Gravitational wave background from Standard Model physics

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In collaboration with Mikko Laine

2nd eLISA CosWG workshop, Stavanger, Sep 24 2015

GWs from equilibrium sources

- GWs can be produced from eq. too. Well known Weinberg
- In thermal eq. particle scatter $\Rightarrow$ GW production
- Naive power counting: for momentum $k>T$

$$\Gamma \sim \alpha \frac{T^3}{m_{\rm Pl}^2} e^{-k/T}$$

with some internal plasma coupling, the gravitational coupling and a Boltzmann suppression

- Since $k{\sim}3T$ Γ must be small. Is that always true?

In this talk

- Go beyond this usual assumption
- Use a modern, consistent Thermal Field Theory framework
- Try to give reliable estimates for $T > 160$ GeV
- In particular, concentrate on the IR: for $k \ll T$ collective phenomena enter the rate and change the previous estimate

JG Laine **JCAP1507** (2015)

Outline

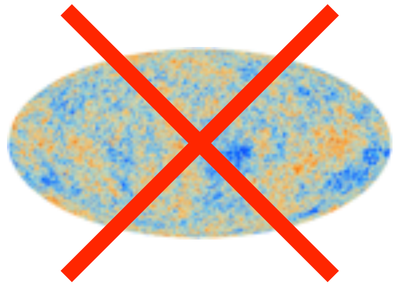
- ✓ Introduction and motivation
- Overview and formalism
- The IR rate and the viscosity of plasmas
- The $k \sim T$ rate
- Embedding the rates in cosmology: limits and prospects for detection

Overview

Equilibrium production

- GWs produced from an equilibrium plasma, but *not in equilibrium with it.*

- Similar to photon production from the QCD plasma in heavy-ion collisions. Common aspect: reinteraction (rescatterings/absorptions) and backreaction (cooling) negligible. In the photon case because $\alpha_{\mathrm{EM}} \ll \alpha_{\mathrm{s}}$



- There $<n_{\mathrm{em}}>=0$ and $<\mathbf{J}_{\mathrm{em}}>=0$, but thermal fluctuations $\Rightarrow$ charge and current fluctuations $\Rightarrow$ photons

$$\frac{\mathrm{d}\Gamma_\gamma(\mathbf{k})}{\mathrm{d}^3\mathbf{k}} = \frac{1}{(2\pi)^3 2k} \sum_\lambda \epsilon^{(\lambda)}_{\mu,\mathbf{k}} \epsilon^{(\lambda)*}_{\nu,\mathbf{k}} \int_{\mathcal{X}} e^{i\mathcal{K}\cdot\mathcal{X}} \langle J^\mu_{\mathrm{em}}(0) J^\nu_{\mathrm{em}}(\mathcal{X}) \rangle$$

Photon production

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- For $k \gtrsim T$ things go as you'd expect (but a very tricky calculation to get the actual numbers)

$$\frac{\mathrm{d}\Gamma_\gamma(\mathbf{k})}{\mathrm{d}^3\mathbf{k}} \overset{k \gtrsim T}{\approx} \frac{\alpha_{\mathrm{EM}}\alpha_{\mathrm{s}}\ln(1/\alpha_{\mathrm{s}})T^2 e^{-k/T}}{(2\pi)^3 k}$$

LO Arnold Moore Yaffe (AMY) **JHEP0111** **JHEP0112** (2001)
NLO JG Hong Lu Kurkela Moore Teaney **JHEP1305** (2013)

- For $k \ll T$ the amplitude of J fluctuations is related to the conductivity of the plasma, a collective phenomenon

$$\frac{\mathrm{d}\Gamma_\gamma(\mathbf{k})}{\mathrm{d}^3\mathbf{k}} \overset{k \lesssim \alpha_{\mathrm{s}}^2 T}{\approx} \frac{2T\sigma}{(2\pi)^3 k} \sim \frac{\alpha_{\mathrm{EM}}T^2}{(2\pi)^3 k\alpha_{\mathrm{s}}^2\ln(1/\alpha_{\mathrm{s}})}$$

AMY **JHEP0011** (2000), **JHEP0305** (2003)

Graviton production

- Start from textbooks: TT gauge, Minkowski background (cosmological expansion later)

$$\ddot{h}_{ij}^{\rm TT} - \nabla^2 h_{ij}^{\rm TT} = 16\pi G\, T_{ij}^{\rm TT} \qquad\qquad E_{\rm GW} = \frac{1}{32\pi G}\int_{\mathbf{x}\in V}\left[\dot{h}_{ij}^{\rm TT}(t,\mathbf{x})\right]^2$$

- $h^{\rm TT}$ superposition of forward and backward propagating GWs. By taking average over oscillations rewrite E as

$$\langle\langle E_{\rm GW}\rangle\rangle = \frac{1}{64\pi G}\int_{\mathbf{x}\in V}\left\{\left[\dot{h}_{ij}^{\rm TT}(t,\mathbf{x})\right]^2 + \left|\nabla h_{ij}^{\rm TT}(t,\mathbf{x})\right|^2\right\}$$

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$$H \equiv \langle\!\langle E_{\rm GW}\rangle\!\rangle = \frac{1}{64\pi G}\int_{\mathbf{x}\in V}\Big\{\big[\dot{h}_{ij}^{\rm TT}(t,\mathbf{x})\big]^2 + \big|\nabla h_{ij}^{\rm TT}(t,\mathbf{x})\big|^2\Big\}$$

- Canonical form! (Up to trivial normalization) Then do the same as for photons (but taking $\rho_{\rm GW}$ rather than Γ_γ)

$$\frac{{\rm d}\rho_{\rm GW}}{{\rm d}t\,{\rm d}^3\mathbf{k}} = \frac{4\pi G}{(2\pi)^3}\sum_\lambda \epsilon_{ij,\mathbf{k}}^{{\rm TT}(\lambda)}\epsilon_{mn,\mathbf{k}}^{{\rm TT}(\lambda)*}\int_{\mathcal{X}} e^{i\mathcal{K}\cdot\mathcal{X}}\big\langle\, T^{ij}(0)\, T^{mn}(\mathcal{X})\,\big\rangle$$

