Strange Matter:

the many faces

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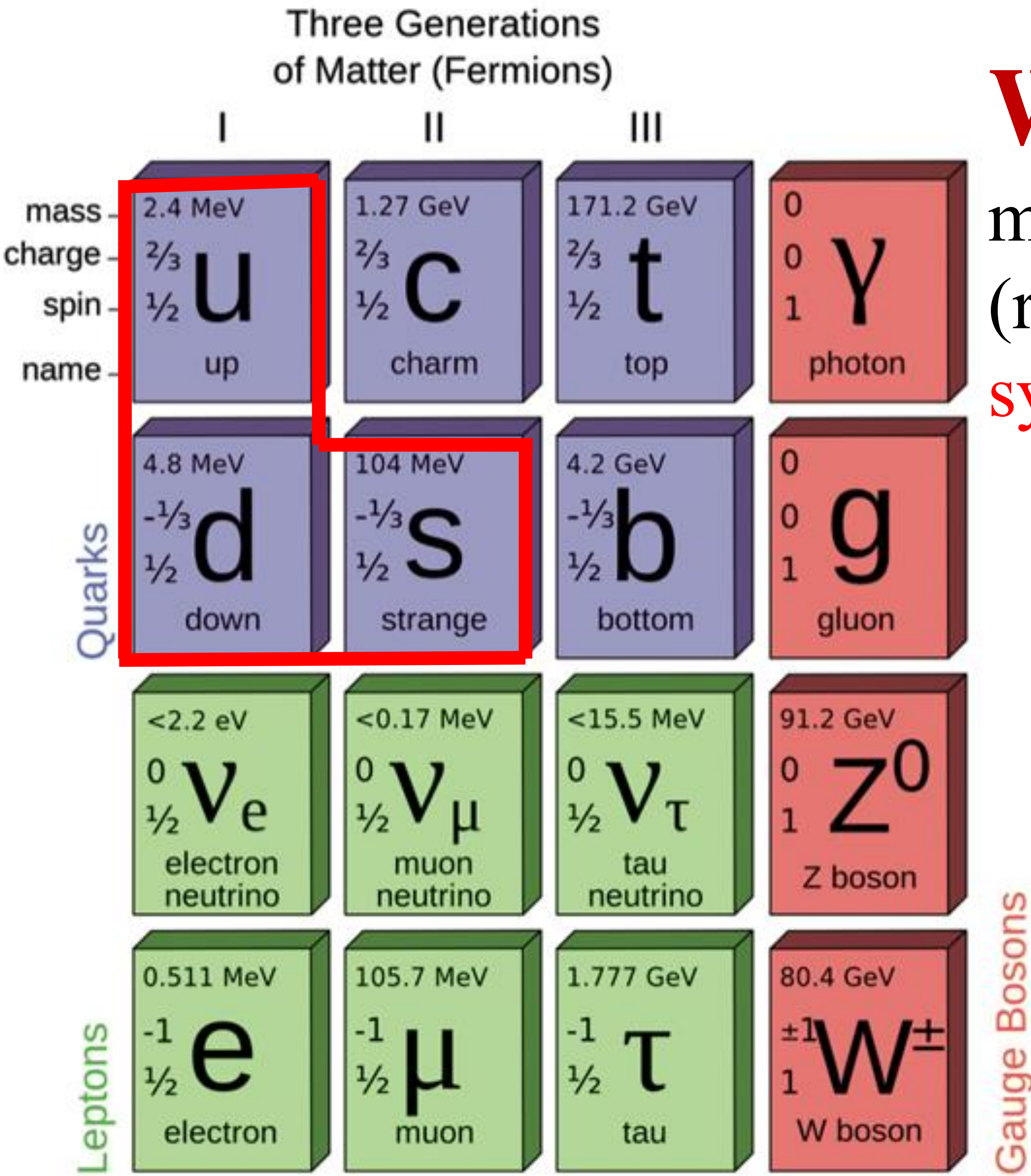


Why our baryonic matter with 2-flavor (rather than ~~1~~- or 3-) symmetry?

Strange Matter

Note: Energy scale ~ **400 MeV** (~0.5 fm) $pc \sim \hbar c \sim 200$ MeV·fm

Anthropic principle?

