A roadmap to Strange Star

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"Compact Stars in the QCD phase diagram"

Aug. 17-21, 2020; ICTS Bangalore, India

A few years ago…

To identify *Strange Star* with *SKA*

Renxin Xu (徐仁新)
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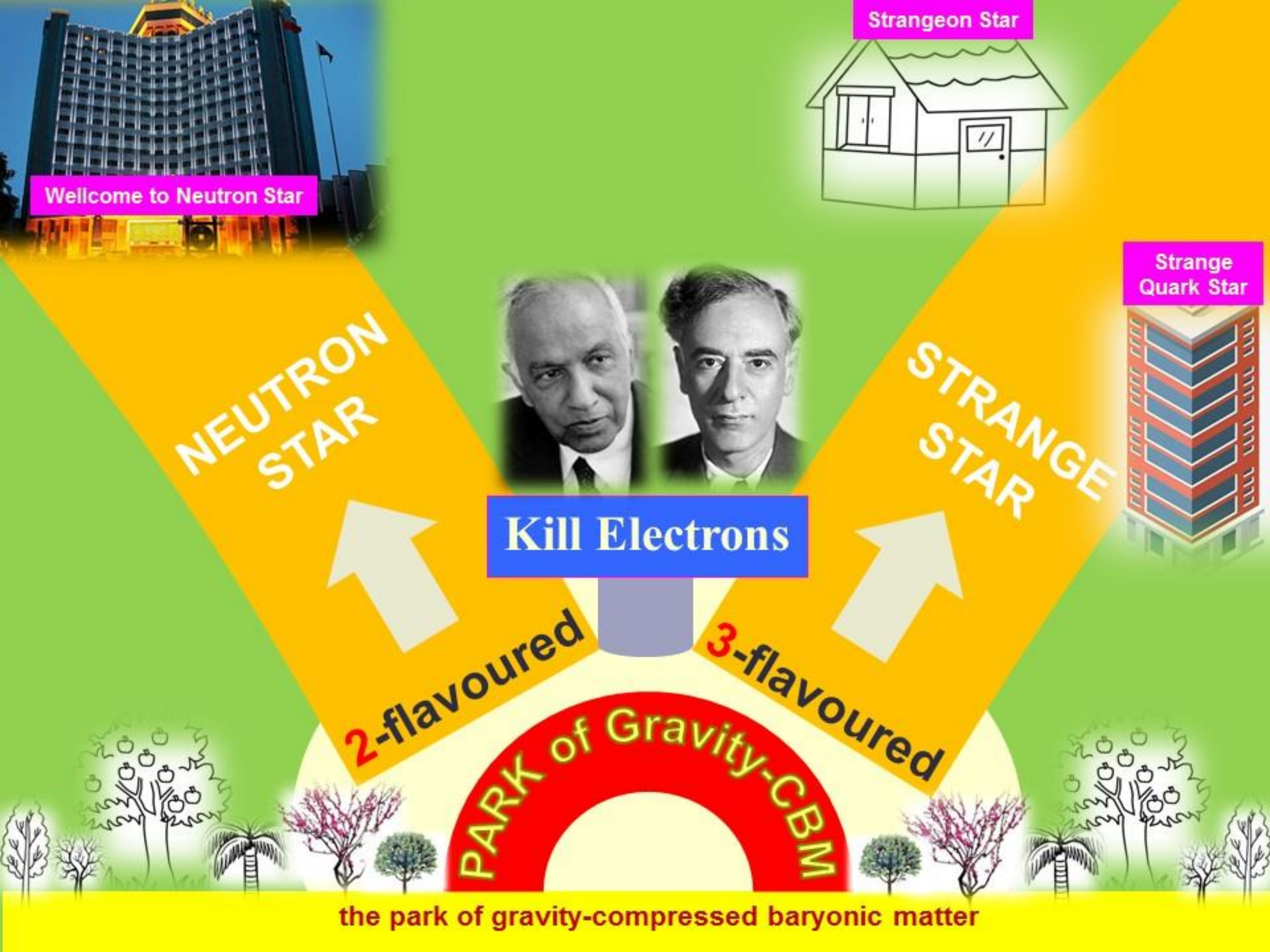
First ASIONS (Asia SKA Initiative On NS) Meeting

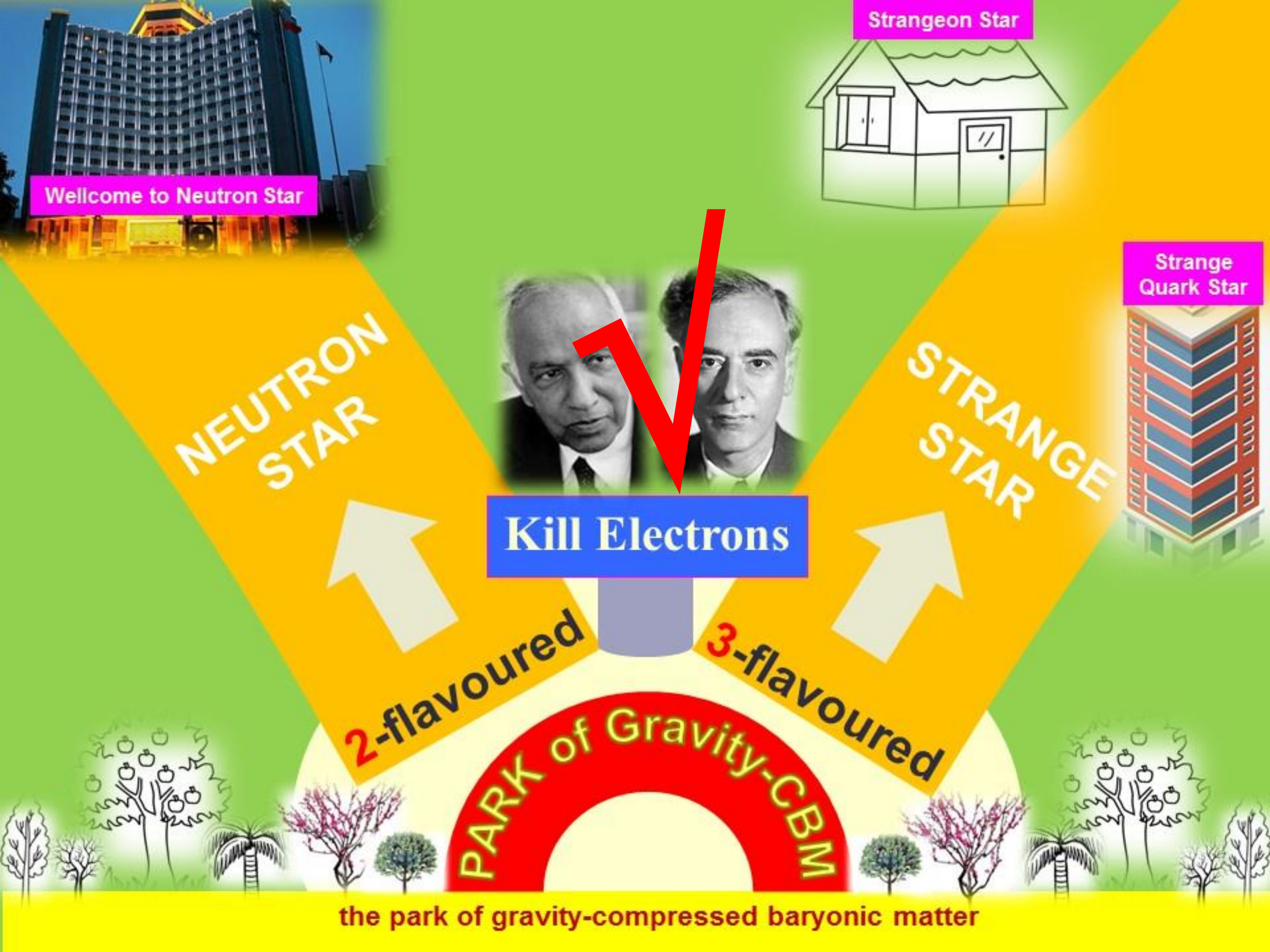
Nov. 4-5, 2016; Le Pearl Resort, Goa, India

