COLD, DENSE,

(but not asymptotically dense)

QUARK MATTER:

PUZZLES AND HINTS

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NEUTRON STARS AT THE CROSSROADS
OF FUNDAMENTAL PHYSICS,
VANCOUVER, 10/8/2005

WHAT IS QCD?

A theory of quarks and gluons ....

WHAT DOES QCD DESCRIBE

Colorless, heavy, hadrons...

Hadrons are the (rather complicate[d]) quasi-particles of the QCD vacuum.

The vacuum, whose excitations are the hadrons, is therefore quite a nontrivial [confinement; chiral symmetry breaking; strong coupling; ...] phase of the theo[ry]

BUT: QCD is asymptotically free ....

DO OTHER (SIMPLER?) PHASES EXIST

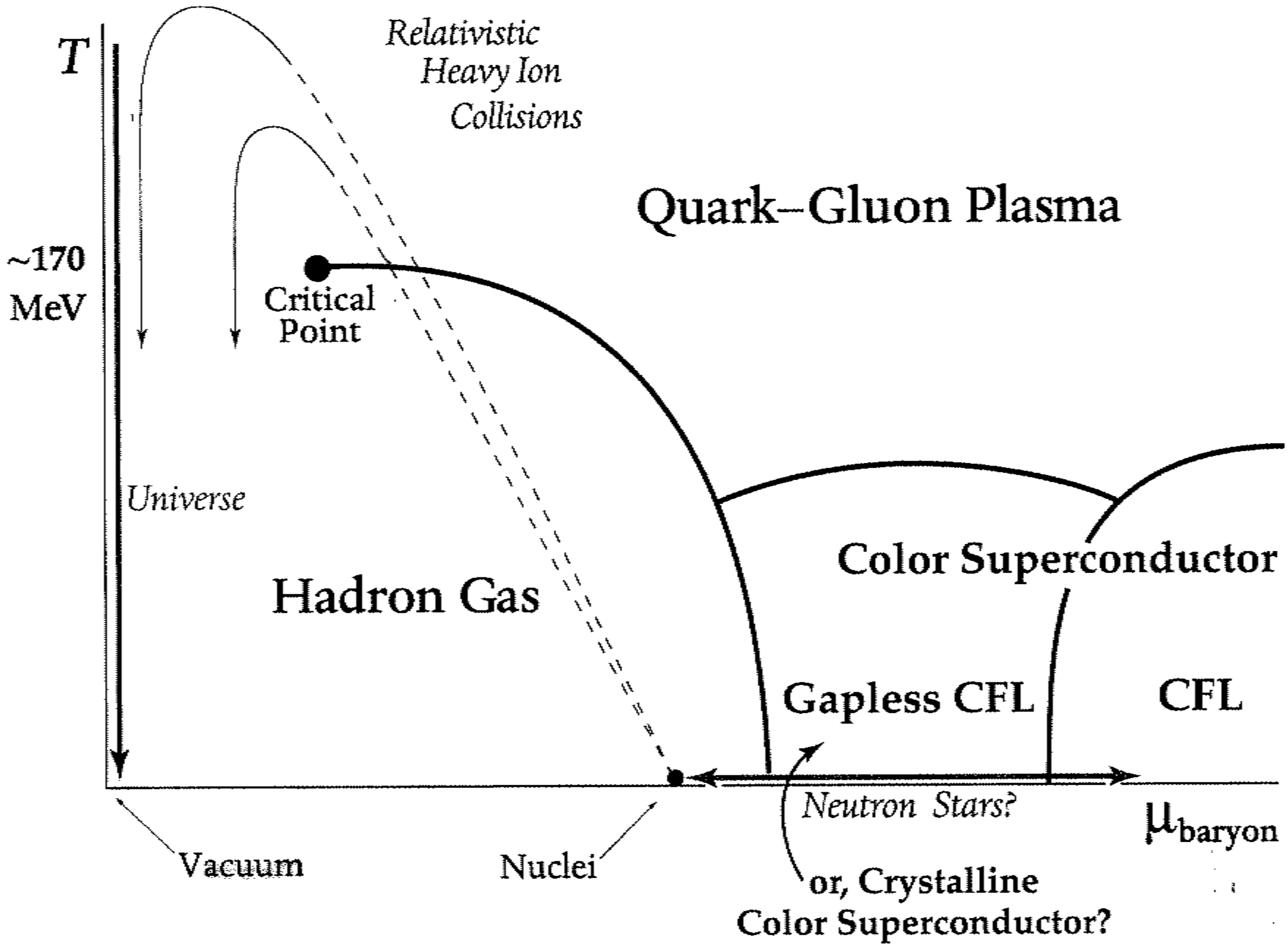
Do other phases exist whose quasiparticles look more like the quarks and gluons of the QCD Lagrangian? And look more like phases familiar from QED?

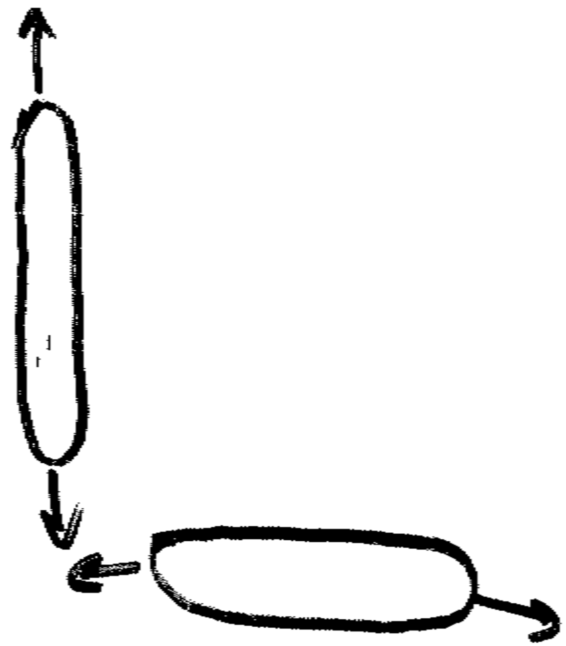
Asymptotic freedom: quarks and gluons weakly interacting
i) when close together
ii) when interact at large momentum.

Suggests look at high density or high temperature.

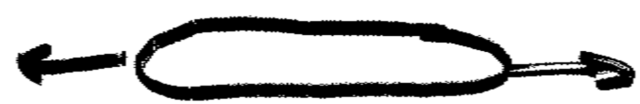
NB: condensed matter physics teaches us that phases may be far from simple even for α as small as $\frac{1}{137}$

EXPLORING *the* PHASES *of* QCD





THE "IN-BETWEEN REGIONS":
PUZZLES & HINTS,
AND ∴ INTERESTING



HIGH DENSITY + LOW TEMPERATURE

Whereas at high T entropy wins

→ quark-gluon plasma with symmetri[es] of QCD Lagrangian manifest

At large μ with small T we find quark matter with new patterns of order:

- Color superconductivity
- Color-Flavor Locking
- Crystalline Color Superconductivity

⋮

- At large enough μ (to be defined below) we have <u>answers</u>.
- At large but notso large μ, we have a <u>puzzle</u>, and <u>hints</u>.
- How can we use astrophysical observations of compact stars to provide answers?

WHY COLOR SUPERCONDUCTIVITY

Large $\mu \rightarrow$ quarks filling Fermi sea up to a large Fermi energy. (E_F)

asymptotic freedom $\rightarrow$ weak interactions between quarks at Fermi surface.

BUT any attractive interaction, no matter how weak, $\rightarrow$ COOPER PAIRS ; $\langle qq \rangle$

One gluon exchange (& instanton interaction) attractive in color $\bar{3}$.

(no need to resort to phonons; ∴ superconductivity more robust in QCD than in metals. Higher T_c/E_F.)

$\langle qq \rangle$, ie Cooper pairs of quarks,

⇒ - electric & color currents supercond.

- mass for photon & (some) gluons
- Meissner effects. (Magnetic & color magnetic fields excluded.

GAP AND T_c

Much work (that I will not review)

suggests that @ $\mu_q \sim 500$ MeV [$\sim 10 \times$ nuclear density]

$$\Delta \lesssim 100 \text{ MeV}$$

$$T_c \lesssim 50 \text{ MeV}$$

Note: $T_c / E_F \sim 1/10 \Rightarrow$ THIS is high T_c s.c.!

Two classes of methods $\sim$ agree:

i) models normalized to $\mu = 0$ physics

(Alford, K.R., Wilczek, Rapp, Schäfer, Shuryak, Velkovsky, Berges, Carter, Diakonov, Evans, Hsu, Schwetz, ...

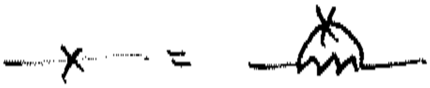
ii) weak-coupling QCD calculations, valid for $\mu \to \infty$; $g \to 0$. (Quantitatively, valid for $g \lesssim 1$ which means $\mu \gtrsim 10^9$ MeV K.R., Shuster

$$\frac{\Delta}{\mu} \sim \underbrace{256 \pi^4 e^{-\frac{\pi^2+4}{8}} \left(\frac{N_f}{2}\right)^{5/2}}_{} \underbrace{\frac{1}{g^5}}_{} \exp\left(-\frac{3\pi^2}{\sqrt{2}\, g}\right)$$

Schaefer, Wilczek; Pisarski, Rischke; Hong, Miransky, Shovkovy, Wijewardhana; Evans, Hsu, Schwetz; Brown, Liu, Ren; Beane, Bedaque, Savage; K.R., Shuster; Rischke, Wang; ...

