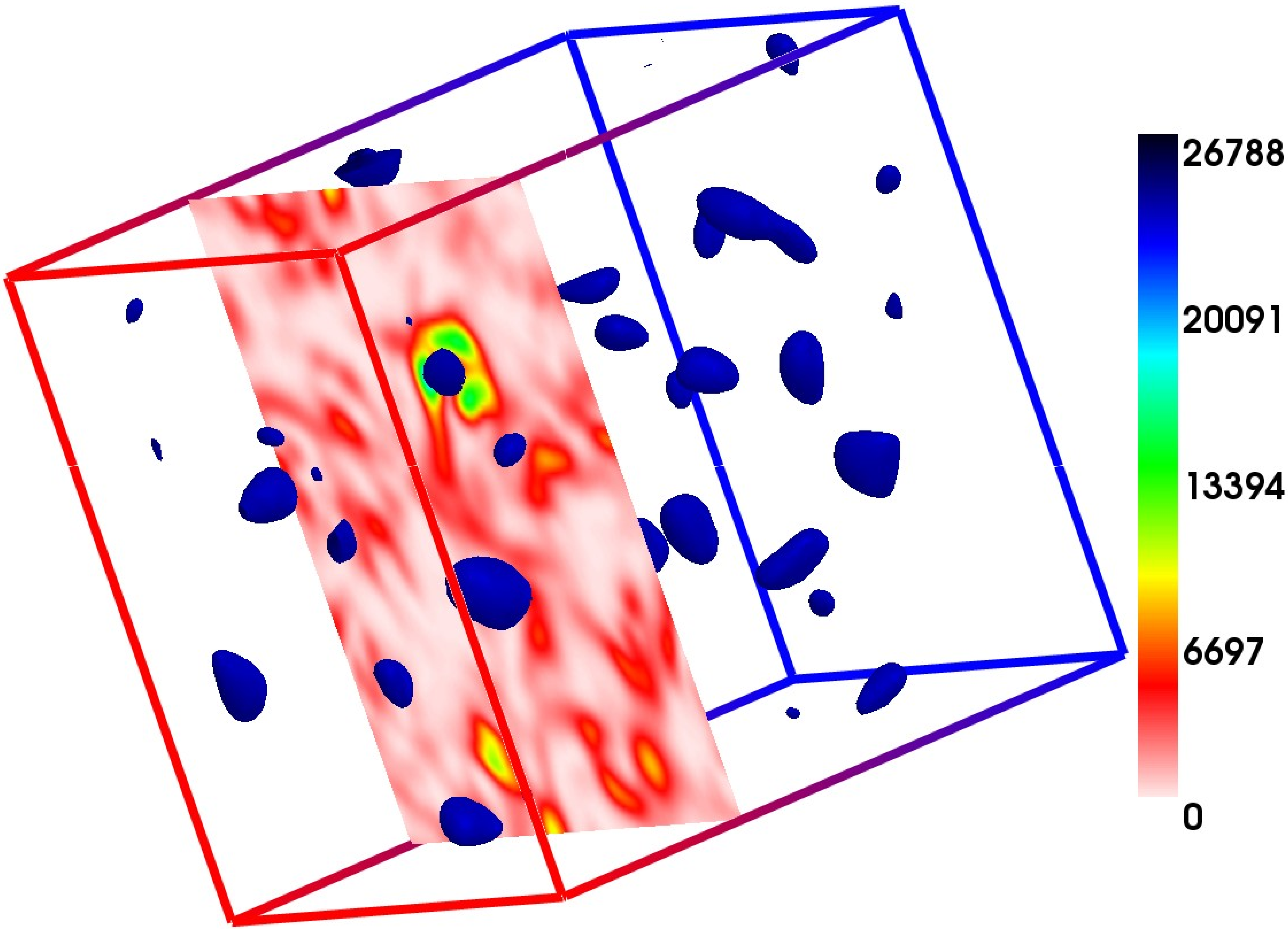
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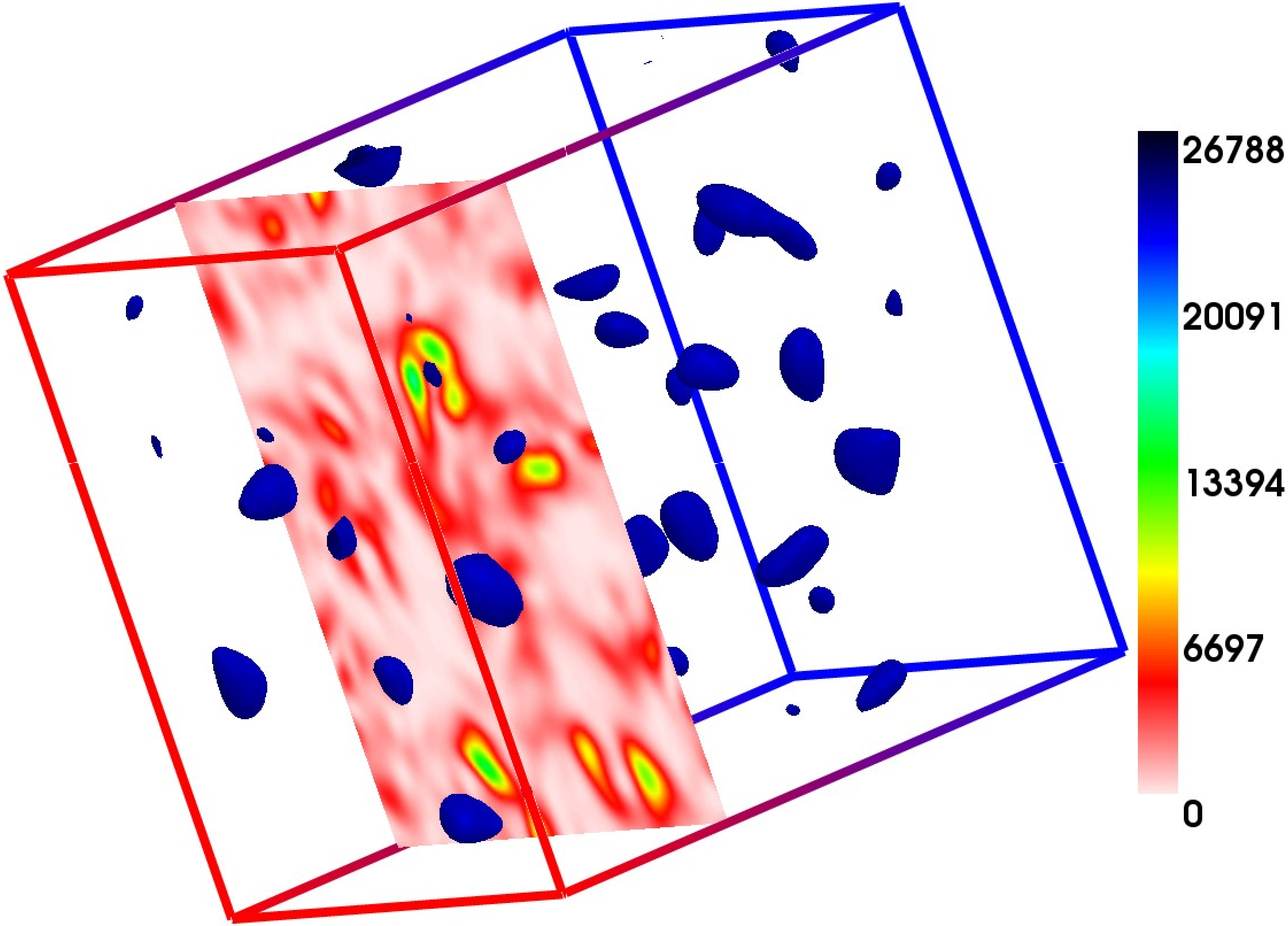

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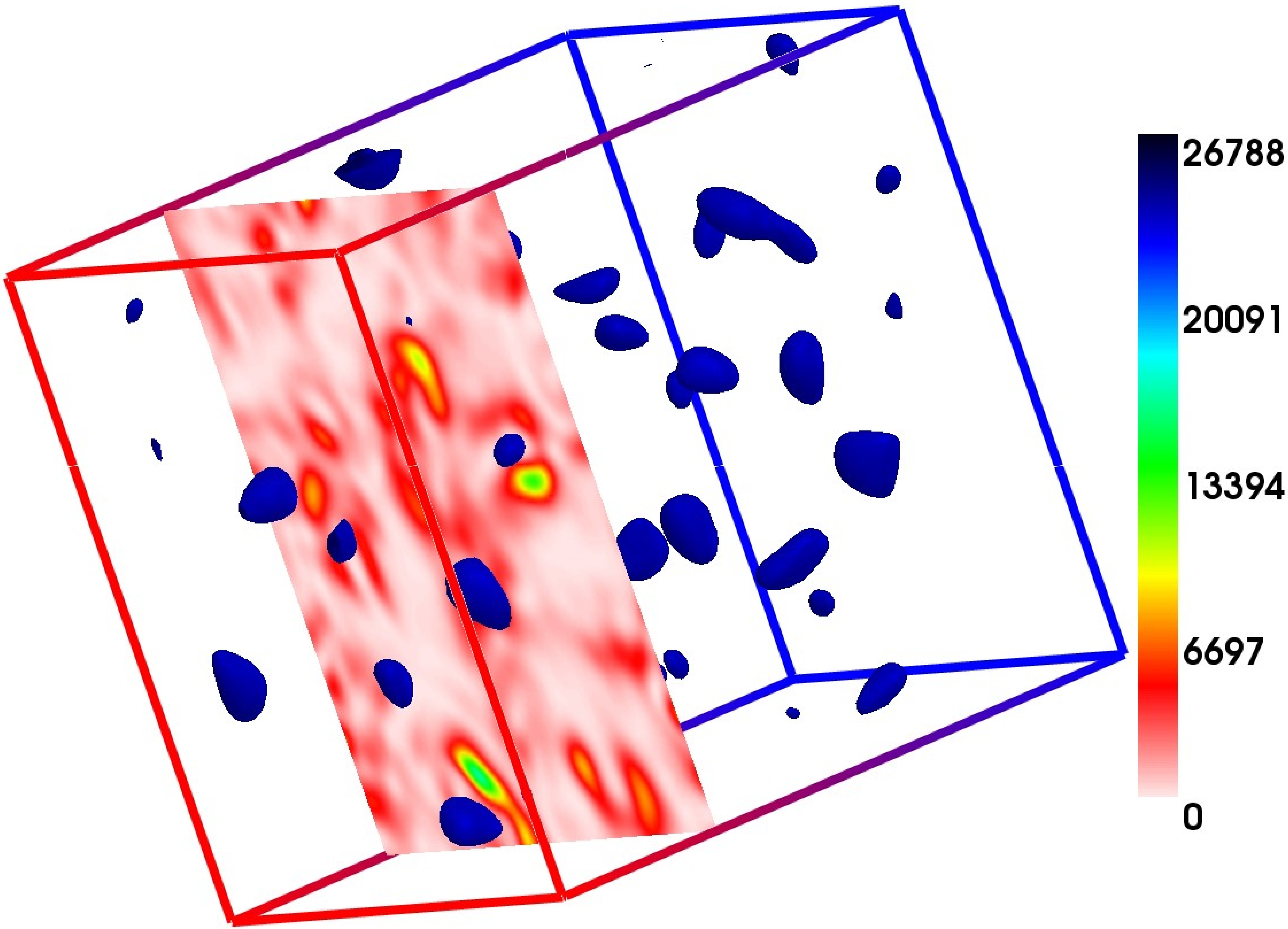