To ID SS with SKA http:// www.phy.pku.edu.cn/~xurenxin/ R. X. Xu

A key to all (PSR/FRB/GRB/SNE…): what's CBM?

- **What** if normal baryonic matter is *compressed*?


Wellcome to Neutron Star
Strangeon Star
Strange Quark Star
NEUTRON STAR
STRANGE STAR
Kill Electrons
2-flavoured
3-flavoured
PARK of Gravity-CBM
the park of gravity-compressed baryonic matter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To kill *e*’s: from Chandra to Landau

- A real historical note： Landau in 1931/1932!

ON THE THEORY OF STARS.

By L. Landau.

(Received 7 January 1932).

From the theoretical point of view the physical nature of Stellar equilibrium is considered.

The astrophysical methods usually applied in attacking the problems of stellar structure are characterised by making physical assumptions chosen only for the sake of mathematical convenience. By this is characterised, for instance, Mr. Milne’s proof of the impossibility of a star consisting throughout of classical ideal gas; this proof rests on the assertion that, for arbitrary *L* and *M*, the fundamental equations of a star consisting of classical ideal gas admit, in general, no regular solution. Mr. Milne seems to have overlooked the fact, that this assertion results only from the assumption of opacity being constant throughout the star, which assumption is made only for mathematical purposes and has nothing to do with reality. Only in the case of this assumption the radius *R* disappears from the relation between *L*, *M* and *R* necessary for regularity of the solution. Any reasonable assumptions about the opacity would lead to a relation between *L*, *M* and *R* … quite exempt from the physical cri… Eddington’s mass-luminosity-rel…

It seems reasonable to try to at… structure by methods of theoretic… gate the physical nature of st… purpose we must at first investigat… of a given mass without generati… for which equilibrium being the … (for given temperature). The p… gravitation is negative and inve…

we have no need to suppose that the radiation of stars is due to some mysterious process of mutual annihilation of protons and electrons, which was never observed and has no special reason to occur in stars. Indeed we have always protons and electrons in atomic nuclei very close together, and they do not annihilate themselves; and it would be very strange if the high temperature did help, only because it does something in chemistry (chain reactions!). Following a beautiful idea of Prof. Niels Bohr’s we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down (as it is experimentally proved by continuous-rays-spectra and also made probable by theoretical considerations).[1] We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

O… these general lines we can try to develop a theory of …ar structure. The central region of the star must consist …f a core of highly condensed matter, surrounded by mat…r in ordinary state. If the transition between these two state… were a continuous one, a mass $M < M_0$ would never … …tate (i. e. without … Because, as far … …nclude that the … …parated by some … …id and its vapour … …ed by some kind … the existence of … …e two states. … …n the above considerations is yet to be constructed, and only such a theory can show how far they are true.

February 1931, Zurich.

[1] L. Landau und R. Peierls, ZS. f. Phys. 69, 56, 1931.

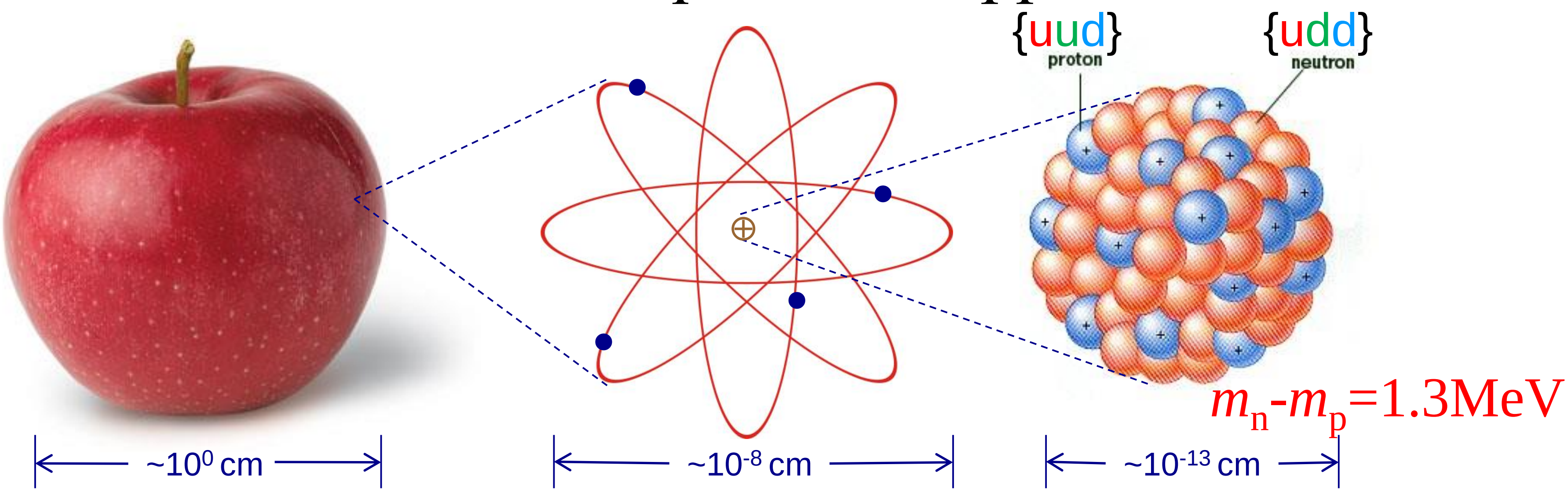
$A_c \simeq \lambda_c^3/\mathrm{fm}^3 \sim 10^9$

Compton $\lambda_c \sim 2.4\mathrm{x}10^3\mathrm{fm}$

Landau L. 1932, *Sov. Phys.*, 1, 285

To kill *e*'s: from Chandra to Landau

- Let's do an exercise…to squeeze an apple!



