Strangeness
in Compact Stars

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"Strangeness Nuclear Physics"

March 12-14, 2017; Osaka Electro-Communication Univ., Japan

Introduction to Astronomy@PKU

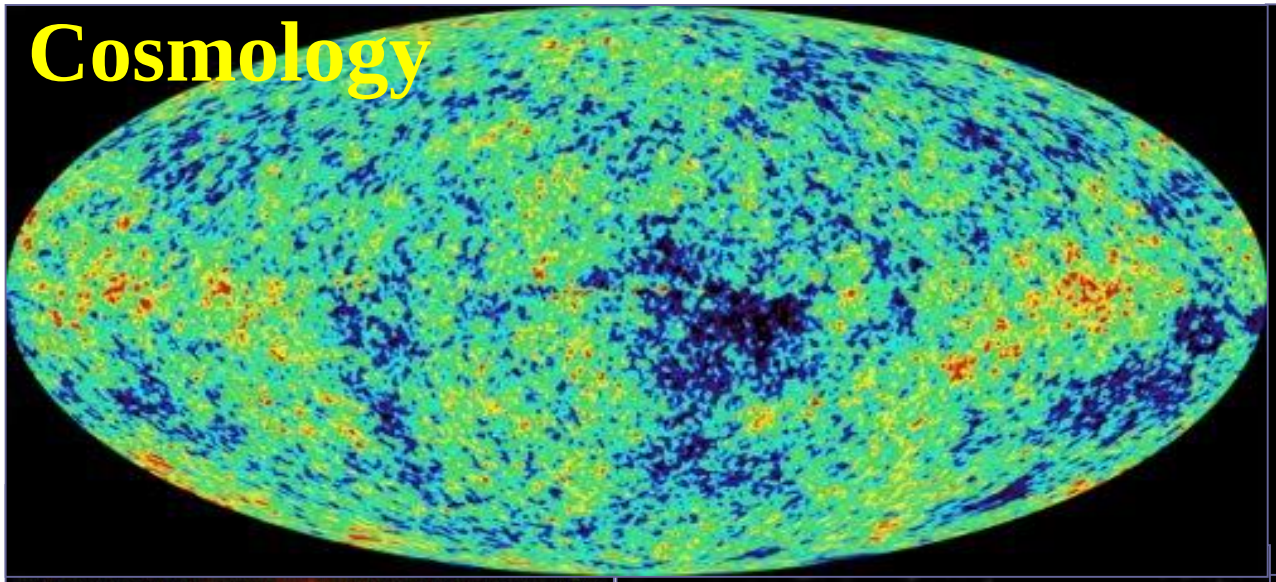
- DoA (Dept. of Astronomy, School of Physics)

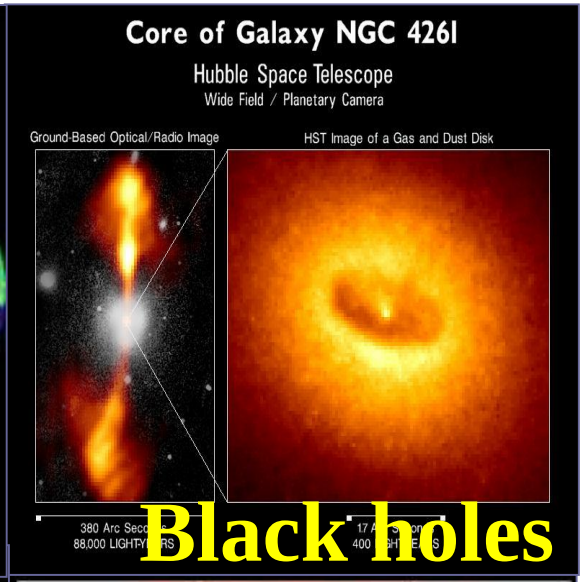
DoA **KIAA**

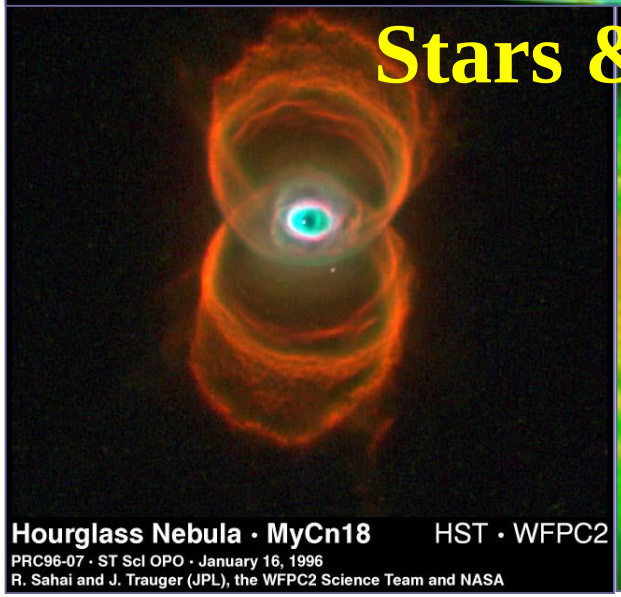
- KIAA (Kavli Inst. for Astro. & Astrophys. at PKU)

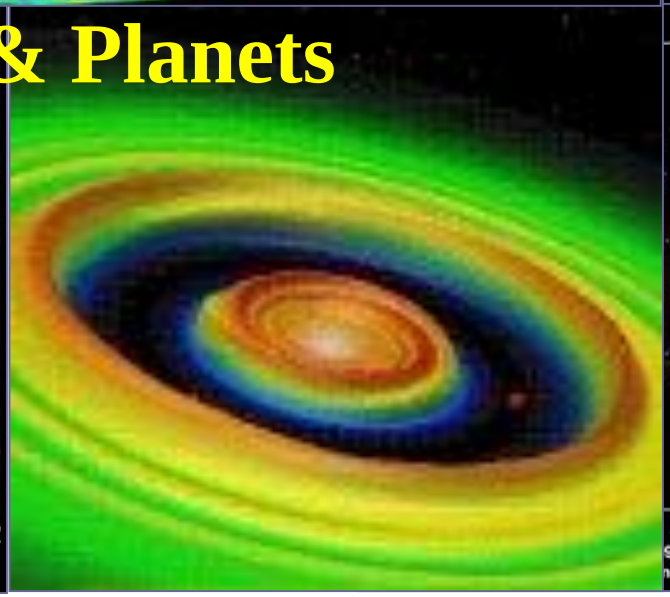
An *international platform* for research of A&A

Astro-programs @ Peking Univ.









