

Strangeness in Cosmic Rays

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Summary

- Strong matter: **2**- or **3**-flavored?
- **3**-flavored cosmic rays?
- Conclusions

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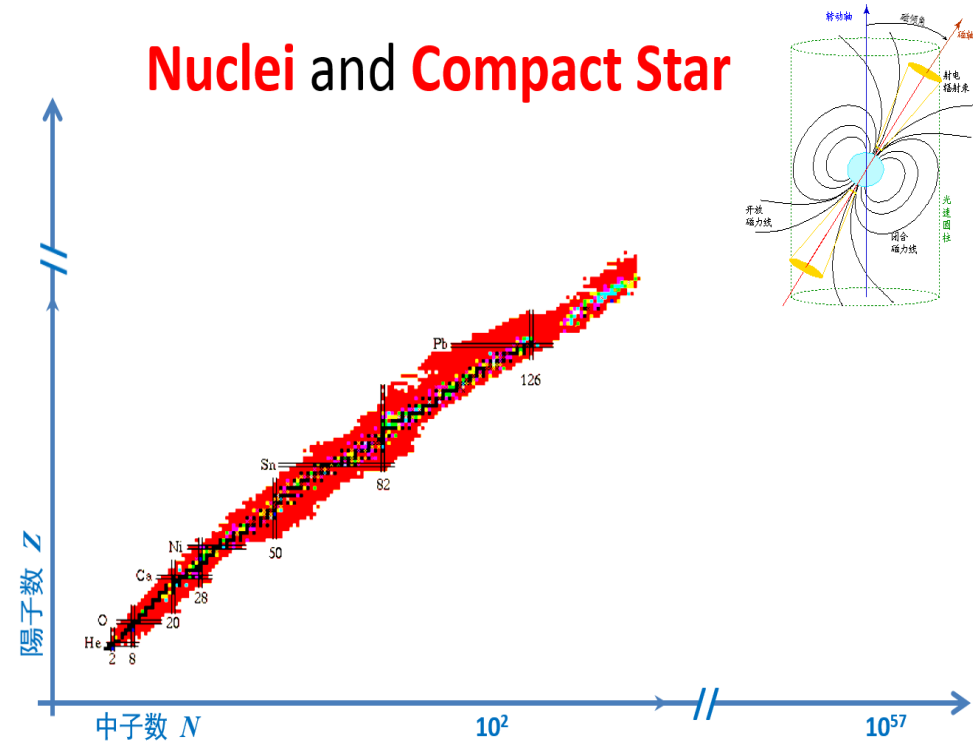
Strong matter: 2- or 3-flavored?

- Electric (electromagnetic) matter *vs.* Strong matter



Electric Matter:

condensed by EM-force



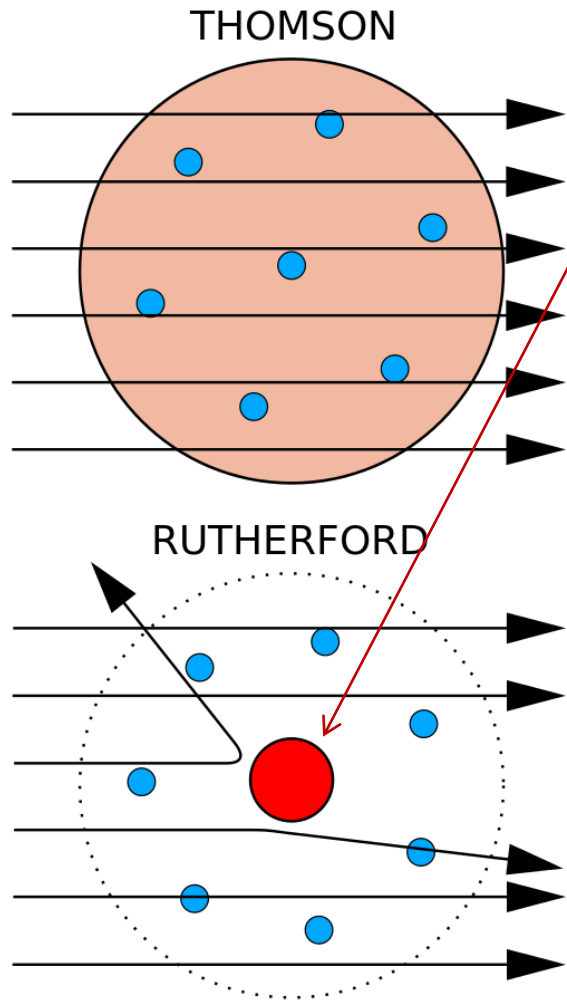
Strong Matter:

condensed by strong force

Strong matter: 2- or 3-flavored?