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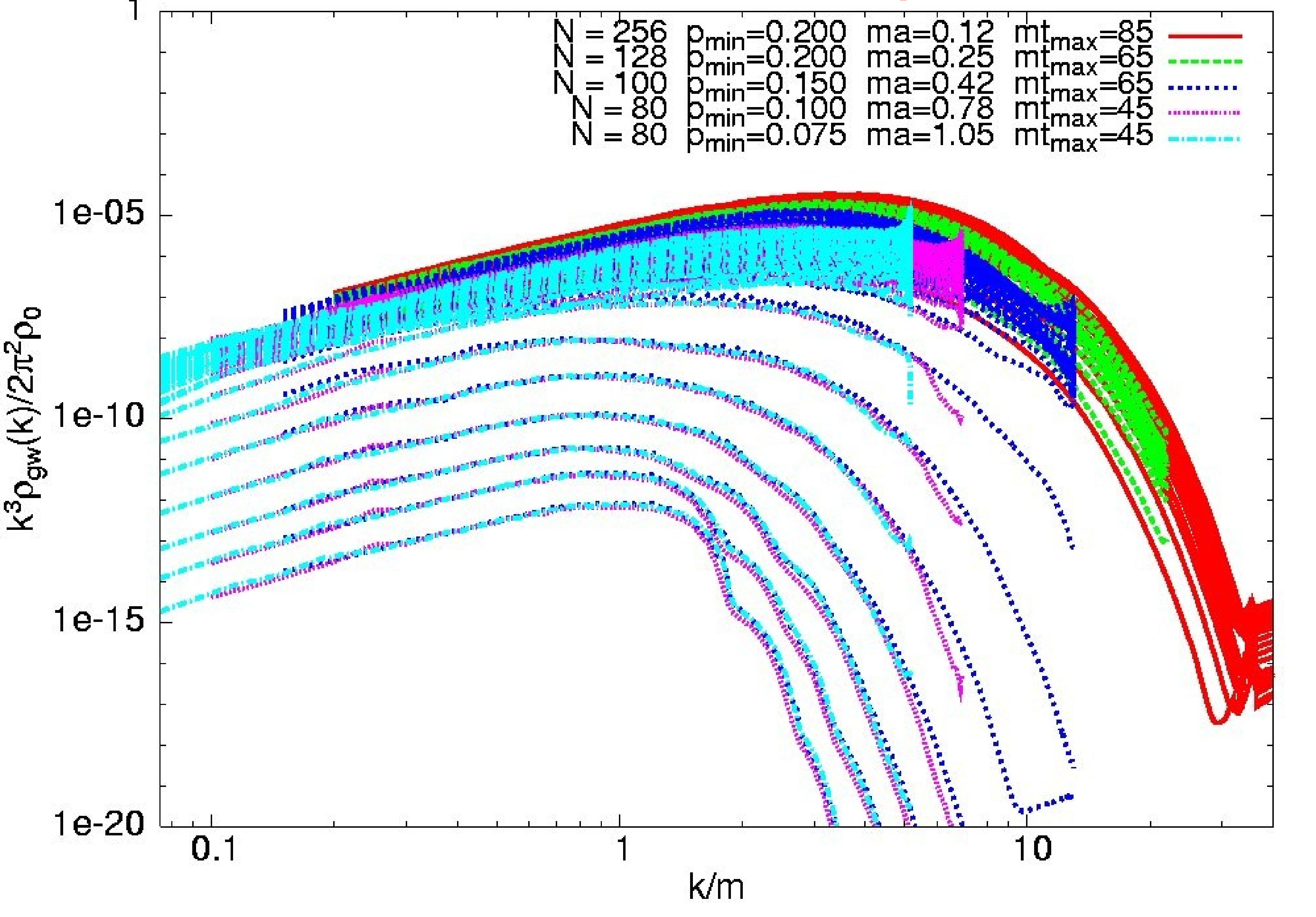
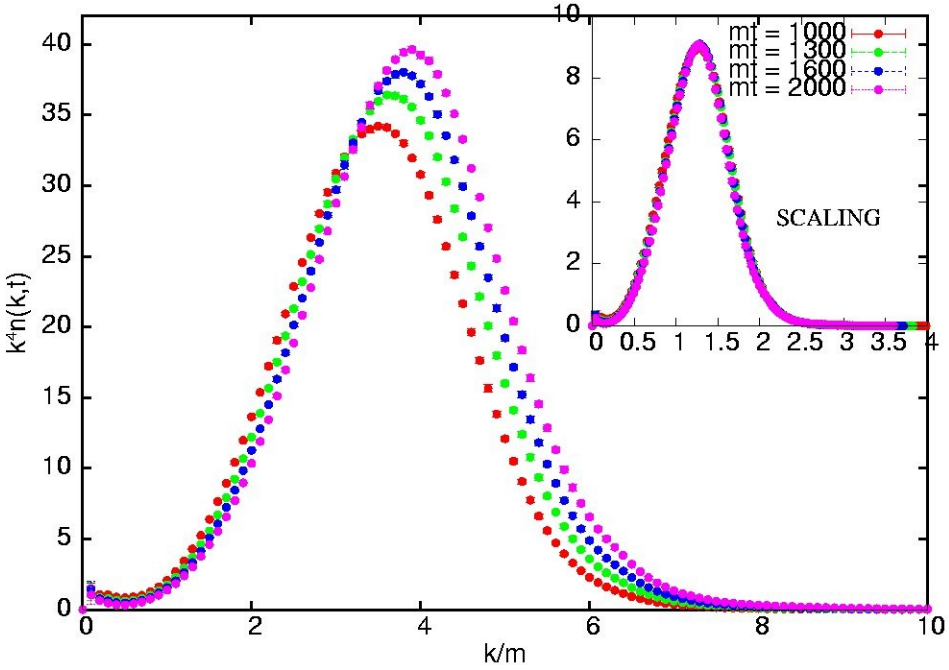
Gravitational wave spectrum



Kinetic Turbulence &



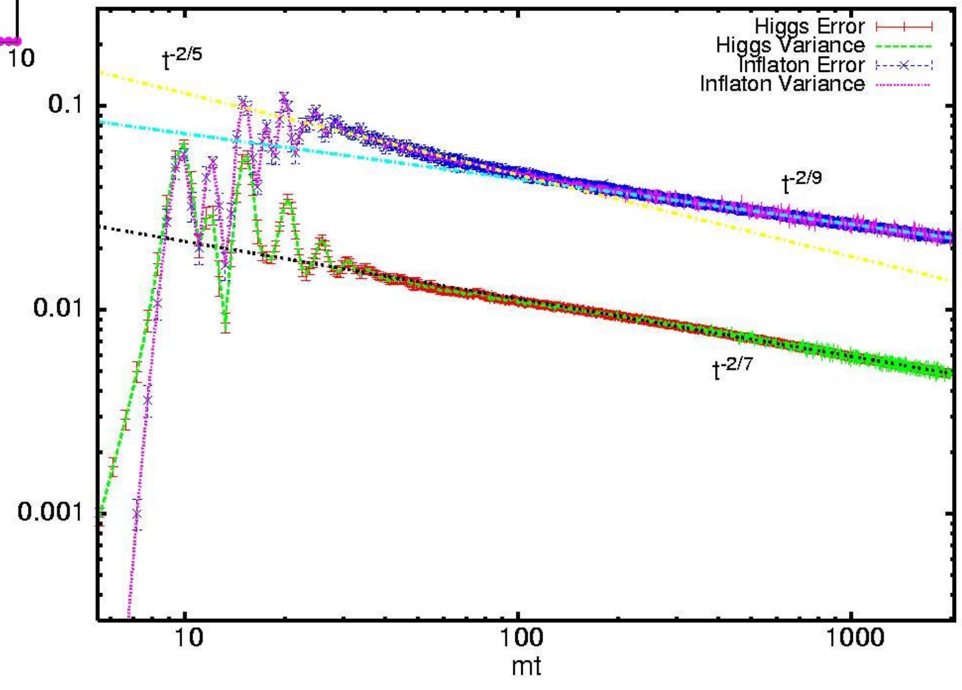
$$n(k,t) = t^{-q} n_0(k t^{-p})$$

$$q = 3.5p$$

$$p = \frac{1}{2m-1}$$

$$\Delta\varphi^2 = \langle \varphi^2 \rangle - \langle \varphi \rangle^2 \propto t^{-\nu}$$

$$\nu = \frac{2}{2m-1}$$



GW spectrum during turbulence

$$\frac{k^3}{2\pi^2}\frac{\rho_{gw}(k,t)}{\rho_0} = 0.002\, G v^2\, t^{1.78} k^2 \exp\left(-0.32\, t^{-2/9} k^2\right)$$

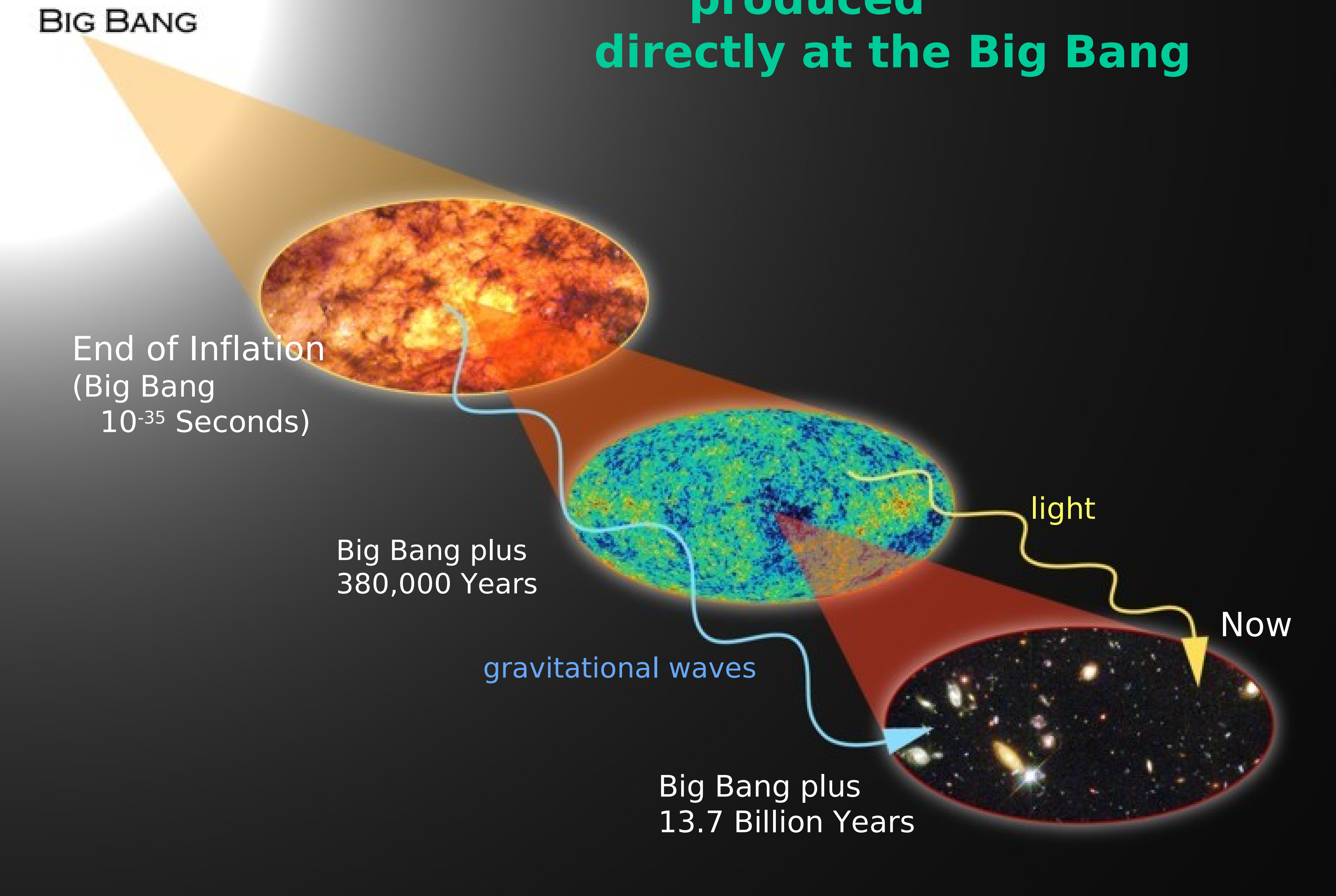
instantaneous spectrum:

$$\Omega_{gw}(t) = \int \frac{dk}{k}\frac{k^3}{2\pi^2}\frac{\rho_{gw}(k,t)}{a^4 \rho_c} = 0.002\ \Omega_{rad}\frac{G v^2 t^2}{a^4}$$

integrated spectrum after end of turbulence (t*):

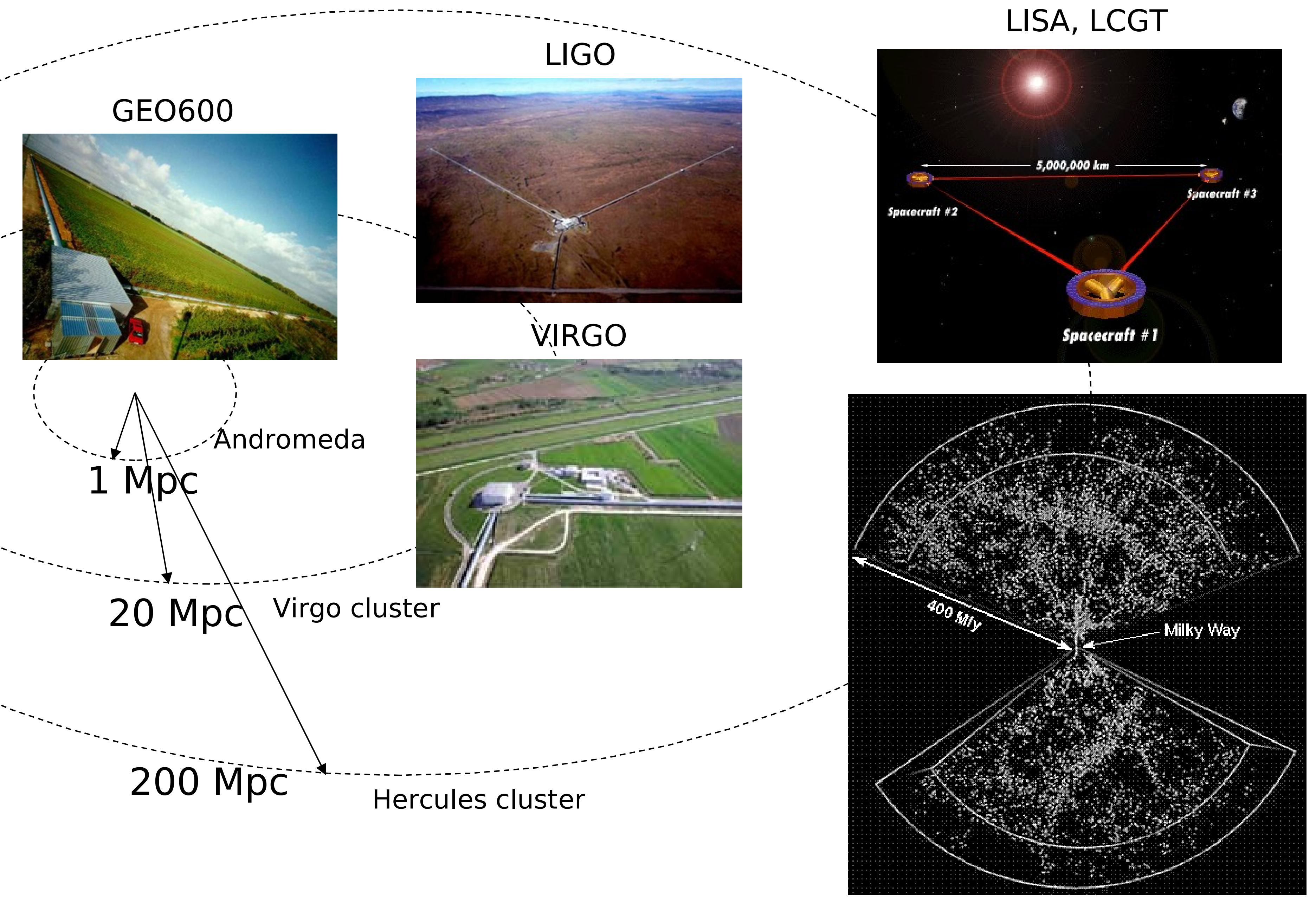
$$\Omega_{gw} = \int dt\ \Omega_{gw}(t) \approx \Omega_{gw}(t_1)\,(mt)^{\alpha} \quad \alpha = 1, \frac{1}{3}$$

