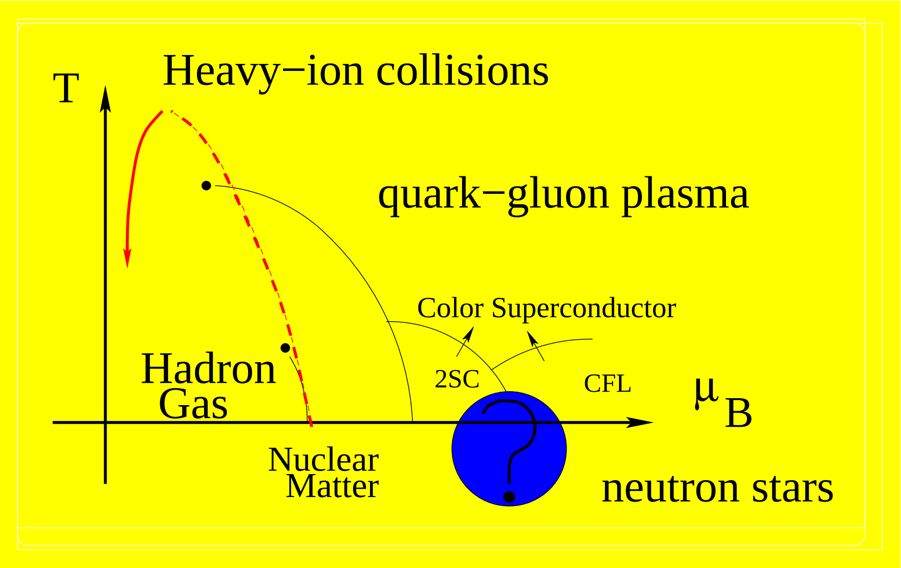
Quark Stars:

Astrophysics at the highest densities



Prashanth Jaikumar

Argonne National Laboratory

WHEPP-9, Bhubaneswar, Orissa

An overview of recent advances in Quantum ChromoDynamics at high density

Collaborators

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🇦🇺 Craig Roberts, Argonne

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Outline

QCD: Symmetries, Excitations, Phases

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High density: Color superconductivity, Neutron stars

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Quark stars: Bulk and surface features, observations

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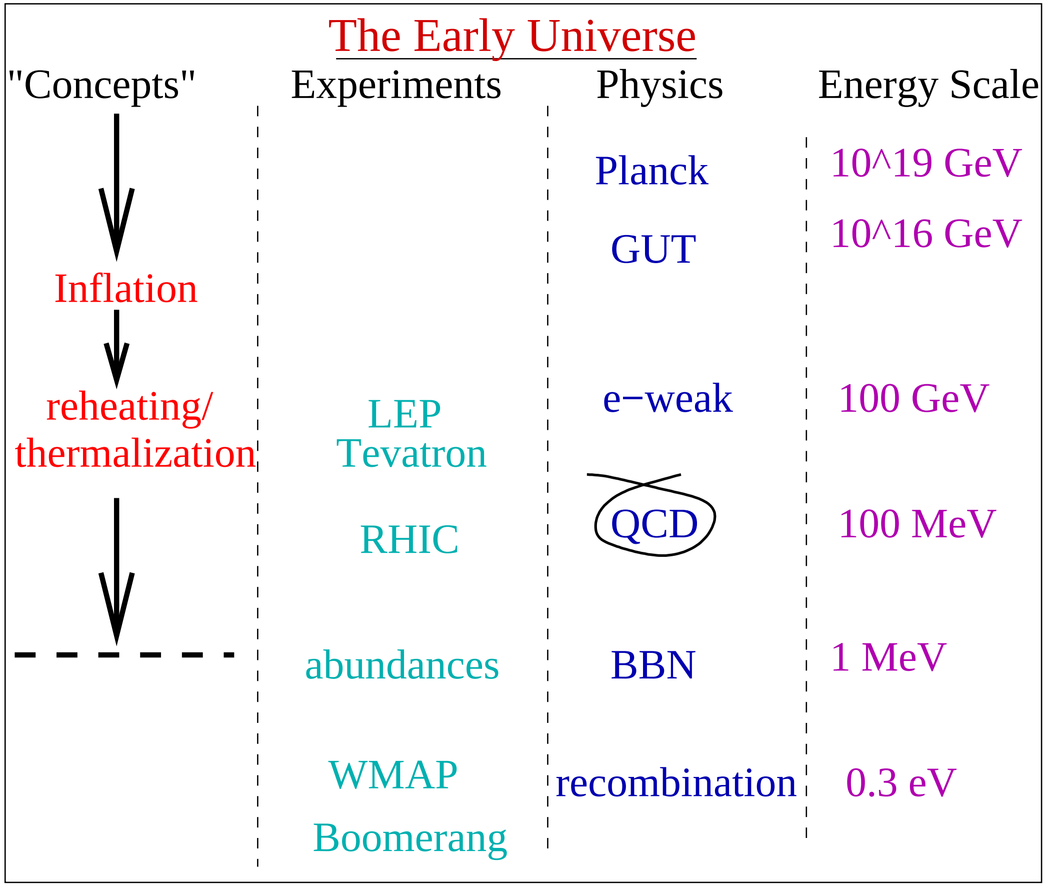
High density: Color superconductivity, Neutron stars

Quark stars: Bulk and surface features, observations

Quark stars: link to r-process nucleosynthesis?

Relevance of QCD

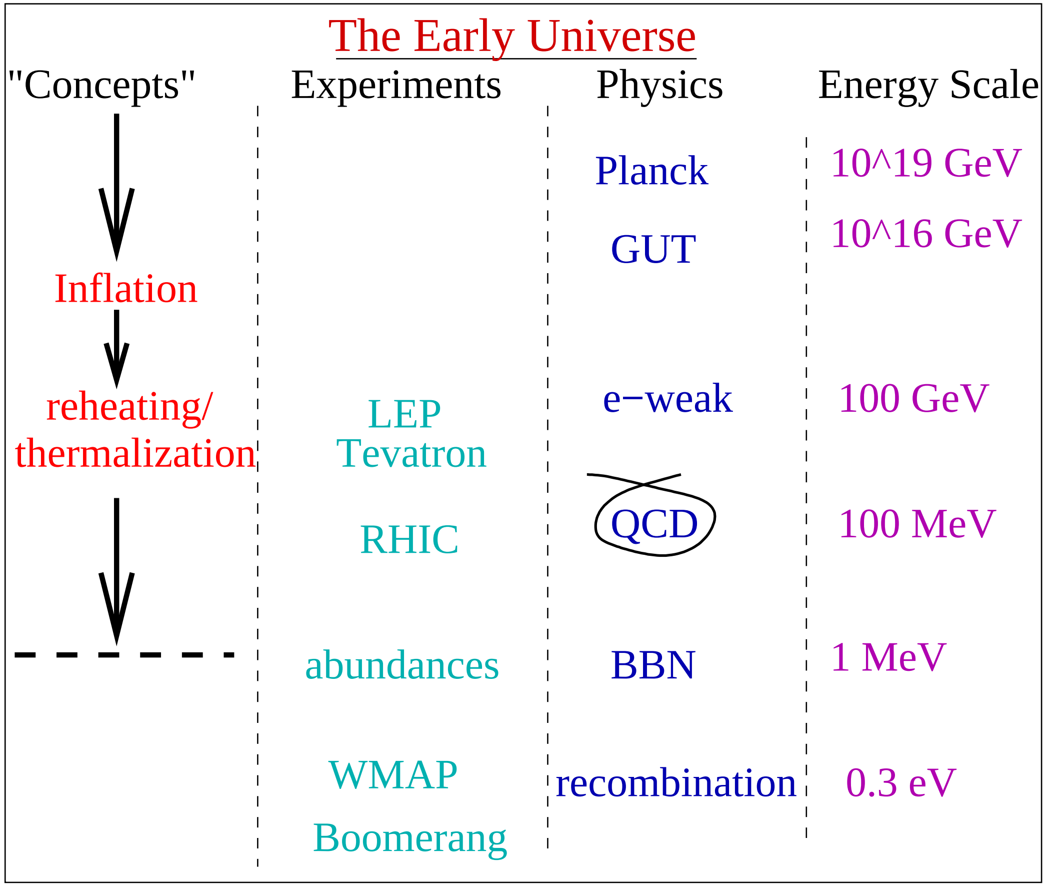
Relevance of QCD



The Early Universe

"Concepts"	Experiments	Physics	Energy Scale
		Planck	10^19 GeV
		GUT	10^16 GeV
Inflation			
reheating/ thermalization	LEP Tevatron	e−weak	100 GeV
	RHIC	QCD	100 MeV
	abundances	BBN	1 MeV
	WMAP Boomerang	recombination	0.3 eV

Relevance of QCD



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- Neutron Star interiors: Baryon density : 1/ fm^{-3}; Energy density $\sim (0.5\,GeV)^4$
- deconfined quarks may exist at these densities

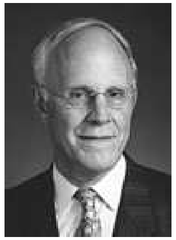
Discovery of QCD

David Gross David Politzer Frank Wilczek

2004 Nobel Prize winners in Physics

- Asymptotic freedom allows for perturbative calculations at large momentum scales; applied to high-temperature and high-density

