Quark matter: the high-density frontier

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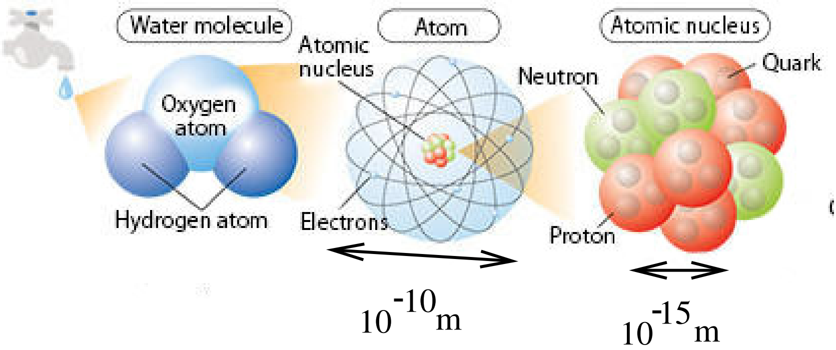
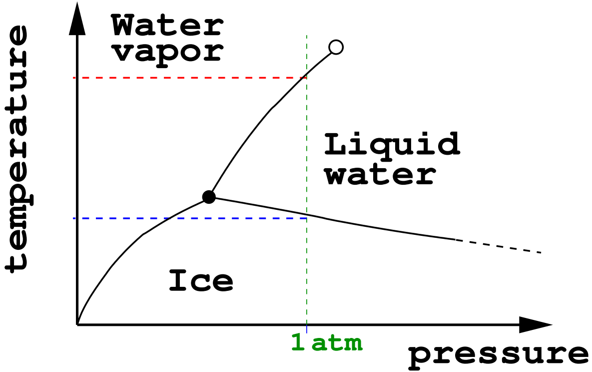
From atoms to quarks



Phase Transitions

When you heat up or compress matter, the atoms *reconfigure* themselves: Phase transitions between solid, liquid, and gas.



Phase transitions for neutrons, protons. . . quarks?

At super-high temperatures or densities, do *neutrons*, *protons*, or even *quarks* reconfigure themselves into different phases? YES!

$$\begin{aligned} T &\sim 150 \text{ MeV} &&\sim 10^{12} \text{ K} \\ \rho &\sim 300 \text{ MeV/fm}^3 &&\sim 10^{17} \text{ kg/m}^3 \end{aligned}$$

At such a density, a oil super-tanker is 1mm^3 in size.

Where might this occur?

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- early universe
- supernovas
- neutron stars
- neutron star mergers

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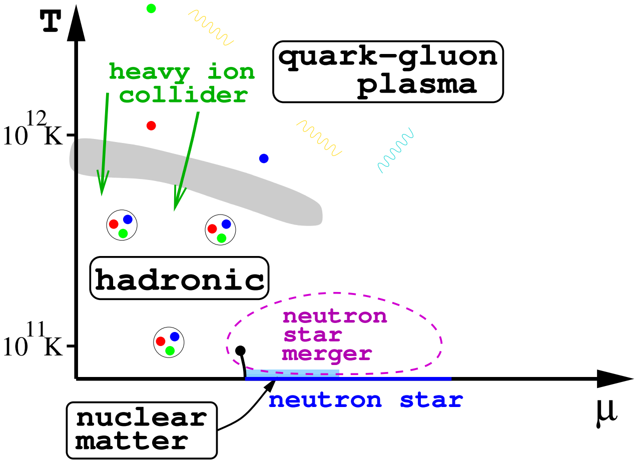
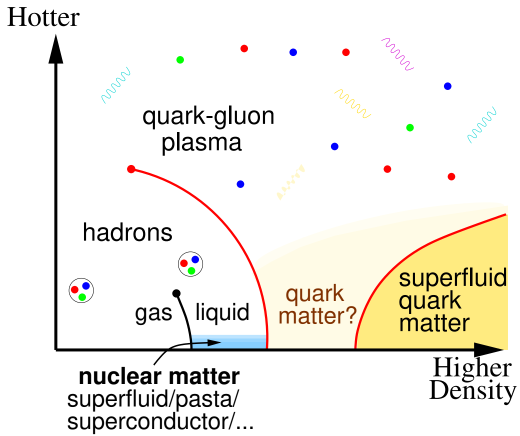
- Brookhaven, NY (RHIC)
- CERN, Switzerland (LHC)
- Darmstadt, Germany (FAIR)
- Michigan State Univ (FRIB)
- Tokai, Japan (J-PARC-HI)