- Flavor symmetry of strong matter: 2(u,d) or 3(u,d,s)?

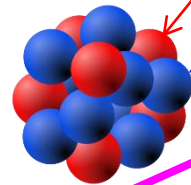
deflecting α -particles passing through a thin gold foil



This is an atomic nucleus, but what about its composition?
The constituent part of nucleus is then called nucleon...

This is NOT surprising because we know, e.g.,
fermion, boson, meson, hadron, pion
lepton, electron, muon, ...

nucleon: proton + neutron



2-flavored world
3-flavored world

strangeon as
the constituent
of 3-flavored matter



very similarly,
strangeon is the constituent part of 3-favour nucleus!

but, a key problem is:
Why 3-flavored? Really?

Strong matter: **2**- or **3**-flavored?

- Why are we **loving** strangeness in strong matter?

For strong matter at **a few nuclear density**, the separation between quarks, $\Delta\ell$, could be order of 0.5 fm.

From Heisenberg's uncertainty relation, $\Delta\ell \cdot \Delta p \approx \hbar$, one may have an energy scale for strong matter, E_{scale} ,

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

Therefore, we may expect 3-flavored strong matter because

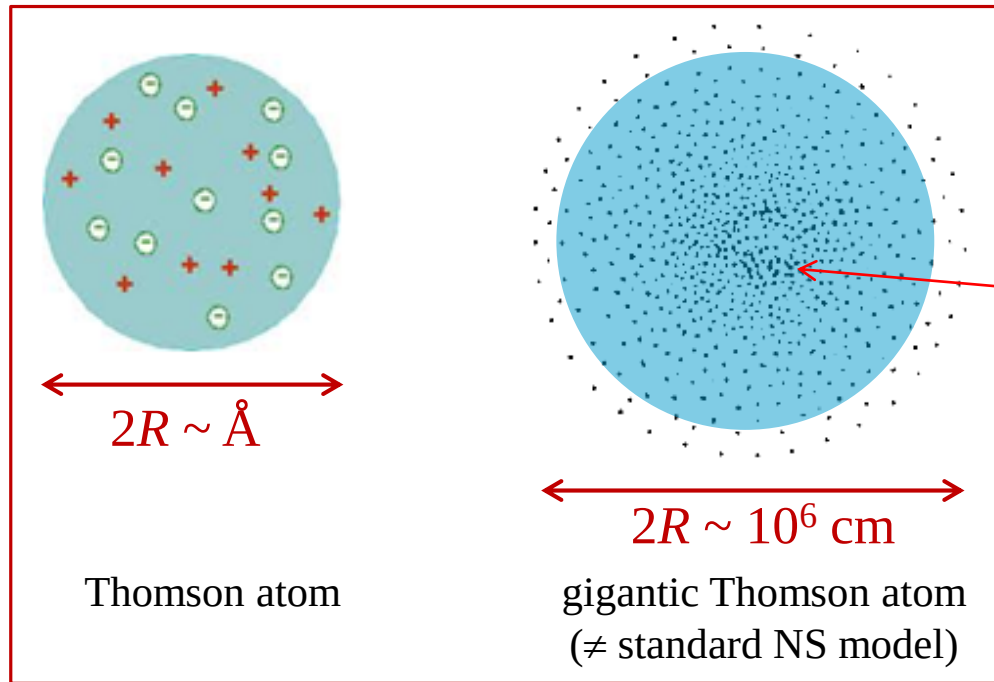
$$E_{\text{scale}} \gg (m_s - m_{ud})c^2!$$

But...our baryonic matter is **not** 3-flavored! **Why?**

Strong matter: **2-** or **3-**flavored?