Discovery of QCD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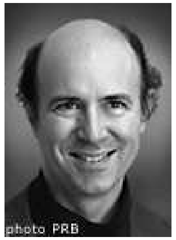
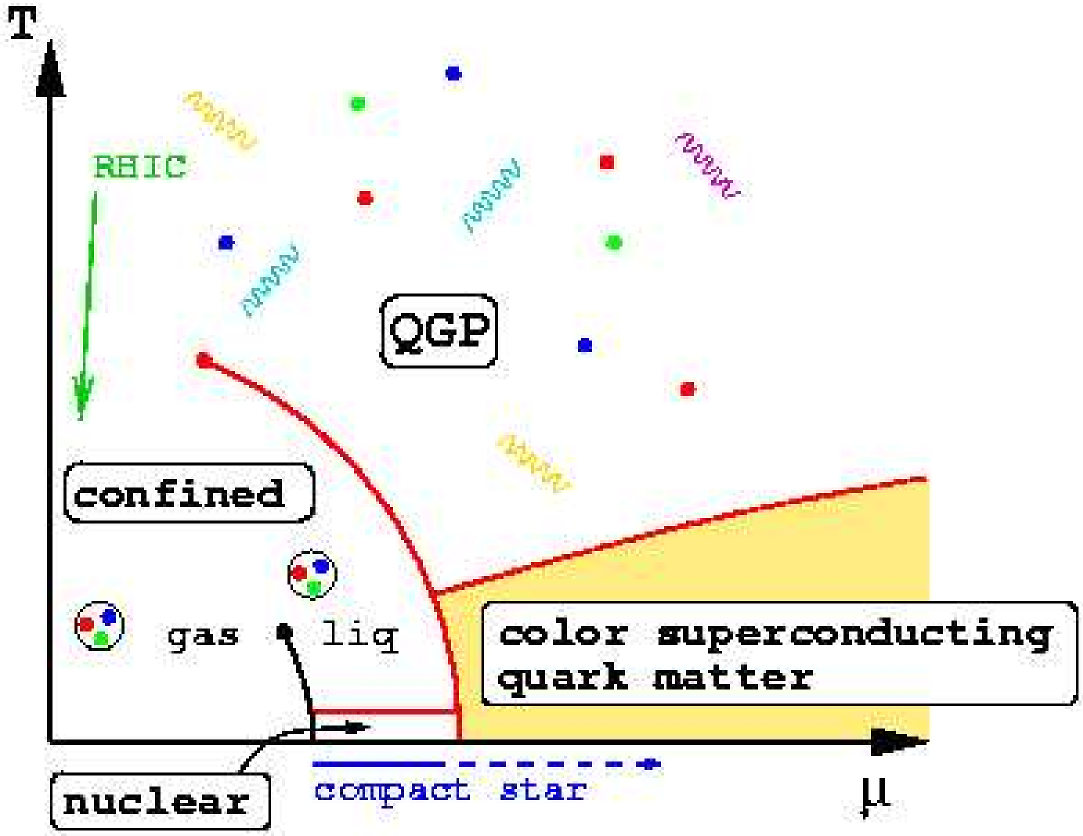


Frank Wilczek

2004 Nobel Prize winners in Physics

- Asymptotic freedom allows for perturbative calculations at large momentum scales; applied to high-temperature and high-density
- smallness of coupling constant enables controlled calculations; non-trivial physics can still emerge (many-body effects eg. BCS)

The QCD phase diagram

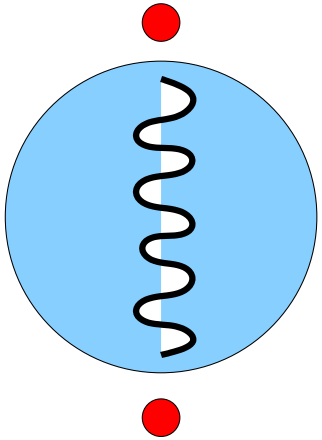


What happens to quarks and gluons at high baryon density? Are symmetries restored/broken?

The answer is important for understanding the interior of neutron stars.

BCS pairing in QCD

Fermi sphere



1-gluon exchange
between quarks.

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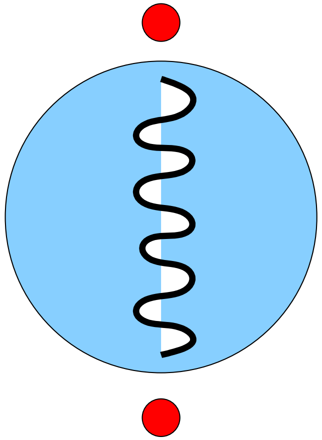

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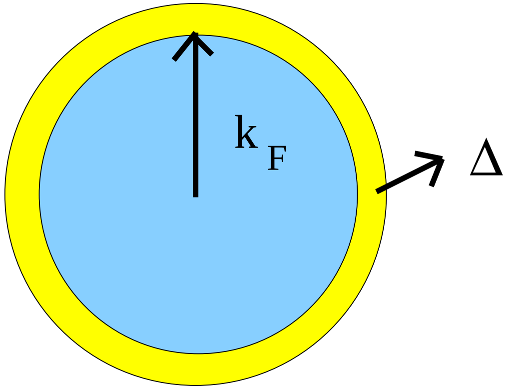

Cooper pairing results
in formation of a gap.

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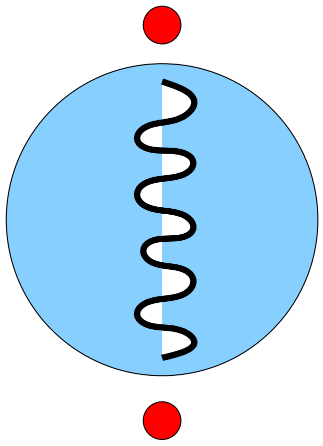

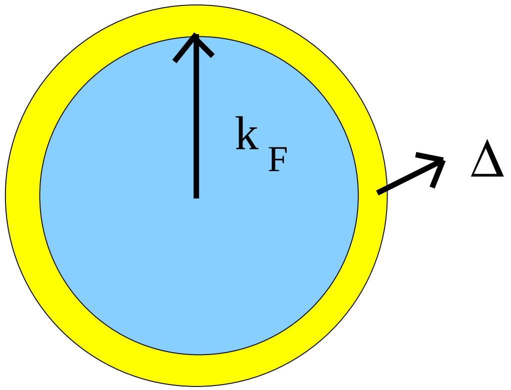

Gap $\Delta \sim c_1 \mu_q \, \mathrm{e}^{-c_2/g}$

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Quark pairing energy (~ 100 MeV) is much larger than in nuclei ($\sim$ MeV)

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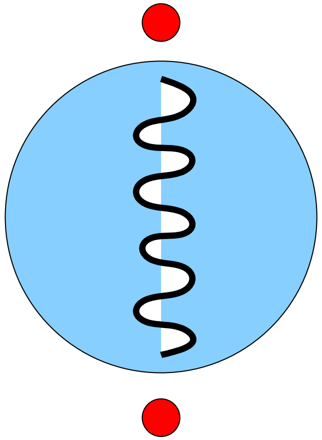

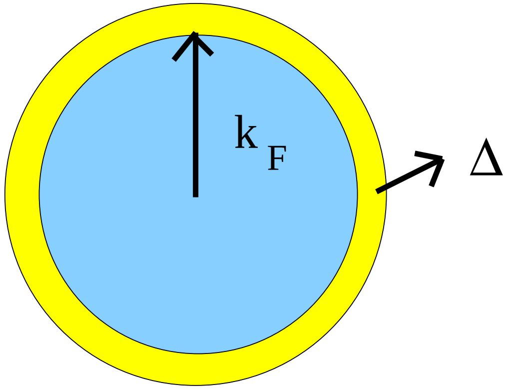

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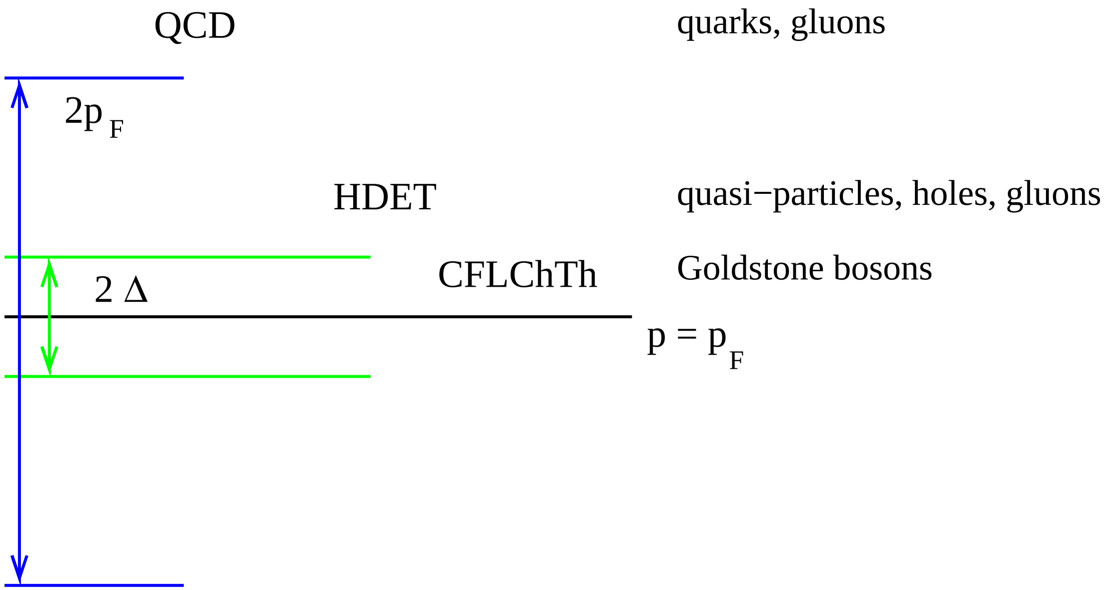
Quarks at the Fermi surface gain pairing energy

