Title: Shocks in the Early Universe

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Abstract:

Shocks in the early universe: g-waves

Neil Turok, Perimeter

w/ Ue-Li Pen arXiv1510.02985

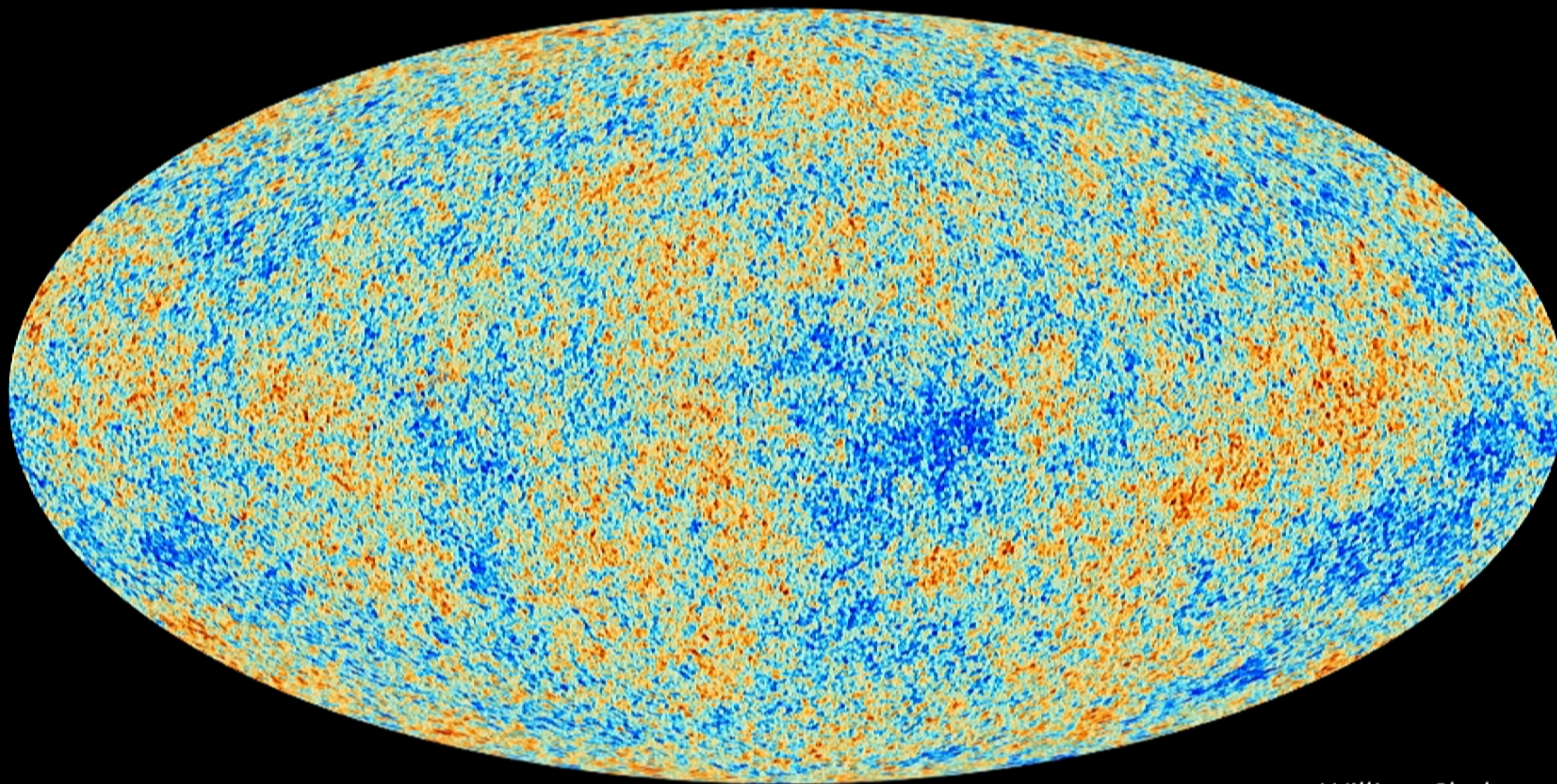
+Job Feldbrugge, Erik Schnetter, in preparation

spinoff of work on quantum cosmology

- For simple conformal matter, and FRW symmetry, one can do the quantum gravitational path integral exactly: you find a "perfect bounce" i.e. smooth passage through the singularity
- Studied generic perturbations at linear and nonlinear order, around flat FRW, semiclassically
- Discovered breakdown of perturbation theory at *large* times

