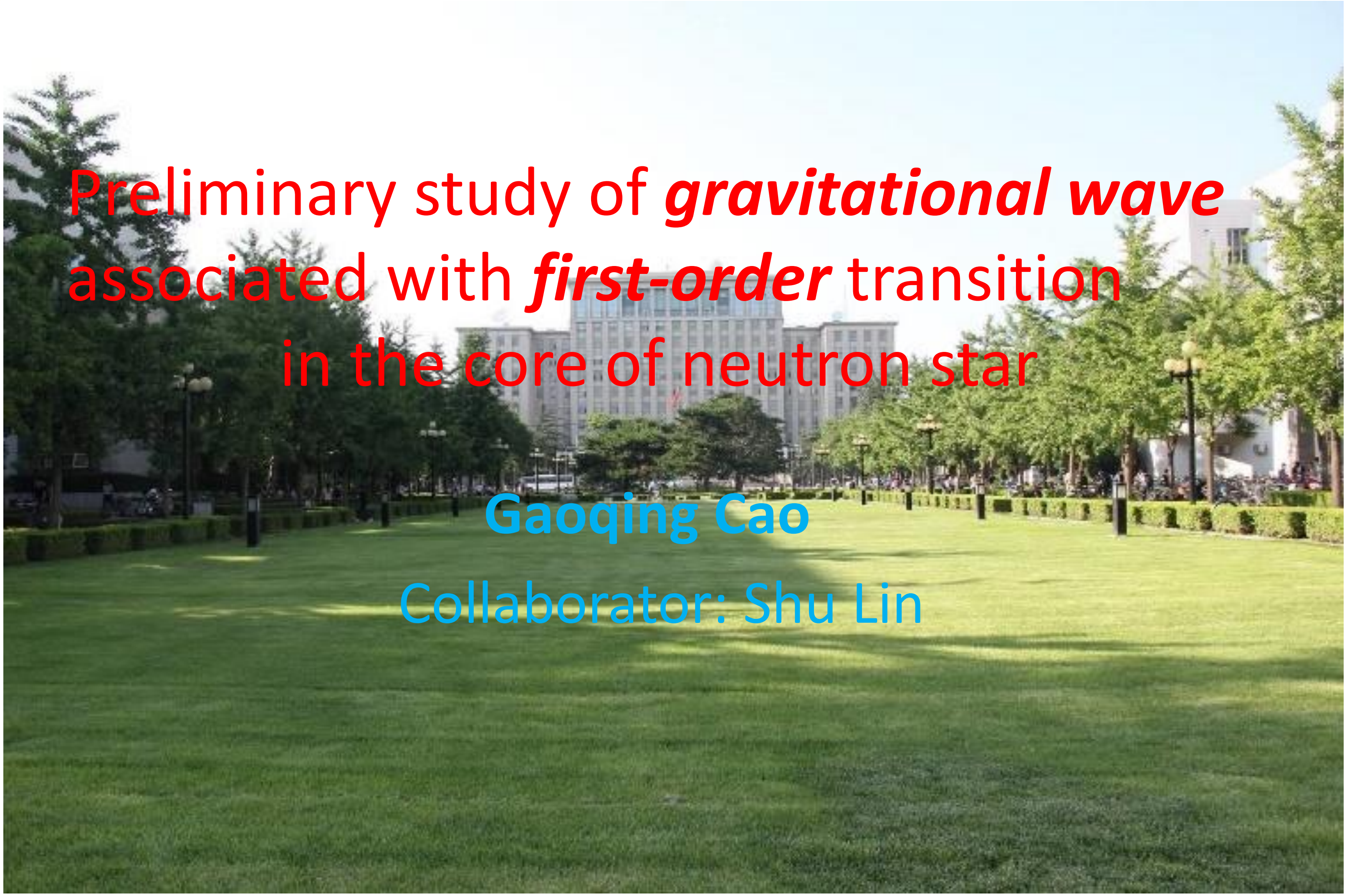
1st Symposium on intermediate-energy Heavy Ion Collisions



Preliminary study of ***gravitational wave*** associated with ***first-order*** transition in the core of neutron star

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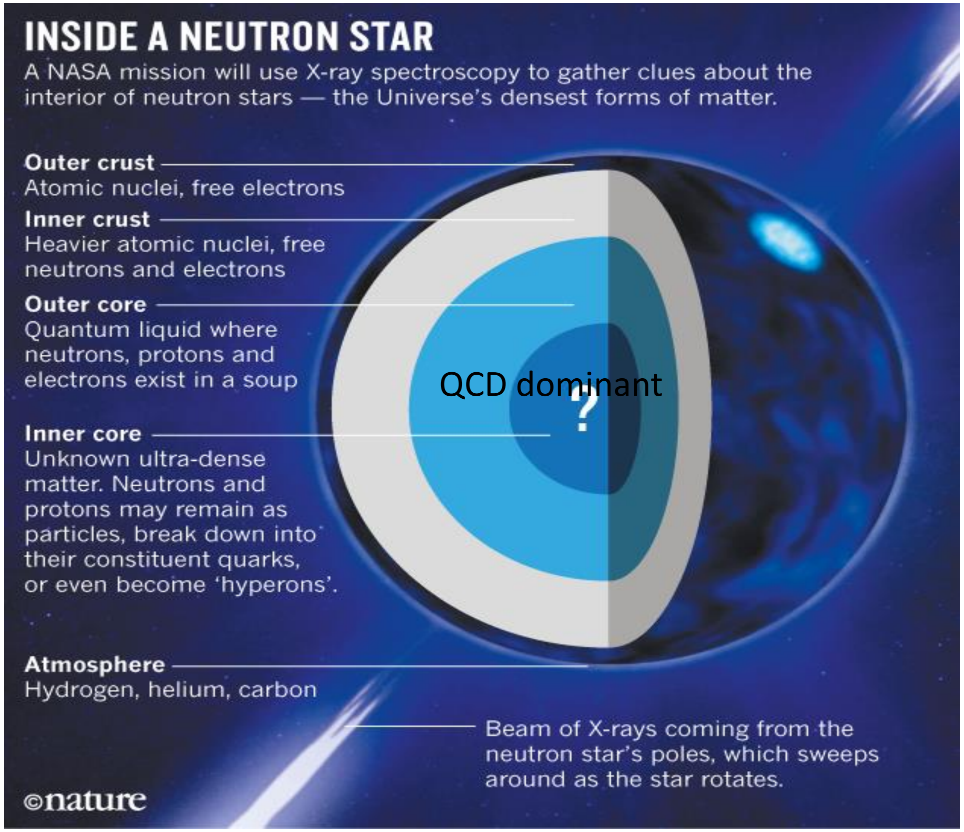
Outline