Summary

- Why *strangeness* in compact stars?
- *Strangeness* manifested in the form of
  - Hyperon
  - Strange quark matter
  - Strangeon
- Conclusions

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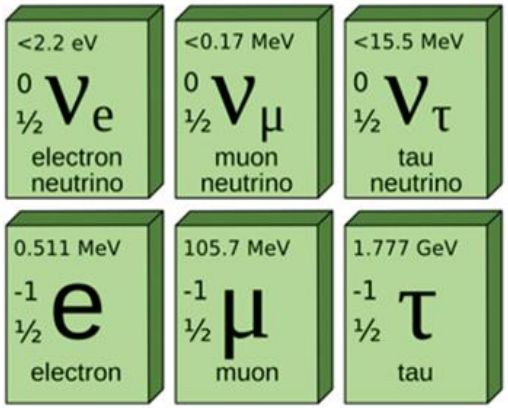
Why strangeness in compact stars?

- Physics (standard): **particles** and **interactions**

Building blocks

quark:

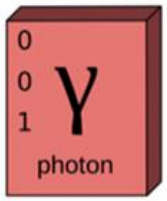
lepton:



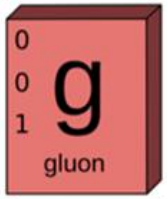
Higgs: H

Fundamental forces

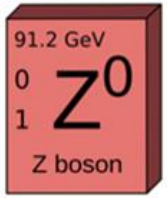
EM:

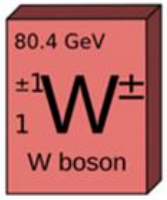


strong:



weak:





gravity: G

Why strangeness in compact stars?

- Why are we ***loving*** strangeness? the scale-energy…

For compact star with mass $M\sim1.5M_\odot$ and radius $R\sim10$km, the separation between quarks is $\Delta\ell$, order of 0.5 fm:

$$\Delta\ell \approx (3M/m_{\rm p})^{-1/3}R \approx (3M_\odot/m_{\rm p})^{-1/3}10{\rm km} = 0.5\ {\rm fm}.$$

From Heisenberg's uncertainty relation, $\Delta\ell\cdot\Delta p \approx \hbar$, one has an energy scale for dense matter inside compact star:

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

Therefore, we may confidently expect that strangeness would not be negligible because

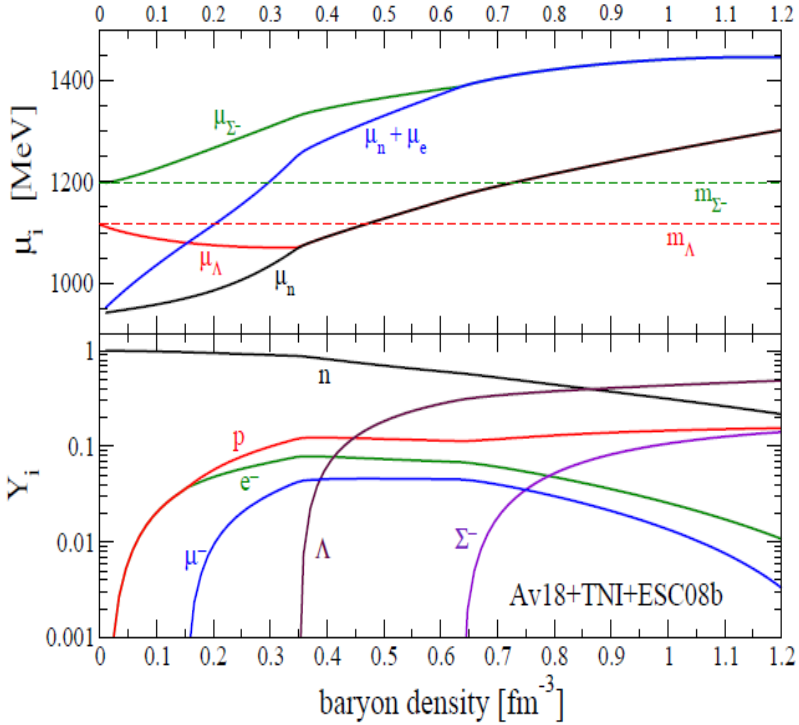
$$E_{\rm scale} \gg (m_{\rm s} - m_{\rm ud})c^2!$$

Summary

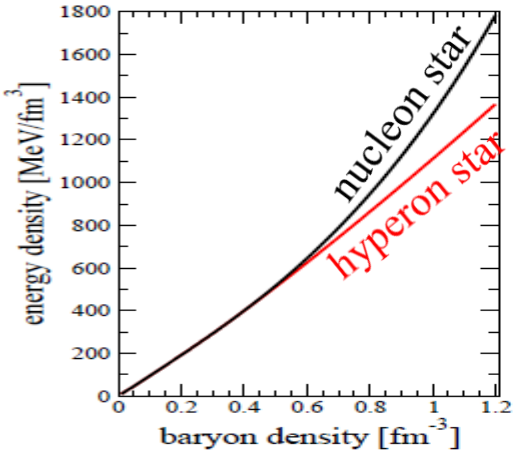
- Why strangeness in compact stars?
- Strangeness manifested in the form of
  - **Hyperon**
  - Strange quark matter
  - Strangeon
- Conclusions

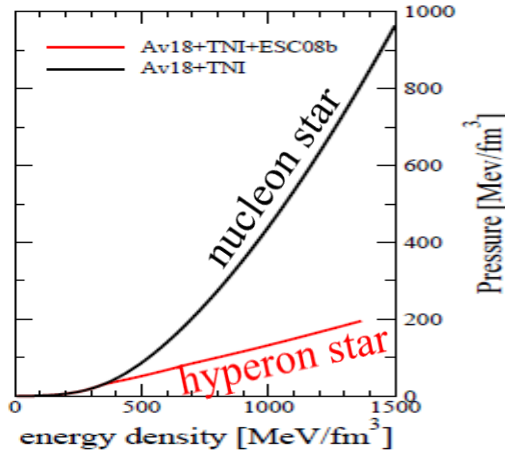
Strangeness manifested: Hyperon?