Excitations



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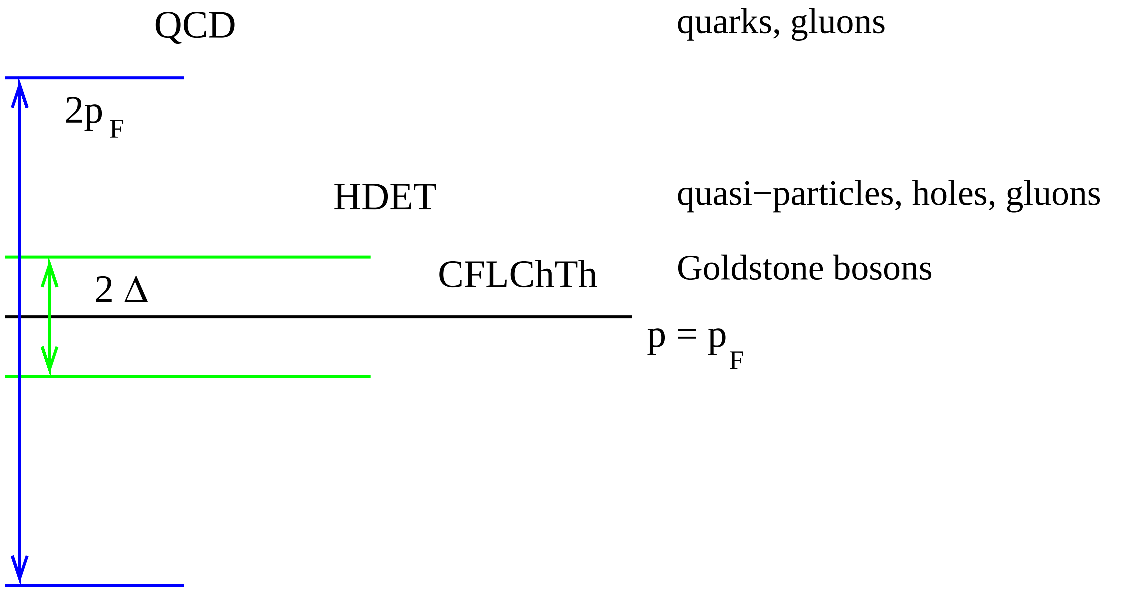

Low-energy excitations ($E < \Delta$) match low-lying multiplets of QCD at zero density

- $\pi^{\pm} \to l^{\pm} + \bar{\nu}_l$, $K^{\pm} \to l^{\pm} + \bar{\nu}_l$, and
- $\pi^0(\eta, \eta') \to \nu + \bar{\nu}$:

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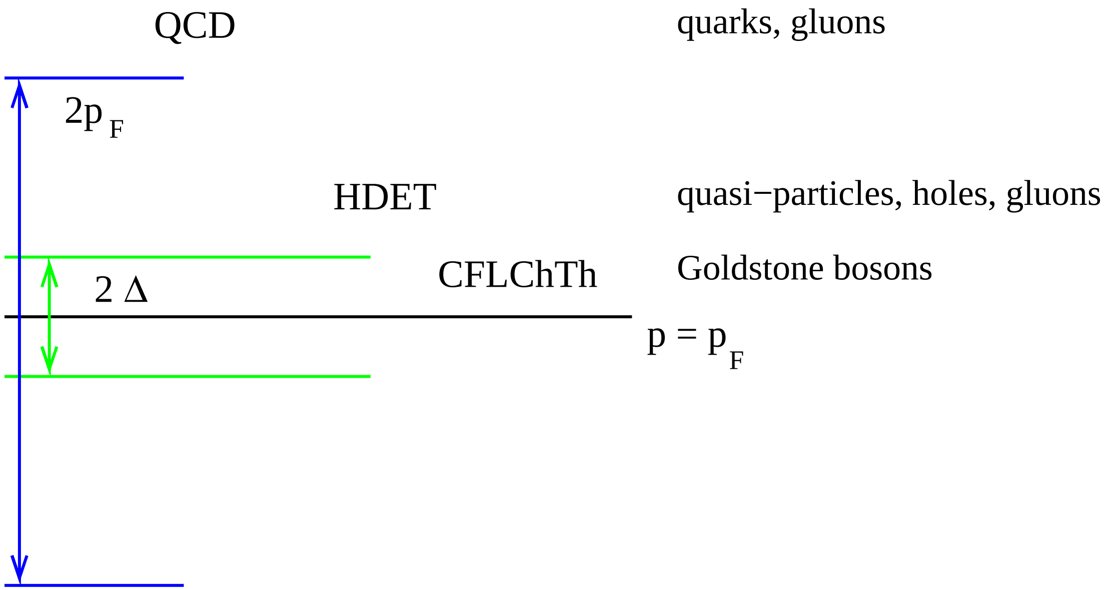

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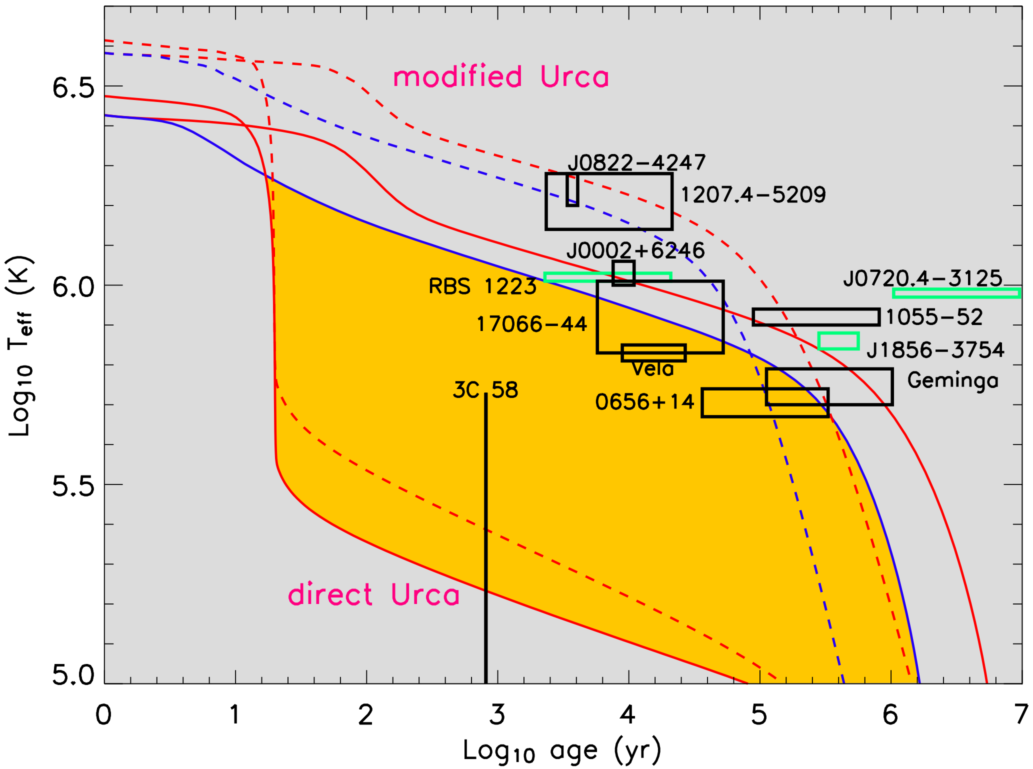
- $\pi^0(\eta, \eta') \to \nu + \bar{\nu}$:

$\beta-$ decays determine neutrino emission rates (important for stellar cooling)

Neutron star cooling (hadronic matter only)



— with superfluidity
— without
—-/- - - (Fe/H envelope)

Prakash & Lattimer, Science V 304 (2004).

