AHMEDABAD UNIVERSITY

Constraints on cosmological viscosity and self-interacting dark matter from gravitational wave observations

Gaurav Goswami
Ahmedabad University

In collaboration with: Girish Kumar Chakravarty, Subhendra Mohanty and A.R. Prasanna.

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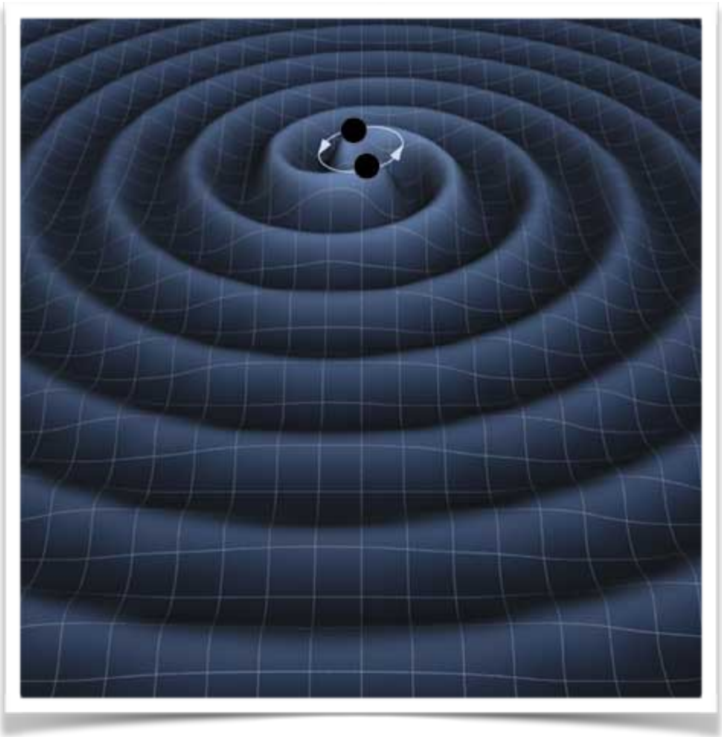
GW150914

* First direct detection of Gravitational Waves (GWs),

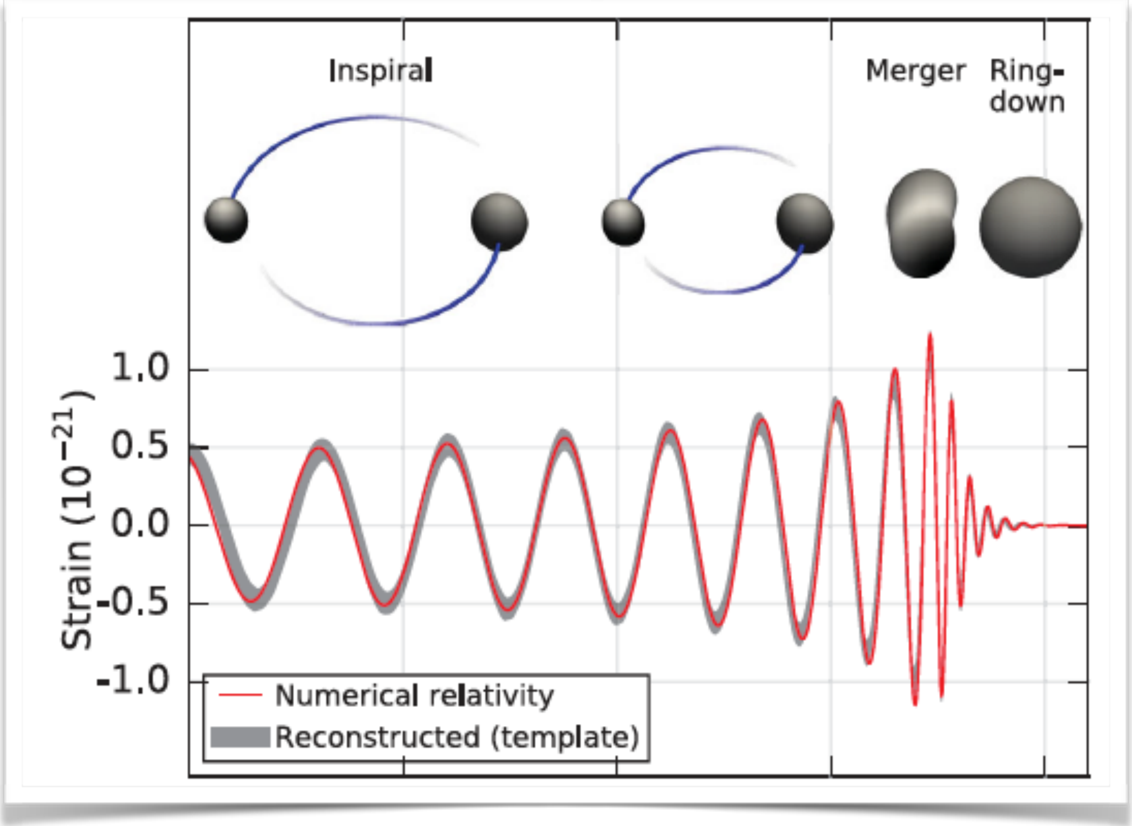
* First observation through a "new window,"
  * a new frontier in astronomy,