- QCD phases in neutron stars
- Gravitational wave — new probe
- Bubble dynamics during first-order transition
- Preliminary calculations
- Summary and prospective

QCD phases in neutron stars



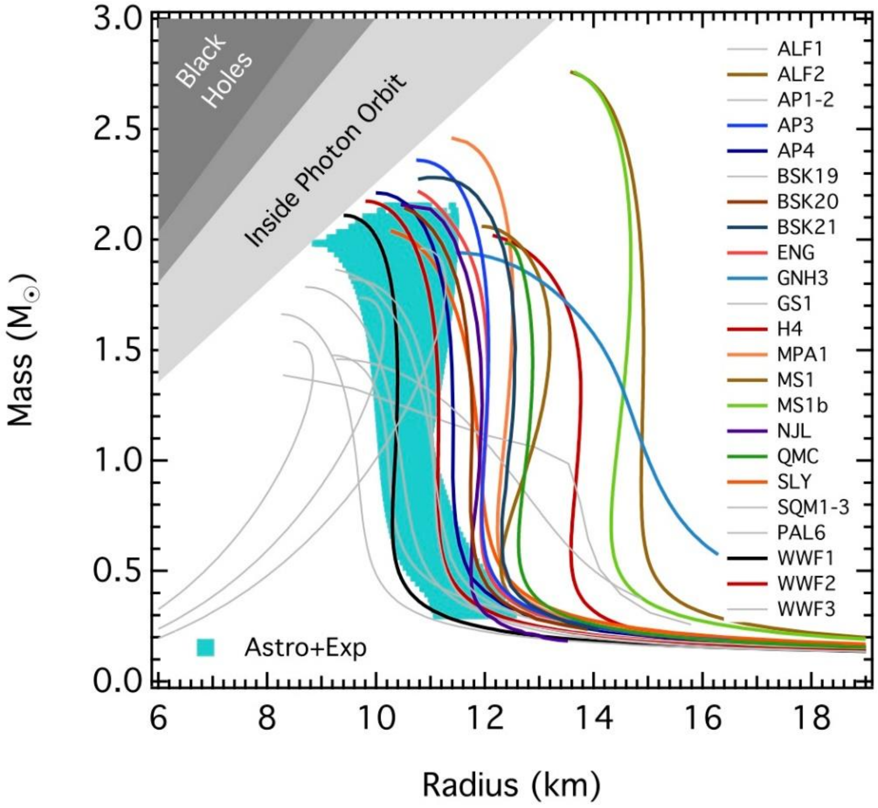
Possible phases for "?":

Chiral restoration,
Quarkyonic matter,
Pion superfluidity,
Kaon superfluidity,
Color superconductivity,
Color-flavor-locking.

Significance: compensate the "criticality" exploration at HIC which is usually limited at low density and high temperature

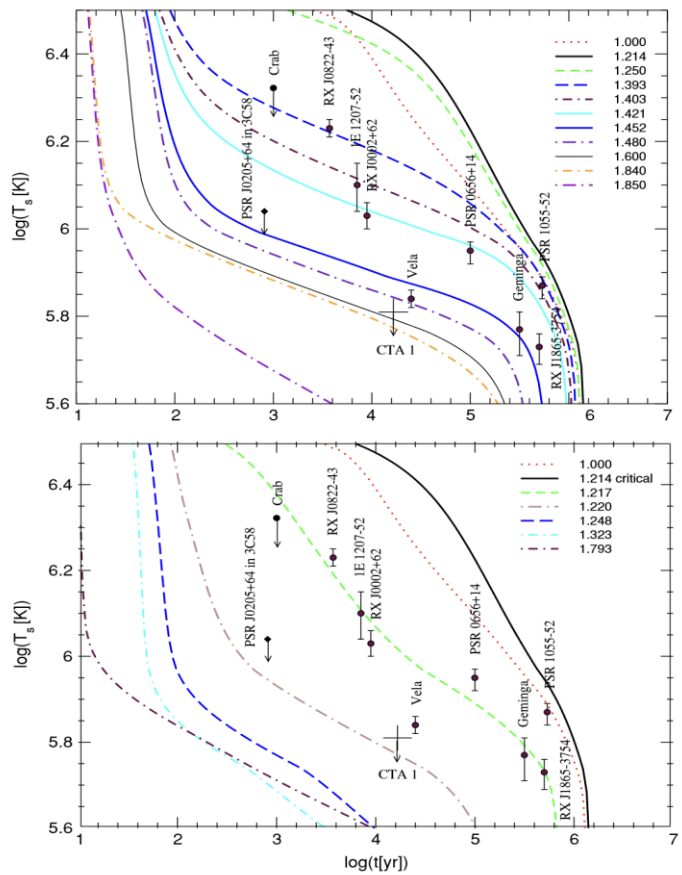
Traditional probes

EM field exploration:
Mass-radius relationship



O. Feryal, et al. Astrophys.J. 820 (2016) no.1, 28

Neutrino emission:



Neutron star

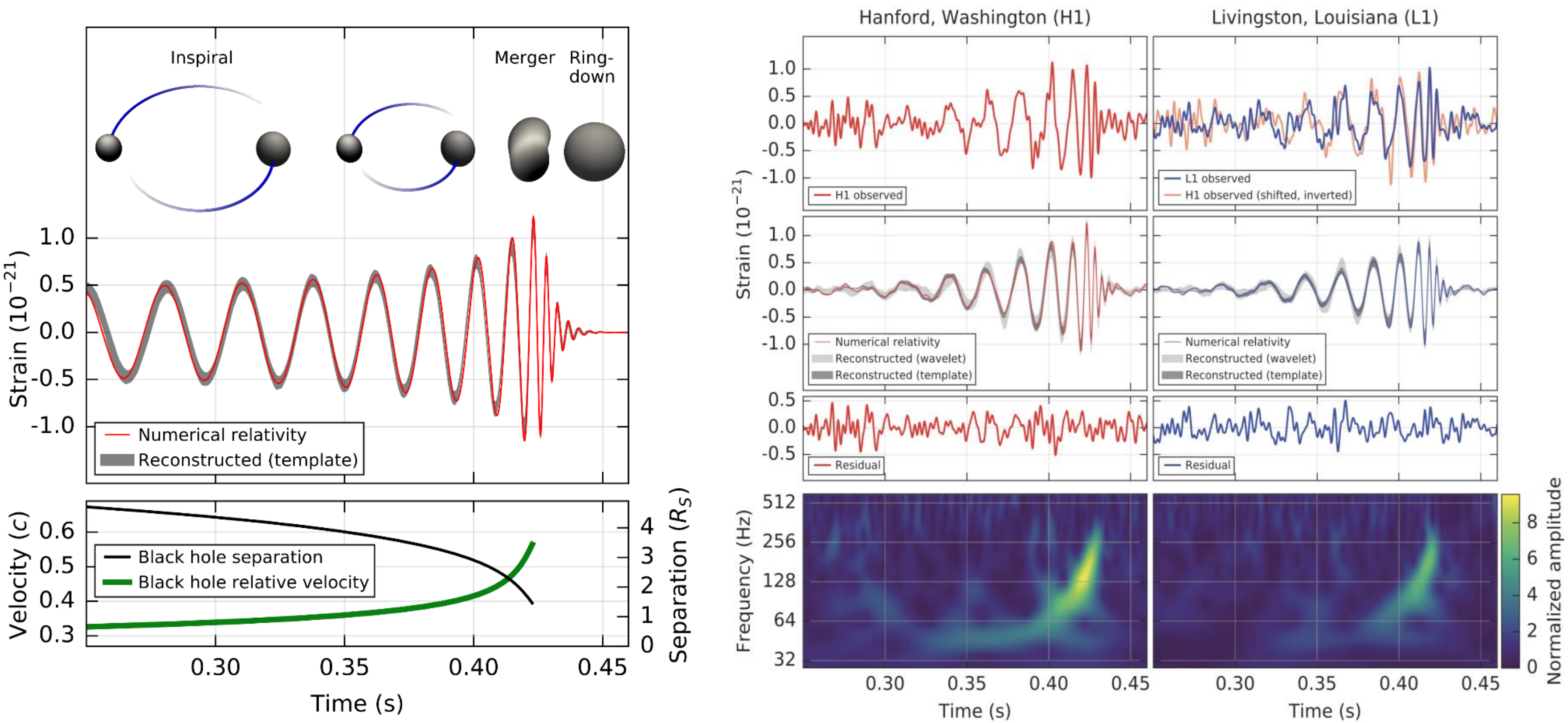
Hybrid star

Hovik Grigorian, et al., Phys. Rev. C 71, 045801 (2005)

2.01±0.04 $M_\odot$ from a combination of radio timing and precise spectroscopy of the white dwarf companion for **PSR J0348+0432**

Gravitational wave — new probe

GW150914 : Binary Black Hole Merger



B.P. Abbott et al., PRL 116, 061102 (2016)

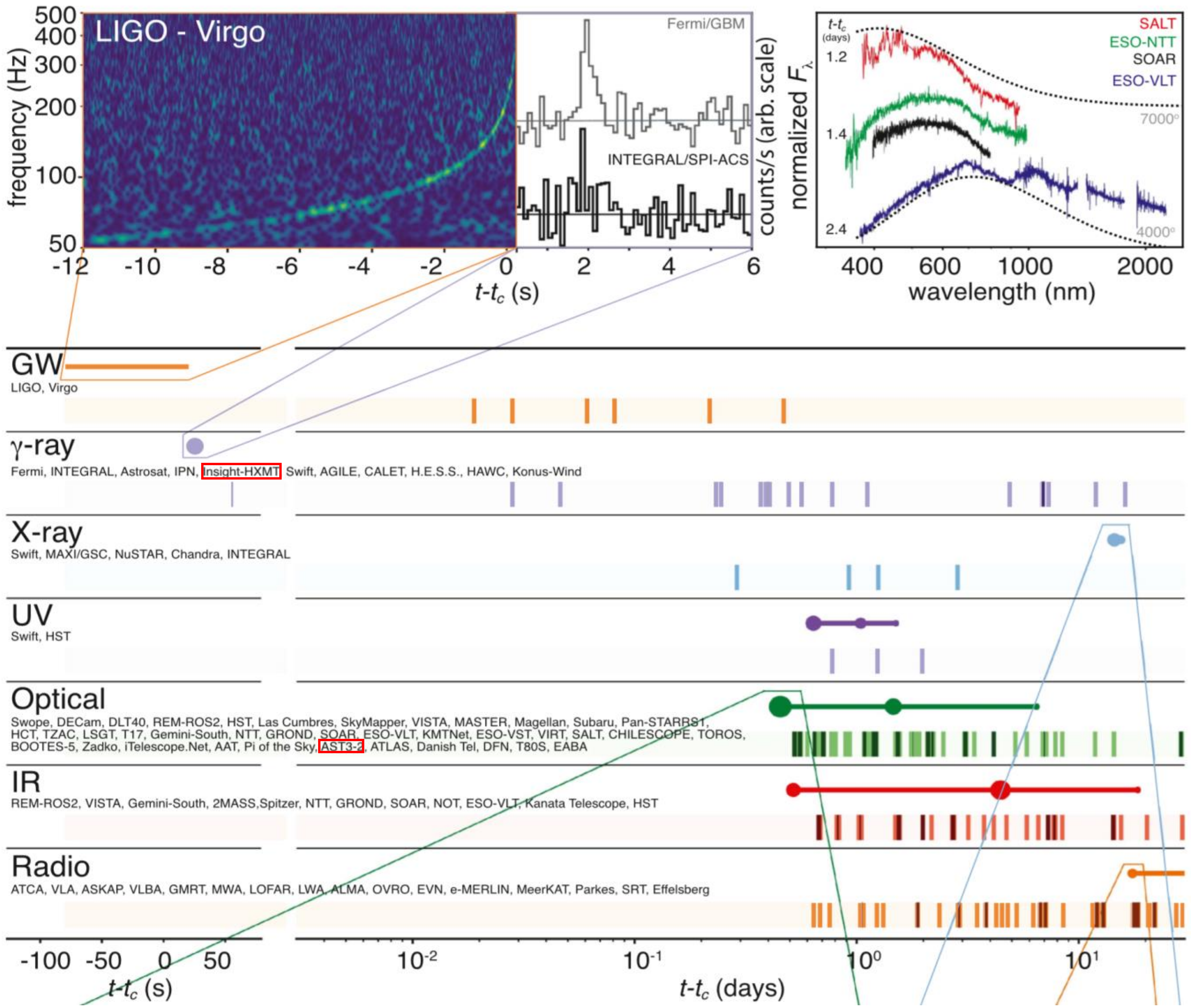
Multi-messenger Observations

GW170817, GRB 170817A, SSS17a/AT 2017gfo:

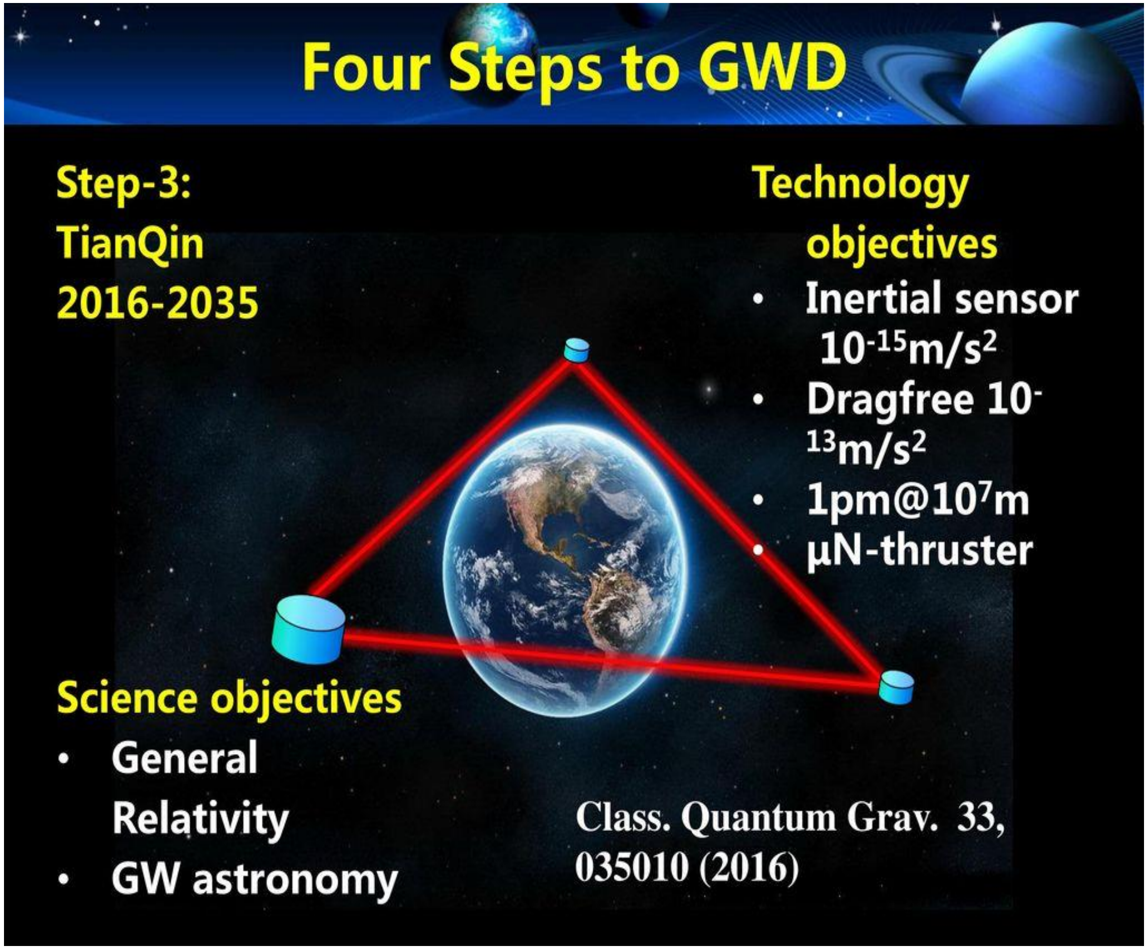
Binary Neutron Star Merger

Refer to C. Horowitz, Liewen Chen, and Ang Li's talks

B. P. Abbott, et al., ApJL, 848:L12, 2017



Tainqin – General environment at School of Physics and Astronomy



Detailed objectives:

Stochastic GW background,
White draft binaries,
Intermedium-mass BH,
Tidal deformation effect…