Cooling equation: $c_V \frac{\partial T}{\partial t} = -\epsilon_\nu$

$$\epsilon_\nu = \frac{N_\nu \langle E_\nu \rangle}{\Delta\ V \Delta\ t}$$

Neutrino emission and scattering rates depend on the dense phase

Implications for neutron/quark stars

Quark matter may be realized in:

- Hybrid stars: Neutron stars with quark cores

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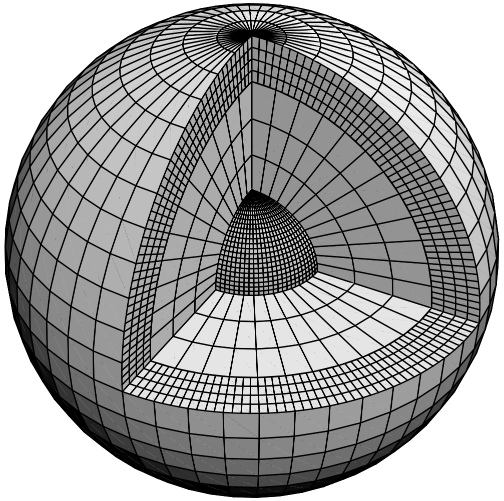
- Hybrid stars: Neutron stars with quark cores
- Bare quark stars: No nuclear mantle/shell at surface

Hybrid stars
2-flavor pairing
3-flavor pairing



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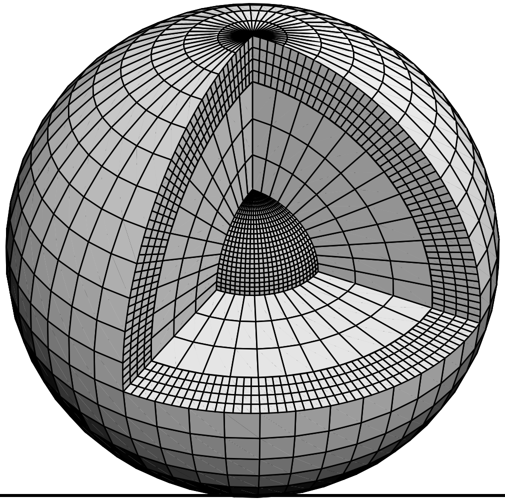
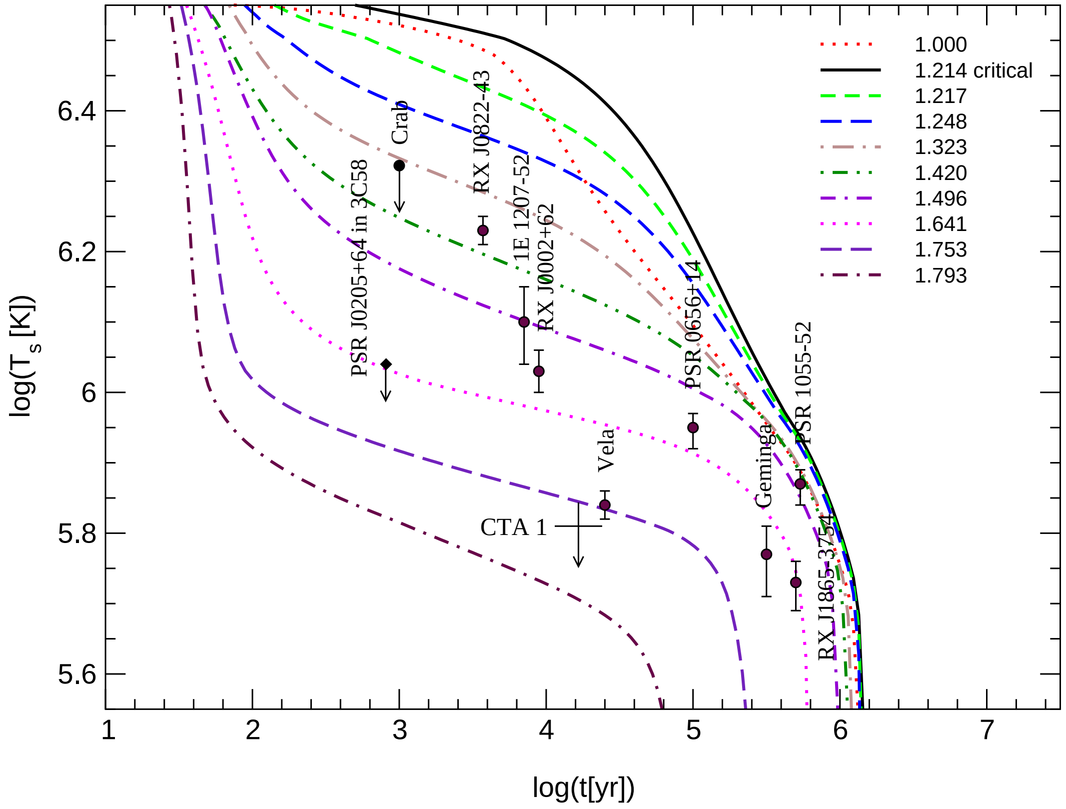


2-flavors: u, d pair, s is heavy ; no global symmetries broken → no Goldstone bosons (except superfluid mode);
charge neutrality requires: $\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$
electrons control the specific heat and thermal conductivity

Quark/gluon contribution is suppressed for $T \ll \Delta$

Cooling curves



2-flavor + density dependent $s-$ quark pairing

Cooling data are consistent with interpretation as 2-flavor spin-0 gap + density-dependent $s-$ quark spin one gap.

Quark matter (generalities)

Witten hypothesis (1984):

At large baryon number, E/A of 3-flavor quark matter is larger than for nuclear matter.

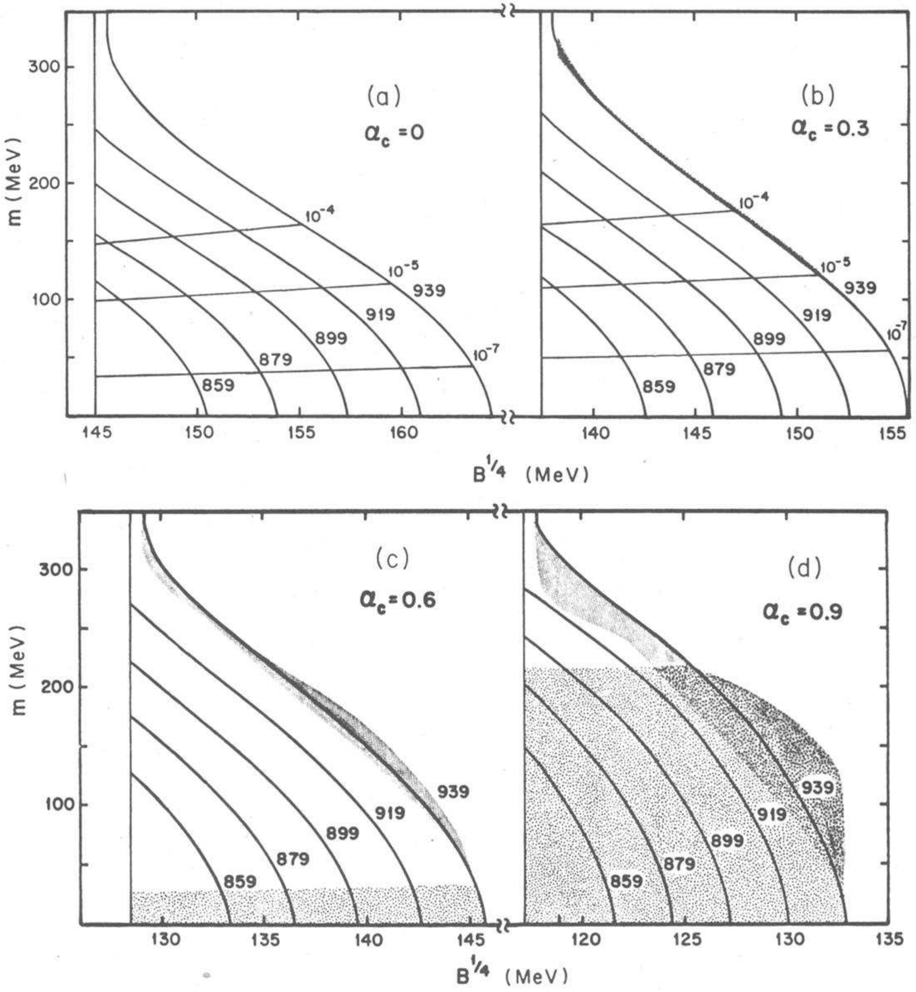


FIG. 1. Contours of fixed E/A in the $B^{1/4}$-m plane for α_c=0, 0.3, 0.6, and 0.9. The vertical line at the left of each figure is the minimum $B^{1/4}$ for which nonstrange quark matter is unbound (see text). In (a) and (b) the nearly horizontal lines are contours of fixed hadronic electric charge per baryon as marked. In (c) and (d) the dotted regions are regions of negative hadronic electric charge. The grey shading around the 939 contour represents the same contour calculated using different renormalization schemes (see text).

