Quest for new states of matter in stars

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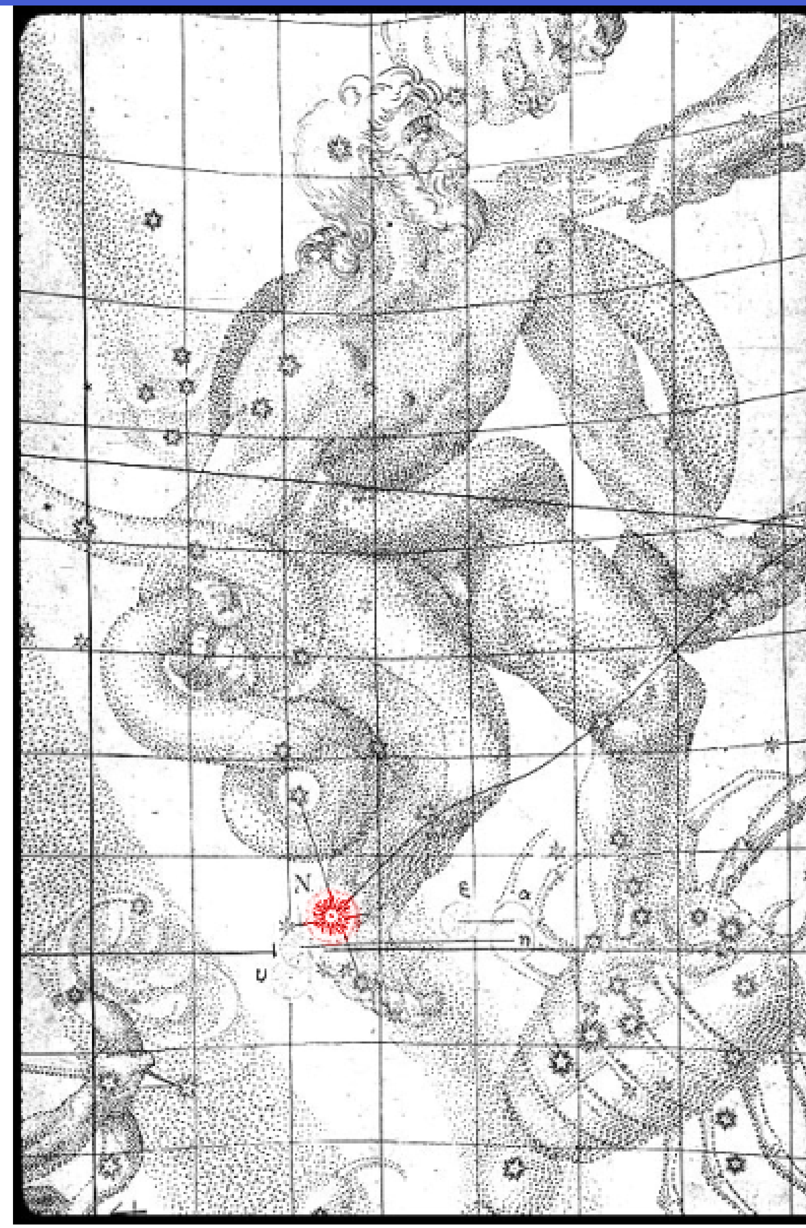
Outline

- Basics properties of neutron stars
- Very dense matter inside stars
- Quark matter and superconductivity
- Properties of quark matter in stars
- Overview of current ideas
- Summary

Neutron stars: prehistory

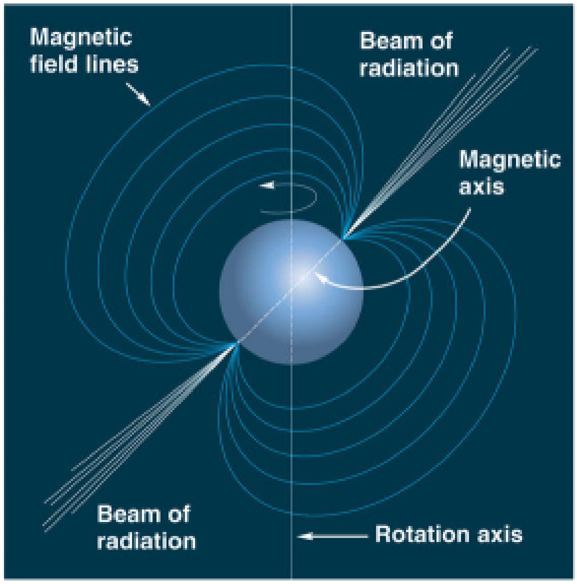
- Historical supernovae (Milky Way):
  - 185 (Chinese): ?
  - 386 (Chinese): ?
  - 393 (Chinese): ?
  - 1006 (China, Japan, Korea, Arab lands, Europe): SNR PKS 1459-41
  - 1054 (China, Japan): Crab Nebula
  - 1181 (China, Japan): SNR 3C58 (?)
  - 1572 (Europe, China, Japan): Tycho's remnant
  - 1604 (Europe, China, Japan, Korea): Kepler's remnant
- 1932: discovery of the neutron by Sir James Chadwick[1935]

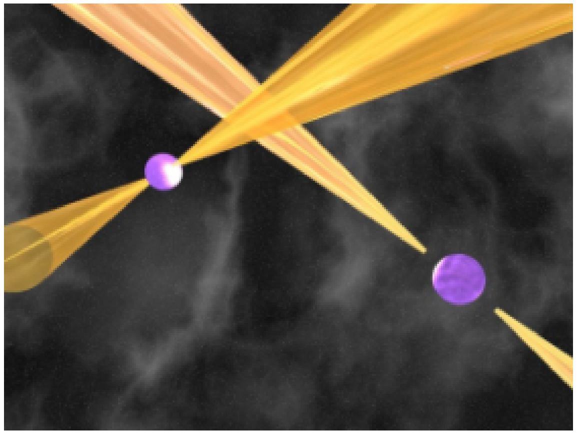


Kepler's drawing of Supernova 1604

Neutron stars: historical overview

- Predicted theoretically
  - by Landau (unpublished) in 1932
  - by Baade & Zwicky in 1934
- Discovery of pulsars
  - 1967: radio pulsating objects
    (Hewish[1974], Bell, Pilkington, Scott & Collins)
  - 1968: Vela and Crab (≡ SN 1054) pulsars
    (Large et al, Staelin et al, Cocke et al,)
  - 1974: 1st pulsar in a binary
    PSR 1913+16 (Taylor & Hulse)[1993]
  - 2003: double pulsar binary
    PSR J0737-3039 (Burgay et al, astro-ph/0312071)