* First ever test of gravity in strong field regime,

* First observation of a binary black hole merger.

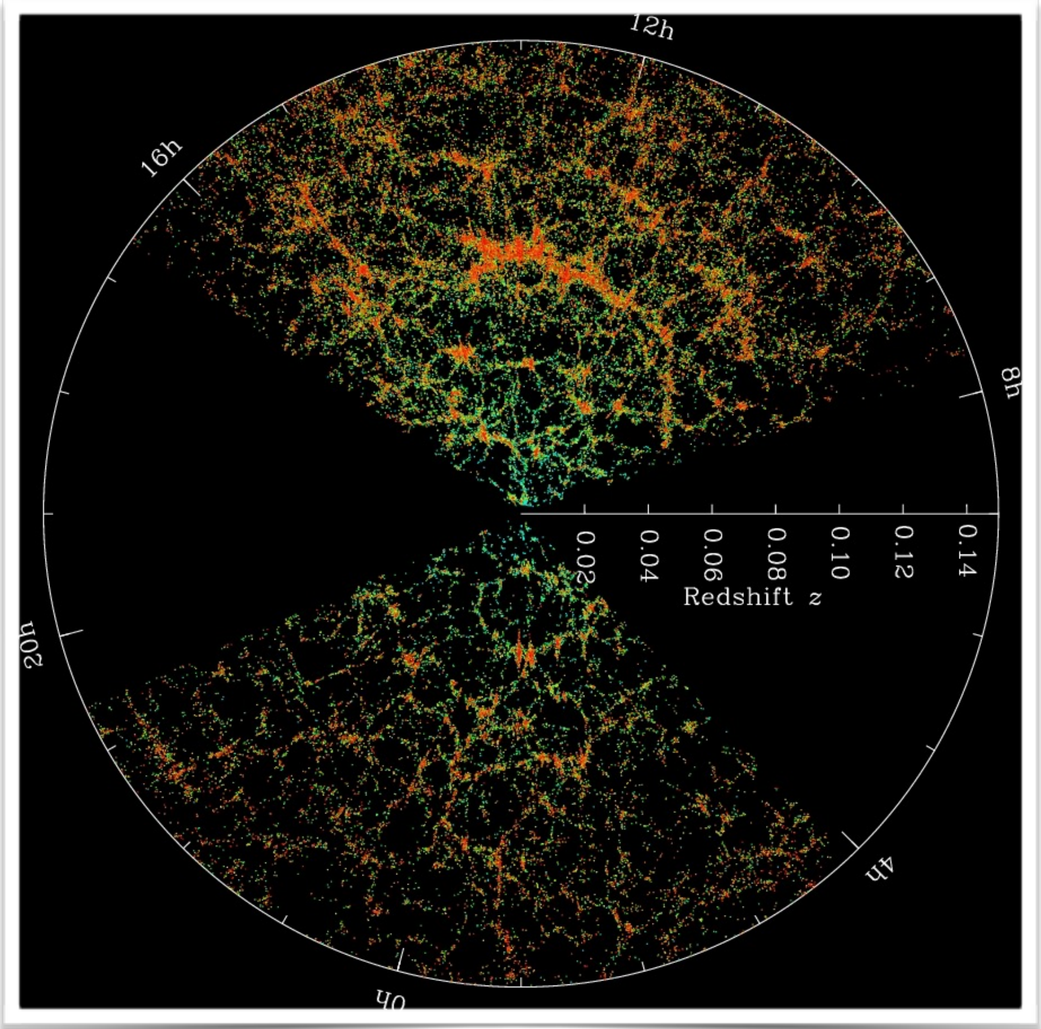


GW150914



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 ...

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

$$\downarrow$$

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

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

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

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

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

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

Matter perturbations ...

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