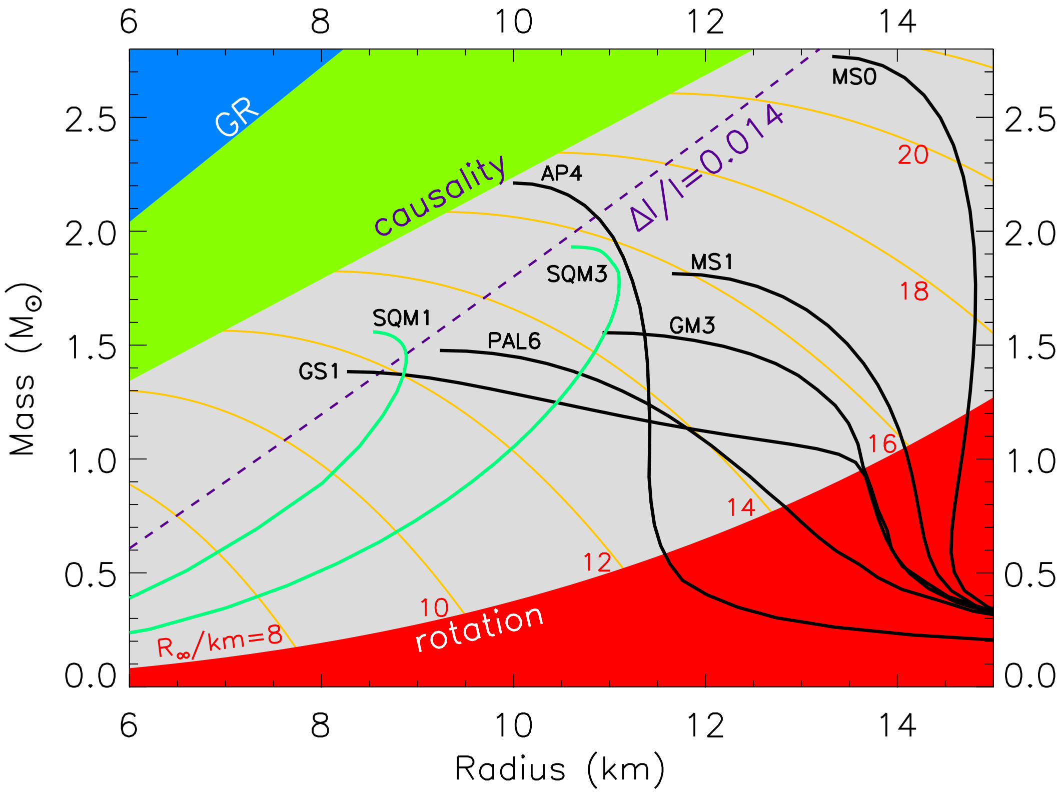
Equation of state

$$\boxed{P = \frac{1}{3}(\epsilon - 4B) \;\leftarrow\; EOS(\alpha_s = 0, m_s = 0)}$$

TOV equations:

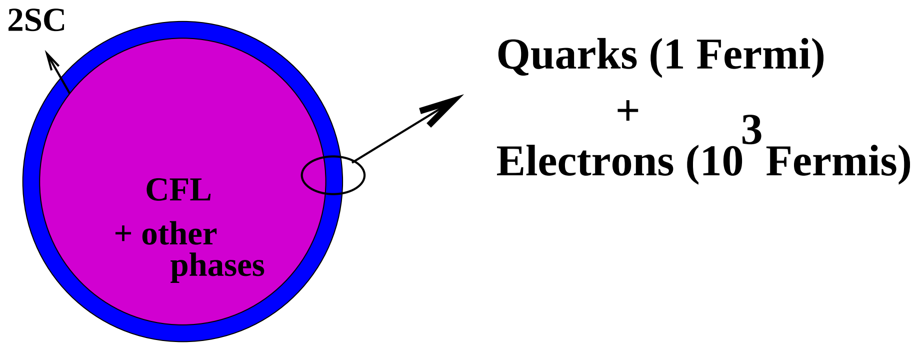
$$\frac{dM(r)}{dr} = 4\pi r^2 \epsilon(r), \quad \frac{dP(r)}{dr} = -\frac{GM(r)\epsilon(r)}{r^2}$$

$$\text{bag constant } B = (145 \text{ MeV})^4 \rightarrow \epsilon(R_s) = 4B = 4 \times 10^{14} \text{g/cc}$$



Prashanth Jaikumar

Surface of bare quark stars (conventional)



Quarks (1 Fermi)
+
Electrons (10^3 Fermis)

Bare Quark Star: 3-flavor core with 2+1 flavor surface layer

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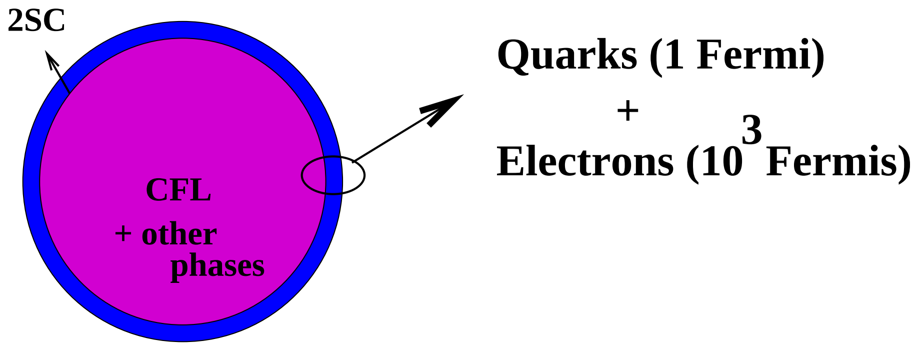

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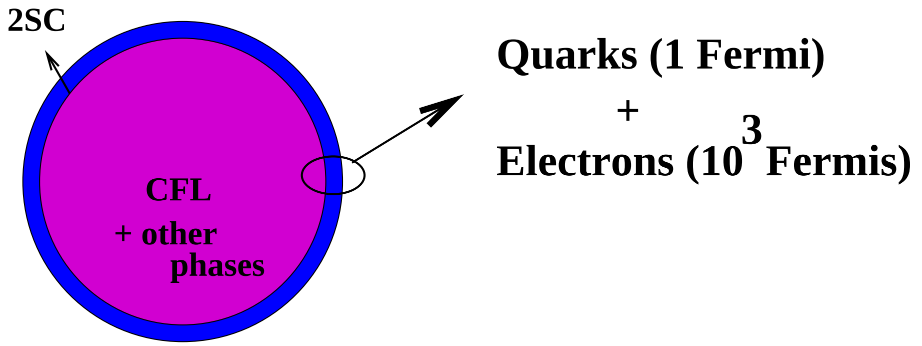

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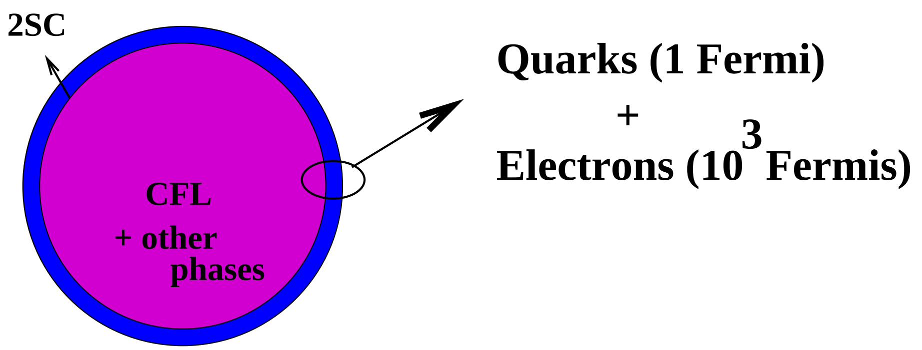
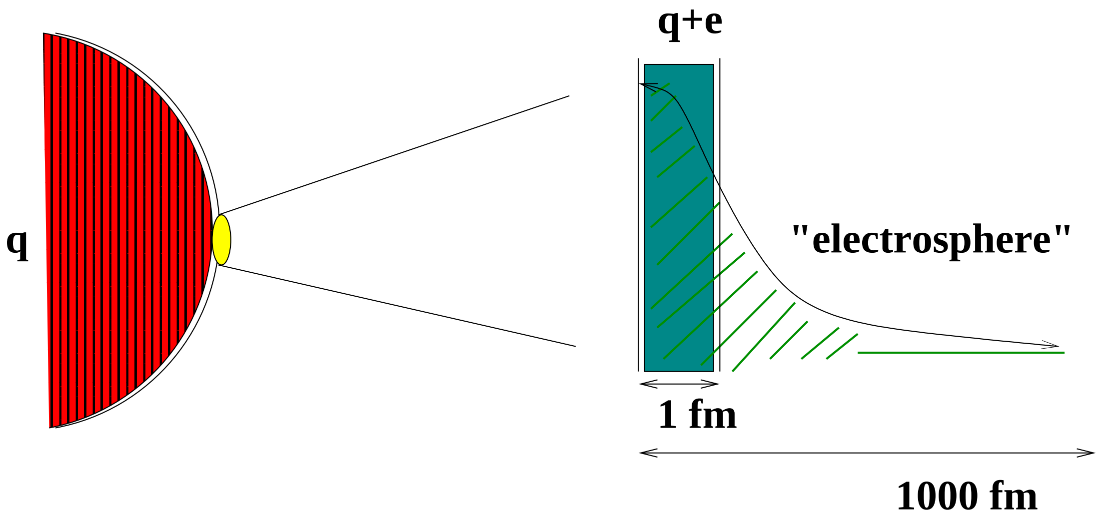