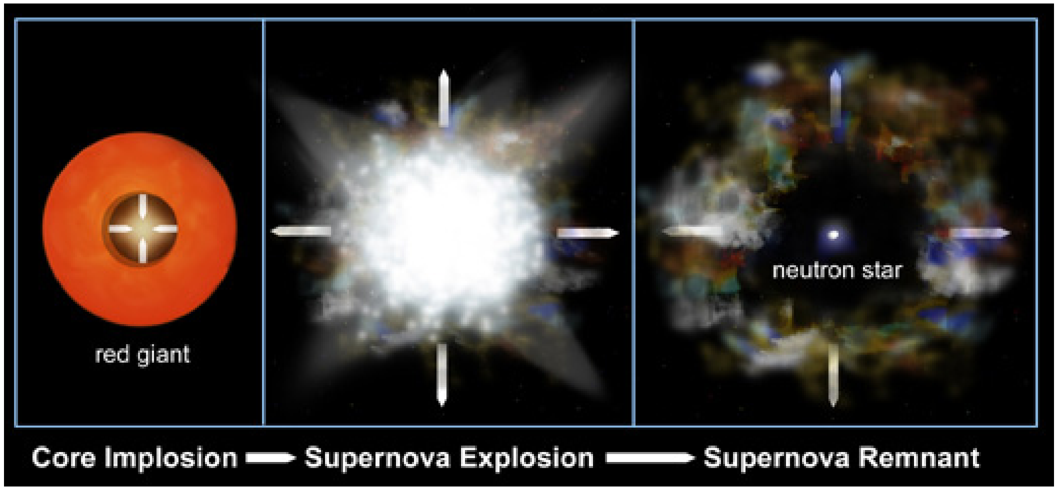




Birth of neutron stars

Compact stars are the end products of stellar evolution

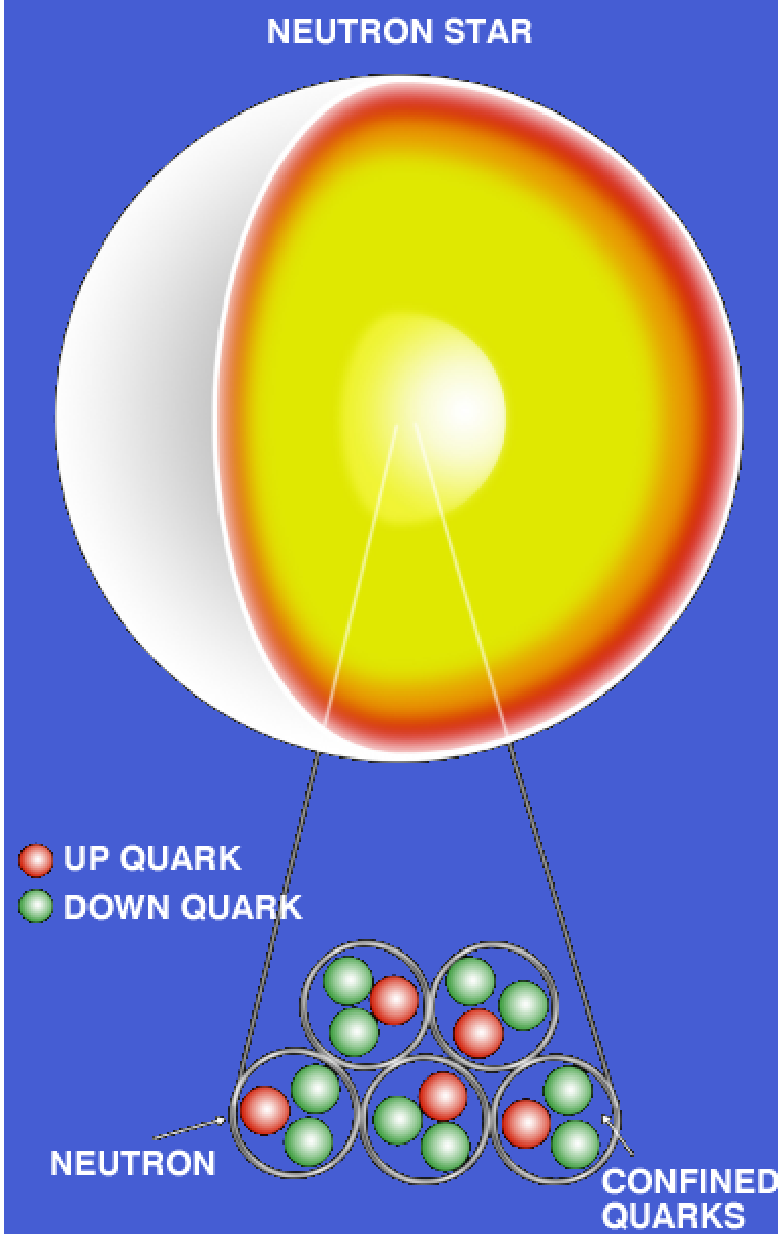
1. An iron core of a massive star ($8M_\odot \lesssim M \lesssim 20M_\odot$) collapses
2. Gravitational energy $\to$ explosion
3. Outcome: neutron star $\oplus$ energy $\oplus$ dust



- So bright it may be seen in the sky during the day!
- Most of energy ($\sim \frac{1}{10} M_\odot c^2 \simeq 10^{53}$ erg) in neutrinos: $p + e^- \to n + \boxed{\nu_e}$
- Estimated rate: 1 supernova every 30 – 60 years in our Galaxy

