Gravitational wave from neutron star phase transition

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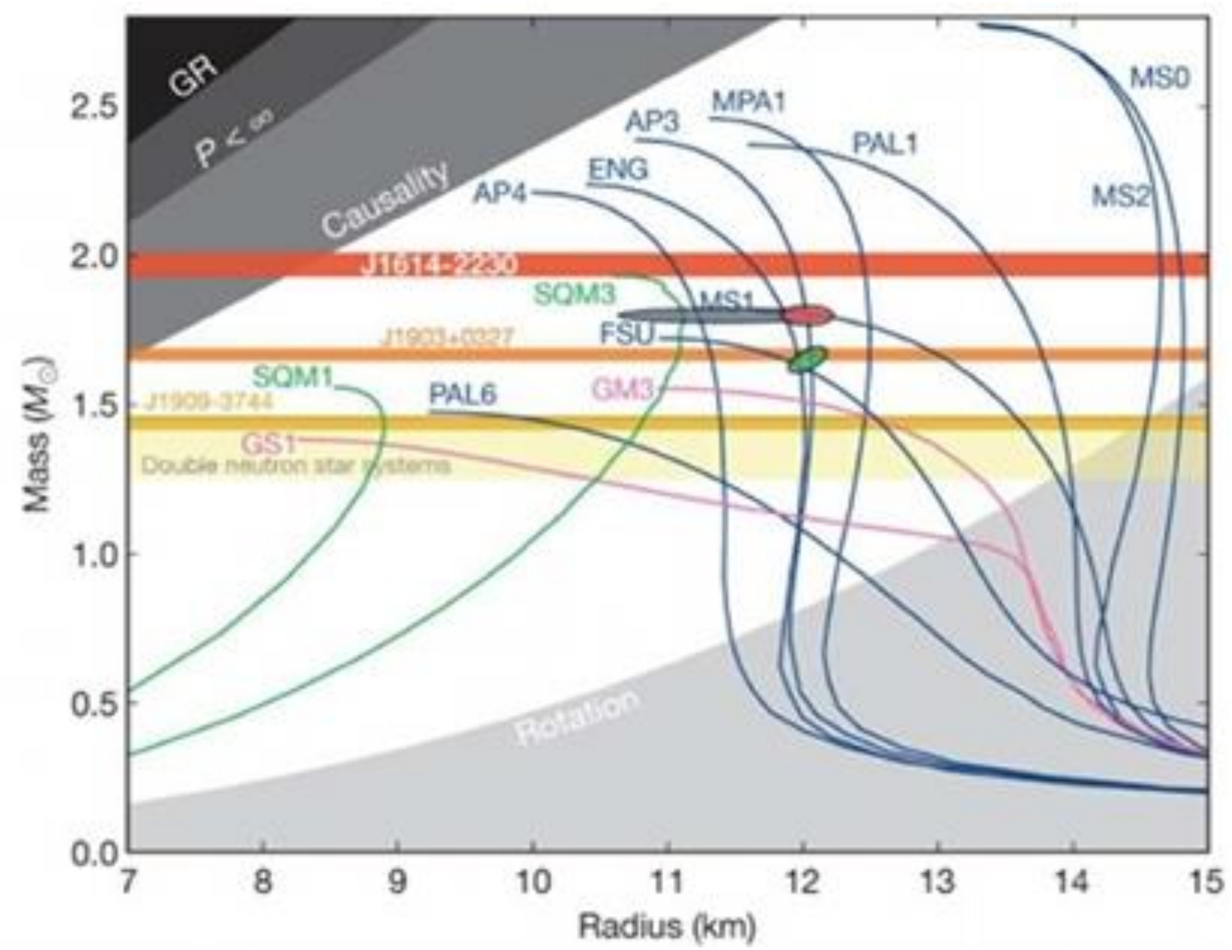
ATHIC 2018, Hefei