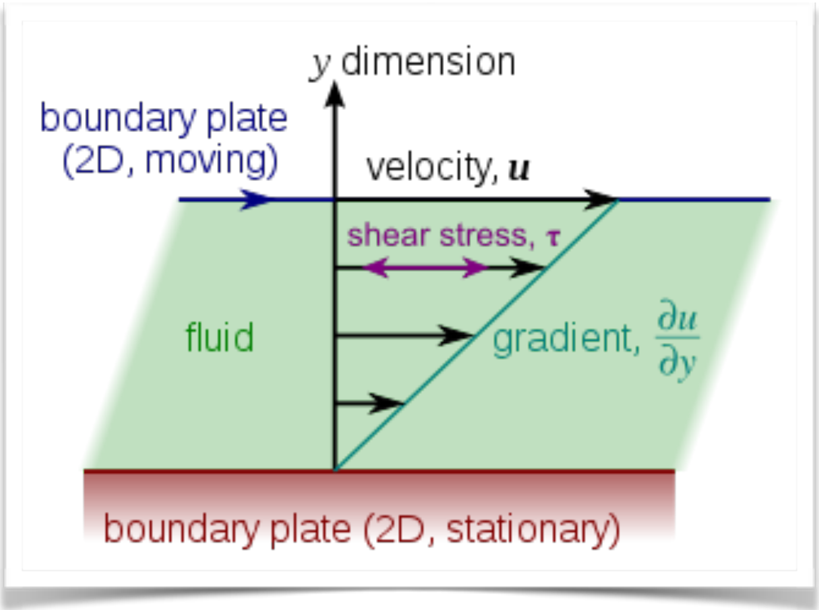
$$\Delta T_{\alpha\beta} = -\eta\left(\frac{\partial u_\alpha}{\partial x^\beta} + \frac{\partial u_\beta}{\partial x^\alpha} + u_\beta u^\gamma \frac{\partial u_\alpha}{\partial x^\gamma} + u_\alpha u^\gamma \frac{\partial u_\beta}{\partial x^\gamma}\right) - (\zeta - \frac{2}{3}\eta)\frac{\partial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

bulk viscosity

shear viscosity

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.



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

For an ideal gas of NR particles

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

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

Effect of intervening medium ?