w/ Steffen Gielen (Imperial College)
1510.00699, PRL in press

that vast shore wash'd with the farthest sea



William Shakespeare,
Romeo and Juliet, 1597

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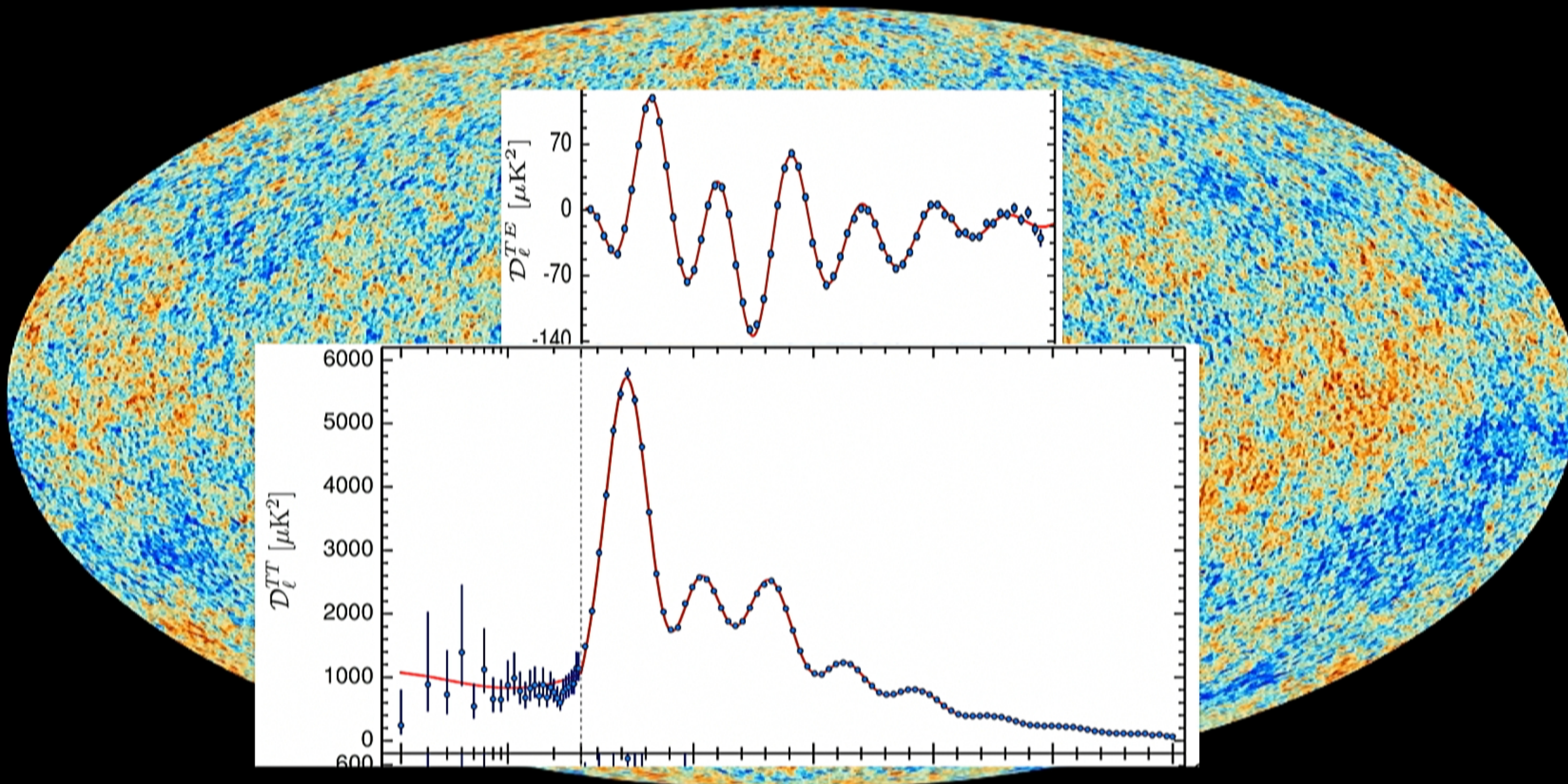
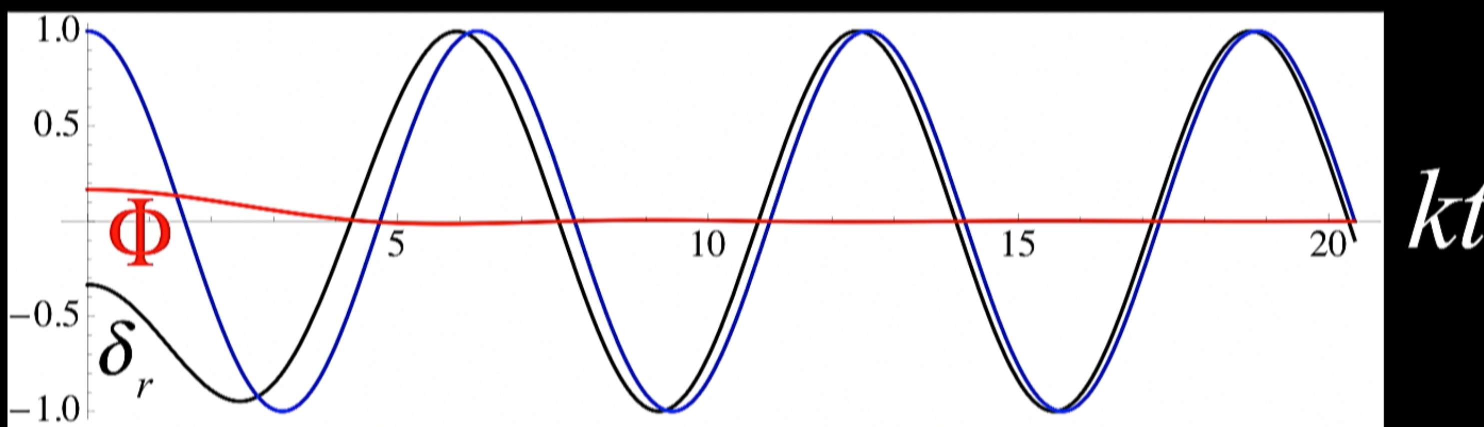


William Shakespeare,
Romeo and Juliet, 1597

standard adiabatic modes

- synchronized with big bang
- nearly scale-invariant spectrum



(conformal Newtonian gauge)

relativistic fluid dynamics

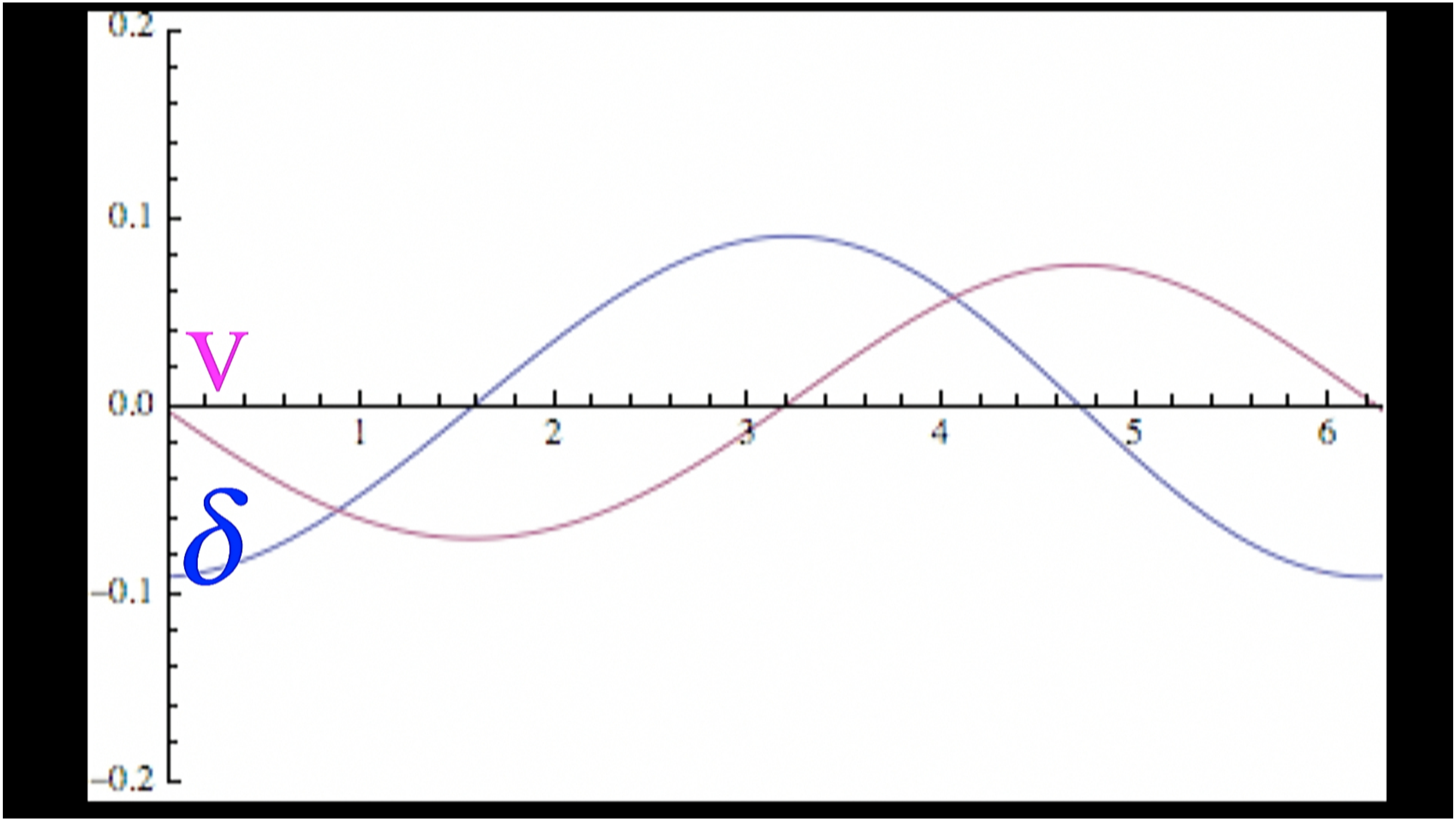
Simplification: since gravitational backreaction is negligible on subhorizon scales, and radiation is conformal invariant, work in a Weyl frame in which the background is Minkowski