based on 1810.00528, Gaoqing Cao, SL

Outline

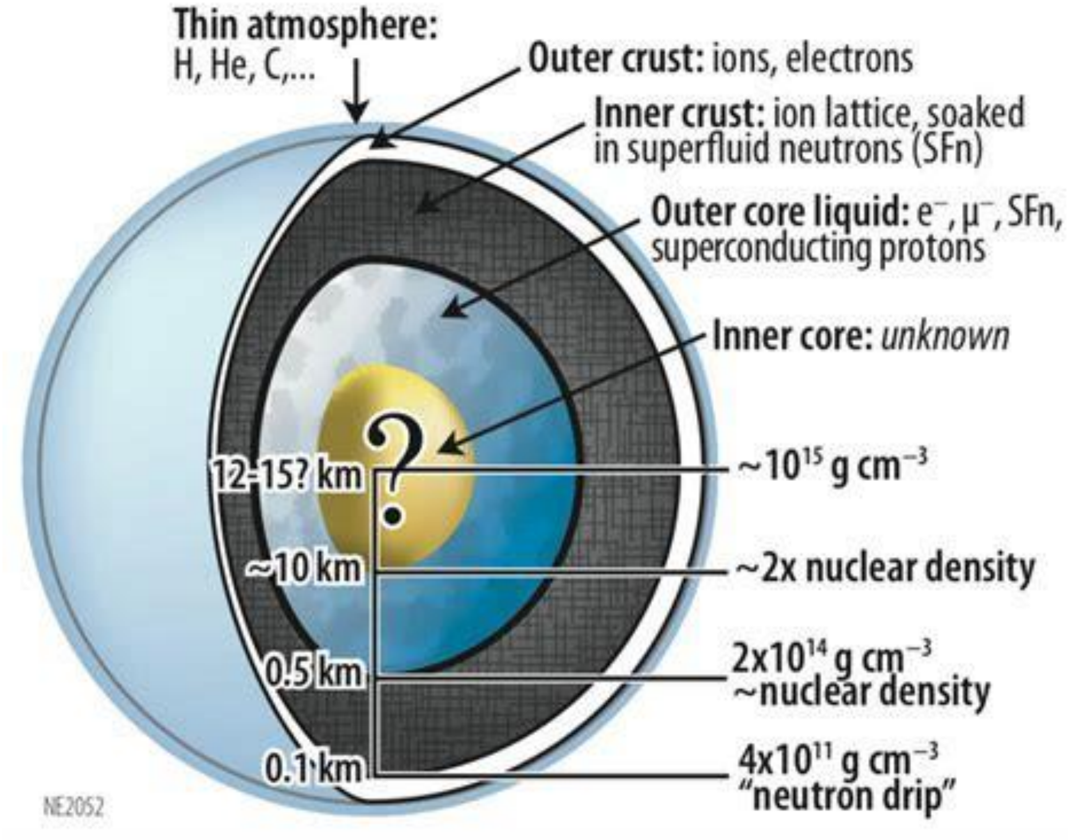
- Introduction
- GW from binary neutron star merger
- GW generation from nuclear/quark matter phase transition
- GW as a probe of the phase transition
- Summary&outlook

