Strong Matter *in Astrophysics*

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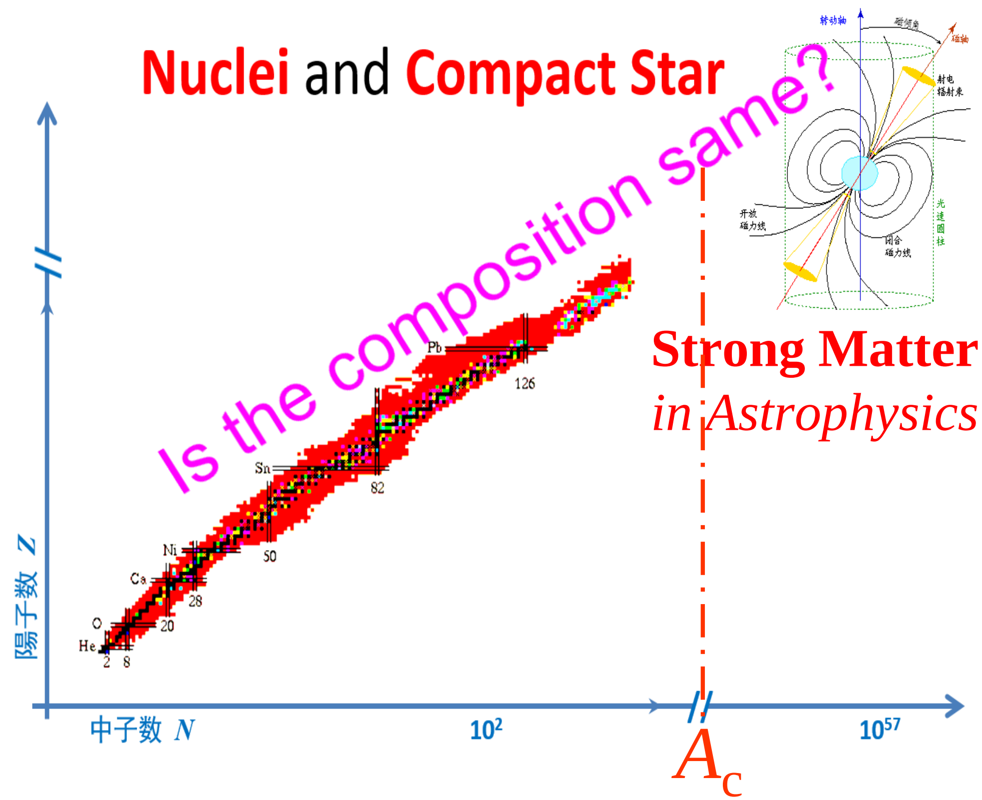
iHIC 2018

April 7-11, 2018; Tsinghua University, Beijing

Matter: electric and strong…

- Electric (electromagnetic) matter ***V.S.*** Strong matter



***Electric Matter*:**
condensed by EM-force

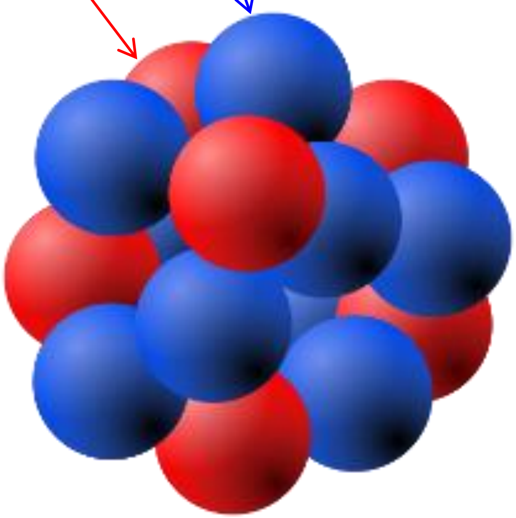
***Strong Matter*:**
condensed by strong force

Strong matter: nucleon/strangeon

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

2-flavored world v.s. 3-flavored world

The constituent part of nucleus is then called nucleon (proton + neutron)



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

Summary

- ✓ Energy scale and consequences
- Observational tests/predictions
- Conclusions

Energy scale and consequences

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

For strong matter at ***a few nuclear densities***, 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, $E_{\rm scale}$,