$$T^{\mu\nu} = \tfrac{4}{3}\rho u^{\mu} u^{\nu} + \tfrac{1}{3}\rho\eta^{\mu\nu};\ u^2 = -1,\ T_{\lambda}^{\lambda} = 0;$$

$$\partial_{\mu} T^{\mu\nu} = 0 \text{ are 4 equations for 4 unknowns}$$

In the absence of viscosity, these equations imply entropy and vorticity conservation. However, when shocks form the differential equations break down and entropy and vorticity are generated.

nonlinear plane waves



0.2
0.1
0.0
−0.1
−0.2
1
2
3
4
5
6
V
δ

wave steepening and shock formation

Fluid velocity is higher behind the wave than in front of it, by of order ε. So wave steepens and shock forms in time $t \approx \lambda / \varepsilon$. Defining $u, v \equiv x \pm c_s t$, To second order in $\Pi \equiv T^{tx} / T^{tt}$, for initially right-moving wave one finds

$$\kappa \partial_v \Pi + \Pi \partial_u \Pi = 0 \qquad \left(\text{with } \kappa \equiv 2c_s \frac{1+c_s^2}{1-c_s^2}\right)$$

i.e., Burger's equation: sinusoidal waves of wavenumber k steepen and shocks form when $kc_s t = \kappa c_s^{-1} \varepsilon^{-1}$ (exact).

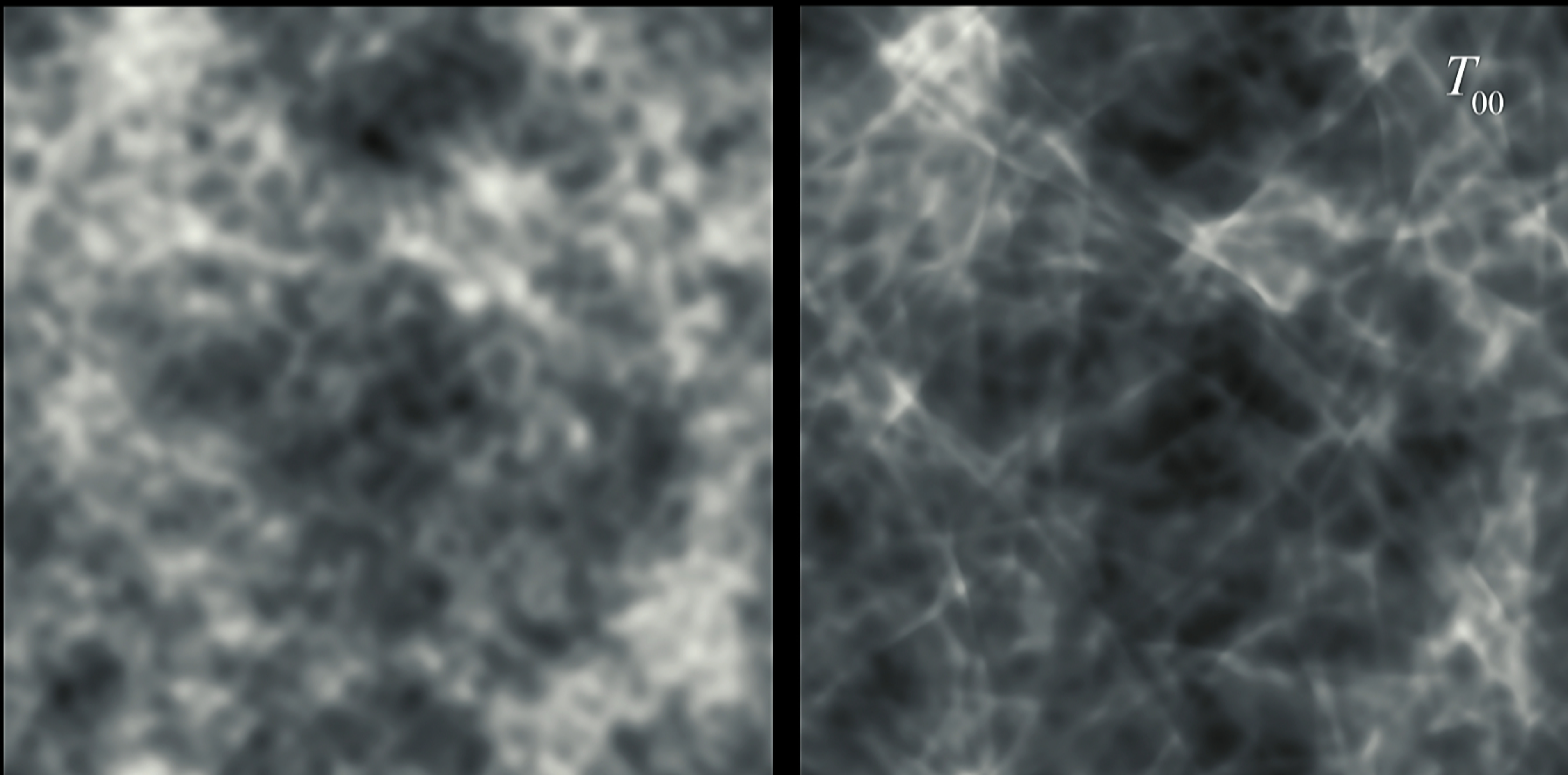
Shock formation also seen in 2d and 3d (analytically and numerically) for

$$kc_s t \approx \varepsilon^{-1}$$

where ε is the fractional density perturbation.