Basic properties of neutron stars

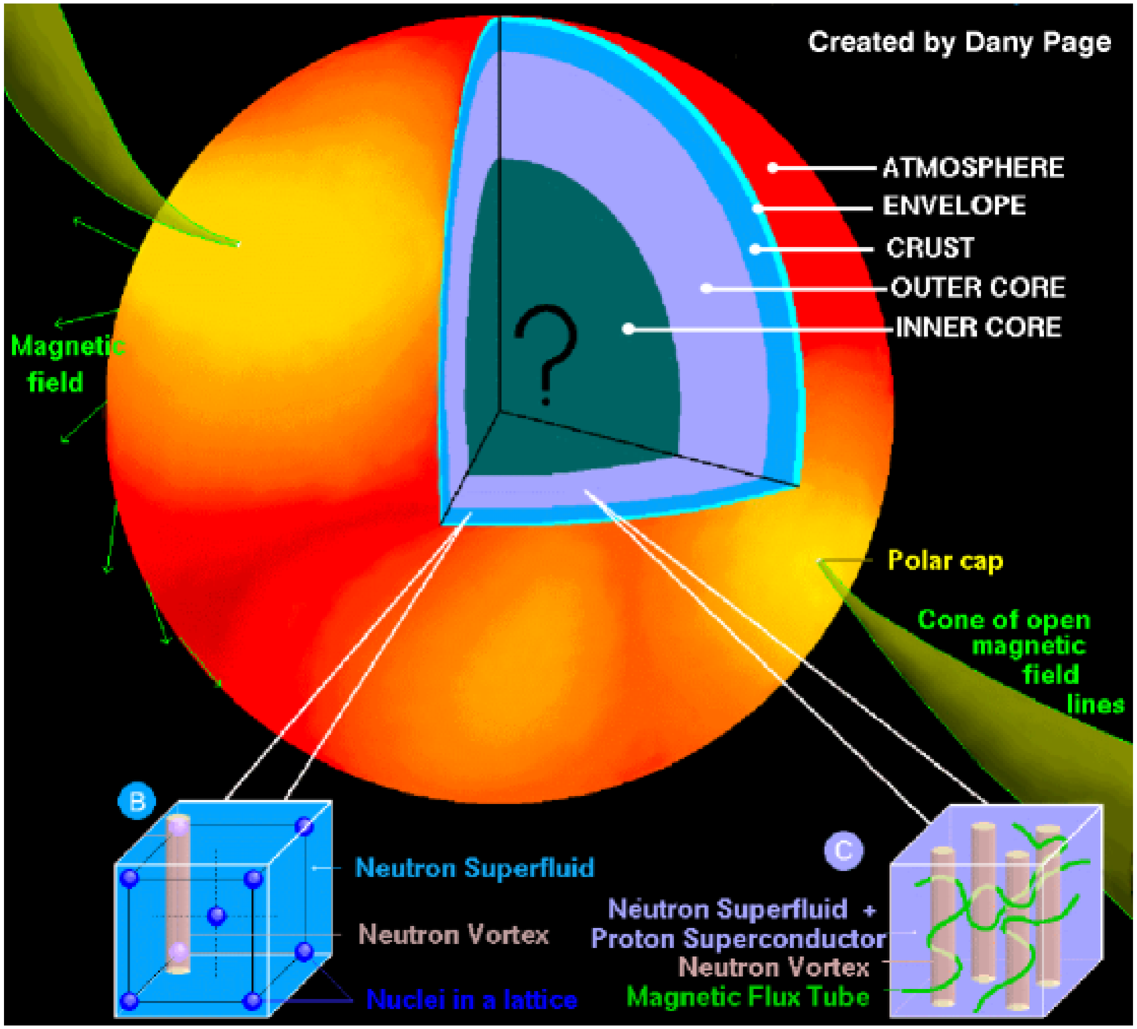
- Diameter:
  $R \simeq 20$ km (12 miles)
- Mass:
  $1.25 M_\odot \lesssim M \lesssim 2 M_\odot$
  where $M_\odot = 1.989 \times 10^{33}$ g
- Core temperature:
  $10 \text{ keV} \lesssim T \lesssim 10 \text{ MeV}$
  where $1 \text{ MeV} = 1.16 \times 10^{10}$ K
- Surface magnetic field:
  $10^8 \text{ G} \lesssim B \lesssim 10^{14} \text{ G}$
- Rotational period:
  $1.6 \text{ ms} \lesssim P \lesssim 12 \text{ s}$
- Surface gravity 10^{11} times that on Earth!