Bare Quark Star: 3-flavor core with 2+1 flavor surface layer

Implications

- Electrons are present at the surface.
  For Temperatures of interest ($\leq \mathrm{MeV}$), they form a degenerate Fermi gas.
- Surface electrons provide large neutrino and photon emissivity at these temperatures (bremsstrahlung process)

The electrosphere



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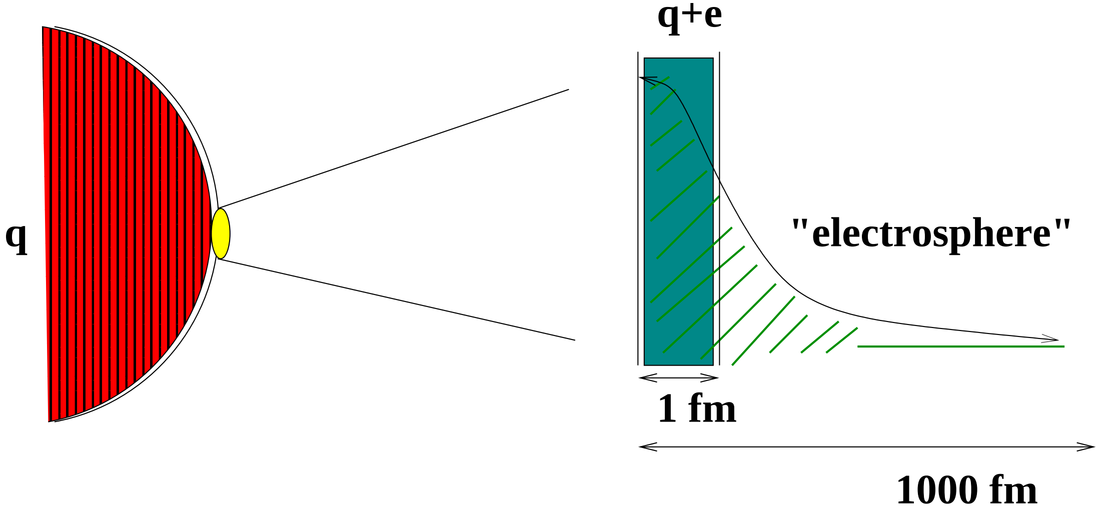
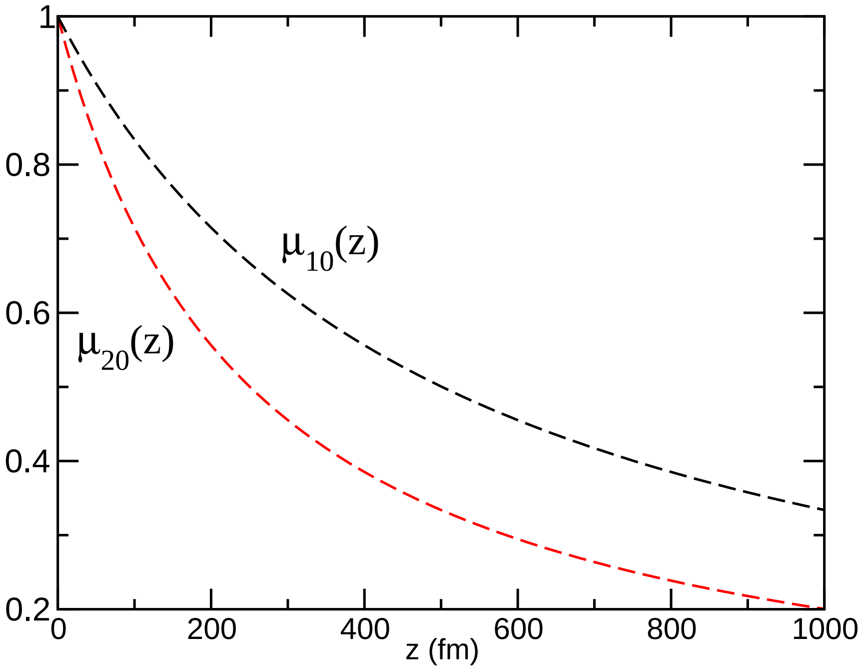


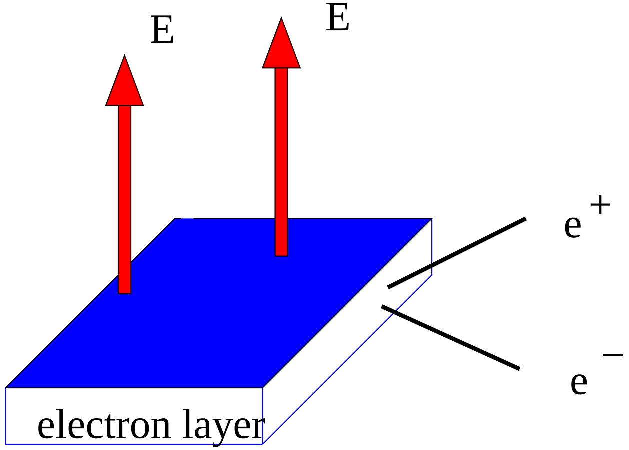


$$n_e = \frac{\mu_e^3}{3\pi^2}, \quad \mu_e = e\phi$$

$$\frac{d^2\phi}{dz^2} = e n_e$$

$$\mu_e(z) = \frac{\mu_e(0)}{1+z/H}, \quad H \sim 500 \text{ fm};$$

Super-critical electric fields



$$l_e \sim 10^3\mathrm{fm}, \quad E \sim 5 \times 10^{16}\ \mathrm{V\ cm}^{-1}$$

$$E_{\mathrm{cr}} = \frac{m_e^2 c^3}{e\hbar} \simeq 1.3 \times 10^{16}\mathrm{V\ cm}^{-1}$$

$$R_{\pm} = \frac{m_e^4 c^5}{24\pi\hbar^4} \simeq 2 \times 10^{50} \left(\frac{E}{E_{\mathrm{cr}}}\right)^2 \mathrm{cm}^{-3}\ \mathrm{s}$$

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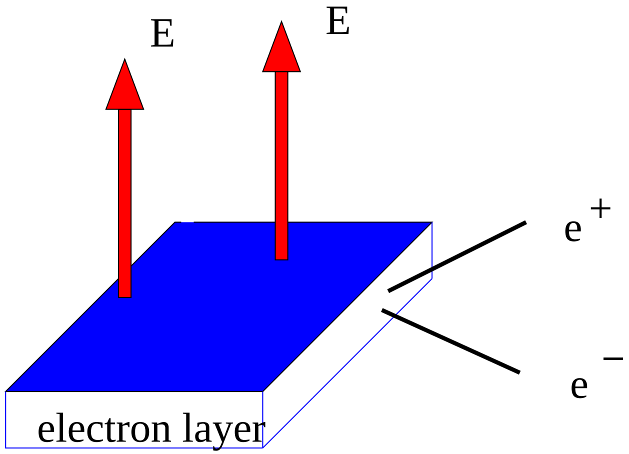

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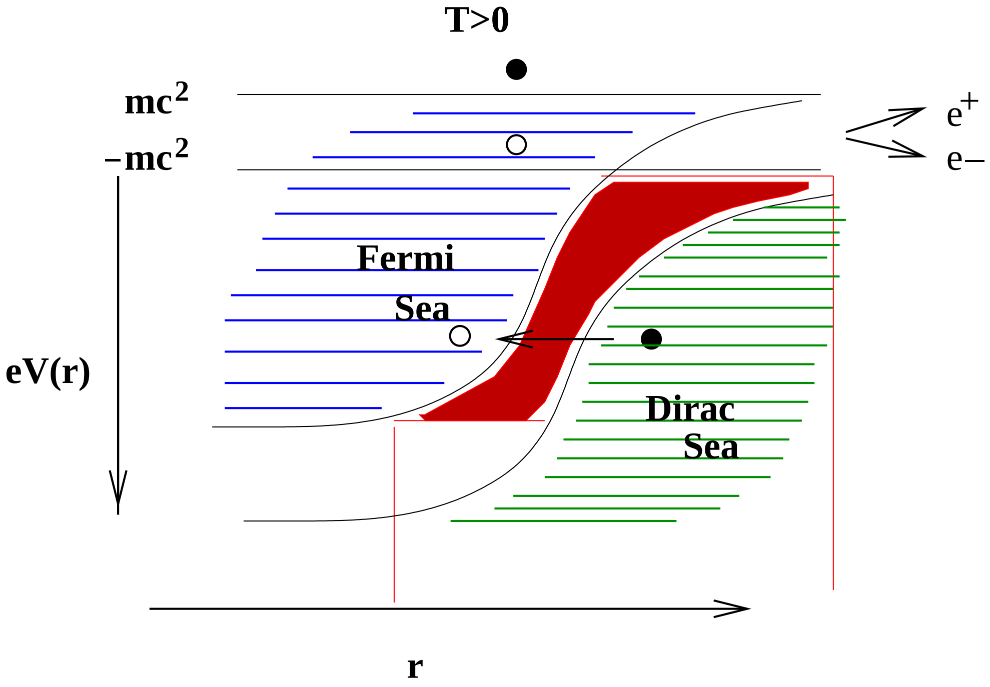

e^+e^- *Pair Emission at the Star's Surface*

e^+e^- Pair winds flow from several astrophysical objects.