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

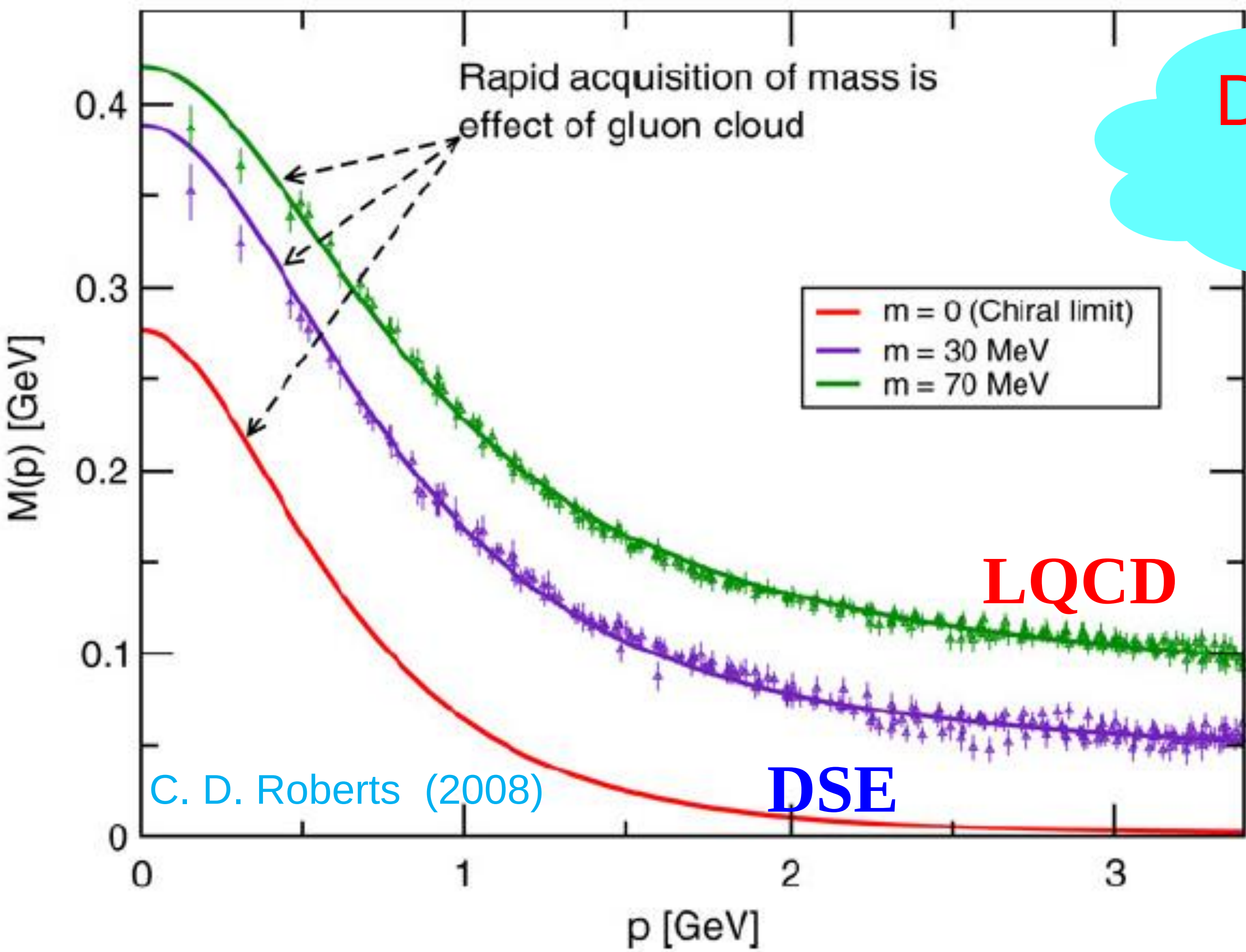
Note that... we may expect 3-flavored strong matter because

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

(but…our baryonic matter is ***not*** 3-flavored! *why*?)

Energy scale and consequences

•**(1) Chiral symmetry broken:** more and more massive



Dress more,
it's cool!

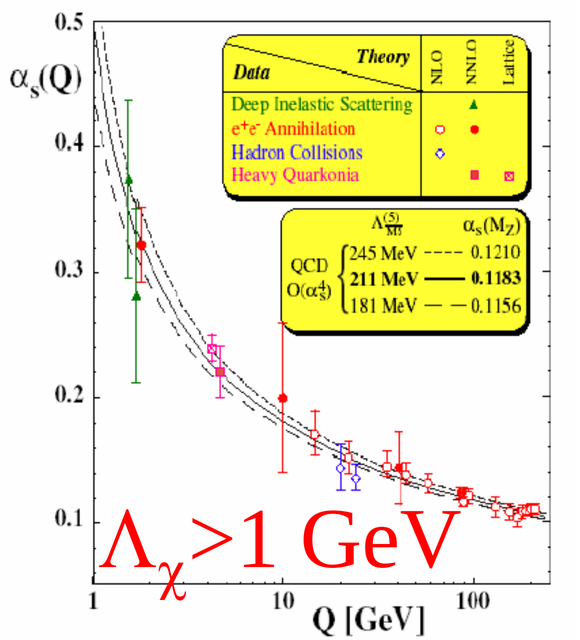
⇒ Quark mass:

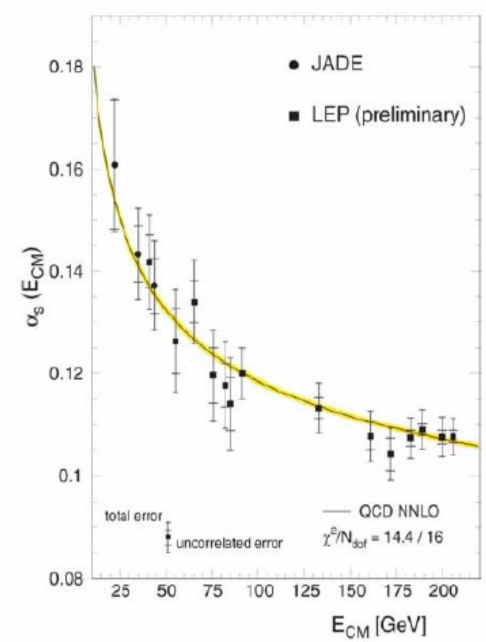
$m_q \sim 300$ MeV !