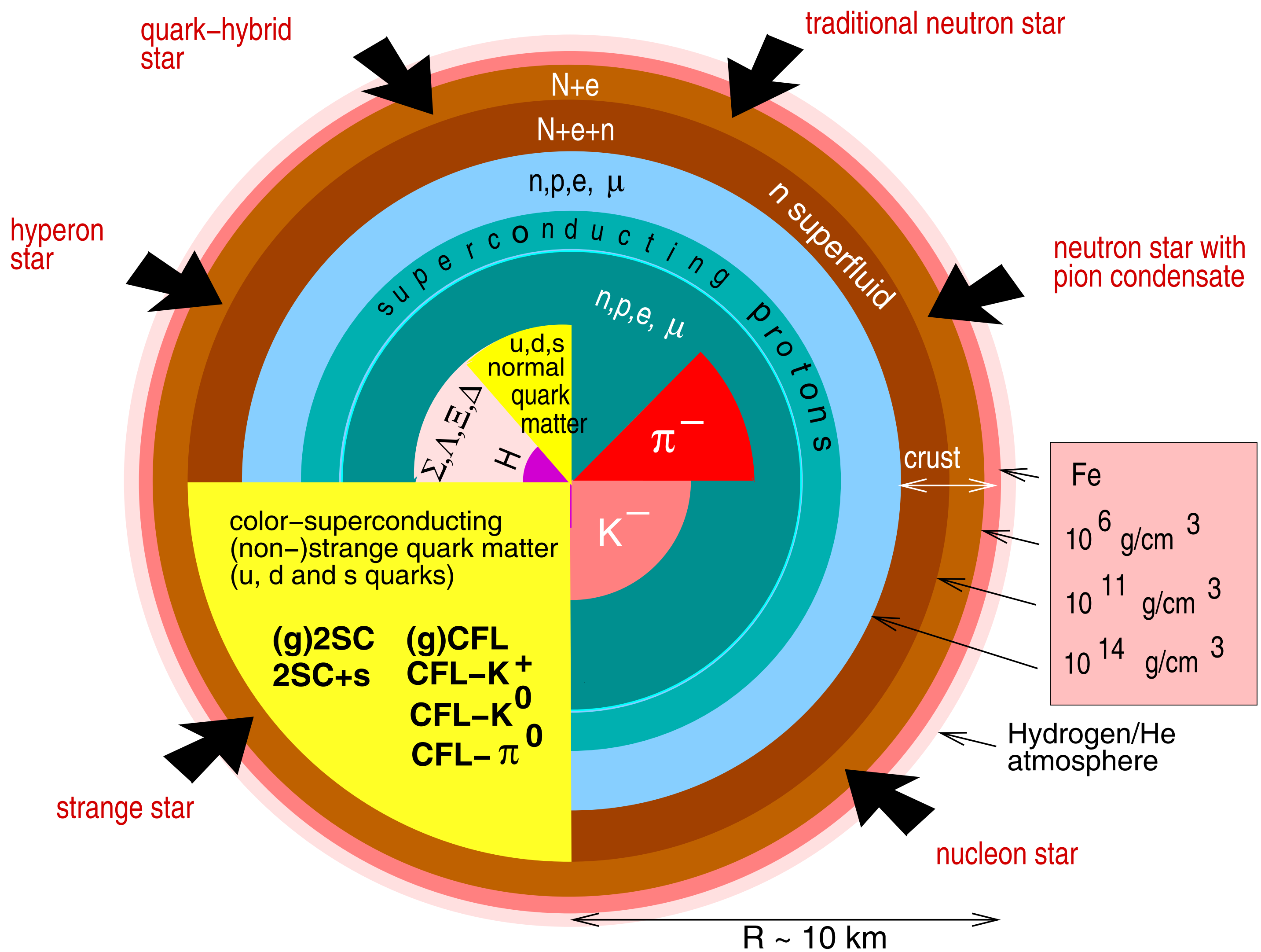
Internal structure

Starting at the surface

- Atmosphere (1 mm — 1 m): ^{56}Fe, ^{4}He, H
- Outer crust ($\sim$ 300 m): nuclei (Fe) & e^-
- Inner crust ($\sim$ 600 m): nuclei, neutrons & e^-
- Outer core (1 – 10 km): neutrons, protons & e^-
- Inner core (?): exotic states of matter (?)



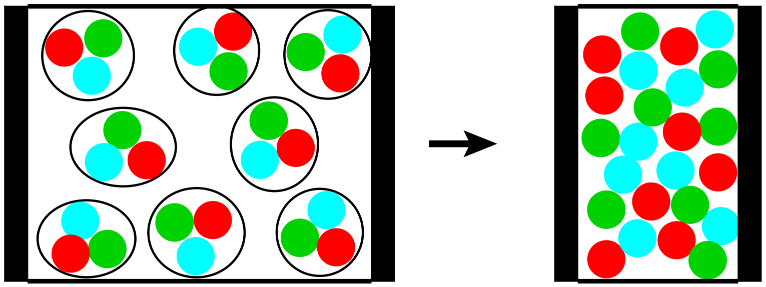
Possible states of matter in the stellar core

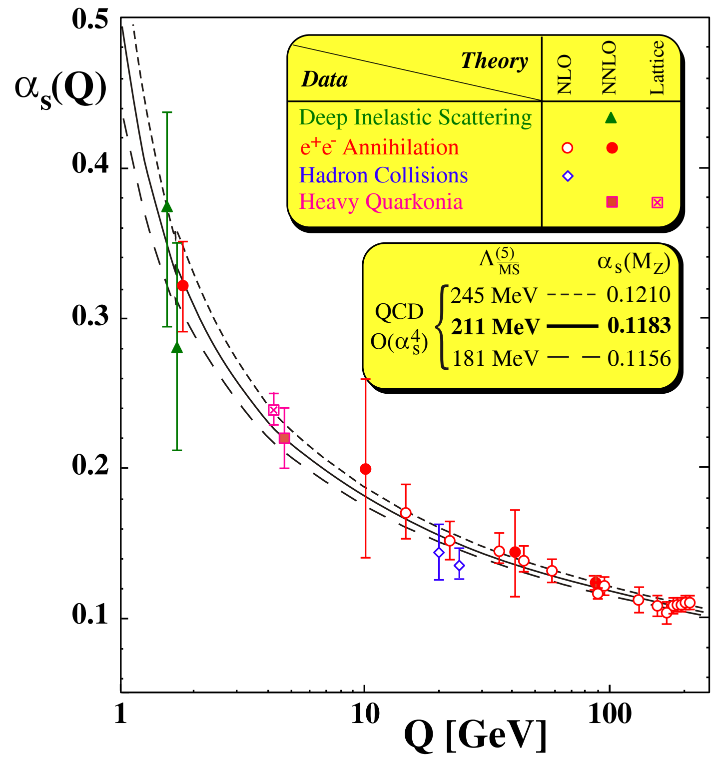


[figure from F. Weber, astro-ph/0407155 (modified)]

Very dense baryonic matter

Baryons at high density → quark matter





- Asymptotic freedom: $\alpha_s(\mu) \ll 1$

  $1/\mu$ – average interparticle distance

  [Gross&Wilczek; Politzer,'73][2004]

⇒ **Weakly** interacting regime

[Collins&Perry,'75]

Note: realistic densities in stars are not sufficiently large:

$$\rho \lesssim 10\rho_0, \text{ where } \rho_0 \approx 0.15 \text{ fm}^{-3} \quad \Rightarrow \quad \mu \lesssim 0.5 \text{ GeV}$$