Son

$\Delta \sim \exp(-1/g)$ comes from divergence in small angle scattering via exchange of unscreened magnetic gluons:

 $\rightarrow 1 = g^2 \underbrace{\ln \frac{\Delta}{\mu}}_{} \underbrace{\ln \frac{\Delta}{\mu}}_{}$

CFL

In cold quark matter, quarks near their Fermi surfaces pair

→ color superconductivity

Pattern of pairing:

$$\langle \psi^{\alpha}_{a} \, C\gamma_5 \, \psi^{\beta}_{b} \rangle \sim \Delta_1 \epsilon^{\alpha\beta 1} \epsilon_{ab1} + \Delta_2 \epsilon^{\alpha\beta 2} \epsilon_{ab2} + \Delta_3 \epsilon^{\alpha\beta 3} \epsilon_{a}$$

(β ← color; a ← flavor; $C\gamma_5$: Lorentz scalar)

- antisymmetry in color + Dirac indices energetically favored; flavor antisym. forced by Pauli
- If density great enough that M_s can be neglected, $\Delta_1 = \Delta_2 \simeq \Delta_3$
- All 9 quarks pair, maximizing condensation energy; leaves largest symmetry unbroken
- Demonstrated rigorously at asymptotic density.
- unbroken summetries all are color + flavo

	ru	gd	bs	rd	gu	bu	rs	gs	bd
ru		$-\Delta_3$	$-\Delta_2$						
gd	$-\Delta_3$		$-\Delta_1$						
bs	$-\Delta_2$	$-\Delta_1$							
rd					Δ_3				
gu				Δ_3					
bu							Δ_2		
rs						Δ_2			
gs									Δ_1
bd								Δ_1	

Define

$$\tilde{Q} = \begin{pmatrix} 2/3 \\ -1/3 \\ -1/3 \end{pmatrix} \text{for} \begin{matrix} u \\ d \\ s \end{matrix} + \begin{pmatrix} -2/3 \\ 1/3 \\ 1/3 \end{pmatrix} \text{for} \begin{matrix} r \\ g \\ b \end{matrix}$$

and check $\tilde{Q} = 0$ for every pair in the condensate.

$\Rightarrow$ One linear combination of photon & gluon does <u>not</u> get "Meissnered".

$$U(1)_{EM} \times SU(3)_{color} \rightarrow U(1)_{\tilde{Q}}$$

COLOR-FLAVOR LOCKED QUARK MATTER

- occurs for $\mu \to \infty$, and at any μ if $m_s = m_u = m_d$
- all 9 quarks pair and are gapped
- superfluid
- chiral symmetry spontaneously broken, by a new mechanism (CFL).
  - ⇒ "pions" and "kaons" lightest excitations
    - massless if $m_s = m_u = m_d = 0$
    - ~ few MeV mass ($\ll \Delta$) for real $m_{s,u,d}$.
    - "K_0" may condense
- Unbroken gauged $\tilde{U}(1)$ ⇒ massless photon
- As long as $T <$ meson masses ~ few MeV:
  - Transparent insulator (neutral without electrons) and reflection/refraction
    - index of refraction and reflection/refraction coefficients known
  - Very small specific heat, neutrino emissivity, viscosity. Good thermal conduct
- All these properties, and more, rigorously calculable in $\mu \to \infty$, $g \to 0$ limit. Chiral symmetry breaking and all its consequences understood at high density.
- Occurs in nature wherever $\mu > M_s^2 / 2\Delta$. (density dependent)
- What are the properties of quark matter at lower density???

WHAT CAN BE CALCULATED?

from QCD from first principles?

- At asymptotic densities, answer is "everything"; more than in any other circumstance in QCD.
  - in the CFL phase, there are no unresolved nonperturbative ambiguities: no gapless fermions; no massless gluons. No IR difficult
  - calculation of Δ is nonperturbativ but controlled by smallness of g.
  - analogues of confinement and chiral symmetry breaking are calculable at weak coupling.

- At potentially accessible densities, g not small. Means Δ cannot be calculated precisely (barring a major lattice QCD breakthrough.)

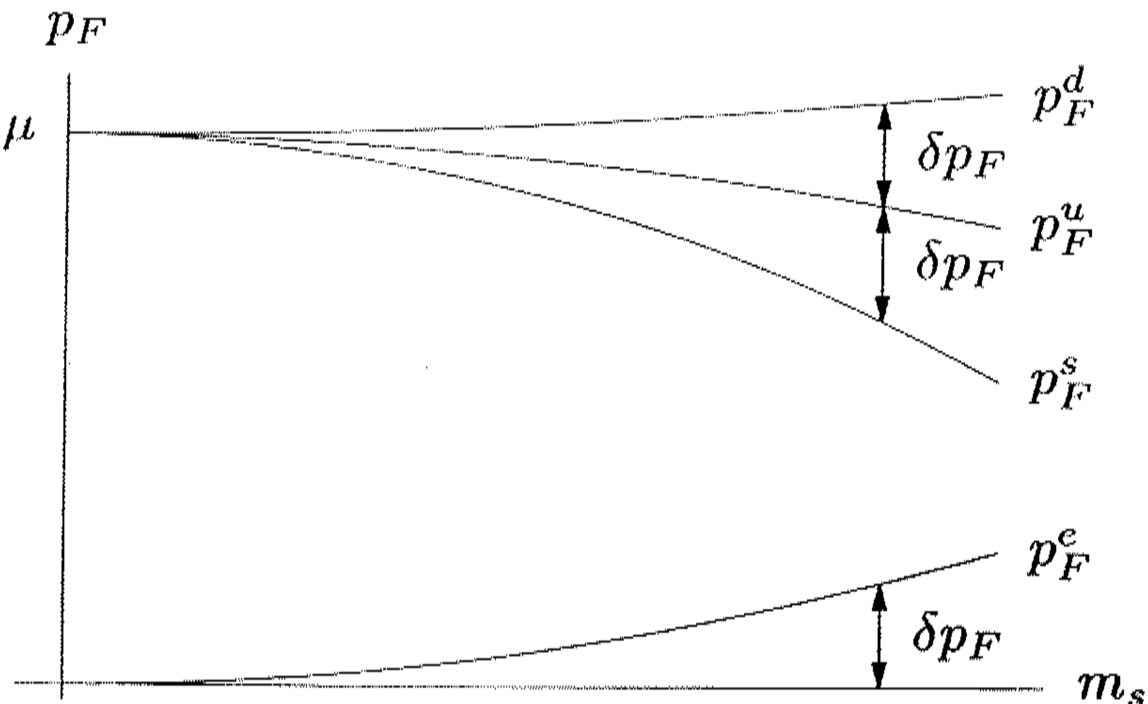
BUT: if you take Δ as given (ie treat as a parameter whose value known at order of magnitude level) then <u>many</u> physical properties calculable in terms of Δ.

Eg: specific heat, thermal conductivity, index of refraction, neutrino opacity, neutrino emissivity, shear viscosity, bulk viscosity, ...

[Many of these described within an effective field theory for the Goldstone bosons, whose parameters are determined by Δ.]

INTERMEDIATE DENSITY QUARK MATT.

- M_s important
- For orientation, consider noninteracting quarks, $M_u = M_d = 0$ $M_s \neq 0$, impose electrical neutrality and weak eqbm:



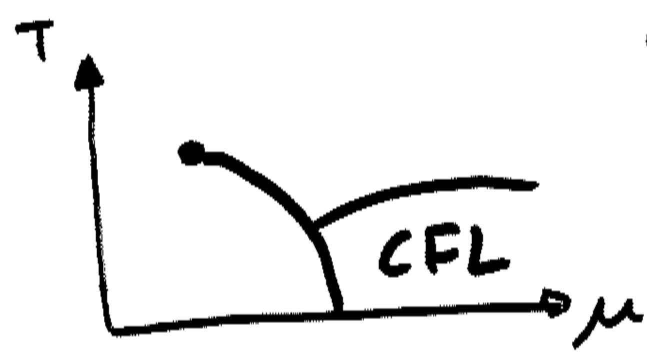
- In noninteracting quark matter, $\delta p_F \simeq \frac{M_s^2}{4\mu}$
- Motivates result that CFL pairing "breaks" when $\frac{M_s^2}{4\mu} > \Delta$??
- Also, when CFL "breaks", no residual $\langle ud \rangle$ pairing either. Alford, KR

WHAT REPLACES CFL, AT LOWER μ?

We don't yet know.....

We do know:

- CFL pairing is unstable once $\mu < \frac{M}{2\ldots}$
  (Alford Kouvaris KR)
  and stable for larger μ.
- ∴ If Δ large enough & M_s not too large, CFL quark matter is stable all the way down to transition to nuclear matter.



eg: $M_s = 300$ MeV
$\Delta > 125$ MeV
or
$M_s = 200$ MeV
$\Delta > 55$ MeV

QUESTIONS:

What if less symmetrically paired quark matter intervenes? Ie, what are properties of quark matter with $\mu < M_s^2/2\Delta$?

What are astrophysical consequences if neutron stars have CFL cores?

LESS SYMMETRICALLY PAIRED Q.M.

Gapless CFL Phase?

- 2nd highest density phase within a spatially uniform ansatz
- nice distinctive astrophysical signature (Alford Jotwani Kouvaris Kundu
- unstable to currents → inhomogeneit (Huang Shovkovy; Casalbuoni et al; Giannakis Ren Fukushima)

Crystalline Color Superconductivity?