- **Bigger** is different!

Huge Thomson atom if 2-flavor symmetry keeps...



disadvantages:

➤ though Coulomb energy could not be significant, but the Fermi energy of electrons:

$$E_F \sim \hbar c n^{1/3} \sim 10^2 \text{ MeV!}$$

advantages if strangeness ...

➤ electrons *negligible*, $n_e \ll n_q$

$$E_F \sim 10^1 \text{ MeV},$$

because $E_{\text{scale}} > \Delta m_{\{s, ud\}}!$

Litter nuclei with 2-flavour symmetry: nucleon matter → atom

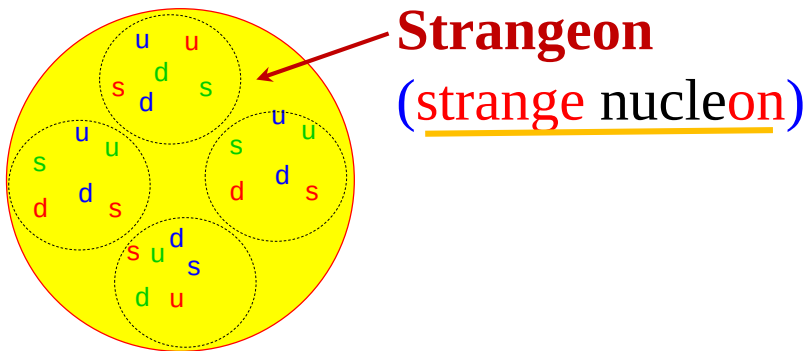
Bigger nuclei with 3-flavour symmetry: strangeon matter

Strong matter: **2**- or **3**-flavored?

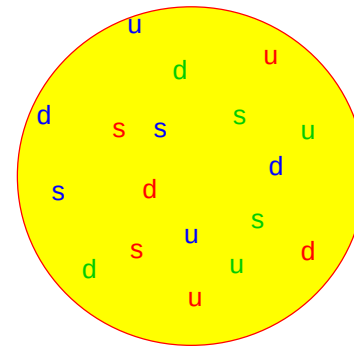
- **Note:** another kind of 3-flavored matter (e.g., **Witten'84**)

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 .



Strangeon Matter
(strangeon number $\sim 10^{57}$ for star)



Strange Quark Matter
(quark number $\sim 10^{57}$ for star)

Witten's conjecture

Strong matter: 2- or 3-flavored?

- To understand observations with *strangeon star*

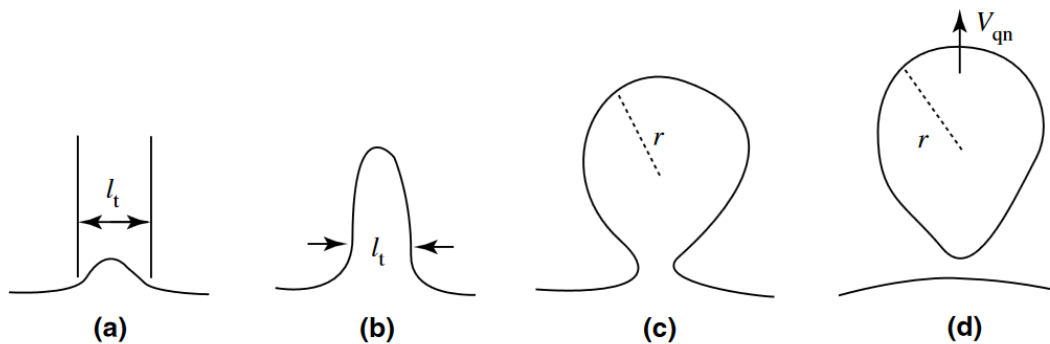
	Peculiarity	Manifestation	Mechanism	Ref.
surface	binding energy.	drifting subpulse, μ structure	gap sparking in RS75	Xu et al. (1999), Yu & Xu (2011)
		clean fireball for SNE/SGR	photon-driven explosion	Chen et al. (2007), Dai et al. (2011)
	self-bound	mass as low as $\sim 10^{-2}M_{\odot}$	bound not by gravity	Xu & Wu (2003), Xu'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	2 <i>f</i> matter separated from 3 <i>f</i>	Xu (2014)
optical/UV exce. of XDINS		bremsstrahlung radiation	Wang et al. (2017)	
global	stiff EoS	high M_{max} ($2\sim 3M_{\odot}$)	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)