Gravitational Waves are produced directly at the Big Bang



Detection Gravitational Waves

Ranges of Gravitational Wave Detectors in the Wor

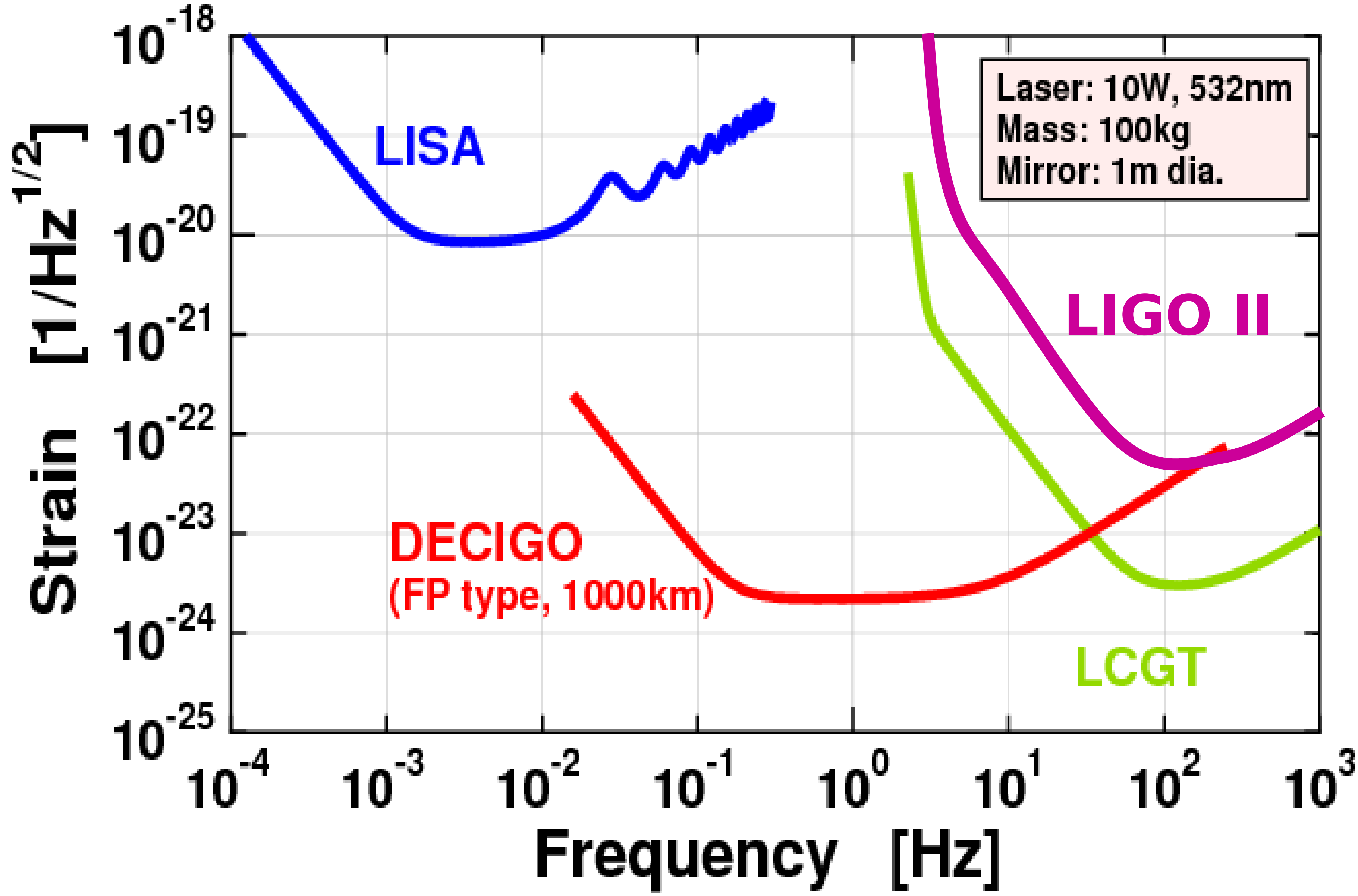


Dimensionless stress amplitude

$$\langle h_{ij}(t)\, h^{ij}(t)\rangle = 2\int_0^{\infty} \frac{df}{f}\, h_c^2(f)$$

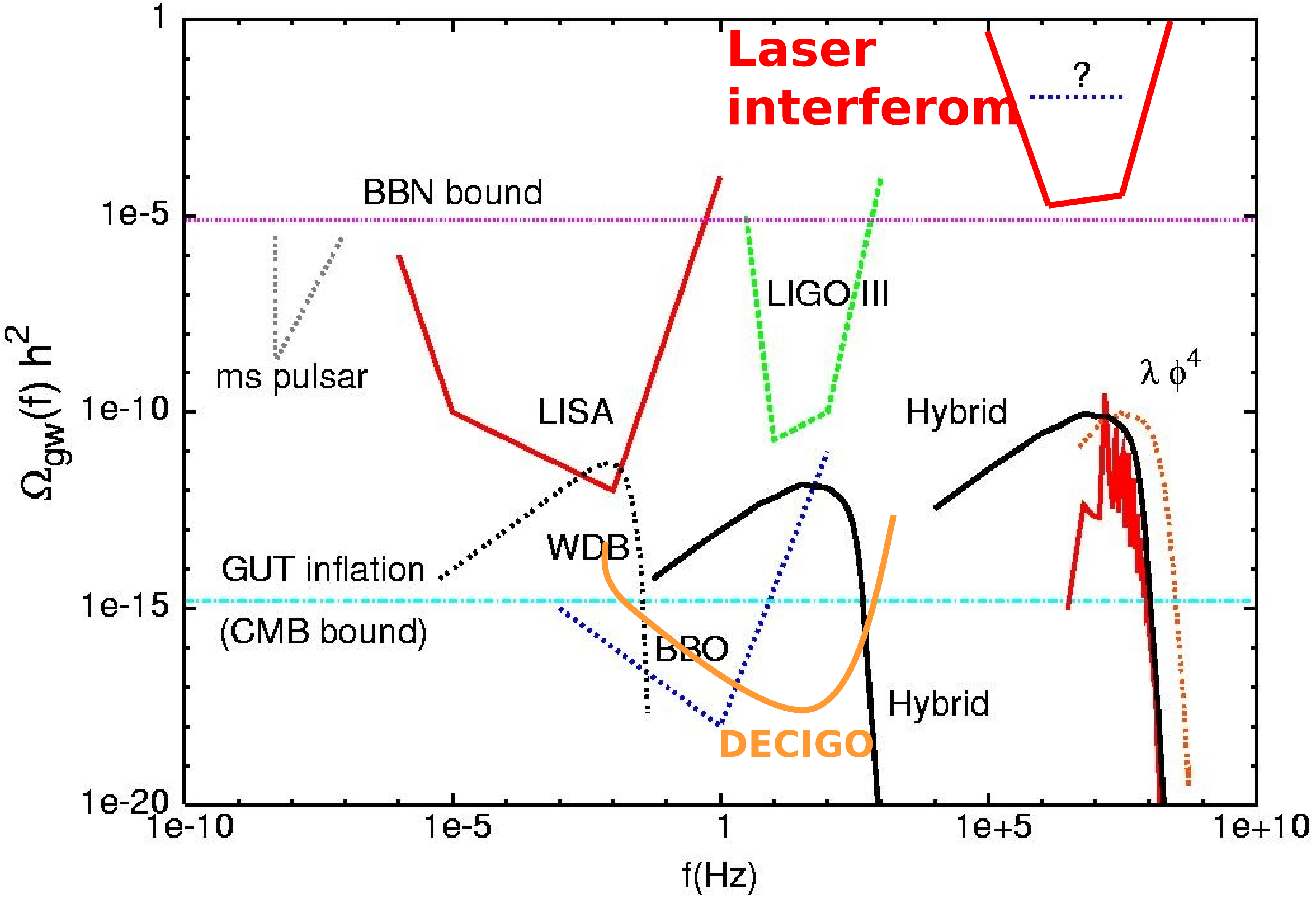
$$\Omega_{gw}(f) = \frac{f}{\rho_c}\frac{d\rho_{gw}}{df} = \frac{2\pi^2}{3H_0^2}\, f^2 h_c^2(f)$$

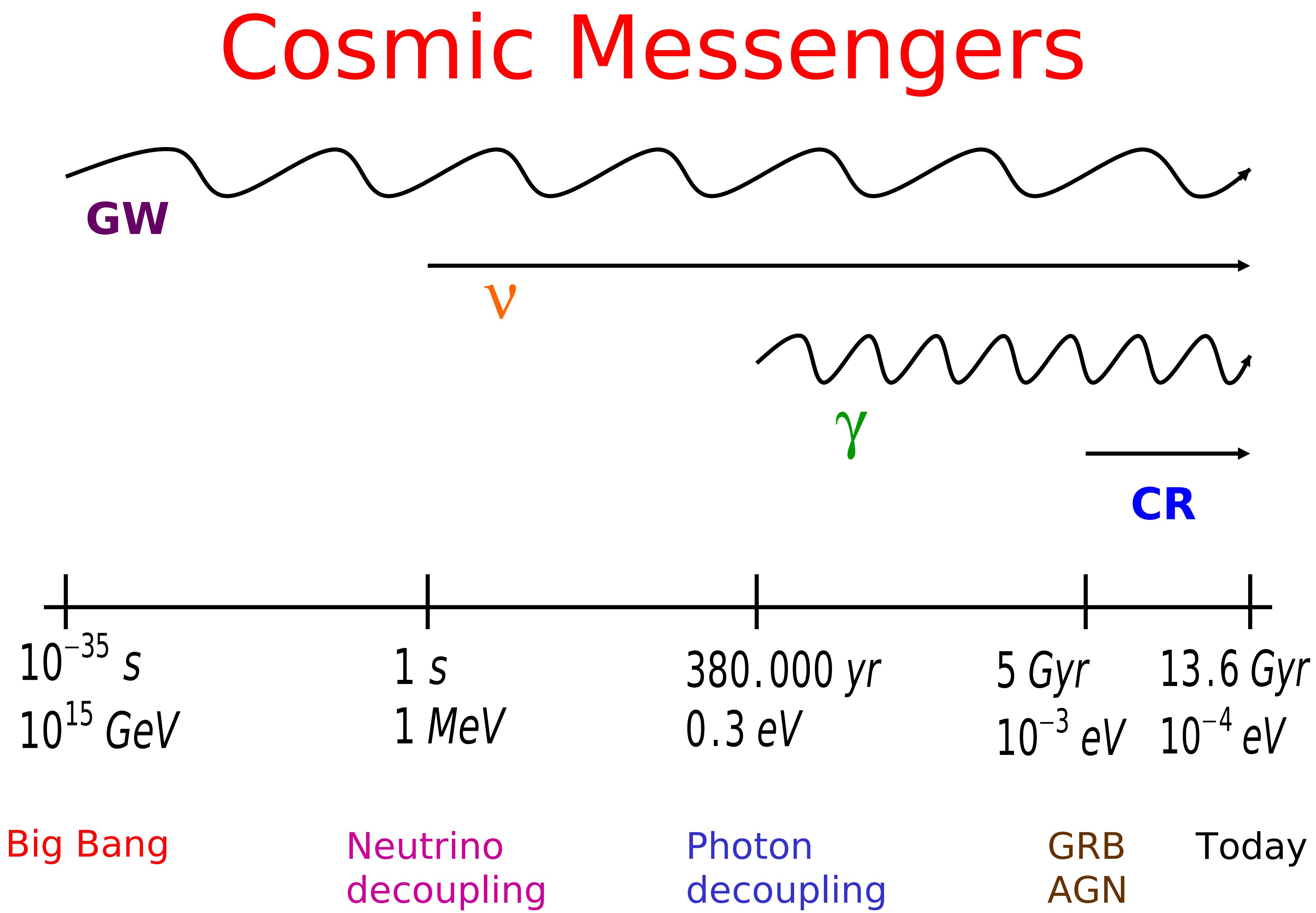
$$h_c(f) = 1.3\times 10^{-18}\left(\frac{1\,Hz}{f}\right)\sqrt{\Omega_{gw}(f)\, h_0^2}$$



Strain [1/Hz^1/2]
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
Frequency [Hz]
LISA
LIGO II
DECIGO
(FP type, 1000km)
LCGT
Laser: 10W, 532nm
Mass: 100kg
Mirror: 1m dia.

Backgrounds, Bounds & Sensitivity





Cosmic Messengers
GW
ν
γ
CR
$10^{-35}\ s$
$10^{15}\ GeV$
$1\ s$
$1\ MeV$
$380.000\ yr$
$0.3\ eV$
$5\ Gyr$
$10^{-3}\ eV$
$13.6\ Gyr$
$10^{-4}\ eV$
Big Bang
Neutrino decoupling
Photon decoupling
GRB
AGN
Today

Telescope	*Person*	*Date*	*Objective*	*Discovery*
Optical	**Galileo**	**1608**	**Navigation**	**Jupiter’s moons**
Geiger	**Hess**	**1912**	**Geothermal**	**Cosmic Rays**
Optical	**Hubble**	**1929**	**Nebulae**	**Universe Expansion**
Radio	**Jansky**	**1932**	**Atmos. Noise**	**Radio Galaxies**
Microwaves	**Penzias, Wilson**	**1964**	**Telecommunication**	**Backgr. Radiation**
X Rays	**Giacconi**	**1965**	**Sun, Moon**	**Neutron Stars**
Radio	**Hewish, Bell**	**1967**	**Ionosphere**	**Pulsars**
Rays	**military**	**1960s**	**Nuclear Tests**	**Gamma Ray Bursts**
Radio	**Hulse, Taylor**	**1974**	**Binary Pulsar**	**Gravitational Waves**
Cerenkov	**Koshiba**	**1998**	**Proton Decay**	**Sol./Atm. Neutrinos**
Optical	**Kirschner** **Perlmutter**	**1998**	**Supernovae**	**Universe Acceleration**
Laser Interferom.	**?**	**2020?**	**Gravitational Waves**	**Big Bang, Inflation?**

Conclusions

- CMB anisotropies suggest inflation
- The end of inflation is our local Big Bang
- It is extremely violent at preheating
- Production of gravitational waves at Big Bang
- New detectors of GW are under construction

Primordial Magnetic Fields

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Margarita Garcia-Perez
Antonio Gonzalez-Arroyo