Summary

✓ Strange Matter: ***bigger*** is diff.!

- ***Many faces*** of strange matter

- Conclusions

Strange Matter: bigger is diff.!

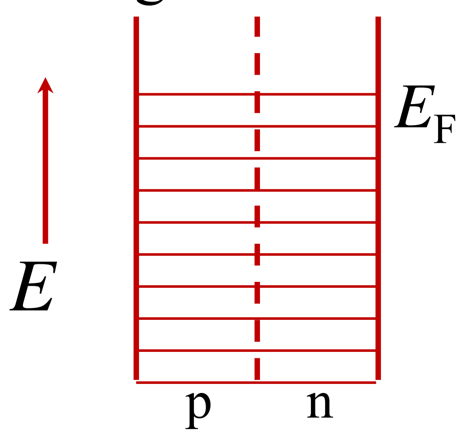
- The symmetry-energy in liquid-drop model

Five terms in mass formula of nucleus with Z protons and N neutrons ($A = Z + N$):

$$E\,(Z,N) = a_v A - a_s A^{2/3} - a_4 \frac{(N-Z)^2}{A} - a_c \frac{Z(Z-1)}{A^{1/3}} + a_p \frac{\Delta(N,Z)}{A^{1/2}}$$

volume *surface* *symmetry* *Coulomb* *pairing*

- Why does there exist symmetry-energy?
  - Fermi gas of nucleons: still ***weakly*** interaction inside a nucleus?



➢For non-relativistic neutrons and protons: $p_F \propto n^{1/3}$, $E_F \propto n^{2/3}$

$$\left.\begin{aligned} E_{Fn} &\sim (N/A)^{2/3} \\ E_{Fp} &\sim (Z/A)^{2/3} \end{aligned}\right\} E_k = \frac{3}{5}(E_{Fn} N + E_{Fp} Z)$$

$$\Rightarrow E_k(Z,N)\,|_{Z=A/2} = \ldots + a\,\frac{(N-Z)^2}{A} + \ldots$$

The kinetic term of Nuclear Symmetry Energy

➢Interaction really negligible?

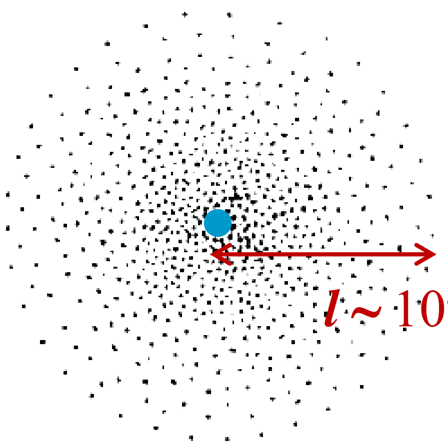
Strange Matter: bigger is diff.!

- **2**-flavuor *micro*-nuclei is energetically *favored*!
  - Fermi gas of nucleons: still ***weakly*** interaction inside a nucleus?
  - Alternatively, a 2-flavour symmetry? (an analogy: NaCl, ***interaction***!)

The potential term of Nuclear Symmetry Energy dominates!

A note: 2-flavour symmetry matter should be ***positively charged***!
…but it doesn't matter for microscopic nuclei because of $\alpha_{\rm em} \ll \alpha_{\rm s}$.

kinematic motion is bound by EM interaction: $p^2/m_{\rm e} \sim e^2/l$
Heisenberg's relation: $p \cdot l \sim \hbar$