- may be the answer, but:
- prior to last week, analyzed only in 2-flavor setting, without imposing neutrality
- potential for astrophysical signatures, (Alford, Bowers, KR) but not yet analyzed sufficiently to say how distinctive

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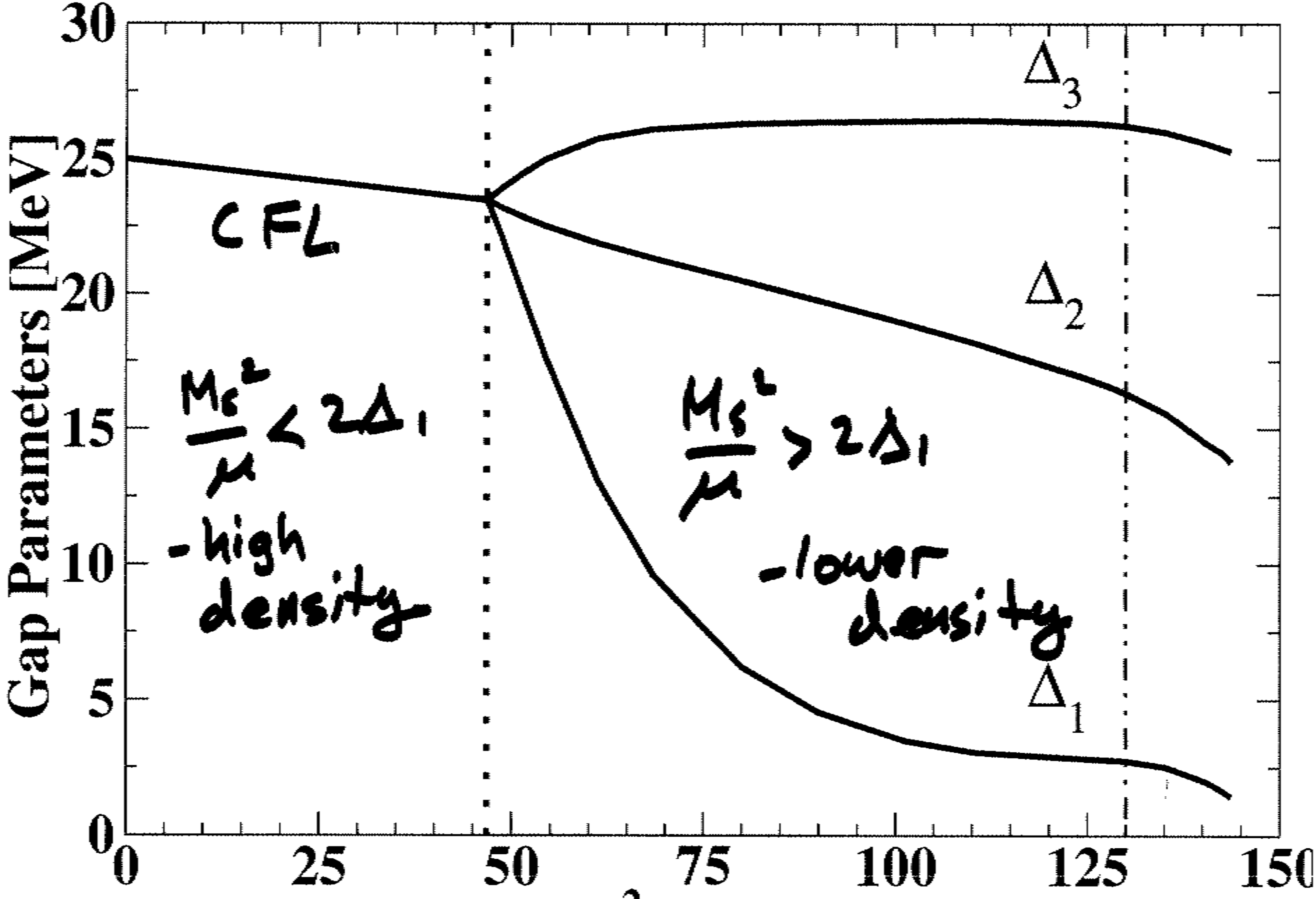
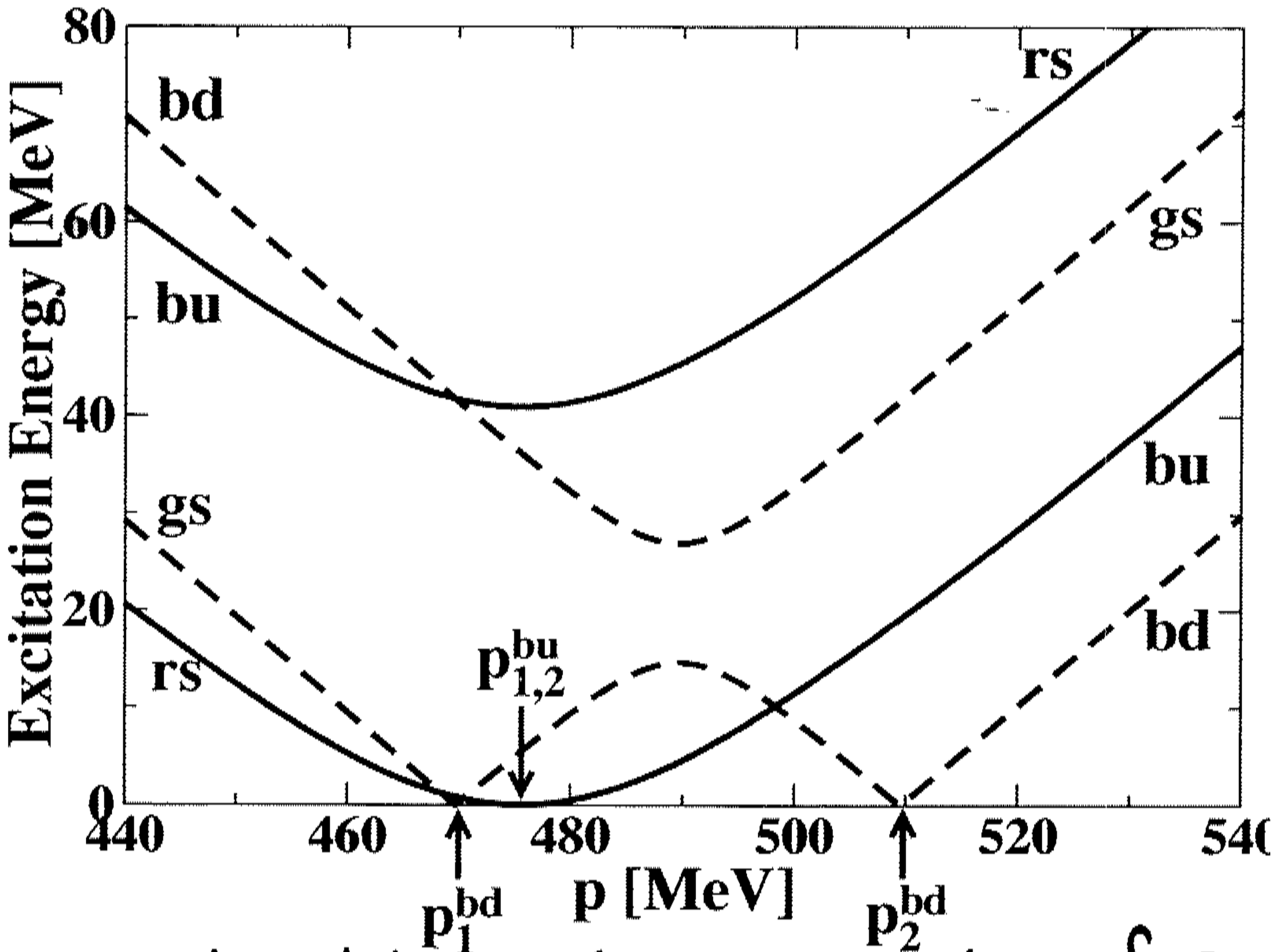
THE GAPLESS CFL PHASE

- All 9 quarks still pair, with same partners as before. BUT:
  - $\Delta_1 < \Delta_2 < \Delta_3$
  - there are shells in momentum space containing unpaired quarks
    Eg: for some momenta, find bd quarks with no gs (sb quarks) with which to pair.
    - bd - gs pairing disrupted; Fermi surfaces split.
  - Nonzero density of electrons needed to maintain neutrality
  - CFL → gCFL transition is an insulator → conductor transition, 2nd order at T=0 and crossover at T>0.