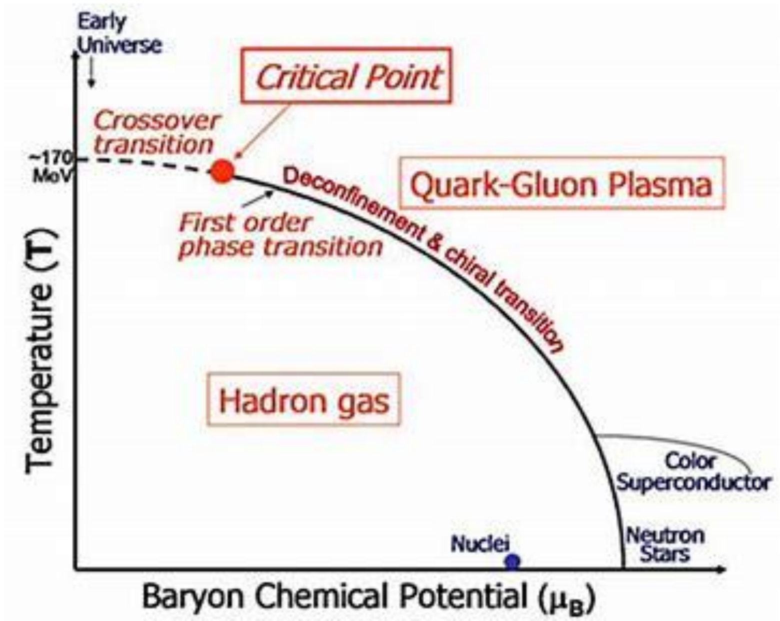
Equation of state of NS



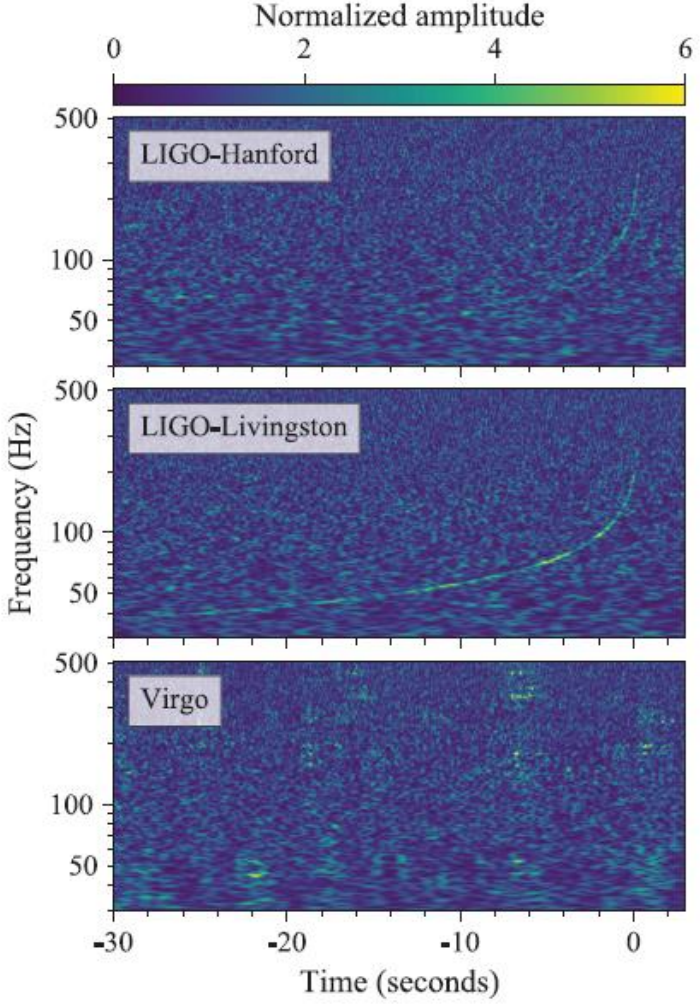
EOS of NS not accessible by first principle lattice simulation
A variety of phenomenological EOS exist

Possible quark matter in core of NS





GW radiation as a new messenger: NS merger



GW170817: first observation of GW signal from binary NS merger

GW frequencies: ~10-~100Hz

LIGO and Virgo: PRL 119, (2017)

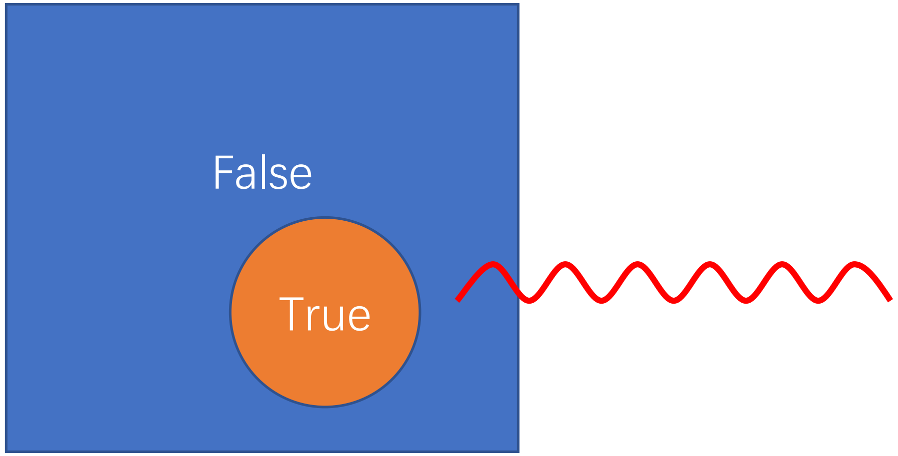
Constraining power of GW

Tidal deformability: Annala, Gorda, Kurkela, Vuorinen, PRL (2018)
Nuclear symmetry energy: Zhang, Li, **1807.07698**
Signature of quark matter phase: Most, Jens Papenfort, Dexheimer, Hanauske, Schramm, Stocker, Rezzolla, **1807.03684**