Total baryon number $A_{\rm apple}$~100g/u~10^{26}.

Electrons no-relativistic before squeezing, but what after?

A giant "nucleus": ~50μm, ~$\rho_{\rm nucl}$, E_e~200MeV if *e* keeps

Gravity-squeezed core: *A* >> $A_{\rm apple}$ and *not gravity-free*!

Two ***uncertainties***: Quarks de-*confined*? *Strangeness*?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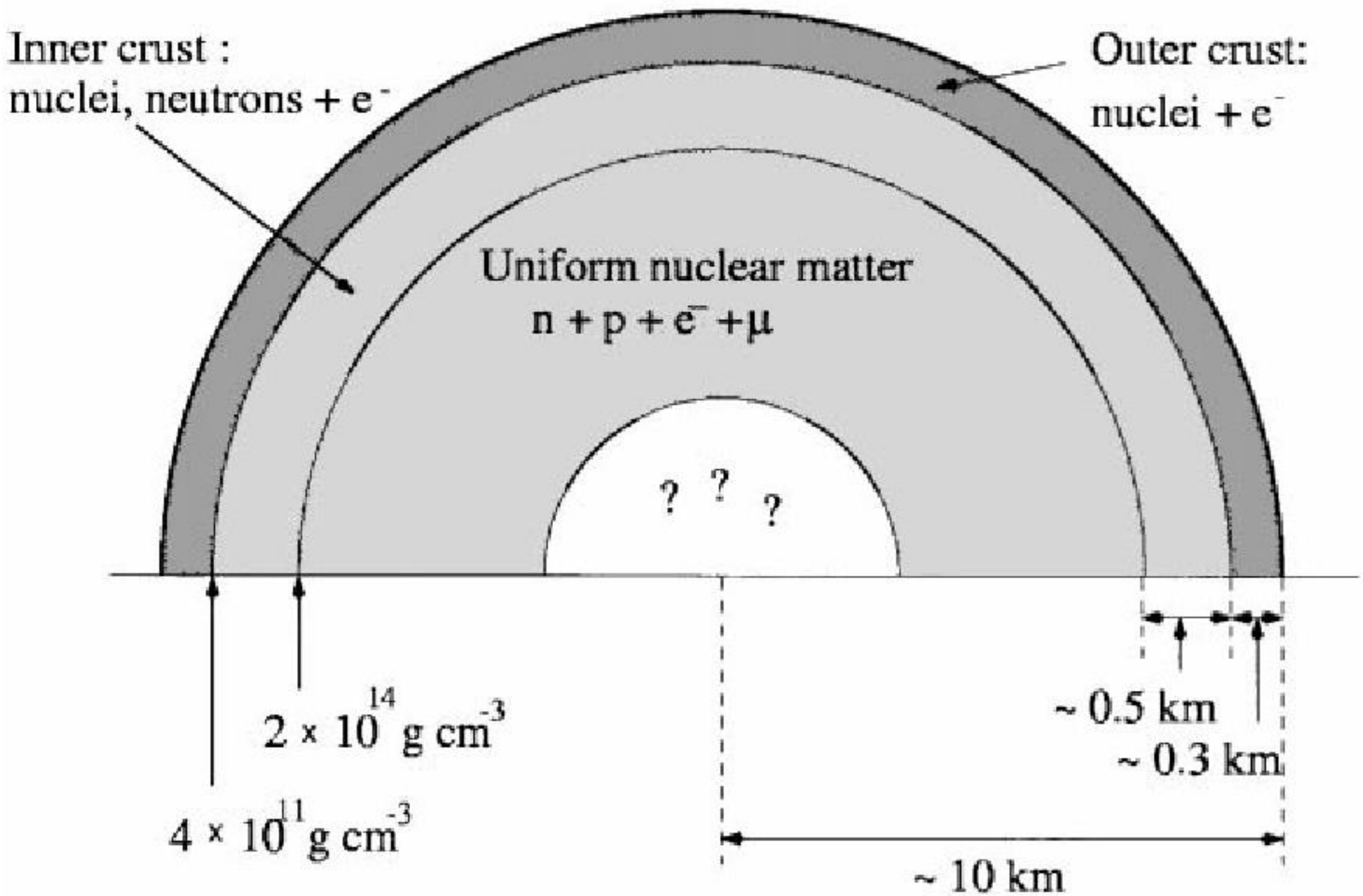
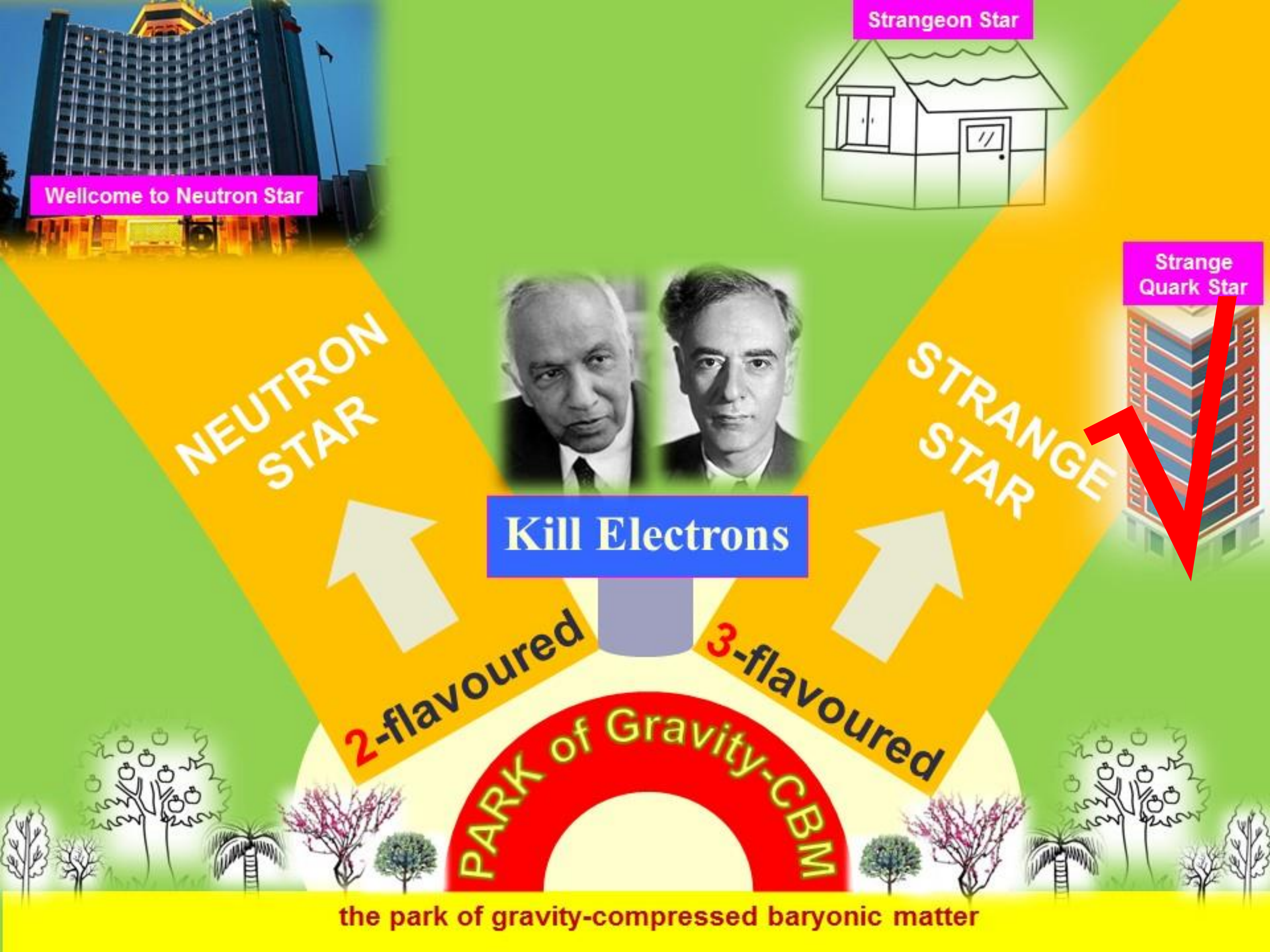
Neutron Stars

