Searching for
Strange Quark Planets Around Pulsars

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Outline

1. Background: strange quark stars

2. Strange stars vs. neutron stars

3 Strange star-Strange planet system

4. Conclusions

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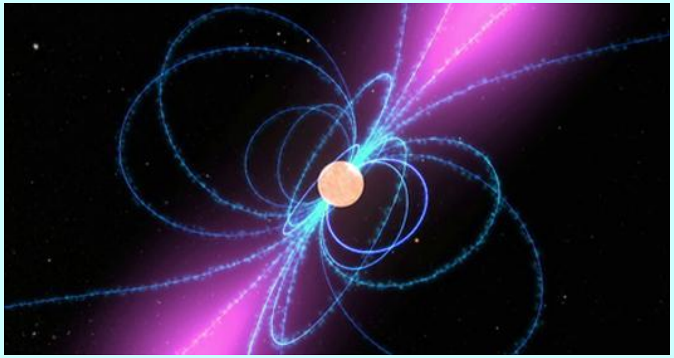
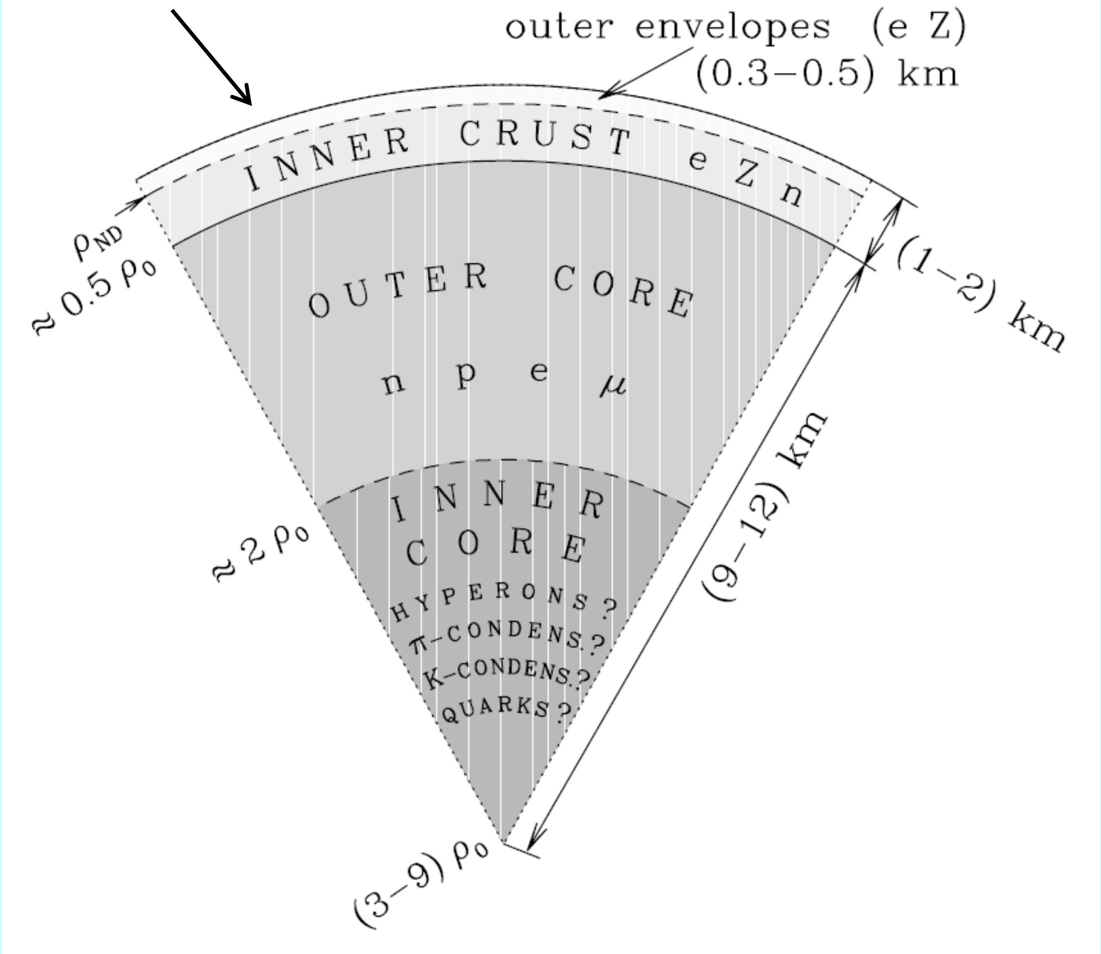
Pulsars as neutron stars



Atmosphere: H/He, iron nuclei



Haensel et al. (2007):
neutron star structure

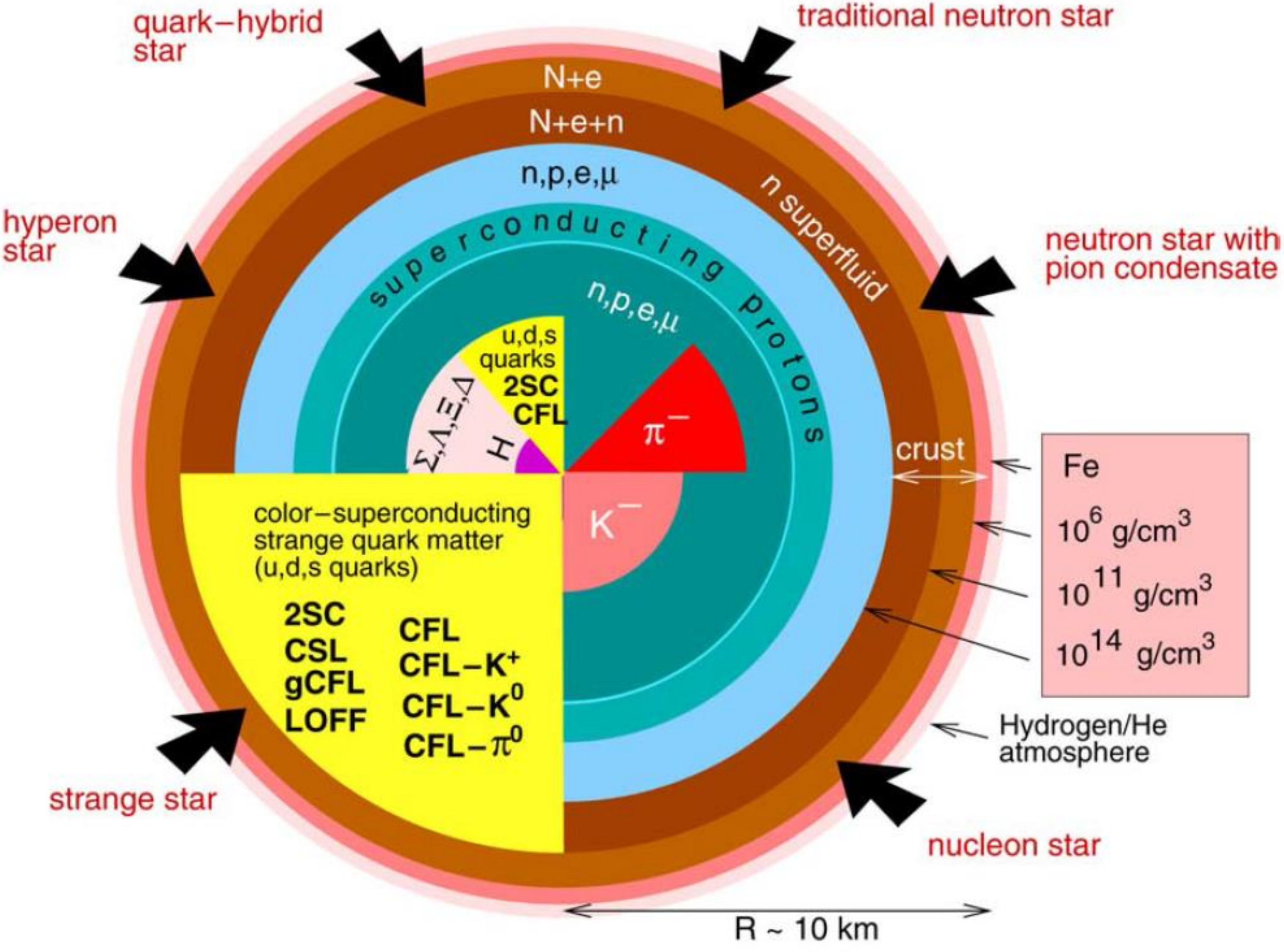


Fig. 1. Competing structures and novel phases of subatomic matter predicted by theory to make their appearance in the cores ($R \lesssim 8$ km) of neutron stars [1].