Graviton production

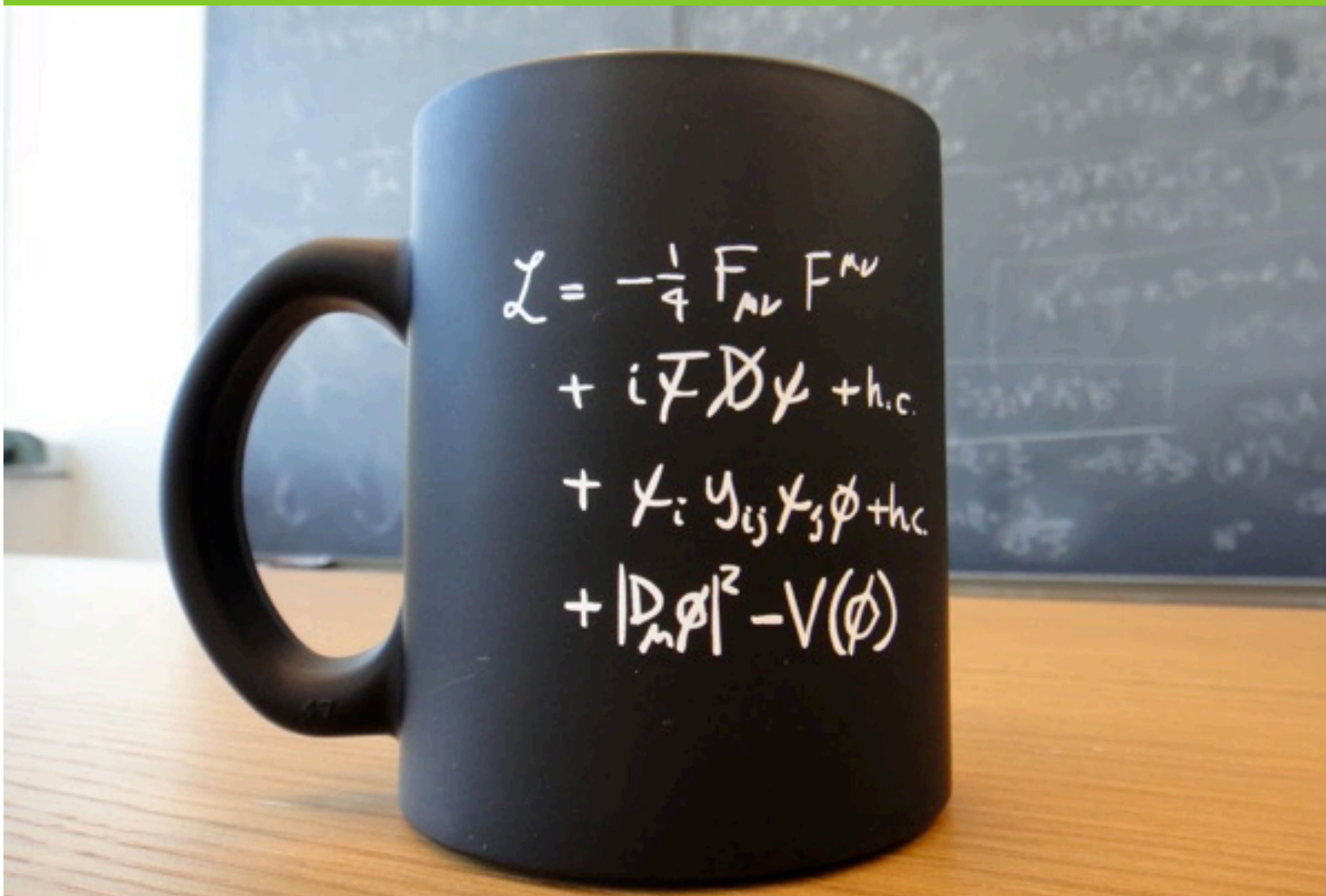
$$\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}t\,\mathrm{d}^3\mathbf{k}} = \frac{4\pi G}{(2\pi)^3}\sum_{\lambda}\epsilon^{\mathrm{TT}(\lambda)}_{ij,\mathbf{k}}\,\epsilon^{\mathrm{TT}(\lambda)*}_{mn,\mathbf{k}}\int_{\mathcal{X}} e^{i\mathcal{K}\cdot\mathcal{X}}\langle\, T^{ij}(0)\,T^{mn}(\mathcal{X})\,\rangle$$

- Take a sum over the polarizations with $k \parallel z$
- Rotate T^{11}-T^{22} into T^{12}

$$\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}t\,\mathrm{d}\ln k} = \frac{8k^3}{\pi m_{\mathrm{Pl}}^2}\int_{\mathcal{X}} e^{ik(t-z)}\langle\, T_{12}(0)\,T_{12}(\mathcal{X})\,\rangle$$

- The same results can be obtained with a purely classical derivation

GW rate for $k \ll T$ at $T > 160\text{GeV}$



Hydrodynamic limit

- Field theories admit a long-wavelength hydrodynamical limit. Hydrodynamics: Effective Theory based on a gradient expansion of the flow velocity

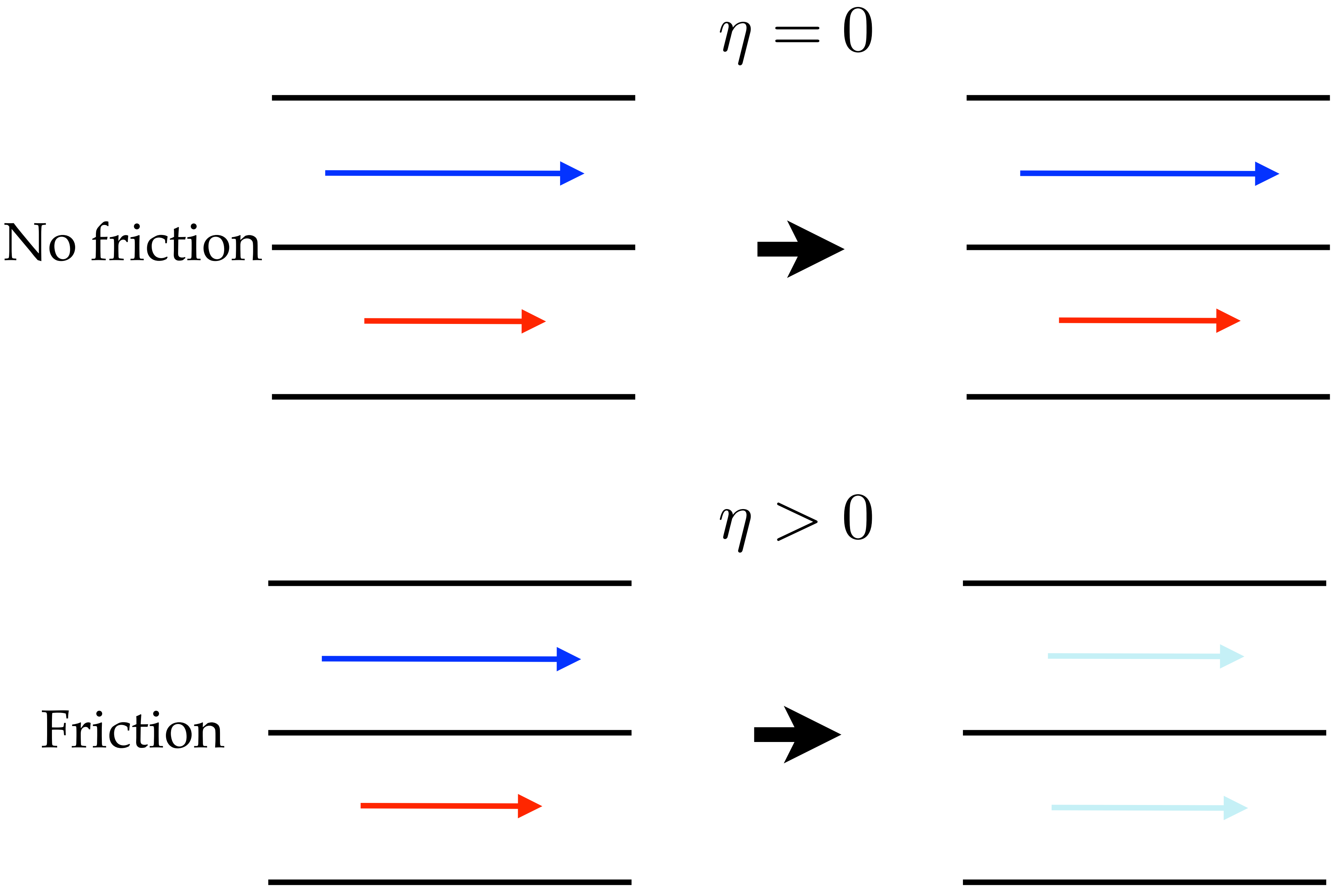
- For hydro fluctuations with local flow velocity **v** around an eq. state (with temp. T), at first order in the gradients and in **v**

$$T^{00} = e, \qquad T^{0i} = (e+p)v^i$$

$$T^{ij} = (p - \zeta \nabla \cdot \mathbf{v})\delta^{ij} - \eta \left(\partial_i v^j + \partial_j v^i - \frac{2}{3}\delta^{ij} \nabla \cdot \mathbf{v} \right)$$