•***Neutronization***: p+e $\rightarrow$ n+ν_e (u+e $\rightarrow$ d+ν_e) if 2-favoured

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Why strange?

Hobby

- God may love a matter state with *f*lavor-maximization…

For strong matter around the ***nuclear density***, the separation between quarks, $\Delta\ell$, could be ~ 0.5 fm, determined by α_s!

From Heisenberg's uncertainty relation, $\Delta\ell\cdot\Delta p \approx \hbar$, one may have an energy scale for strong matter, $E_{\rm scale}$, ~~(c,b,t)~~

$$E_{\rm scale} \approx \hbar c/\Delta\ell \approx 0.2\text{GeV}\cdot\text{fm}/0.5\text{ fm} = 0.4\text{ GeV}.$$

Note that... we may expect 3-flavored strong matter because

$$E_{\rm scale} \gg \Delta m_{\rm uds} \equiv (m_{\rm s} - m_{\rm ud})c^2!$$

- Strong matter should be **3**-flavored (***u***,***d***,***s***), but why are normal stable atomic nuclei **2**-flavored (***u***,***d***) ? ← **Nuclear Symmetry Energy**

Strange Quark Stars

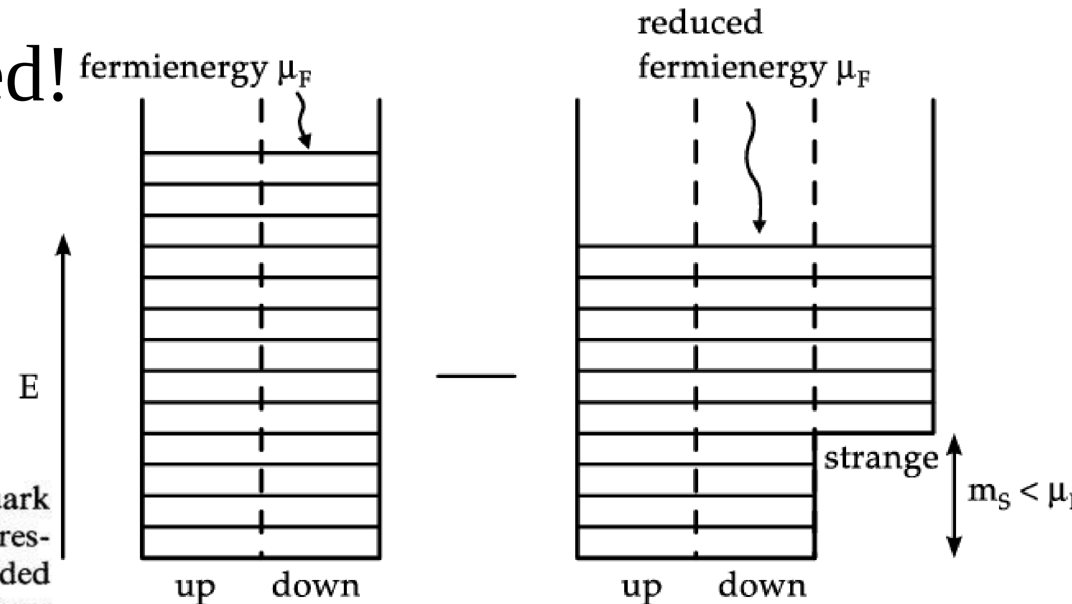
- ***Free*** quarks 3-flavourved!

As noted in Witten (1984), SQM matter in bulk may constitute the true ground state.

A. Stable macroscopic quark matter

The most extreme possibility is that macroscopic quark matter is bound and stable at zero temperature and pressure. At first sight, one might think that this is excluded by the fact that ordinary nuclei do not spontaneously turn into the hypothetical dense quark state. This is not quite so, however. Observations of nuclear physics only show that in the absence of strange quarks, nuclear matter is more stable than quark matter. Addition of strangeness does not help stabilize nuclear matter, because strange baryons are heavier than nonstrange baryons. For quark matter, the story is different. (This point has been noted before in Refs. 19 and 26.) The likely Fermi momentum in quark matter is 300–350 MeV, more than the strange-quark mass, so it is energetically favored for some of the nonstrange quarks to become strange quarks, lowering the Fermi momentum and the energy.

This effect can easily be estimated in the simplest form of the bag model.[21] A single quark flavor of Fermi