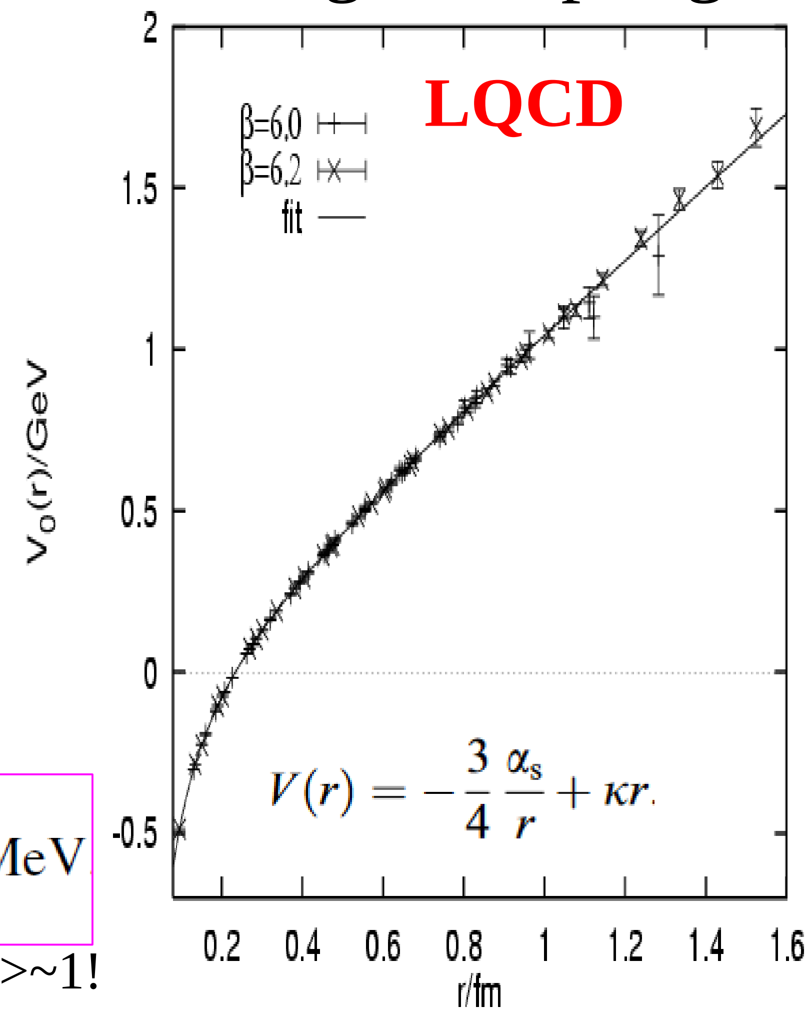
at $E_{scale} \sim 0.5$GeV

Energy scale and consequences

- (2) **Color confinement?** stronger and stronger coupling!







Coulomb-like color interaction at small distance:

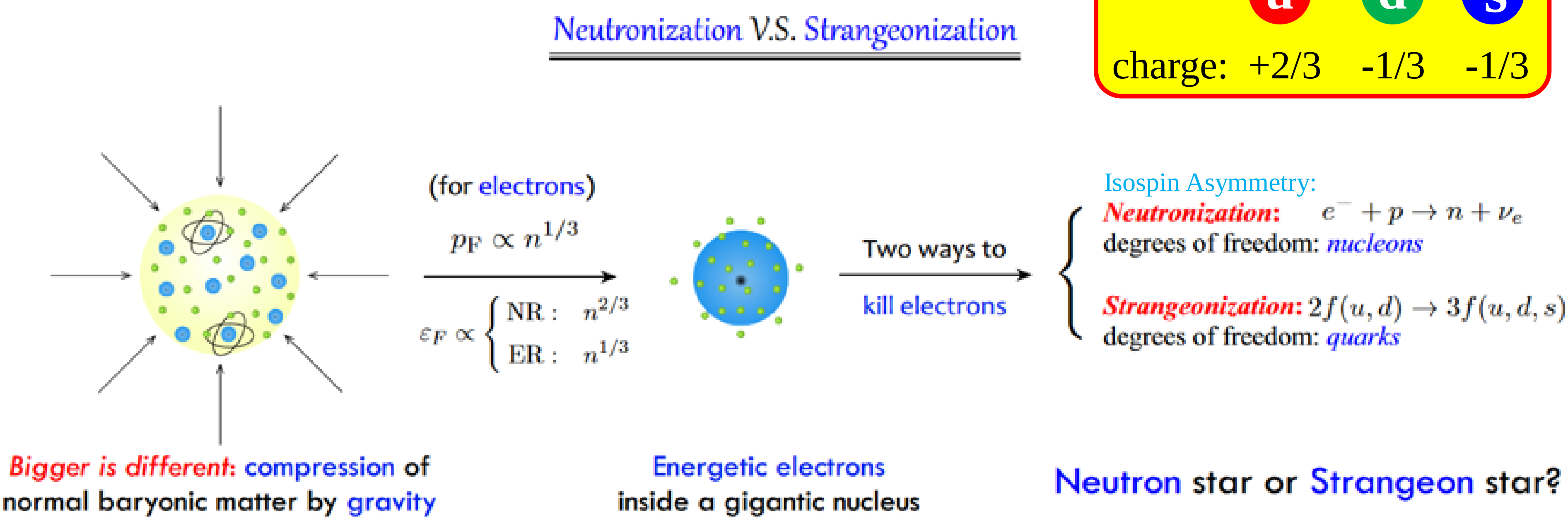
$$l_q \sim \frac{1}{\alpha_s}\frac{\hbar c}{m_q c^2} \simeq \frac{1}{\alpha_s}\ \text{fm}, \quad E_q \sim \alpha_s^2 m_q c^2 \simeq 300\alpha_s^2\ \text{MeV}$$

Xu (CSQCD, 2009): CSC could be dangerous if α_s>~1!

Energy scale and consequences

- **(3) Strangeness:** strangeon matter?
  To ***kill the electrons*** by weak interaction when normal baryonic matter is compressed by gravity in a core of massive evolved star: *3-flavor symmetry restoration*?

	u	d	s
charge:	+2/3	-1/3	-1/3



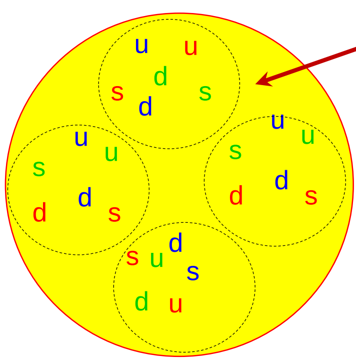
Energy scale and consequences

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

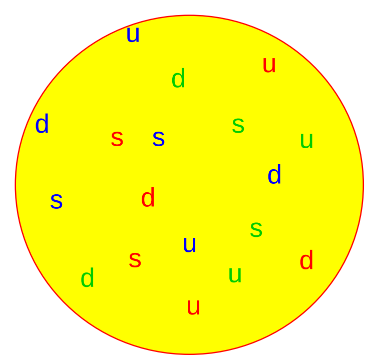
Strangeon matter in bulk constitutes the true ground state of the strong-interaction matter rather than ^{56}Fe.