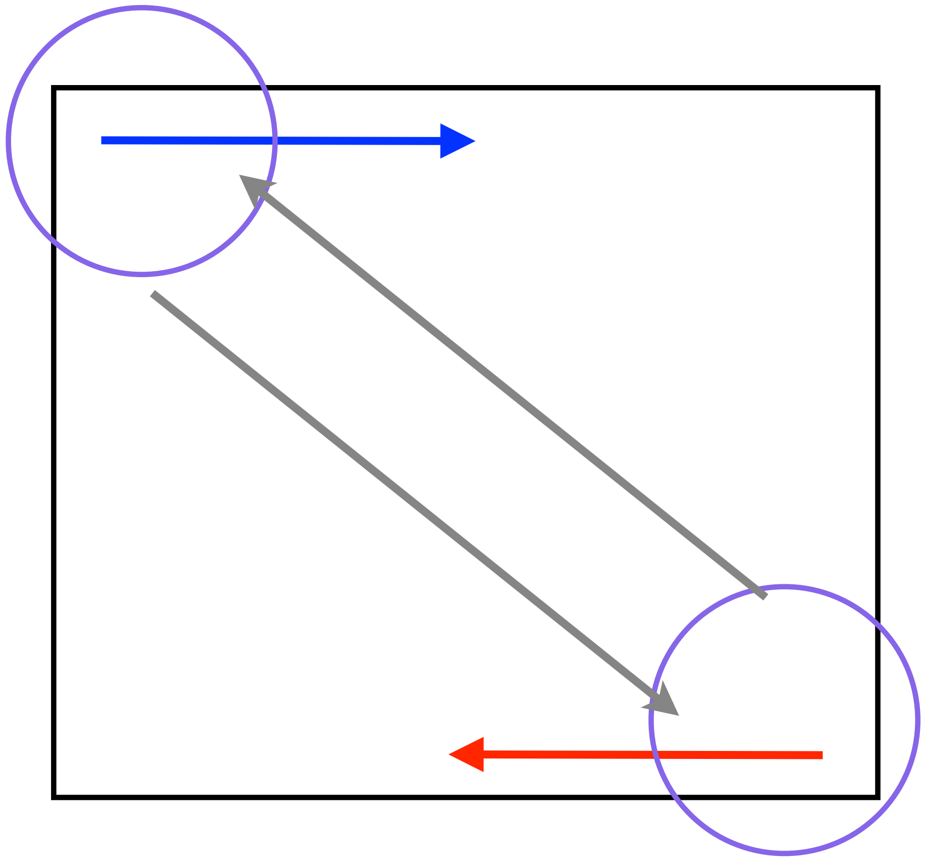
Navier-Stokes hydro, two *transport coefficients*: bulk and shear viscosity

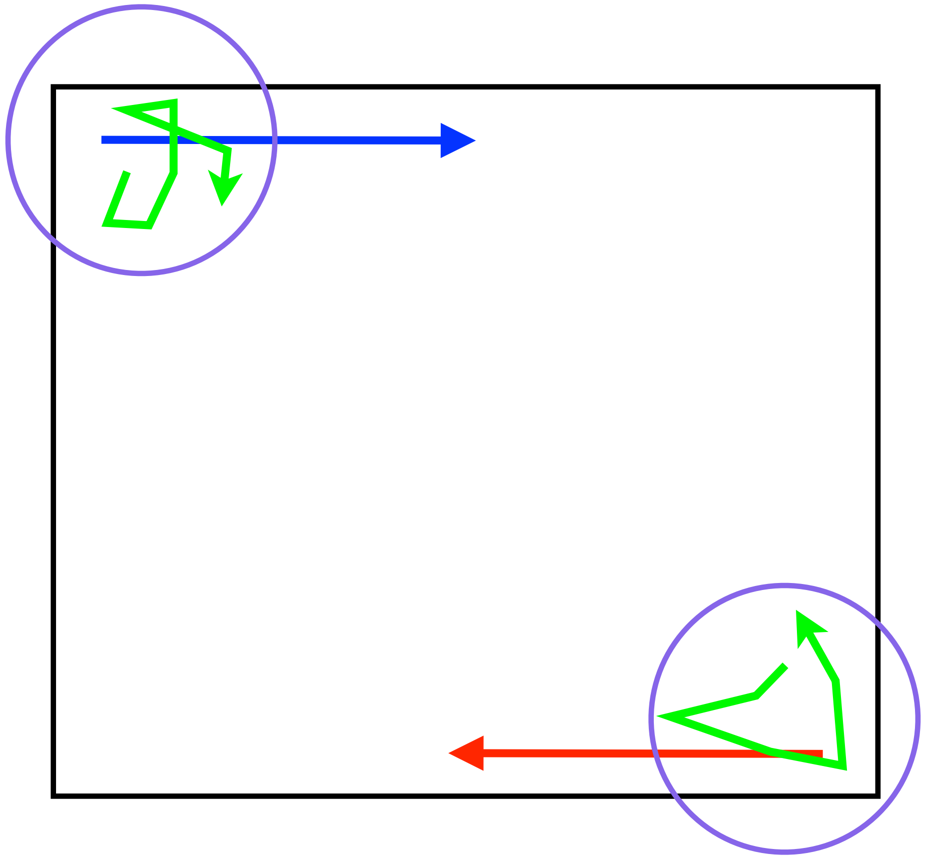
The shear viscosity



- Finite shear viscosity smears out flow differences (diffusion)

Estimating η: counterintuitive?