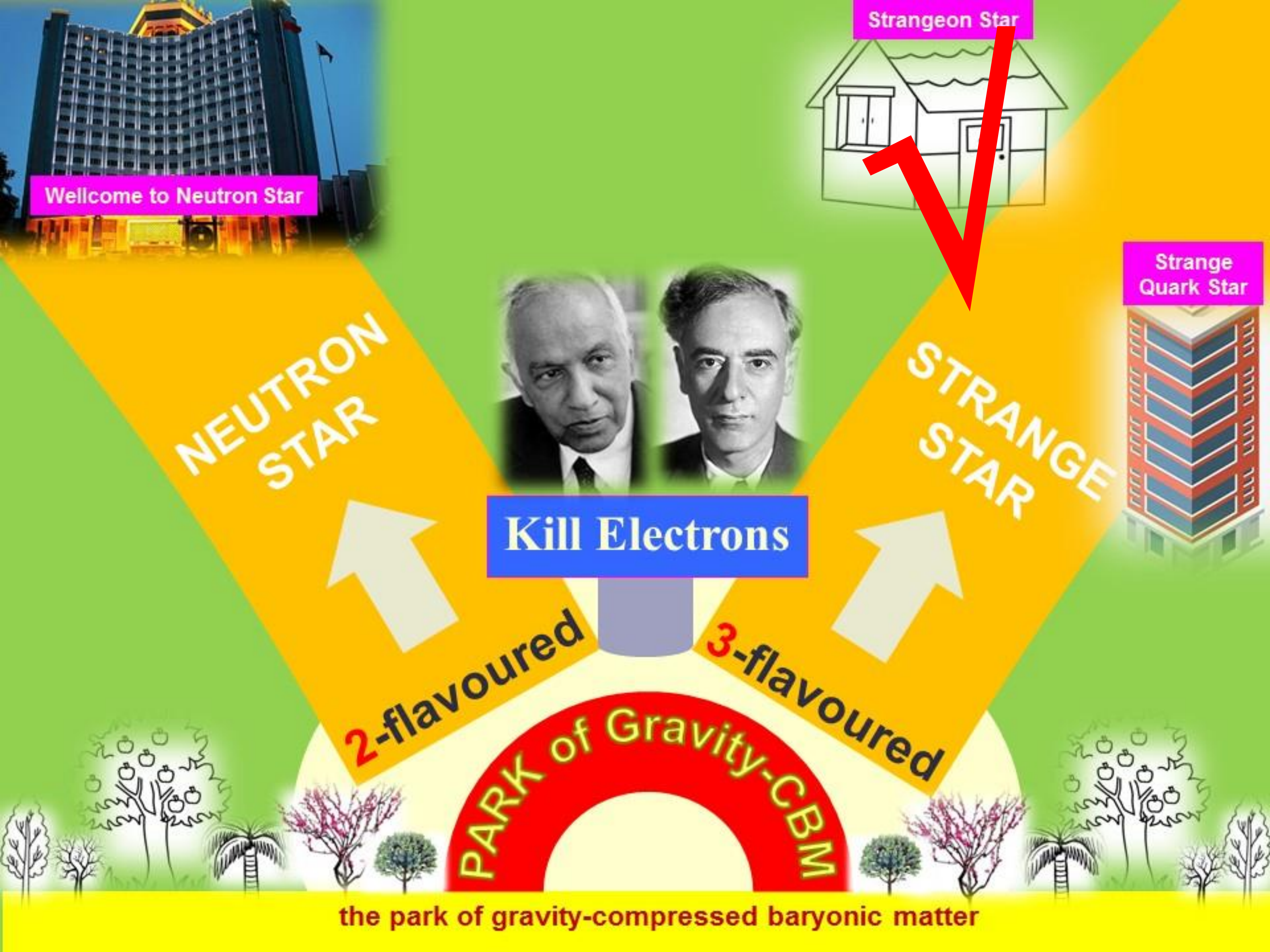
$$\left(\frac{E_{tot}}{A}\right)_2 > \left(\frac{E_{tot}}{A}\right)_3$$

Greiner et al. (1998)

$$m_u = 2\sim8 \text{ MeV}$$
$$m_d = 5\sim15 \text{ MeV}$$
$$m_s \sim 100 \text{ MeV}$$

$$\rho = 2\rho_N$$

$$\mu_F \sim 500 \text{ MeV}$$



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Strangeon Stars

- Can quarks be ***free*** at a few $\rho_{\rm nucl}$???

The state of *cold* quark matter:

a model-independent view

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School of Physics, Peking Univers

Compact stars in the QCD phase diag

(CSQCD II), PKU

May 24th, 2009.

Quark cluster = Strangeon

- What ***if*** strong ***color***-interaction exists?

Strong interaction ⇒ ***quark cluster***?

Diquark: color SU(3), ***Coulomb***-like

$$3 \times 3 = 6(\textit{repulsion}) + 3^*(\textit{attraction})$$

Let's estimate the length scale of and interaction strength in a quark cluster:

$$l_{\rm q} \sim \frac{1}{\alpha_{\rm s}} \frac{\hbar c}{mc^2} \sim 1{\rm fm}/\alpha_{\rm s}, \quad E_{\rm q} \sim 300\alpha_{\rm s}^2{\rm MeV},$$

if quarks are dressed, with mass ~ 300MeV.

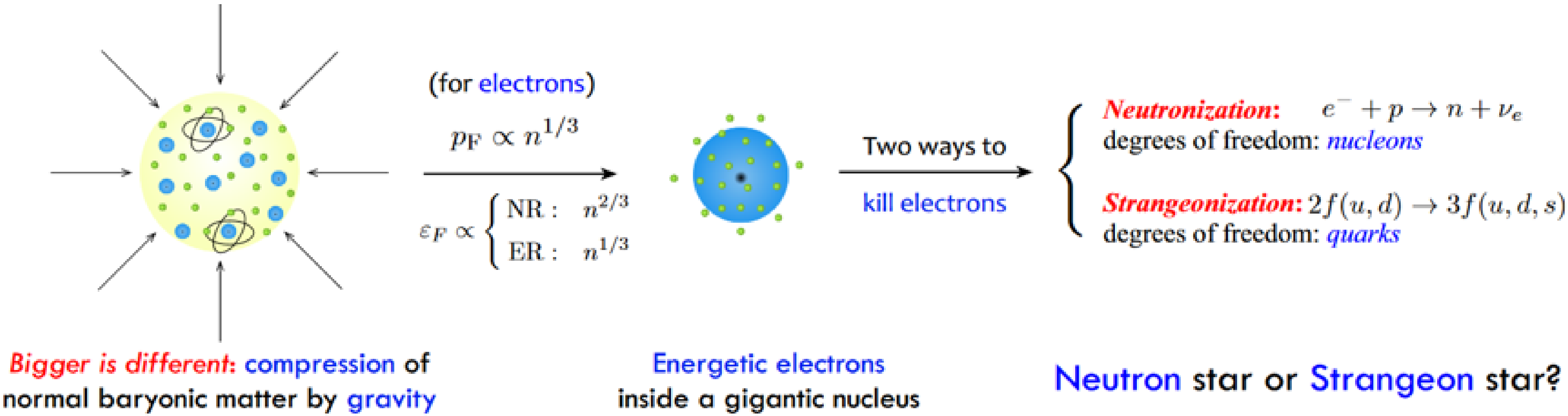
What about α_s?

