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Constraints on cosmological viscosity from GW150914 observation

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Based on: 1603.02635

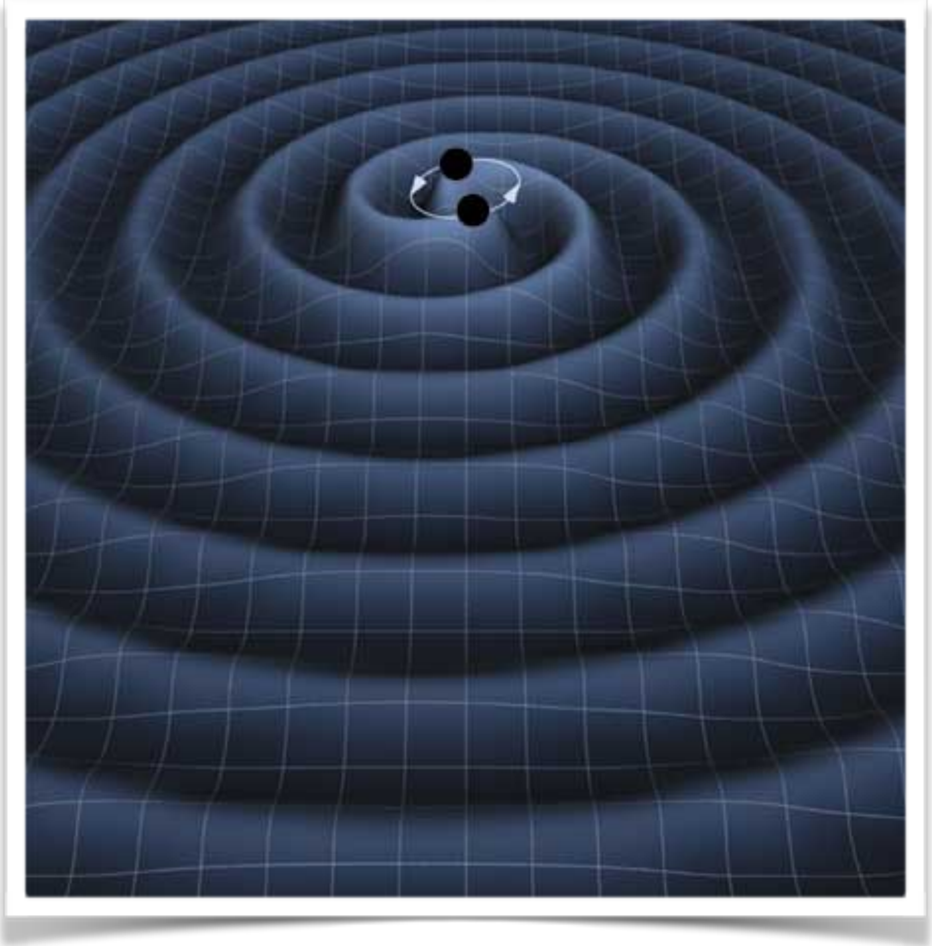
GW150914