- Stiff **nucleon matter** ⇒ high $M_{\max}$ of **nucleon star**, but **hyperon** seems unavoidable and **soften** the EoS!



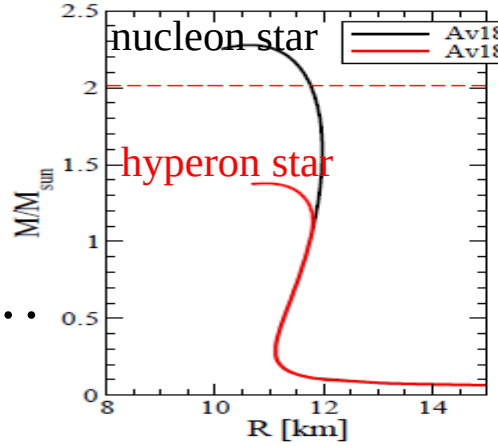
I. Bombaci (arXiv160105339)

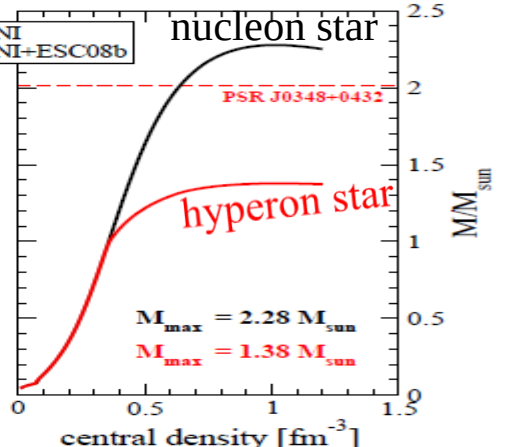




many-body interaction, but…

any tests independent?





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- Why strangeness in compact stars?
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  - **Strange quark matter**
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Strangeness manifested: SQM?

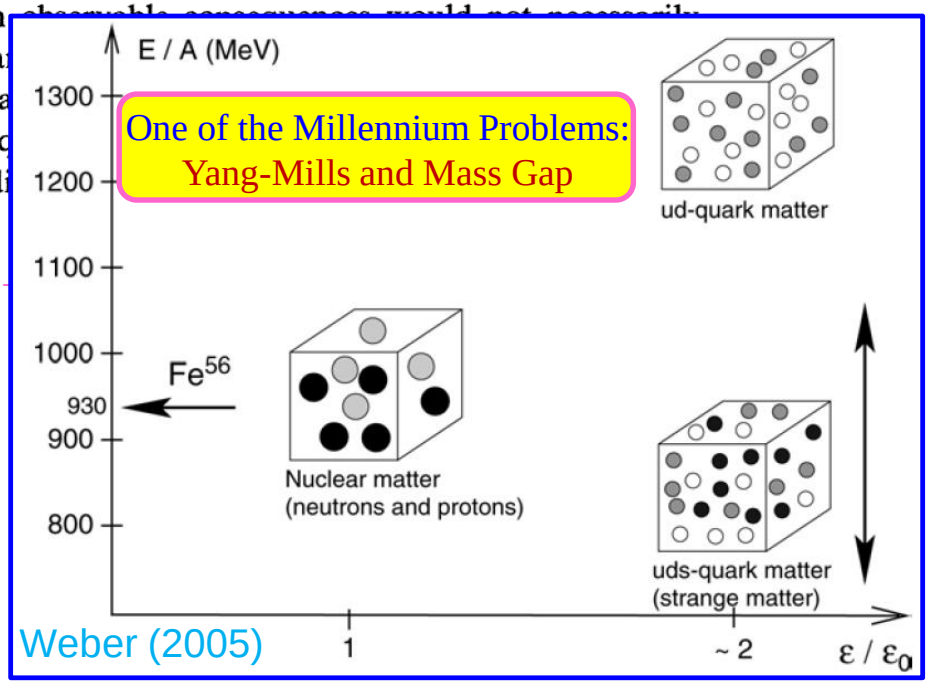
- Witten's impact on dense matter/*strangeness* phys.

PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase tra cess in dense, invisible quark nuggets, providing a QCD effects only. This possibility is viable only if c MeV. Two related issues are considered in appendi quark-matter component of cosmic rays, and the have produced a detectable gravitational signal.



Strange quark matter in bulk may constitute the true ground state of the strong-interaction matter rather than ^{56}Fe.

Strangeness manifested: SQM?