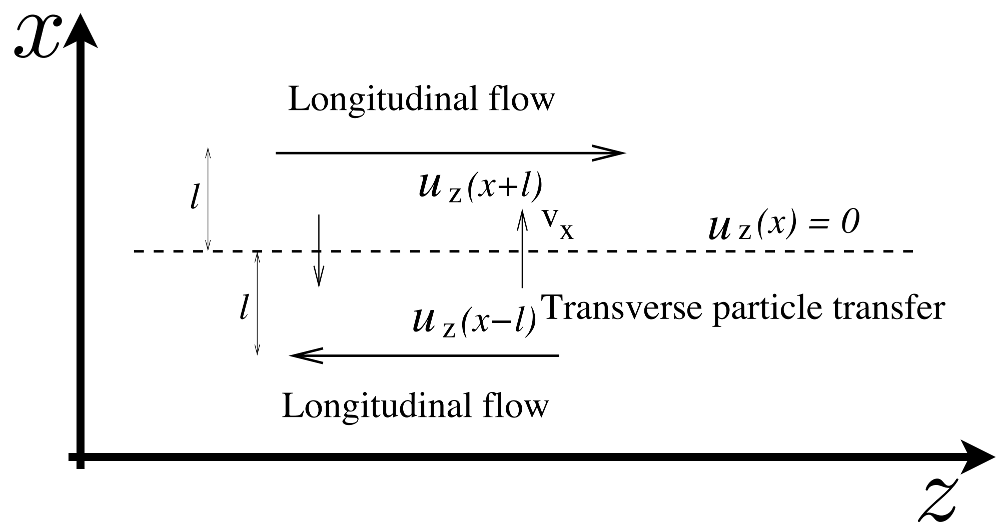




- Weak coupling: long distances between collisions, easy diffusion. **Large** η
- Strong coupling: short distances between collisions, little diffusion. **Small** η

Estimating η

- u flow velocity, v_x microscopical velocity of particles



- $T^{0z}=(e+P)u^0u^z$ diffuses along x with $v^x=u^x/u^0$. Net change

$$(e+p)v^x u^0 (u^z(x-l_{\rm mfp}) - u^z(x+l_{\rm mfp})) \approx -2(e+p)v^x u^0 l_{\rm mfp}\partial_x u^z(x) \sim -\eta u^0 \partial_x u^z(x)$$

- Using $e+p=sT$ and in the high-T limit ($v^x \sim 1$)

$$\frac{\eta}{s} \sim T l_{\rm mfp}$$

Estimating η

- (Mean free path)$^{-1}$~ cross section x density

$$\frac{\eta}{s} \sim T l_{\mathrm{mfp}} \sim \frac{T}{n\sigma} \sim \frac{1}{T^2\sigma}$$

- Cross section in a perturbative gauge theory (*T* only scale*)

$$\sigma \sim \frac{g^4}{T^2} \qquad \frac{\eta}{s} \sim \frac{1}{g^4}$$

* Coulomb divergences and screening scales ($m_D \sim gT$) in gauge theories

$$\sigma \sim \frac{g^4}{T^2}\ln(1/g) \qquad \frac{\eta}{s} \sim \frac{1}{g^4\ln(1/g)}$$

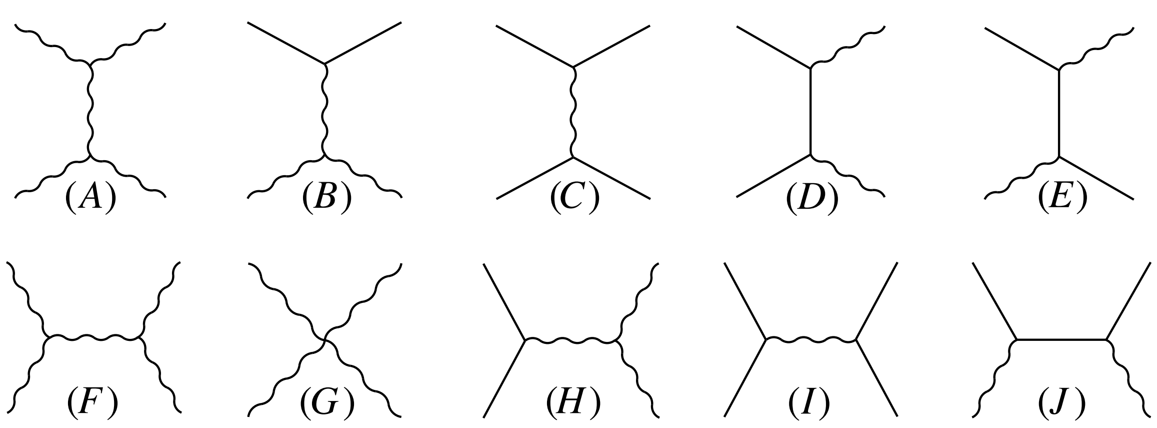
Computing η

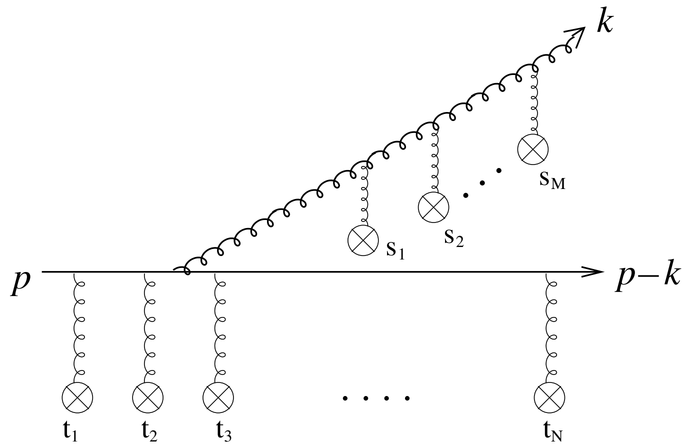
- Kubo formula (S TT part of T)

$$\eta = \frac{1}{20}\lim_{\omega\to 0}\frac{1}{\omega}\int d^4x\, \mathrm{e}^{i\omega t}\left\langle\left[\mathcal{S}^{ij}(t,\mathbf{x}),\,\mathcal{S}^{ij}(0,\mathbf{0})\right]\right\rangle\theta(t)$$

- Not practical at weak coupling: use effective kinetic theory with 2↔2 and 1↔2 processes AMY (2000-2003)

$$(\partial_t + \mathbf{v}\cdot\nabla_{\mathbf{x}})f(t,\mathbf{x},\mathbf{p}) = C^{2\leftrightarrow 2}[f] + C^{1\leftrightarrow 2}[f]$$