* First direct detection of Gravitational Waves (GWs),

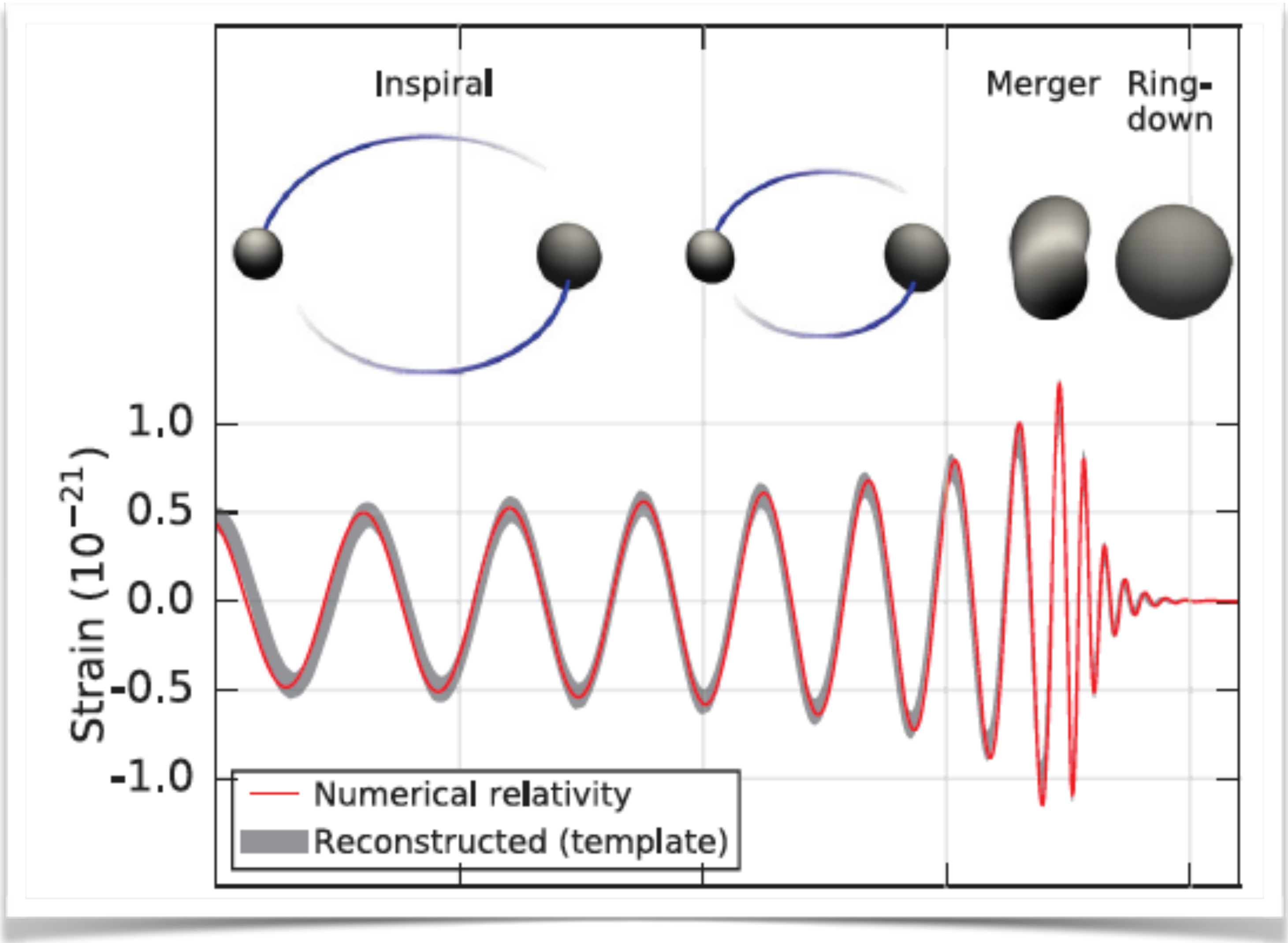
* First observation through a "new window,"
  * a new frontier in astronomy,

* First ever test of gravity in strong field regime,

* First observation of a binary black hole merger.