- An intuitional explain of ***Witten's conjecture***

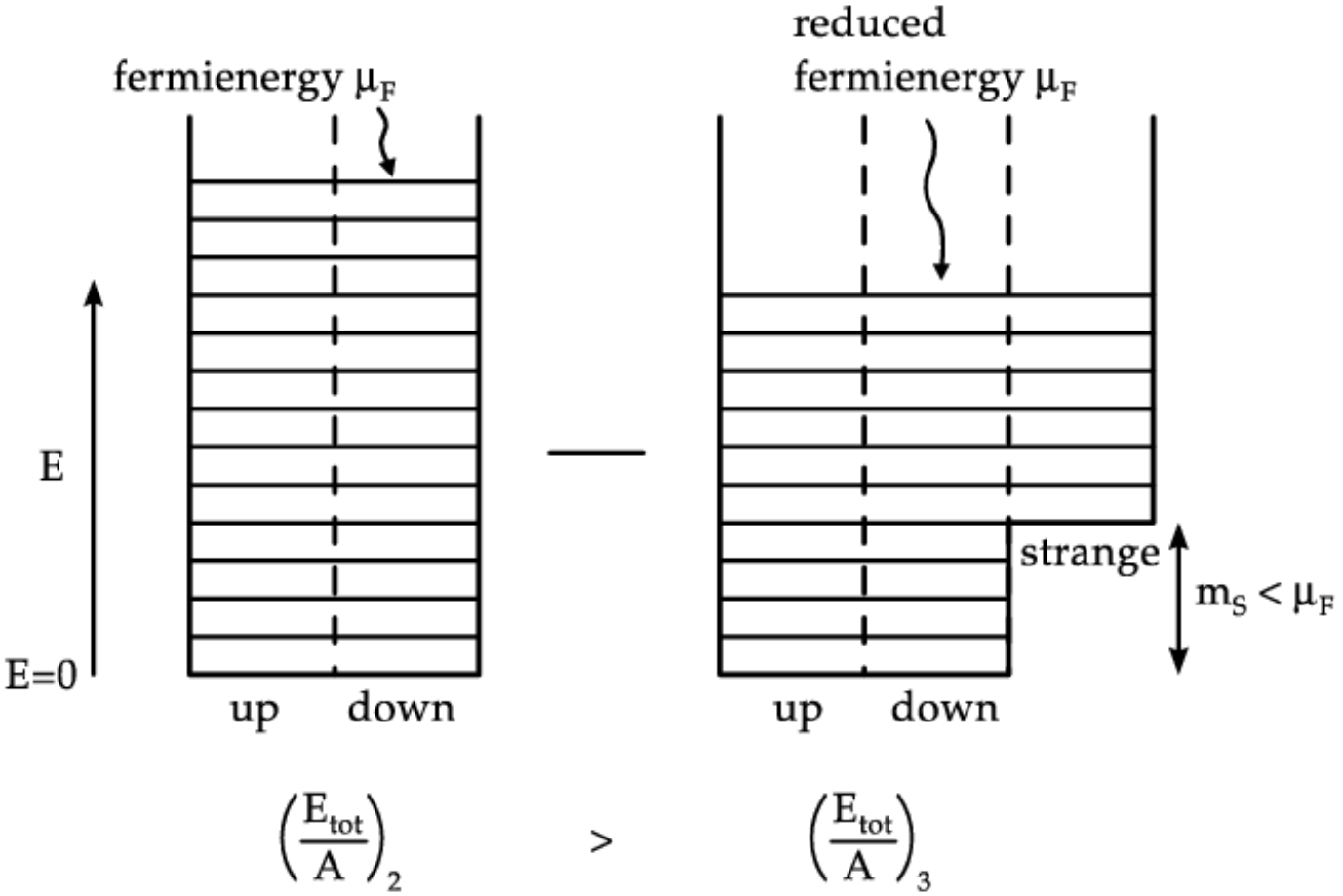
m_u = 2~8 MeV

m_d = 5~15 MeV

m_s ~ 100 MeV

$\rho = 2\rho_N$

μ_F ~ 500 MeV



Greiner et al. (1998)

Strangeness manifested: SQM?

- but…**free** quarks (SQM) seems also **soften** the EoS...

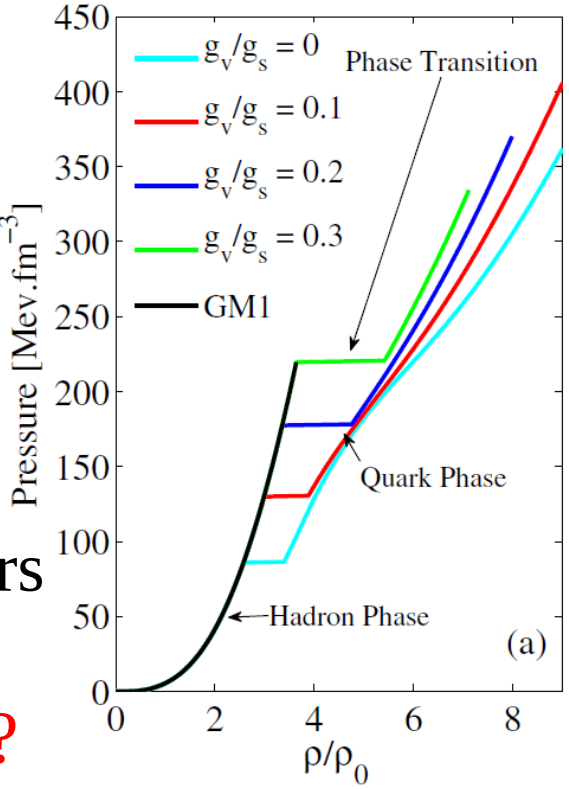
MIT-bag-based EoS tends to be too soft, but stiff EoS could be possible if introducing ***repulsive forces*** between quarks, forming hybrid stars.

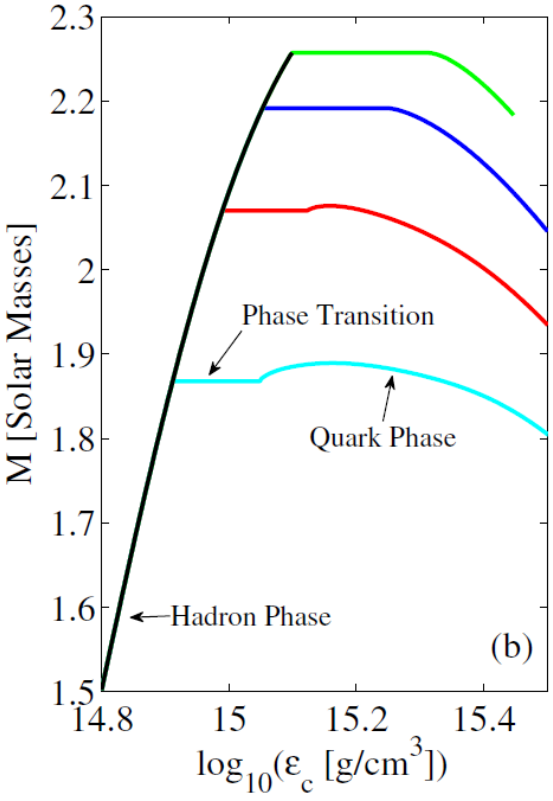
The vector coupling constant g_v is treated as a ***free parameter***.

Lenzi & Lugones (2012)

Yes, massive hybrid stars could be stable, but…

any tests independent?





