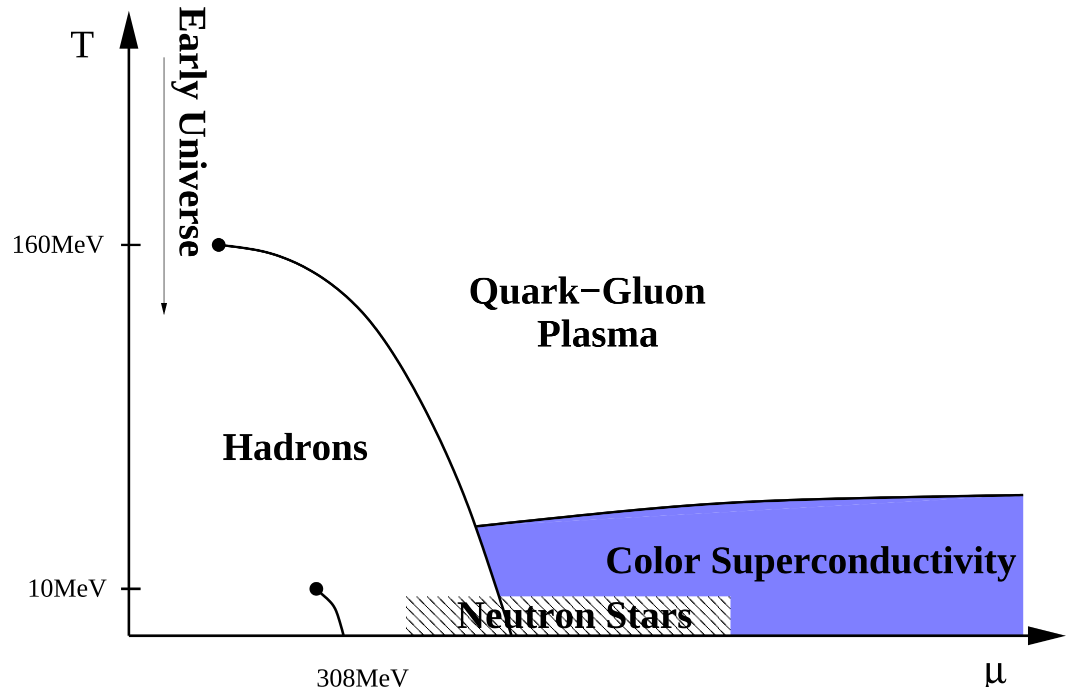
Neutrino emissivity from spin-1 color superconductors

Andreas Schmitt[1], Igor Shovkovy[2], Qun Wang[3]

[1]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2]Frankfurt Institute for Advanced Studies, J.W. Goethe-Universität, D-60438 Frankfurt am Main, Germany
[3]Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China

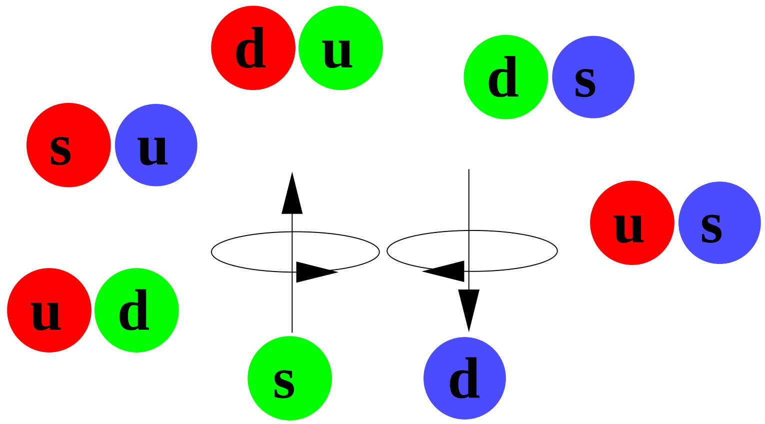
- **Outline**
  - color superconductivity with $J = 1$ Cooper pairs
  - properties of several phases (CSL, planar, polar, A)
  - **neutrino emission via direct Urca processes**
    1. **emissivities** ϵ_ν
    2. **cooling curves** $T(t)$ **from** ϵ_ν **and specific heat** c_V
    3. **anisotropy in neutrino emission**

- **QCD phase diagram and CFL phase**



Sufficiently high density:
Color-flavor locked (CFL) phase
M. Alford, K. Rajagopal, F. Wilczek,
Nucl. Phys. B537, 443 (1999)