Observed Phase diagram

according to a nuclear/particle physicist



Conjectured QCD Phase diagram



heavy ion collisions: deconfinement crossover and chiral critical point

neutron stars: quark matter core?

neutron star mergers: dynamics of warm and dense matter

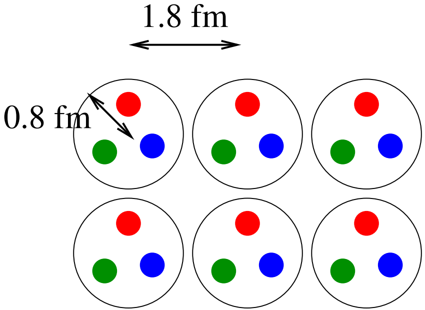
Quark matter at high density

Nuclear density

$$n_B \approx \frac{1}{(1.8\,\mathsf{fm})^3} = 0.17\,\mathsf{fm}^{-3}$$

Nucleons are distinguishable:

Nuclear Matter



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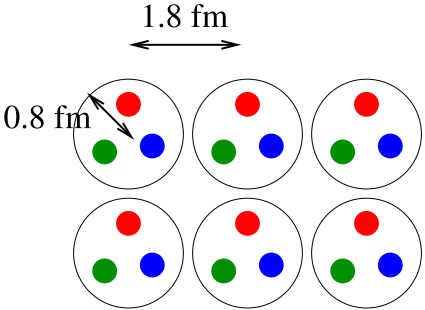
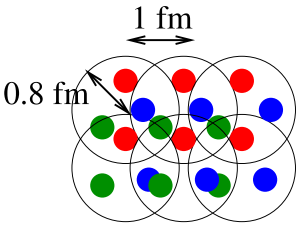


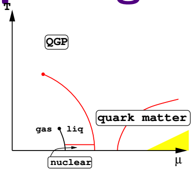
$6\ \times$ **Nuclear density**

$$n_B \approx \frac{1}{(1.0\,\mathsf{fm})^3} = 1.0\,\mathsf{fm}^{-3}$$

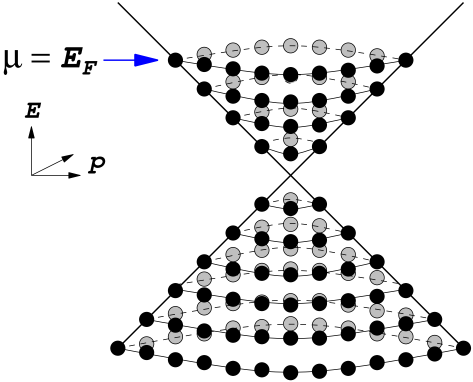
Not clear which nucleon
a given quark "belongs" to:
Quark Matter



Compressed Fermions: Cooper pairing



At sufficiently high density and low temperature, there is a Fermi sea of almost free quarks.



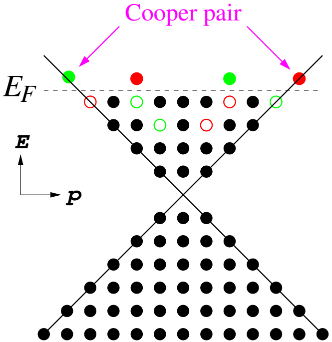
Non-interacting quarks:
Quark states up to the Fermi energy are all filled.

But in reality quarks have attractive QCD interactions. . .

Any attractive fermion-fermion interaction causes a rearrangement of the Fermi surface: a condensate of "Cooper pairs"

What is a condensate of Cooper pairs?