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

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

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

$$k = k_R + ik_I$$

$$\beta \ll \omega$$

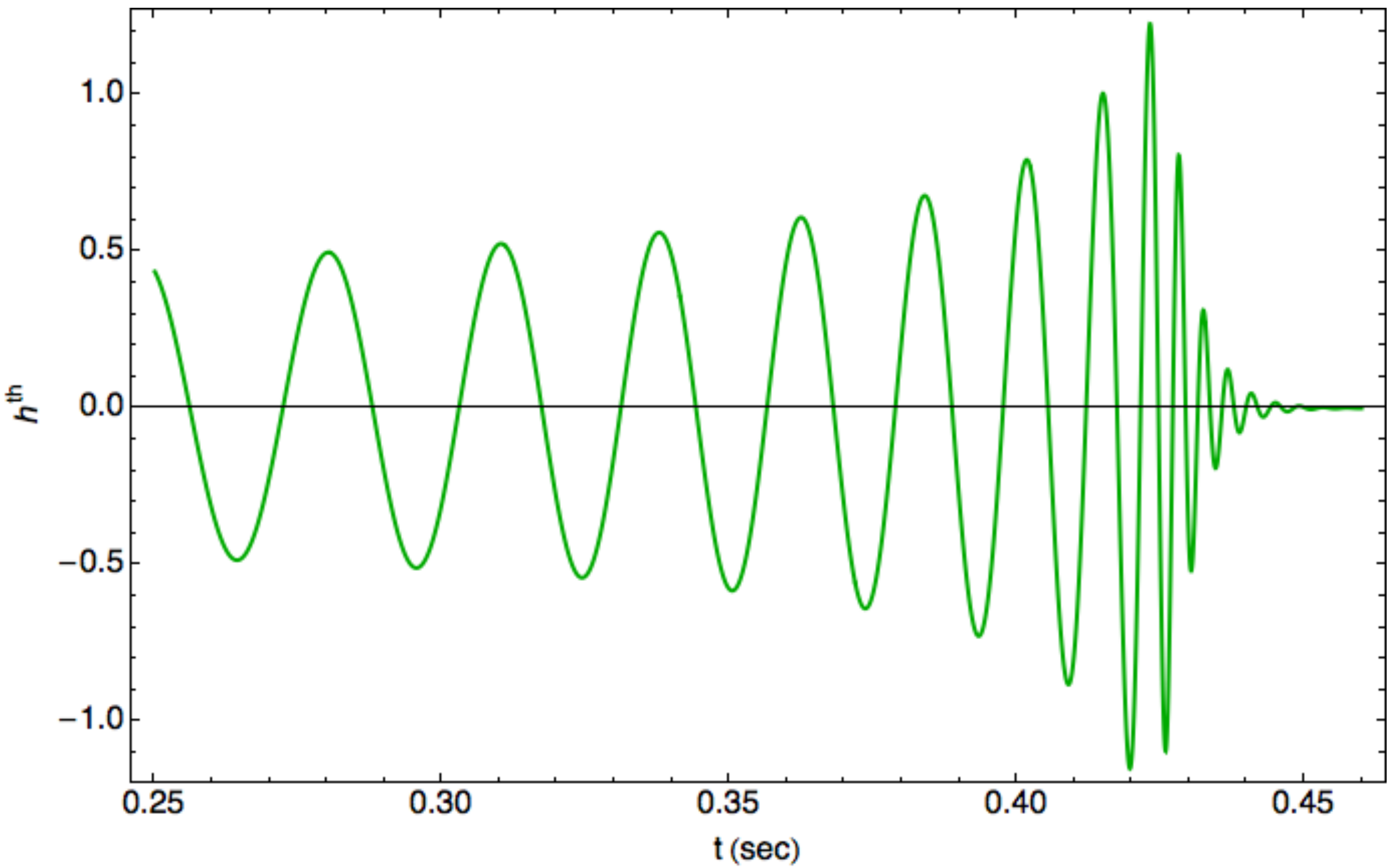
$$k_R = \omega \,, \quad k_I = \frac{\beta}{2} \,.$$