Large scale observations indicate $\varepsilon \sim 10^{-4}$ with an almost scale-invariant spectrum

3d simulations



$\varepsilon = 0.01$ $\varepsilon = 0.1$ Credit: J. Feldbrugge and E. Schnetter

Shock profile with viscosity

include viscosity a la Landau/Lifshitz:

shear viscosity

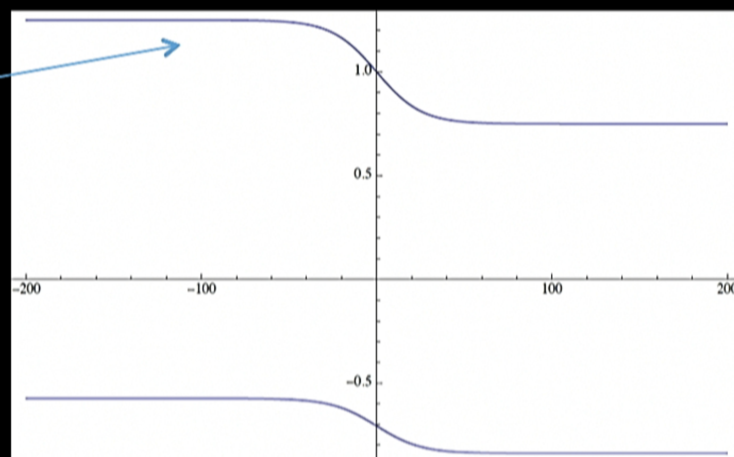
$$T^{\mu\nu} = \rho(\tfrac{4}{3}u^{\mu}u^{\nu} + \tfrac{1}{3}\eta^{\mu\nu} - L(u^{\mu,\nu} + u^{\nu,\mu} - u^{\mu}u^{\alpha}\,\partial_{\alpha}u^{\nu} - u^{\nu}u^{\alpha}\,\partial_{\alpha}u^{\mu})); \; \mathrm{L} \equiv \eta/\rho$$

stationary solution:

$$\partial_x T^{x0} = \partial_x T^{xx} = 0 \Rightarrow L\partial_x u^x = f(u^x, u_0^x) \approx \varepsilon(\tfrac{8}{27}(\delta u^x)^2 - \tfrac{1}{48})$$

$$\rho \approx 1 - \tfrac{\varepsilon}{2}\tanh(\tfrac{\varepsilon}{9\sqrt{2}}\tfrac{x}{L})$$

$$u^x \approx -\tfrac{1}{\sqrt{2}} - \tfrac{3\varepsilon}{8\sqrt{2}}\tanh(\tfrac{\varepsilon}{9\sqrt{2}}\tfrac{x}{L})$$



Assuming only standard model physics, at temperatures above the electroweak transition,

$$\text{viscosity } \eta \approx 16T^3 g_1^{-4} \ln(1/g_1) \approx 400T^3$$

$$\text{viscous scale } L \equiv \eta / \rho \sim T^{-1} \sim \tfrac{T}{M_{Pl}} R_H$$

$$\text{shocks form if } L_s \sim 9\sqrt{2}\,\tfrac{L}{\varepsilon} < \varepsilon R_H$$

with only standard model physics, and $\varepsilon \approx 10^{-4}$, shocks form in the temperature range

$$1\,\mathrm{GeV} < T < 10^{7}\,\mathrm{GeV}$$

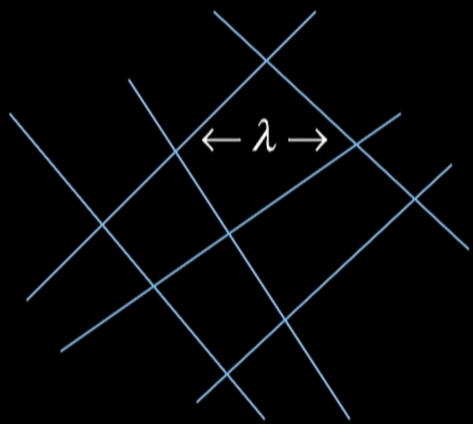
neutrino damping — diffusion > wave steepening

for larger values of $\varepsilon \approx 0.2$ (see later), shocks form in the range