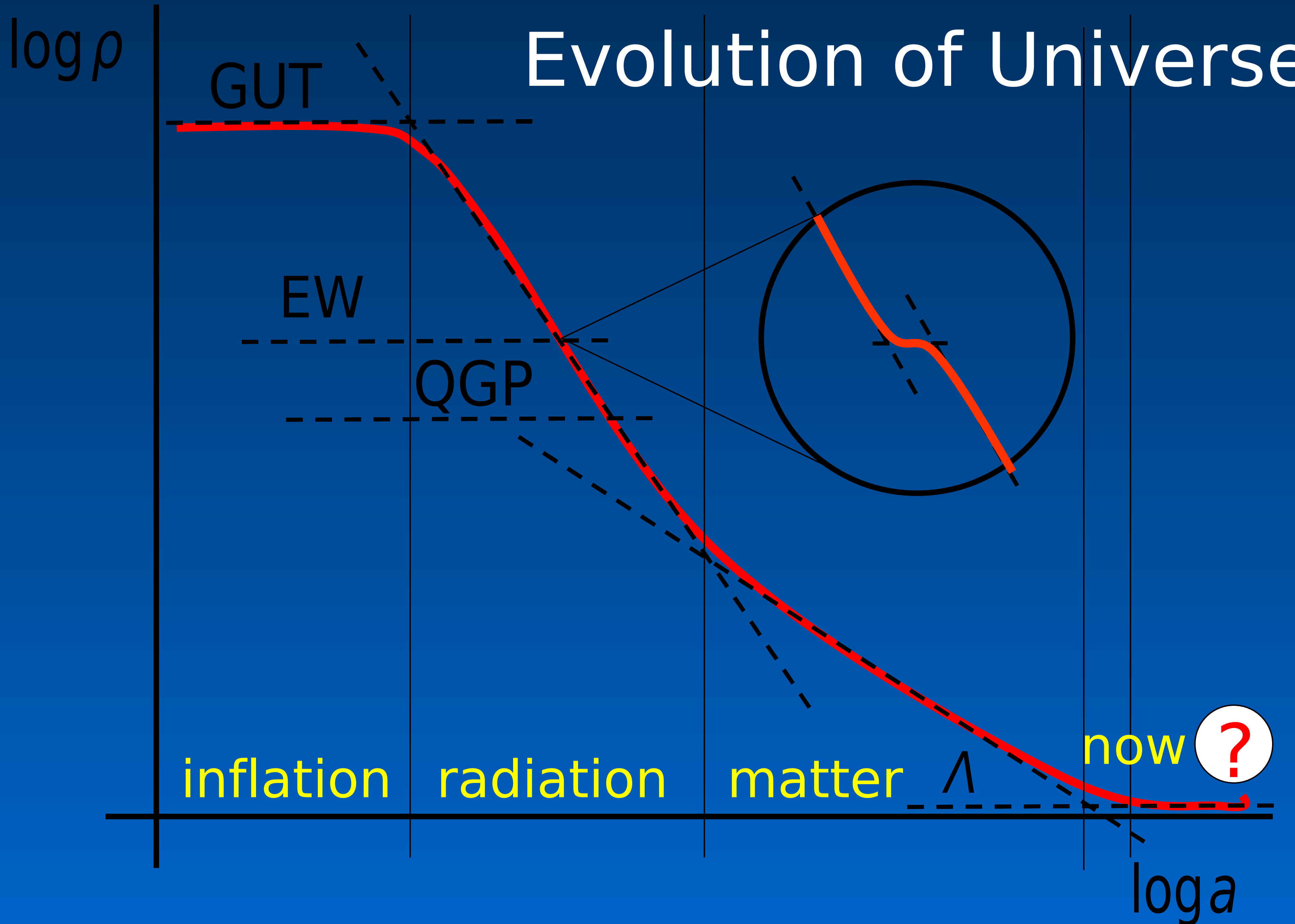
hep-lat/0509094
arXiv:0710.0580 [hep-lat]
arXiv:0712.4263 [hep-ph]

EW Tachyonic Preheating

Spinodal growth of long wave Higgs modes

- At the end of EW Hybrid Inflation
- Inflaton couples to Higgs
- Higgs couples to SM fields
- Strong production of fermions and gauge fields

Evolution of Universe



The SU(2)xU(1) Higgs-Inflaton mode

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + Tr\left[\left(D_\mu \Phi \right)^+ D^\mu \Phi \right] + \frac{1}{2} \left(\partial_\mu \chi \right)^2 - V\left(\Phi , \chi \right)$$

$$D_\mu = \partial_\mu - \frac{i}{2} g_W A^a_\mu \tau_a - \frac{i}{2} g_Y B_\mu \tau_3$$

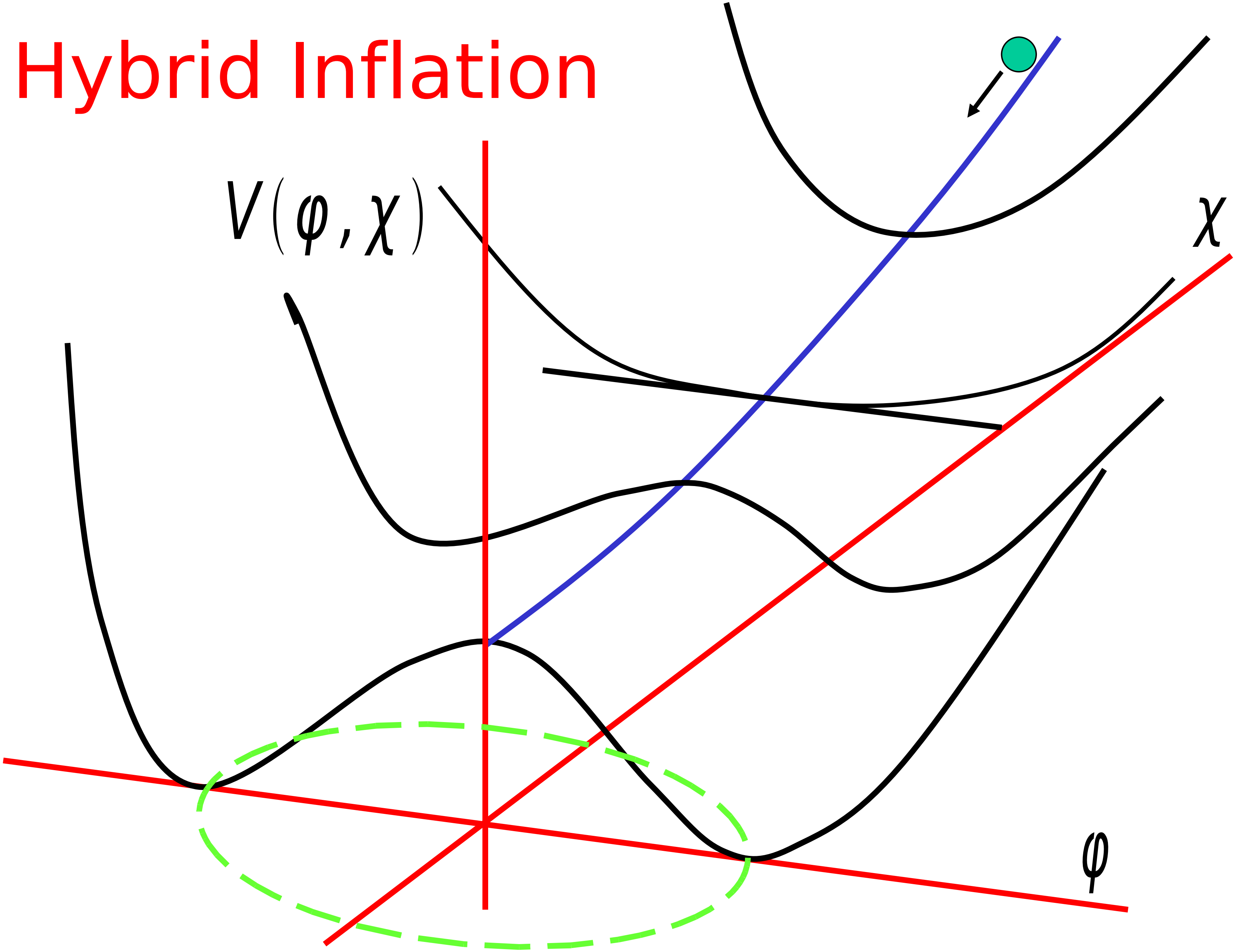
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_W \varepsilon^{abc} A^b_\mu A^c_\nu$$

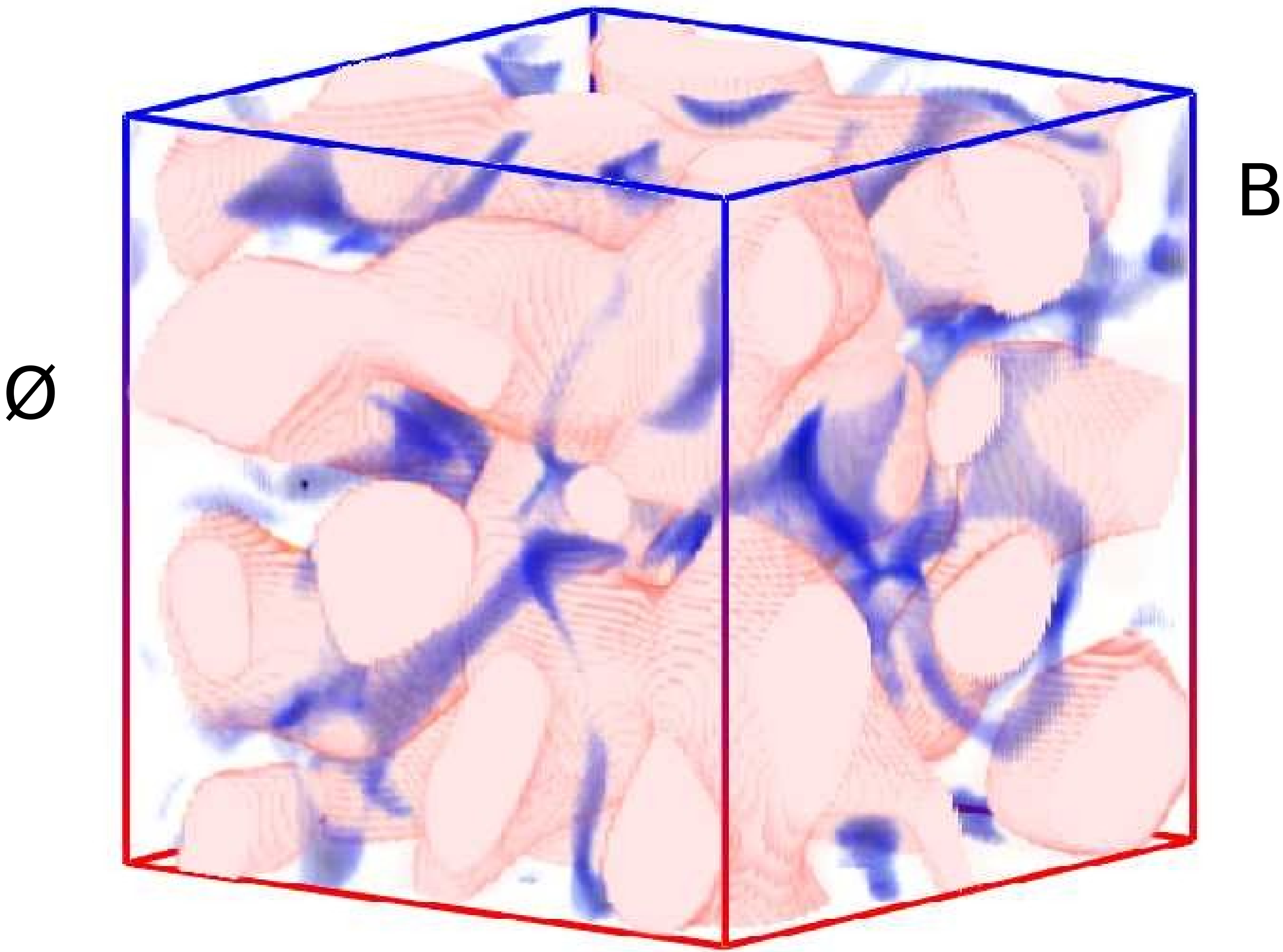
$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$Tr\left[\Phi^+ \Phi \right] = \frac{1}{2} \left(\varphi_0^2 + \varphi^a \varphi_a \right) \equiv \frac{1}{2} \varphi^2$$

$$V\left(\varphi , \chi \right) = \frac{\lambda}{4} \left(\varphi^2 - v^2 \right) + \frac{g^2}{2} \varphi^2 \chi^2 + \frac{1}{2} m^2 \chi^2$$