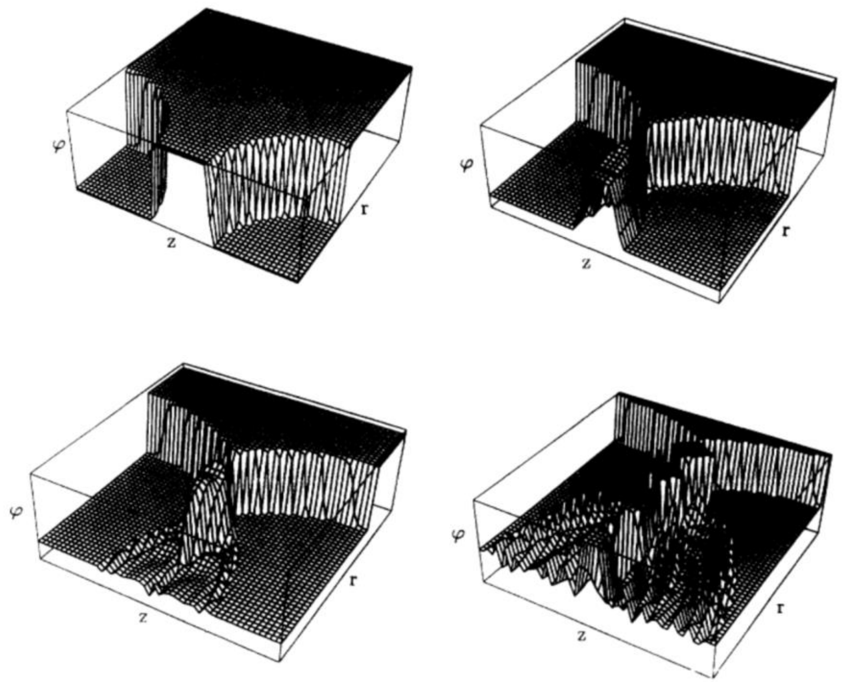
Our proposal:
QCD transition signal

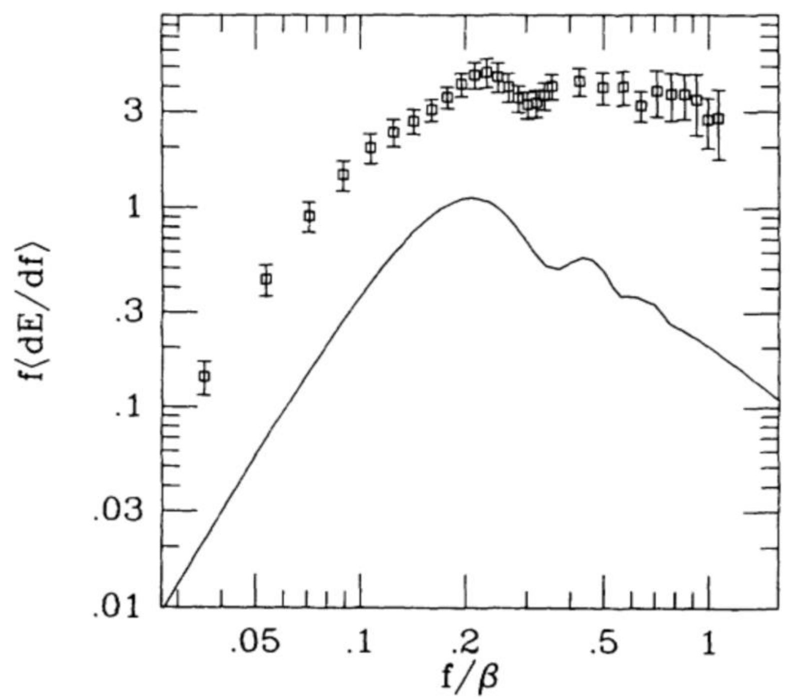
Collapses of rapidly rotating NS:
L.-M. Lin, et al., ApJ 639: 382–396, 2006

Early universe cooling:
Y. Chen,M. Huang and Q. Yan, arXiv:1712.03470

GW from first-order transition

Supercooling for first-order transition





Bubble collisions produce quadrupole moment

Peaks show in the differential spectrum at $\frac{f}{\beta}\sim\mathbf{0.2}$ for early universe phase transition

A. Kosowsky, M.S. Turner, and R. Watkins, Phys. Rev. D45, 4514 (1992); Phys. Rev. Lett. 69, 2026 (1992).

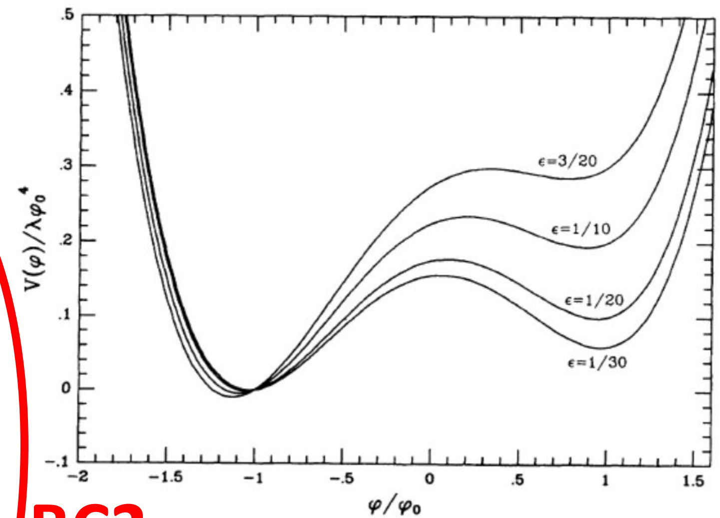
Bubble dymanics

One bubble - $O(4)$ symmetry $\varphi=\varphi(\rho),\quad \rho=(t_E^2+\mathbf{x}^2)^{1/2}$:

$$\mathcal{L}=\tfrac{1}{2}\partial^\mu\varphi\,\partial_\mu\varphi-V(\varphi)$$

EOM1:
$$\frac{d^2\varphi}{d\rho^2}+\frac{3}{\rho}\frac{d\varphi}{d\rho}=\frac{\partial V}{\partial\varphi}$$

BC1:
$$\lim_{\rho\to\infty}\varphi(\rho)=\varphi_+,\quad \left.\frac{d\varphi}{d\rho}\right|_{\rho=0}=0$$



BC2

$$V_0(\varphi)=\frac{\lambda}{8}(\varphi^2-\varphi_0^2)^2\,,$$

$$V(\varphi)=V_0(\varphi)+\epsilon\lambda\varphi_0^3(\varphi+\varphi_0)\,,$$

Two bubble - $O(3)$ symmetry :

$$\mathcal{L}=\frac{1}{2}\left[\frac{\partial\varphi}{\partial s}\right]^2-\frac{1}{2}\left[\frac{\partial\varphi}{\partial z}\right]^2-V(\varphi)\,,$$

EOM2:
$$\frac{\partial^2\varphi}{\partial s^2}+\frac{2}{s}\frac{\partial\varphi}{\partial s}-\frac{\partial^2\varphi}{\partial z^2}=-\frac{\partial V}{\partial\varphi}\,.$$

$$\varphi(\mathbf{x},t)=\varphi(t^2-r^2,z)$$

Based on S. Coleman, Phys. Rev. D 15, 2929 (1977); C. Callan and S.Coleman, ibid. 16, 1762 (1977).

Effective potential in quark-meson model

Lagrangian density (Renormalizable):

$$\mathcal{L}_{QM} = \bar{q}\left[i\partial\!\!\!/ + (\mu_B/N_c + \mu_I\tau_3)\gamma^0 - g_q\left(\sigma + i\gamma^5\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]q$$

$$+\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}\right) - \frac{\lambda}{4}\left(\sigma^2 + \boldsymbol{\pi}\cdot\boldsymbol{\pi} - \upsilon^2\right)^2 + c\,\sigma$$