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

Witten's conjecture



Strangeon
(strange nucleon)



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

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

Summary

- Energy scale and consequences

✓ Observational tests/predictions

- Conclusions

Observational tests

- Strangeon matter passes ***dynamical*** test I: M_{max}

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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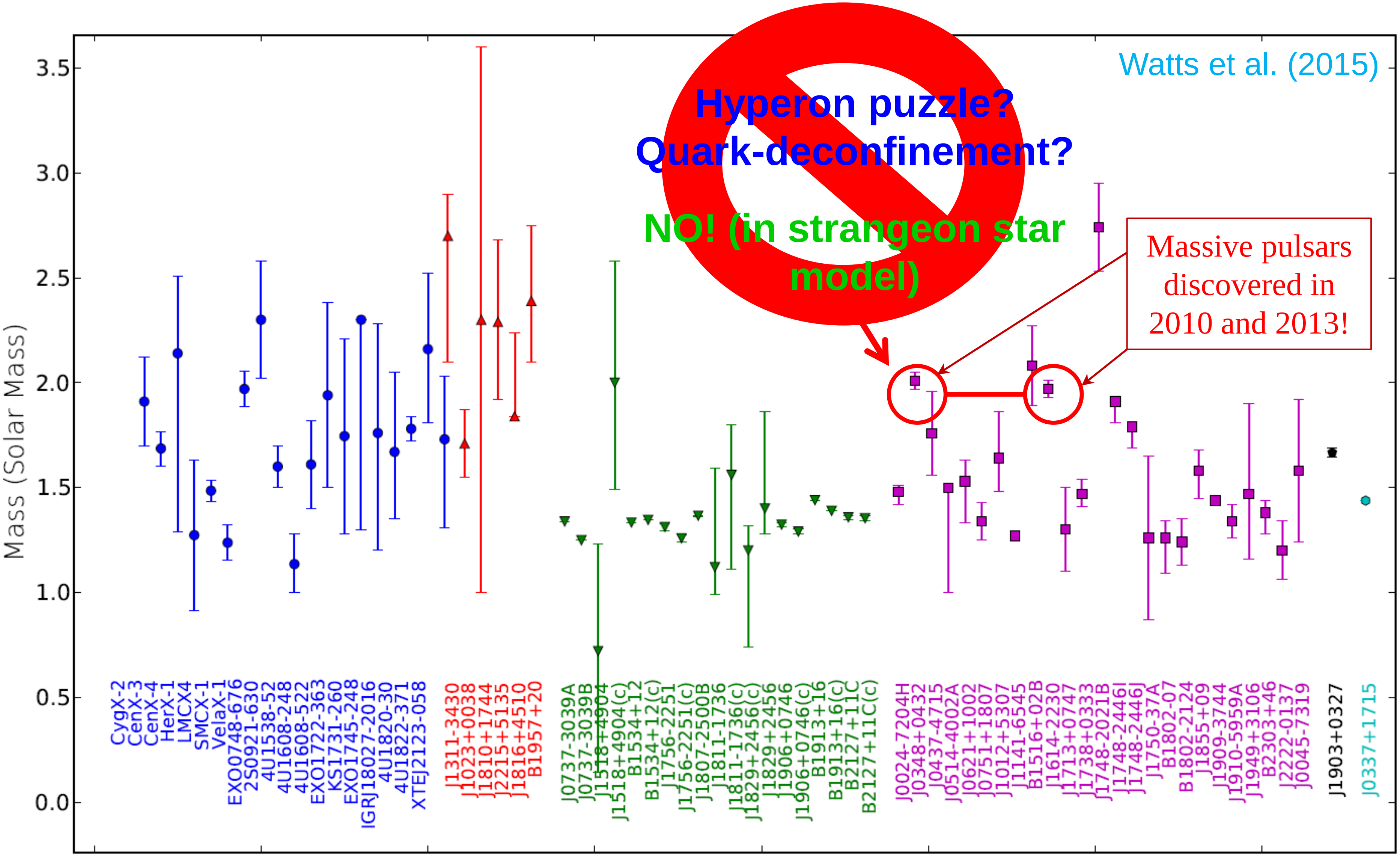
Accepted 2009 June 16. Received 2009 June 8; in original form 2009 May 17

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.

Observational tests



Observational tests

- Strangeon matter passes ***dynamical*** test II: Λ

Xu & Guo, 2016/2017, ***Strange Matter: a state before black hole***, in: centennial of general relativity, Ed. Cesar A. Zen Vasconcellos, World Scientific Publishing Company, p.119-146

Note added in proof

After submission of this chapter, the discovery of the gravitational waves is announced (Abbott *et al.* *PRL* **116**, 061102 (2016)). The proposed model of strange star with rigidity (i.e., solid strange quark-cluster star) is quite likely to be tested further by kilo-Hz gravitational wave observations of two kinds of events as follow, at least. (1) Merger of pulsar–pulsar/pulsar–black hole binary. The predicted waveform depends on the state equation of supra-nuclear matter, and the tidal effects during inspiral should be much weaker for solid strange star than for normal neutron star. (2) Starquake of pulsar-like compact star. Sensitive detectors may discover starquake-induced gravitational waves of compact stars, and then show very different signatures of neutron and strange stars.