Weber 2005

Different possible EOS

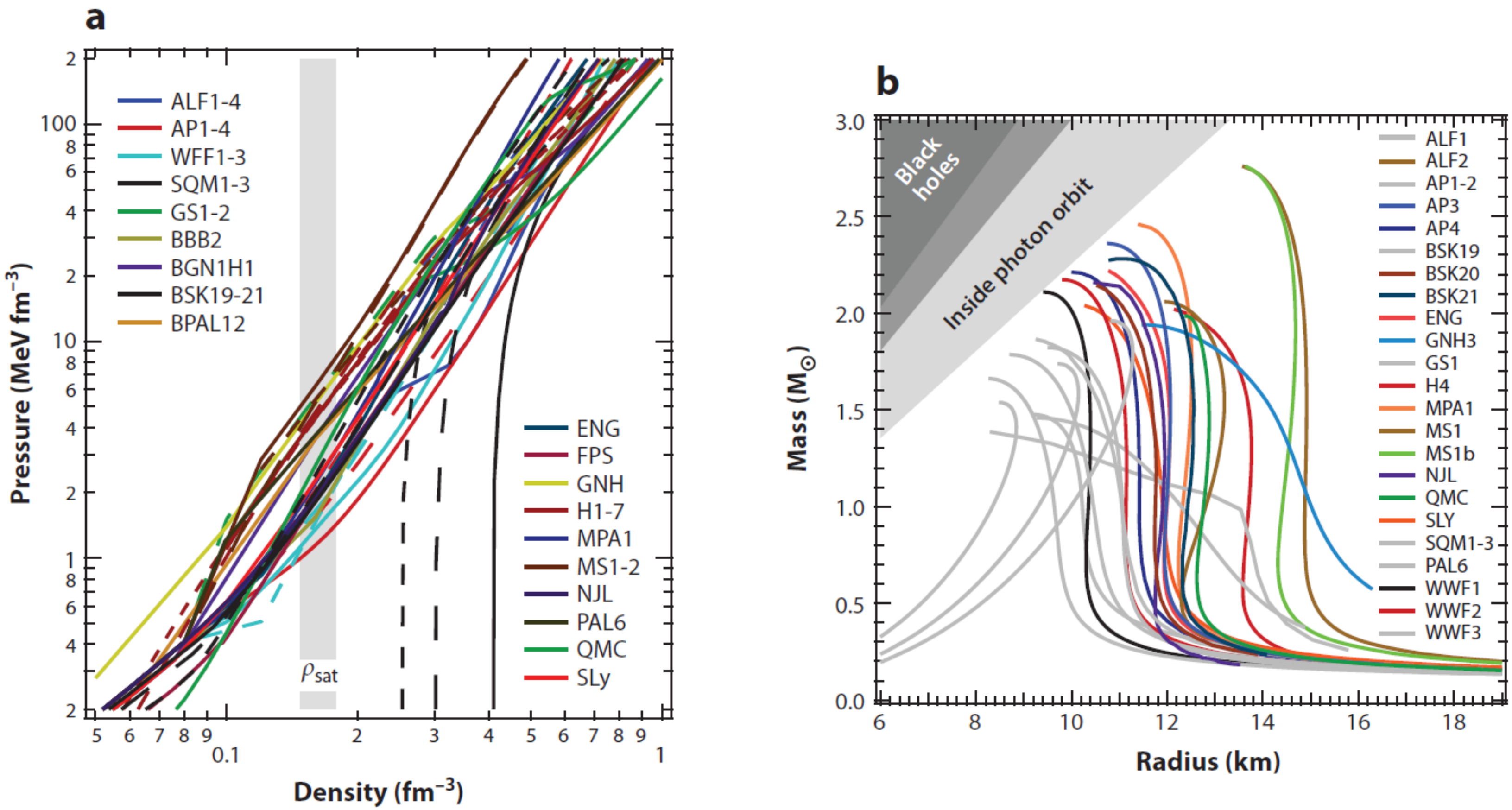


Figure 7

(*a*) A large sample of proposed EoSs calculated under different physical assumptions and using a range of computational approaches. See the text for the descriptions of the EoSs, the acronyms, and the references. (*b*) The mass-radius curves corresponding to the EoSs shown in panel *a*.

F. Ozel & P. Freire, 2016,

$$d \rightarrow u + e + \bar{\nu}_e \,,$$
$$u + e \rightarrow d + \nu_e \,,$$
$$s \rightarrow u + e + \bar{\nu}_e \,,$$
$$u + e \rightarrow s + \nu_e \,,$$
$$s + u \leftrightarrow d + u \,.$$

$$\mu_d = \mu_u + \mu_e \,,$$
$$\mu_d = \mu_s$$

combined with condition of charge neutrality,

$$\tfrac{2}{3} n_u(\mu_u) = \tfrac{1}{3}[n_d(\mu_d) + n_s(\mu_s)] + n_e(\mu_e) \,.$$

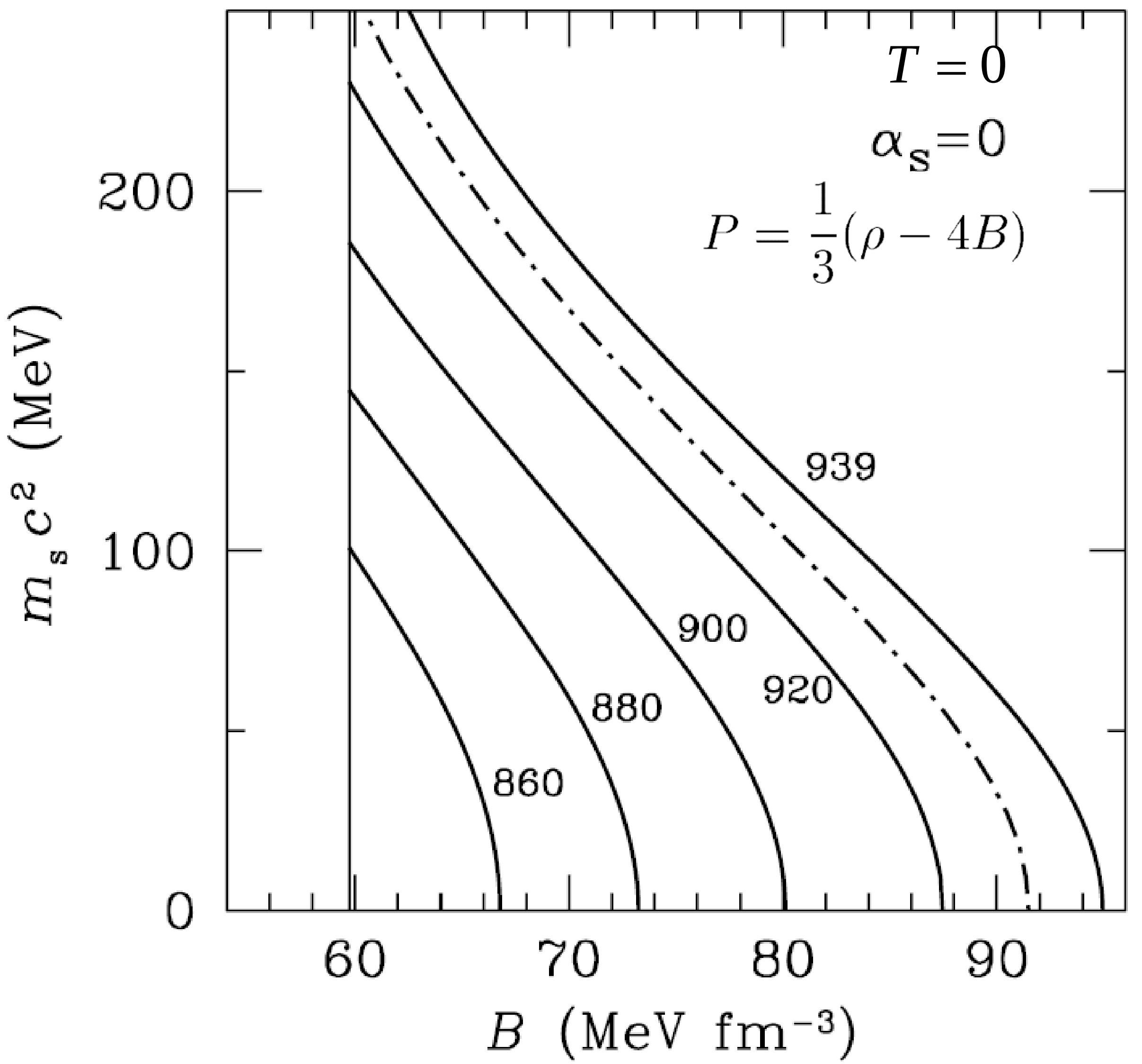
The thermodynamic potential for the *u*, *d*, and *s* quarks, and for the electrons, are

$$\Omega_f(\mu_f) = -\frac{\mu_f^4}{4\pi^2(\hbar c)^3}\left(1 - \frac{2\alpha_c}{\pi}\right), \quad f = u, d, \tag{1}$$

$$\begin{aligned}\Omega_s(\mu_s) = -\frac{1}{4\pi^2(\hbar c)^3}\Bigg\{&\mu_s(\mu_s^2 - m_s^2 c^4)^{1/2}\left(\mu_s^2 - \frac{5}{2} m_s^2 c^4\right) + \frac{3}{2} m_s^2 c^8 \; ln\left(\frac{\mu_s + (\mu_s^2 - m_s^2 c^4)^{1/2}}{m_s c^2}\right) \\ &- \frac{2\alpha_c}{\pi}\left[3\left(\mu_s(\mu_s^2 - m_s^2 c^4)^{1/2} - m_s^2 c^4 \ln\left(\frac{\mu_s + (\mu_s^2 - m_s^2 c^4)^{1/2}}{m_s c^2}\right)\right)^2 - 2(\mu_s^2 - m_s^2 c^4)^2 - 3 m_s^4 c^8 \ln^2\left(\frac{m_s c^2}{\mu_s}\right)\right. \\ &\left. + 6 \ln\left(\frac{\varrho}{\mu_s}\right)\left(\mu_s m_s^2 c^4 (\mu_s^2 - m_s^2 c^4)^{1/2} - m_s^4 c^8 \ln\left(\frac{\mu_s + (\mu_s^2 - m_s^2 c^4)^{1/2}}{m_s c^2}\right)\right)\right]\Bigg\},\end{aligned}$$

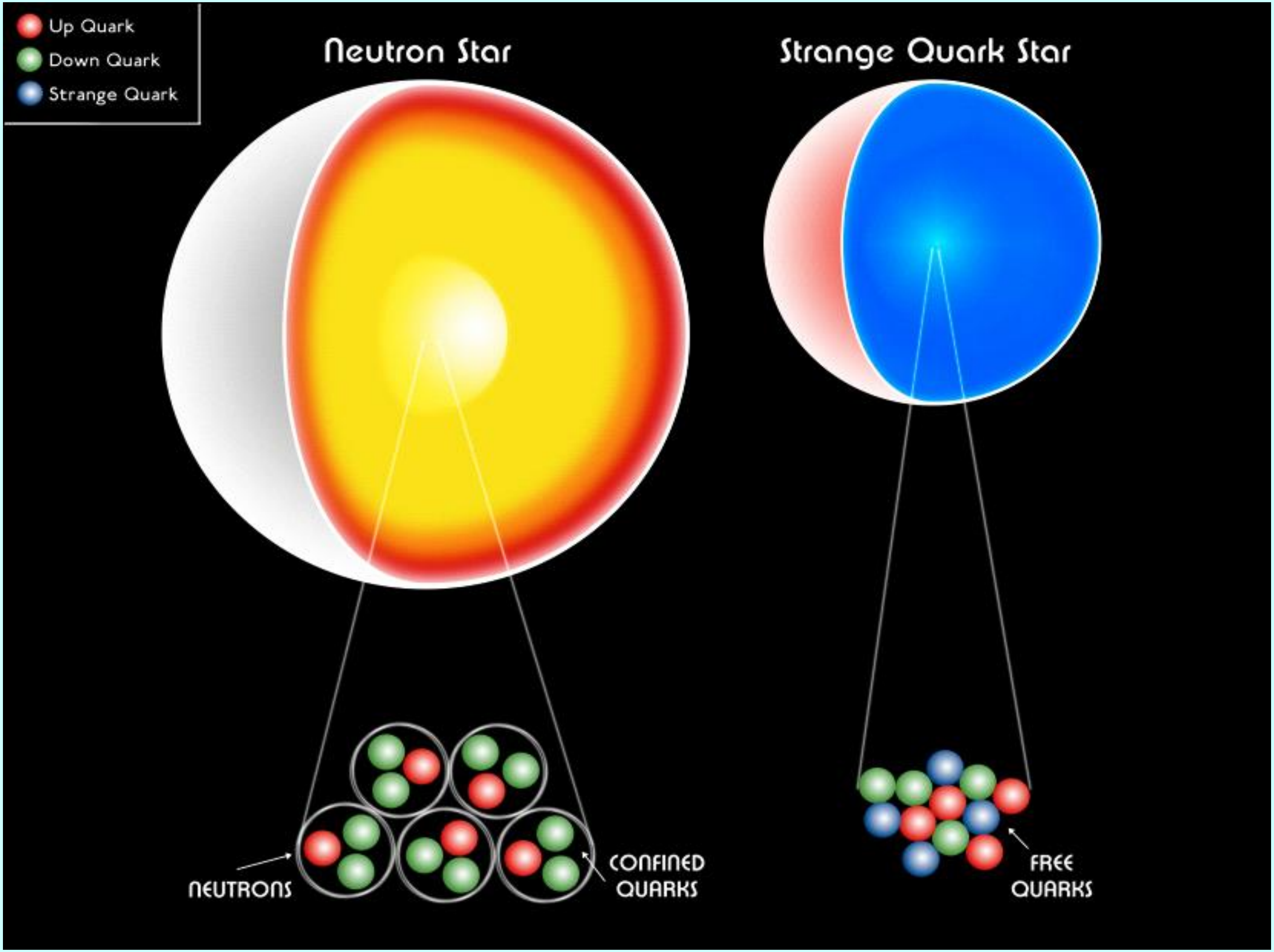
$$\Omega_e(\mu_e) = -\frac{\mu_e^4}{12\pi^2(\hbar c)^3} \,. \tag{3}$$