$$10\ \mathrm{MeV} < T < 10^{13}\,\mathrm{GeV}$$

neutrino damping — diffusion > wave steepening

network of shocks



network forms on scale λ when $t_f \sim \dfrac{\lambda}{\varepsilon}$

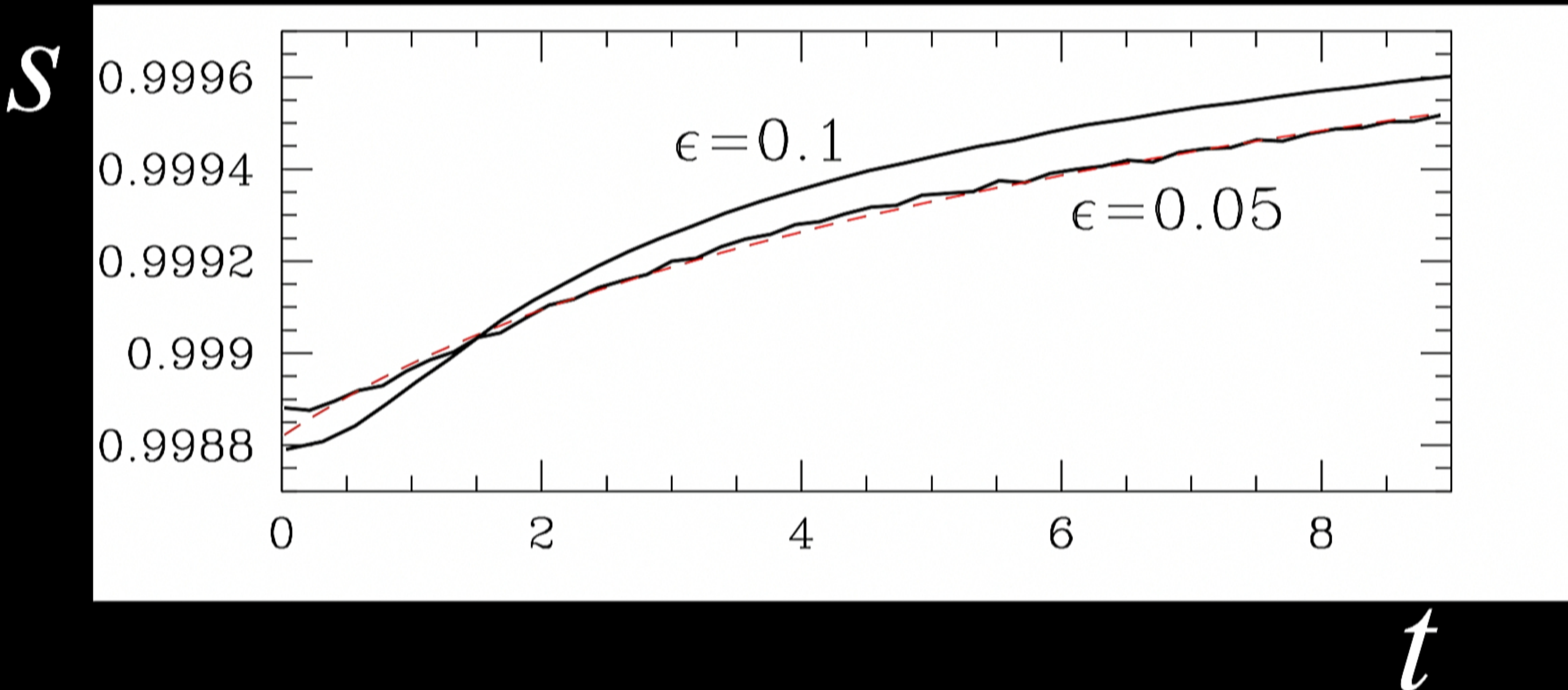
entropy density $\left\langle s^0 \right\rangle = \left\langle \dfrac{\rho^{3/4}}{\sqrt{1-\mathrm{v}^2}} \right\rangle \approx \rho_0^{\frac{3}{4}}(1 - \frac{3}{32}\left\langle \delta^2 \right\rangle)$

Conservation of energy+momentum

$\Longrightarrow$ entropy jumps by factor $\frac{1}{64}\varepsilon^3$ across shock

shock amplitude $\dot{\varepsilon} = -\dfrac{1}{6}\dfrac{c_s}{\lambda}\varepsilon^2$

return to equilibrium via shocks



potential effects and signatures

Departures from local thermal equilibrium – necessary condition for baryogenesis

Creation of primordial vorticity and magnetic fields, possibility of fully developed turbulence

Local inhomogeneties in $\frac{n_b}{s}$

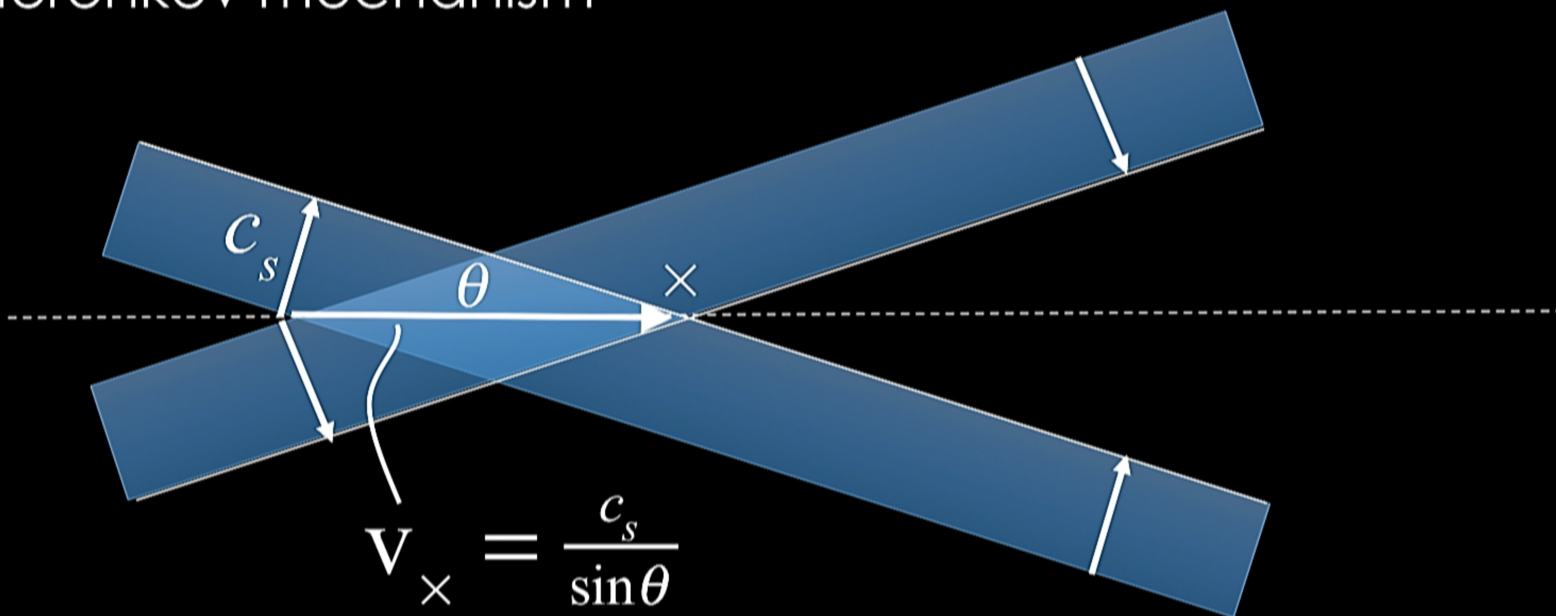
Stochastic gravitational wave background

$$\Omega_{gw} \sim \varepsilon^4 \Omega_{rad}$$

Matarese et al
Noh-Hwang, Nakamura,
Baumann-Steinhardt

g-waves from shocks

Cherenkov mechanism

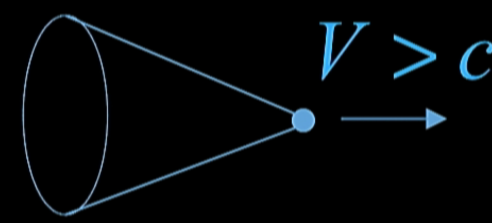


spatial stress at intersection moves faster than light

Cherenkov wedges: electromagnetism

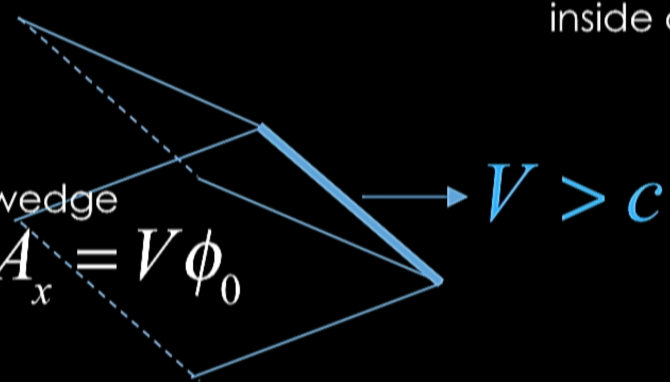
$$\phi = \frac{1}{\sqrt{x^2+y^2+z^2}}$$

$$\phi = \frac{\gamma}{\sqrt{\gamma^2(x-\frac{V}{c}t)^2+y^2+z^2}} = \frac{1}{\sqrt{(x-\frac{V}{c}t)^2-(\frac{V^2}{c^2}-1)(y^2+z^2)}}$$