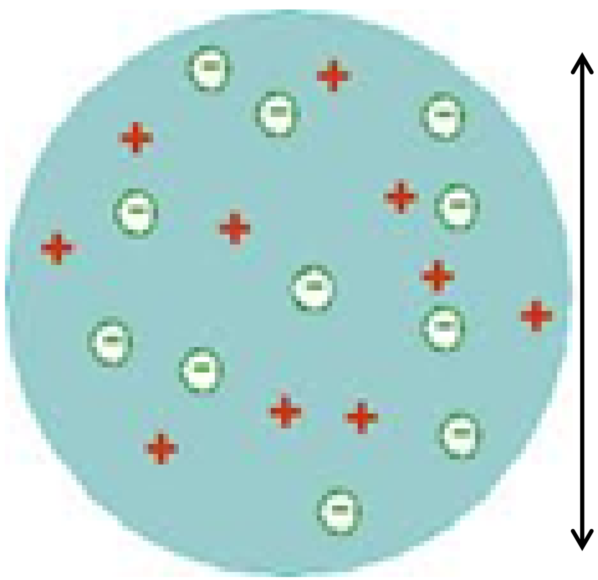
$l \sim 10^{-1}$ Å $\sim 10^4$ fm

$$\Rightarrow l \sim \frac{1}{\alpha_{\rm em}} \frac{\hbar c}{m_{\rm e} c^2}, \quad \frac{e^2}{l} \sim \alpha_{\rm em}^2 m_{\rm e} c^2 \sim 10^{-5}\ {\rm MeV}$$

∴ Electrons contribute negligible energy for micro-nuclei!

Strange Matter: bigger is diff.!

- A 3-flvuor symmetry in gigantic/macro-nuclei?
  - Huge Thomson atom if 2-flavour symmetry keeps...



disadvantages:

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

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

advantages ***if strangeness*** ...

➢electrons *negligible*, $n_e << n_q$

$E_F \sim 10^1$ MeV!

➢new strangeness degree *possible*:

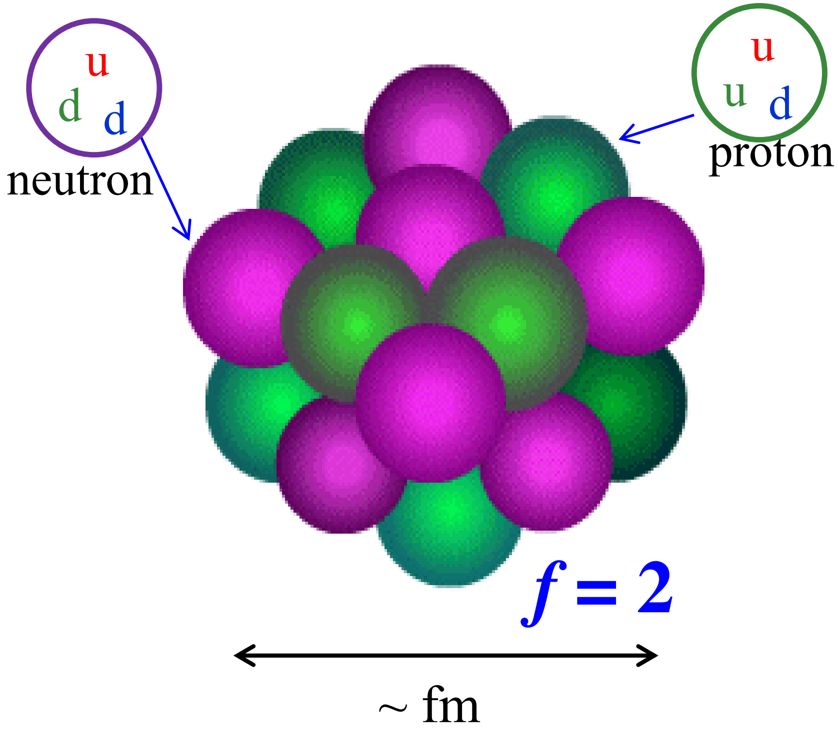
either Heisenberg's relation or Fermi energy ⇒

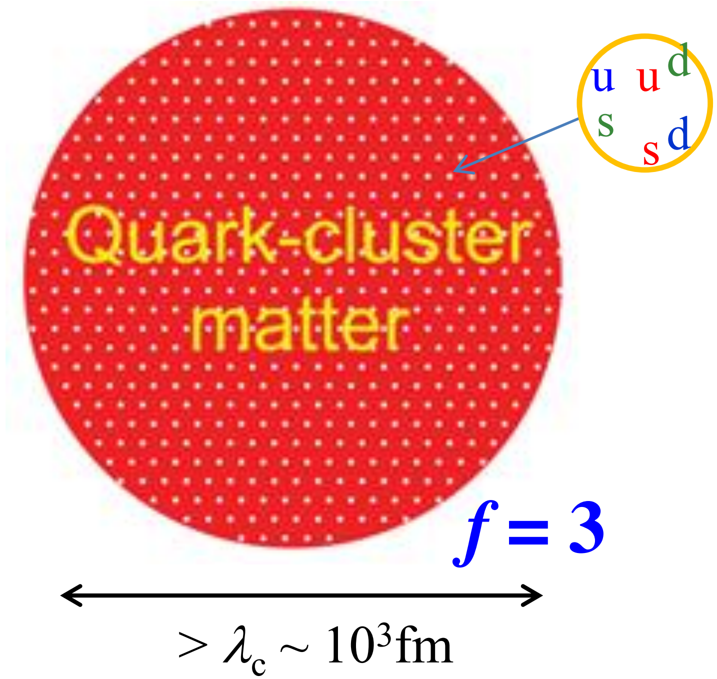
$E_{scale} > \Delta m_{\{s,\ ud\}} \sim 100$MeV