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

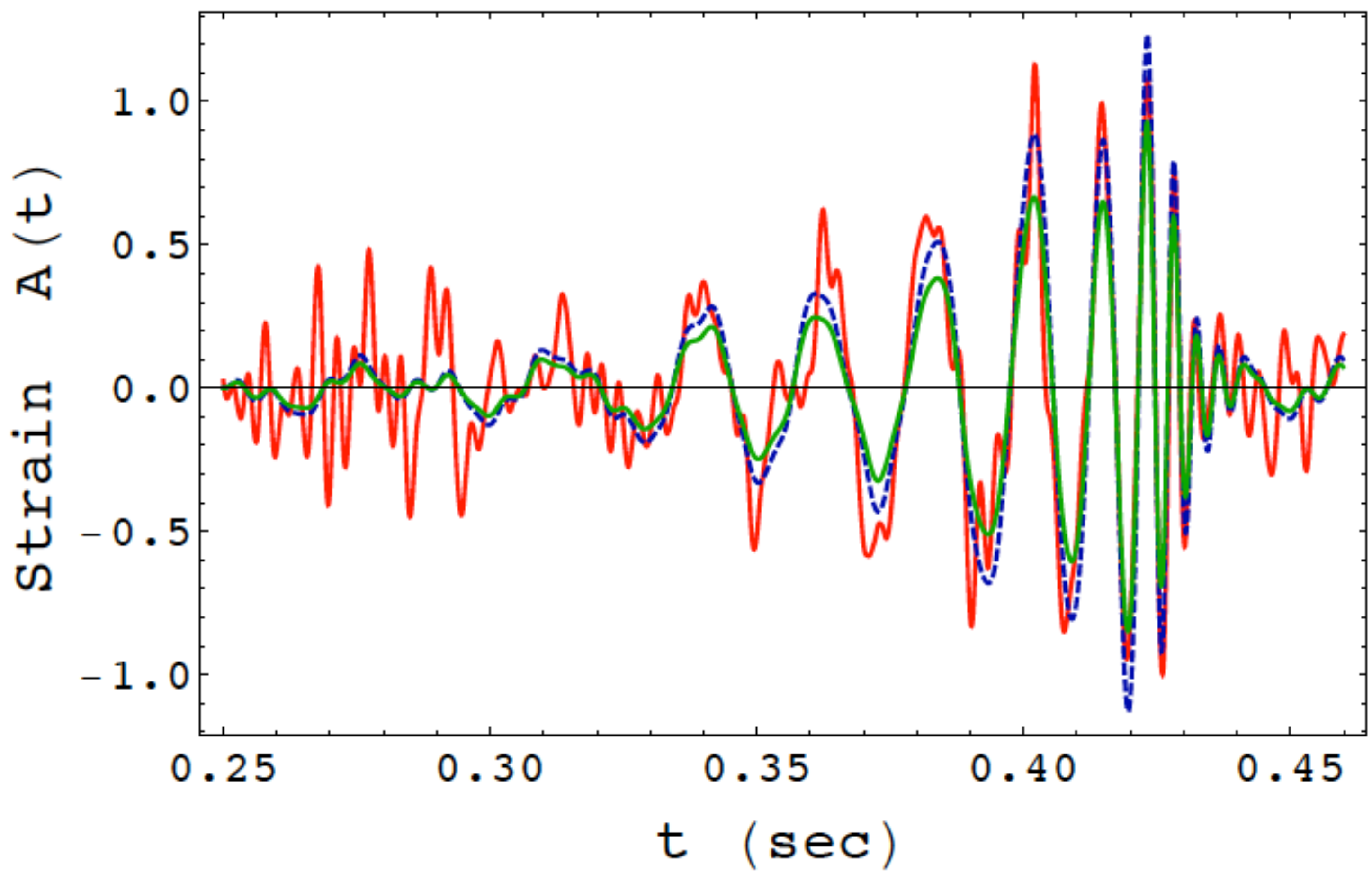
$$e^{-k_I L} = e^{-(8\pi G\eta L)}$$

- 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).