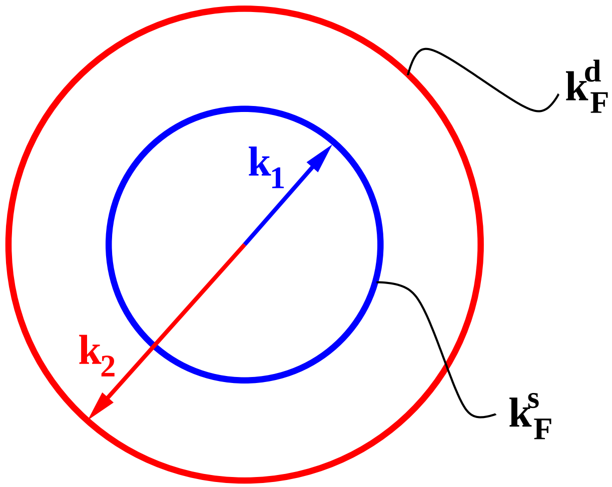
Order parameter $\Delta \in [\bar{\mathbf{3}}]_c^a \otimes [\mathbf{3}]_f^a \otimes [\mathbf{1}]_{J=0}^a$
$\Delta_{ij} \sim \delta_{ij}$



- **CFL phase in neutron stars?**

At moderate quark chemical potentials ($\mu \simeq 500\mathrm{MeV}$):

- m_s not negligible
- β-equilibrium
- electrical & color neutrality



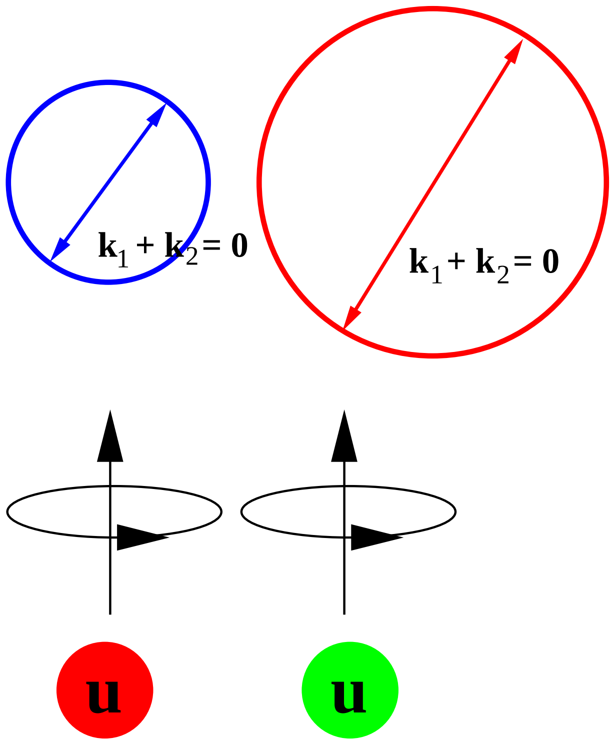
Conventional BCS pairing requires equal Fermi momenta, and $\mathbf{k_1} + \mathbf{k_2} = 0$!

$\rightarrow$ **Non-conventional** pairing:

- LOFF phase   M. Alford, J. Bowers, K. Rajagopal, PRD 63, 074016 (2001)
- Gapless 2SC/CFL phase   I. Shovkovy, M. Huang, Phys. Lett. B 564, 205 (2003); M. Alford, C. Kouvaris, K. Rajagopal, PRL 92, 222001 (2004)
  - "Chromomagnetic" instability in gapless phases
    M. Huang, I.A. Shovkovy, PRD 70, 051501 (2004);
    R. Casalbuoni, R. Gatto, M. Mannarelli, G. Nardulli, M. Ruggieri, PLB 605, 362 (2005)
- Or, "simplest", . . .

- **One-flavor color superconductors**

D. Bailin, A. Love, Phys. Rep. 107, 325 (1984)
T. Schäfer, PRD 62, 094007 (2000)



$\rightarrow$ No Fermi surface mismatch

However, $J = 1$**!**

$$\boxed{\Delta \in [\bar{\mathbf{3}}]_c^a \otimes [\mathbf{3}]_{J=1}^s}$$

Like in **superfluid** ^{3}**He** (A, B, A_1 phases): Many theoretically possible phases!