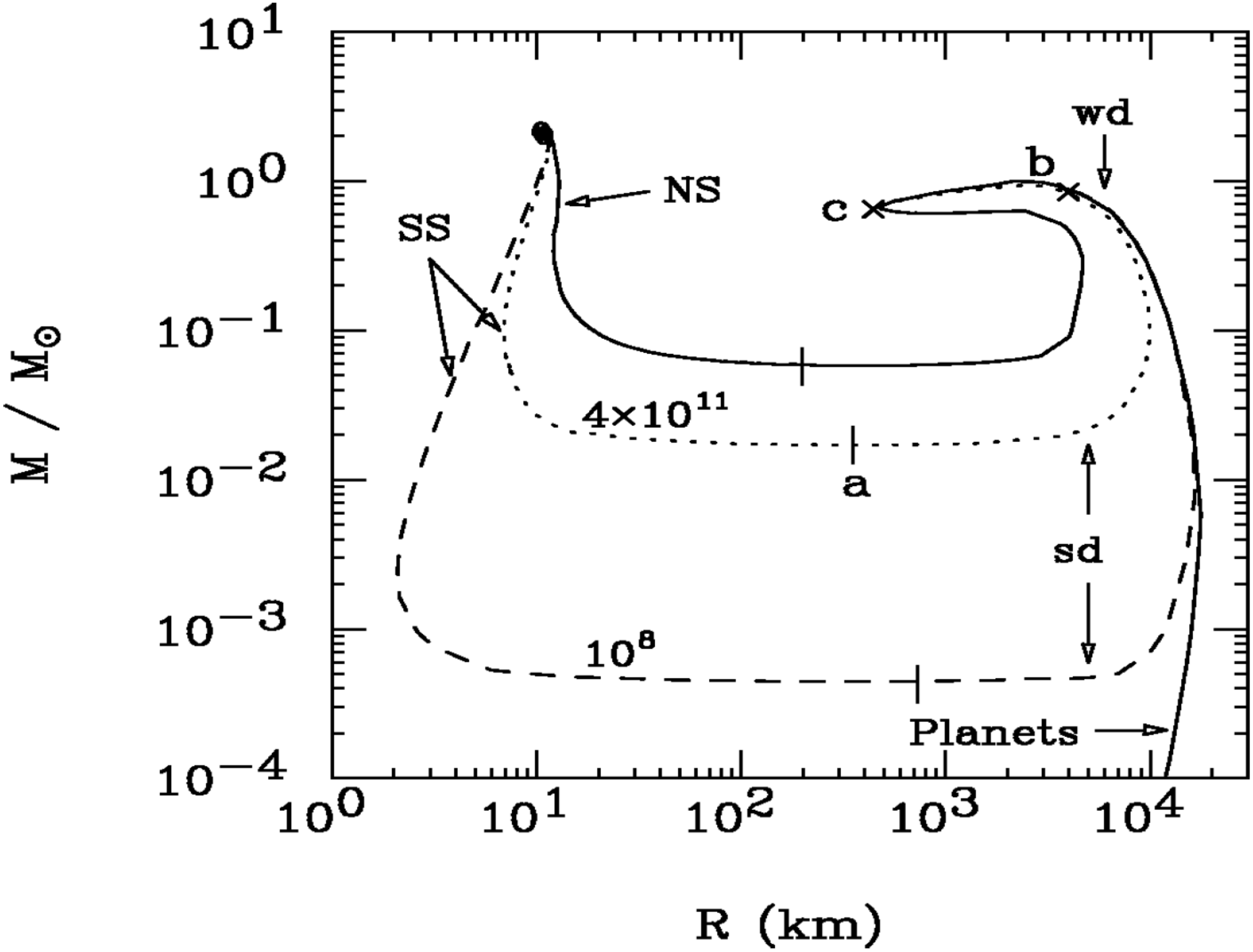
Farhi & Jaffe (1984)



Energy per baryon can be less than that of iron.

Witten (1984); Haensel et al. (2007)


Up Quark
Down Quark
Strange Quark
Neutron Star
Strange Quark Star
NEUTRONS
CONFINED QUARKS
FREE QUARKS



Strange star - strange dwarf sequences (Glendenning 1995).

A brief history of the study of SQM and SS

- Ivanenko & Kurdgelaidze (1969) suggested a quark matter core in the interior of compact objects.
- Itoh (1970) got the M_{max} of quark stars by assuming the EOS of free, Fermi *uds* quark gas, $\sim 10^{-3} M_\odot$;
- Bodmer (1971) conjectured the existence of a collapsed *uds* quark nucleus;
- Chodoset al. (1974), DeGrand et al. (1975), Chin & Kerman (1979) studied an *uds* quark nucleus in the bag model;
- Witten (1984) showed that strange quark matter (SQM) could be absolutely stable, and proposed strange quark stars (SS))-1845 citations (95018);
- Farhi & Jaffe (1984) explored the properties of SQM, including effects of the finite s-quark mass and lowest-order QCD interactions;
- Qingde Wang & Tan Lu (1984) first showed strong damping effect of SQM.

From Dai's PPT (2015)

A brief history of the study of SQM and SS

- **Haensel et al. (1986) and Alcock et al. (1986) studied the structure of SQSs;**
- **Olinto (1987) discussed the deflagration/detonation process of neutron stars (NSs) to SQSs;**
- **Dai et al. (1993) proposed the two-step conversion process of NSs to SQSs and neutrino bursts;**
- **Gentile et al. (1993) explored effects of SQSs on SNe, and Dai et al. (1995) studied effects of the two-step conversion process of proto-NSs to SQSs on SNe;**
- **Cheng & Dai (1996) and Dai & Lu (1998) suggested conversion of NSs-SQSs as an origin of GRBs.**
- **Xu, Qiao & Zhang (1999) proposed bare SQSs.**

From Dai's PPT (2015)

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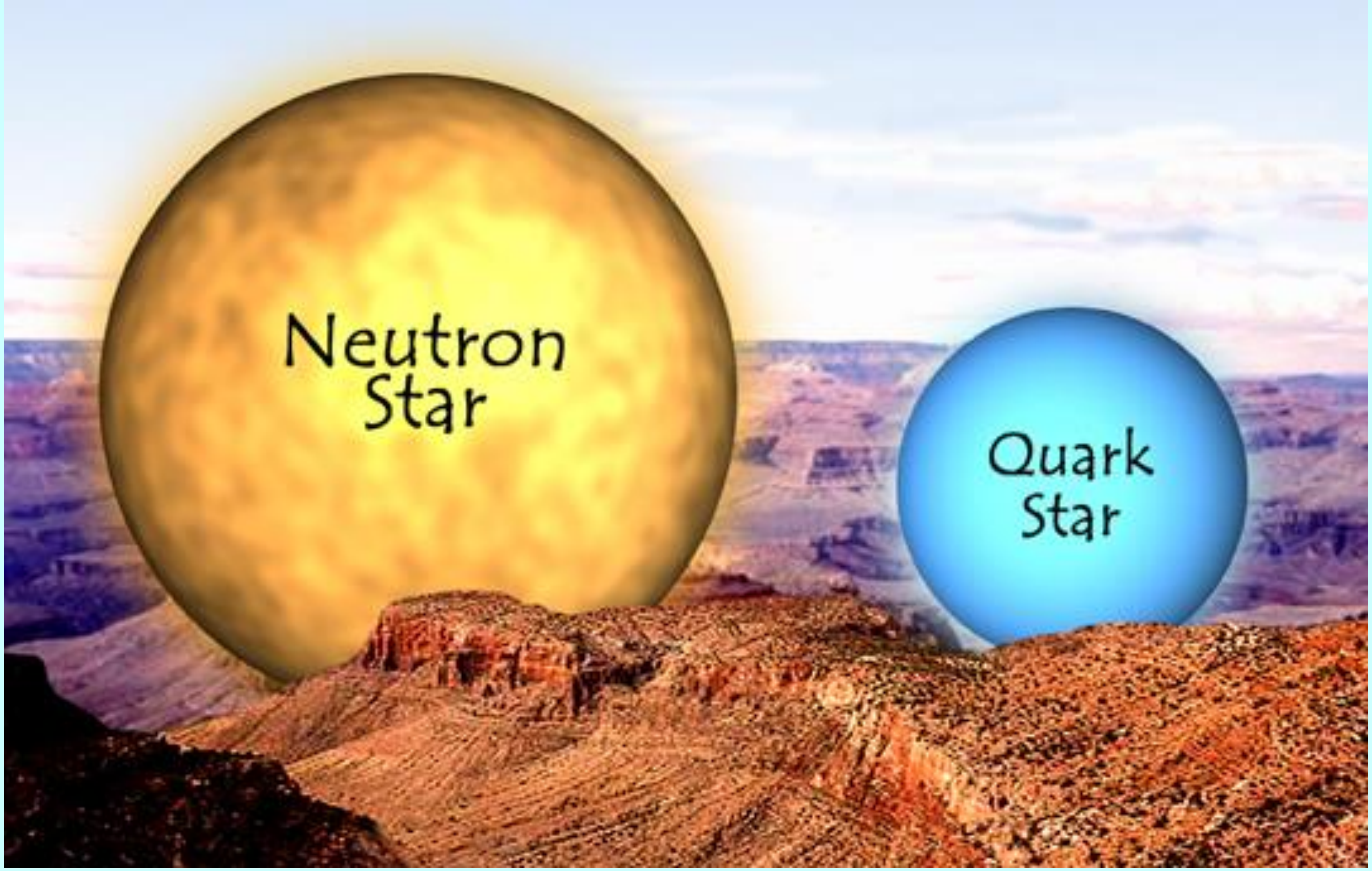


http://chandra.harvard.edu

How to discriminate strange stars / neutron stars?