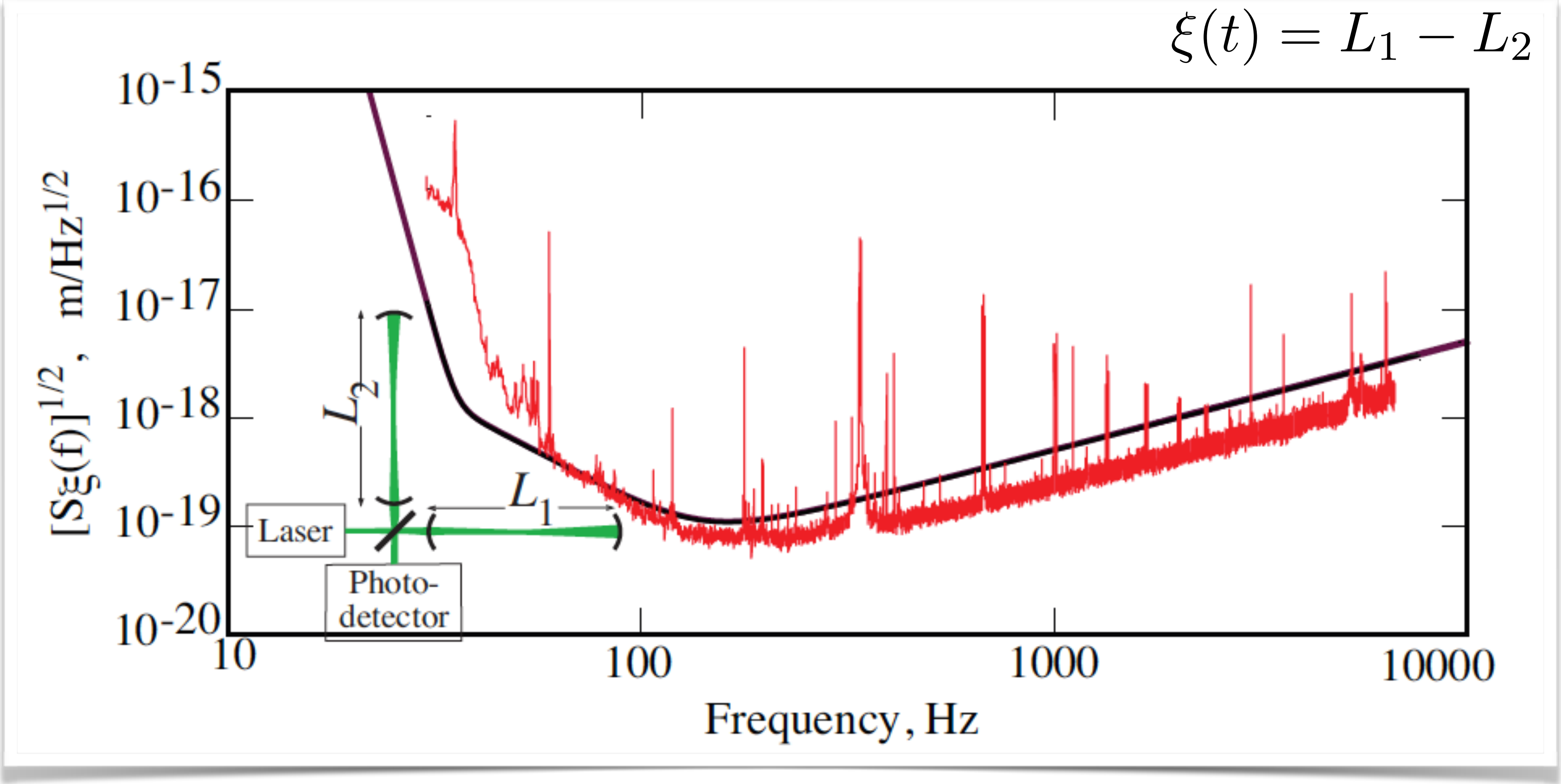
Effect of intervening medium ?



Effect of intervening medium ?