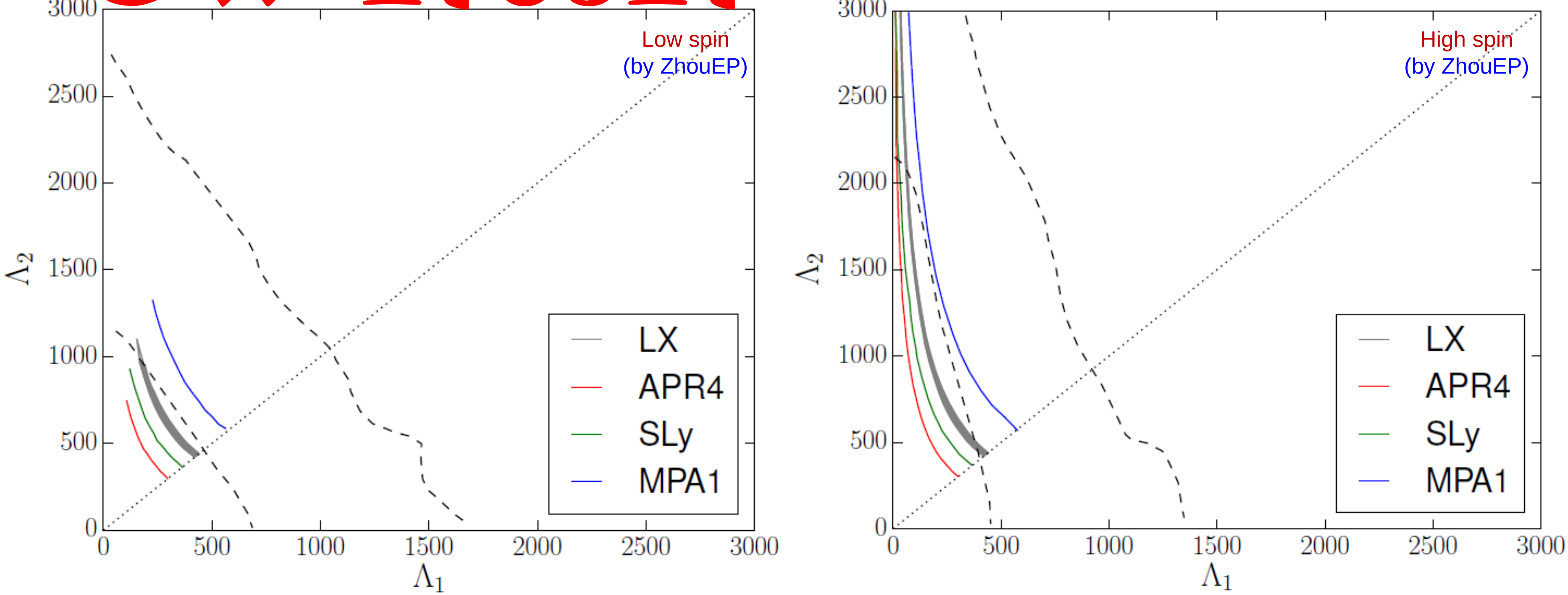
http://www.worldscientific.com/worldscibooks/10.1142/9690

Observational tests

- Strangeon matter passes ***dynamical*** test II: Λ

GW 170817

Lai et al. (2018)



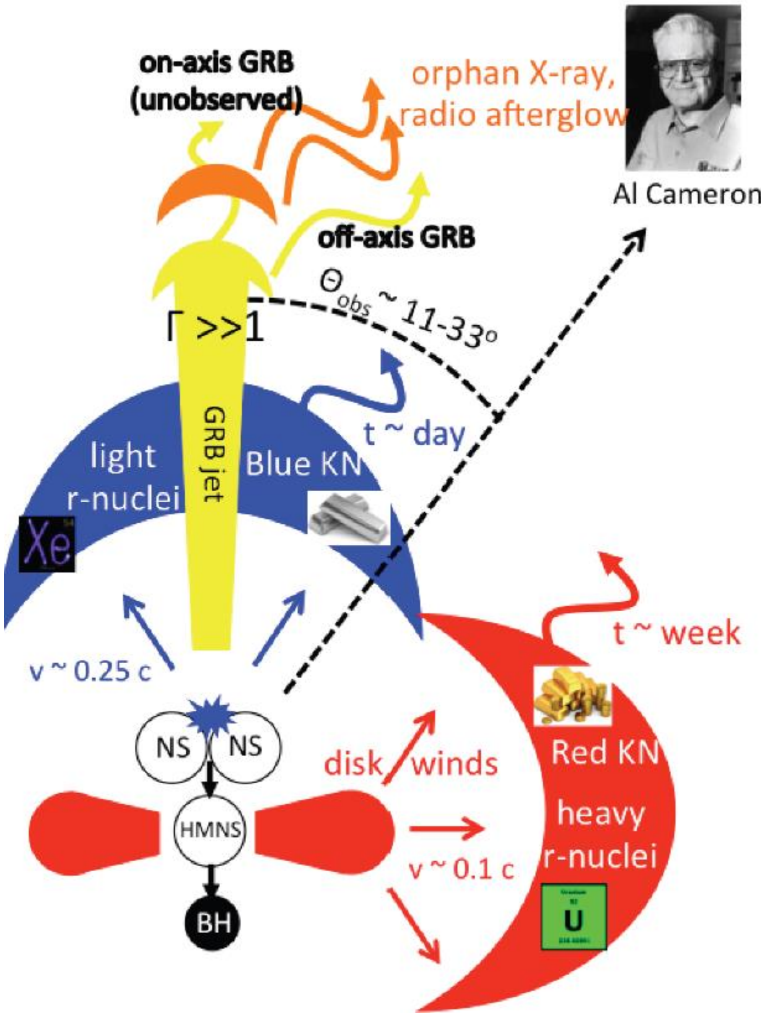
- $M_{\max}$: {$npe\mu$}-SLy 2.0$M_\odot$, {$npe\mu$}- APR4 2.2$M_\odot$, LX ~3$M_\odot$
- To discovery pulsars with mass > 2.3$M_\odot$?