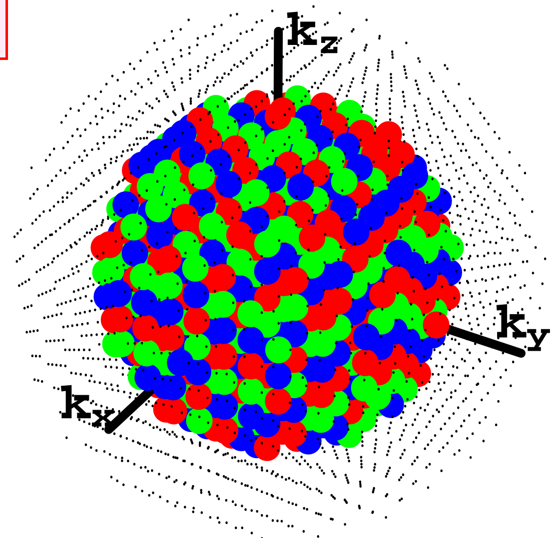
Ground state of dense quark matter

Noninteracting quarks:

(i) Deconfined quarks ($\mu \gg \Lambda_{QCD}$)

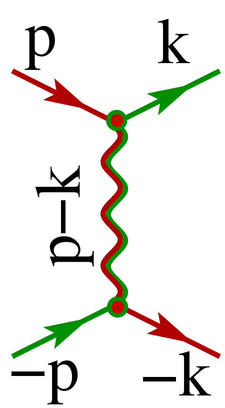
(ii) Pauli principle ($s = \frac{1}{2}$)

$\Rightarrow$



Interacting quarks:

- Quarks interact by a Coulomb-like interaction (exchanging gluons), i.e.,



$\Rightarrow$ Cooper theorem

$\Downarrow$

Instability

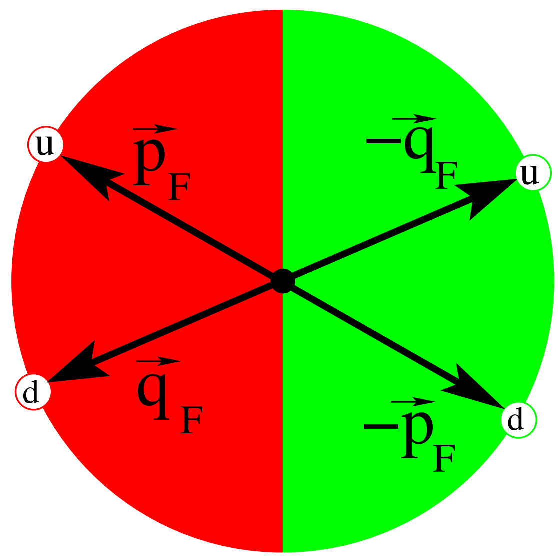
$\Downarrow$

Color superconductivity

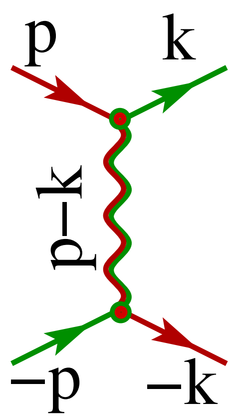
Cooper pairs of quarks

Quarks come in various colors and flavors:

- Flavors: “up”, “down” and “strange”
- Colors: “red”, “green” and “blue”



Quarks of different colors attract each other

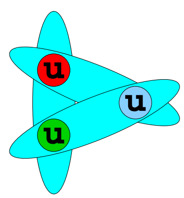
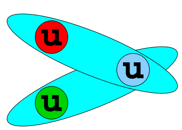
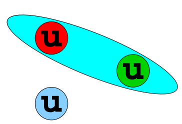
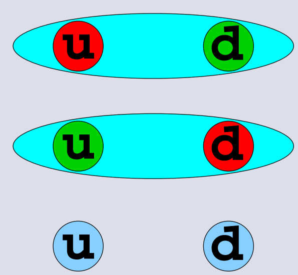
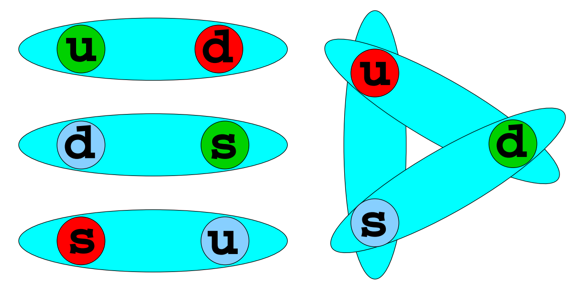


Then, Pauli principle requires the following structure of Cooper pairs:

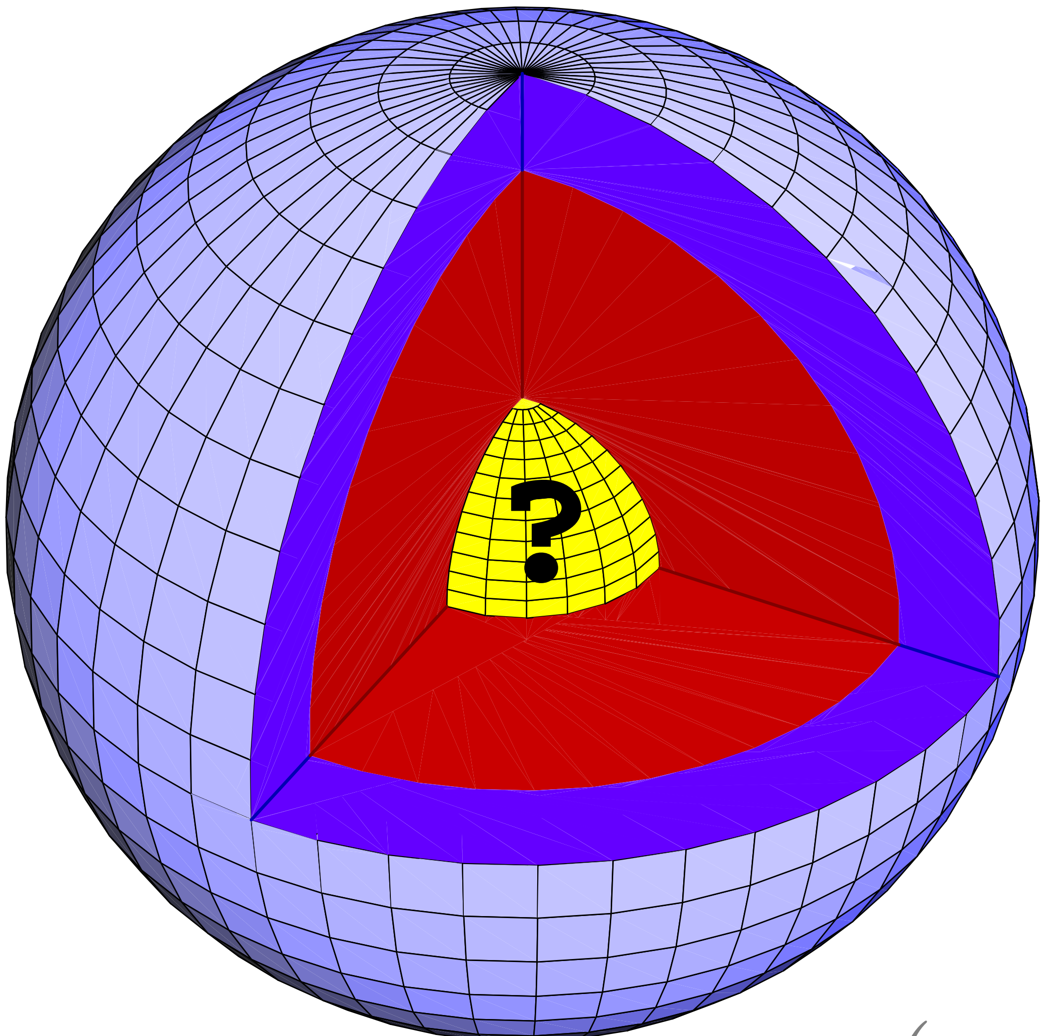
$$\big(|{\color{red}\bullet}{\color{green}\bullet}\rangle - |{\color{green}\bullet}{\color{red}\bullet}\rangle\big)_{\bar{3}} \otimes \big(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\big)_0 \otimes \big(|\mathrm{u,d}\rangle - |\mathrm{d,u}\rangle\big)$$

Main types of quark superconductors

- Density of quark matter is controlled by chemical potential μ
- Quarks of mass m_i appear if $\mu > m_i$
- Different compositions $\rightarrow$ different types of quark superconductors

1 quark flavor e.g., up	2 quark flavors up and down	3 quark flavors up, down and strange
CSL:  Planar:  A/polar: 	2SC 	CFL 
Meissner effect: ✓ * superfluidity: ✓ *	Meissner effect: ✗ superfluidity: ✗	Meissner effect: ✗ superfluidity: ✓

Which of these types can exist in stars?



(Answer: NONE)

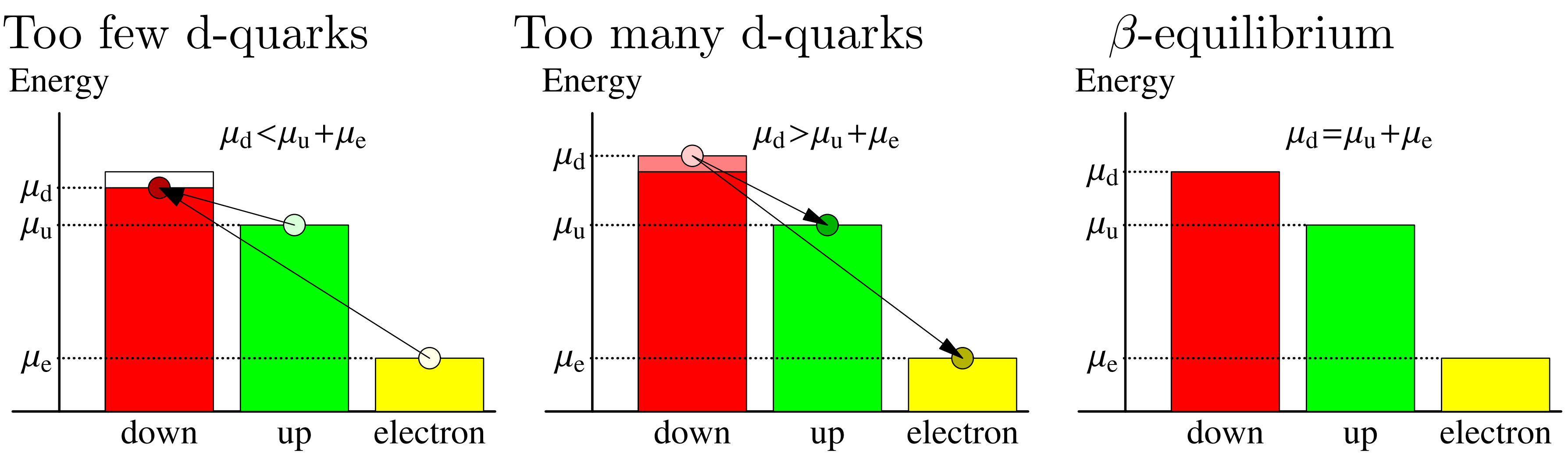
Conditions inside stars: β-equilibrium

Weak processes

$$u + e^- \rightarrow d + \nu \qquad \text{(electron capture)}$$

$$d \rightarrow u + e^- + \bar{\nu} \qquad (\beta\text{-decay})$$

should have equal rates



$$\beta\text{-equilibrium} \Rightarrow \mu_d = \mu_u + \mu_e$$

Conditions inside stars: charge neutrality

Matter inside a star should be electrically neutral $n_Q^{\text{el}} = 0$

i.e.,

$$\frac{2}{3}n_u - \frac{1}{3}n_d - n_e = 0 \quad \left(\text{or} \quad \frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0 \right)$$

in order to avoid a huge energy price

Let us assume for a moment that $n_Q \neq 0$:

Then, the Coulomb energy of a quark matter core of radius R is

$$E_{\text{Coulomb}} \sim n_Q^2 R^5 \sim M_\odot c^2 \left(\frac{n_Q}{10^{-15} e/\text{fm}^3} \right)^2 \left(\frac{R}{1\ \text{km}} \right)^5$$

e.g., $\quad 10^{-2} \lesssim n_Q \lesssim 10^{-1} e/\text{fm}^3 \quad \Rightarrow \quad E_{\text{Coulomb}}^{\text{2SC}} \sim 10^{26} M_\odot c^2 \gg M_\odot c^2$ ⋆

⋆ Note: this is about 1000 000 000 000 000 000 000 000 000 times more powerful than a supernova explosion!

Unconventional Cooper pairing

- The "best" Cooper pairing occurs when $\mu_d \approx \mu_u$, i.e.,

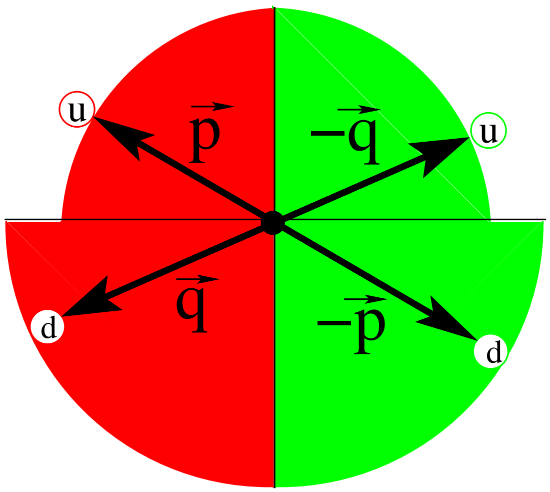
$$n_d \simeq \frac{\mu_d^3}{\pi^2} \simeq \frac{\mu_u^3}{\pi^2} \simeq n_u$$

- Neutral matter, however, appears when $n_d \approx 2n_u$
- There are not enough electrons in β equilibrium to help ...

$$\mu_e = \mu_d - \mu_u \approx 2^{1/3}\mu_u - \mu_u \approx \frac{1}{4}\mu_u \;\Rightarrow\; n_e \approx \frac{1}{192} n_u \ll n_u$$

Therefore, Cooper pairing is unavoidably distorted by the "mismatch"

$$\delta\mu \equiv \frac{\mu_d - \mu_u}{2} = \frac{\mu_e}{2} \neq 0$$



What happens then?

New states of matter

Many suggestions,

1. Gapless superconductivity

   [Shovkovy&Huang, PLB**564**(2003)205], [Alford,Kouvaris&Rajagopal,PRL**92**(2004)222001], ...

2. Crystalline superconductivity

   [Alford,Bowers&Rajagopal,PRD**63**(2001)074016], ...

3. Phases with additional Bose condensates

   [Bedaque&Schäfer,NPA**697**(2002)802], ...

4. Other "exotic" phases

   [Gorbar,Hashimoto&Miransky,PLB**632**(2006)305], ...

but the issue is still under debate ...

Observational data as a tool

Cooling of neutron stars:

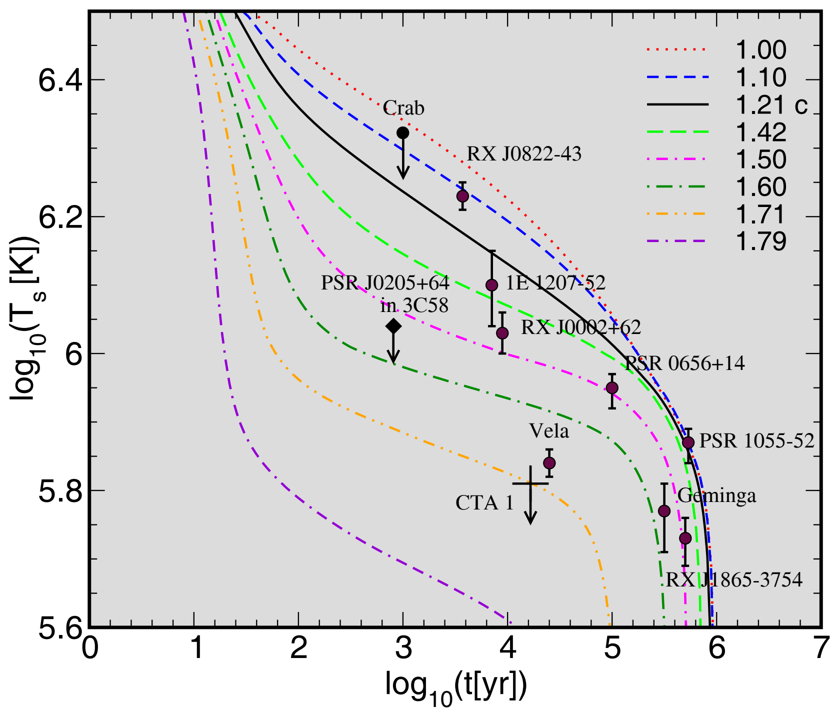
(i) thermal relaxation: $t \lesssim 100$ yr