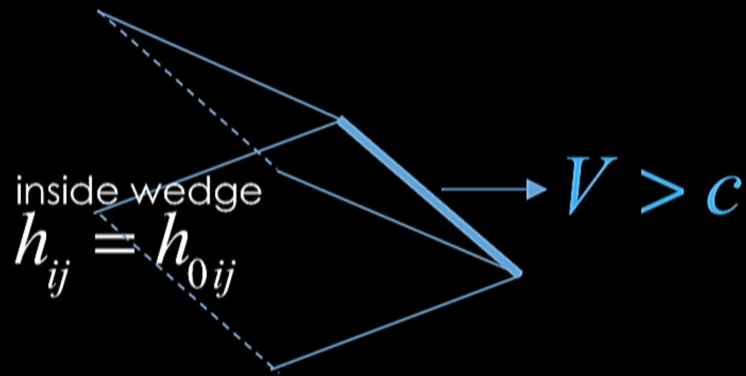
inside cone, zero outside

Integrate over z



$$\phi = \phi_0,\ A_x = V\phi_0$$

Cherenkov wedges: gravitational waves



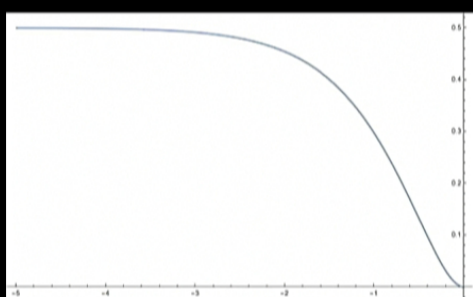
$$(-\partial_t^2 + \partial_x^2 + \partial_y^2) h_{ij}^T (x - \tfrac{t}{\sin\theta}, y) = 16\pi G T_{ij}^T$$

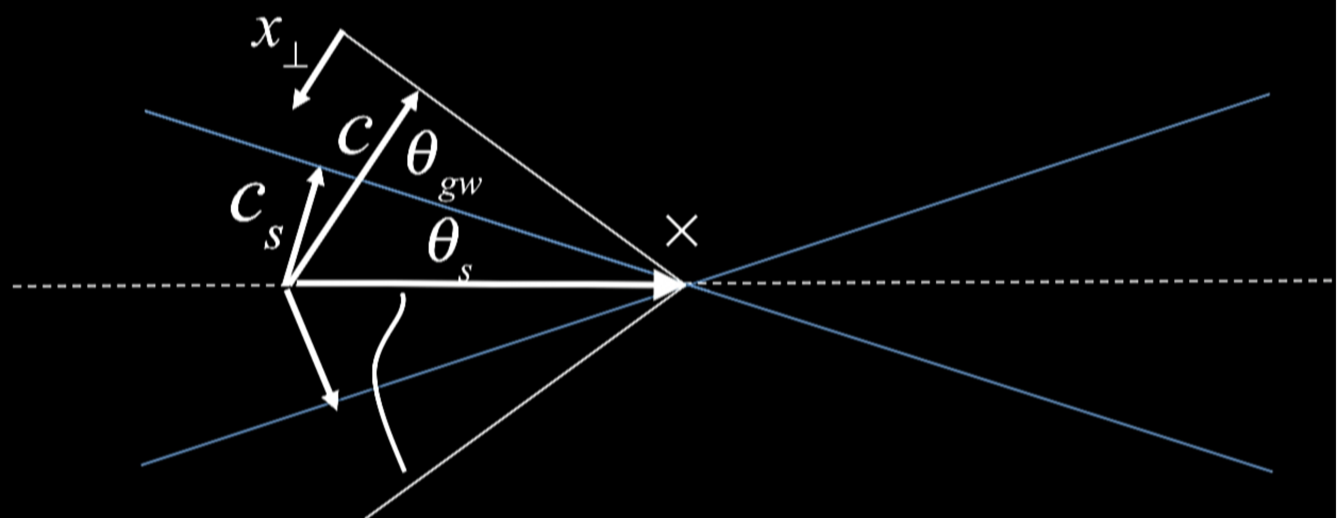
$$\Rightarrow (-\partial_x^2 + (\tan\theta)^2 \partial_y^2) h_{ij}^T = (\tan\theta)^2 16\pi G T_{ij}^T$$

$$T_{ij}^T = \tfrac{2}{3} \bar{\rho} (\Delta \mathrm{v})^2 (x) (\sin\theta)^2 O \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} O^T ; O = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