- ***Macro-nuclei with 3-f symmetry***: **strange** *quark-cluster* **matter!**

Strange Matter: bigger is diff.!

- 2-f micro-nuclus **VS** 3-f macro-nucleus





Each cluster has nearly equal numbers of $\{u,d,s\}$.

Macro-nucleus: ***condensed matter*** of quark-clusters!

Summary

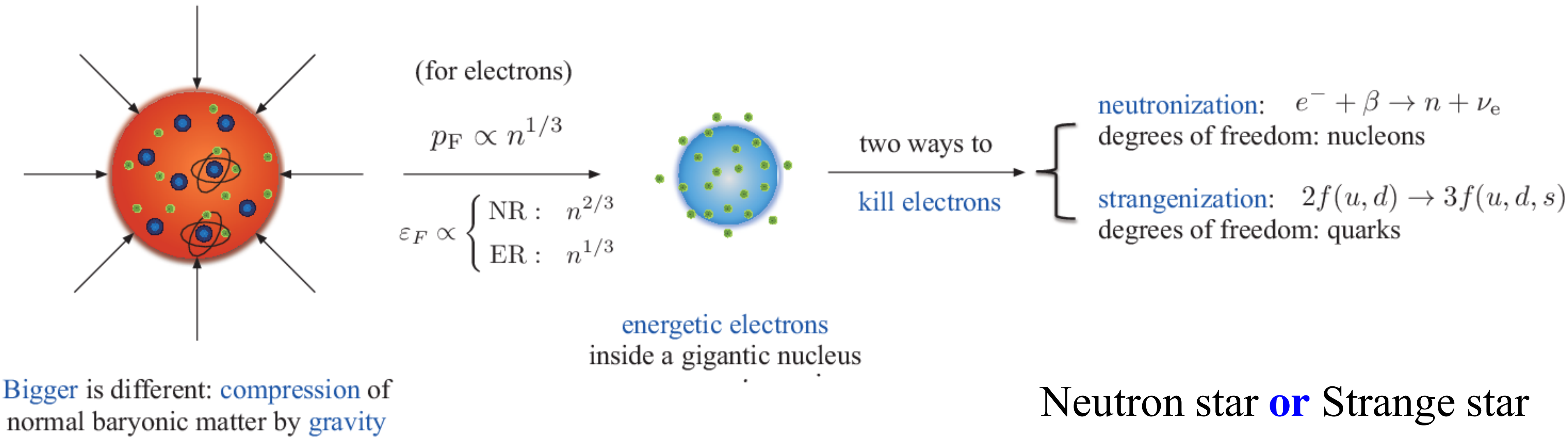
- Strange Matter: ***bigger*** is diff.!