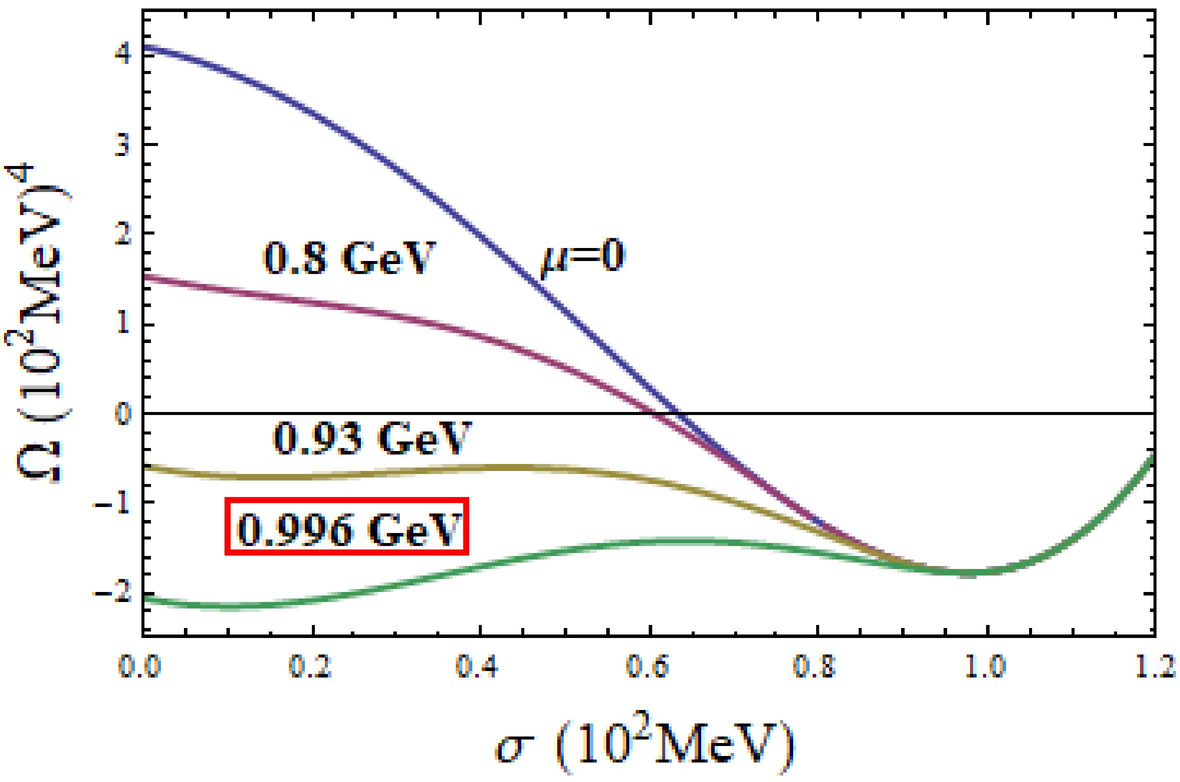
Integrate over quark degrees of freedom and keep only $\boldsymbol{\sigma}$ dynamics:

$$\mathcal{L}_s = \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma\right) - \frac{\lambda}{4}\left(\sigma^2 - \upsilon^2\right)^2 + c\,\sigma + \Omega^t_{QM}(\sigma)$$

$$\Omega^t_{QM}(\sigma) = \frac{1}{12\pi^2}\left[2p_F^3\mu_B - 3\left(p_F\mu_B m_q^2 - N_c m_q^4 \operatorname{arccosh}\left(\frac{\mu_B}{N_c m_q}\right)\right)\right]\theta(\mu_B - N_c m_q)$$

$$p_F(\sigma(x)) = \left((\mu_B/N_c)^2 - m_q^2(x)\right)^{1/2} \qquad m_q(x) = g_q\sigma(x)$$

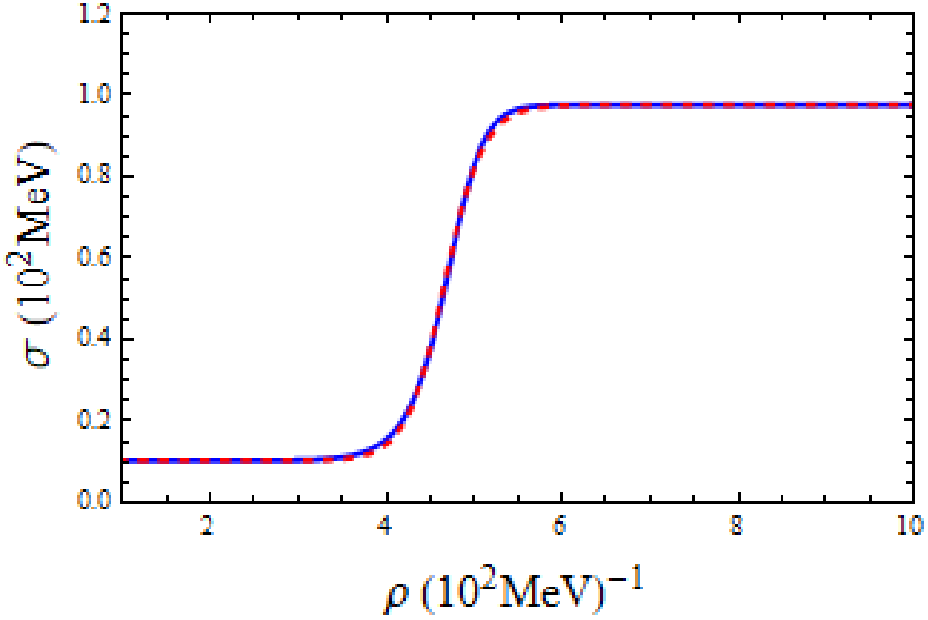
Chiral symmetry for different μ_B



Chiral symmetry is gradually restored by increasing chemical potential – first order

Bubble dynamics for chiral restoration

One bubble generation



1) Fine tuned: $10^{-4}\%$ for true vacuum;
2) Well-fitted to solitonic solution

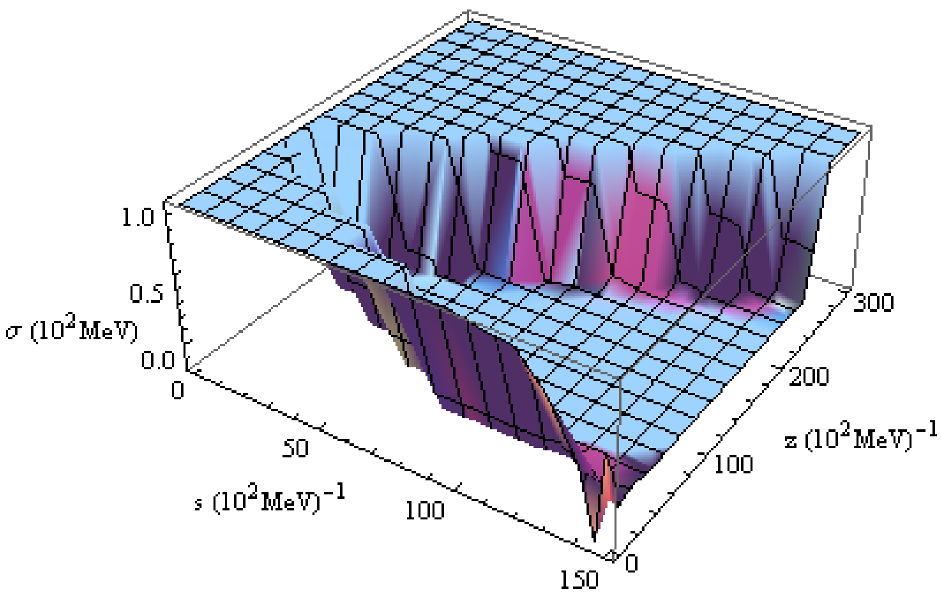
$$\sigma(\rho) = \frac{\sigma_T}{2}\left(1 - \tanh\left(\frac{\rho - R_B}{d_W}\right)\right) + \frac{\sigma_F}{2}\left(1 + \tanh\left(\frac{\rho - R_B}{d_W}\right)\right)$$