This work is about another source of GW radiation: phase transition itself

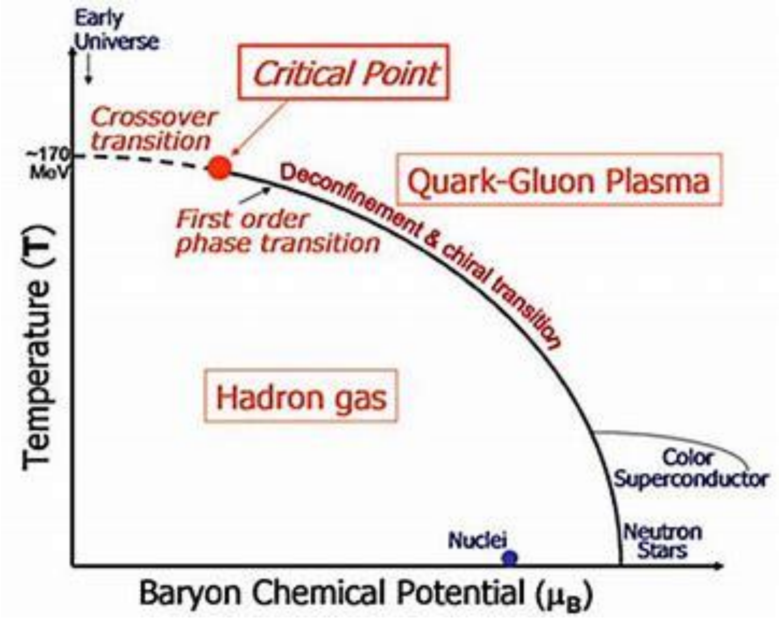
GW from phase transition in early universe

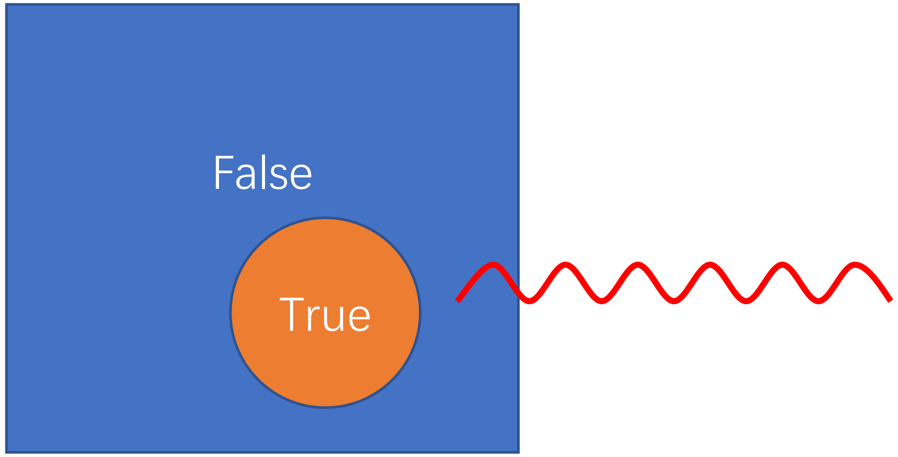
First order phase transition in early universe:
phase transition proceeds with nucleation of bubbles in supercooled phase



Kosowsky, Turner, Watkins, PRD (1992), PRL (1992)