- **Properties of spin-1 color superconductors (page 1/2)**

A. Schmitt, PRD 71, 054016 (2005)

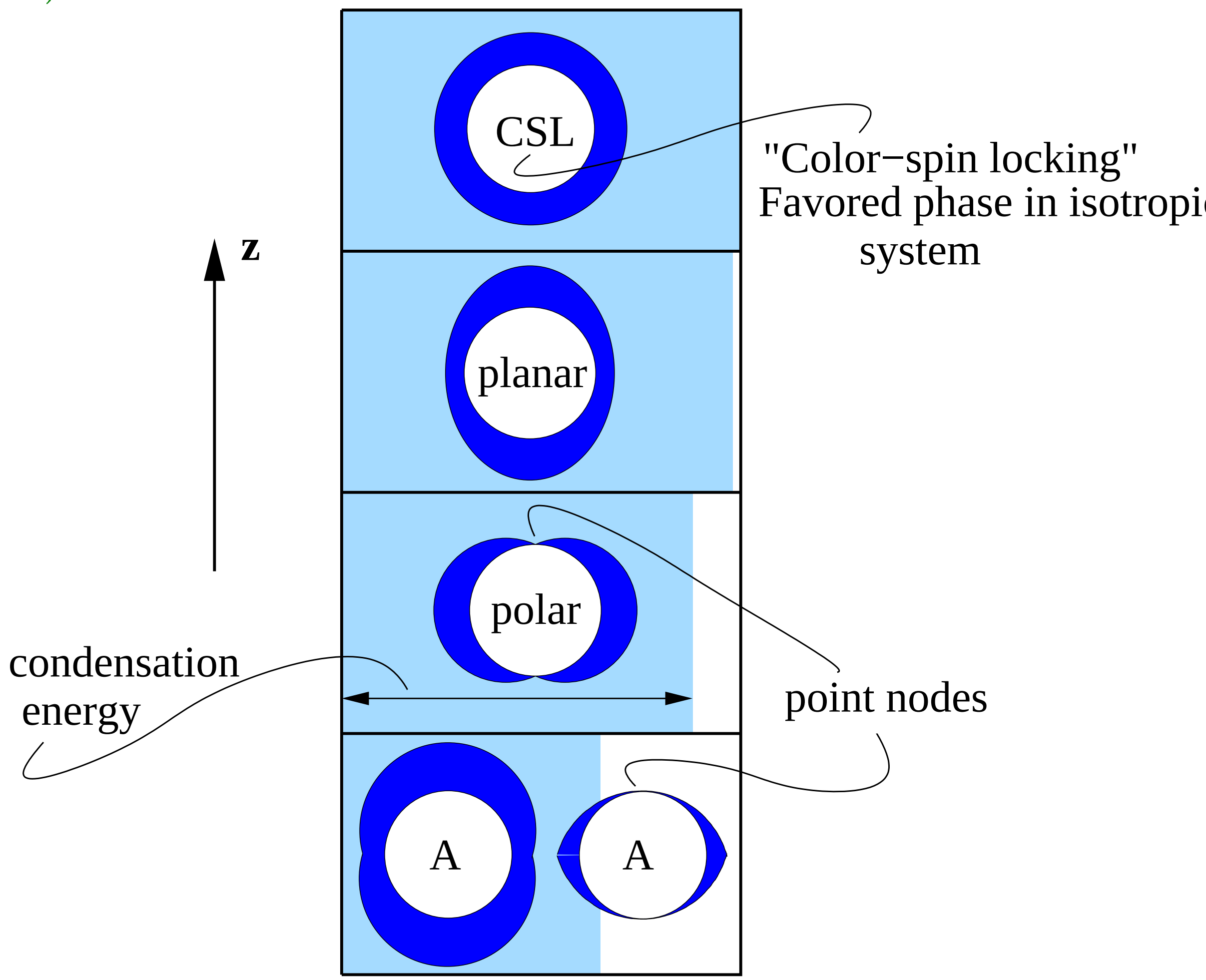
- quasiparticle energies

$$\epsilon_{\mathbf{k},r} = \sqrt{(k-\mu)^2 + \boldsymbol{\lambda}_{\hat{\mathbf{k}},r}\,\phi^2}$$

$$r = 1, 2, (3)$$

ungapped modes: $\boldsymbol{\lambda}_{\hat{\mathbf{k}},1} = 0$

gapped modes $\boldsymbol{\lambda}_{\hat{\mathbf{k}},2}$, $(\boldsymbol{\lambda}_{\hat{\mathbf{k}},3})$



- **Properties of spin-1 color superconductors (page 2/2)**

- magnitude of energy gap

$$\phi \simeq 10 - 100\text{keV} \qquad (\text{spin-0: } \phi \simeq 10\text{MeV})$$

- transition temperature (modified BCS ratio)

$$T_c \simeq 10 - 60\text{keV} \qquad \frac{T_c}{\phi} = 0.57\, e^{\bar{\zeta}} \qquad (0.87 < e^{\bar{\zeta}} < 1.43)$$

- Cooper pairs of quarks of same (RR, LL) or different (RL, LR) chirality possible