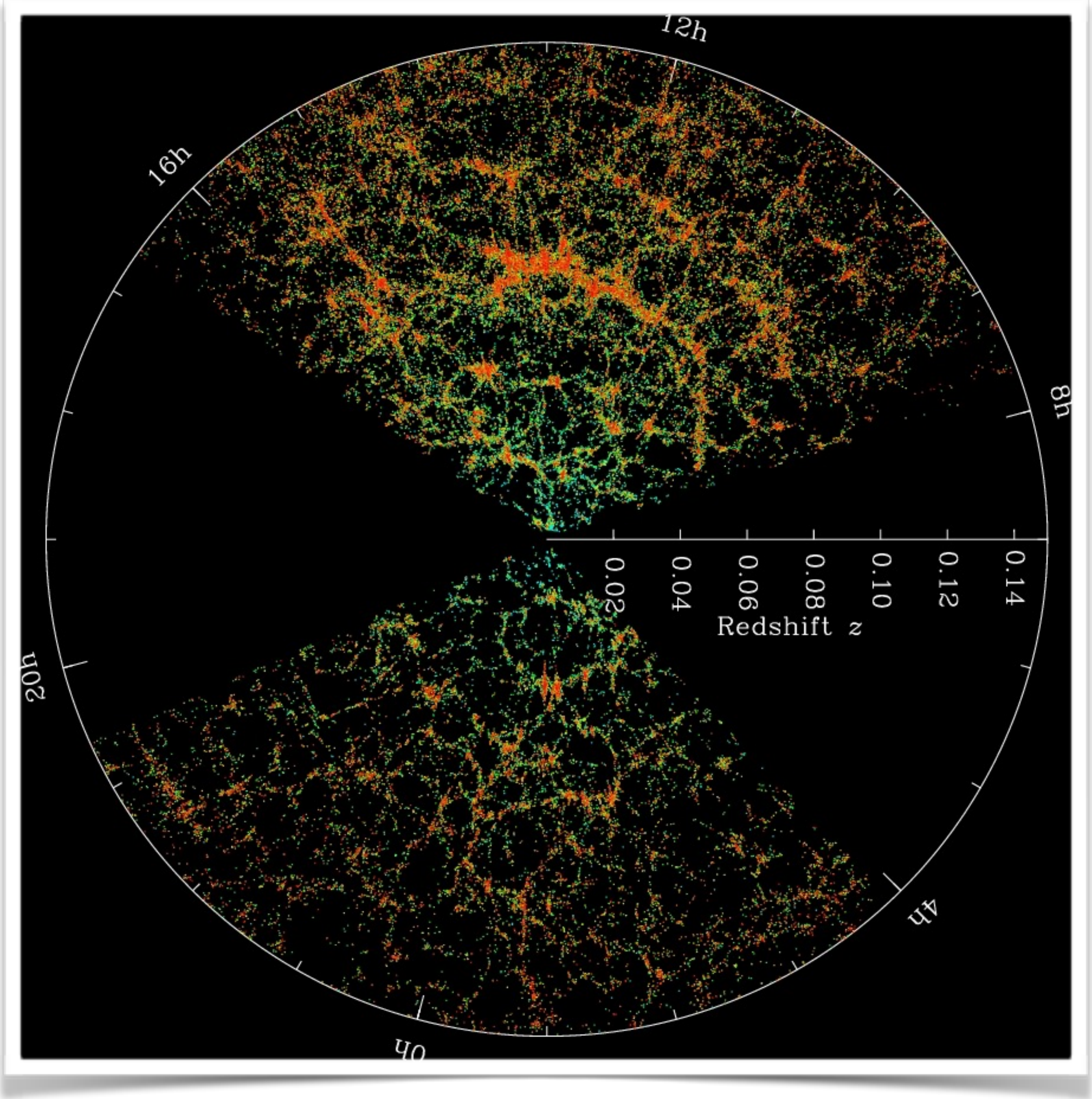


GW150914



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Effect of intervening medium ?



Cosmological perturbations ...

Einstein Equations...

$$\left(\begin{array}{c} \text{a measure of local} \\ \text{spacetime curvature} \end{array} \right) = \left(\begin{array}{c} \text{a measure of local} \\ \text{stress-energy density} \end{array} \right) .$$

$$\boxed{G_{\mu\nu} = 8\pi G\, T_{\mu\nu}} \; ,$$

Perturbed Einstein Equations...

$$g_{\mu\nu} \;=\; \bar{g}_{\mu\nu}(\tau) + \delta g_{\mu\nu}(\tau, \boldsymbol{x}) \;,$$

$$\begin{aligned} G_{\mu\nu} &= \bar{G}_{\mu\nu}(\tau) + \delta G_{\mu\nu}(\tau, \boldsymbol{x}) \;, \\ T_{\mu\nu} &= \bar{T}_{\mu\nu}(\tau) + \delta T_{\mu\nu}(\tau, \boldsymbol{x}) \;. \end{aligned}$$

Metric perturbations ...

$$ds^2 \equiv \bar{g}_{\mu\nu}(\tau)\,dx^\mu dx^\nu \;=\; a^2(\tau)(d\tau^2 - \delta_{ij}dx^i dx^j)\ ,$$

$$\downarrow$$

$$ds^2 = a^2(\tau)\left\{(1+2\Psi)d\tau^2 - 2B_i\,dx^i d\tau - \left[(1-2\Phi)\delta_{ij} + 2E_{ij}\right]dx^i dx^j\right\}\ ,$$

$$B_i = \underbrace{\partial_i B}_{\text{scalar}} + \underbrace{\hat{B}_i}_{\text{vector}}\ , \qquad \partial^i \hat{B}_i = 0.$$

$$E_{ij} = \underbrace{\partial_{\langle i}\partial_{j\rangle}E}_{\text{scalar}} + \underbrace{\partial_{(i}\hat{E}_{j)}}_{\text{vector}} + \underbrace{\hat{E}_{ij}}_{\text{tensor}}\ ,$$

$$\partial_{\langle i}\partial_{j\rangle}E \equiv \left(\partial_i\partial_j - \frac{1}{3}\delta_{ij}\nabla^2\right)E\ ,$$

$$\partial_{(i}\hat{E}_{j)} \equiv \frac{1}{2}\left(\partial_i E_j + \partial_j E_i\right)\ .$$

$$\partial^i \hat{E}_i = \partial^i \hat{E}_{ij} = 0.$$

Matter perturbations ...