Hybrid Inflation

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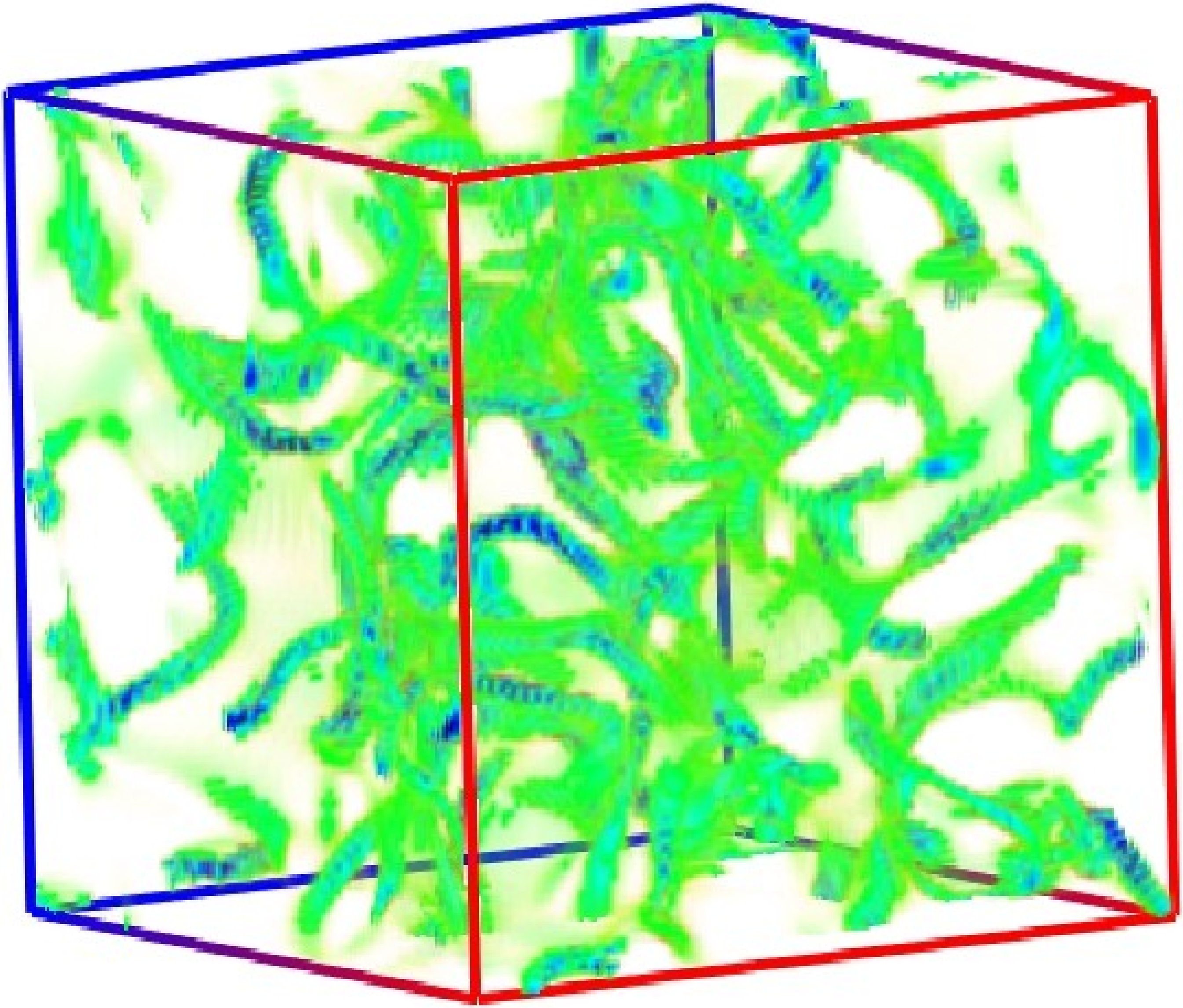
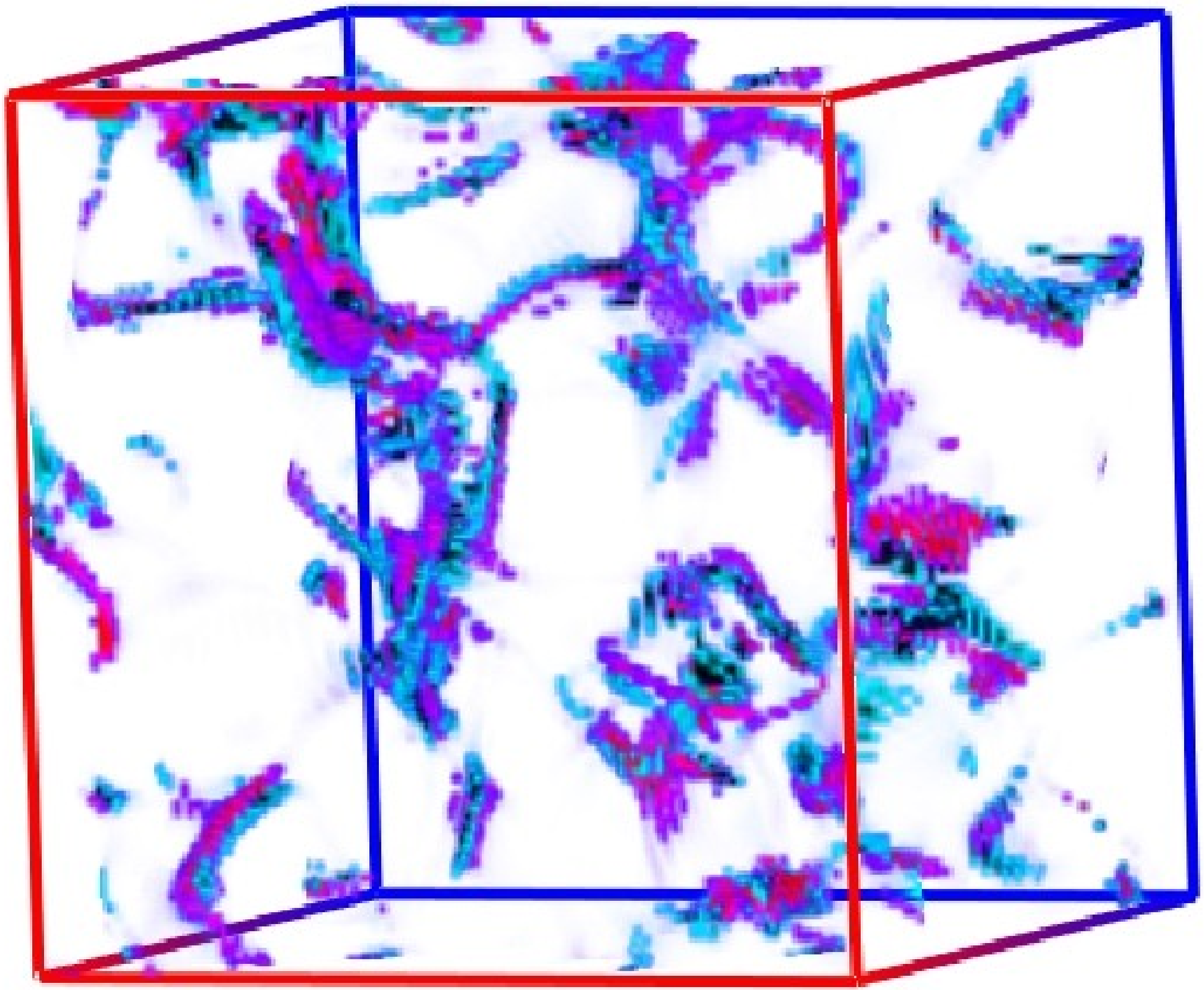
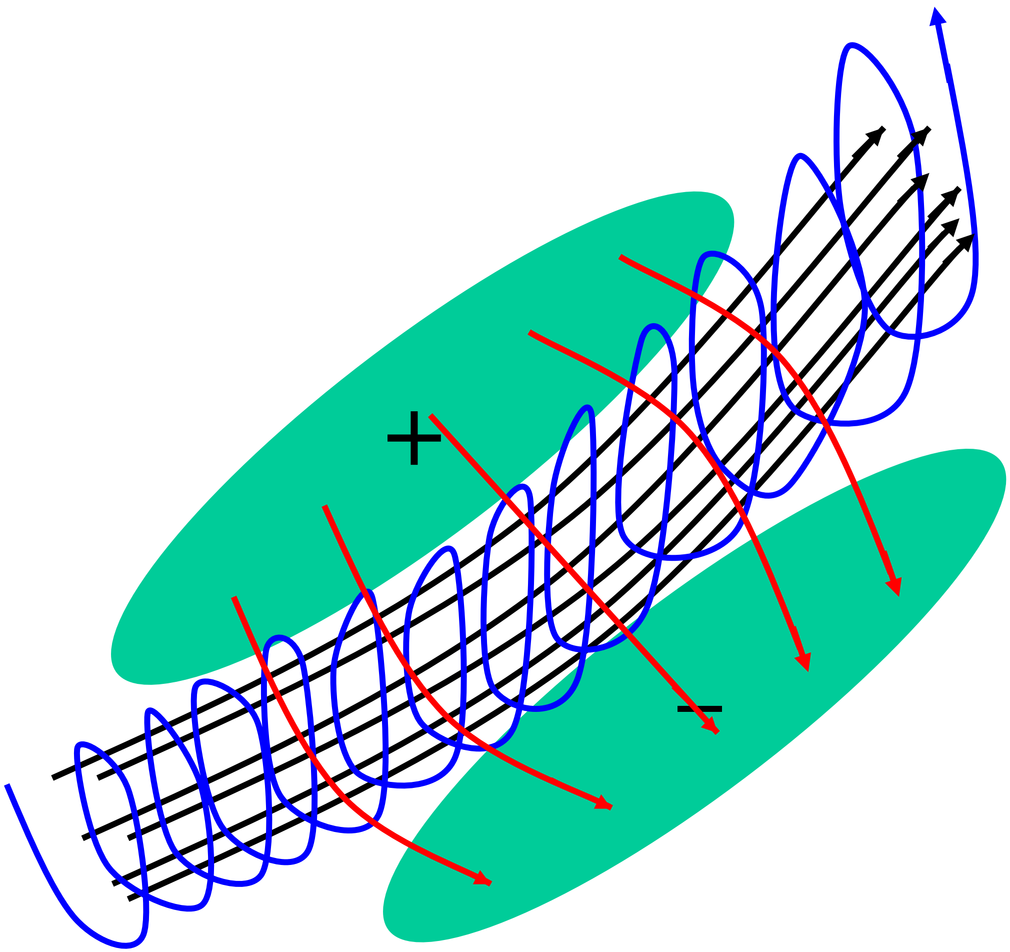