$\rightarrow$ RL, LR pairs preferred

- electromagnetic Meissner effect

A. Schmitt, Q. Wang and D. H. Rischke, PRL 91, 242301 (2003)

$$\text{photon Meissner mass} \qquad m_\gamma = q\frac{e\,\mu}{\pi} \qquad (\text{CSL phase})$$

in contrast: $m_\gamma = 0$ in 2SC, CFL phases

• Neutrino emission

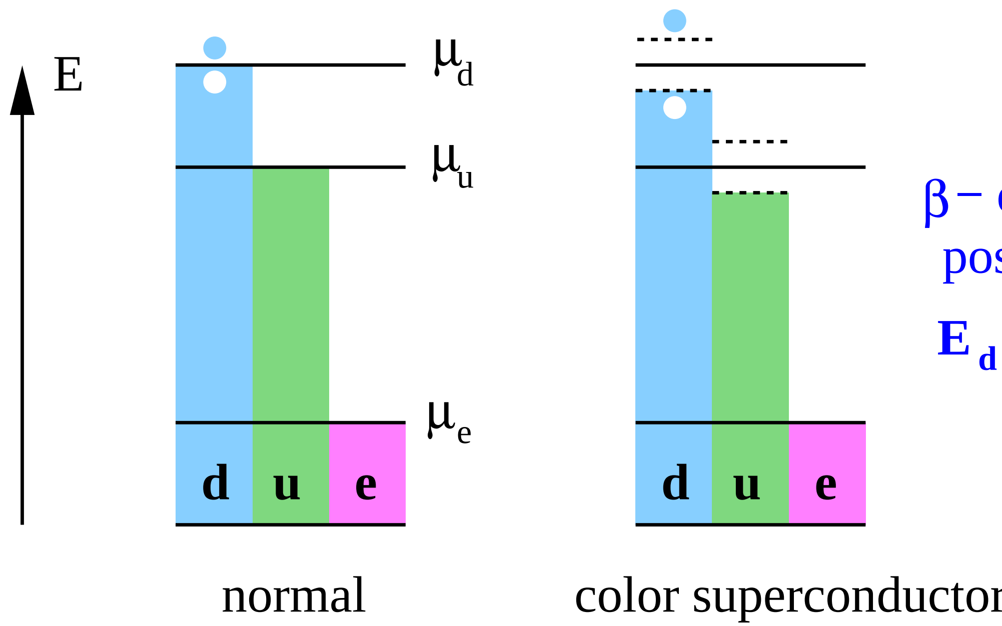
Consider system of u and d quarks + electrons e

direct Urca processes:

$u + e \to d + \nu$ "electron capture"

$d \to u + e + \bar{\nu}$ "β-decay"

$\to$ emissivity proportional to density of thermally excited quasiparticles, e.g., β-decay:



$\beta-$ decay only possible if

$\mathbf{E_d > E_u + E_e}$

$\to$ **Suppression of emissivity due to energy gap**

$\to$ **Suppression for anisotropic gaps? Effect of nodes?**

- **Results for the emissivity ϵ_ν**

total energy loss per volume and time due to neutrino emission:

$$\epsilon_\nu \equiv -\frac{\partial}{\partial t} \int \frac{d^3\mathbf{p}_\nu}{(2\pi)^3} \, p_\nu \, f_\nu(t, \mathbf{p}_\nu)$$

$f(\mathbf{p}_\nu, t)$ neutrino distribution function

- **normal-conducting** quark matter N. Iwamoto, PRL 44, 1637 (1980)

$$\epsilon_\nu = \frac{457}{630} G_F^2 \, \alpha_s \, \mu_e \, \mu_u \, \mu_d \, T^6$$