We shall see that this phase
Same unbroken U(1)

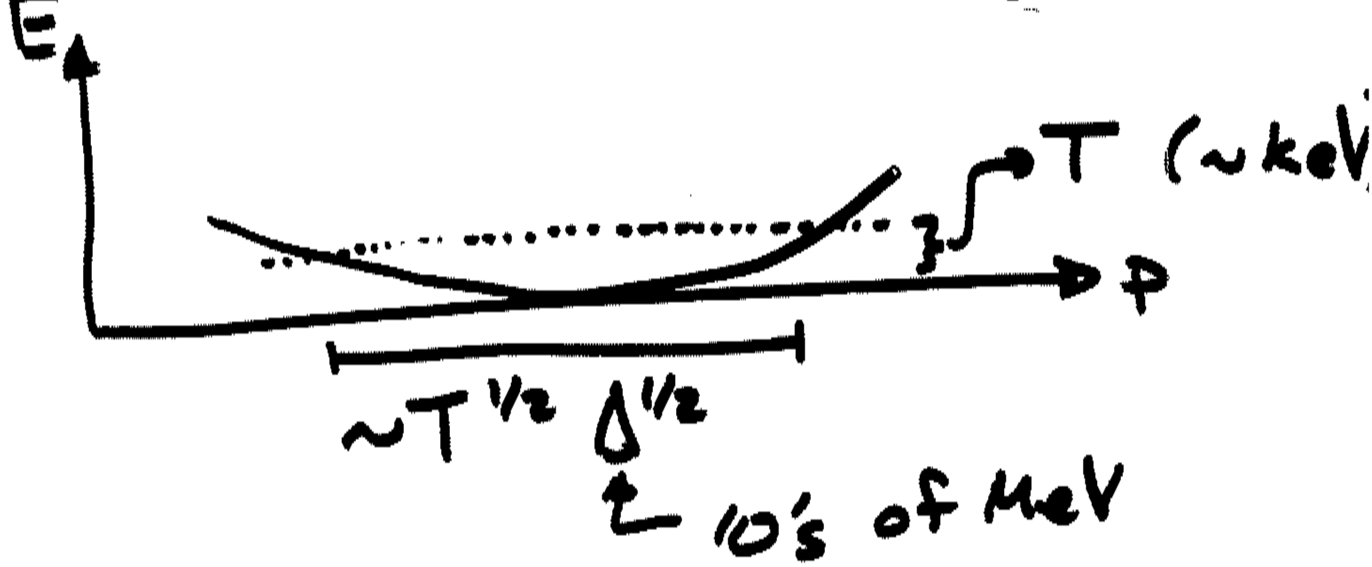
gCFL DISPERSION RELATIONS



- conventional linear dispersion relations for gapless fermions at two momenta (with unpaired quarks between these momenta
- unconventional "grazing" dispersion relation practically quadratic, at a third momentum
  - characteristic of and unique to gCFL
  - due to the way electric neutrality is maintained, not due to any fine tuning
  - and, has consequences....

CONSEQUENCES OF A "GRAZING" DISPERSION RELATION

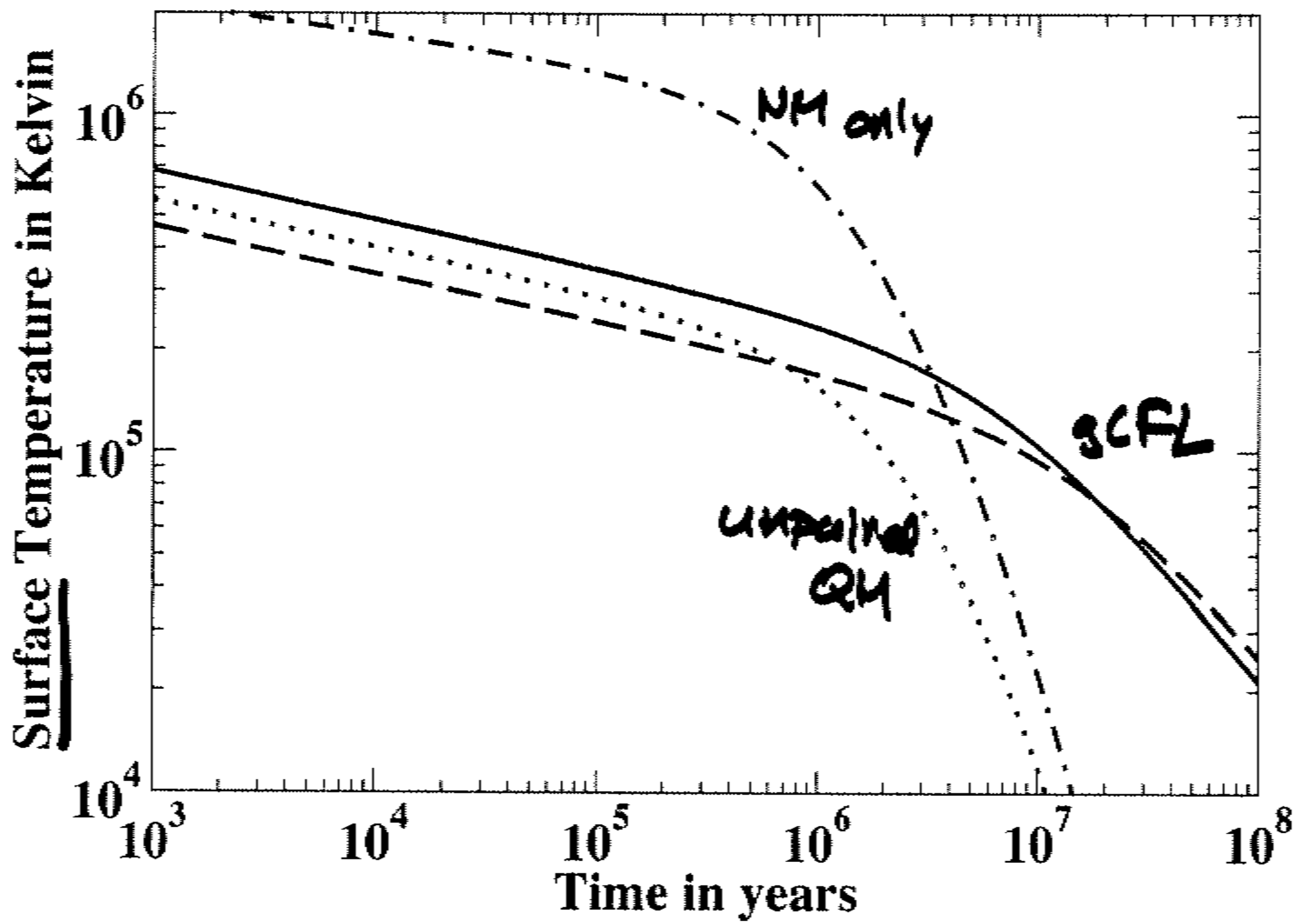
Alford Jotwani Kouvaris Kundu K...



$\Rightarrow C_V \sim P_F^2 T^{1/2} \Delta^{1/2} \gg P_F^2 T$

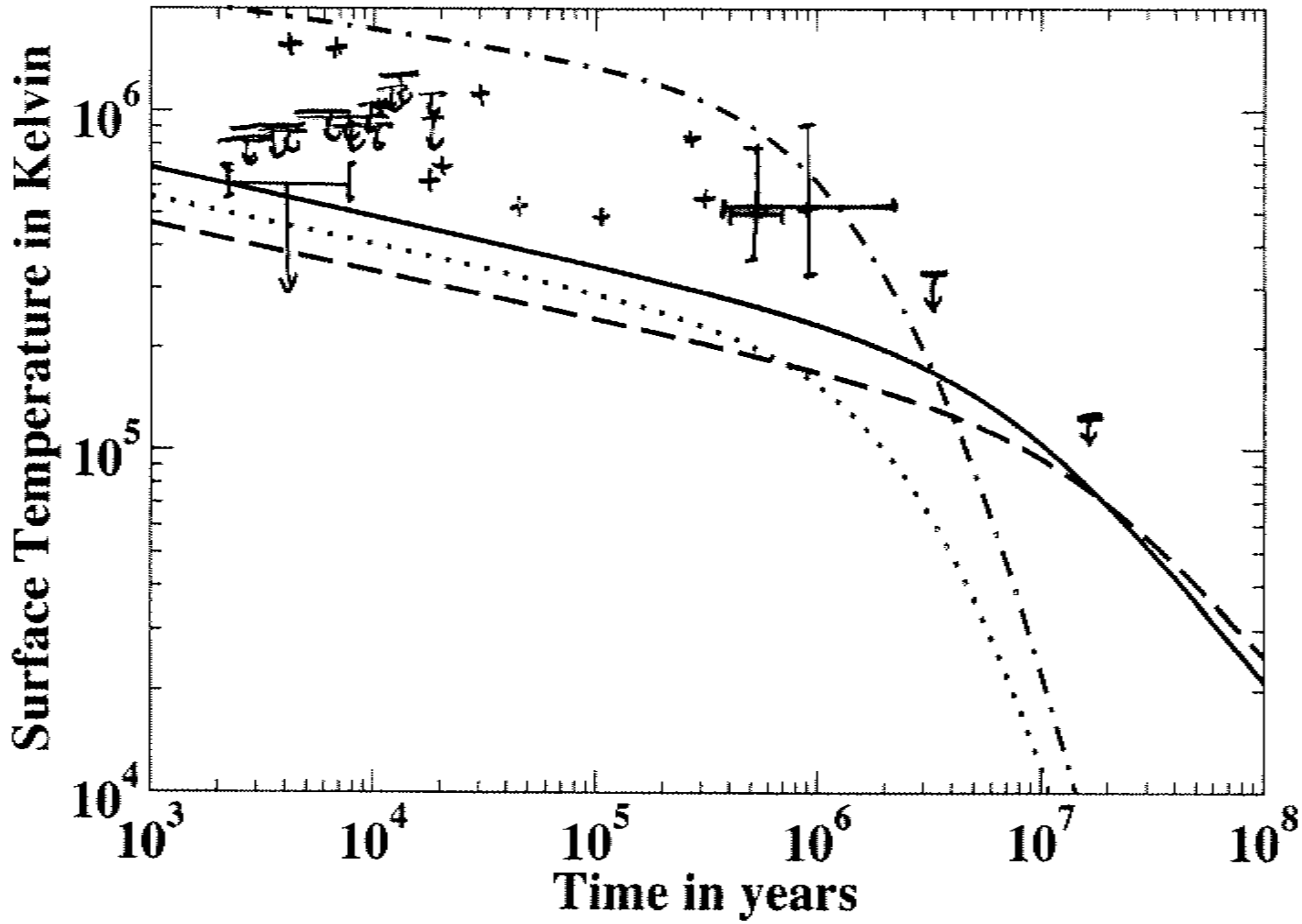
$\Rightarrow$ If present, a gCFL layer acts like a "hot water bottle", keeping aging neutron stars anomalously warm late in their life, because of its large heat capacity.