"BCS" pairing mechanism



Applies to *any* system of degenerate fermions with an attractive interaction:

— electrons in a cold metal
— ^{3}He atoms
— neutrons in nuclear matter
— quarks in quark matter

$$|BCS\rangle \propto \prod_{\substack{p>p_F \\ \text{particles}}} \left(1 + \sigma_{\mathbf{p}}\, a^\dagger_{\mathbf{p}} a^\dagger_{-\mathbf{p}}\right) \prod_{\substack{p<p_F \\ \text{holes}}} \left(1 + \rho_{\mathbf{p}}\, a_{\mathbf{p}} a_{-\mathbf{p}}\right) \left| \begin{matrix}\text{Fermi} \\ \text{sea}\end{matrix} \right\rangle$$

$|BCS\rangle$, not $|\text{Fermi sea}\rangle$, is the ground state.

Spontaneous Symmetry Breaking

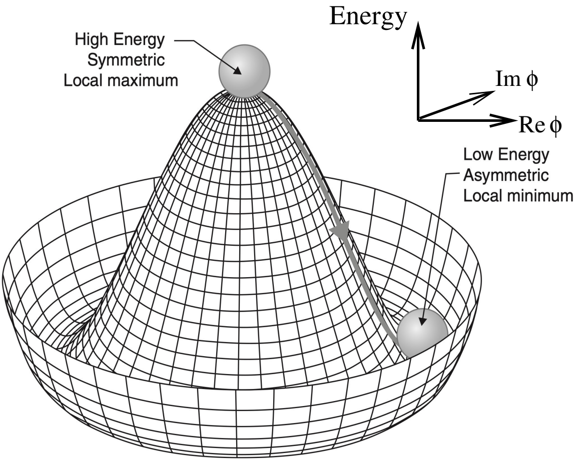
Fermion number is "spontaneously broken"

$$|BCS\rangle = |\text{Fermi sea}\rangle + |2\,\text{particles}\rangle + |4\,\text{particles}\rangle + \cdots$$
$$+ |2\,\text{holes}\rangle + |4\,\text{holes}\rangle + \cdots$$

- The ground state $|BCS\rangle$ is not an eigenstate of fermion number $\hat{N}|BCS\rangle \neq n|BCS\rangle$
- Excited states built on $|BCS\rangle$ are not eigenstates of fermion number.
- The dynamics still conserves fermion number, $[\hat{H}, \hat{N}] = 0$, so an eigenstate of $\hat{N}$ always remains an eigenstate, but the physical states aren't eigenstates, so this doesn't mean much.

  SSB $\sim$ GIGO (Garbage In, Garbage Out)
- The fermion-pair field $\phi \equiv \psi_{\boldsymbol{k}}\,\psi_{-\boldsymbol{k}}$ has an expectation value $\langle BCS|\,\psi_{\boldsymbol{k}}\,\psi_{-\boldsymbol{k}}\,|BCS\rangle \neq 0$

Spontaneous Symmetry Breaking



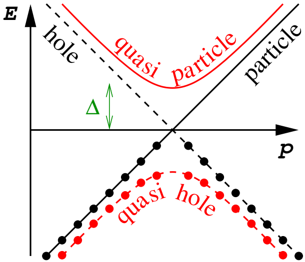
Physical consequences of Cooper pairing

Changes low energy excitations, affecting *transport properties*.

- Goldstone bosons: massless degrees of freedom arising from spontaneous breaking of **global** symmetries.
  Dominate low energy behavior, e.g.: Superfluidity
- Meissner effect: exclusion of magnetic fields arising from spontaneous breaking of **local (gauged)** symmetries.
  Massive gauge bosons, e.g.: Superconductivity
- Gap in fermion spectrum.
  Adding a fermion near the Fermi surface now costs energy because it disrupts the condensate.

$$a_p^\dagger(1 + \sigma\, a_p^\dagger a_{-p}^\dagger) = a_p^\dagger$$

Fermions frozen out of transport



Color superconducting phases

Attractive QCD interaction $\Rightarrow$ Cooper pairing of quarks.