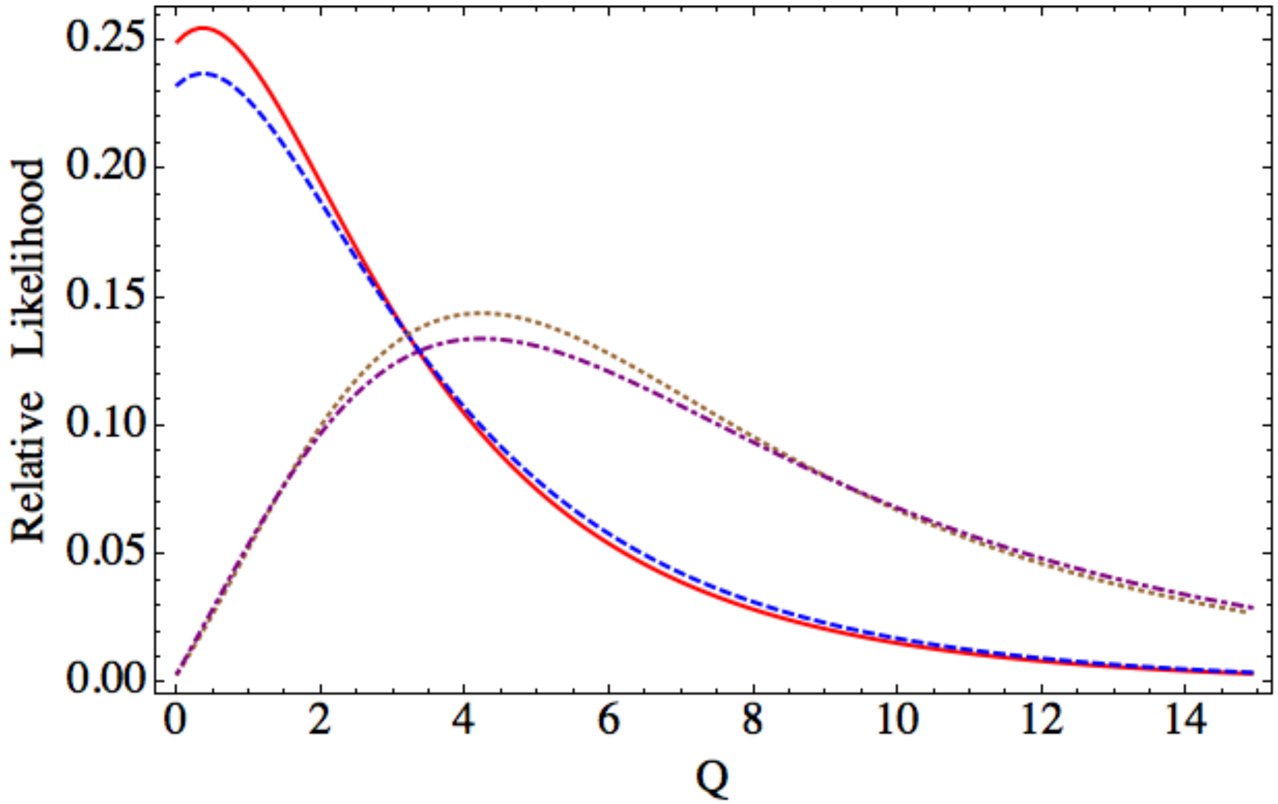


Likelihood (Gaussian and stationary noise)



$$\mathcal{L} = \frac{1}{((2\pi)^N \det C_{jj'})^{1/2}} \exp\left\{ -\frac{1}{2} \sum_{jj'} \xi_j \, C^{-1}_{jj'} \, \xi_{j'} \right\} \qquad \langle \tilde{n}(f)\tilde{n}^*(f') \rangle = \frac{1}{2}\delta(f-f')S_n(f)$$

Upper bounds on viscosity of the cosmic fluid:



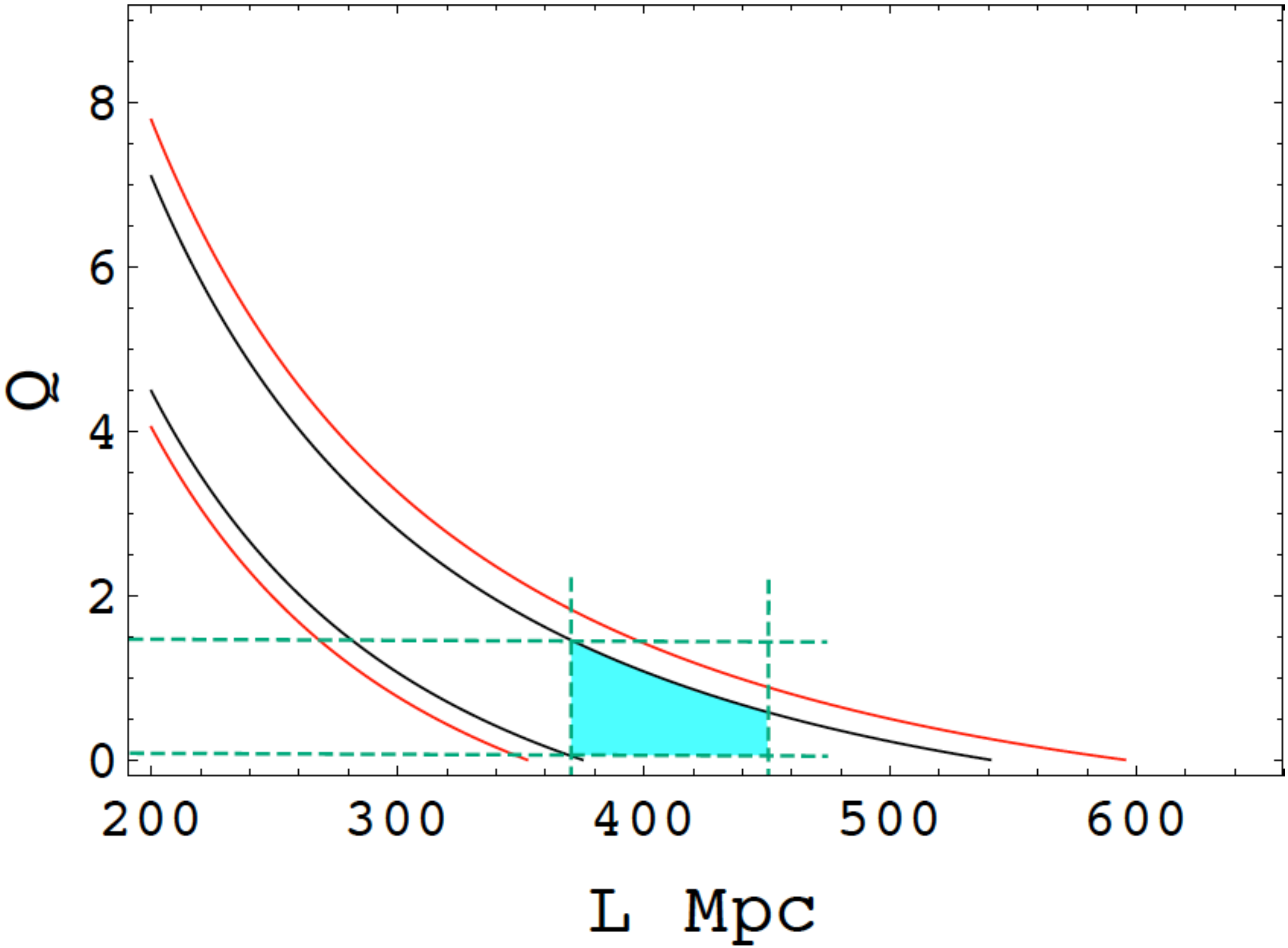
Stuff	Viscosity (Pa sec)
QGP at RHIC	~ 10^{11}
Observable cosmos	< 10^{9}
Water	10^{-3}
Steam	10^{-5}
Honey	10

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

Possible Issues:

* Shouldn't one recalculate all the parameters?
  * Some of them won't affected.
* Isn't this degenerate with measured distance?
  * Can we find the distance of the source independently?
* Will this large viscosity be ruled out by other means?
* What's the effect of the non-linear structure in the Universe?
* What kind of DM can give this much viscosity?
  * NOT: Cold, collisionless, no self-interactions etc

Joint constraints on viscosity and distance:



Take Away...

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

* The present data does not allow for competitive limits to be placed on cosmological viscosity,

* A proof-of-principle demonstration of how GW measurements can be used to constrain cosmological parameters such as cosmic shear viscosity.

* One possible interpretation: upper limits on shear viscosity of DM (and DE?),

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

Thank You