$$T^{\alpha\beta} = p\eta^{\alpha\beta} + (p+\rho)u^{\alpha}u^{\beta} + \Delta T^{\alpha\beta}$$

$$\Delta T_{\alpha\beta} = -\eta\left(\frac{\partial u_\alpha}{\partial x^\beta} + \frac{\partial u_\beta}{\partial x^\alpha} + u_\beta u^\gamma \frac{\partial u_\alpha}{\partial x^\gamma} + u_\alpha u^\gamma \frac{\partial u_\beta}{\partial x^\gamma}\right)$$
$$-(\zeta - \frac{2}{3}\eta)\frac{\partial u^\gamma}{\partial x^\gamma}\left(\eta_{\alpha\beta} + u_\alpha u_\beta\right) ,$$

bulk viscosity

shear viscosity

Matter perturbations …

If non-ideal fluid (with shear viscosity) as source …

* FRW universe: background dynamics unaffected,

* First order scalar perturbations unaffected,

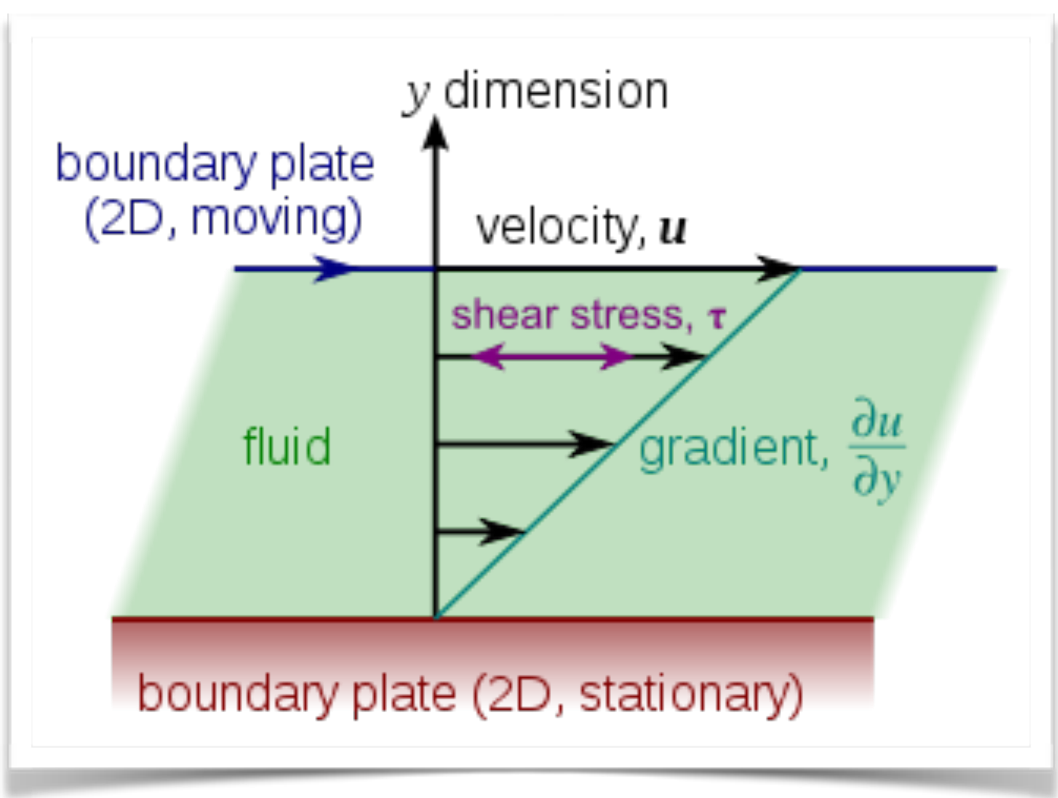
* First order tensor perturbations DO get affected,

* Scalars and Tensors evolve independently (at linear order),

* So, if the "cosmic fluid" has a shear viscosity, GWs will be affected by it while linear scalar perturbations won't feel it!

Effect of intervening medium ?

- Ideal fluids do not attenuate/disperse GWs,
- To leading order, the universe filled with ideal fluid,
- Ideal fluid: no shear stresses (in rest frame).
- Non-ideal fluid: (shear) viscosity, can attenuate GWs.



$$\frac{F}{A} = \eta \, \frac{du}{dy}$$

$$\eta = \rho \, v_{\rm rms} \, \lambda$$

Hawking (1966), Dyson (1969), Esposito (1971), Weinberg (1972), Madore (1973), Anile & Pirronello (1978), Ehlers & Prasanna (1987,1996), Prasanna (1999).