✓ ***Many faces*** of strange matter

- Conclusions

Many faces of Strange Matter

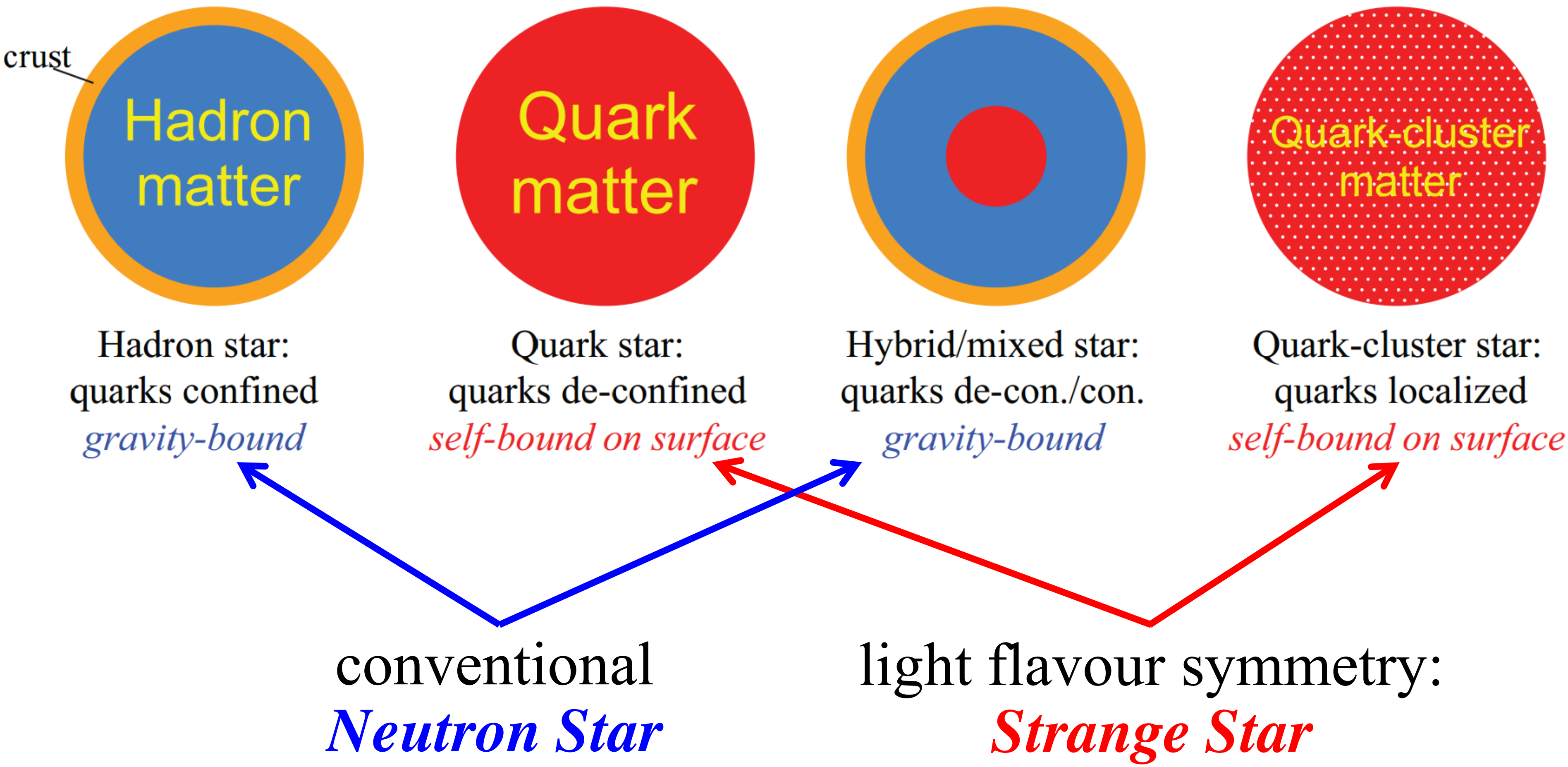
- **Compact stars**: Neutron star **VS** Strange star



Neutron star **or** Strange star

Many faces of Strange Matter

- **Compact stars**: different pulsar models



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•Compact stars: Observational hints?

Table 1. Neutron stars vs. Quark stars: to explain the observational features of pulsar-like stars in these two kinds of models.