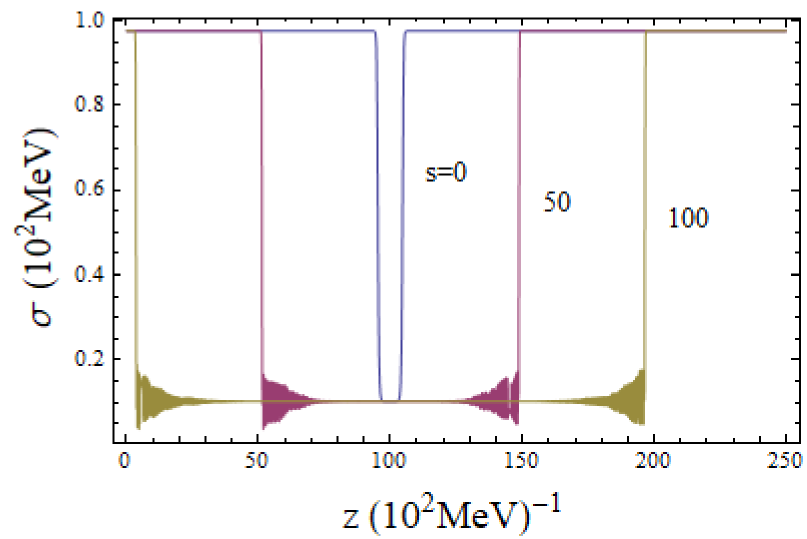
$$R_B = 4.66 * 10^{-2} MeV^{-1} \text{ and } d_w = 4.38 * 10^{-3} MeV^{-1}$$

Bubble dynamics for chiral restoration

Two bubble evolution

Stephen William Hawking, J. M. Stewart, and I. G. Moss, Phys. Rev. D 26, 2681 (1982).





1) **Bubble walls expand relativistically and nearly symmetrically;**
2) **Oscillations have developed before bubble collision.**

Preliminary results for the GW energy emission

$$\frac{dE}{d\omega\, d\Omega} = G\omega^2 \left| T^{zz}(\hat{\mathbf{k}},\omega)\sin^2\theta + T^{xx}(\hat{\mathbf{k}},\omega)\cos^2\theta - T^{yy}(\hat{\mathbf{k}},\omega) - 2T^{xz}(\hat{\mathbf{k}},\omega)\sin\theta\cos\theta \right|^2$$

Inside light-cone

$$T_1^{xx}(\hat{\mathbf{k}},\omega) = \frac{1}{2}\int_0^\infty s^2 ds \int_{-\infty}^{\infty} dz\, e^{i\omega_z z} \left| \frac{\partial\varphi}{\partial s} \right|^2 \int_1^\infty du\,(u^2-1) e^{i\omega s u} \{ J_0[\omega_x s(u^2-1)^{1/2}] - J_2[\omega_x s(u^2-1)^{1/2}] \} C(su) \,,$$

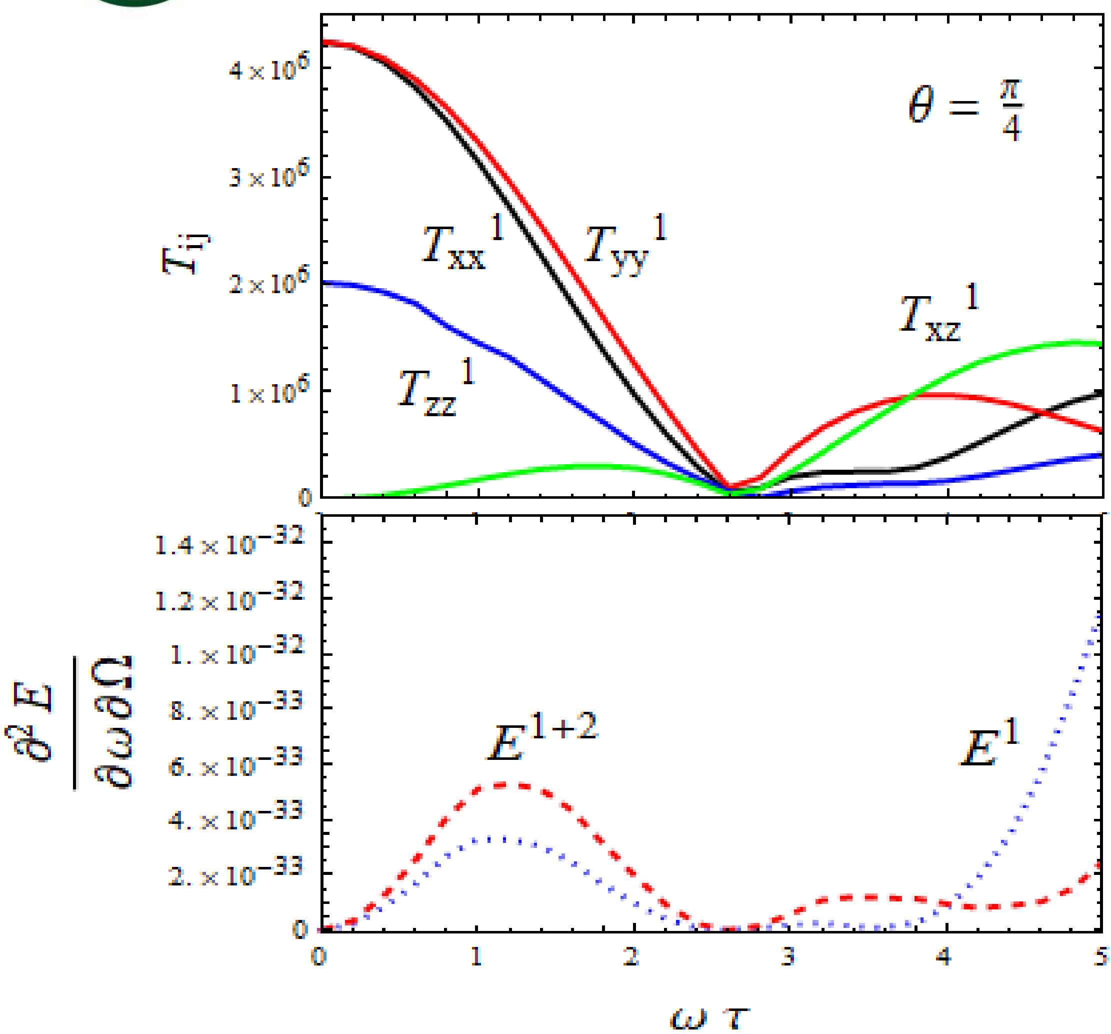
$$T_1^{yy}(\hat{\mathbf{k}},\omega) = \frac{1}{2}\int_0^\infty s^2 ds \int_{-\infty}^{\infty} dz\, e^{i\omega_z z} \left| \frac{\partial\varphi}{\partial s} \right|^2 \int_1^\infty du\,(u^2-1) e^{i\omega s u} \{ J_0[\omega_x s(u^2-1)^{1/2}] + J_2[\omega_x s(u^2-1)^{1/2}] \} C(su) \,,$$