Effect of intervening medium ?

$$\beta = 16\pi G\eta$$

$$\ddot{A} + k^2 A + \beta \dot{A} = 0 \ ,$$

$$(-\omega^2 + k^2 + i\beta\omega)\tilde{A}(\omega, k) = 0 \ .$$

$$k = k_R + ik_I$$

$$\beta \ll \omega$$

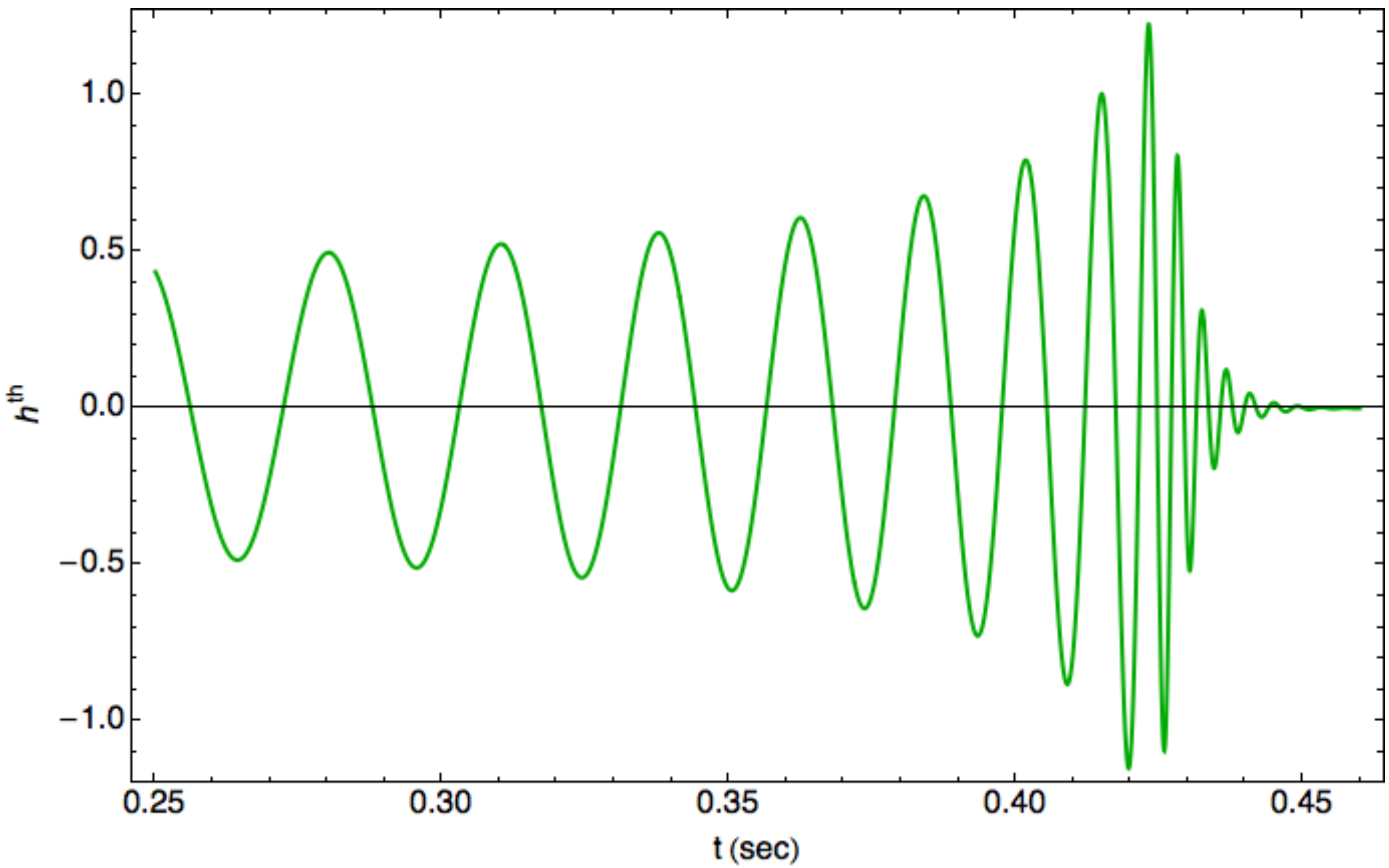
$$k_R = \omega \ , \quad k_I = \frac{\beta}{2} \ .$$