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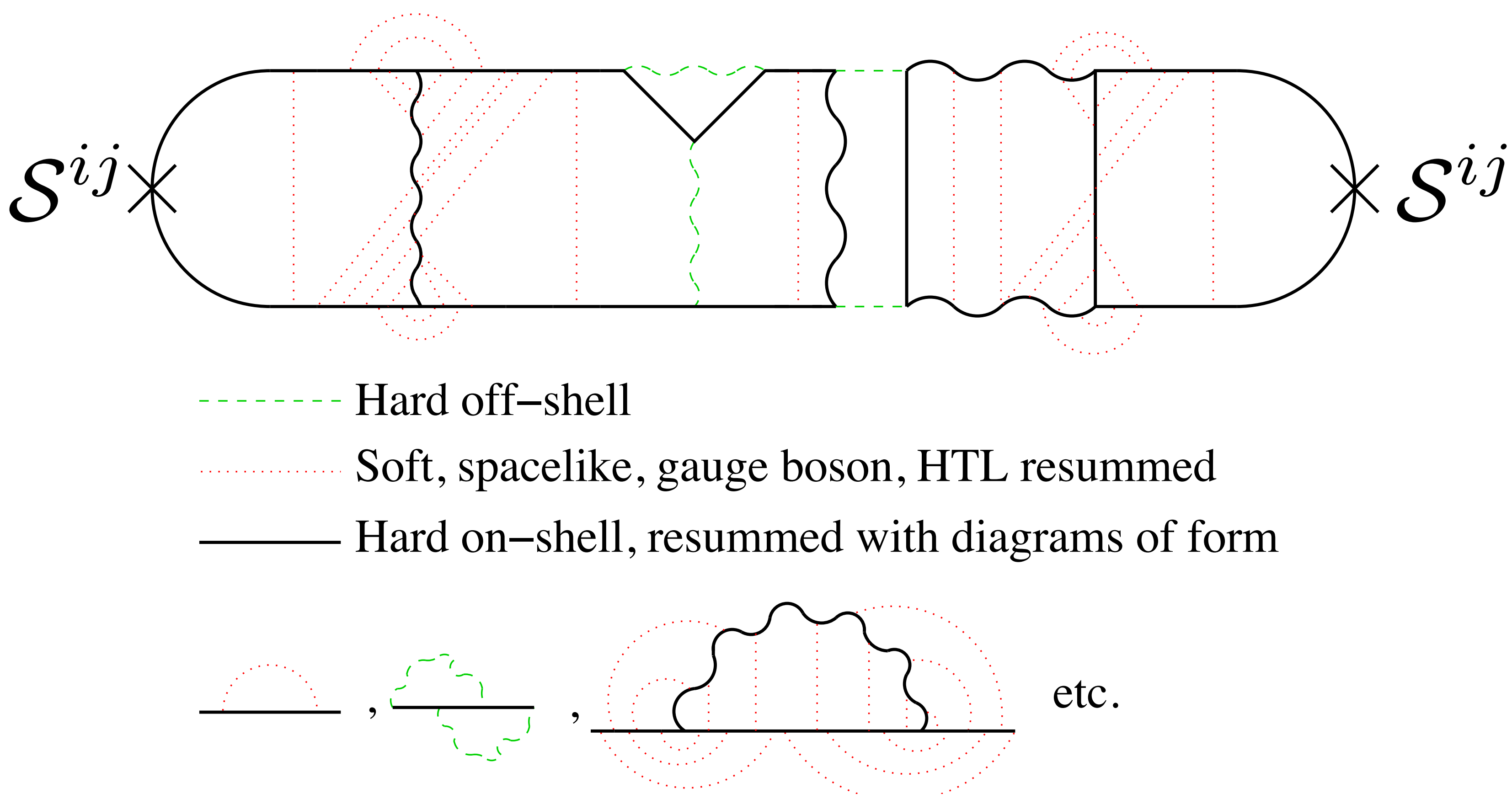

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- For the SM at T>160 GeV η is dominated by the slowest processes, those involving right-handed leptons only

$$\eta \simeq \frac{16T^3}{g_1^4\ln(5T/m_{\mathrm{D1}})} \quad \rightarrow \quad \eta \simeq 400\,T^3$$

g_1 hypercharge coupling with screening mass $m_{\mathrm{D1}} = \sqrt{11/6}\,g_1 T$
Only a leading-log estimate, no complete LO for T>160 GeV
AMY (2000-2003)

Hydrodynamic limit

- 4-momentum conservation for a perturbation along z: decoupling of v^1 and v^2

$$\partial_0 T^{0j} + \partial_i T^{ij} = 0 \quad \Rightarrow \mathbf{v}_\perp(t,\mathbf{k}) = \mathbf{v}_\perp(0,\mathbf{k})\, e^{-\eta k^2 t/(e+p)}$$

- Now look at the $T^{0\mathrm{i}}$ correlator (operator ordering irrelevant in the soft limit), $i', j' = \{1,2\}$

$$\frac{1}{V}\int_{-\infty}^{\infty} \mathrm{d}t\, e^{i\omega t} \left\langle \frac{1}{2}\left\{T^{0i'}(t,\mathbf{k}), T^{0j'}(0,-\mathbf{k})\right\}\right\rangle$$

$$= \frac{\frac{2\eta k^2}{e+p}}{\omega^2 + \frac{\eta^2 k^4}{(e+p)^2}} \int_{\mathbf{x}\in V} e^{-i\mathbf{k}\cdot\mathbf{x}} \left\langle T^{0i'}(0,\mathbf{x})\, T^{0j'}(0,\mathbf{0})\right\rangle$$

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$$= \frac{\frac{2\eta k^2}{e+p}}{\omega^2 + \frac{\eta^2 k^4}{(e+p)^2}} \left(T \chi_{\mathbf{p}} \delta^{ij} + \mathcal{O}(k^2) \right)$$

- For small k this becomes the momentum susceptibility

$$\chi_{\mathbf{p}} = e + p$$

Hydrodynamic limit

- Use a Ward identity to go from $T^{0i'}$ to $T^{3i'}$

$$\int_{\mathcal{X}} e^{i(\omega t - kz)} \left\langle \frac{1}{2}\left\{ T^{3i'}(\mathcal{X}), T^{3j'}(0) \right\} \right\rangle \overset{\omega,k \lesssim \alpha^2 T}{=} \frac{2\eta T \omega^2 \delta^{i'j'}}{\omega^2 + \frac{\eta^2 k^4}{(e+p)^2}}$$

- What we want (T^{12}) is different but related. Since v^1 and v^2 are uncoupled from the EOMS, their fluctuations are uncorrelated in spacetime ⇒ ω, k independent

$$\left\langle \frac{1}{2}\left\{ T^{\rm TT}_{i'j'}(t_1,\mathbf{x}_1), T^{\rm TT}_{k'l'}(t_2,\mathbf{x}_2) \right\} \right\rangle \;=\; \Phi_{i'j'k'l'}\,\delta(t_1-t_2)\,\delta^{(3)}(\mathbf{x}_1-\mathbf{x}_2)$$