(ii) neutrino cooling: $100 \lesssim t \lesssim 10^6$ yr

(ii) surface cooling: $t \gtrsim 10^6$ yr

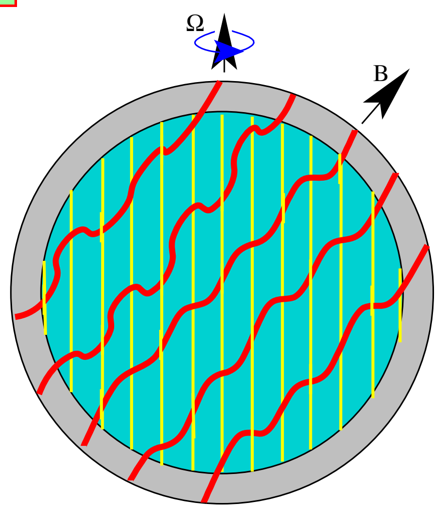
[Alford et al, astro-ph/0411560],

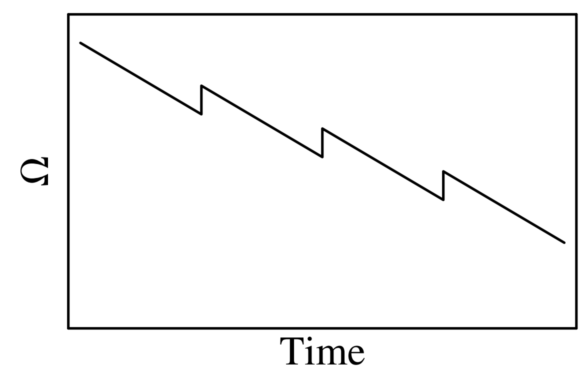
[Blaschke et al, astro-ph/0411619]



Other potential observables

- R-mode instabilities
- Magnetic field decay
- Glitches
- ...





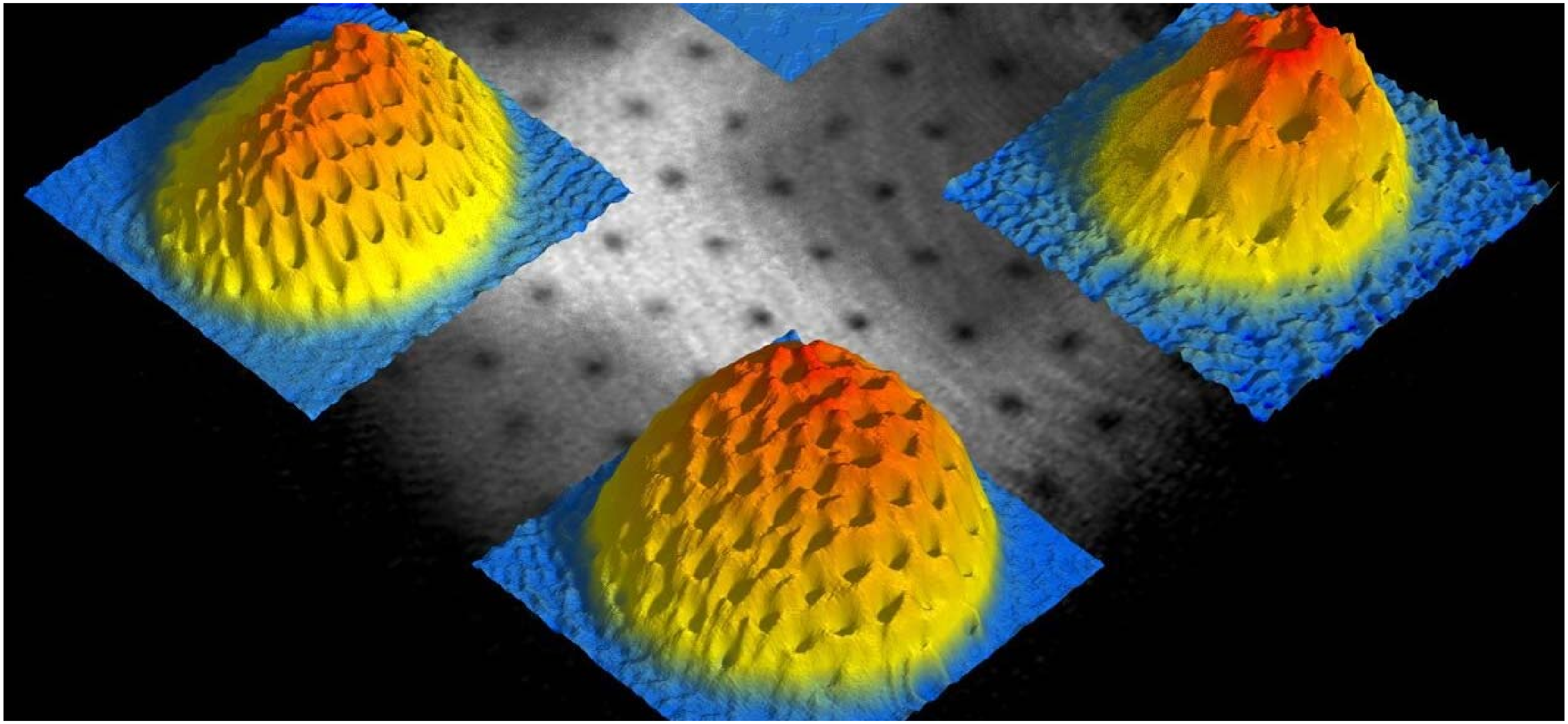
"Neutron star" in a laboratory . . .

☹ Neutron stars are very far and very hard to study

Instead, one may study trapped cold gases of atoms (e.g., ^{6}Li or ^{40}K)

First experimental results on polarized systems

[Zwierlein *et. al.*,, cond-mat/0511197], [Partridge *et. al.*,, cond-mat/0511752]



Summary

- Neutron stars give a unique natural laboratory of matter under extreme conditions
- It is likely that new states of matter exist in stars and that they have unusual properties
- Current theoretical investigations of dense matter suggest many new interesting possibilities
- Physics of stars and physics of matter around us might be closer related than one might naively expect . . .

Outlook

(i) resolving the debate on the ground state of dense matter

(ii) studying physical properties of exotic states of matter

(iii) search for astrophysical observables . . .

Thanks!

Hole
Blue Supergiant
Supers
Protostar
Blue Supergiant
Supernova
Black Hole
Blue Supergiant
Protostar
Blue Supergiant
Red Giant (with stellar winds)
Supernova (with neutron star)
Solar TYpe Star
Red Giant
Planetary Nebula
Red Dwarf
Red Dwarf