$$\eta_{\rm crit} \equiv \frac{\rho_{\rm crit}}{H_0}$$

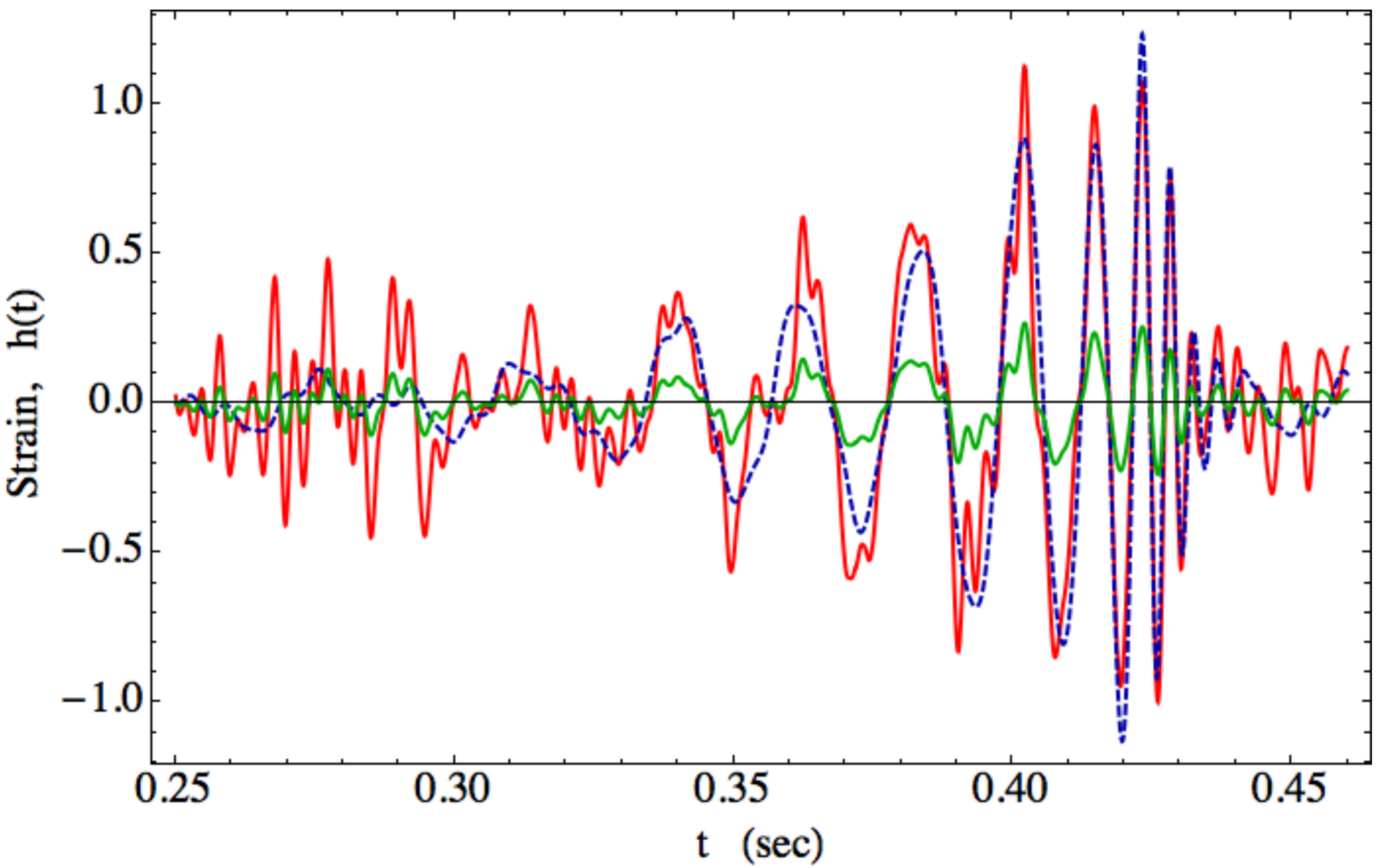
$$\boxed{e^{-k_I L} = e^{-(8\pi G\eta L)}}$$

* To leading order, attenuation but no dispersion!
* Upper limits on shear viscosity
* large distance better, more effect, more stringent limits (bullet cluster has lum. dist. 1500 Mpc).