Unlike electrons or neutrons, quarks have many ways to pair.

Quark Cooper pair: $\langle q^\alpha_{ia} q^\beta_{jb} \rangle$

color $\alpha, \beta = r, g, b$
flavor $i, j = u, d, s$
spin $a, b = \uparrow, \downarrow$

Each possible pairing pattern P is an 18×18 color-flavor-spin matrix

$$\langle q^\alpha_{ia} q^\beta_{jb} \rangle_{1PI} = \Delta_P \, P^{\alpha\beta}_{ij\,ab}$$

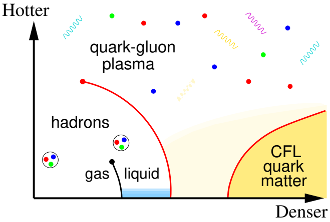
The attractive channel is:

color antisymmetric	[most attractive]
space symmetric	[s-wave pairing]
spin antisymmetric	[isotropic]
$\Rightarrow$ flavor antisymmetric	

We expect pairing between *different flavors*.

Three massless quark flavors

Valid at very high density $(E_F \gg m_s)$



Color-Flavor Locked (CFL) pairing

$$\langle q_i^\alpha q_j^\beta \rangle \sim \delta_i^\alpha \delta_j^\beta - \delta_j^\alpha \delta_i^\beta = \epsilon^{\alpha\beta n}\epsilon_{ijn}$$

$$\sim (rg - gr)(ud - du) + (gb - bg)(ds - sd) + (br - rb)(su - us)$$

As expected:

color antisymmetric [most attractive]
space symmetric [s-wave pairing]
spin antisymmetric [isotropic]
$\Rightarrow$ flavor antisymmetric

Color-flavor-locked quark matter

$$\langle q_i^\alpha q_j^\beta \rangle \sim \delta_i^\alpha \delta_j^\beta - \delta_j^\alpha \delta_i^\beta = \epsilon^{\alpha\beta n}\epsilon_{ijn} \sim \begin{array}{l} \quad (rg - gr)(ud - du) \\ + (gb - bg)(ds - sd) \\ + (br - rb)(su - us) \end{array}$$

This state is invariant under equal and opposite rotations of color and (vector) flavor

$$SU(3)_{\text{color}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\supset U(1)_Q} \times U(1)_B \to \underbrace{SU(3)_{C+L+R}}_{\supset U(1)_{\tilde{Q}}} \times \mathbb{Z}_2$$

- Breaks baryon conservation $\Rightarrow$ superfluid
- Breaks chiral symmetry, but *not* by a $\langle \bar{q} q \rangle$ condensate
- Unbroken "rotated" electromagnetism: photon-gluon mixture
- CFL quark matter is a Transparent superfluid insulator

Predicting the phase diagram

1. Choose a model of the strong interaction
   i.e., a Hamiltonian for the quarks
2. Guess a color-flavor-spin pairing pattern P, of size (gap) Δ_P
3. Using the model, calculate its free energy $\Omega(\Delta_P, \{\mu_i\}, T)$
4. Minimize the free energy with respect to the size of the P condensate, imposing color and electric neutrality

$$\frac{\partial\Omega}{\partial\Delta_P} = 0 \qquad \frac{\partial\Omega}{\partial\mu_i} = 0$$

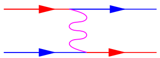
The pattern P with the lowest free energy wins!

NJL model gives $\Delta \sim 100$ MeV for CFL pairing pattern.

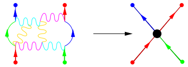
Modeling quark interactions

Lattice: "Sign problem"— oscillatory integral

pert: Applicable far beyond nuclear density.
Neglects confinement and instantons.



NJL: Semi-quantitative model
Very widely used.