- Different radius at $M \sim 1.4\ M_{sun}$?
- Different M~R relation?
- Different M_{max} ?
- Different cooling rate?
- Can spin more quickly ($P < 1ms$)?
- ……

Observational constraints on the M --- R relation

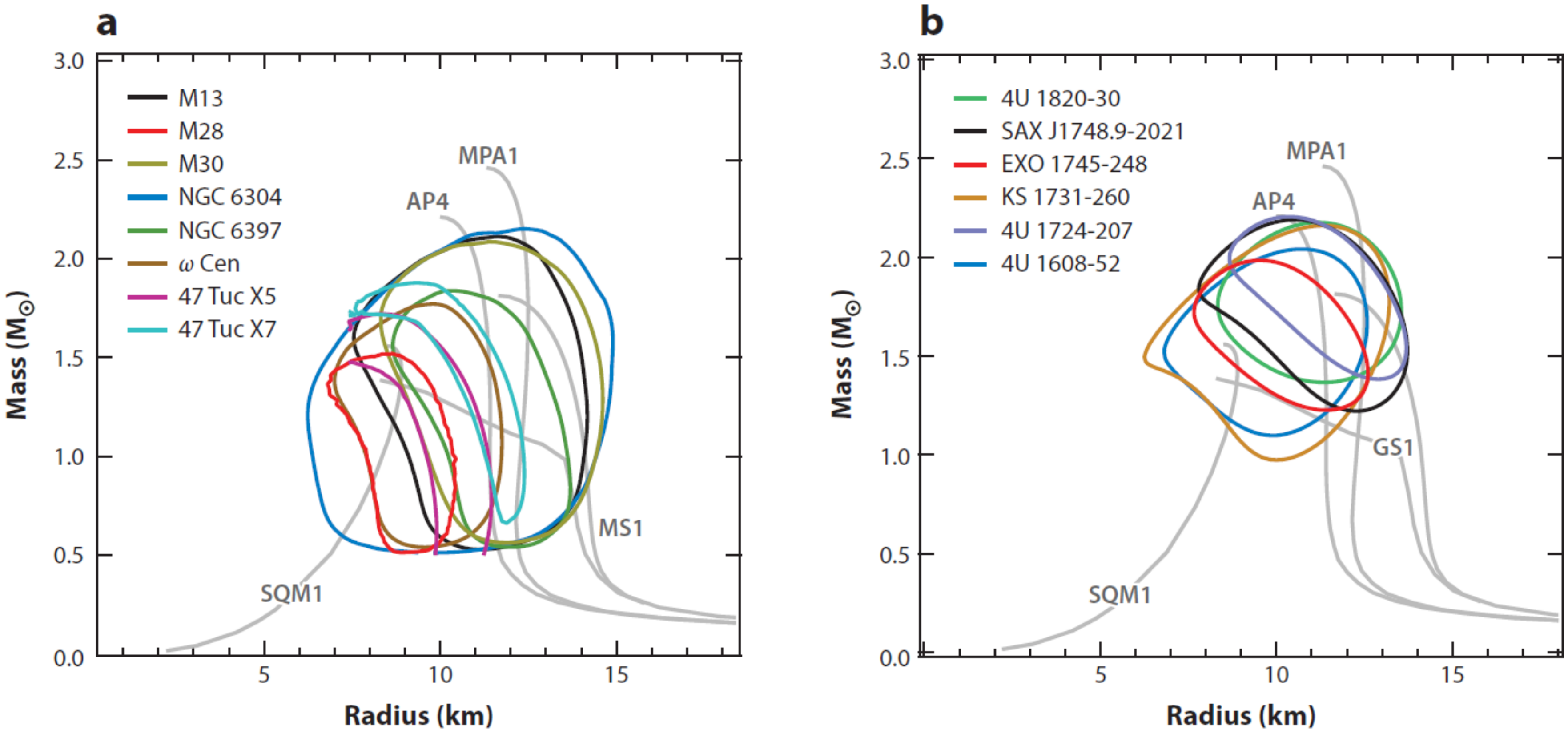


Figure 4

The combined constraints at the 68% C.L. over the neutron-star mass and radius obtained from (*a*) all neutron stars in low-mass X-ray binaries during quiescence and (*b*) all neutron stars with thermonuclear bursts. The light gray lines show mass relations corresponding to a few representative EoSs (see Section 4.1 and **Figure 7** for detailed descriptions and the naming conventions for all equations of state).

F. Ozel & P. Freire, 2016, ARA&A

Constraints on the M --- R relation: results from Timing method

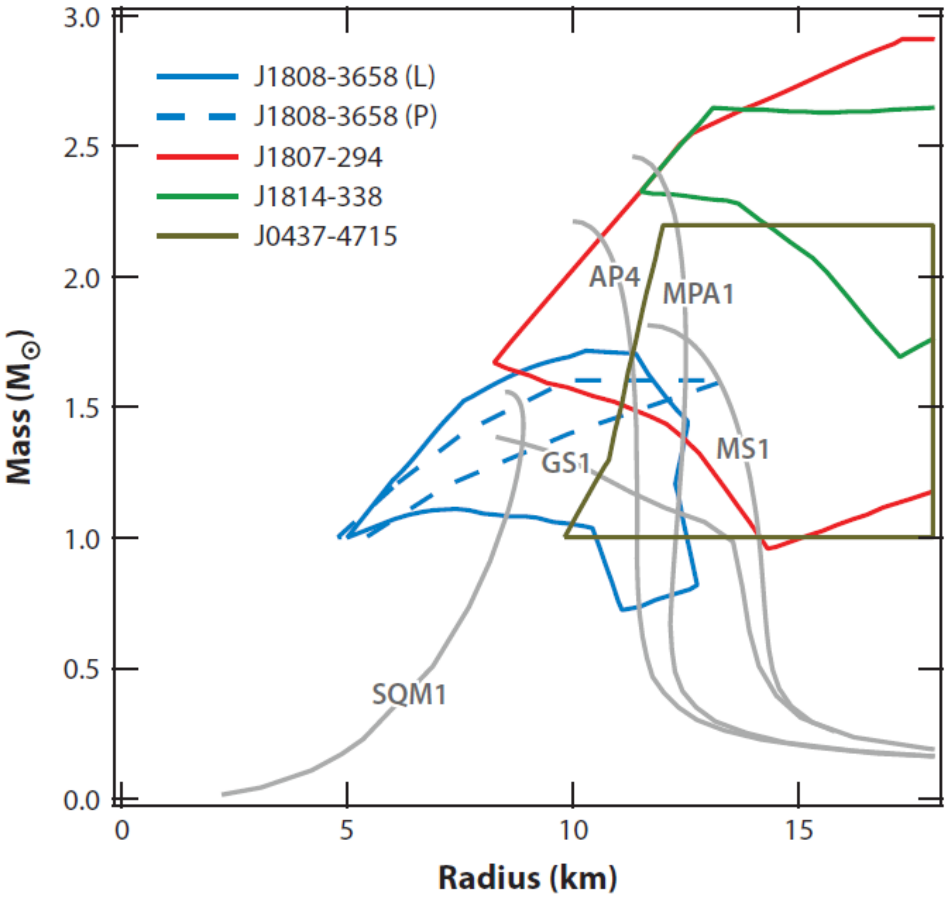
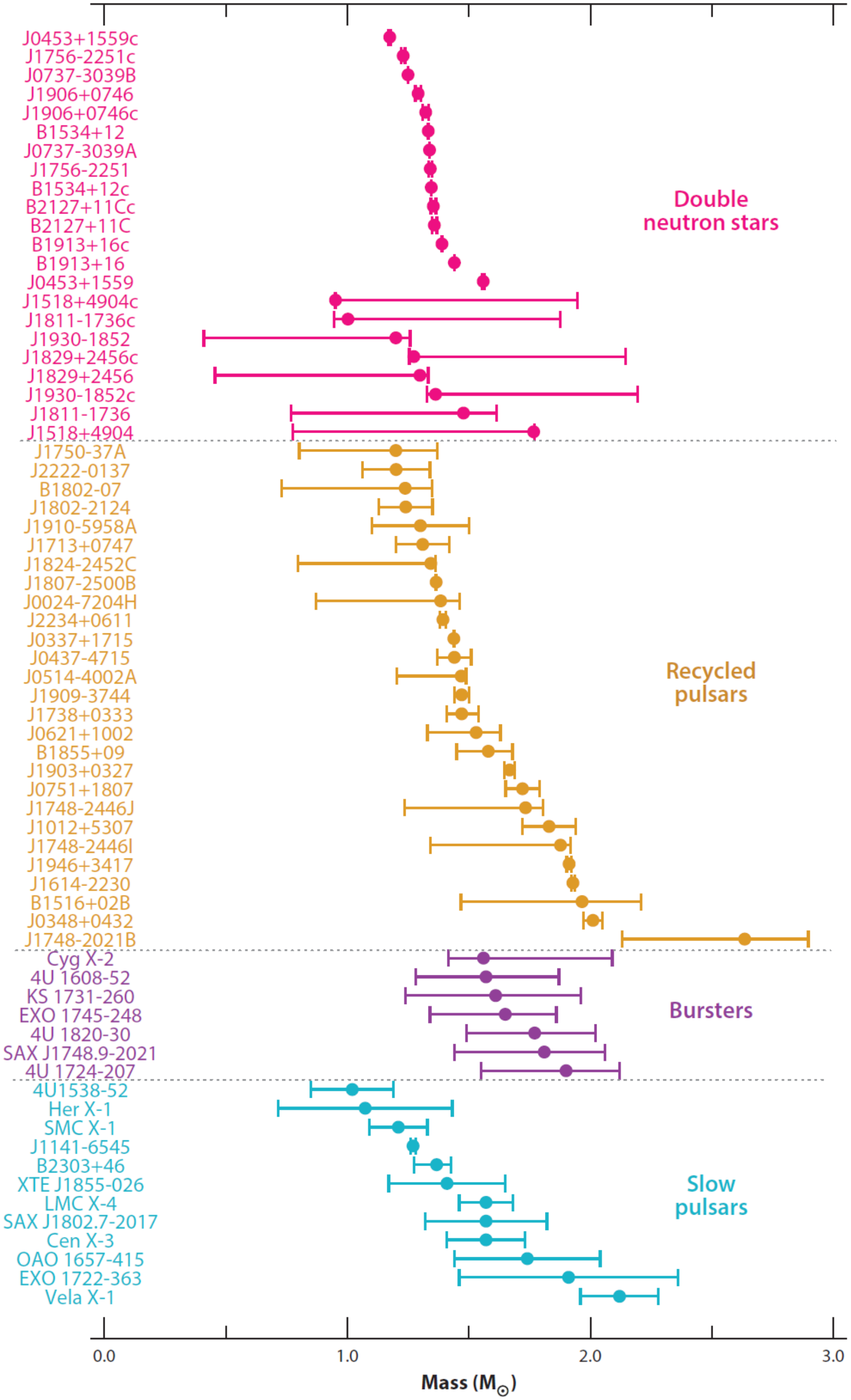
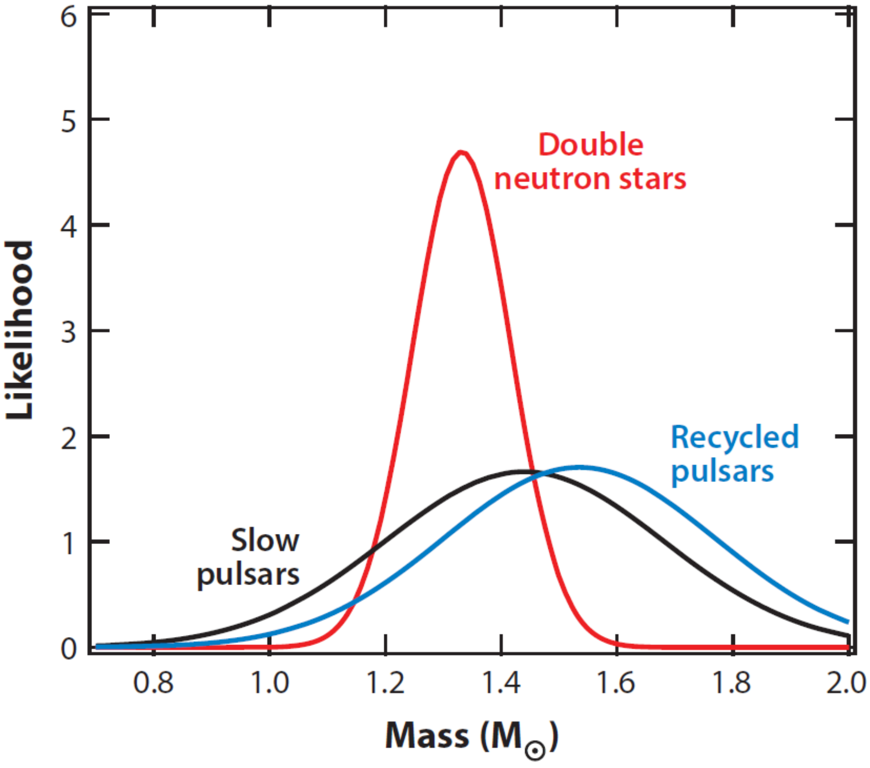