GW from nuclear/quark matter phase transition





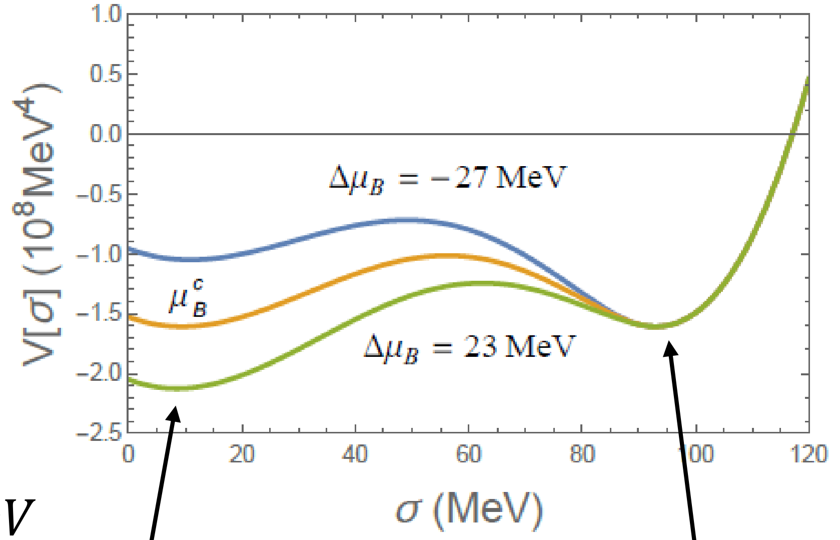
If nuclear/quark matter transition is first order, and over-compressed phase is realized, it also generates GW!

1810.00528, Gaoqing Cao, SL

Mechanism of GW generation in FPT

$$\mathcal{L}_{QM} = \frac{1}{2}\left[(\partial_\mu \sigma)^2 + (\partial_\mu \boldsymbol{\pi})^2\right] - \frac{\lambda}{4}\left(\sigma^2 + \boldsymbol{\pi}^2 - \upsilon^2\right)^2 + c\,\sigma$$
$$+ \bar{q}\left[i\partial\!\!\!/ + \frac{\mu_B}{N_c}\gamma^0 - g\left(\sigma + i\gamma^5 \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]q, \qquad (1)$$

Effective potential for σ



$\mu_B^c = 957MeV$

true vacuum(QM)

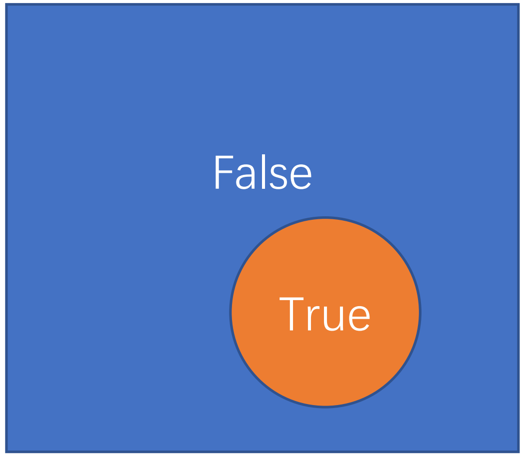
false vacuum(NM)

Over compression of NS by gravitational collapse at supernova explosion or afterward

part of energy released in the form of GW

Bubble nucleation in first order phase transition

Bubble nucleation in false vacuum: O(4) symmetric Euclidean solution



Coleman, PRD (1977)
Callan, Coleman, PRD (1977)

Probability of nucleation rate

$$\Gamma = A\frac{B^2}{4\pi^2}e^{-B}$$

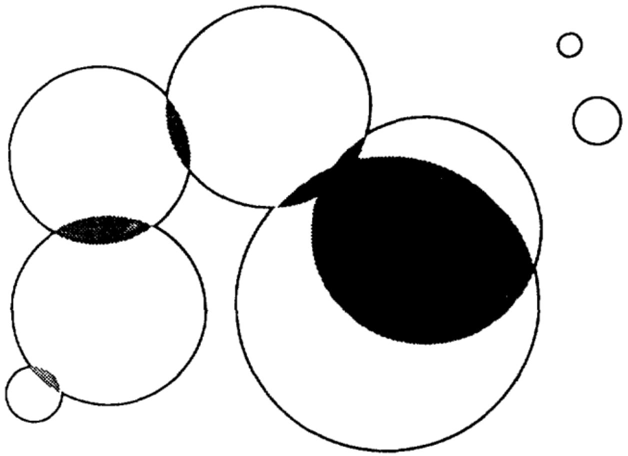
$$A = \left|\frac{\mathrm{Det}'(-\partial^2 + V''[\sigma_b])}{\mathrm{Det}(-\partial^2 + V''[\sigma_F])}\right|^{-1/2},$$