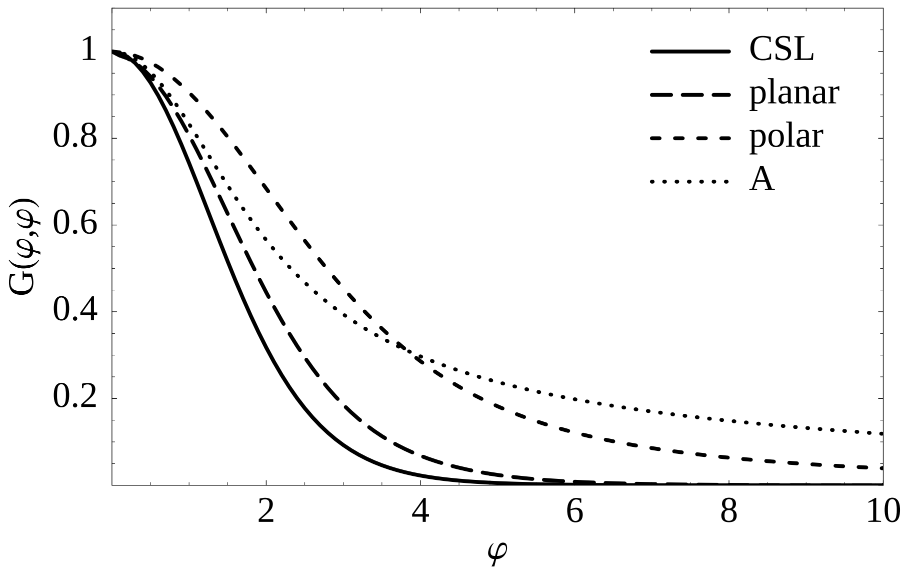
- **spin-one color superconductors**

$$\epsilon_\nu = \frac{457}{630} G_F^2 \, \alpha_s \, \mu_e \, \mu_u \, \mu_d \, T^6 \, \left[\frac{1}{3} + \frac{2}{3} G(\varphi_u, \varphi_d)\right]$$

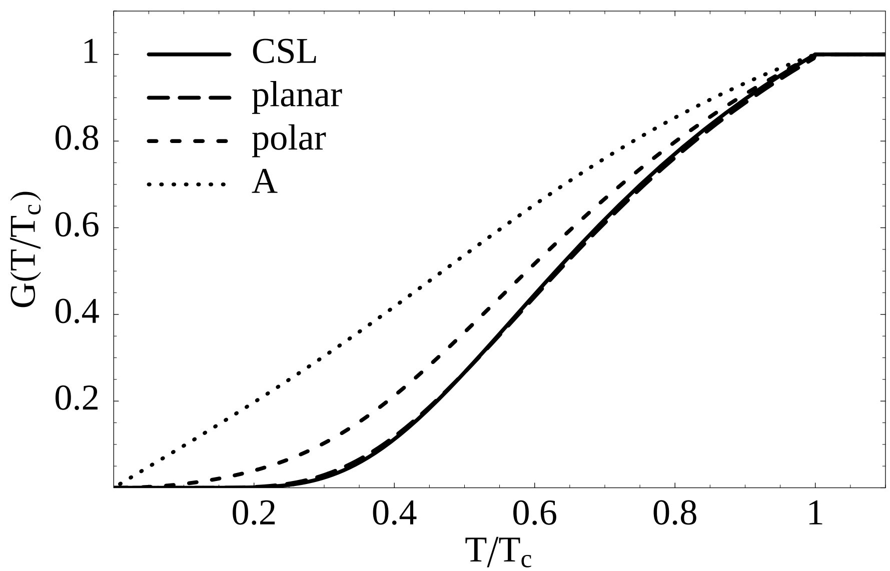
with $\varphi_{u,d} \equiv \frac{\phi_{u,d}}{T}$

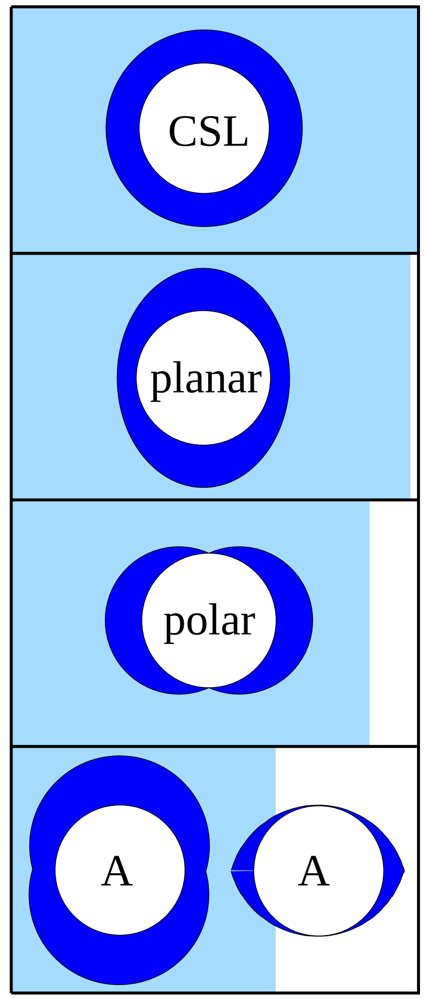
$G(\varphi_u, \varphi_d)$ has to be evaluated numerically $\rightarrow$

• Emissivity from gapped modes



and with $\phi(T) = \phi_0\sqrt{1-(T/T_c)^2}$:





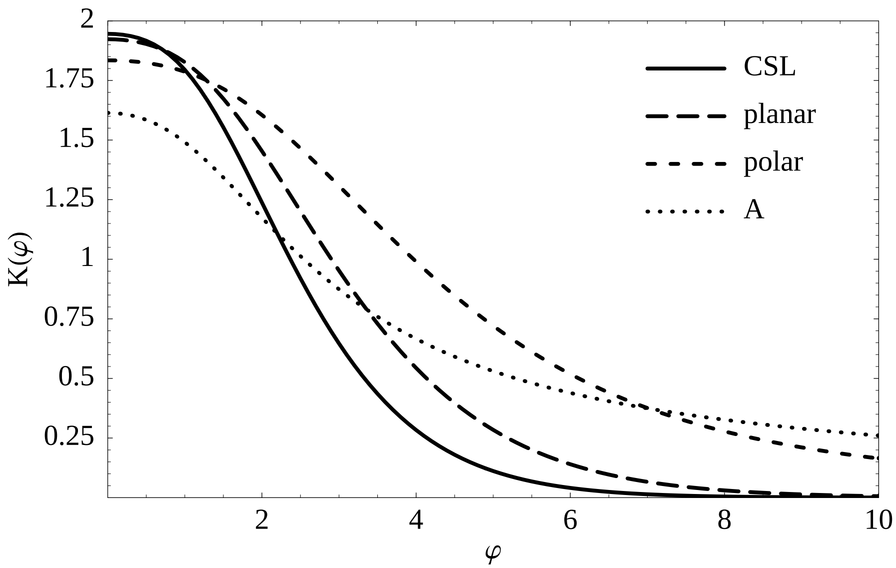
• $\varphi \to \infty$:

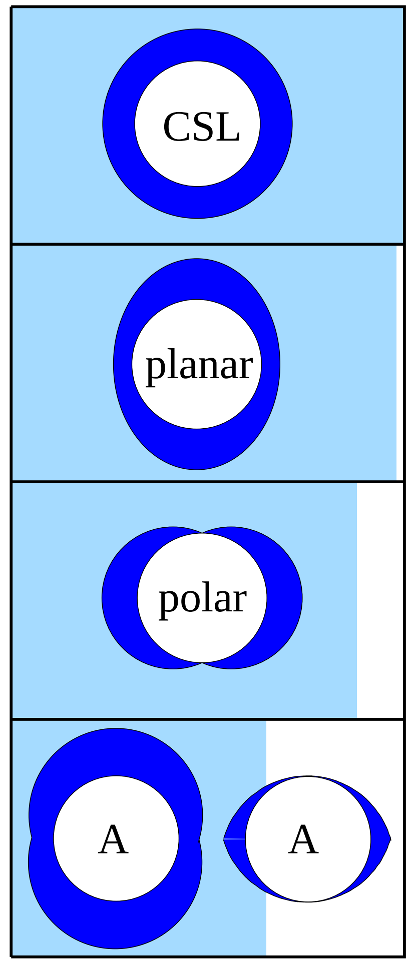
	$G(\varphi,\varphi)$
CSL	$\exp(-\varphi)$
planar	$\exp(-\varphi)$
polar	$1/\varphi^2$
A	$1/\varphi$

- **Results for the specific heat c_V**
- **normal phase** $c_V = T\,(\mu_u^2 + \mu_d^2)$
- **spin-one color superconductor**

$$c_V = T \sum_{f=u,d} \mu_f^2 \left[\frac{1}{3} + \frac{2}{3} K(\varphi_f)\right]$$

- **Gapped modes**





- $\varphi \to \infty$:

	$G(\varphi,\varphi)$
CSL	$\exp(-\varphi)$
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polar	$1/\varphi^2$
A	$1/\varphi$

$K(0) > 1$: Jump of c_V at phase transition

$$\Delta c_V \sim \frac{\Delta p}{T_c}$$

Δp "condensation energy" at $T = 0$

- **Cooling**

temperature drop due to neutrino emission:

$$\epsilon_\nu(T) = -c_V(T)\frac{dT}{dt}$$

- **spin-one color superconductors**

$$t - t_0 = -\frac{630}{457}\,\frac{\mu_u^2+\mu_d^2}{\alpha_s\,G_F^2\,\mu_e\,\mu_u\,\mu_d}\int_{T_0}^{T} dT\,\frac{1}{T^5}\,\frac{1+2\,K(T)}{1+2\,G(T)}$$