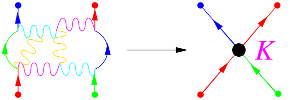


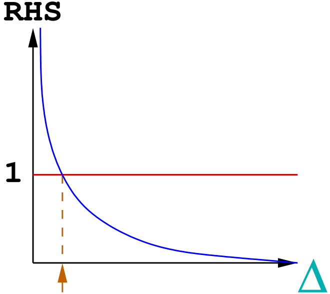
large N_{color}: Quarkyonic phase?

Holography: AdS/QCD "Gravity dual" for large N_{color} SUSY theories

EFT: Effective field theory for lightest degrees of freedom.
"Parameterization of our ignorance": assume a phase, guess coefficients of interaction terms (or match to pert theory), obtain phenomenology.

Gap equation in a simple NJL model





Minimize free energy wrt Δ:

$$1 \;=\; \frac{8K}{\pi^2}\int_0^{\Lambda} p^2 dp \left\{ \frac{1}{\sqrt{\Delta^2 + (p-\mu)^2}} \right\}$$

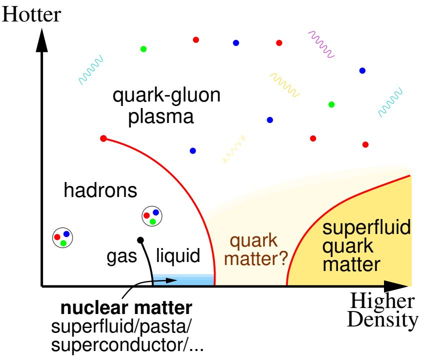
Note BCS divergence as $\Delta \to 0$: there is *always* a solution, for any interaction strength K and chemical potential μ.

$$1 \;\sim\; K\mu^2 \ln\left(\Lambda/\Delta\right)$$
$$\Rightarrow \Delta \;\sim\; \Lambda \exp\left(-\frac{1}{K\mu^2}\right)$$

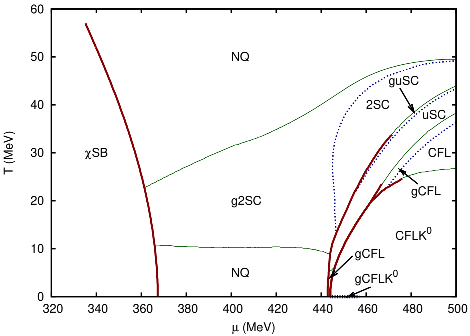
Superconducting gap is non-perturbative

Phases of quark matter, again

Conjectured phase diagram



NJL model, uniform phases only



Basler & Buballa, arXiv:0912.3411

There are also non-uniform phases, such as the crystalline ("LOFF"/"FFLO") phase.

Signatures of quark matter in compact stars

Observable	←	Microphysical properties (and neutron star structure)	← Phases of dense matter

	Property	Nuclear phase	Quark phase
mass, radius	eqn of state $\varepsilon(p)$	known up to $\sim n_{\rm sat}$	unknown; many models

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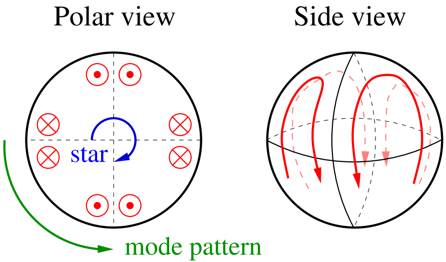
Observable ← Microphysical properties (and neutron star structure) ← Phases of dense matter

Observable	Property	Nuclear phase	Quark phase
mass, radius	eqn of state $\varepsilon(p)$	known up to $\sim n_{\text{sat}}$	unknown; many models
cooling (temp, age)	heat capacity neutrino emissivity thermal cond.	Depends on phase: $n\,p\,e,\mu$ $n\,p\,e,\mu,\Lambda,\Sigma^-$ n superfluid p supercond π condensate	Depends on phase: unpaired CFL CFL-K^0 2SC CSL LOFF 1SC …
spindown (spin freq, age)	bulk viscosity shear viscosity		
glitches (superfluid, crystal)	shear modulus vortex pinning energy		
mergers (grav waves, kilonova)	EoS, bulk visc, neutrino transport		

r-modes and gravitational spin-down

An r-mode is a quadrupole flow that emits gravitational radiation.