$$B = 2\pi^2\int_0^\infty \rho^3 d\rho\left\{\frac{1}{2}\left(\frac{d\sigma_b}{d\rho}\right)^2 + V[\sigma_b] - V[\sigma_F]\right\}$$

Bubble dynamics

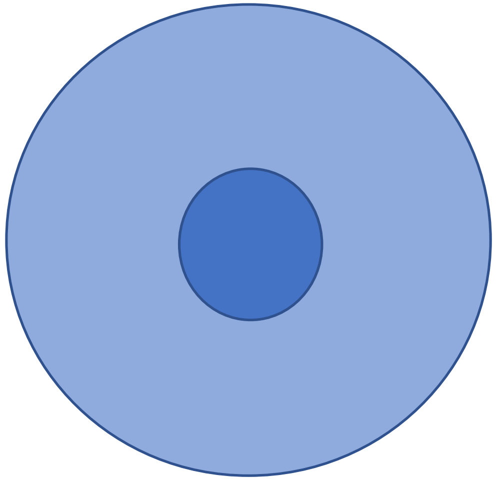
Bubbles expand classically and collide with each other, radiating GW.

$$T_{ij}(\hat{\mathbf{k}},\omega)=\frac{1}{2\pi}\int_0^{\infty}dte^{i\omega t}\int d^3x\partial_i\sigma\partial_j\sigma e^{-i\omega\hat{\mathbf{k}}\cdot\mathbf{x}}$$



Kosowsky, Turner, Watkins, PRD (1992), PRL (1992)
Kosowsky, Turner, PRD (1993)

Volume and duration of PT



Simple model of NS profile

$$\mu_B = \mu_{B1}\theta(R_c - r) + \mu_{B2}\theta(r - R_c)$$

$$\mu_{B1} > \mu_B^c \text{ and } \mu_{B2} < \mu_B^c.$$

$R_c = 1km$ (inner core of NS),
$T = R_c/c$ (expansion with speed of light)

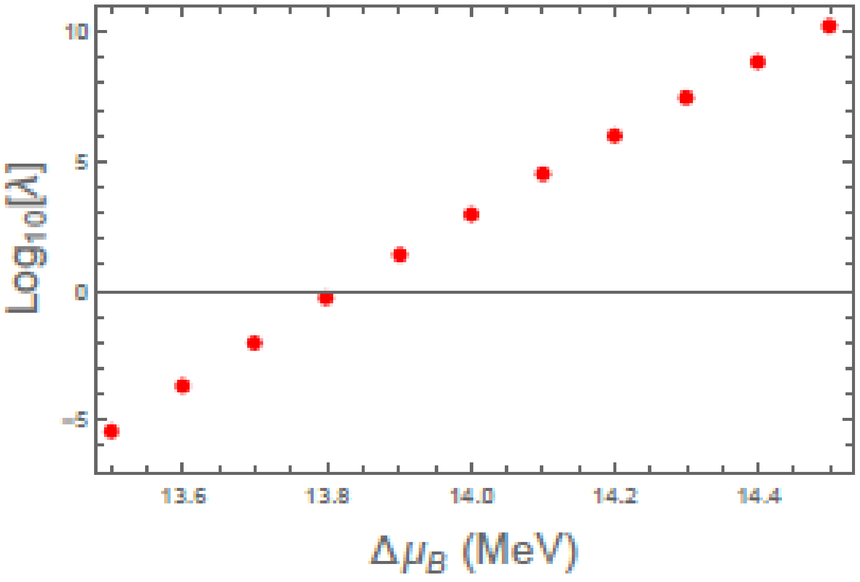
Nucleation rate

Bubble nucleation is random,
following Poisson distribution:

$$P(k) = e^{-\lambda}\frac{\lambda^k}{k!}$$

Guth, PRD (1981)