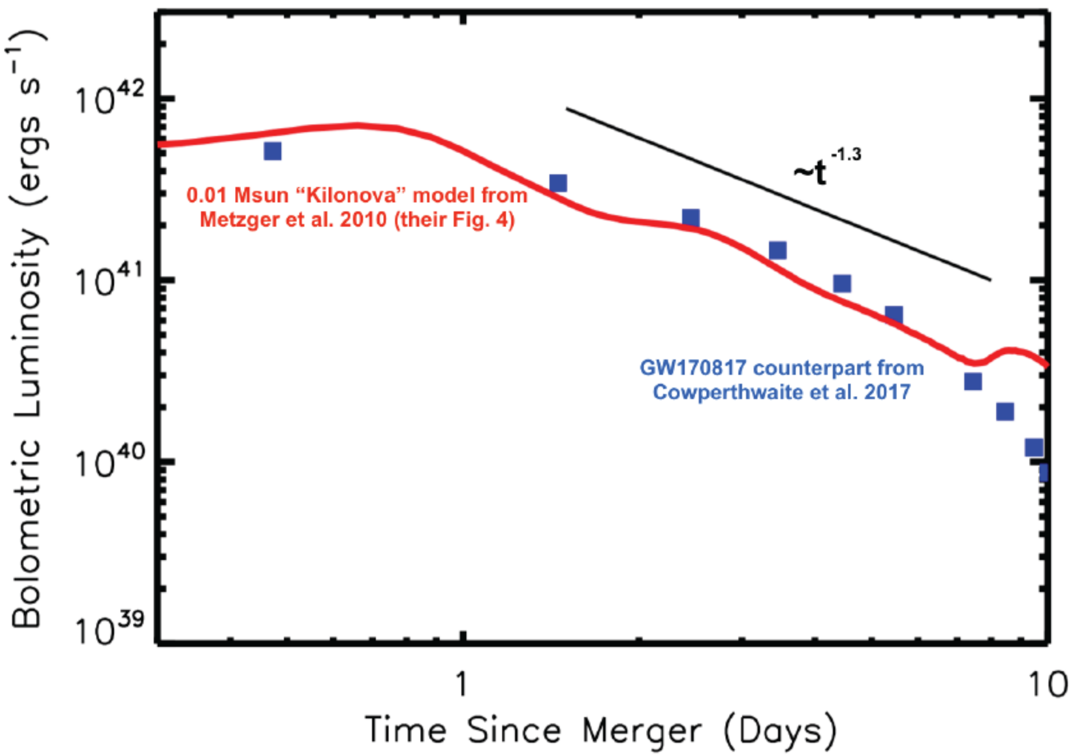
Observational tests

•Kilonova: neutron kilonova

r−process nucleosynthesis and radiative decay...

Metzger (arXiv:1710.05931)





Observational tests

- The *first* astro-meeting after detecting GW170817!

Session 8: Theory IV

Chair: Ke Fang

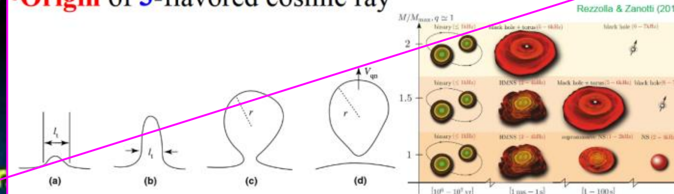
16:00 -- 16:30 Mingming Kang[photo]: *Cosmic Rays during BBN to Solve Lithium Problem* [ppt]

16:30 -- 17:00 Jorge Horvath[photo]: *There may be no "gold" coming out from compact star mergers* [pdf]

17:00 -- 17:30 Renxin Xu[photo]: *Strangeness in cosmic rays* [pdf]

* * * Banquet * * *

- **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

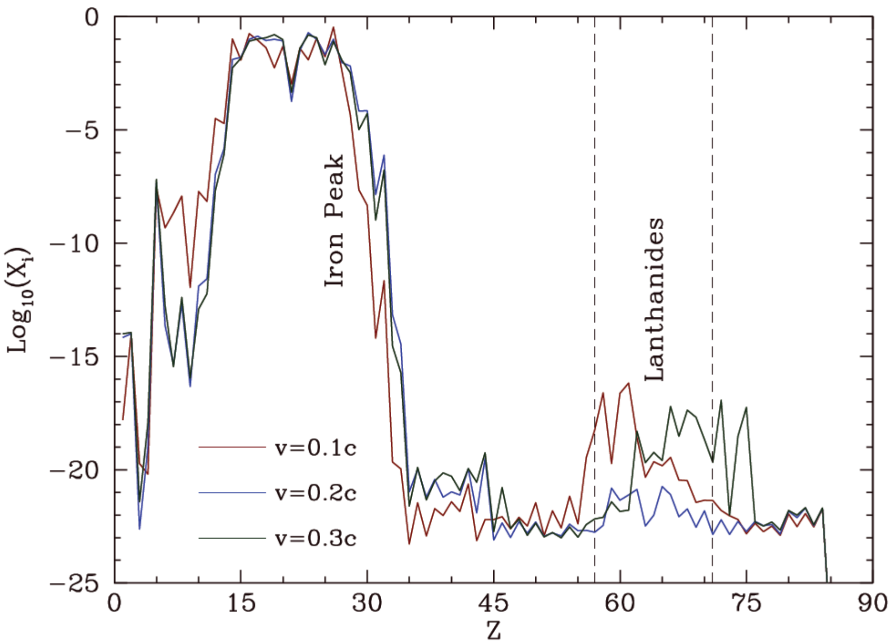
Madsen (2005, *PRD*)