Stiff EoS ⇒ low ρ_c

strangeon[ˈstreɪdʒɪɒn]= **strange** + nucle**on** with strangeness S = -B

Strangeon Stars

- Core collapse SN： Neutronization ***v.s.*** Strangeonization



from a symmetrical perspective

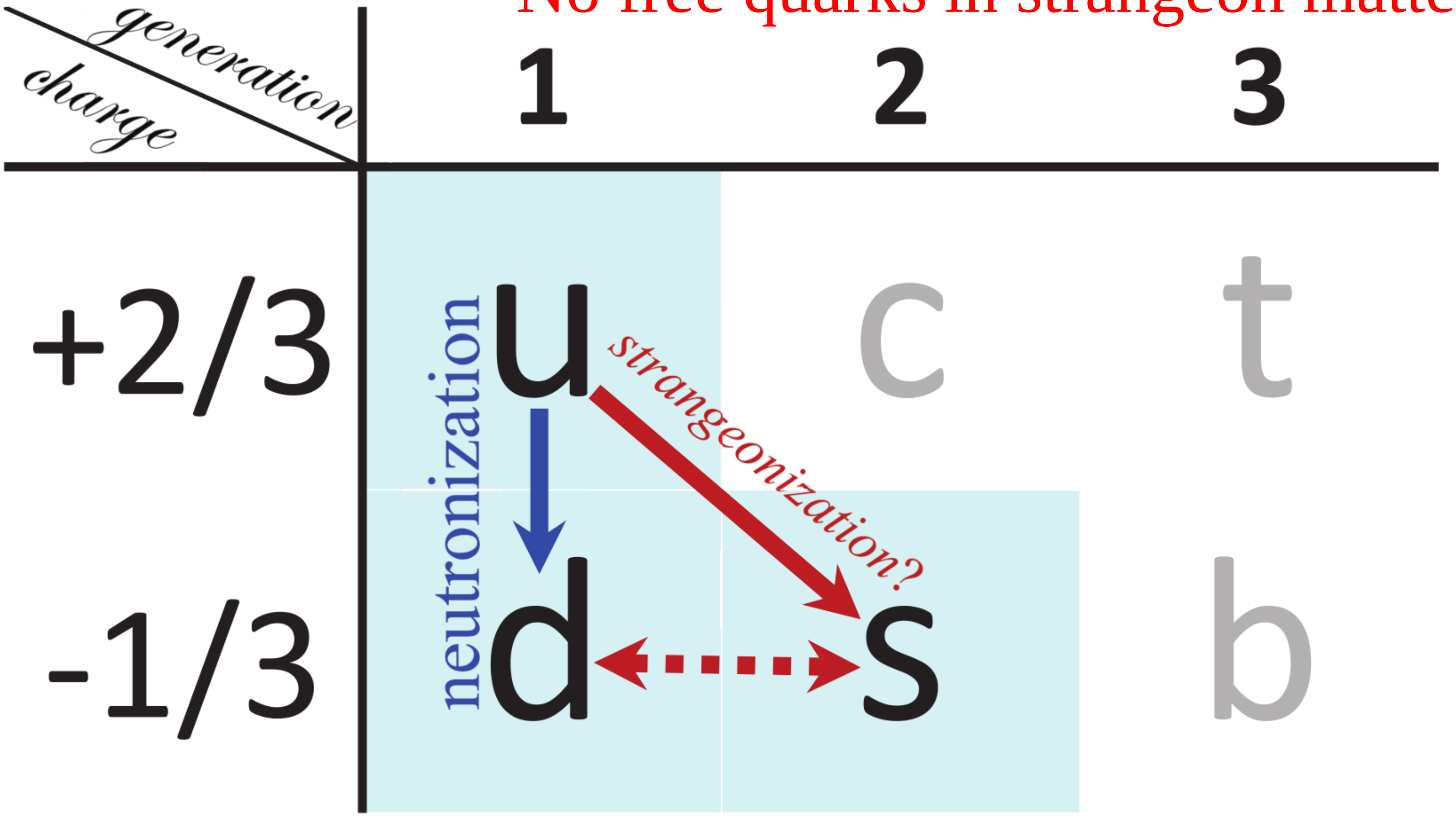
TABLE 2. Compact star models: a comparison.

Models	Basic unit	Flavour	Asymmetry	Quark coupling, EoS	Surface binding
Neutron Star	nucleon	**2** (u & d)	$\delta > 0.8$	strong, stiff if no hyperon	gravity
Strange Quark Star	quark	**3** (u, d & s)	$\delta < 10^{-4}$	weak, softened with s	self strong force
Strangeon Star	strangeon	**3** (u, d & s)	$\delta < 10^{-4}$	strong, stiff in any case	self strong force

Strangeon Stars

•***N.***/***S.*** in the standard model of particle physics...

No free quarks in strangeon matter!



Strangeon Stars

- A linked bag-model of strangeon matter…

A ***philosophical argument*** about ***f***lavor-maximization

quarks inside a bag-like vacuum perturbative

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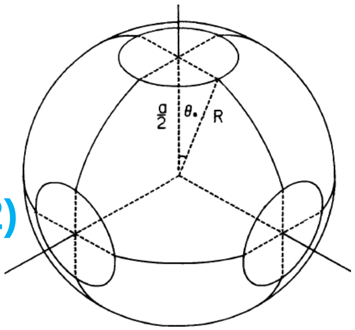
Nuclear equation of state in the MIT bag crystal model for nuclear matter

Zhang & Liu (1992)



We may come to a conclusion of

If length $\ell << \lambda_e$, the **2**-*f* matter is energetically favored;

if length $\ell >\sim \lambda_e$, the **3**-*f* matter is energetically favored.

Strangeon Stars

• A linked bag-model of strangeon matter…

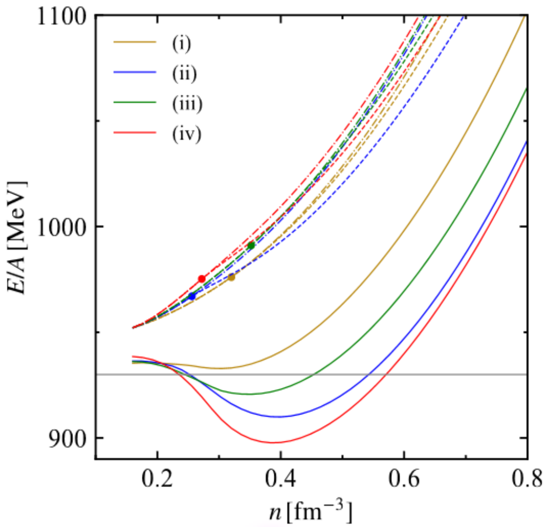
Miao et al. (arXiv: 2008.06932)

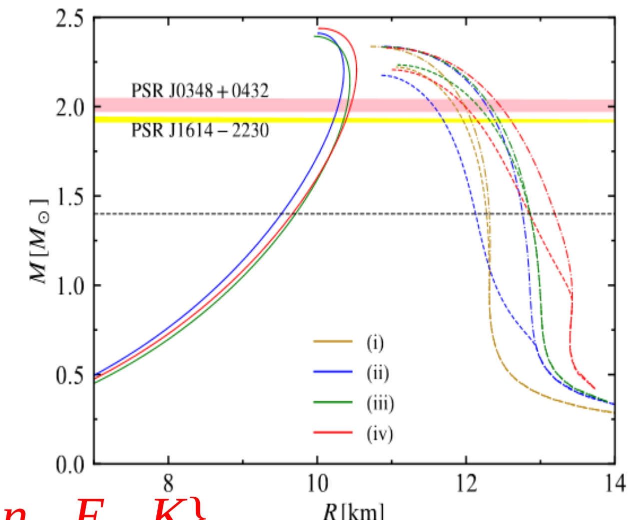
In the Fermi-gas approximation, the energy per lattice cell is obtained with