Average number of bubbles: $\lambda \equiv \Gamma V_c T$

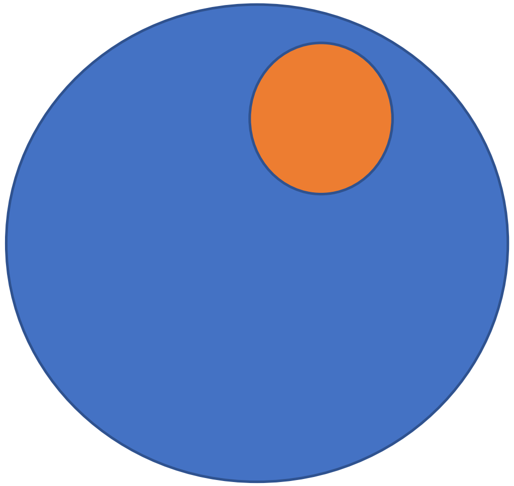


significant nucleation only for
$\Delta\mu_B \gtrsim 14MeV$

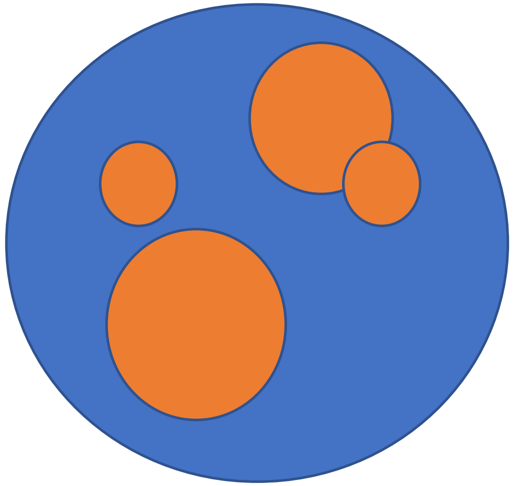
low nucleation rate favors for
over-compression

Scenarios of phase transition

Few-bubble scenario



Many-bubble scenario



Generic features of GW in NS phase transition

GW strain $$h_{ij}(t) = \frac{8G}{L}\mathrm{Re}\int_0^\infty d\omega\ e^{-i\omega(t-L)}\left[T_{ij} - \frac{g_{ij}}{2}T^\mu_\mu\right](\hat{\mathbf{k}},\omega)$$

GW energy spectrum $$\mathcal{E}^{+/\times}_{GW} = \frac{4G\omega^2}{\pi}\left|T_{+/\times}(\hat{\mathbf{k}},\omega)\right|^2 .$$