A HOT WATER BOTTLE FOR AGING NEUTRON STARS



- 10^3-10^5 years : gCFL → colder stars, as for many scenarios where direct Urca allowed
- 10^7 → years: unique signature of gCFL quark matter due to its characteristic dispersion rel.

COMPARISON OF COOLING OF TOY STARS TO DATA ON REAL STARS



Ⱡ: upper bounds on T from nonobservation of neutron stars in 14 supernova remnants. Kaplan et al.

+ : measurements or upper bounds on T of various observed neutron stars. (Compilation of Page et al) All + have error bars comparable to the two shown.

HOW DO NEUTRON STARS LOSE HEAT?

PHOTON EMISSION:

$$L_\gamma \sim R^2 T_{surface}^4$$

$$\sim R^2 T_{interior}^{2.2}$$

Neutron stars older than a few years are isothermal with temperature $T_{interior} \equiv T$ except for outer ~100 m, wherein there are gradients. The results of a calculation of the heat transport in the envelope are well fit by

$$T_{surface} \sim 10^6 K \left(\frac{T_{interior}}{10^8 K} \right)^{0.55}$$

Pethick et al, 1982
Page et al

COOLING

$$\frac{dT}{dt} = - \frac{\varepsilon_\nu^{NM} V_{NM} + \varepsilon_\nu^{QM} V_{QM} + L_\gamma}{C_V^{NM} V_{NM} + C_V^{QM} V_{QM}}$$

	Early Times, when ε_ν dominates	Late times, when L_γ dominates
NM only	$\varepsilon_\nu \sim T^8$ $C_V \sim T$ $\rightarrow T \sim t^{-1/6}$	$L_\gamma \sim T^{2.2}$ $\rightarrow T \sim t^{-1/0.2} \sim t^{-5}$
unpaired QM core	$\varepsilon_\nu \sim T^6$ $C_V \sim T$ $\rightarrow T \sim t^{-1/4}$	$T \sim t^{-5}$
gCFL core	$\varepsilon_\nu \sim T^{5.5}$ $C_V \sim T^{.5}$ $\rightarrow T \sim t^{-1/4}$	$T \sim t^{-1/0.7} \sim t^{-1.4}$

If a gCFL core or layer is present, it dominates total C_V, ~~total~~ L_ν, and $\therefore$ controls the cooling.

DETECTING WARM OLD STARS?

- First cut analysis by Kaplan (not worth doing second cut until more realistic density profile, atmosphere, added to calculation)
- It will be a challenge to find these stars, without knowing where they are. → Fig.
- Limits on thermal emission from pulsars with age ~10^7 yrs?
  - one example within a factor of two
- The gCFL hot water bottle keeps 10^7–10^8 yr. old stars warmer by orders of magnitude than if core has any other composition
- Not ruled out by current data
- An observational challenge.

gCFL INSTABILITY

Before astrophysical observations have had a chance to rise to the challenge of ruling out the presence of gCFL quark matter, theorists have done so first:

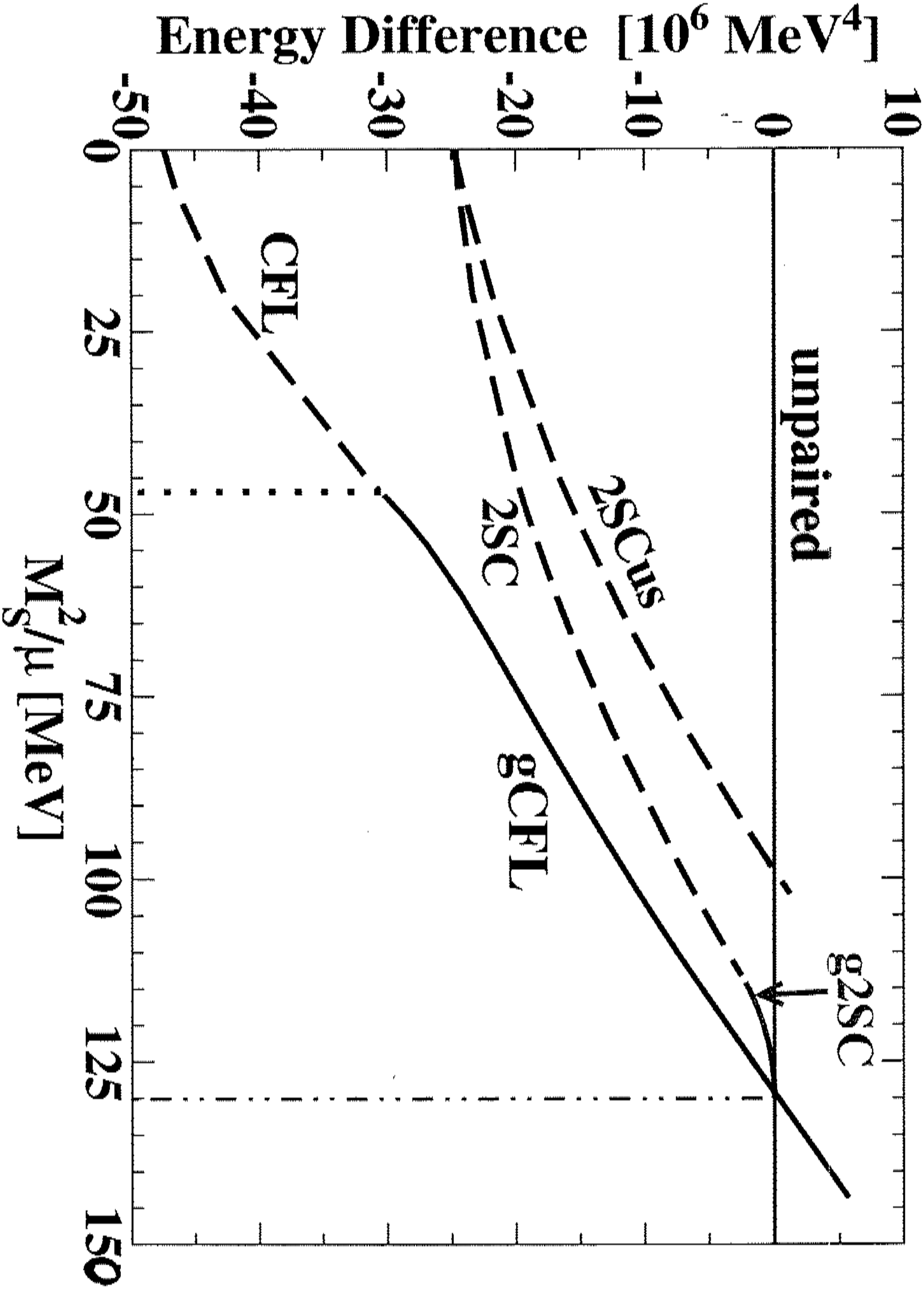
The gCFL phase has a "magnetic instability." (Huang Shovkovy; Casalbuoni Giannakis Ren; Fukushima)

⇒ It can lower its energy by turning on currents.

BUT: ground state of a system has no net current. (Bloch's theorem)

SO: the instability tells us there must be some lower energy phase but does not tell us what.

- Not 2SC or variants. Not a mixed phase
- Currents hint we should revisit....

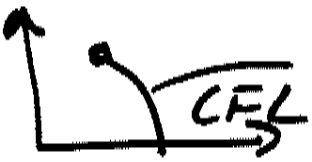

Energy Difference [10^6 MeV^4]
10
0
-10
-20
-30
-40
-50
0
25
50
75
100
125
150
M_S^2/μ [MeV]
unpaired
2SCus
2SC
CFL
gCFL
g2SC

INSTABILITY

Challenge: Find a phase with lower energy than gCFL.