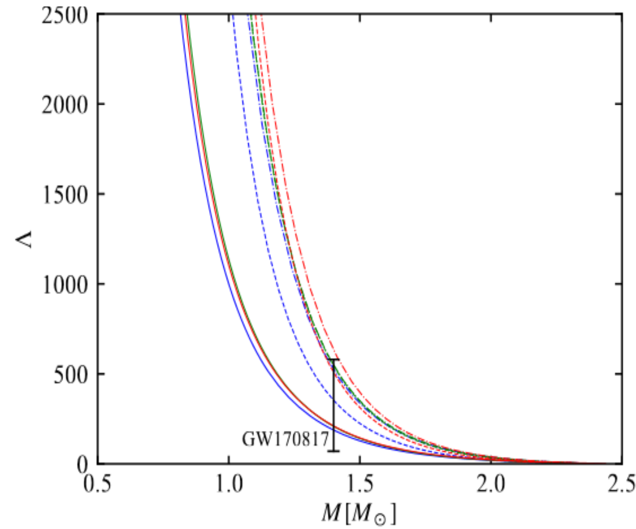
$$E = \sum_j (\Omega_j + N_j \mu_j) + BV - \frac{z_0}{r_{\rm bag}} \frac{\omega}{4\pi}, \qquad (1)$$

$$\Omega_i = \Omega_{i,V} V + \Omega_{i,S} S + \Omega_{i,C} C, \qquad (2)$$

$$B = B_0 + B_1 \xi + B_2 \xi^2 + B_3 \xi^3, \qquad (8)$$







$\{n_0, E_0, K\}$

	C_1	$\hat{m}_s$ [MeV]	B_2 [MeV/fm^3]	B_3 [MeV/fm^3]	$z_0(n_0)$	L [MeV]
(i)	2.7	220	136.7	50	2.944	45.1
(ii)	2.7	220	112.7	100	2.926	52.7
(iii)	2.7	280	125.0	100	2.908	56.6
(iv)	3.2	280	162.3	100	2.843	62.8

Strangeon Stars

•focus： evidence model-dependent in astrophysics

	Peculiarity	Manifestation	Mechanism	Ref.
surface	binding energy.	*drifting subpulse*, μstructure	gap sparking in RS75	Xu et al. (1999), Yu & Xu (2011)
		clean fireball for SNE/SGR	photon-driven explosion	Chen et al. (2007), Dai et al. (2011)
	self-bound	mass as low as $\sim 10^{-2} M_\odot$	bound not by gravity	Xu & Wu (2003), Xu (2005)
	none-atomic X	Plankian radiation of X-ray	no-atmosphere if bare	Xu (2002)
		absorption in thermal spec.	hydromagnetic oscillation	Xu et al. (2012)
	strangeness bar.	low-*z* emission, type-I XRB	$2f$ matter separated from $3f$	Xu (2014)
		optical/UV exce. of XDINS	bremsstrahlung radiation	Wang et al. (17/18)
global	stiff EoS, Λ	high M_{max} ($2 \sim 3 M_\odot$)	NR strangeons, hard core	Lai et al. (09ab, 18) Guo et al. (2014)
	anisotropic *P*	SGR/AXP's burst and flare	quake-induced ener. release	Xu et al.'06, Zhou et al.'14, Lin et al.'16
	rigidity	precession, GW radiation	solid, mountain building	Xu (2003) Xu (2006)

Strangeon Stars

- Welcome to FAST： the biggest single-dish telescope!

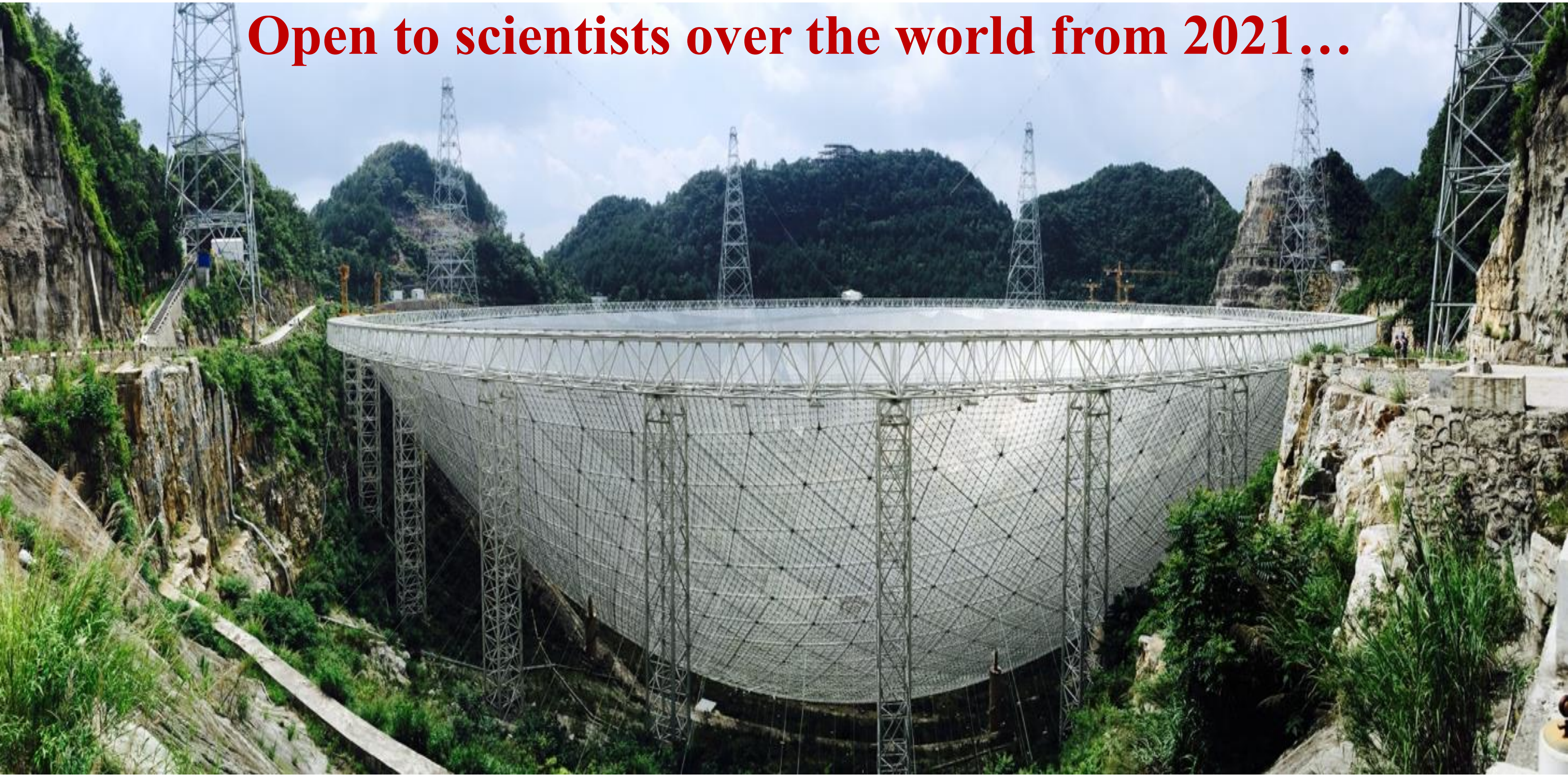
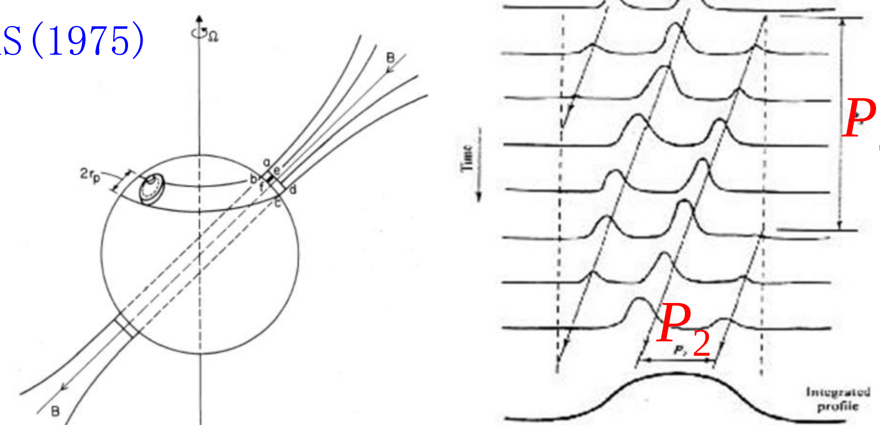