Figure 6

The radii constraints obtained from analysis of the waveforms from accretion-powered (Poutanen & Gierliński 2003; Leahy et al. 2008, 2009, 2011) and rotation-powered millisecond pulsars (Bogdanov 2013). Two different analyses of the SAX J1808.4−3658 data by Poutanen et al. (2003; denoted by P) and Leahy et al. (2008; denoted by L) are included.

Measured Pulsar Masses

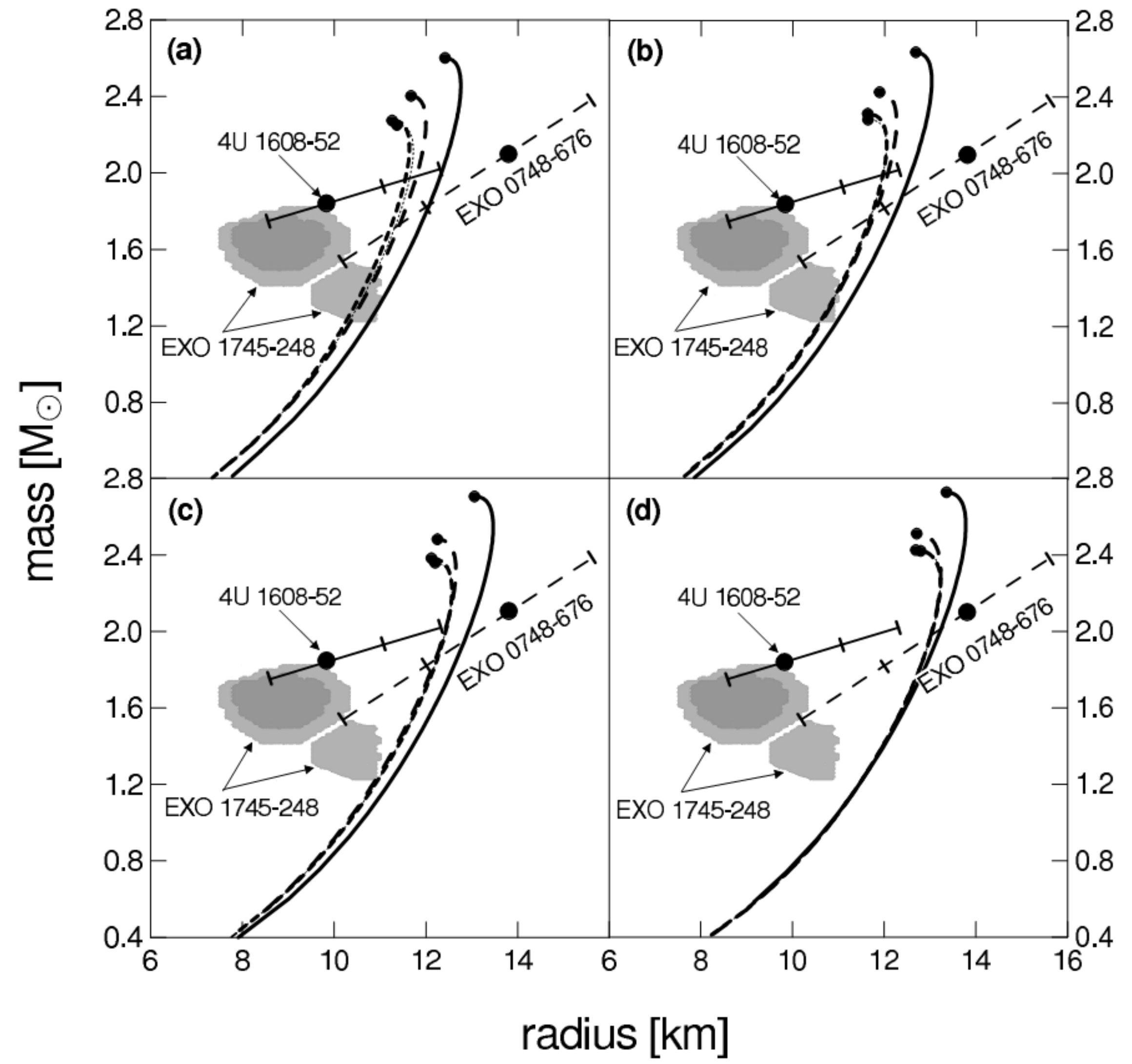




The inferred mass distributions for the different populations of neutron stars.

F. Ozel & P. Freire, 2016, ARA&A

SQSs remain one class of hypothetical compact objects!



Rodrigues et al. (2011, ApJ): density-dependent m_q model

Demorest+(2010, Nature), Antoniadis+ (2013, Science): $M_{\mathrm{pulsar}} \approx 2.0 M_\odot$ From Dai (2015, ppt)

How to discriminate strange stars / neutron stars?

- Different radius at M ~ 1.4 M_{sun}?
- Different M~R relation?
- Different M_{max} ?
- Different cooling rate?
- Can spin more quickly (P < 1ms)?
- ……

- We do not have an unambiguous criterion!

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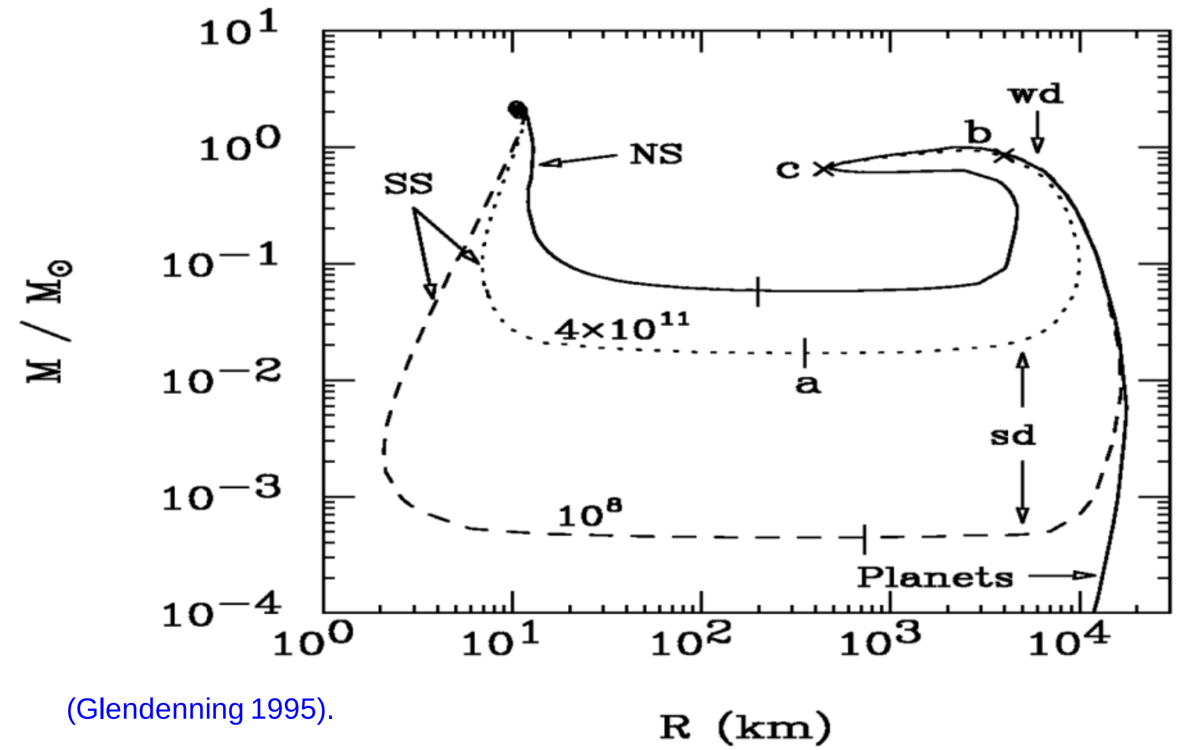
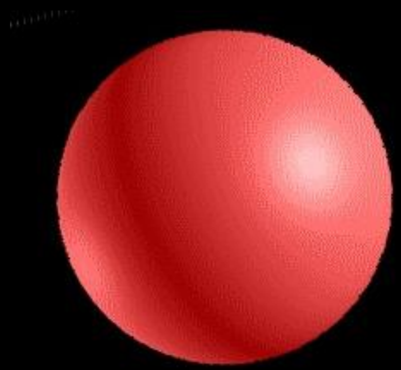


(Glendenning 1995).