	Phenomena observed	Normal neutron stars	(solid) quark stars	Note
Radio pulsars:	magnetospheric emission	ok?	ok?	$e^{\pm}$ plasma
	normal glitch	vortex (un)pinning	star-quake	to be tested
	slow glitch	???	in low-mass quark star	not in NS model
	(bi)-drifting sub-pulses	binding??	binding!	surface condition
	(free) precession	damped?	no damping	rigid or not
	timing noise	high in msPSRs?	solar or low mass	random torque
AXPs/SGRs*:	energy source	B-field	gravity & strain	magnetar?
	burst with glitch 10^{-6}	?	AISq*	sometimes
	super-flare	high-B magnetar?	giant-quake?	
CCOs*:	age discrepancy	?	quark star with fossil disk	
	erratic timing	?	torque by disk	
DTNs*:	non-atomic feature	high B or Z?	bare quark stars!	
Thermal radii	why small?	polar cap?	low-mass quark stars	local or global
APXPs*:	ADmsPSRs*	ok?	low-mass quark star?	spin up & down
XRBs*:	bursts	nuclear power	crusted quark star?	
Sub-msPSR*:	spuper-Kepler spin	no!	possible	prediction (QS)
Others:	supernova	ν-driven??	γ-driven?	not successful
	MACHOs*	?	(low-mass) quark stars?	
	UHECRs*	?	strangelets?	

*AXPs/SGRs: anomalous X-ray pulsars/soft γ-ray repeaters; CCOs: compact central objects; DTNs: dim thermal "neutron stars"; APXPs: accretion-powered X-ray pulsars; XRBs: X-ray bursters; Sub-msPSRs: sub-millisecond pulsars; MACHOs: massive compact halo objects; UHECRSs: ultra-high energy cosmic rays; AISq: accretion-induced star-quake.

①

Xu (2008)

Many faces of Strange Matter

- Non-thermal emission: bound strongly?
  - ***Subpulse drifting***: PSG or self-bound surface?
  - ***Bi-drifting***: strong self-bound quark surface?
- Thermal emission: featureless & clear?
  - ***Nonatomic spectra***: quark surface?
  - ***Clean fireball*** for SNE & GRB?

Surface

- Quark-cluster stars in a solid state?
  - ***Precessions*** of pulsars?
  - ***Quake***-induced free energy for AXP/SGRs?
- Obs. tests of ***stiff equation of state***?

Global

Many faces of Strange Matter

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.

Low mass ($\sim 10^{-2} M_\odot$) is a direct consequence of self-bound surface!