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- Why strangeness in compact stars?
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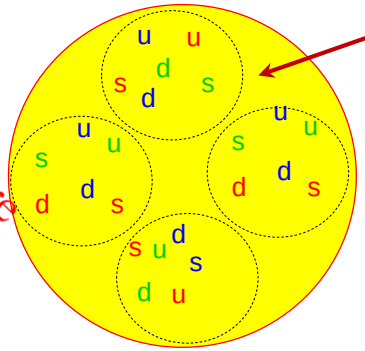
Strangeness manifested: Strangeon!

- A *generalized* Witten's conjecture ($E_{scale} < 1$GeV!)

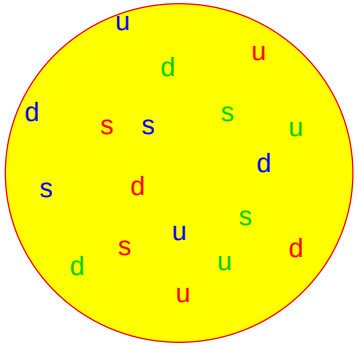
Strangeon matter in bulk constitutes the true ground state of the strong-interaction matter rather than ^{56}Fe.

Strange quark matter in bulk constitutes the true ground state of the strong-interaction matter rather than ^{56}Fe.

General Witten's conjecture



Strangeon
(strange nucleon)



Witten's conjecture

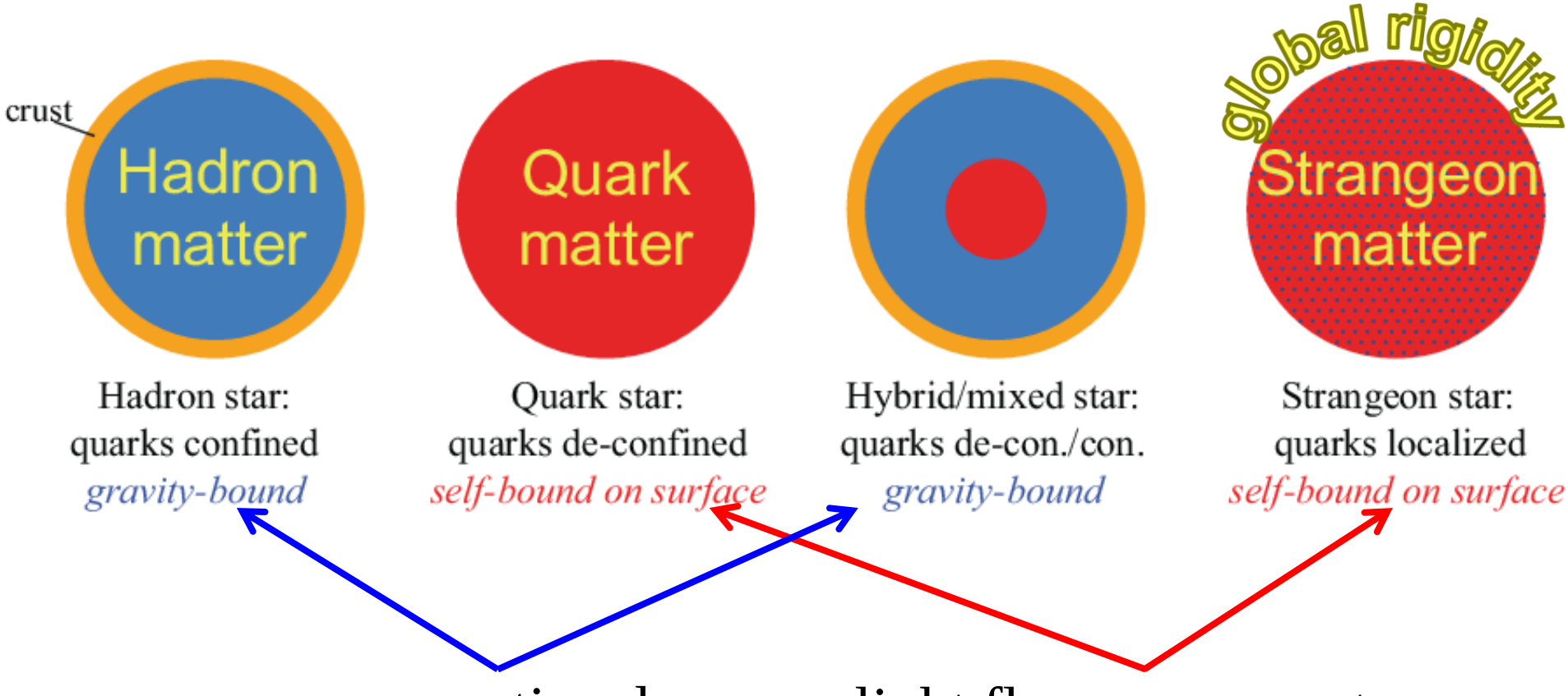
Strangeon Matter
(strangeon number ~ 10^{57} for star)

Strange ***Quark*** Matter
(quark number ~ 10^{57} for star)

strangeon['streɪdʒɪɒn]= **strange** + nucle**on** with strangeness $S = -B$

Strangeness manifested: Strangeon!

- Different models of pulsar's nature in the market



Strangeness manifested: Strangeon!

Mon. Not. R. Astron. Soc. **398,** L31–L35 (2009) doi:10.1111/j.1745-3933.2009.00701.x

Lennard-Jones quark matter and massive quark stars

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ABSTRACT

Quark clustering could occur in cold quark matter because of the strong coupling between quarks at realistic baryon densities of compact stars. Although one may still not be able to calculate this conjectured matter from the first principles, the intercluster interaction might be analogized to the interaction between inert molecules. Cold quark matter would then crystallize in a solid state if the intercluster potential is deep enough to trap the clusters in the wells. We apply the Lennard-Jones potential to describe the intercluster potential and derive the equations of state, which are stiffer than those derived in conventional models (e.g. MIT bag model). If quark stars are composed of the Lennard-Jones matter, they could have high maximum masses ($>2\,M_\odot$) as well as very low masses ($<10^{-3}\,M_\odot$). These features could be tested by observations.

NR & hard core

→ **Stiff** EoS

Self-bound

→ **Low** mass

Strangeness manifested: Strangeon!

Any tests independent?