..from Neutron stars/pulsar magnetospheres ($\gamma\, B \rightarrow e^+e^- B$)

NEW! ..from pair-creation at the surface of a bare quark star

(Jaikumar et al, Phys.Rev. **D70** (2004))

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Surface Photon Emission

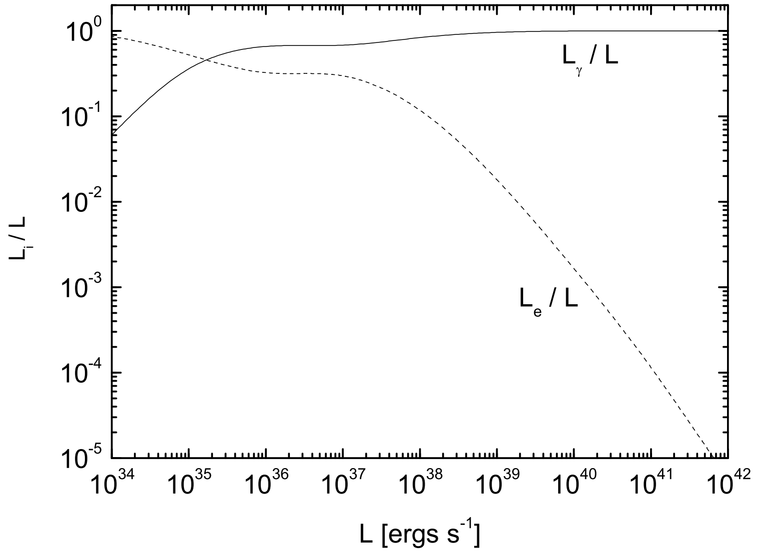
- $e^+e^- \rightarrow \gamma\gamma$
- $e^-e^- \rightarrow e^-e^-\gamma$
- $e^-\gamma \rightarrow e^-\gamma\gamma$
- $\gamma\gamma \rightarrow e^+e^-\gamma$

$2 \rightarrow 2$ *processes do not affect the luminosity.*

Surface Photon Luminosity

Average photon energy is 0.5 MeV or more due to $e^{+}e^{-}$ annihilation.

($\sim$ keVs for Neutron Stars)



Photon luminosities exceed Eddington limit.

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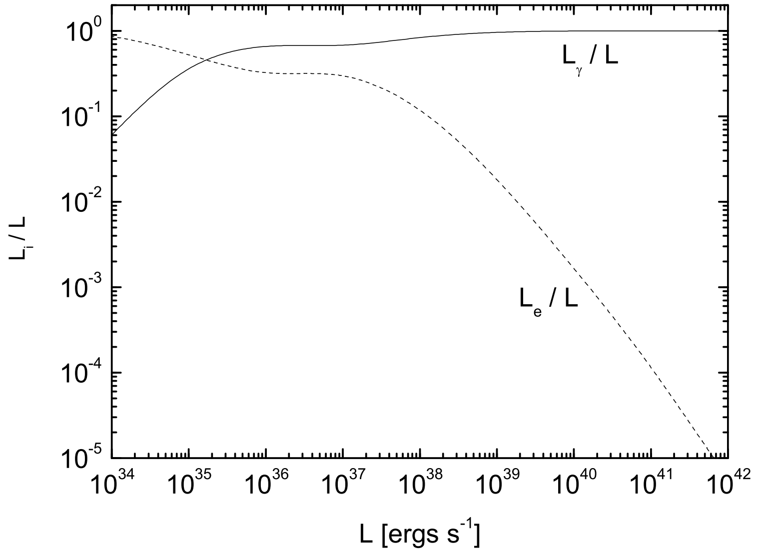

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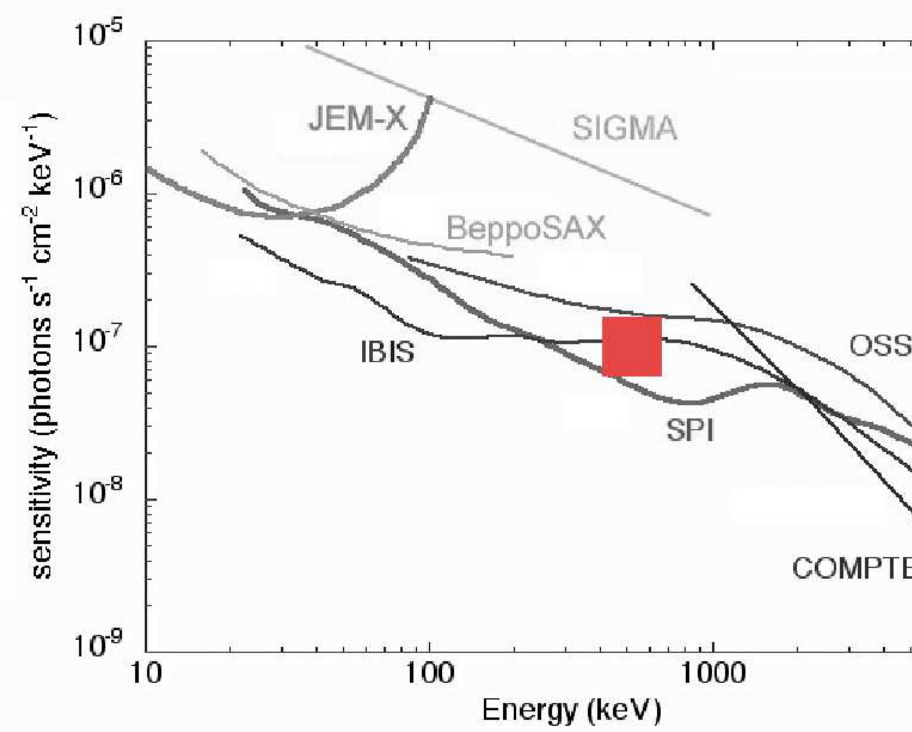
Prospects with INTEGRAL satellite (2002)



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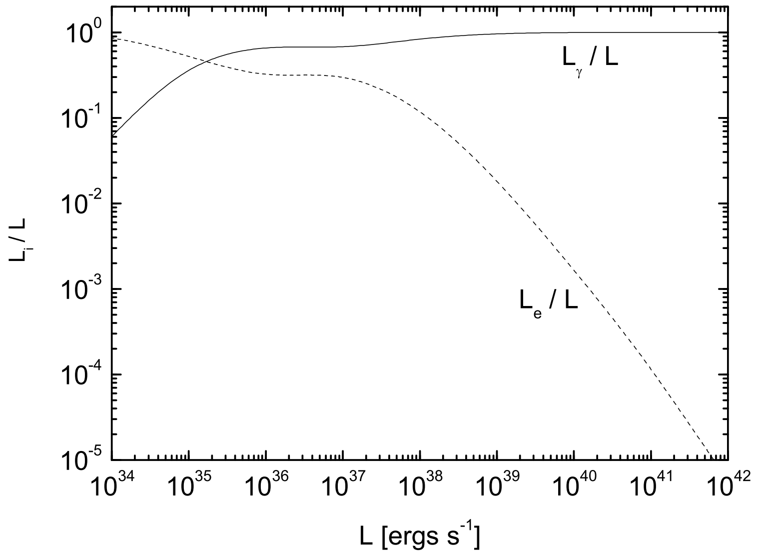

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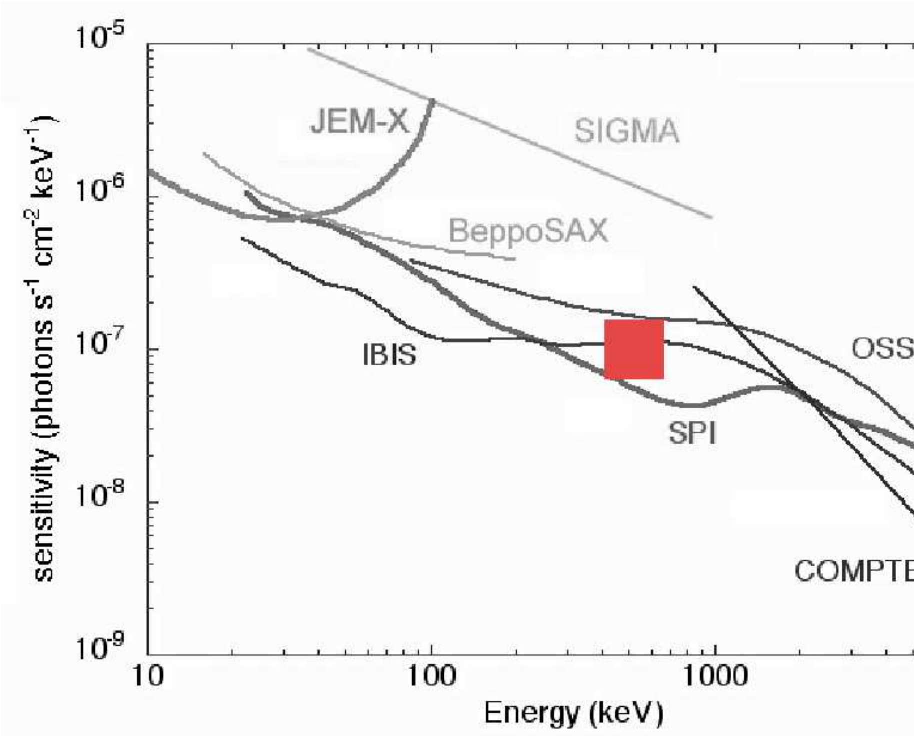
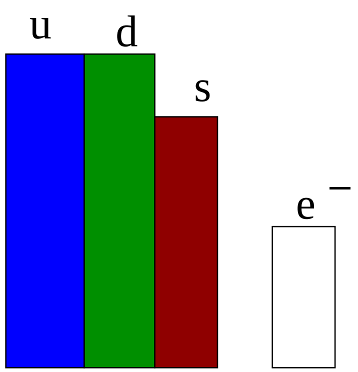