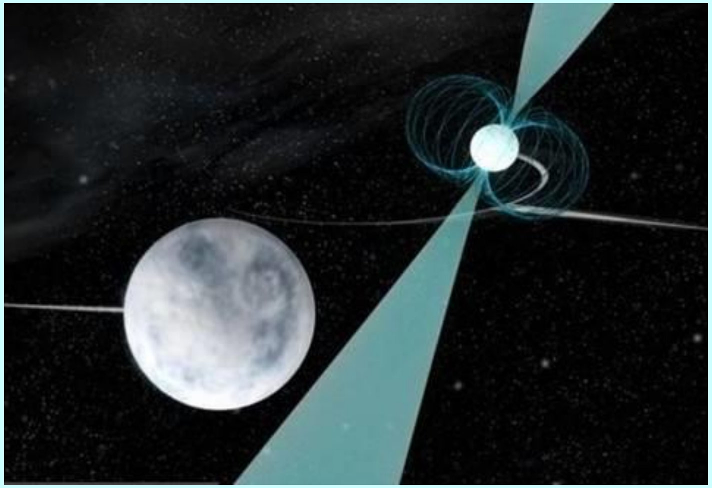


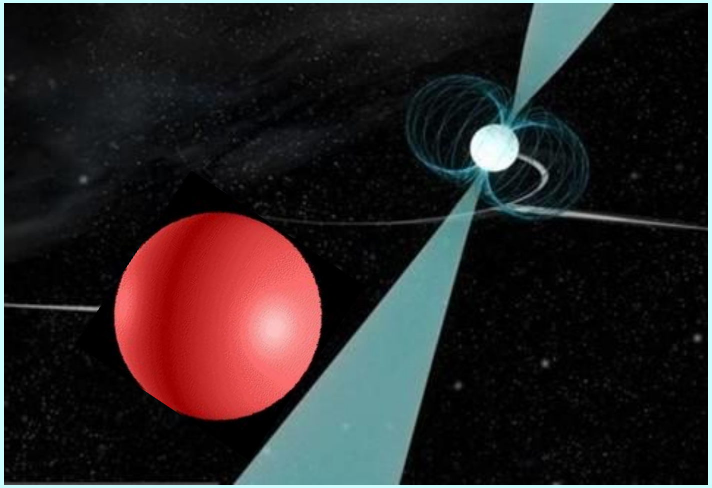
Parameters of bare strange planets $(\rho \sim 10^{15} g/cm^3)$

M	**$10^{-9}M_{sun}$**	**$10^{-6}M_{sun}$**	**$10^{-5}M_{sun}$**	**$10^{-4}M_{sun}$**
R	8m	80 m	170 m	370 m

How can strange planets be produced?

- Plenty of small SQM nuggets could be ejected from a strange star, contaminating the surrounding normal planets and converting them into SQM planets.
- SQM clumps of planetary masses may be ejected from a strange quark star at its birth, because the newly formed SQM host star should be hot and highly turbulent (Xu R.X. & Wu F., 2003, CPL).
- Planetary SQM objects may be directly formed at an early stage of our Universe, i.e. the so-called quark phase stage, when the mean density of the Universe is extremely (Cottingham et al. 1994, PRL).
- ……



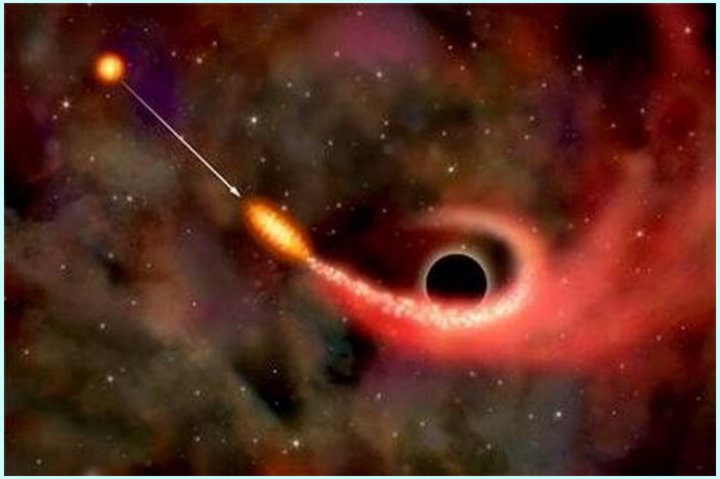


Tidal disruption radius of normal planets：

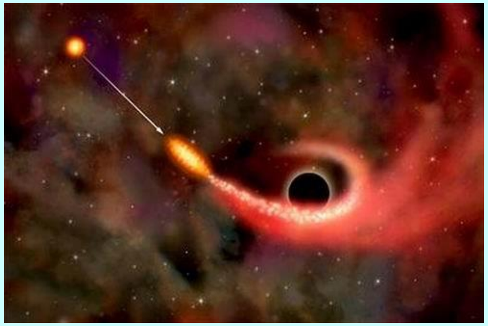
$$r_{\rm td} \approx 5.1 \times 10^{10} \left(\frac{M}{1.4\,M_{\odot}} \right)^{1/3} \left(\frac{\rho_0}{10\ {\rm g\ cm^{-3}}} \right)^{-1/3} {\rm cm}.$$

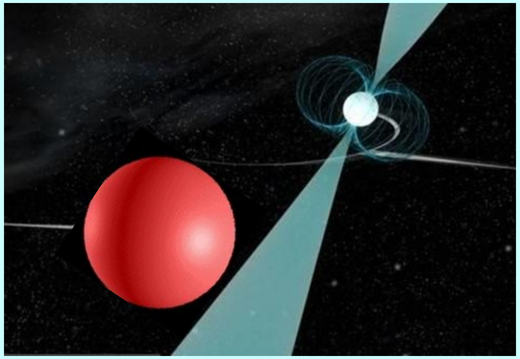
Tidal disruption radius of a strange planet:

$$r_{\rm td} = 1.5 \times 10^{6}\ {\rm cm}$$



Searching for strange quark matter objects in exoplanets





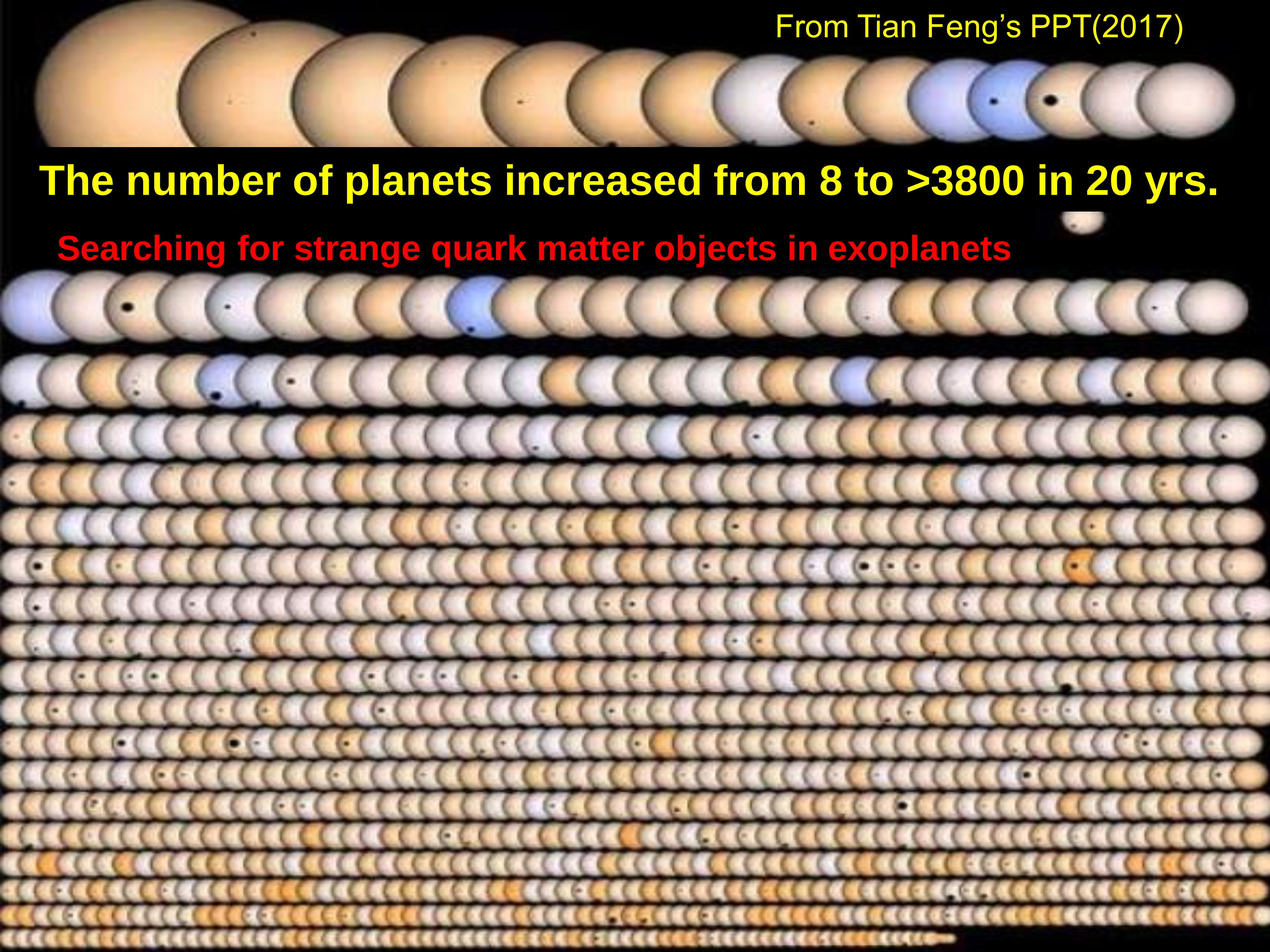
Normal planets： $r_{td} = 5 \times 10^{10}$ cm

Strange planet: $r_{td} = 1.5 \times 10^{6}$ cm

Huang Y.F. & Yu Y.B., 2017, submitted, arXiv:1702.07978

The number of planets increased from 8 to >3800 in 20 yrs.

Searching for strange quark matter objects in exoplanets



From Tian Feng’s PPT(2017)

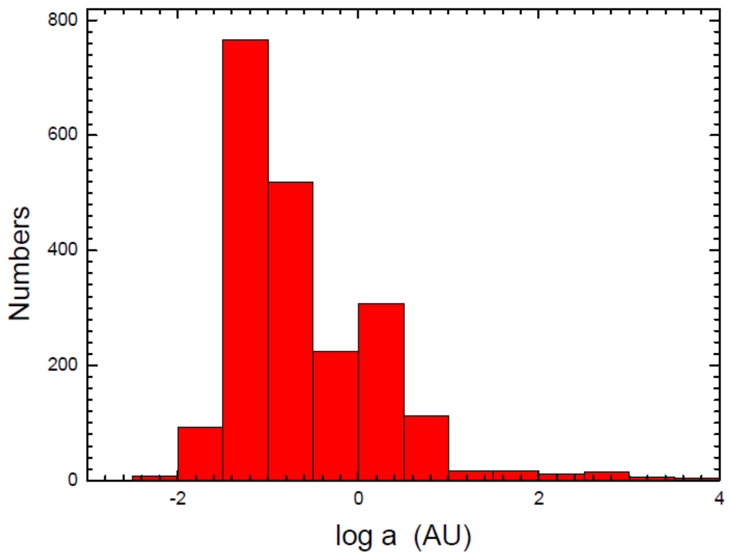


Figure S3. Orbital radius distribution for all the confirmed exoplanets around normal main sequence stars. Most exoplanets have orbital radii larger than 0.01 AU. The smallest orbital radius recorded currently is 0.006 AU (9×10^{10} cm). The observational data are taken from the Exoplanet Orbit Database website (http://exoplanets.org/, queried by 2017 May 27).