Observational tests

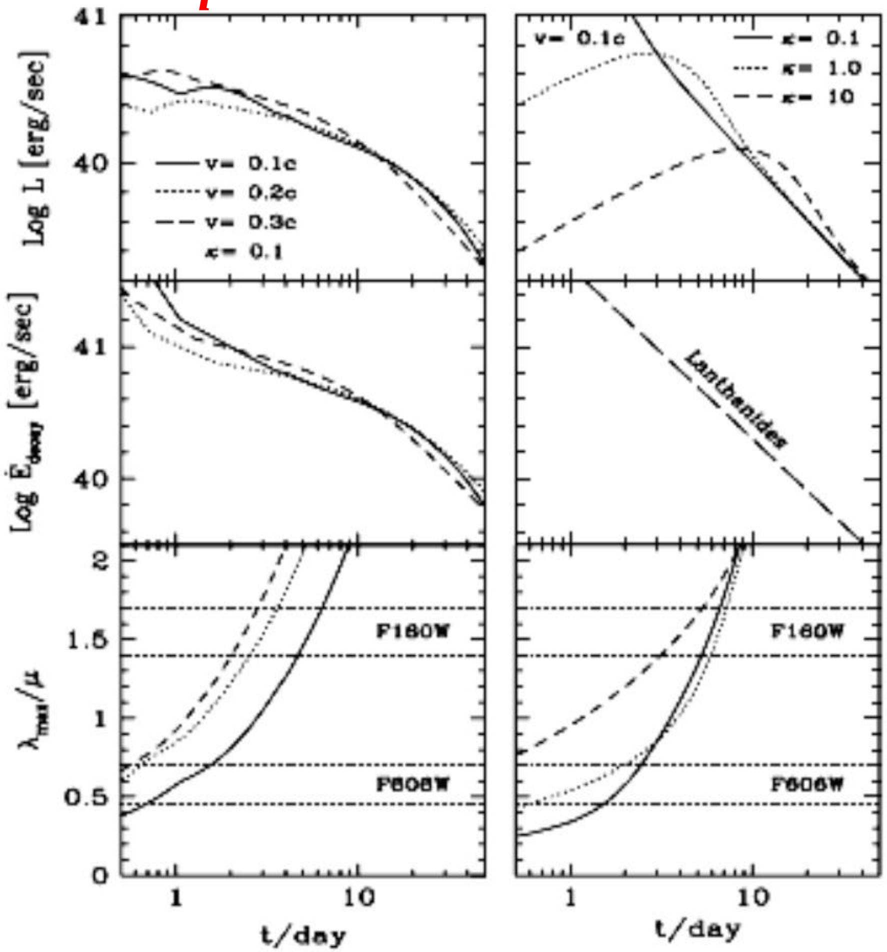
• Kilonova： quark kilonova (Horvath's talk in KIAA-WAP II)

There are no lanthanides, nor "gold" (*r*-process actinides) in quark-kilonova.

Crucial observation: detection of *r*-elements and/or lanthanides!!!