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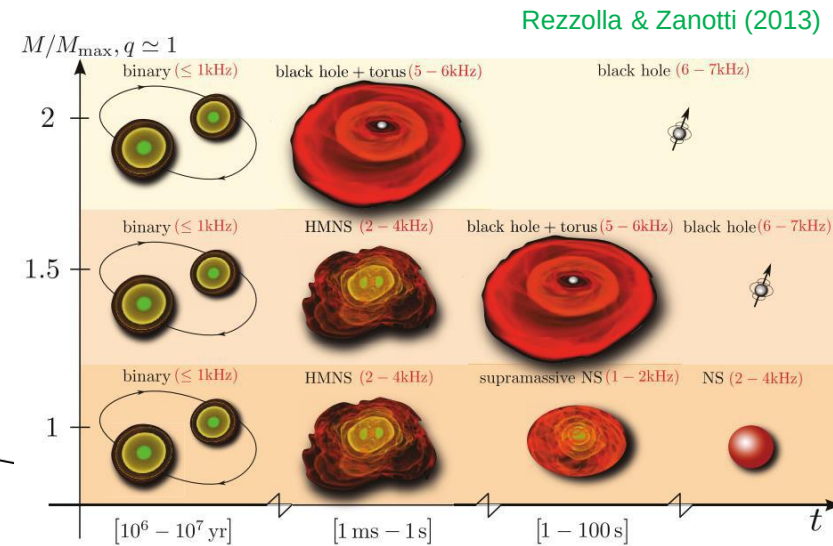
3-flavored cosmic rays?

•Origin of 3-flavored cosmic ray



- ① 3-flavored cosmic ray could be ejected from strangeon star surface during **CCSN**, 4 steps

Fig. 1 in Xu (2006, *Astroparticle Physics*)



- ② although speculative, but could also happen during **merger**, GW

Madsen (2005, *PRD*)

3-flavored cosmic ray is a direct consequence of strangeon matter!

3-flavored cosmic rays?

- **Air-shower** of 3-flavored cosmic ray: μ -excess?
 - The baryon number of 3-flavored cosmic ray $A \gg 10^2$
 - 3 components in EAS: nuclearactive, electromagnetic, and μ
 - μ -number $N_\mu \propto N^{3/4}$ (N shower size) for low $E_{\text{primary}} < 10^2 \text{ GeV}$
 - $N \sim \gamma A$ (total energy), for normal shower $A_0 = 1 \sim 56 \approx \text{constant}$ one then has $N_\mu \propto N^{3/4} \propto (\gamma A_0)^{3/4} \propto \gamma^{-1/4} (\gamma A_0)^{4/4} \propto \gamma^{-1/4} N!$
 - For ultra-high energy cosmic rays, maybe huge $A \gg 10^2$, we will have $N_\mu \propto \gamma^{-1/4} N \propto A^{1/4} N!$ (note: $\gamma A = \text{constant!}$)
 - 3-flavored rays ($A \gg 10^2$) would have significant μ -excess!

3-flavored cosmic rays?

•Evidence for 3-flavored cosmic ray?