$\rightarrow$ **Very fast** cooling like in normal phase

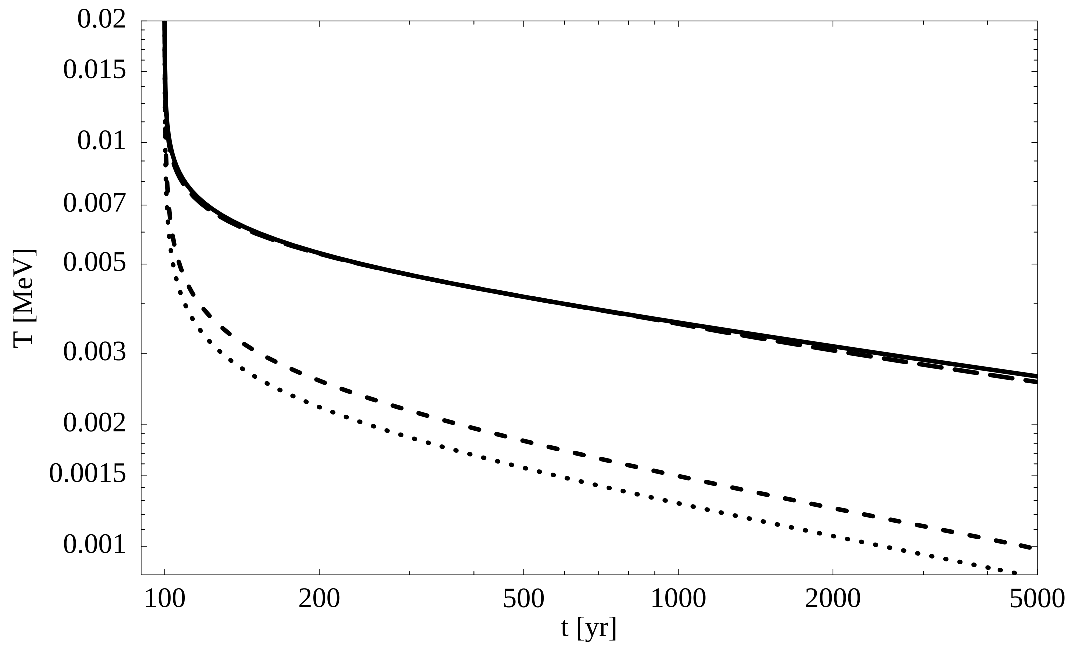
$$T(t) \simeq \frac{T_0\,\tau^{1/4}}{(t-t_0+\tau)^{1/4}}\,, \qquad \tau \equiv \frac{630}{1828}\,\frac{\mu_u^2+\mu_d^2}{\alpha_s\,G_F^2\,\mu_e\,\mu_u\,\mu_d}\,\frac{1}{T_0^4}$$