Strangeness manifested: Strangeon!

- Strangeon is not new…speculated 14 years ago

THE ASTROPHYSICAL JOURNAL, 596:L59–L62, 2003 October 10

SOLID QUARK STARS?

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Received 2003 July 9; accepted 2003 August 22; published 2003 September 15

ABSTRACT

It is conjectured that cold quark matter with very high baryon density could be in a solid state, and strange stars with low temperatures should thus be solid stars. The speculation could be close to the truth if no peculiar polarization of thermal X-ray emission (as in, e.g., RX J1856) or no gravitational wave in postglitch phases are detected in future advanced facilities or if spin frequencies beyond the critical ones limited by *r*-mode instability are discovered. The shear modulus of solid quark matter could be $\sim 10^{32}$ ergs cm^{-3} if the kilohertz quasi-periodic oscillations observed are relevant to the eigenvalues of the center star oscillations.

Subject headings: dense matter — elementary particles — pulsars: general — stars: neutron

- condensation in ***x***-space, rather than ***p***-space, in ***solid*** state…astrophy.
- former names: strange cluster, quark cluster, solid quark...

Strangeness manifested: Strangeon!

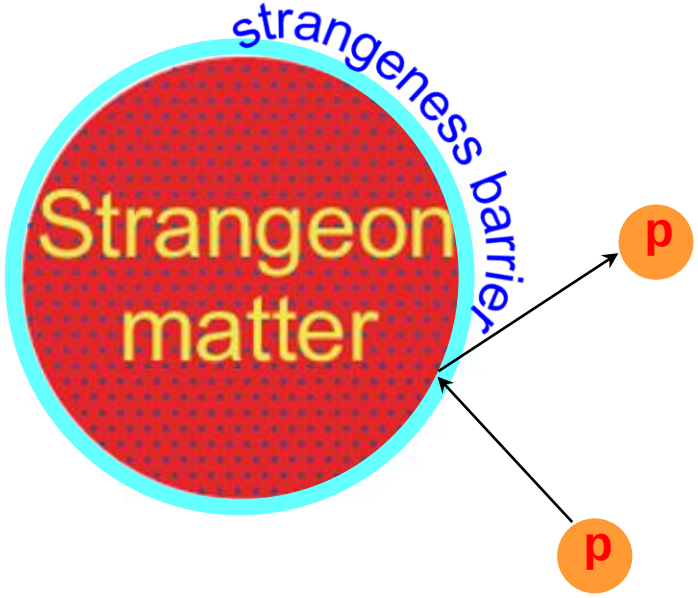
- To understand observations with strangeon star

	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 ~$10^{-2}M_\odot$	bound not by gravity	Xu & Wu (2003), Xu'05 √Li et al.'15
	none-atomic X	Plankian radiation of X-ray	no-atmosphere if bare	Xu (2002)
		absorption in thermal spec.	hydrodynamics of e-sea	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. (2017)
global	stiff EoS	high $M_{\rm max}$ (2~3$M_\odot$)	NR strangeons, hard core	Lai et al. (09ab, 13) 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)

Strangeness manifested: Strangeon!

- Accreting strangeon star: *strangeness barrier*

Trumper et al. (2005): The main ***puzzle*** of RXJ1856 is the observational fact that its X-ray spectrum is completely featureless.
van Kerkwijk et al. (2008): RX J1856.5-3754 is the X-ray brightest among the nearby isolated neutron stars. Its X-ray spectrum is thermal, and is reproduced remarkably well by a black-body, but its interpretation has remained ***puzzling***.



A strangeon star could have an **atmosphere** which could simply be regarded as the **upper layer** of a normal neutron star, that is

thin in X-ray band ⇒ dimmer, featureless

thick in optics ⇒ brighter (Optical excess)

Strangeness manifested: Strangeon!

The Astrophysical Journal, 837:81 (10pp), 2017 March 1 https://doi.org/10.3847/1538-4357/aa5e52

The Optical/UV Excess of X-Ray-dim Isolated Neutron Stars. I. Bremsstrahlung Emission from a Strangeon Star Atmosphere