g-waves from shocks

$$h_{ij}^{T}(x_{\perp})$$





$$v_{\times} = \frac{c_s}{\sin\theta_s} = \frac{c}{\sin\theta_{gw}}$$

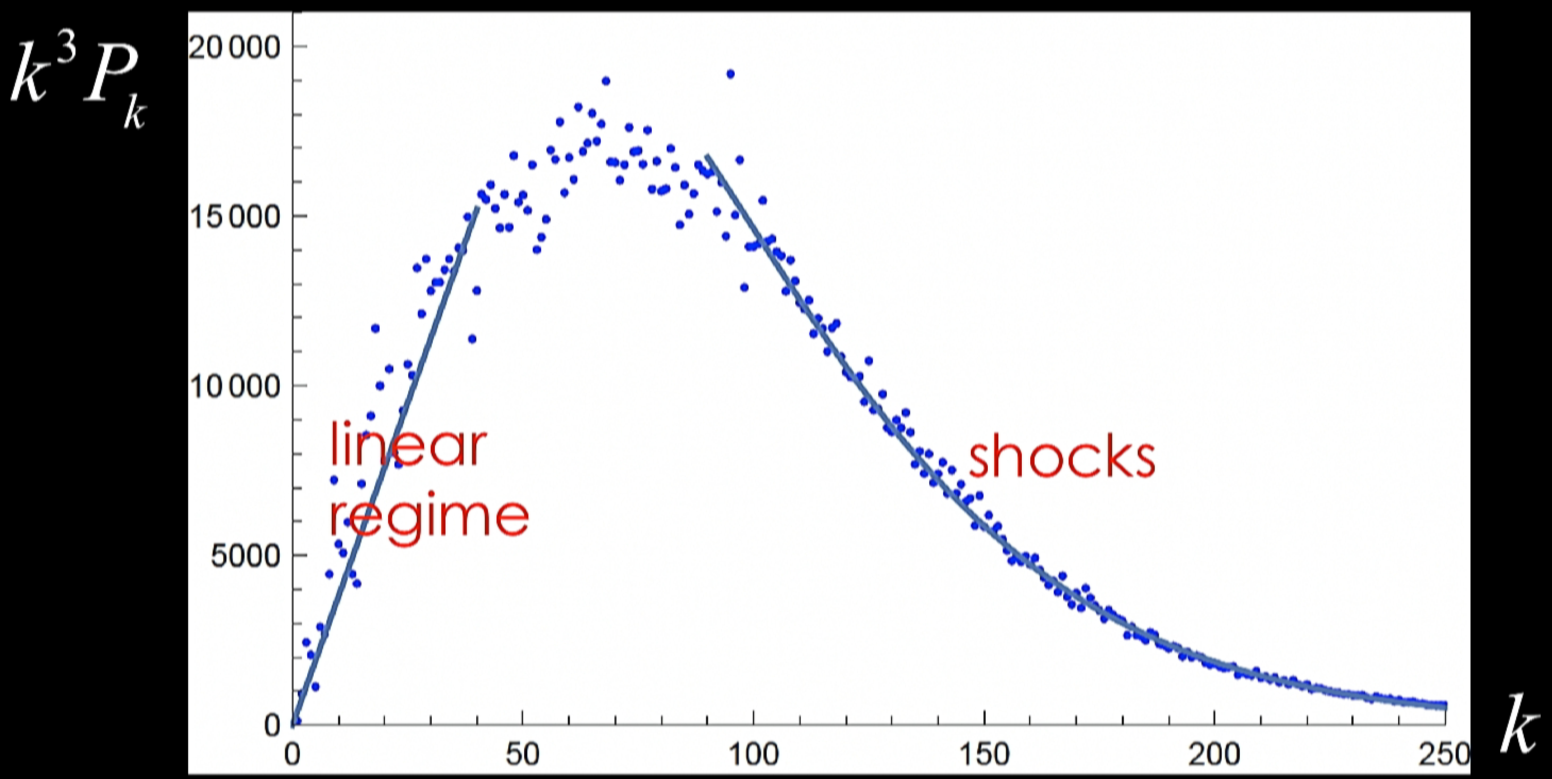
Scalar/Vector/Tensor decomposition

$$T_{ij}(\mathbf{x}) = \sum_{\mathbf{k}} T_{ij}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}};$$

$$T_{ij}(\mathbf{k}) = \frac{1}{3}\delta_{ij}T + (\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij})T^S + (\hat{k}_i T_j^V + \hat{k}_j T_i^V) + T_{ij}^T, \text{ where } k_i T_i^V \equiv k_i T_{ij}^T \equiv k_j T_{ij}^T \equiv T_{ij}^T \equiv 0$$

We measure and model unequal-time stress tensor correlators in numerical simulations, model them and then solve analytically for the radiation of gravitational waves. This should allow us to determine predictions (and constraints) with high accuracy.

Power spectrum from shocks (2d, T^{00})



Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

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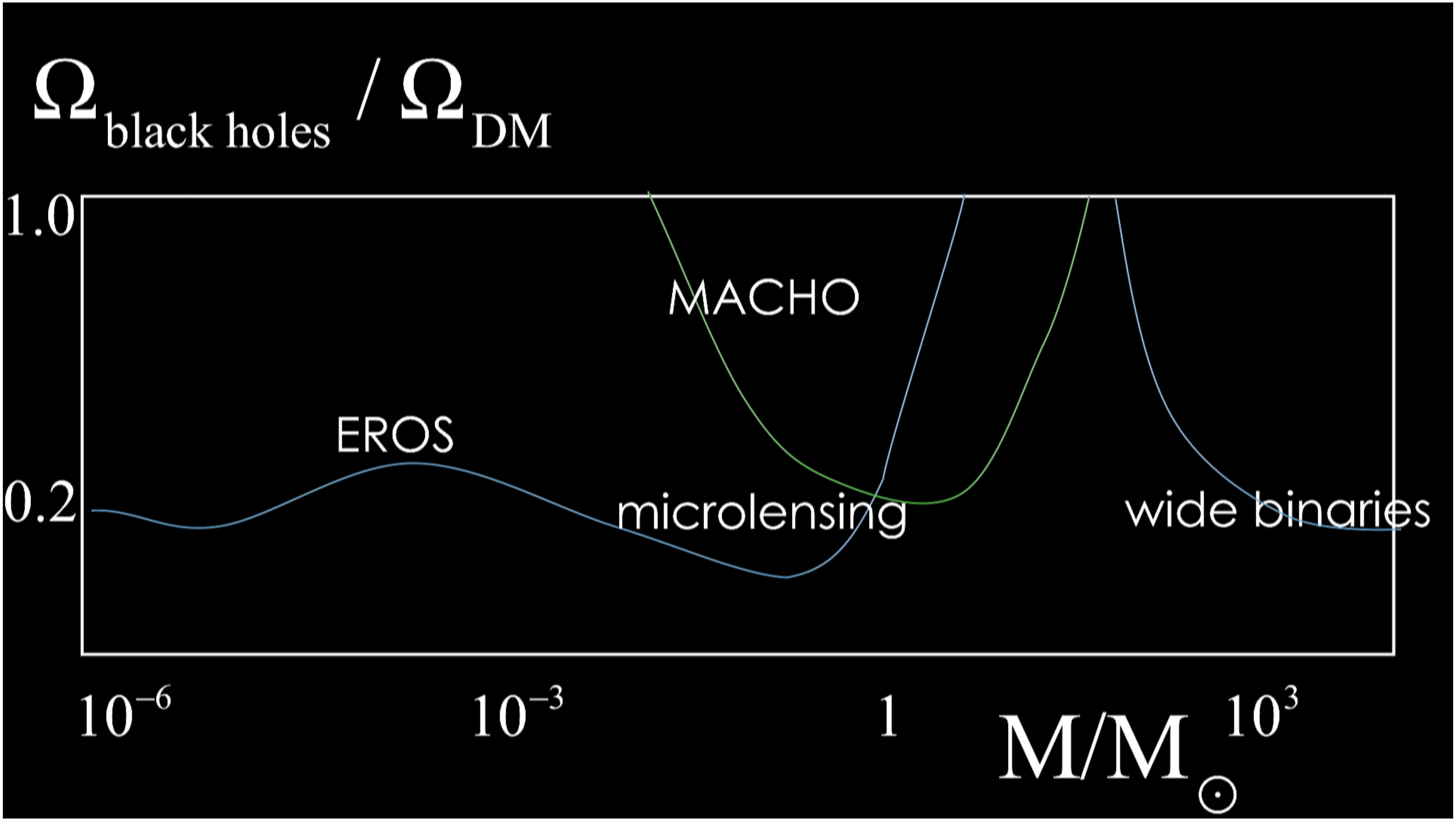
We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $10\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they can radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will then rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