Consider only gapped modes
$K(T)$, $G(T)$

$T_0 = 100\text{keV}$

$t_0 = 100\text{yr}$

$T_c = 50\text{keV}$

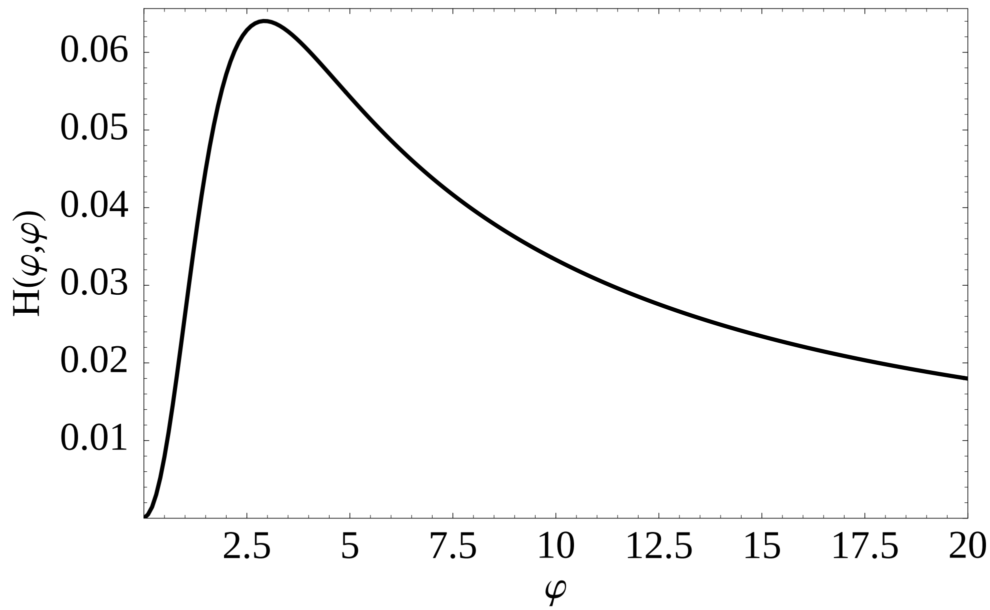


• Asymmetry in the A phase

Momentum projection of emitted neutrinos

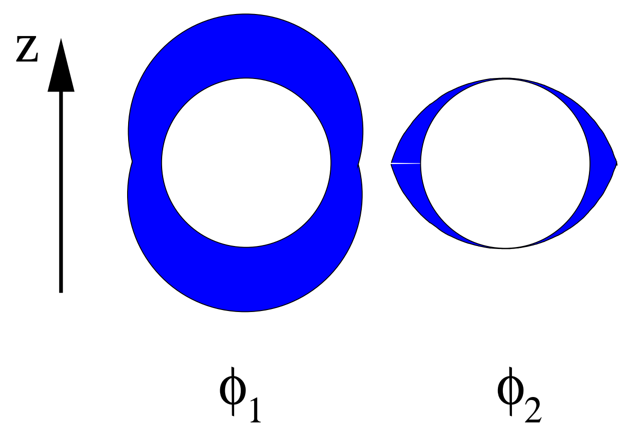
$$\frac{dp_z}{dV\,dt} = \frac{2}{3}\,H(\varphi)\,\frac{457}{630}\,G_F^2\,\alpha_s\,\mu_e\,\mu_u\,\mu_d\,T^6$$

$H(\varphi) \neq 0$ *only* in **A phase**



Remember gap structure

No sign of broken Z_2 symmetry?!



- **Explanation of asymmetry**

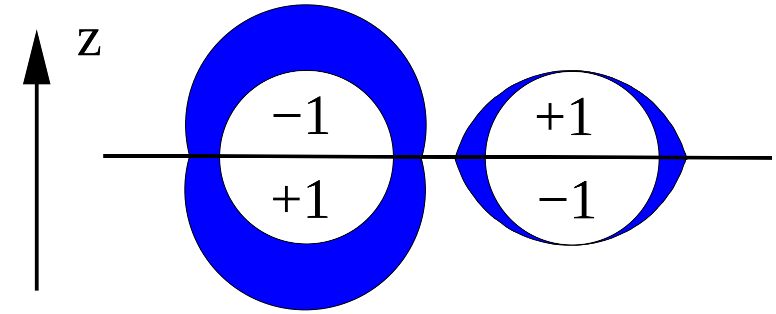
$\rightarrow$ projectors onto quasiparticle modes:

$$\mathcal{P}_{1,2} = \frac{1}{2} J_3^2 \, [1 \mp \mathrm{sgn}(\cos\theta)] \; H^+(\hat{\mathbf{k}}) + \frac{1}{2} J_3^2 \, [1 \pm \mathrm{sgn}(\cos\theta)] \; H^-(\hat{\mathbf{k}})$$

with the helicity projectors

$$H^\pm(\hat{\mathbf{k}}) \equiv \frac{1}{2}\left(1 \pm \mathbf{\Sigma}\cdot\hat{\mathbf{k}}\right)$$

$\rightarrow$**Helicity order in the A phase!**



What does that mean for neutrino emission?

only **left-handed** quarks participate in Urca processes

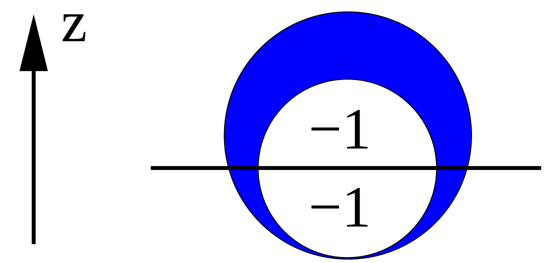
$\downarrow$

ultrarelativistic limit:

quasiquarks with **helicity -1** are picked

$\downarrow$

"effective gap" for neutrino emission



$\Rightarrow$ **asymmetry with respect to $+z$ and $-z$ directions!**

Discussion, outlook

Consequences of asymmetry in A phase?

1. Explanation for pulsar velocities? Up to v ∼1000km/s with model $T \sim t^{-1/4}$
   A. Schmitt, I. A. Shovkovy, Q. Wang, PRL 94, 211101 (2005)
2. However: v several orders of magnitude smaller with realistic cooling

Finite quark masses

1. effect of massive s quarks: Cabibbo suppression, however: larger phase space for Urca process
2. massive u, d quarks: no ungapped modes in CSL phase
   D. N. Aguilera, D. Blaschke, M. Buballa, V. L. Yudichev, arXiv:hep-ph/0503288

Ground state in neutron star

1. favored state among spin-one phases: CSL (without external fields)
2. with star rotation: anisotropic phase favored? (see ^{3}He)
3. compare quantitatively to LOFF phase, gapless phases (?)