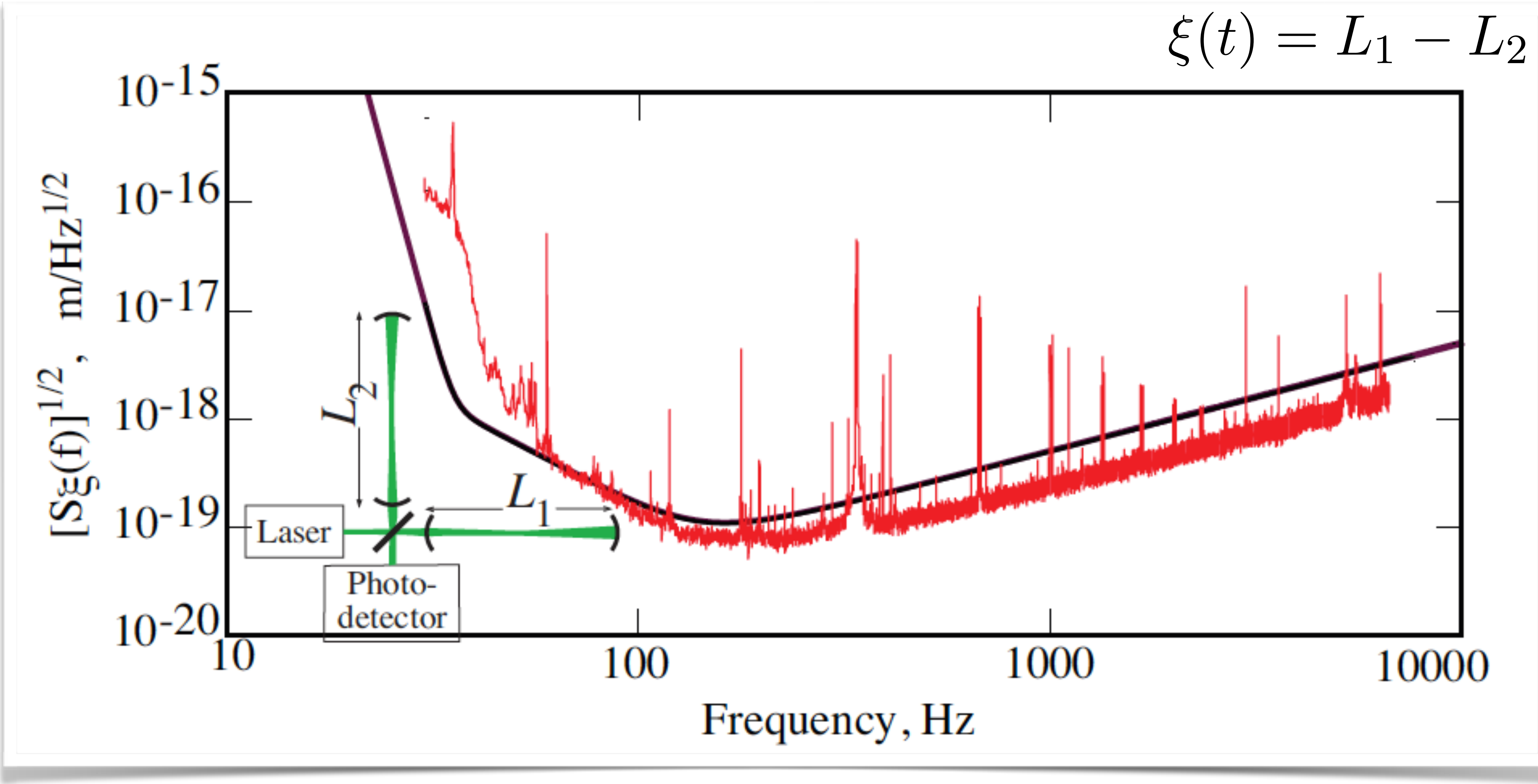
Effect of intervening medium ?



Effect of intervening medium ?