(J. Knodlseder, CESR)

Caveats

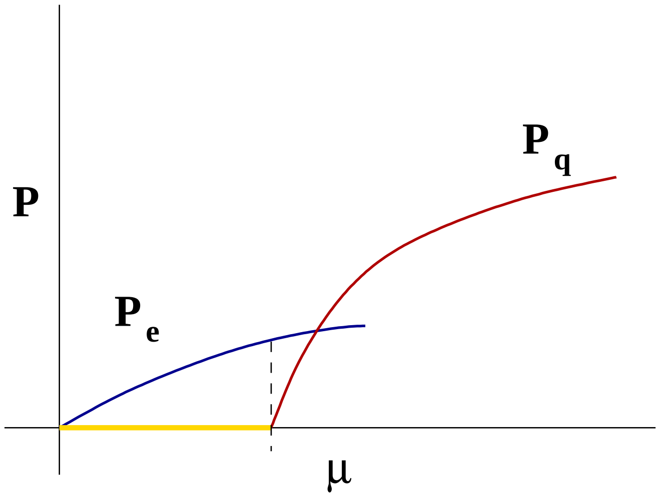
- Quark star surface may support a crust

Heterogenous Quark Matter?



(Jaikumar, Reddy and Steiner, nucl-th/0507055)

Low density ($m_s \neq 0$): local neutrality



- $\frac{2}{3}n_u - \frac{2}{3}n_d - \frac{1}{3}n_s - n_e = 0$
- $P_q = P_0 - n_Q\mu_e + \chi_Q\mu_e^2 + \ldots;$
- $P_q < 0 \rightarrow$ nugget phase$+e^-$??

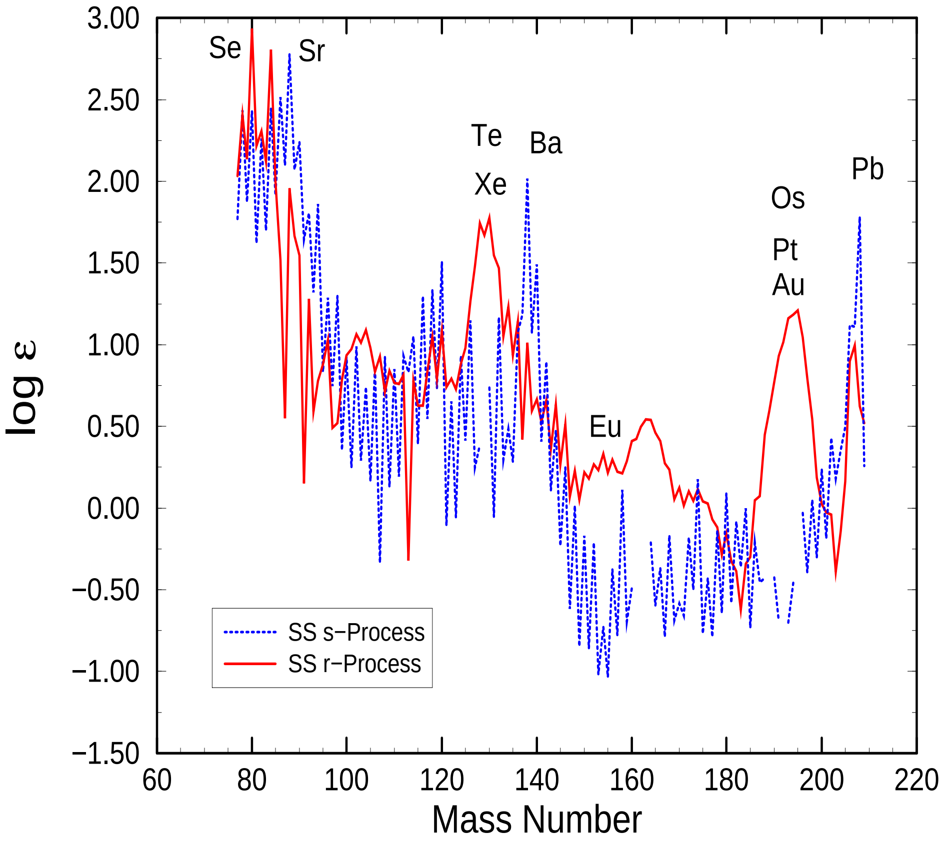
Strange stars and Astrophysics

Strange stars are linked with several unexplained phenomena:

- Soft-gamma repeaters (SGRs): Flash-heating followed by photon emission from strange star surface
  (V. V. Usov, PRL 87 (2001) 021101)
- Gamma-ray bursters (GRBs): Fireball energy obtained from phase transitions in quark matter
  (R. Ouyed and F. Sannino, AA 387 (2002) 725)
- X-ray variability in LMXBs:
  kHz quasi-periodic oscillations explained by rapidly rotating strange stars
  (J. Zdunik and E. Gourgoulhon, PRD63 (2001) 087501)

Quark stars might even be candidates for nucleosynthesis - The Quark Nova

observations of n-capture elements in stars



The s-process (blue) and r-process (red) abundances after deconvolution

The s-process yields are well-understood from theory of AGB stars

r-process yields are derived (Total=r+s)

Candidate sources:

1. Type II Supernovae
2. Neutron star mergers

Alt: decompression of neutron matter

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Advantages:

1. large neutron density means $(n-\gamma)$ equilibrium is easily attained.
2. small electron fraction $Y_e \sim 0.03 - 0.2$ in neutron matter implies enough neutrons to produce heaviest elements (actinides).

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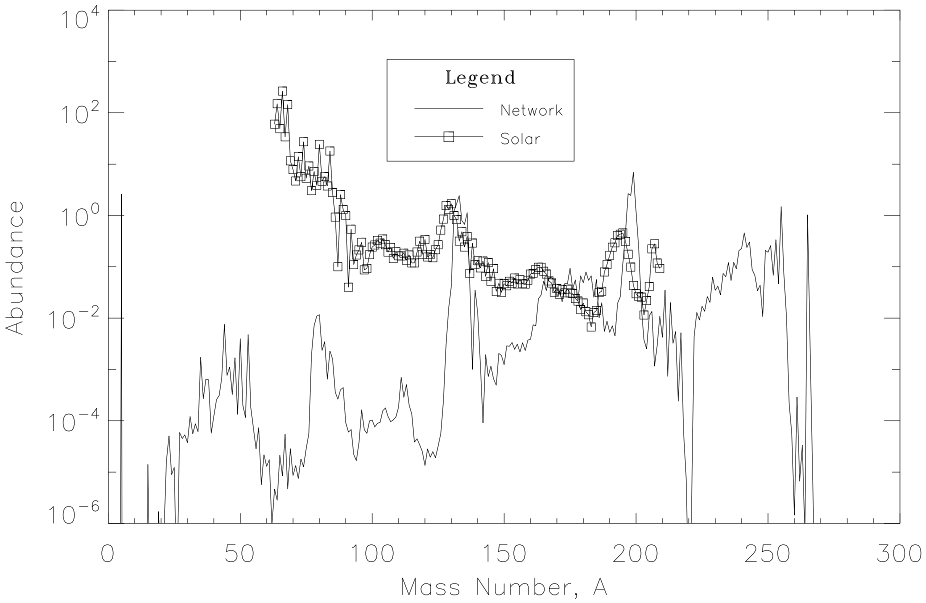
$\rho[\mathrm{g/cc}]$	$T_9[10^9\mathrm{K}]$	Y_e	Z
10^{14}	0	0.03	35
10^{11}	1	0.04	$40-70$

- dynamical expansion is modelled
  $|d\rho/dt| = 4.46\alpha\rho_{10}^{-1/2}\ \mathrm{ms}; \quad \alpha = 0.1 - 10$
- During decompression, density falls, T rises initially (due to $\beta-$ decays)
- r-process conditions reached at $\rho \sim 10^{11}$ g/cc, $T \sim 0.1$ MeV.

Element abundance ($Y_e = 0.03, \tau_{\text{exp}} = 0.1$ *ms*, $S/k_B = 1$)



- α-decays (^{206}Pb and beyond) not included yet.
- r-process peaks are sharper than solar.

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