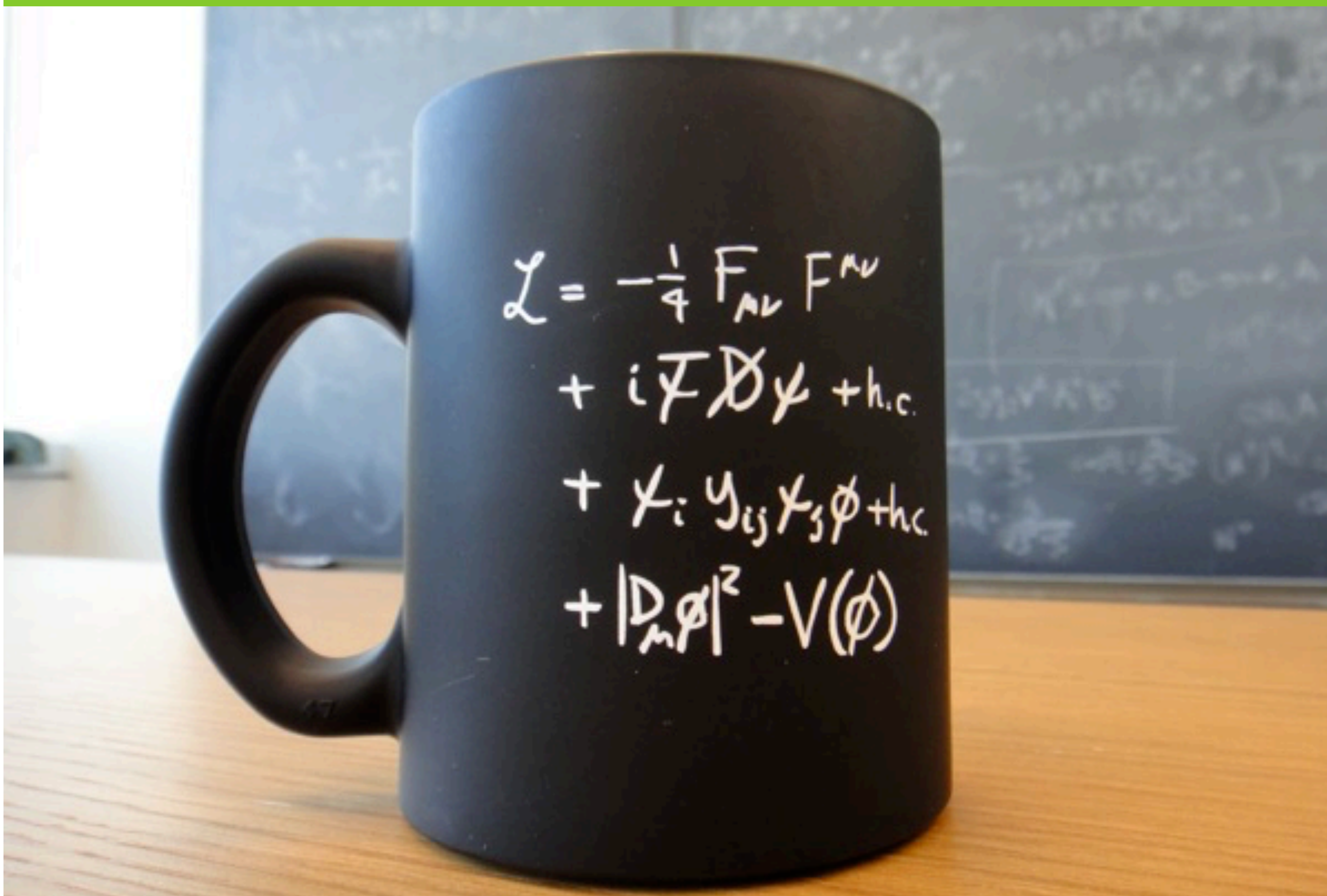
- Setting $\omega = k$ and sending $k \to 0$ restores 3D symmetry, so that by comparing

$$\lim_{k\to 0} \int_{\mathcal{X}} e^{ik(t-z)} \left\langle \frac{1}{2}\left\{ T_{12}(\mathcal{X}), T_{12}(0) \right\} \right\rangle = 2\,\eta\, T$$

$$\frac{{\rm d}\rho_{\rm GW}}{{\rm d}t\,{\rm d}\ln k} \overset{k \lesssim \alpha^2 T}{=} \frac{16 k^3 \eta T}{\pi m_{\rm Pl}^2}$$

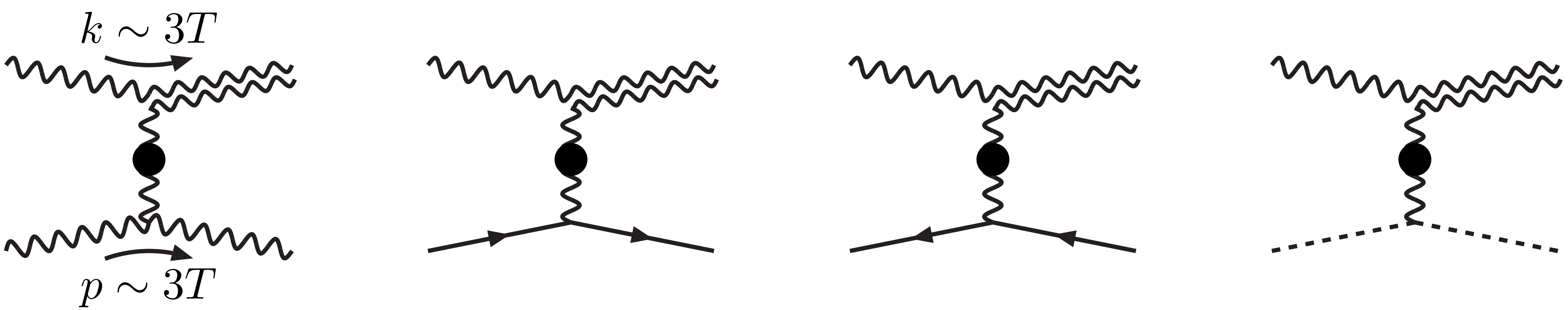
Obtainable formally by linear response Hong Teaney (2010)

GW rate for k~T at T>160GeV



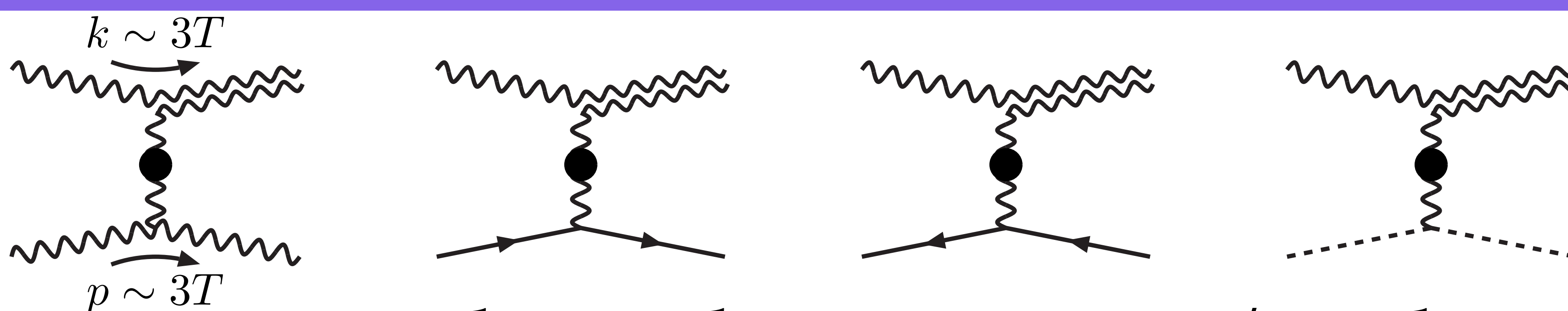
A leading-log estimate

- A complete leading-order calculation for $k \sim T$ is not easy: requires all 2↔2 scatterings between SM particles
- However, scatterings with intermediate gauge bosons are IR sensitive: logarithmic divergence with bare propagators



- The cure is Hard Thermal Loop resummation (collective physics: screening, plasma oscillations and Landau damping)

A leading-log estimate



- This diagrams are then enhanced by *ln(1/g)*. The coefficient of this term is easy to determine: a *leading-log calculation*

$$\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}t\,\mathrm{d}\ln k} = \frac{2k^4 T n_B(k)}{\pi^2 m_{\mathrm{Pl}}^2}\left\{\sum_{i=1}^{3} d_i\, m_{\mathrm{D}i}^2 \ln\frac{5T}{m_{\mathrm{D}i}} + \mathcal{O}\left(g^2T^2\chi\left(\frac{k}{T}\right)\right)\right\}$$

- d_i multiplicities of the gauge groups (d_1=1, d_2=3, d_3=8), m_{Di} Debye masses $m_{\mathrm{D1}}^2 = 11g_1^2T^2/6,\ m_{\mathrm{D2}}^2 = 11g_2^2T^2/6,\ m_{\mathrm{D3}}^2 = 2g_3^2T^2$
Non-logarithmic unknown part