$$T_1^{zz}(\hat{\mathbf{k}},\omega) = \int_0^\infty s^2 ds \int_{-\infty}^{\infty} dz\, e^{i\omega_z z} \left| \frac{\partial\varphi}{\partial z} \right|^2 \int_1^\infty du\, e^{i\omega s u} J_0[\omega_x s(u^2-1)^{1/2}] C(su) ,$$

$$T_1^{xz}(\hat{\mathbf{k}},\omega) = -i\int_0^\infty s^2 ds \int_{-\infty}^{\infty} dz\, e^{i\omega_z z} \left| \frac{\partial\varphi}{\partial s} \right| \left| \frac{\partial\varphi}{\partial z} \right| \int_1^\infty du\,(u^2-1)^{1/2} e^{i\omega s u} J_1[\omega_x s(u^2-1)^{1/2}] C(su) \,.$$

$$\hat{\mathbf{k}}_x = \sin\theta, \quad \hat{\mathbf{k}}_y = 0, \quad \hat{\mathbf{k}}_z = \cos\theta \qquad C(t) = \begin{cases} 1, & 0 \le t \le \tau_c, \\ \exp[-(t-\tau_c)^2/\tau_0^2], & \tau_c \le t \le \tau \end{cases}$$

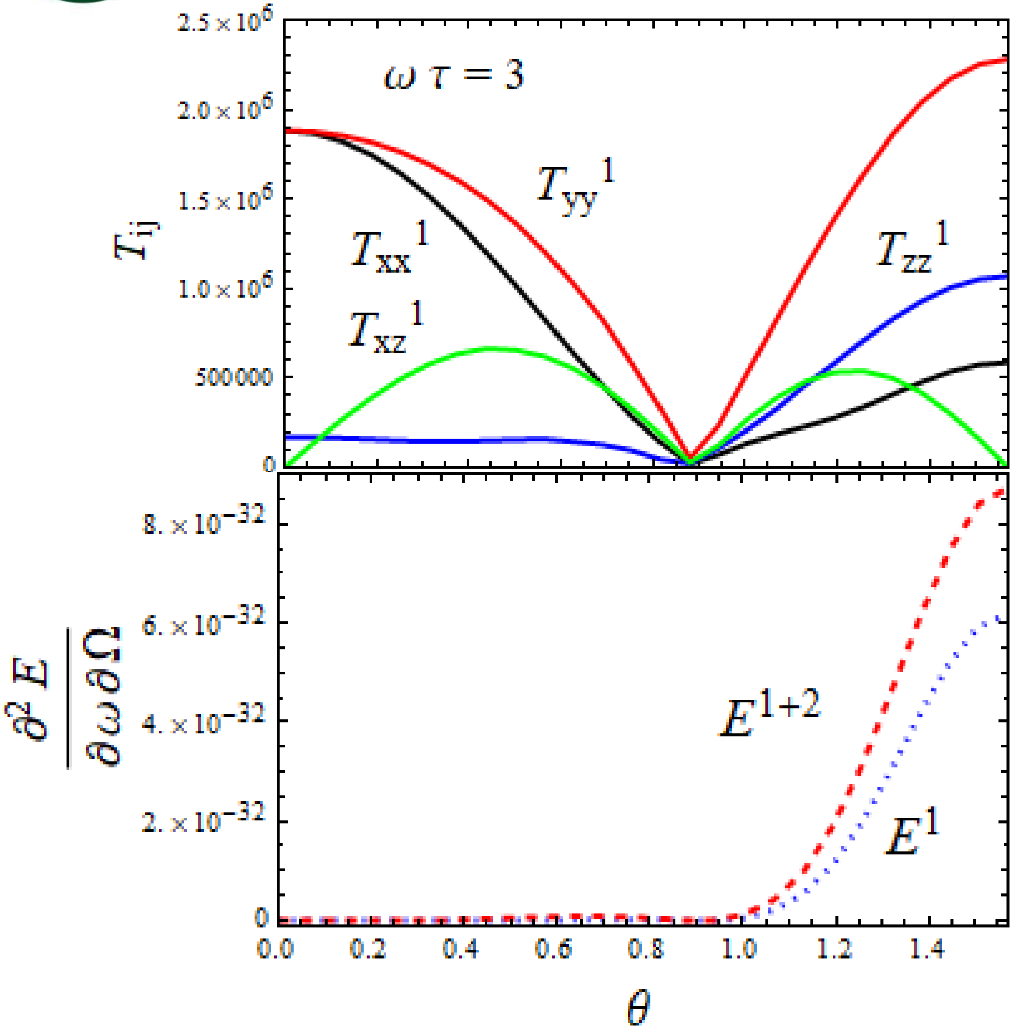
Vary with frequency



1) Transverse terms dominate at low frequency
2) Cross term contribute at large frequency
3) All show minima at the same point

1) Inside light-cone dominats GW emission at low frequency
2) Large cancellation between inside and outside light-cone contribution
3) Oscillation for the total emission

Vary with angle



1) **Transverse terms dominate at low angle**
2) **Cross term jumps twice**
3) **All show minima at the same point**

1) **Inside light-cone dominates GW emission**
2) **Only large angle is important for the emission**

Consistent with

A. Kosowsky, M.S. Turner, and R. Watkins, Phys. Rev. D45, 4514 (1992).

Summary and prospective

- GW emission from first-order QCD transition is preliminarily studied by following bubble dynamics
- This applies to the collapse of neutron star with large chemical potential in the inner core, maybe to EM emission if first-order transition is realized in HIC
- Angle integrated GW emission、multi-bubble dynamics、bubble generation rate
- More realistic study: non-Lorentz invariant dynamics、contributions from pion interactions、including nuclear matter phase
- Further extensions: color superconductivity、liquid-gas transition、neutron star-black hole binary

Thanks!