RELATION TO TALKS TO COME

(by Schmitt, Aguilera, Shovkovy)

- For large enough Δ_{CFL}, phase diagram is just 

- For smaller Δ_{CFL} (preceding plot was for $\Delta_{CFL} = 25$ MeV) gCFL beats 2SC, mixed phases, ..., but is unstable. Unstable to what??
- For intermediate Δ_{CFL}, the 2SC phase can insert itself in the phase diagram. In this phase, only 4 of 9 quarks pair. But some of the other 5 may pair with small (~keV) spin-one gaps. Interesting consequences, so worth investigating even though "intermediateness" → model dependence

CRYSTALLINE COLOR SUPERCONDUCTIVITY

Alford Bowers KR; Bowers Kundu KR Shuster; Leibovich KR Shuster; Casalbuoni Gatto Mannarelli Nardulli; Giannakis Liu Ren; Bowers KR

As $\mu \downarrow$, if CFL "breaks" before you get to hadronic matter, quark matter at intermediate density may have:

Pairing between quarks with <u>different p_F</u>

<u>GOAL</u>: both quarks in a pair on respective Fermi surfaces

<u>IDEA</u>: Cooper pairs with momentum!

$$(\vec{p}+\vec{q}, -\vec{p}+\vec{q}) \text{ for any } \vec{p}.$$

Each pair has total momentum $2\vec{q}$

- $|\vec{q}| \simeq 1.2\, \delta p_F$ determined energetically
- "pattern" of $\{\hat{q}_i\}$ " " Bowers KR

$$\langle \psi\psi \rangle \sim \Delta \sum_i e^{i\vec{q}_i\cdot\vec{x}}$$

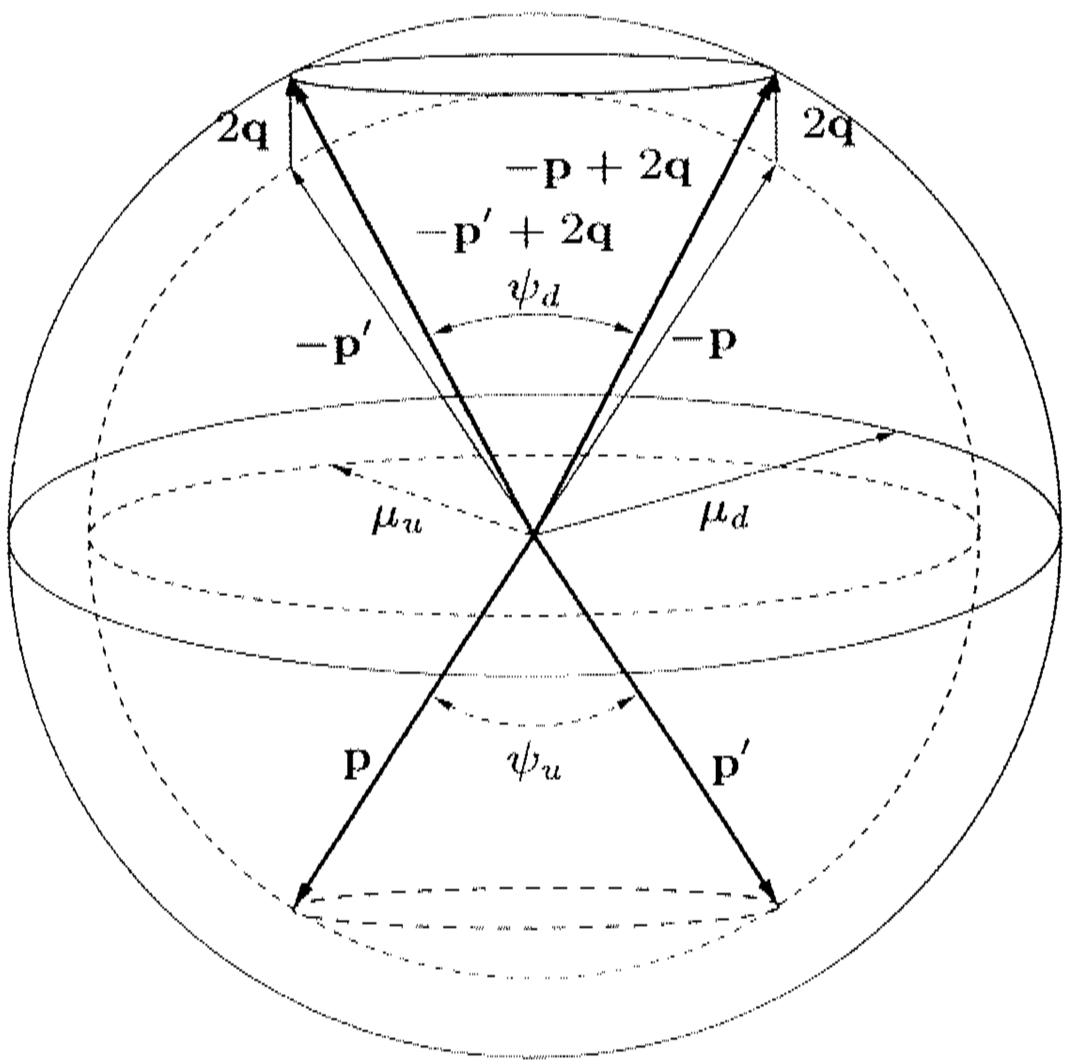
- spontaneous breaking of rotational and translational symmetry.

<u>LOFF</u>: Larkin Ovchinnikov Fulde Ferrell (1964) considered this state for $\langle e_\uparrow e_\downarrow \rangle$ pairing with Zeeman splitting. State not seen in condensed matter. Problem is that $\vec{B} \to$ orbital effects, not just Zeeman. QCD, with its "flavor Zeeman splitting" turns out to be the natural context for LOFF's idea!

Basic LOFF idea

Try Cooper pairs $(\mathbf{p}, -\mathbf{p}+2\mathbf{q})$

- total momentum $2\mathbf{q}$ for each and every pair
- each quark at its Fermi surface, even with $p_F^u \neq p_F^d$
- $\hat{q}$ chosen spontaneously, $|\mathbf{q}|$ determined variationally (result is $|\mathbf{q}| = q_0 \approx 1.20\delta\mu$)
- condensate forms a ring on each Fermi surface, with opening angle $\psi_u \approx \psi_d \approx 2\cos^{-1}(\delta\mu/q_0) \approx 67.1°$



MULTIPLE PLANE WAVES

If system unstable to formation of 1 plane wave, this allows quarks lying on one ring on each F.S. to pair. Much of F.S. remains unpaired....

Why not multiple $\vec{q}$'s ? i.e. multiple rings?

Want to compare many different possible $\{\vec{q}_i\}$;

$$\langle \psi(x)\, \psi(x) \rangle = \sum_{\{\vec{q}_i\}} \Delta\, e^{i 2\vec{q}_i \cdot \vec{x}}$$

and for each $\{\vec{q}_i\}$ calculate Δ and Ω

$\{q_i\}$, ie crystal structure, with lowest Ω wins.

FCC Crystal

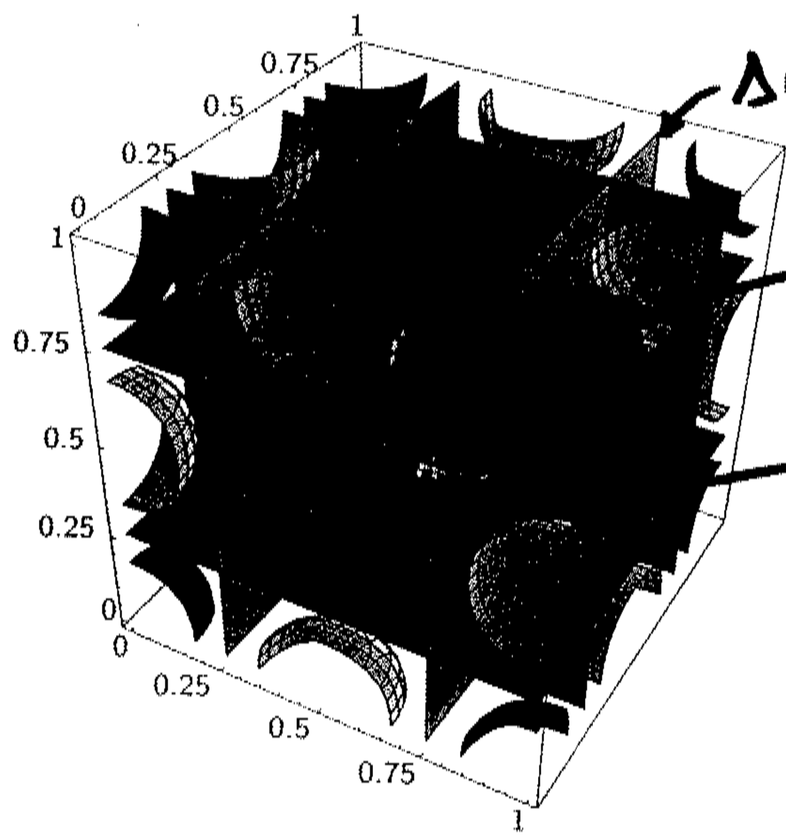
Favored according to Ginzbu Landau analysis, that is not yet quantitatively reliable. Bowers 16,

- The cube structure is the favored ground-state: eight wave vectors pointing towards the corners of a cube, forming the eight shortest vectors in the reciprocal lattice of a face-centered-cubic crystal. The gap function is

$$\Delta(\mathrm{x}) = 2\Delta\left[\cos\frac{2\pi}{a}(x+y+z)+\cos\frac{2\pi}{a}(x-y+z)\right.$$
$$\left.+\cos\frac{2\pi}{a}(x+y-z)+\cos\frac{2\pi}{a}(-x+y+z)\right]$$

$\Delta \sim \Delta_{CFL}$

A unit cell:



with contours $\Delta(\mathrm{x}) = +4\Delta$ (black), 0 (gray), -4Δ (white). Lattice constant is $a = \sqrt{3}\pi/|\mathbf{q}| \simeq 6.012/\Delta_0$.

Sum of 8 currents; zero net current.