It becomes unstable (i.e. arises spontaneously) when a star spins fast enough, and if the shear and bulk viscosity are low enough.

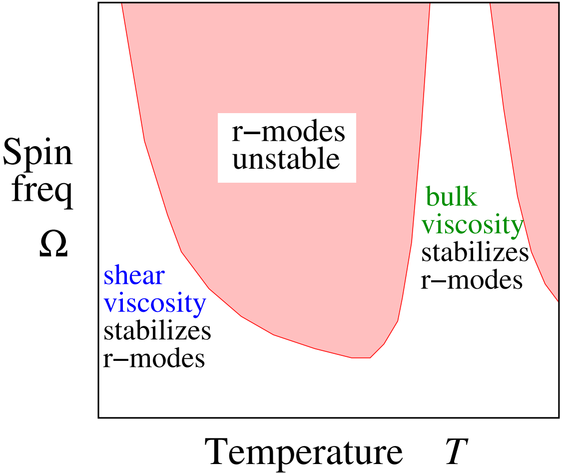


The unstable r-mode can spin the star down very quickly, in a few days if the amplitude is large enough

a neutron star spins quickly	$\Rightarrow$	some interior physics must be damping the r-modes

Predicted r-mode instability region

for nuclear matter



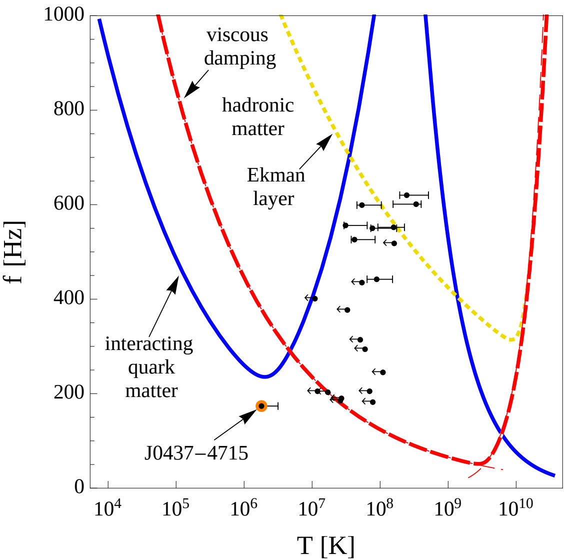
Shear viscosity grows at low T (long mean free paths).

Bulk viscosity has a resonant peak when beta equilibration rate matches r-mode frequency

- Instability region depends on viscosity of star's interior.
- Behavior of stars inside instability region depends on saturation amplitude of r-mode.

Spindown of old neutron stars

Above curves, r-modes go unstable and spin down the star



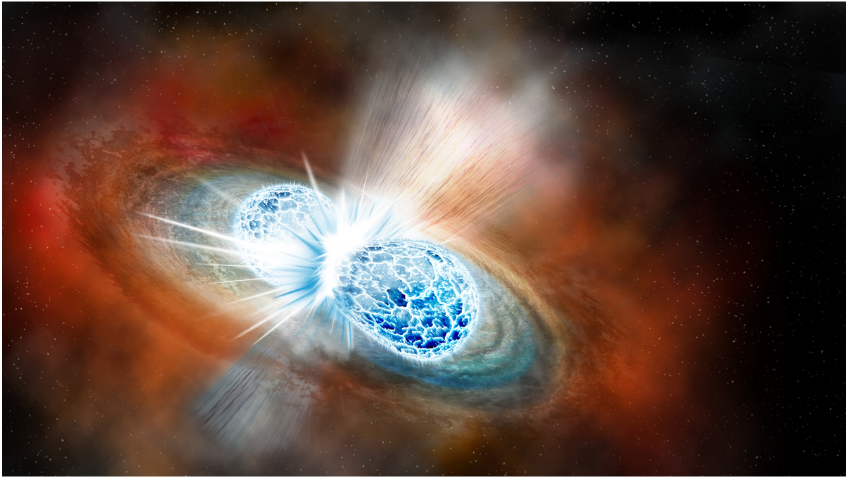
Data for accreting pulsars in binary systems (LMXBs) vs instability curves for nuclear and hybrid stars.