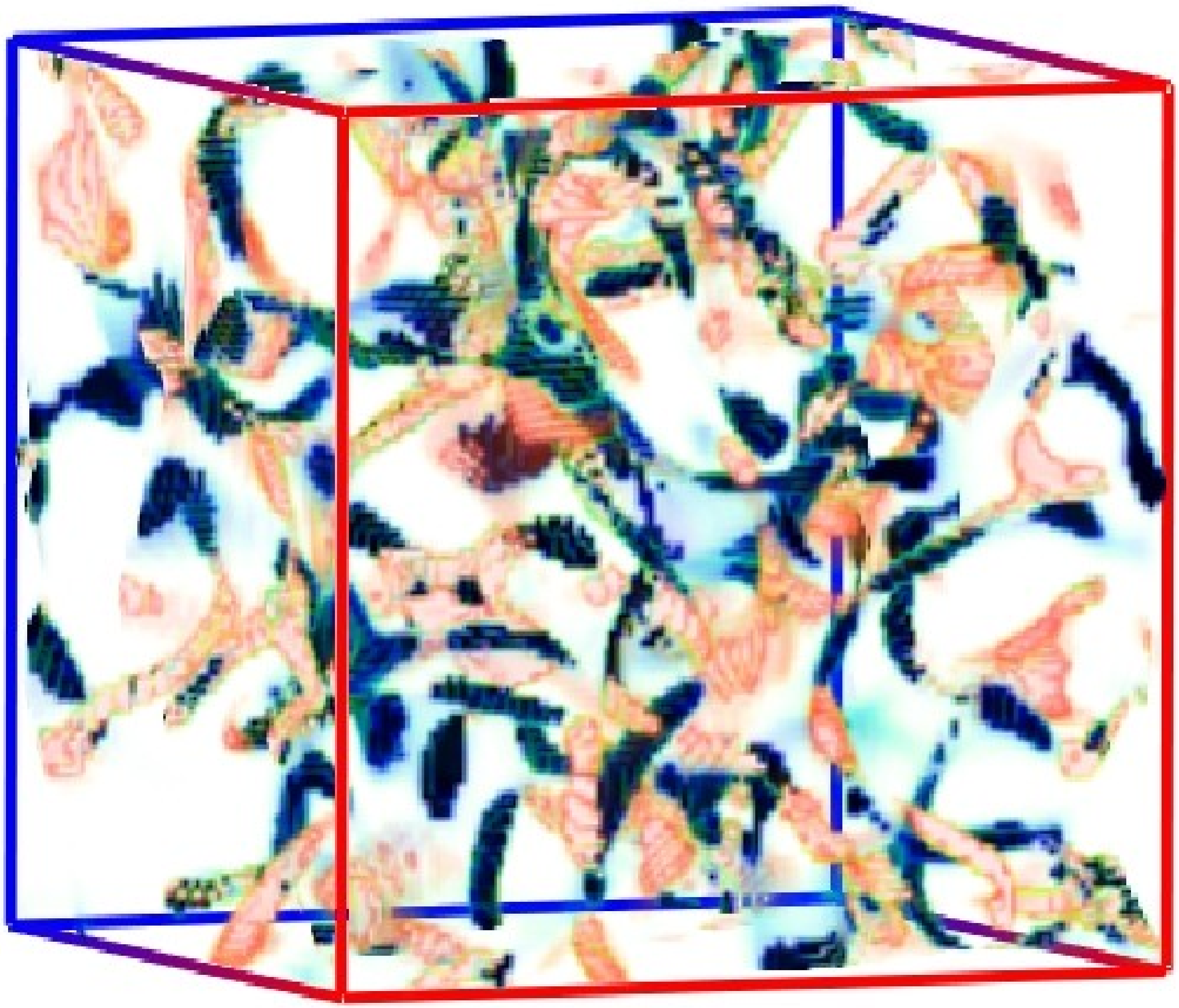
Charges in W^+_-

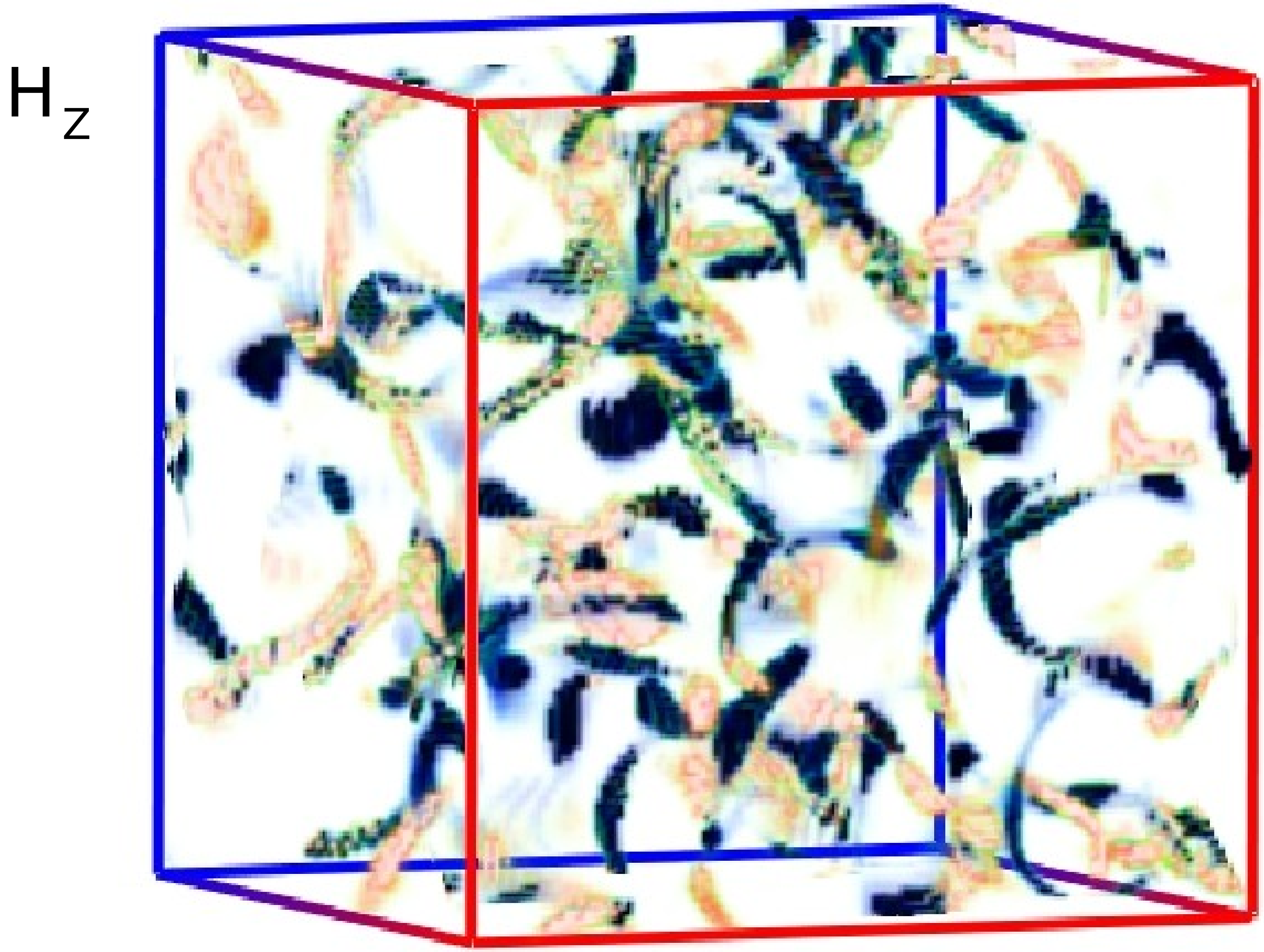


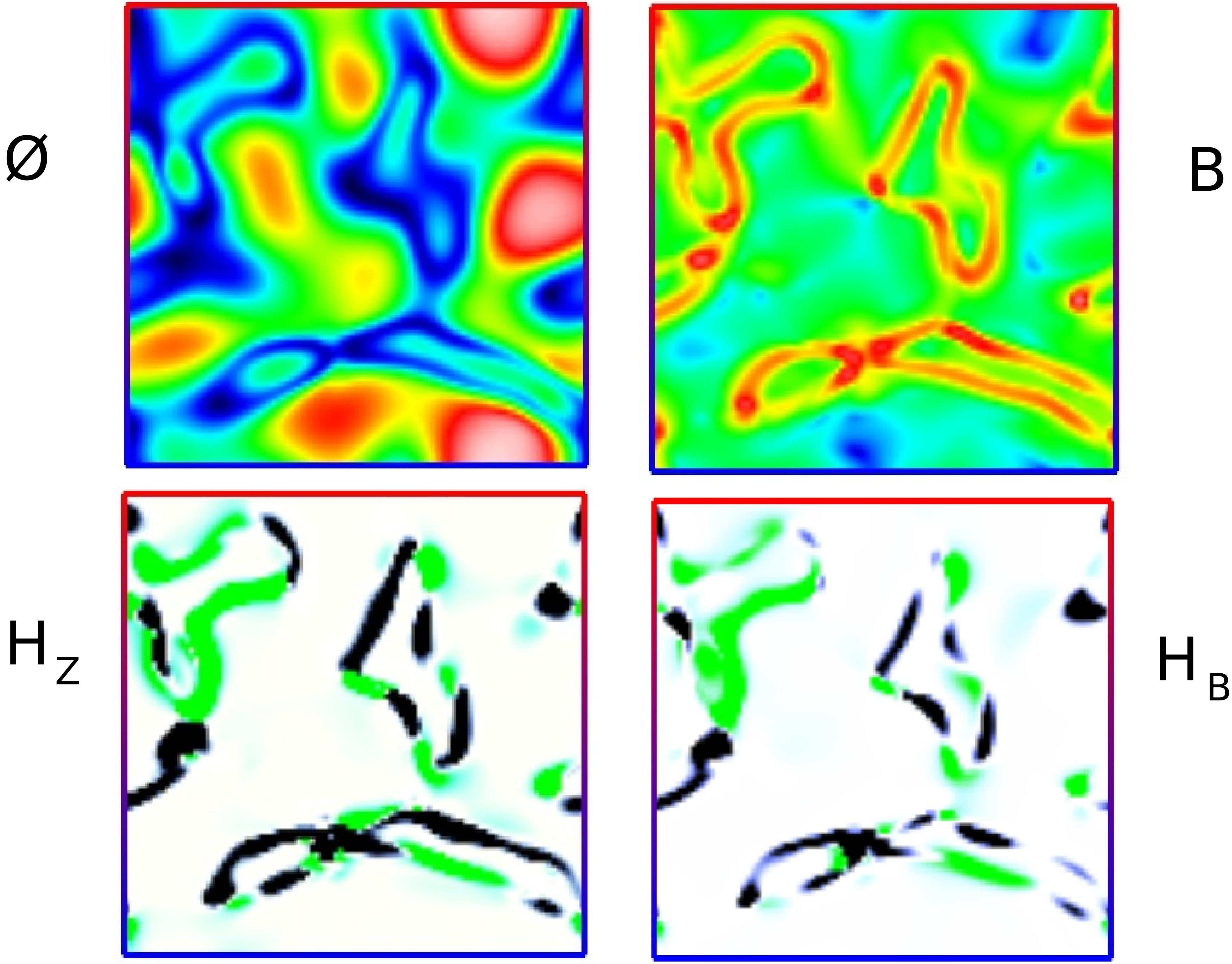
Charged plasma



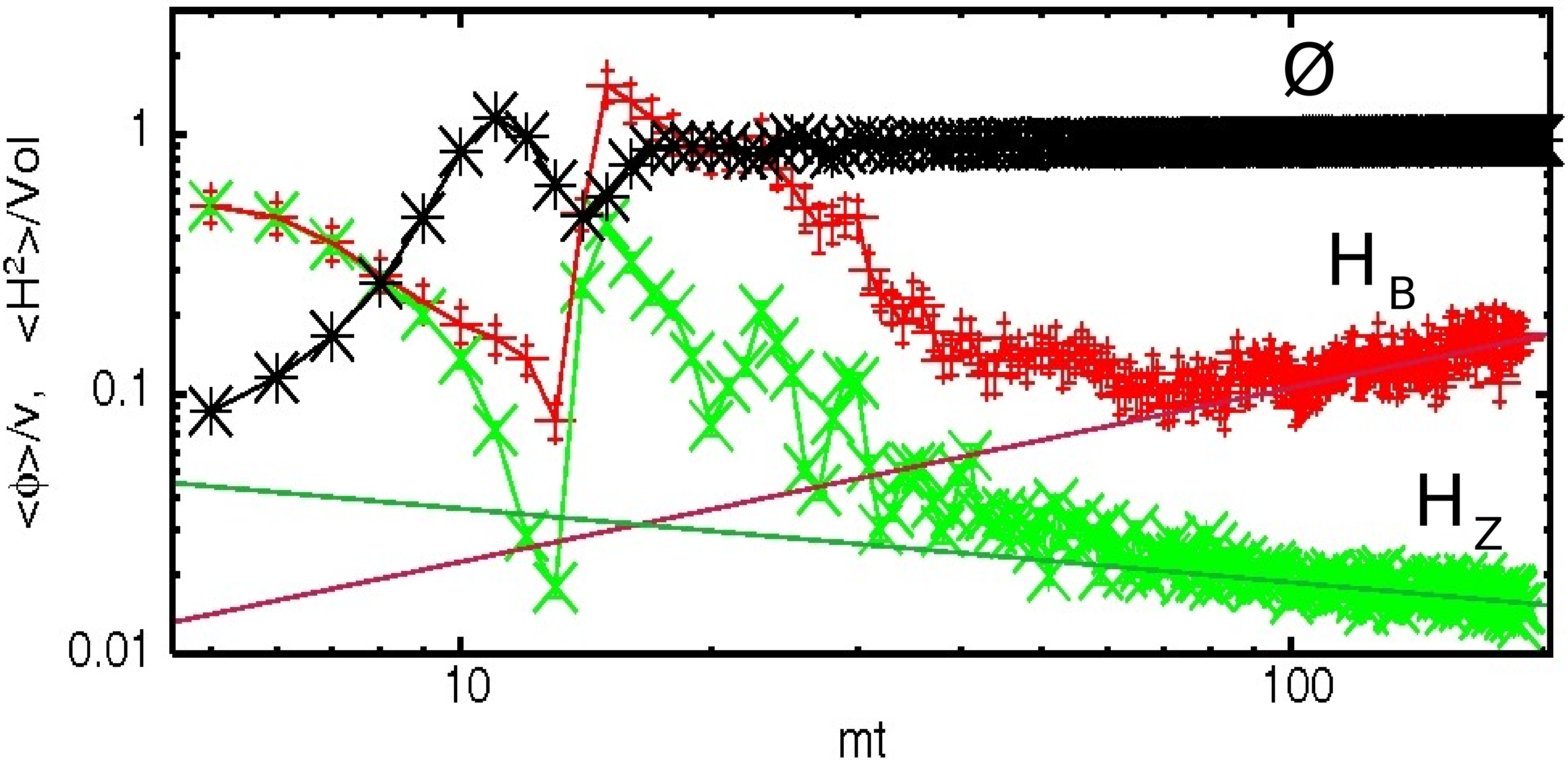
H_B



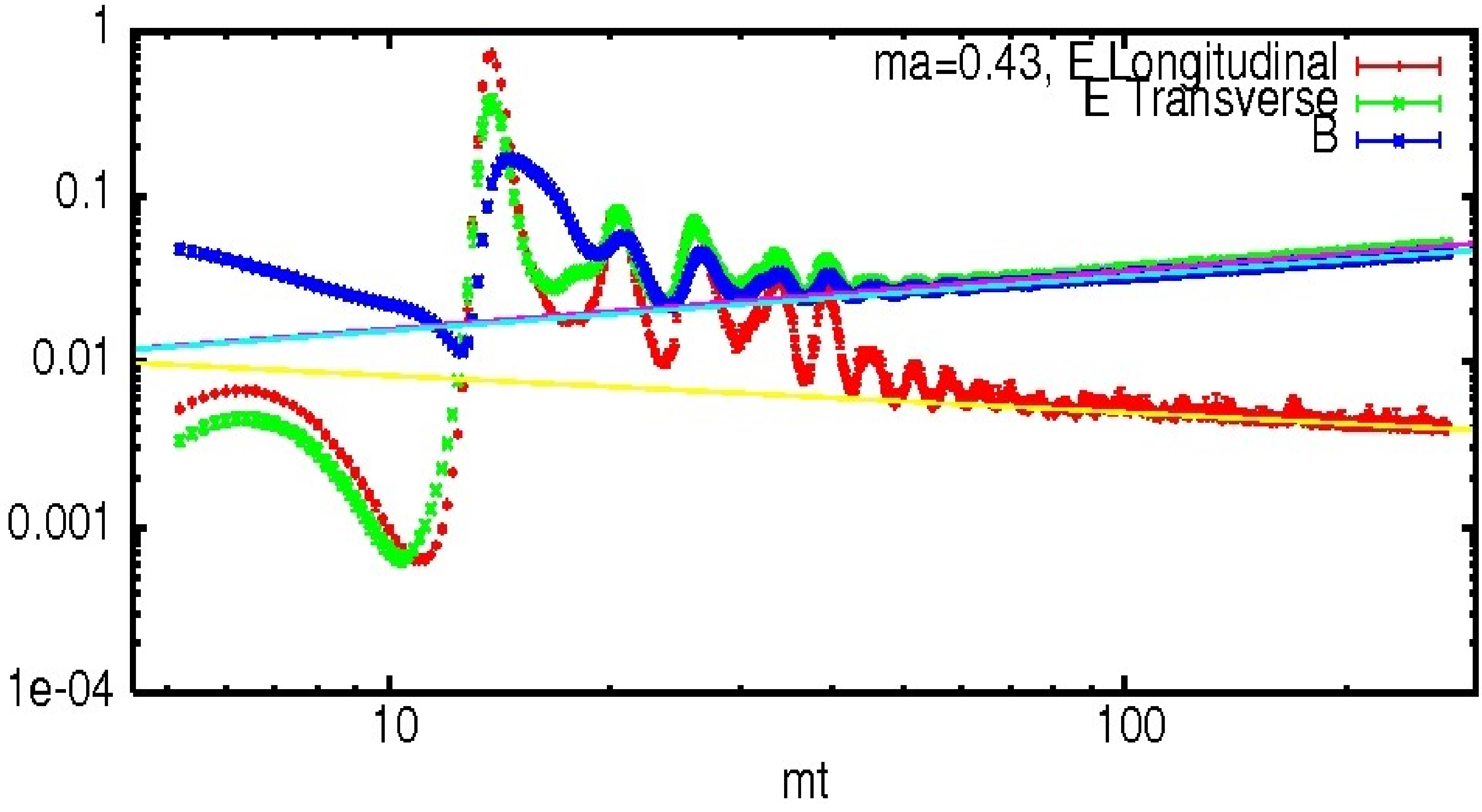

H z


Ø
B
H Z
H B

Time evolution



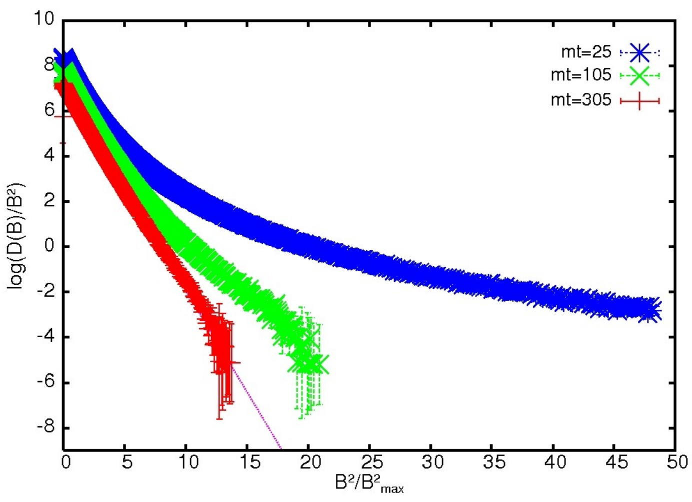
Time evolution

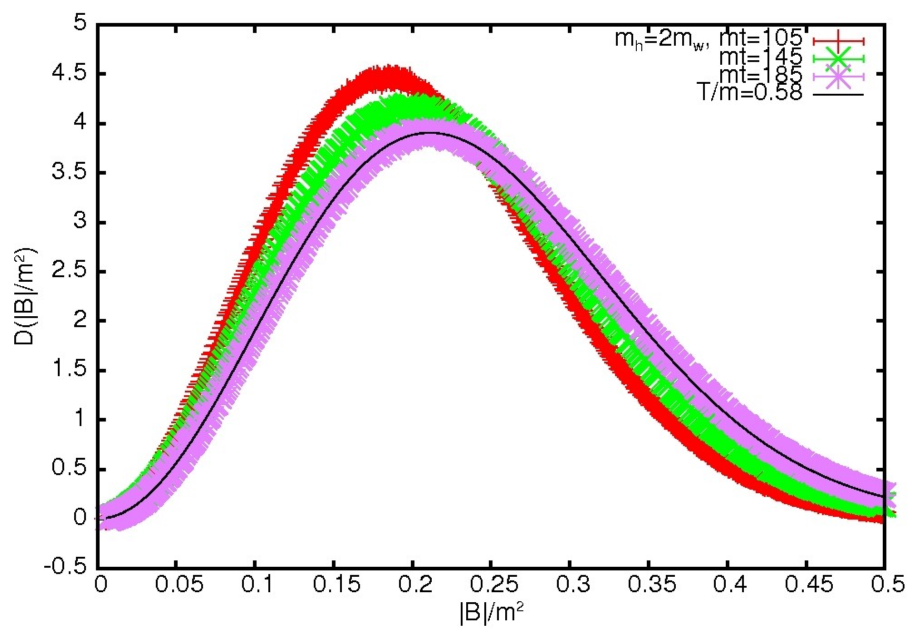


Boltzman-Maxwell distribution

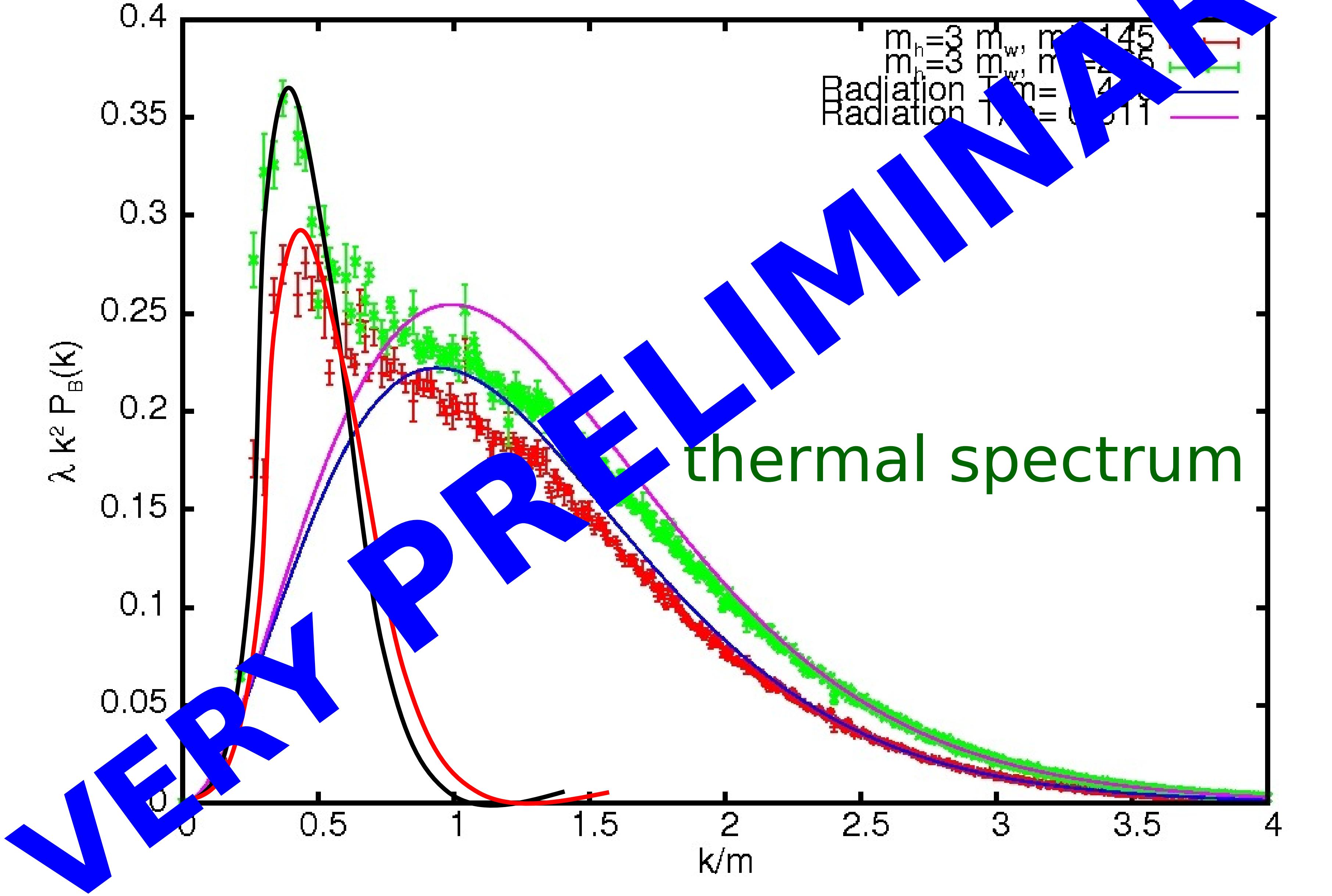
$$P(B)=B^2\exp\left\{\frac{3B^2}{2\langle B^2\rangle}\right\}\qquad\langle B^2\rangle=\frac{\pi^2}{15}T^4$$

$$T\approx 0.4-0.6\,m$$





Inverse Cascade



Spatial averages

$$B_{(1)}(L) = \frac{1}{L} \int_C \vec{B} \cdot d\vec{x}$$ Linear average

$$B_{(2)}(L) = \frac{1}{L^2} \int_S \vec{B} \cdot d\vec{S}$$ Magnetic flux

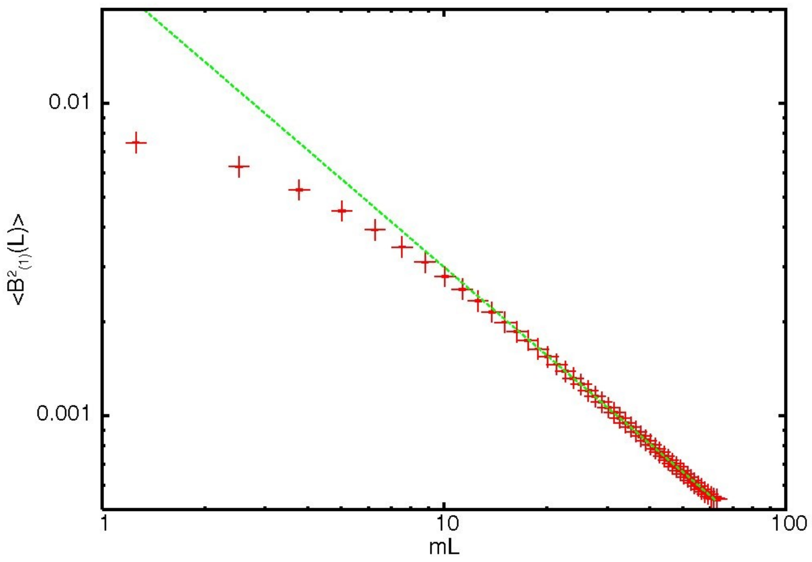
$$B_{(3)}(L) = \frac{1}{L^3} \int_V \vec{B} \cdot d^3\vec{x}$$ Volume average

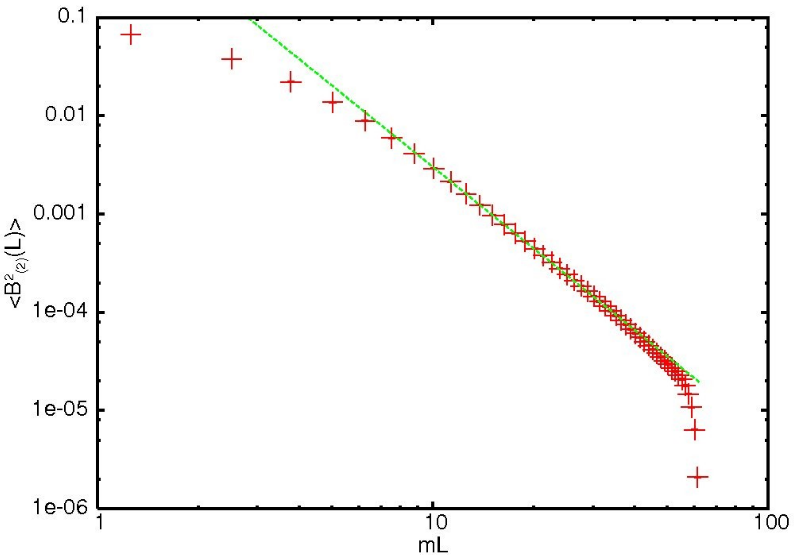
Spatial averages