- Bonus: all fundamental[1] forces in one equation

[1]As of 24/9/2015

Cosmological implications

Summary

- Our computations can be summarized as

$$\frac{\mathrm{d}\rho_{\rm GW}}{\mathrm{d}t\,\mathrm{d}\ln k} = \frac{16k^3\eta T}{\pi m_{\rm Pl}^2}\,\phi\Big(\frac{k}{T}\Big)$$

with

$$\phi\Big(\frac{k}{T}\Big) \simeq \begin{cases} 1 & , \quad k \lesssim \alpha^2 T \\ \dfrac{k f_{\rm B}(k)}{8\pi\eta}\displaystyle\sum_{i=1}^{3} d_i\, m_{{\rm D}i}^2\Big(\ln\frac{5T}{m_{{\rm D}i}} + \mathcal{O}(1)\Big) & , \quad k \gtrsim 3T \end{cases}$$

Embedding in Hubble expansion

- Take as reference temperature $T_0 \equiv 160$ GeV (EW crossover)
- Since $\rho_{\rm GW}(t) = \int_{\mathbf{k}} k\, f(t,k)$, with f GW phase space distribution

$$(\partial_t + 4H)\rho_{\rm GW}(t) = \int_{\mathbf{k}} R(T,k) = \frac{32\pi}{m_{\rm Pl}^2}\int_{\mathbf{k}} 32\pi\eta T\phi(k/T)$$

- Normalize by $s^{4/3}$ to get rid of H and integrate

$$\frac{\rho_{\rm GW}(t_0)}{s^{4/3}(t_0)} = \int_{t_{\rm min}}^{t_0} {\rm d}t \int_{\mathbf{k}} \frac{R(T,k)}{s^{4/3}(t)} = \int_{T_0}^{T_{\rm max}} {\rm d}T \int_{\mathbf{k}} \frac{R(T,k)}{TH(T)3c_s^2(T)s^{4/3}(T)}$$

at initial time $t_{\rm min}$ (maximum temperature $T_{\rm max}$) no thermally produced GWs present

Embedding in Hubble expansion

- Finally, redshift momenta to k_0 at T_0

$$\begin{aligned}\Omega_{\rm GW}(k_0) &\equiv \frac{1}{e(T_0)}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln k_0} \\ &= \frac{8k_0^3 s^{1/3}(T_0)}{m_{\rm Pl}\sqrt{6\pi^3}e(T_0)}\int_{T_0}^{T_{\rm max}}{\rm d}T\,\frac{\eta(T)}{c_s^2(T)s^{1/3}(T)e^{1/2}(T)}\,\phi\Big(\frac{k_0}{T}\Big[\frac{s(T)}{s(T_0)}\Big]^{\frac{1}{3}}\Big)\end{aligned}$$

- Approximate form for $c_s^2 = 1/3$ and dimensional scaling $s = \hat{s}T^3, \eta = \hat{\eta}T^3, e = \hat{e}T^4$

$$\Omega_{\rm GW}(k_0) \simeq \frac{24\hat{\eta}}{\sqrt{6\pi^3\hat{e}^3}}\,\frac{T_{\rm max}}{m_{\rm Pl}}\,\frac{k_0^3}{T_0^3}\,\phi\Big(\frac{k_0}{T_0}\Big)$$

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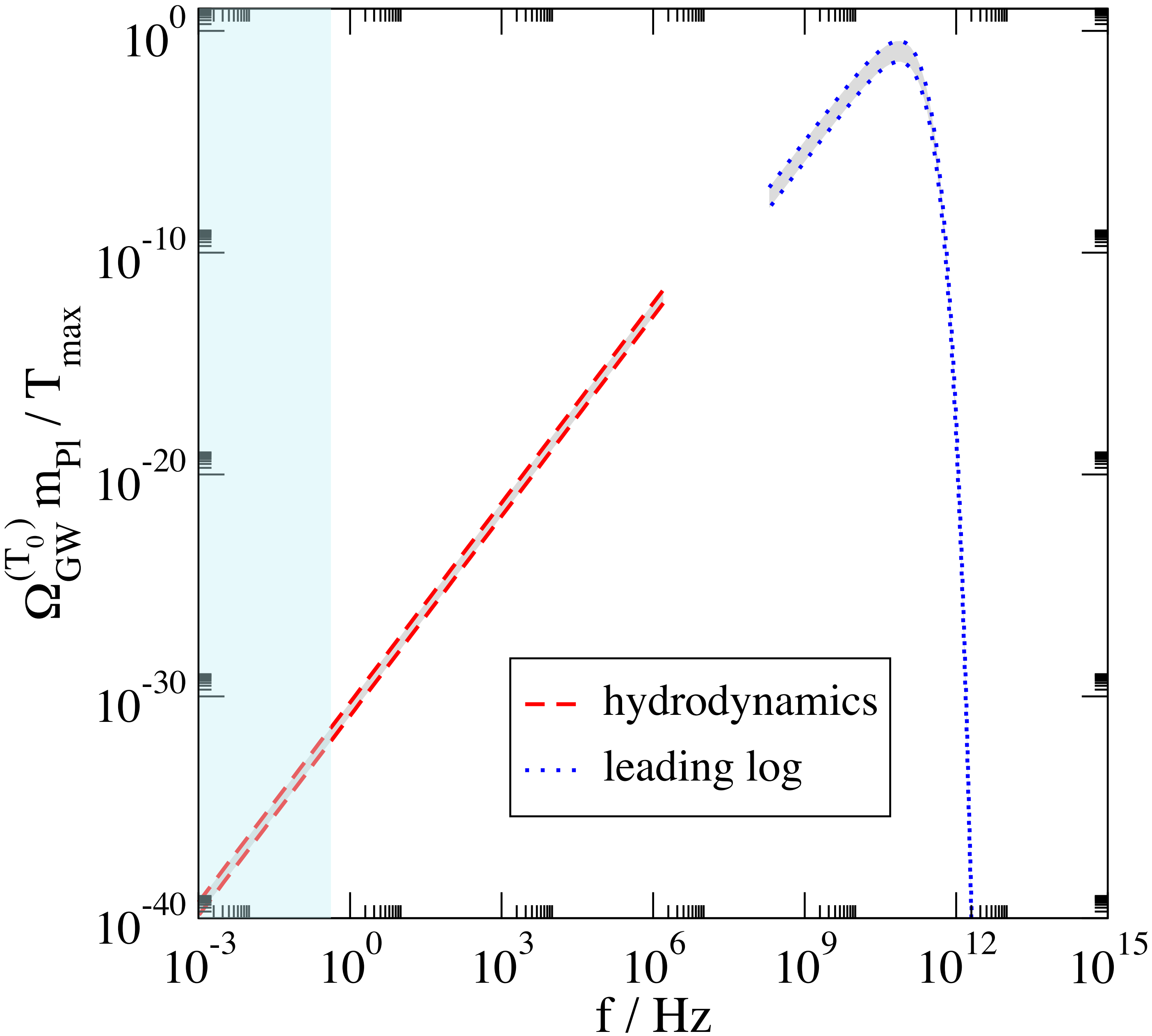
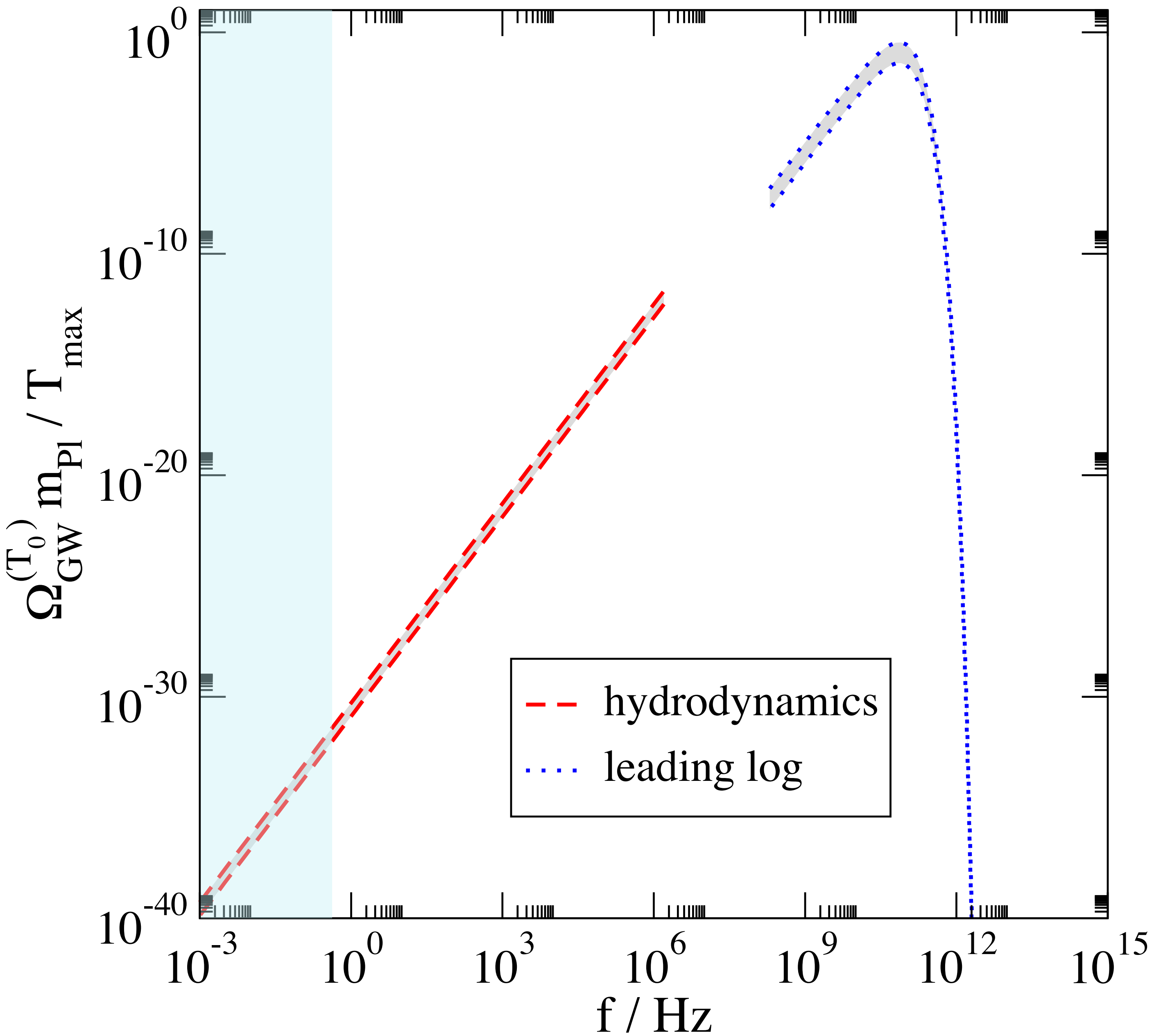