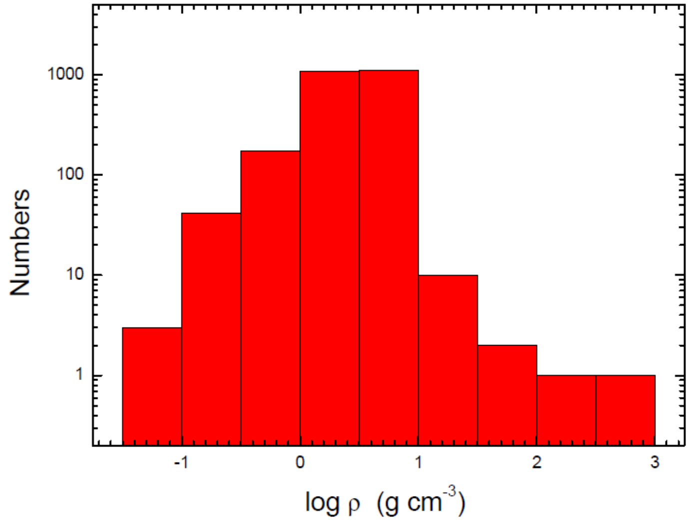
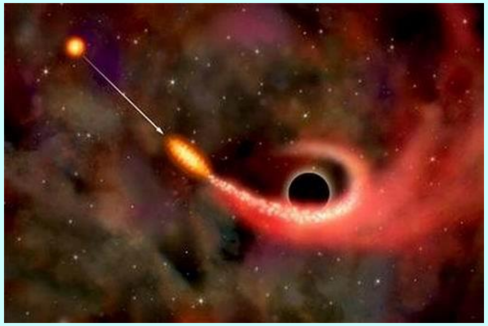


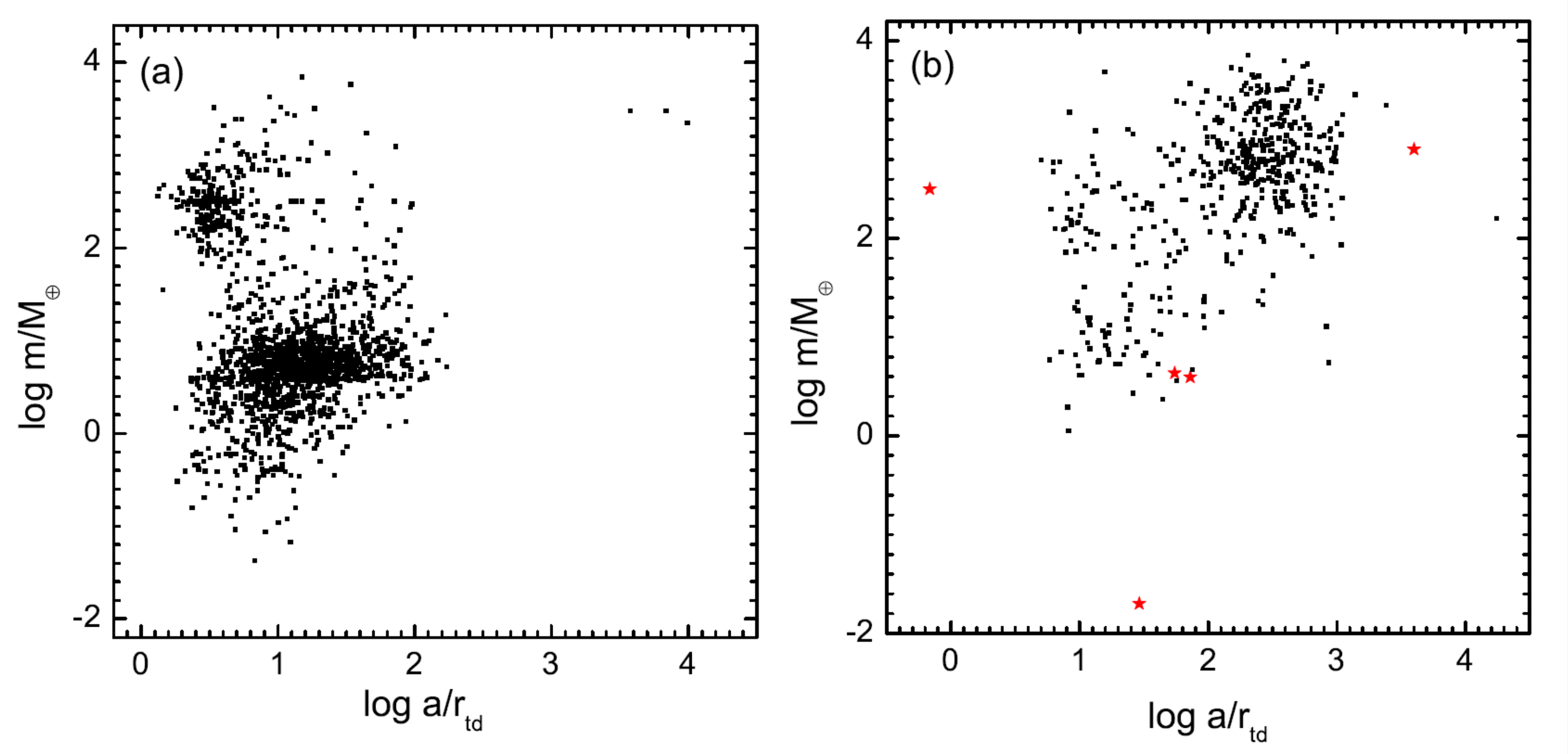
Figure S2. Density distribution for all the confirmed exoplanets with a density measurement. Only 14 planets have densities larger than 10 g/cm^3. Note that the error bars of those extremely high density planets ($\rho > 30$ g/cm^3) are generally too large to be credible. The observational data are taken from the Exoplanet Orbit Database website (http://exoplanets.org/, queried by 2017 May 27).

Huang Y.F. & Yu Y.B., 2017, submitted, arXiv:1702.07978

Searching for strange quark matter objects in exoplanets



Normal planets： $r_{td} = 5 \times 10^{10}$ cm



Huang Y.F. & Yu Y.B., 2017, submitted, arXiv:1702.07978

The interesting planet of PSR J1719−1438

PSR J1719−1438, a 5.7-millisecond pulsar

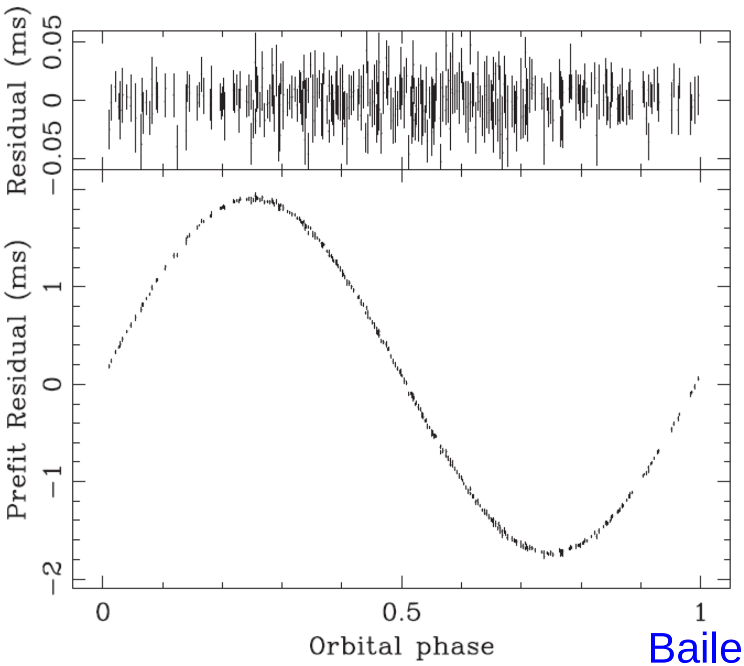
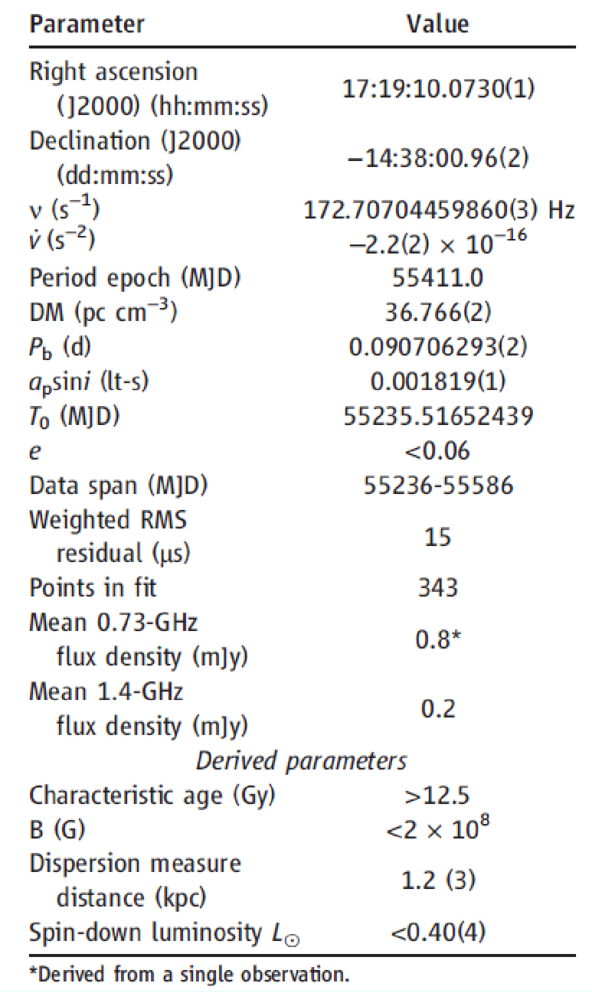


Fig. 1. (**Top**) Pulse timing residuals for PSR J1719–1438 as a function of orbital phase using the ephemeris in Table 1. (**Bottom**) Residuals after setting the semimajor axis to zero to demonstrate the effect of the binary motion. There is no significant orbital eccentricity. At superior conjunction (orbital phase = 0.25), there is no evidence for solid-body eclipses or excess dispersive delays. The arrival times and ephemeris are provided in the supporting online material.