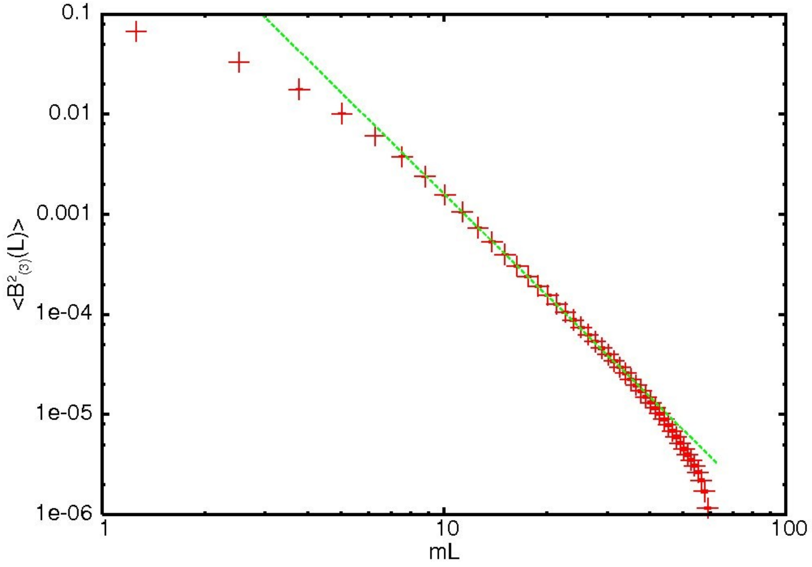
$$\langle B^2_{(1)}(L)\rangle \approx B^2_\xi \left(\frac{\xi}{L}\right)$$

$$\langle B^2_{(2)}(L)\rangle \approx B^2_\xi \left(\frac{\xi}{L}\right)^2$$

$$\langle B^2_{(3)}(L)\rangle \approx B^2_\xi \left(\frac{\xi}{L}\right)^{2p+3}$$



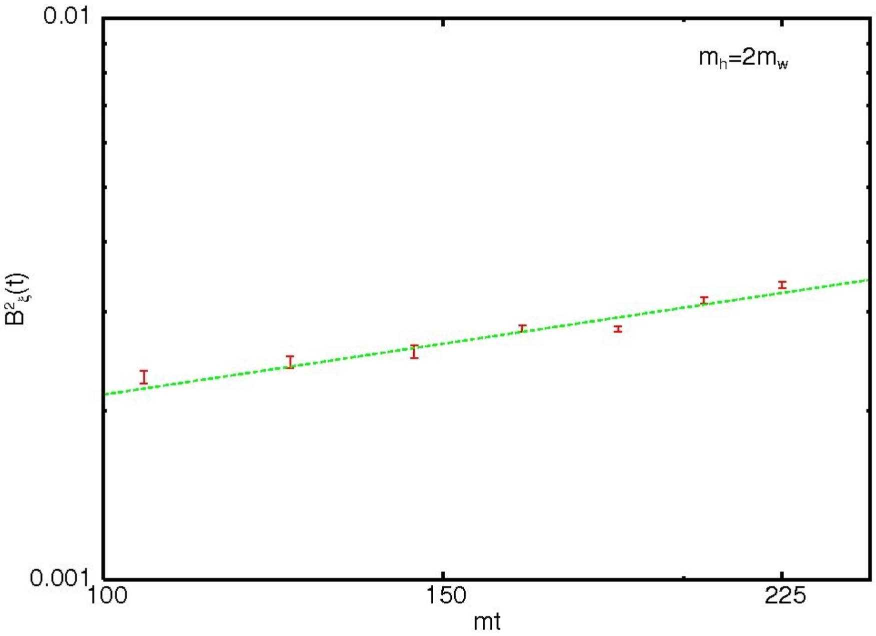


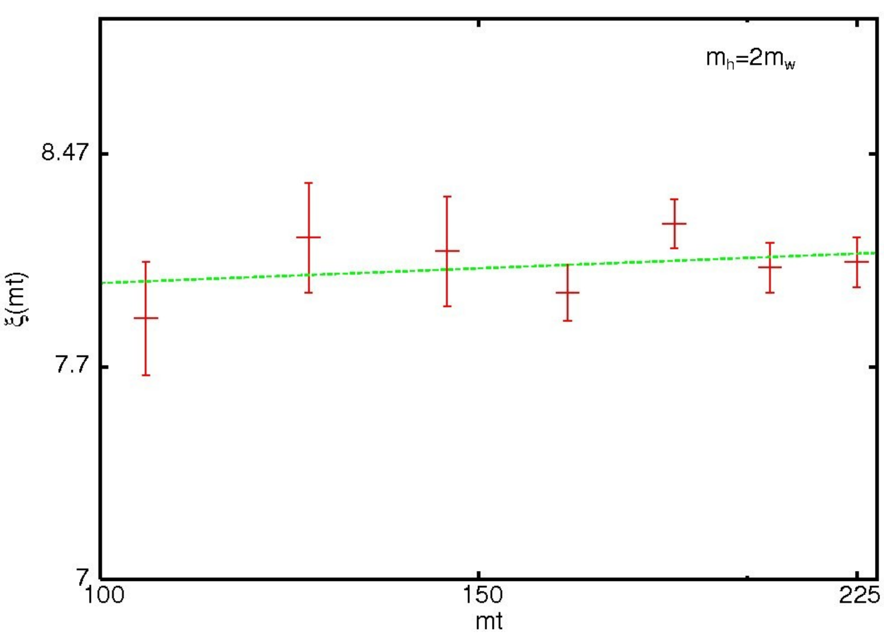


Spatial averages

$$B_\xi^2 \approx 3\times10^{-3}\, t^{0.5}\, \rho_0$$

$$\xi \approx 8\, t^{0.02}\, m^{-1}$$





The amplitude of magnetic fields

$$\rho_{mag} \leq 10^{-3} \rho_0 \approx 10^{-4} m_H^2 v^2 = (10\, GeV)^4$$

$$\rho_{mag}^{(0)} = \left(\frac{T_0}{T_{EW}}\right)^4 \rho_{mag} \approx (0.5\, \mu G)^2/8\pi$$

$$\frac{1}{8\pi} Gauss^2 = 1.39 \times 10^{-42} GeV^4$$

Conversion factor

he coherence scale of magnetic fiel

$\xi \propto t$ During inverse cascade

$\xi \propto a(t)$ After photon decoupling

$$\xi_0 \approx 3\, cm \left(\frac{a_{dec}}{a_{EW}}\right)^2 \left(\frac{a_0}{a_{dec}}\right) \approx 20\, Mpc$$