Weiyang Wang[1,2,3], Jiguang Lu[1], Hao Tong[4], Mingyu Ge[5], Zhaosheng Li[6], Yunpeng Men[1], and Renxin Xu[1,7]
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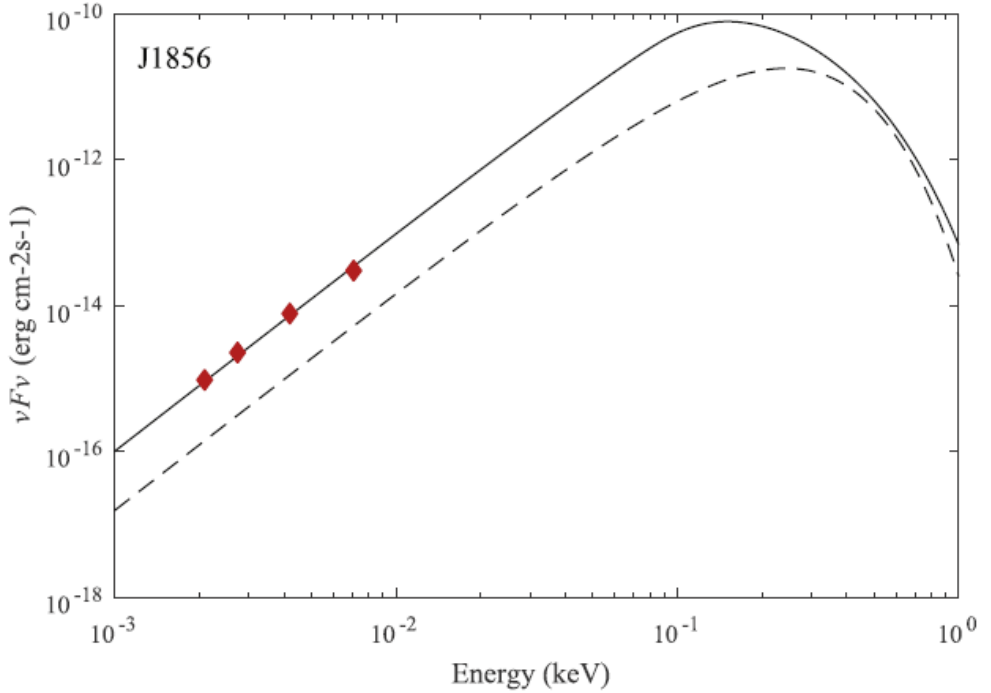
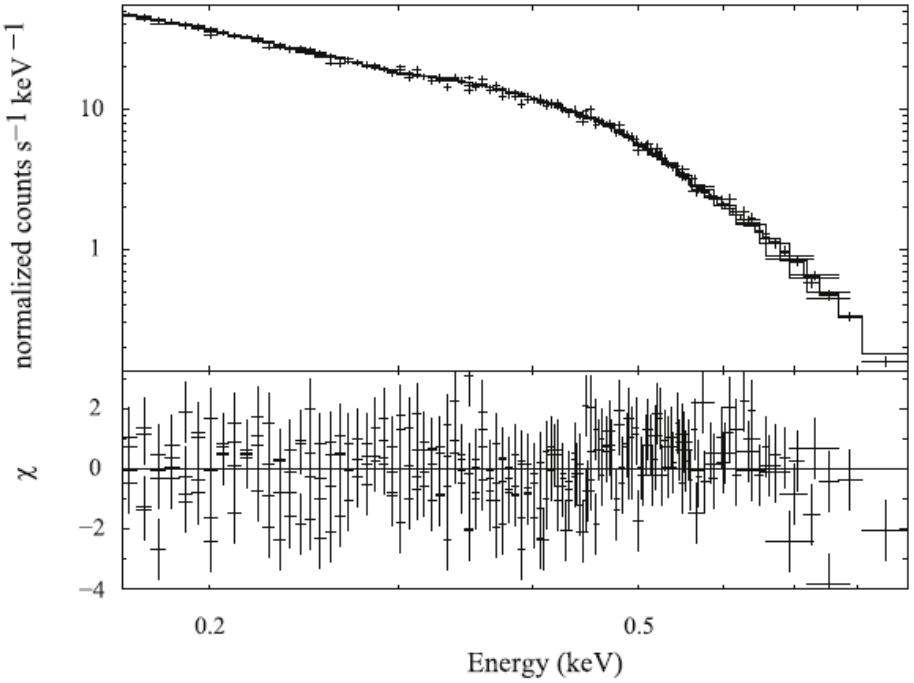
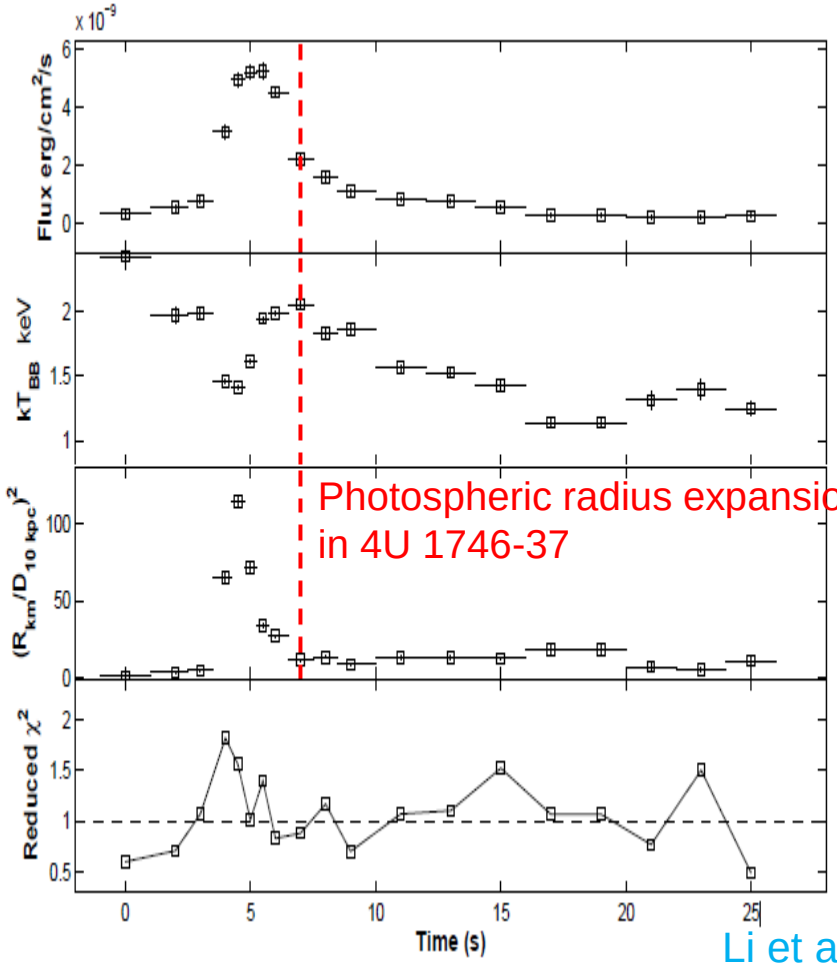
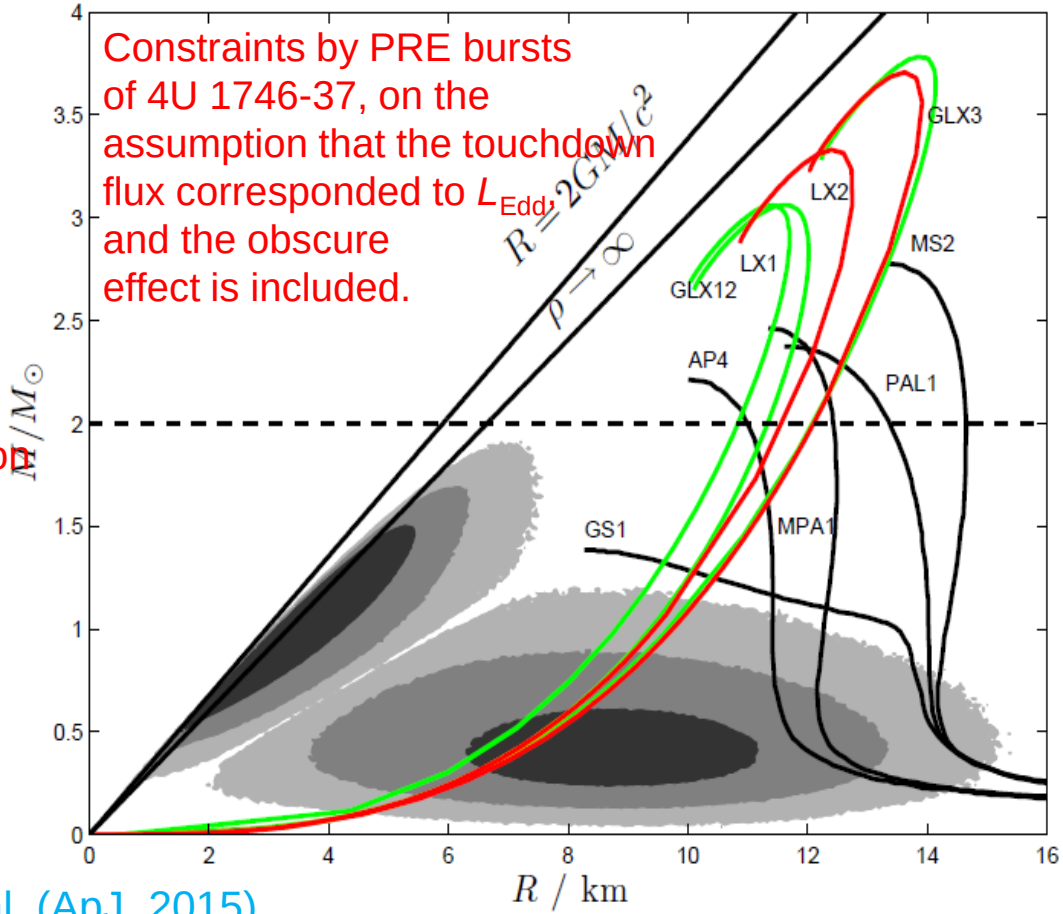