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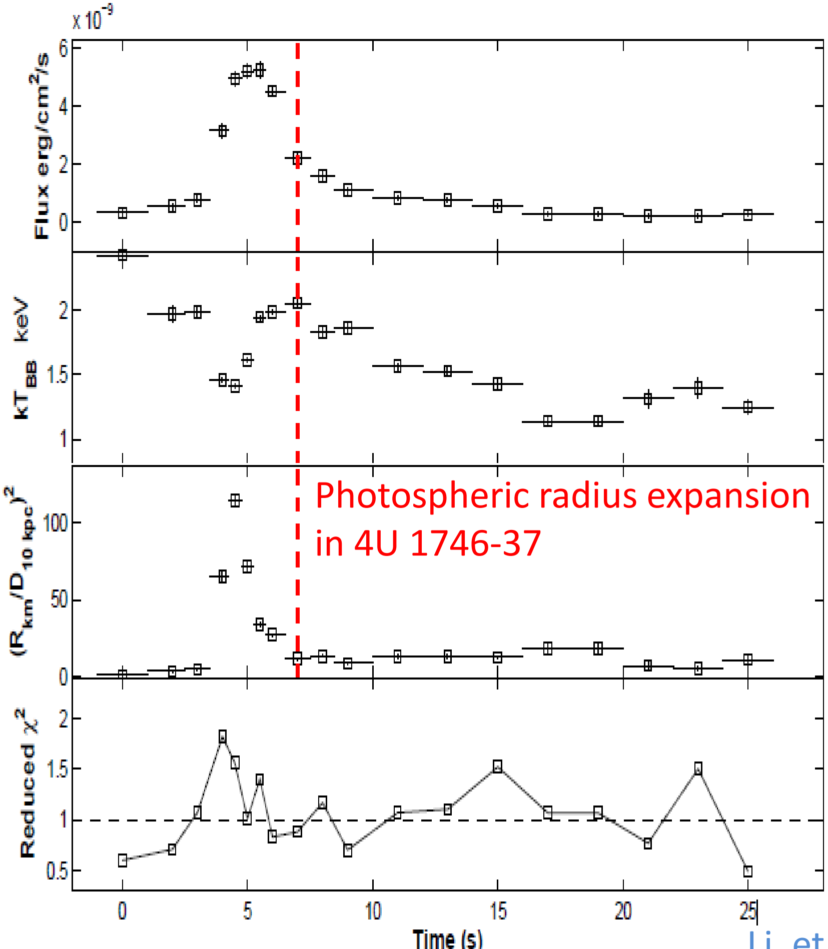
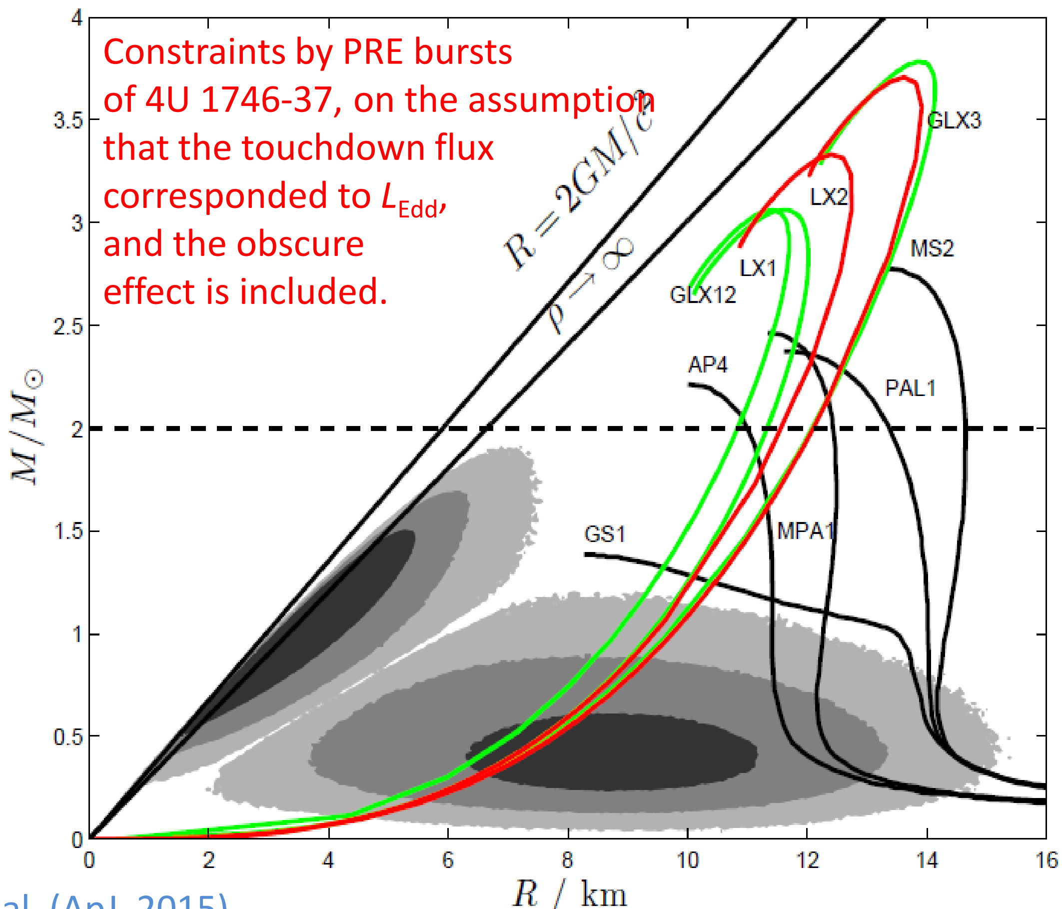
- **Compact stars**: low-mass pulsar-like star?





Li, et al. (ApJ, 2015)

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- **Cosmic hadronisation**: relics of strange nugget?

$$A \in (\sim 10^{24}, \sim 10^{35})$$ Dark matter?

BBN He abundance would not be affected significantly

Strange nuggets may help formations of high-z (~6) supermassive BHs

Lai & Xu (2010)

- **Cosmic ray**: relativistic/non-relativistic nugget?

Merging binary strange stars
Nuggets after cosmic QCD transition
→ Cosmic rays even UHECRs?