Observation

Magnetic Fields

Coherent Magnetic Fields

$B \approx 50\ \mu G\ \ at\ \ L < 5\ kpc$

$B \approx 5 - 10\ \mu G\ \ at\ \ L \approx 10\ kpc$

galaxies

$B \approx 1\ \mu G\ \ at\ \ L \approx 1\ Mpc$ clusters

$B < 10^{-2} - 10^{-3}\ \mu G\ \ at\ \ L \approx 1 - 50\ Mpc$ superclusters

$B < 10^{-3} - 10^{-5}\ \mu G\ \ at\ \ L > 100\ Mpc$ CMB

$B < 10^{11}\ G\ \ at\ \ T = 10^{9}\ K$ BBN

Coherent Magnetic Field in M31

$B \approx 1 - 3\ \mu G$

$l \approx 10\ kpc$

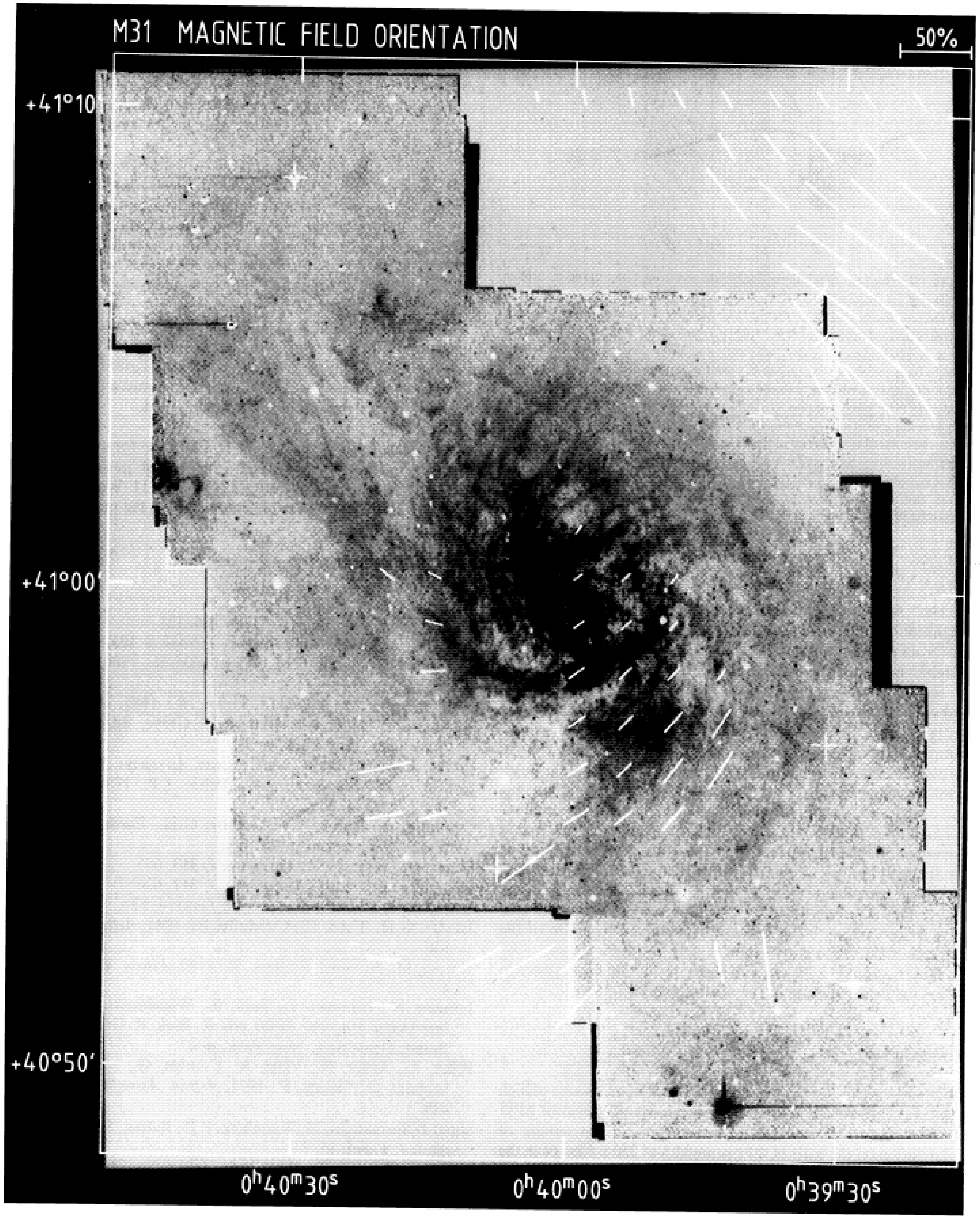
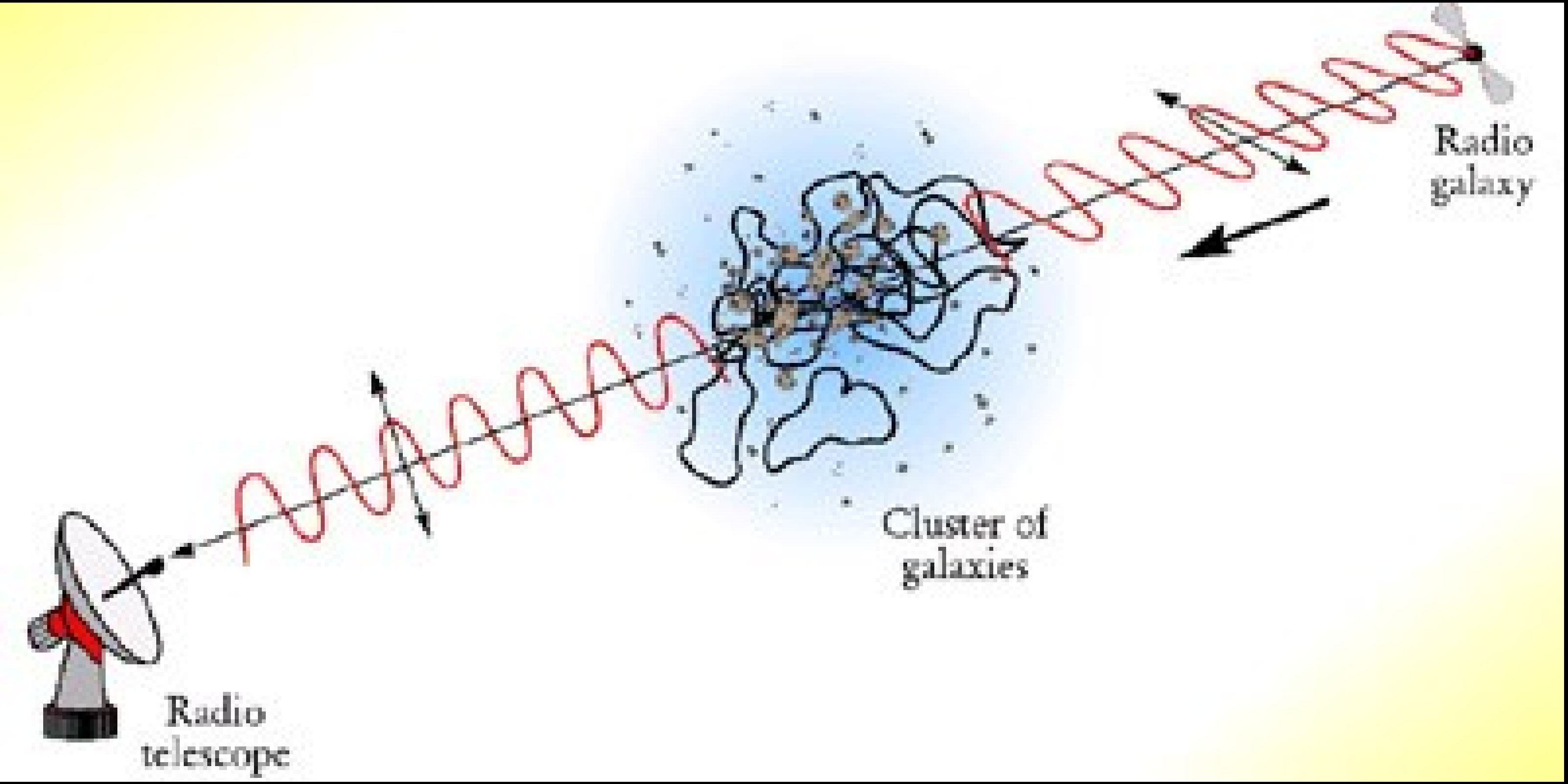
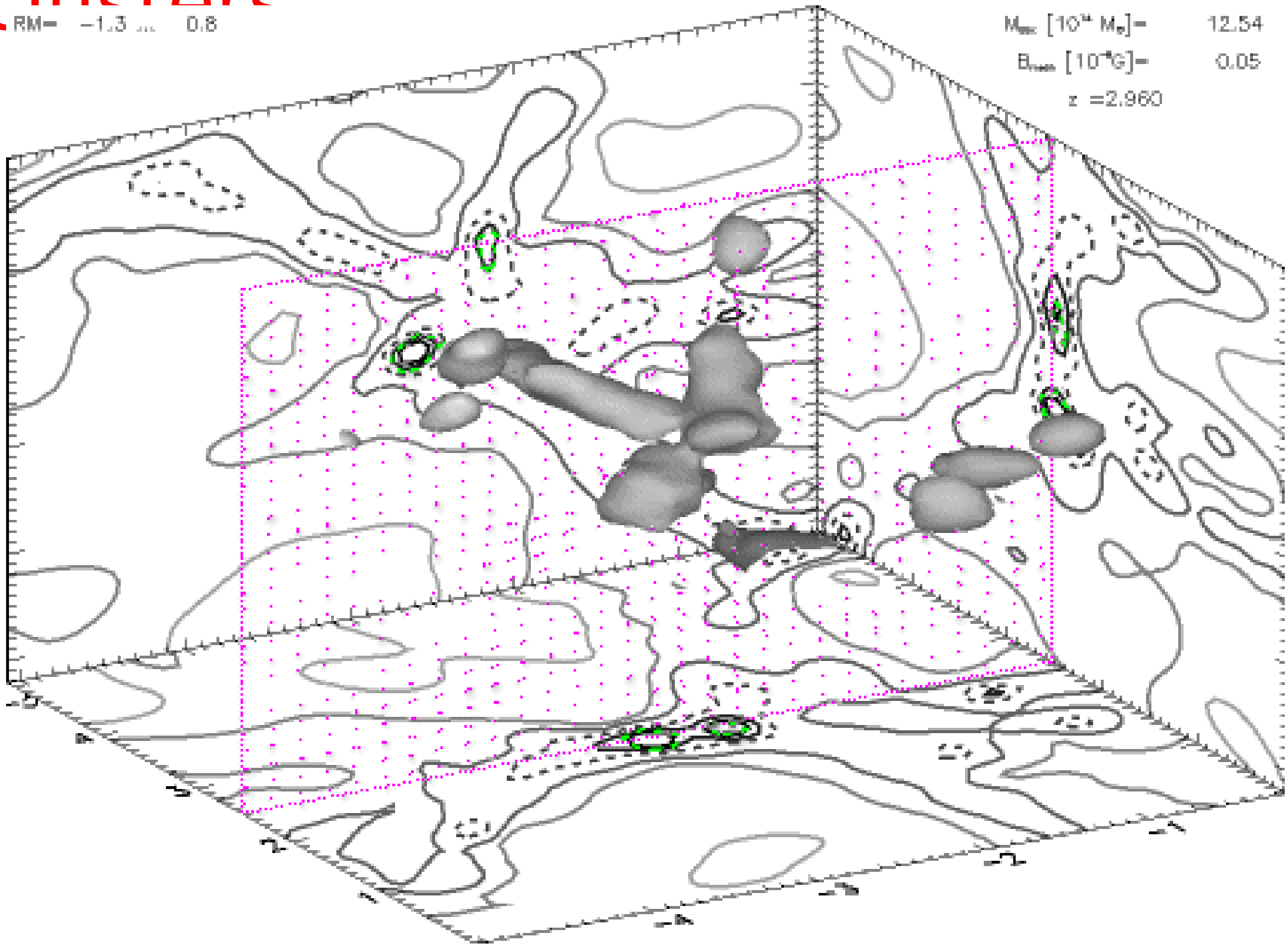


Fig. 11. Orientation of the magnetic field (χ_B) in the central region of M 31 overlayed onto the Hα photograph of Ciardullo et al. (1988). The lengths of the vectors indicate the degree of linear polarization at λ6.3 cm

Faraday rotation by cluster galaxies



Coherent Magnetic Fields in clusters



EW Symmetry Breaking can lead to the production of primordial magnetic fields at tachyonic preheating after hybrid inflation

The right amplitude and scale of magnetic fields depends on the extent of kinetic turbulence

Initial conditions for magneto-Hydrodynamic simulations