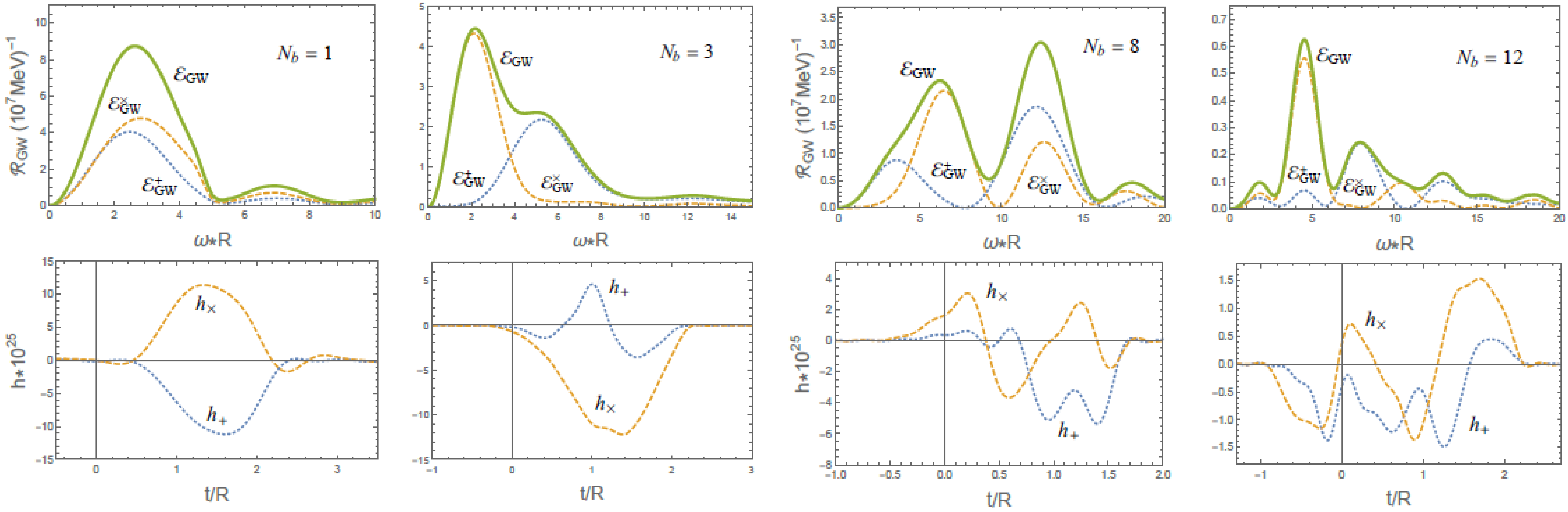
characteristic frequency of GW

$$\omega \sim \frac{2\pi}{T} = \frac{2\pi c}{R_c} \sim 6\pi \times 10^5 rad/s$$

duration of GW pulse

$$\Delta t \sim R_c/\mathrm{c}$$

Few-bubble vs Many-bubble



$L = 0.1$ Mpc

One-bubble case, two polarizations in phase

As number of bubbles increase, the strain and energy decreases, with the energy spectrum spans a wider region

Detectability of GW

Characteristic frequency $\omega \sim 6\pi \times 10^5 rad/s$ distinguishes from other sources

Strain $h \sim 10^{-25} - 10^{-24}$ for $L = 0.1Mpc$.
Larger strain for larger quark matter core and nearer NS

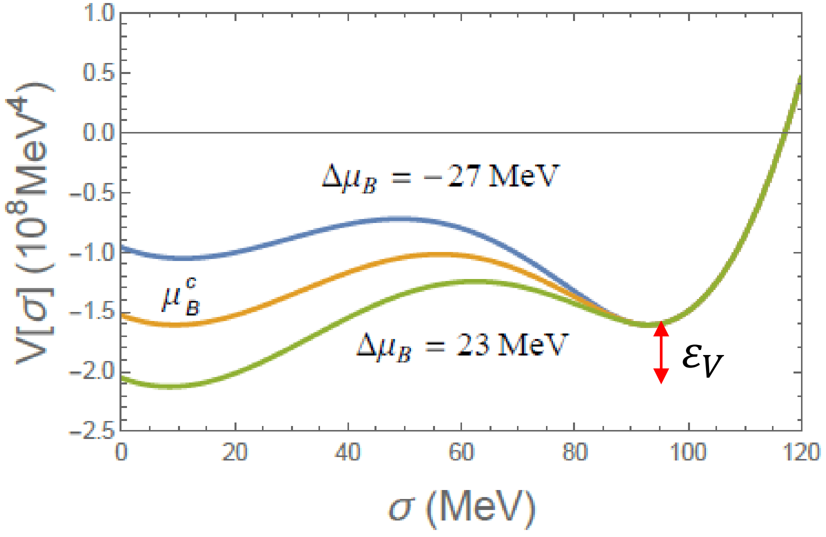
Damping rate of GW by outer nuclear matter core $\gamma \lesssim 8\pi G \frac{PR_{\mathrm{NM}}}{\omega} \sim 0.03$
GW can escape from the NS

Baym, Patilm Pethick, PRD (2017)

Summary & Outlook

GW from neutron star phase transition carries information about the transition:

- Order of phase transition
- Radius of quark matter core $R_c \sim 2\pi c/\omega$
- Latent energy density $\varepsilon_V \propto h$
- GW waveform implies scenario of bubble nucleation



- GW spectrum modification due to interaction (jet-medium interaction)
- EM radiation or neutrino radiation from phase transition?

Thank you!