Strangeness manifested: Strangeon!

- Mass-radius constrained by PRE bursts?





Li et al. (ApJ, 2015)

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Conclusions

- Strangeness would play an important role in the physics of compact star, and thus a key to solve the EoS problem of dense matter.

- Strangeness could have three manifestations in compact stars: hyperon, strange quark matter, and strangeon.

- We proposed fourteen years ago that the nature SN-produced compact star are strangeon star, which fits observations and …

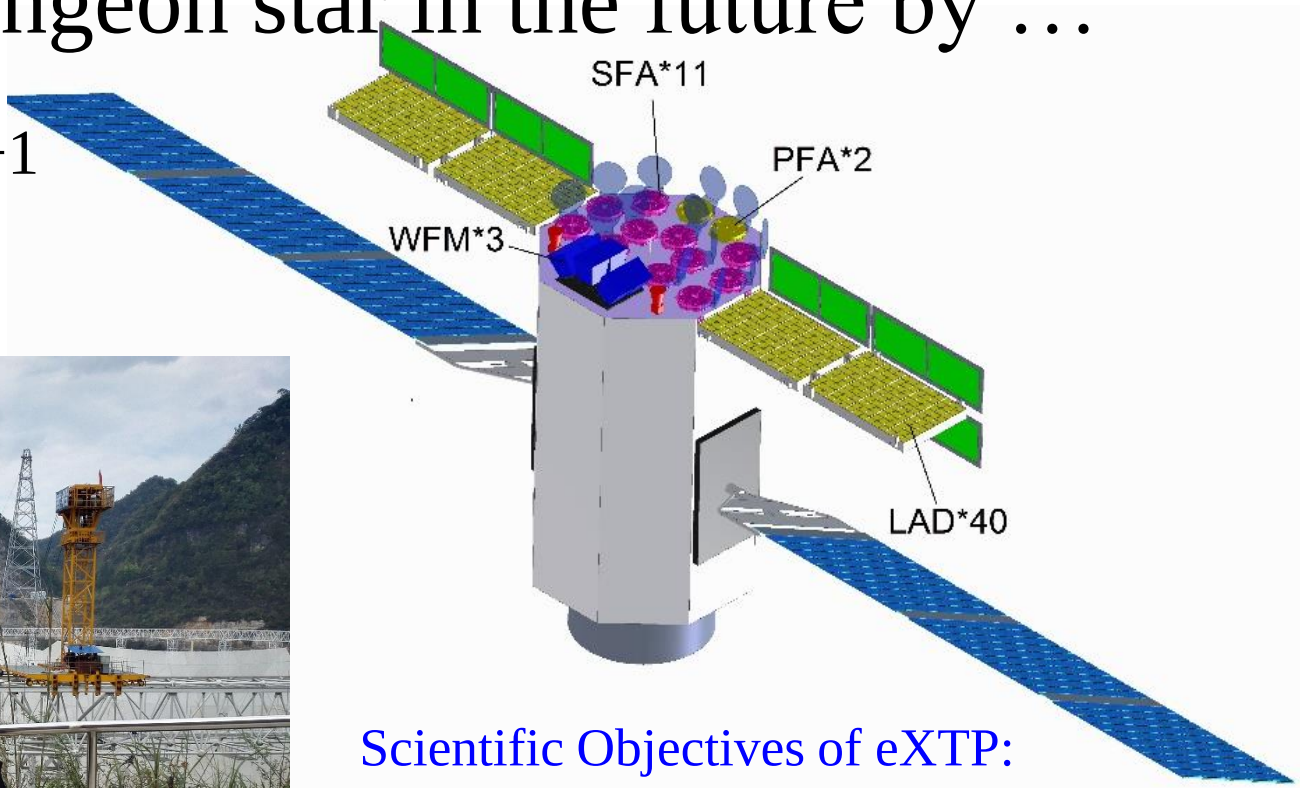
Conclusions

- To identify strangeon star in the future by …

Chinese FAST/SKA 2+1

"2" = HI & PSR

"1" = others



Scientific Objectives of eXTP:

One singularity (BH)
Two stars (NS or SS)
Three extremes (gravity, density, magnetism)

THANKS!