The bands for the hydrodynamic and leading-log results correspond to varying η=100...400 and to varying the constant $O(1)$ within the range 0...10. The couplings were fixed at a scale $\mu = \pi T$ with $T \simeq 10^6$ GeV. For obtaining the current day energy fraction the result needs to be multiplied by $\Omega_{\rm rad} \sim 5 \times 10^{-5}$



- If for instance $T_{\mathrm{max}}=10^6$ GeV (horizon radius~eLISA arm length) then ~40 orders of magnitude below sensitivity
- The peak is in the μ-wave range, as the CMB, since it happens for $k \sim 3T_{\mathrm{max}}$ and redshifts at decoupling to $k \sim 3T_{\mathrm{dec}}(3.9/106.75)^{1/3} \sim T_{\mathrm{dec}}$. Interesting for future exps?
- In other words the thermal background continues to grow with k for 10+ decades after the peak eLISA frequency
- If compared to EWPT sources, this peak will eventually overtake their rapidly falling spectra

The total energy

- The peak at $k \sim 3T_{\max}$ also implies that the total energy might not be so negligible

$$\int \mathrm{d}\ln k_0\,\Omega_{\mathrm{GW}}(k_0) \simeq \frac{24\hat{\eta}}{\pi\sqrt{6\pi\hat{e}^3}}\frac{T_{\max}}{m_{\mathrm{Pl}}T_0^3}\int_0^\infty \mathrm{d}k_0\,k_0^2\,\phi\left(\frac{k_0}{T_0}\right) \simeq \frac{24}{\pi\sqrt{6\pi\hat{e}^3}}\left(8\ldots\frac{\hat{\eta}}{3}\right)\frac{T_{\max}}{m_{\mathrm{Pl}}}$$

- Parametrizing our ignorance of $\phi\left(\frac{k_0}{T_0}\right)$ with two limits (lead-log...hydro)

- GWs are constrained not to carry as much energy as one relativistic d.o.f.
  Smith Pierpaoli Kamionkowski **PRL97** (2006) Henrot-Versille *et al* Class. Quant. Grav. **32** (2015)

The total energy

- At T_0~160 GeV we must then require

$$\frac{24}{\pi\sqrt{6\pi\hat{e}^3}}\left(8\ldots\frac{\hat{\eta}}{3}\right)\frac{T_{\rm max}}{m_{\rm Pl}} \ll \frac{1}{100}$$

- This can be used to constrain $T_{\rm max}$. For $\hat{e} \sim 35, \; \hat{\eta} \sim 400$ we have $T_{\rm max} \lesssim 10^{17} \ldots 10^{18}$ GeV
- Not a stringent constraint (reheating temperatures above 10^{16} GeV excluded in standard inflation), but could be sharpened by knowing more about $\phi\left(\frac{k_0}{T_0}\right)$

Conclusions

- We have shown how to set up the determination of the equilibrium contribution to gravitational waves
- We have determined it at leading order in the infrared: it is related to the shear viscosity of the EW plasma, which is not small
- We have obtained a leading-log estimate for k~T, coming from scatterings of thermal plasma constituents

Conclusions

- The resulting Ω_{GW} is tiny in the eLISA window, but it peaks in the GHz range, where it would overtake non-equilibrium EWPT sources

- The best observational prospect is in future hi-freq. exps

- This thermal background is however guaranteed to be present and, since its production spans many decades, the associated total energy is not small

- This energy can be used to (weakly) constrain the highest temperature of the radiation epoch

- Estimates could be sharpened with a full leading-order calculation