arXIv 1603.00464



$\Omega_{\text{black holes}} / \Omega_{\text{DM}}$
1.0
0.2
MACHO
EROS
microlensing
wide binaries
10^{-6}
10^{-3}
1
10^{3}
$M/M_{\odot}$

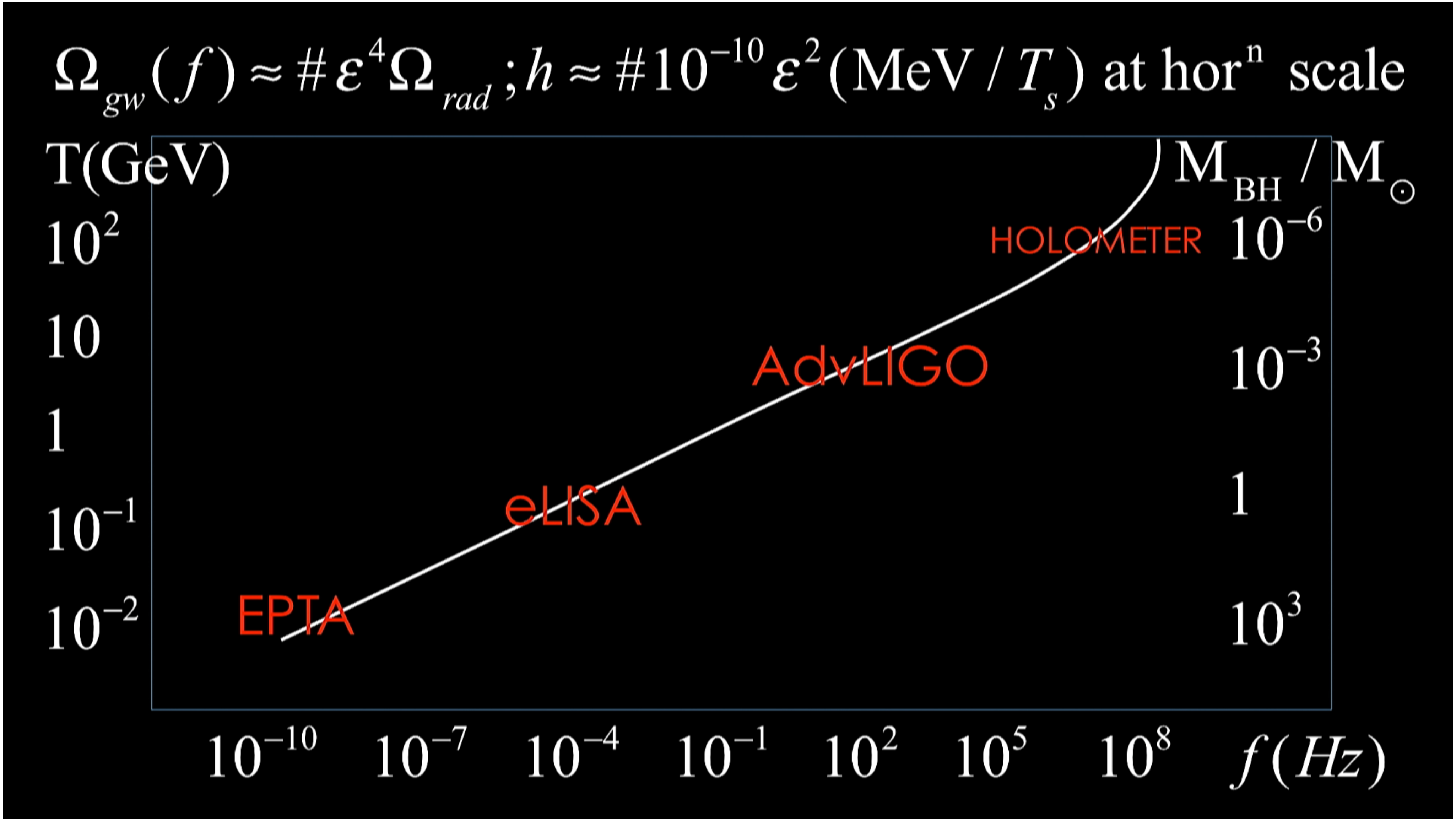
For black holes to contribute Ω_{BH} today, need

$$\mathrm{erfc}[\frac{1}{\varepsilon^2}] \sim \frac{T_{eq}}{T_{form}} \Omega_{BH}$$

on the corresponding comoving scale, *i.e.*,

$$\varepsilon \sim \frac{1}{\sqrt{\ln(\frac{T_{eq}}{T_{form}} \Omega_{BH})}} \sim 0.2 \text{ for } T_{form} \sim 1 \text{ GeV}$$

Note: depends only logarithmically on Ω_{BH}, so constraint improves *exponentially* with bound on gravitational wave background


$\Omega_{gw}(f) \approx \# \varepsilon^4 \Omega_{rad}; h \approx \# 10^{-10} \varepsilon^2 (\mathrm{MeV}/T_s)$ at hor^n scale
T(GeV)
10^2
10
1
10^{-1}
10^{-2}
$M_{BH}/M_\odot$
10^{-6}
10^{-3}
1
10^3
HOLOMETER
AdvLIGO
eLISA
EPTA
10^{-10}
10^{-7}
10^{-4}
10^{-1}
10^2
10^5
10^8
$f(Hz)$

summary

Formation of weak shocks is a beautiful phenomenon
in nonlinear fluid dynamics. It happened in the early universe

Interesting new possibilities for baryogenesis, magnetogenesis,
gravitational waves…

If primordial spectrum has strong features on small scales,
we will be able to see them using gravitational waves.
Already excludes Bird et al scenario using EPTA bound

We will be able to probe the *very* early universe using g-wave
experiments, even in minimal cosmological scenarios