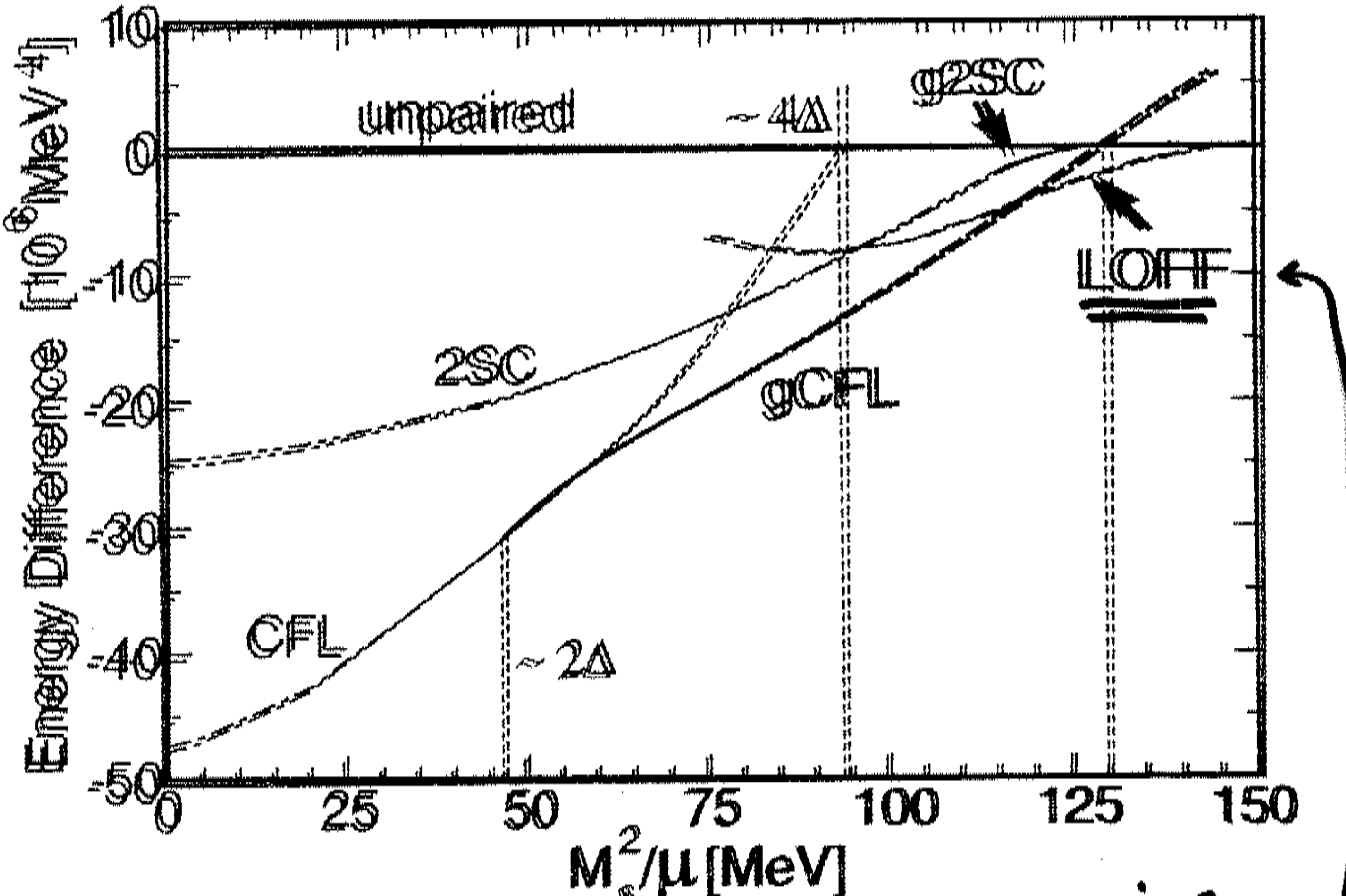
OUTLOOK AND IMPLICATIONS

QUESTION: Is there a crystalline phase with lower energy than gCFL?

- Ginzburg-Landau analysis yields qualitative answers – eg what is favored crystal structure – but is not quantitatively reliable. Must go beyond G.L.
- Need three-flavor analysis.
  → News from last week....
- Current status: nobody has shown that a crystalline phase can have lower energy than gCFL throughout the gCFL window, but the gCFL instability is a strong hint pointing in this direction.

THREE-FLAVOR "CRYSTALLINE" PHASE

Casalbuoni Gatto Ippolito Nardulli Ruggieri



$\langle ud \rangle \sim \Delta_3 e^{+iqz}$; $\langle us \rangle \sim \Delta_2 e^{-iqz}$

Greatly simplified ansatz for "crystal" structure and yet we see this phase does beat gCFL over a part of the gCFL window.

A strong hint, since whatever the favored three-flavor crystal structure turns out to be, it must have lower energy still.

OUTLOOK AND IMPLICATIONS

CRYSTALLINE SUPERFLUIDITY

- A two species version of crystalline superfluid may be created in gases of ultracold fermionic atoms
  Combescot; Son Stephanov
  - trap 2 hyperfine states of atom;
  - arrange strong attractive interaction between 2 "species". (Done via a Feshbach resonance.)
  - load the trap with different number densities for 2 "species".

VORTEX PINNING & PULSAR GLITCHES

- Rotate the crystal; what happens? Alford Bowers KR
  Vortices? Vortices pinned at intersections of crystal's nodal planes?
- If there are <u>pinned</u> <u>vortices</u>, the presence of a layer of crystalline color superconducting quark matter within neutron stars could make this layer a locus for <u>Pulsar Glitches</u>.

IMPLICATIONS FOR COMPACT STARS

or, flipping that around,... How can we use observations of compact stars to determine the high density region of the phase diagra[m]

- If core of "neutron" star is quark matter, then it IS a color superconduct[or]

$$T_{star} \sim keV \lll T_c$$

- Not known whether neutron stars have quark matter cores. Goal: understand observational consequences, so we can find out

FIRST: Can we discover whether there is a crystalline color superconductivity window

- As a function of increasing depth, M_s^2/μ decreases.

  ∴ LOFF WINDOW → LOFF SHELL

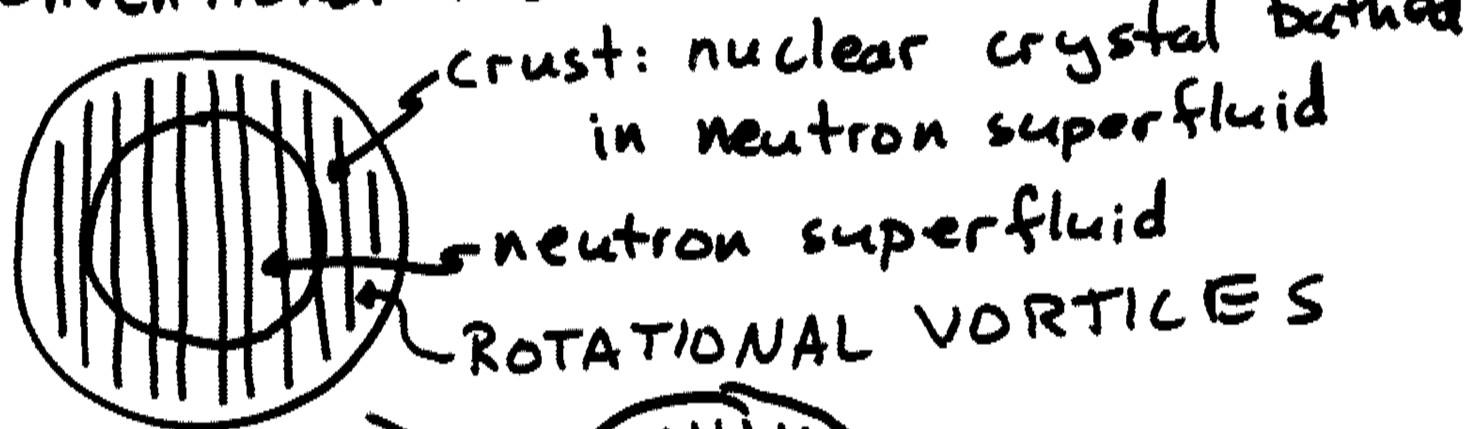
THEN: List other examples of ways to answer this question.

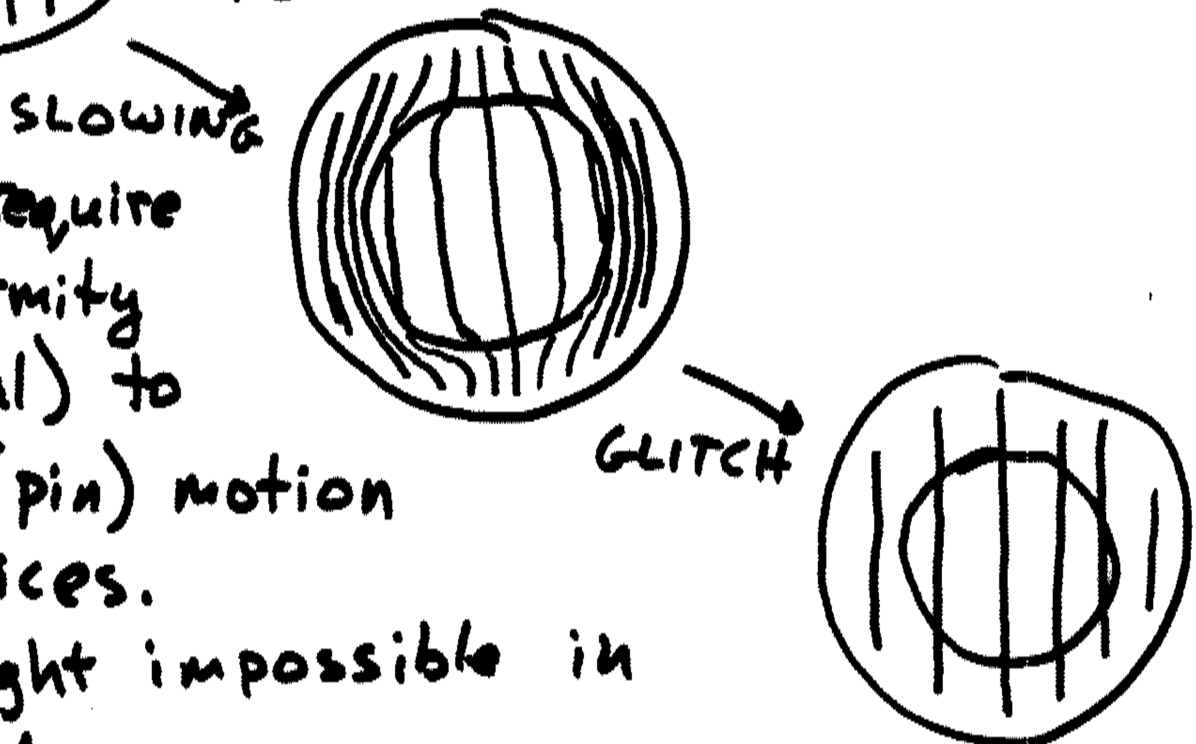
GLITCHES

Pulsars glitch:

$$\frac{\delta\Omega}{\Omega} \sim 10^{-9} \to 10^{-6}$$

Conventional mechanism:



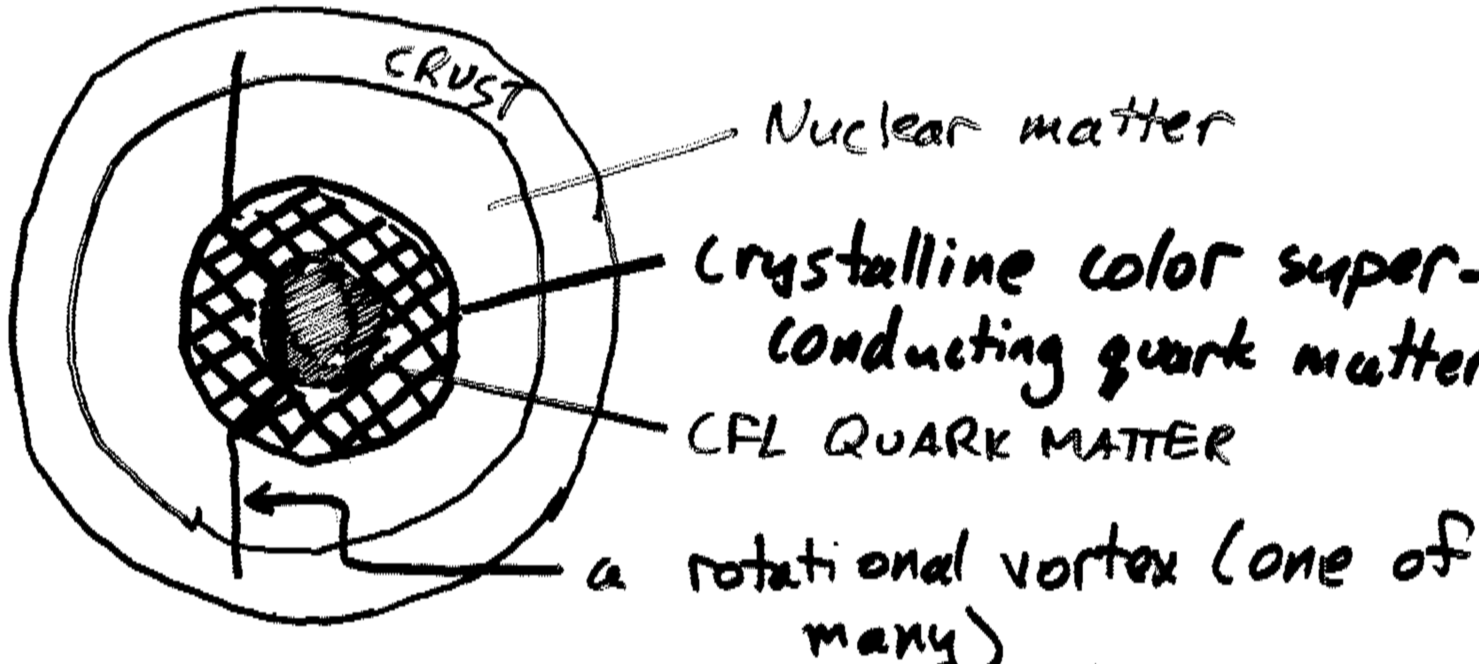


Glitches require non-uniformity (ie crystal) to impede (pin) motion of vortices.

∴ thought impossible in QM.

GLITCHES IN QUARK MATTER?

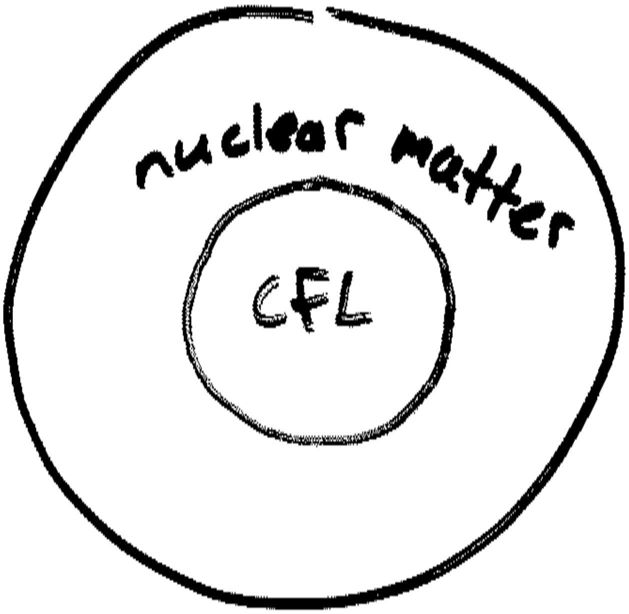
- crystalline condensate may pin vortices, ∵ they prefer to follow intersections of nodal planes



- could some (eg the smaller?) glitches originate in a crystalline layer in core?
- would features of observed glitches rule out existence of crystalline layer?
- serious glitch phenomenology requires calculation of pinning force and shear modulus. Both can be calculated once neutral, 3-flavor, crystalline phase with real crystal structure is in hand.

FROM PHYSICAL PROPERTIES TO ASTROPHYSICAL CONSEQUENCES

How can we learn whether neutron stars have CFL cores?



nb: Unless surface tension is unexpectedly small, this is a case where a single sharp interface (with charged boundary layers) is favored over a mixed phase.

Alford KR Reddy Wilczek

ASTROPHYSICAL CONSEQUENCES IF NEUTRON STARS HAVE CFL CORES

- For given M, R a little smaller. But, uncertainty in R still dominated by nuclear outer layer. Alford Reddy
- At a sharp interface, big density step. $\overset{?}{\rightarrow}$ LIGO signal Alford K.R. Reddy

- If spherical stars have CFL cores but oblate stars do not, → unusual spin-up history. Glendenning, Weber; Blaschke, Grigorian
- Transparent insulator. → $\vec{B}$ in core not in flux tubes; not frozen. → $\vec{B}$ evolution governed by outer layer.
- For T < few MeV:
  - very small specific heat, neutrino emissivity, neutrino opacity. Page Prakash Lattimer Steiner, Jaikumar Prakash Schaefer
  - superfluidity → very large thermal conductivity Shovkovy Ellis

  ⇒ cooling of star controlled by nuclear oute layer
- During supernova, T ~ tens of MeV > meson m
  ⇒ mesons emit and scatter neutrinos Reddy Sadzikowski Tachibana
  - and, also, may be phase transitions Carter Reddy

  $\overset{?}{\rightarrow}$ signals in time distribution of supernova
- Bare quark star would be nice. **NOT** seen...

NEWS

Nice, Splaver, Stairs, Löhmer, Jessner, Kramer, Cordes
astro-ph/0508050 (appeared this week)

A pulsar (named PSR J0751+1807) with mass:

$M = 2.1 \pm 0.2$ solar masses

$1.6 < M < 2.5$ at 95% confidence

- A 3.5 ms pulsar in a 6.3 hr orbit around a 0.19 solar mass white dwarf.
- Over 10 years of observation, the 6.3 hr orbit has slowed by $19.6 \pm 2.5\ \mu s$! due to gravitational wave emission.
- Shapiro delay measured. No accretion, mass transfer, or X-ray emission.
- ie this is gold-plated, as clean as the best previous mass measurements. And, the error bar will shrink like $(1/\text{duration of observation})^{2.5}$
- cf: $M_{NS} \lesssim 2.3\ M_\odot$ (stiff nuclear E.O.S.)
- cf: M_{NS} with quark core $< (1.9-2.0)\ M_\odot$ Alford Ba... Paris Re...

GOALS

PUZZLE: If non-CFL quark matter intervenes between CFL & nuclear, what are its properties?

HINTS: gCFL instability $\overset{?}{\Rightarrow}$ crystalline condensate

COMING: neutral, 3-flavor crystalline color superconductor, with realistic crystal structure: does it have lower energy than gCFL?

LONGER TERM: Improve calculations of properties and consequences of these phases, allowing observations to rule their presence within neutron stars out or in. Eg:

- pinning force & shear modulus of X-tal $\overset{?}{\to}$ glitches
- almost no limit to possible improvement in calculation of CFL properties
- new data coming on M, R, ν-cooling, SN-ν, LIGO, ...