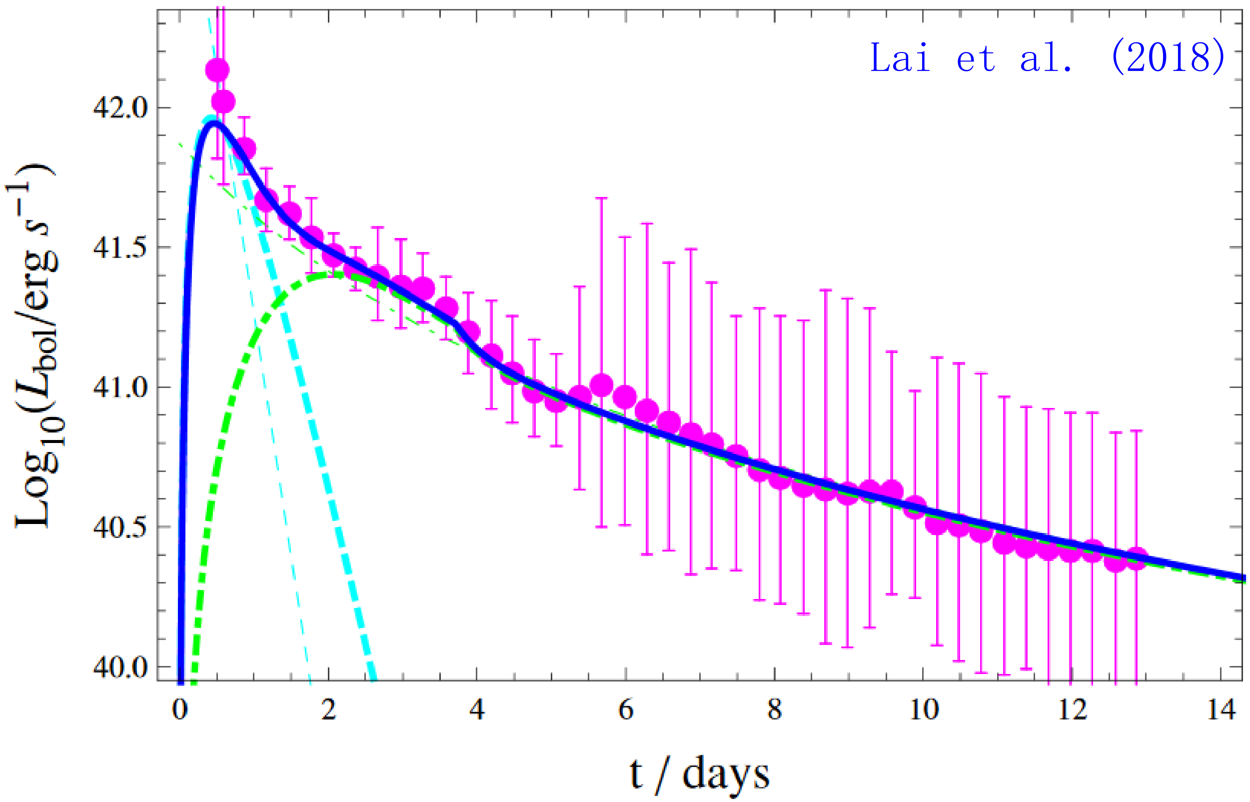
***q*-kilonova** ***n*-kilonova**



Observational tests

• Kilonova: strangenon kilonova

$$L_{\rm strangeon\ kilonova} \sim 10^{42} {\rm erg\ s^{-1}} \left(\frac{M_{\rm unstable}}{10^{-4} M_{\odot}}\right) \left(\frac{\Delta\eta}{1\ {\rm MeV}}\right) \left(\frac{1\ {\rm day}}{\tau}\right)$$



Observational tests

- Other tests model-***dependent***

	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 (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. (2017)
global	stiff EoS	high M_{max} ($2\sim3M_\odot$)	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)

Summary

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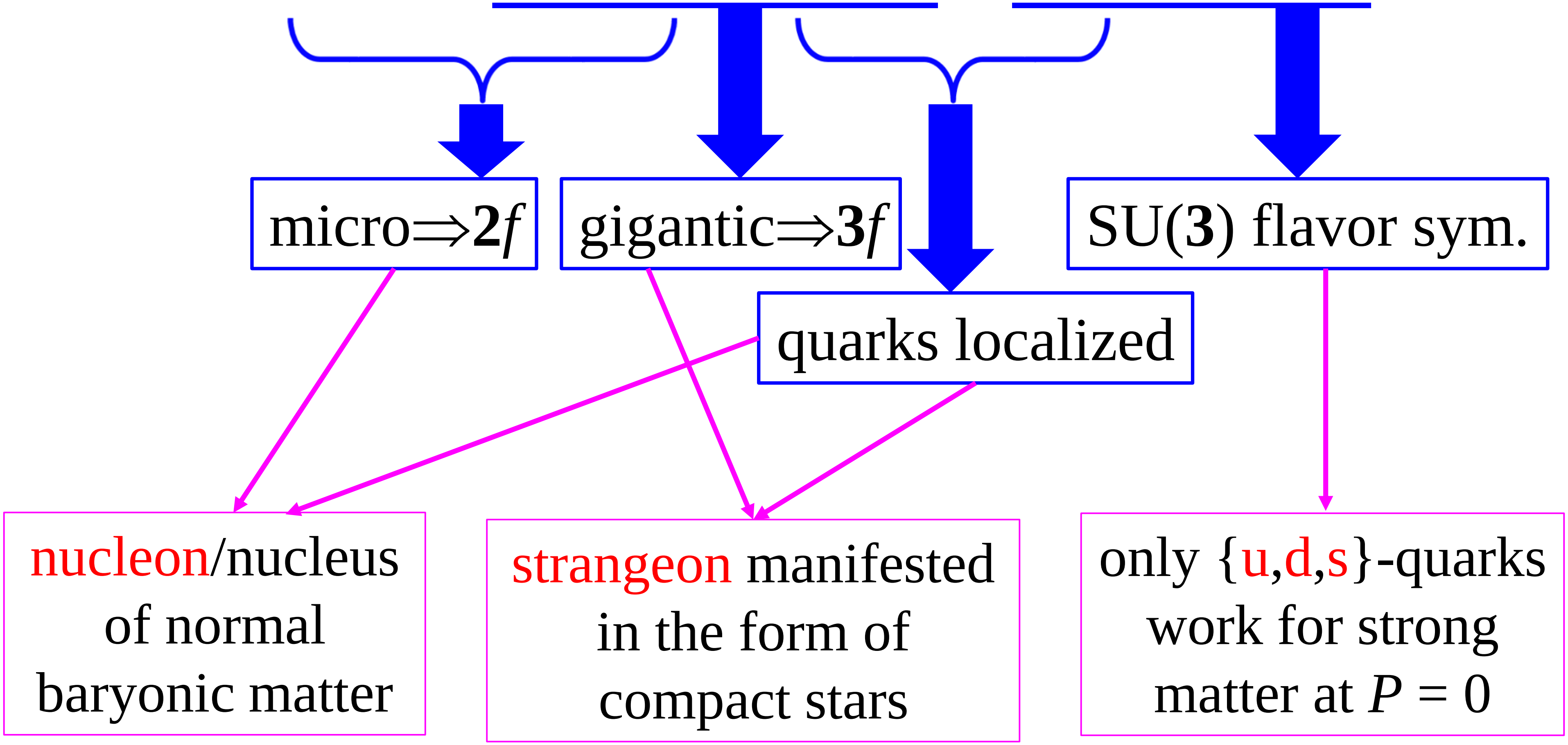
- ✓ Conclusions

Conclusions

$$m_e \ll \Delta m_{uds} \ll E_{scale} < \Lambda_\chi \lesssim m_{heavy}$$



Conclusions

• An extension of Witten's conjecture suggests that strangeon matter in bulk may constitute the true ground state of strong-interaction matter, and pulsar-like stars could then be strangeon stars (condensed matter of strangeons).

• Different manifestations would be understood if pulsars are strangeon stars (2 dynamic tests!), and we expect to test further by advanced facilities.

THANKS!