There are stars in the “forbidden” region for nuclear matter!

Possibilities:

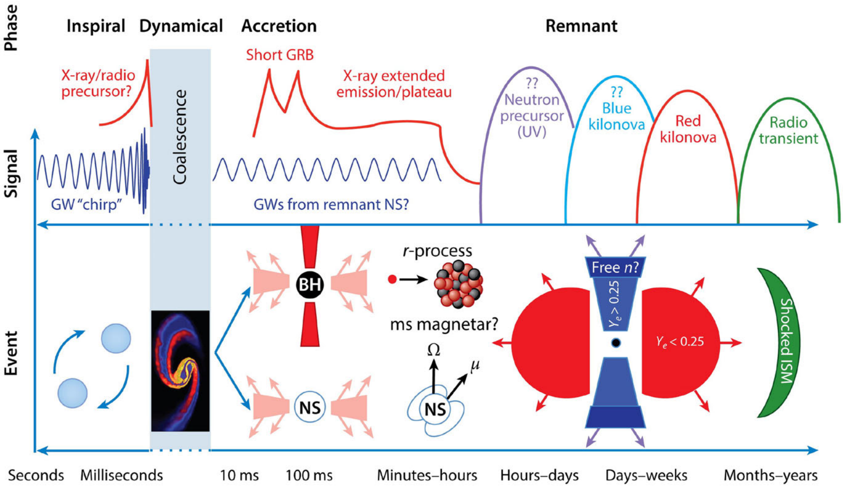
- additional damping (e.g. quark matter)
- r-mode spindown is very slow (small $\alpha_{\rm sat}$)

Neutron star mergers



Probes properties of ultra-dense and hot matter on the millisecond timescale

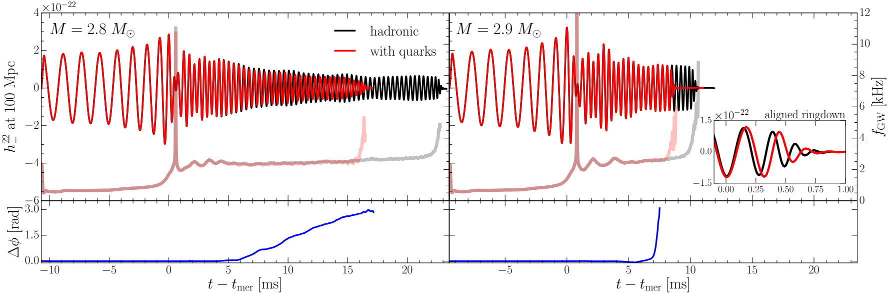
Mergers: observable phenomena



Burns, arXiv:1909.06085

Need accurate simulations connecting microphysics to signatures

Predicting gravitational waves from a phase transition



Most et. al., arXiv:1807.03684

solid lines: grav wave strain; translucent lines: instantaneous freq

Also potentially important: **Out-of-equilibrium phenomena**

- Flavor equilibration — bulk viscosity
- Thermal equilibration — thermal conductivity
- Shear flow equilibration — shear viscosity
- Neutrino equilibration — long-range transport

Looking to the future

What do we need to detect quark matter in neutron star cores??

- More data on observable properties of neutron stars:
  - mass and radius
  - spindown (spin and age); glitches
  - cooling (temperature, age, and mass!)
  - Gravitational and electromagnetic signals from mergers
- Better modeling of neutron stars and mergers:
  - merger simulations: phase transitions, transport/dissipation
  - mechanism of glitches, other phenomena?
  - astrophysical damping and saturation mechanisms for r-modes
- Understand high-density matter
  - medium-density phases of quark matter: crystalline or. . . ?
  - better approx to QCD: Functional RG, Schwinger-Dyson
  - solve the sign problem and do lattice QCD at high density.