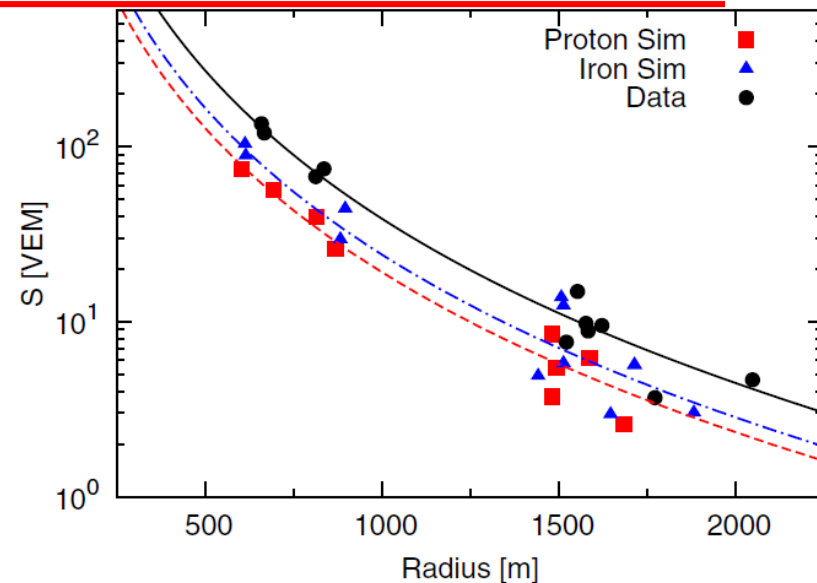
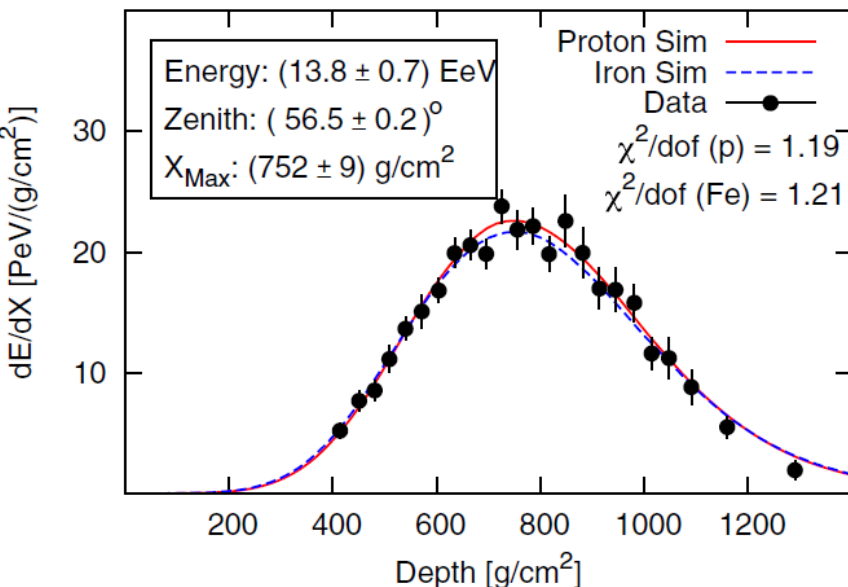
PRL **117**, 192001 (2016)

Selected for a **Viewpoint** in *Physics*
PHYSICAL REVIEW LETTERS

week ending
4 NOVEMBER 2016



Ultrahigh energy cosmic ray air showers probe particle physics at energies beyond the reach of accelerators. Here we introduce a new method to test hadronic interaction models without relying on the absolute energy calibration, and apply it to events with primary energy 6–16 EeV ($E_{\text{CM}} = 110\text{--}170$ TeV), whose longitudinal development and lateral distribution were simultaneously measured by the Pierre Auger Observatory. The average hadronic shower is 1.33 ± 0.16 (1.61 ± 0.21) times larger than predicted using the leading LHC-tuned models EPOS-LHC (QGSJetII-04), with a corresponding excess of muons.



3-flavored cosmic rays?

- To **identify** 3-flavored cosmic ray in the future?
 - A microphysical foundation of the strangeon matter in an *effective model* is really welcome to model EAS (extensive air-shower) of 3-flavored cosmic rays.
 - A 3-flavored (strangeon) cosmic ray *can only be identified* after its EAS event is modelled correctly.
 - Which *facility* is able to do this?

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- **Strangeness** might play a role in the physics of cosmic ray, especially in the ultra-high energy regime.
- **μ -excess** could be expected in EAS of 3-flavored (strangeon) cosmic ray.
- We looking forward to future **facility** to identify strangeon cosmic rays ...

THANKS!