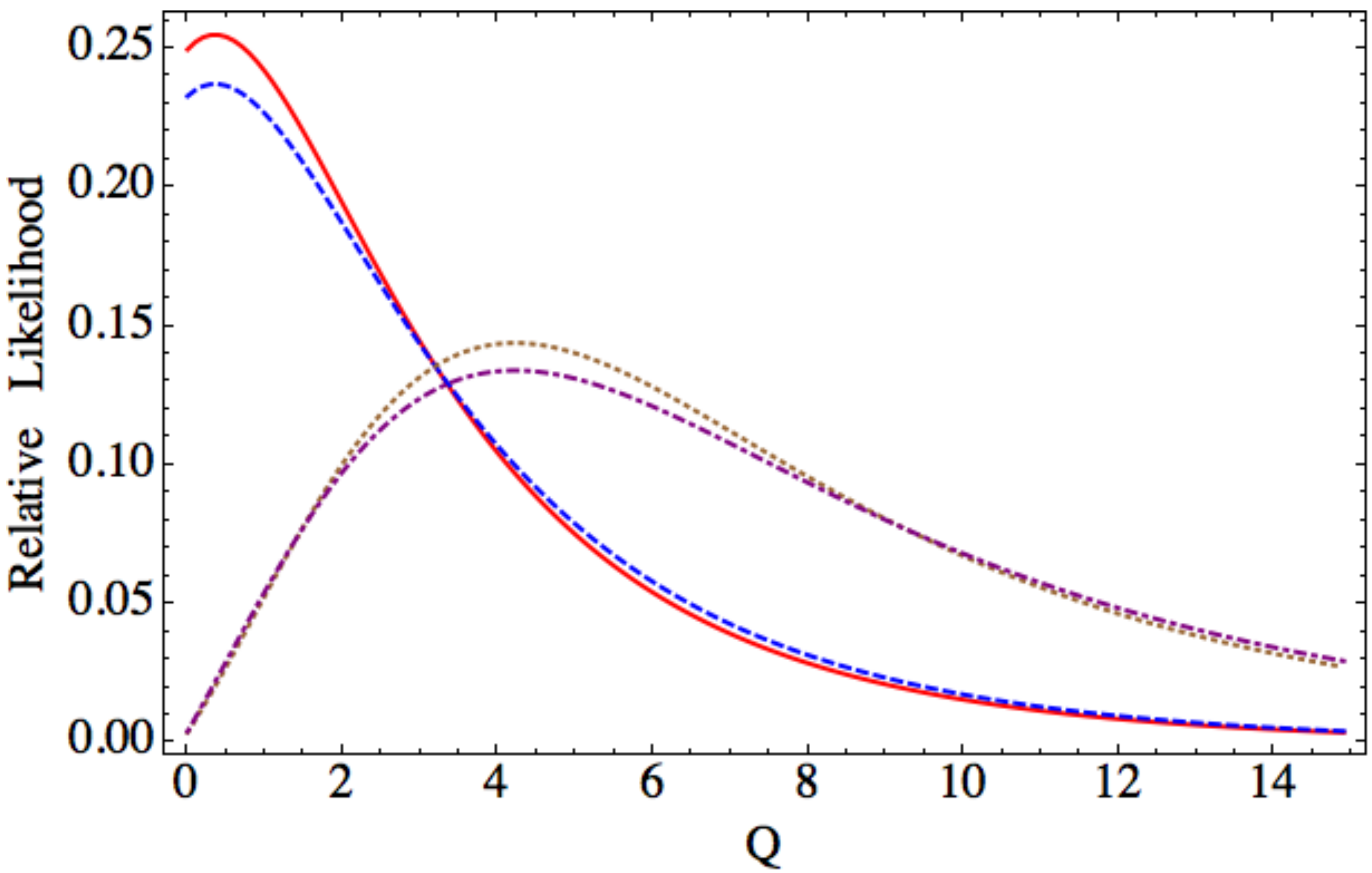
Likelihood (Gaussian and stationary noise)



$$\mathcal{L} = \frac{1}{((2\pi)^N \det C_{jj'})^{1/2}} \exp\left\{ -\frac{1}{2} \sum_{jj'} \xi_j \, C^{-1}_{jj'} \, \xi_{j'} \right\}$$

$$\langle \tilde{n}(f)\tilde{n}^*(f')\rangle = \frac{1}{2}\delta(f - f')S_n(f)$$

Upper bounds on viscosity of the cosmic fluid:



Stuff	Viscosity (Pa sec)
QGP at RHIC	~ 10^{11}
Observable cosmos	< 10^{9}
Water	10^{-3}
Steam	10^{-5}

$$Q \equiv \frac{\eta}{\rho_{\rm crit}\ H_0^{-1}}$$

Issues:

* Shouldn't one recalculate all the parameters?
* Isn't this degenerate with measured distance?
  * Can we find the distance of the source independently?
* What's the effect of the non-linear structure in the Universe?
* Dark Matter self interactions?
  * Upper limit on viscosity means lower limits on self-interaction cross section!

Summary:

* First observational upper limits on cosmic viscosity using GW data,

* In particular, constraints on shear viscosity of DM (and DE?),

* Future GW observations have a potential to probe this a lot better.

THANK YOU