Fig. 1 Panoramic view of FAST (obtained in June of 2017).

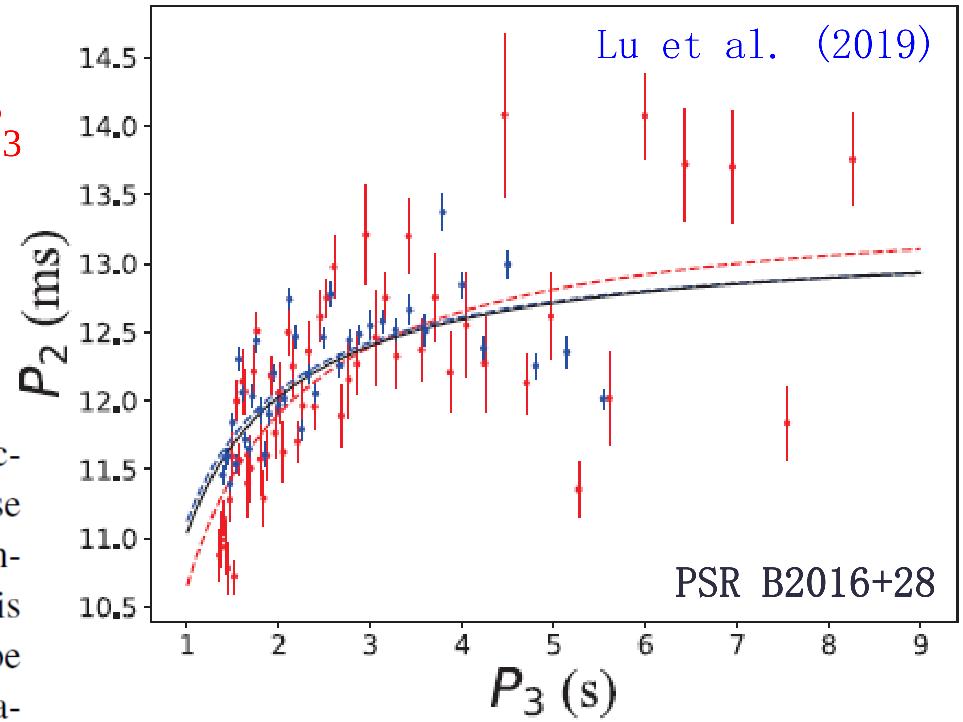
Strangeon Stars

•Welcome to FAST： the biggest single-dish telescope!

RS (1975)



All the observational results suggest an RS-type inner vacuum gap on the polar cap of PSR B2016+28. The mean pulse profiles may imply that the radiation is generated from an annular gap region, in which sparks drift irregularly. In this scenario, the pulse profile shrinking with frequency could be explained. The correlation of drifting periods (positive relation between P_2 and P_3) could also suggest a rough surface of pulsar, and the bonding energy of particles on stellar surface need to be very high (e.g., in strangeon star or bare neutron star with extremely high magnetic field). Single pulse structure width is also found to be shrinking with frequency, and it could be another evidence of RS model.



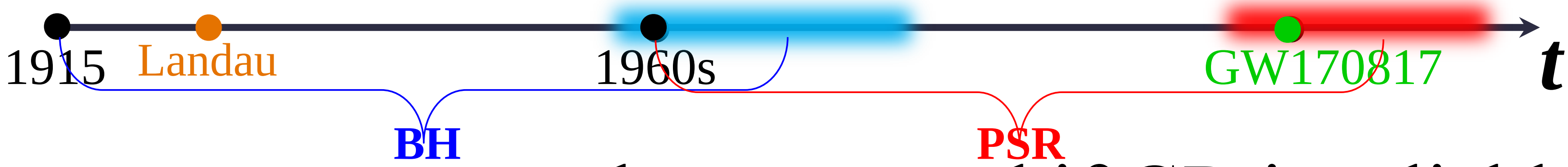
Large P_2 $\Longrightarrow$ Large gap-separation $\Longrightarrow$

Small $\boldsymbol{E}_{\parallel}$ $\Longrightarrow$ Small $\boldsymbol{E}_{\perp}$ $\Longrightarrow$ Small $\frac{\vec{\boldsymbol{E}}_{\perp}\times\vec{\boldsymbol{B}}}{|\vec{\boldsymbol{B}}|^2}$ $\Longrightarrow$

Large P_3 $\Longrightarrow$ A rough surface on pulsar?!

Summary

- **BH** astrophysics was active, but it is a golden era of NS/PSR with multi-messenger astron.:



…to be answered if GR is reliable!

- The basic units inside pulsar-like stars could be **3**-flavour ***symmetric strangeons*** rather than **2**-flavour ***asymmetric nucleons*** if the Nature really loves symmetry when building the world.

- To test strangeon model further… **THANKS!**