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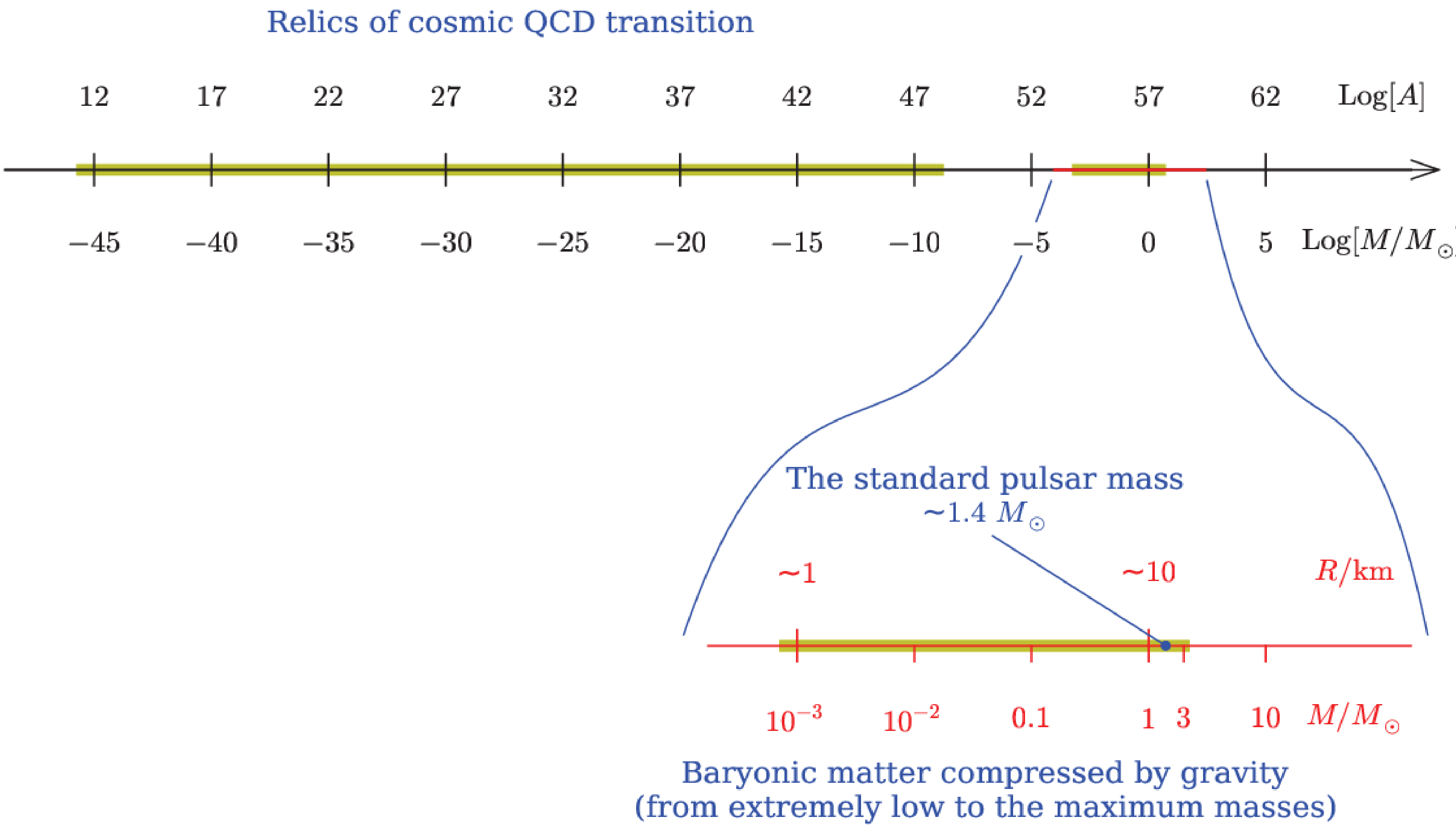
- **Strange matter:** mass spectrum?



Summary

- Strange Matter: ***bigger*** is diff.!
- ***Many faces*** of strange matter

✓ Conclusions

Conclusions

- Strange matter is conjectured to be condensed matter of 3-flavour quark-clusters, which could manifest itself as compact stars, cosmic rays, and even dark matter.

- Future advanced facilities (e.g., FAST, SKA) would provide opportunity to find solid evidence for strange stars, while others (space or ground) could do for strange nuggets.

THANKS!