Bailes et al. 2011, Science



Parameter	Value
Right ascension (J2000) (hh:mm:ss)	17:19:10.0730(1)
Declination (J2000) (dd:mm:ss)	−14:38:00.96(2)
ν (s^{-1})	172.70704459860(3) Hz
$\dot{\nu}$ (s^{-2})	$-2.2(2) \times 10^{-16}$
Period epoch (MJD)	55411.0
DM (pc cm^{-3})	36.766(2)
P_b (d)	0.090706293(2)
$a_p \sin i$ (lt-s)	0.001819(1)
T_0 (MJD)	55235.51652439
e	<0.06
Data span (MJD)	55236-55586
Weighted RMS residual (μs)	15
Points in fit	343
Mean 0.73-GHz flux density (mJy)	0.8*
Mean 1.4-GHz flux density (mJy)	0.2
Derived parameters	
Characteristic age (Gy)	>12.5
B (G)	$<2 \times 10^8$
Dispersion measure distance (kpc)	1.2 (3)
Spin-down luminosity $L_\odot$	<0.40(4)

*Derived from a single observation.

Planet orbital period: 2.2 hours

$$\rho > 23 \text{ g/cm}^3$$

May be an ultralow-mass carbon white dwarf (Bailes et al. 2011).

An exotic quark object (Horvath 2012, RAA).

Searching for strange quark matter objects in exoplanets:

Close-in pulsar planets?

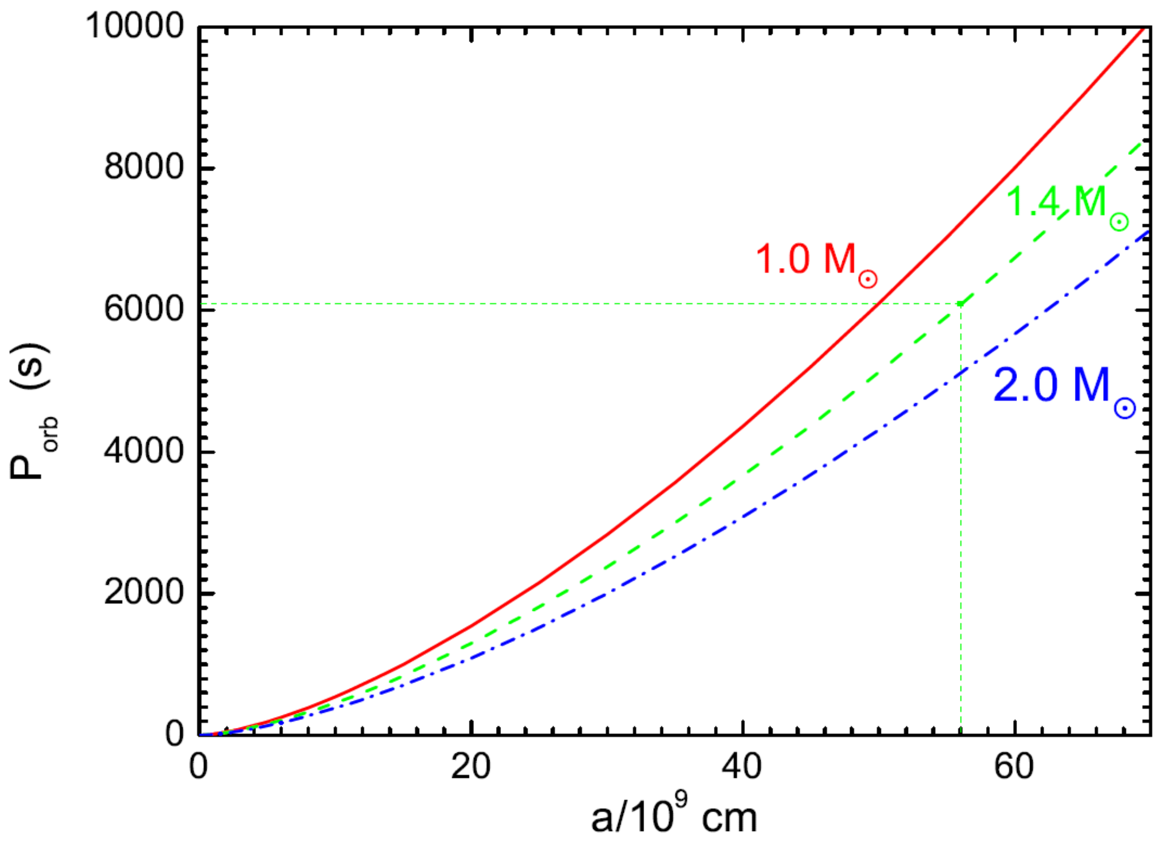
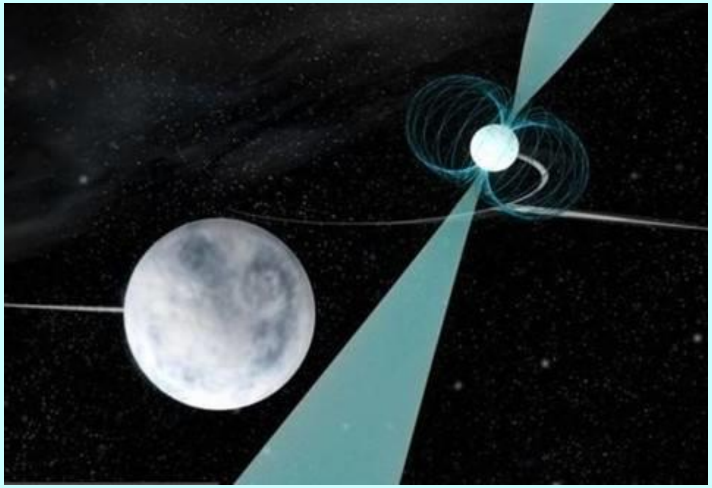
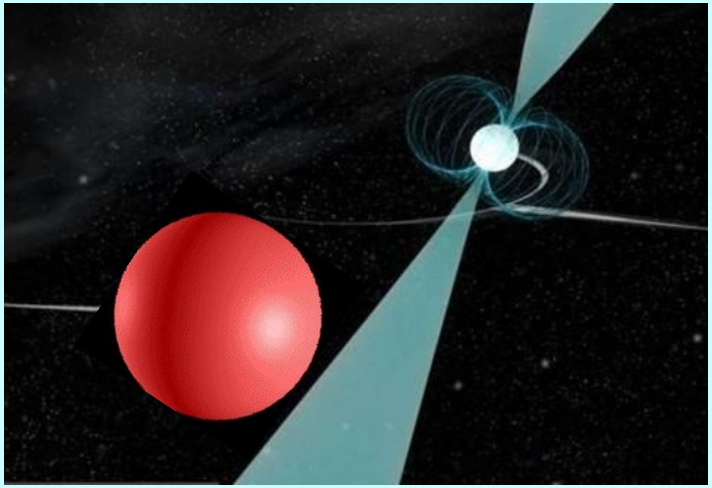


Figure 3 Orbital period vs. orbital radius for close-in planets. This figure is plotted according to Equation (4). The mass of the host pulsar is taken as 1.0 $M_\odot$ (the solid line), 1.4 $M_\odot$ (the dashed line), and 2.0 $M_\odot$ (the dash-dotted line), respectively. For the limiting orbital radius of $a = 5.6 \times 10^{10}$ cm, the corresponding orbital period is ~ 6100 s in the 1.4 $M_\odot$ pulsar case (see the vertical and horizontal dotted lines).

Huang Y.F. & Yu Y.B., 2017, submitted, arXiv:1702.07978





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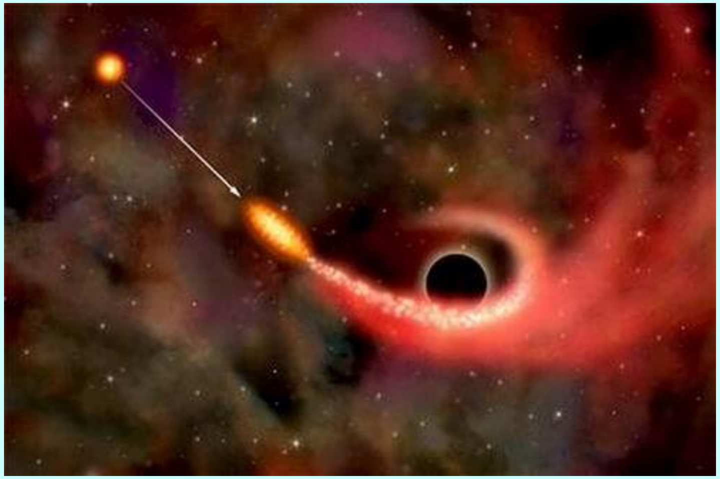
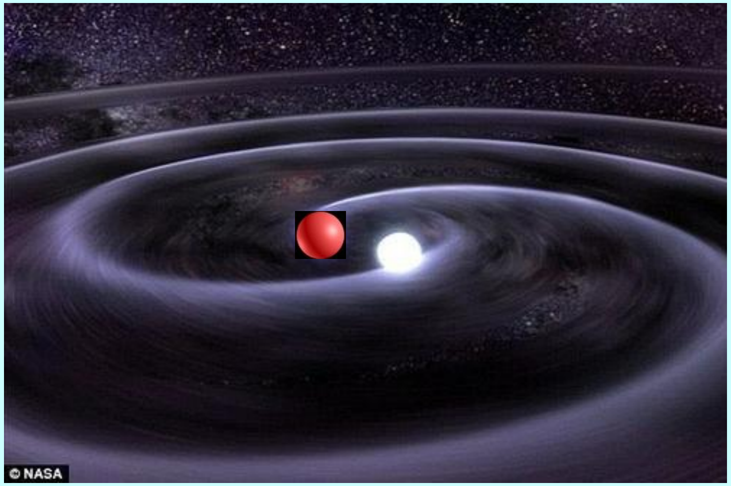
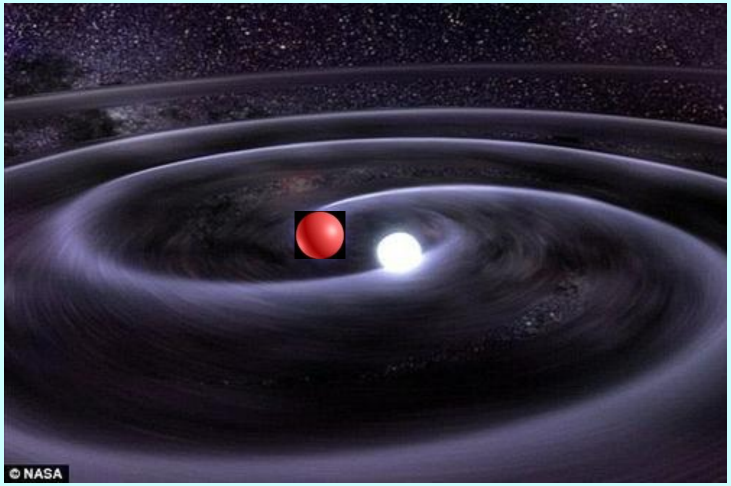
Tidal disruption radius of a strange planet:

$$r_{\rm td} = 1.5 \times 10^6\ {\rm cm}$$







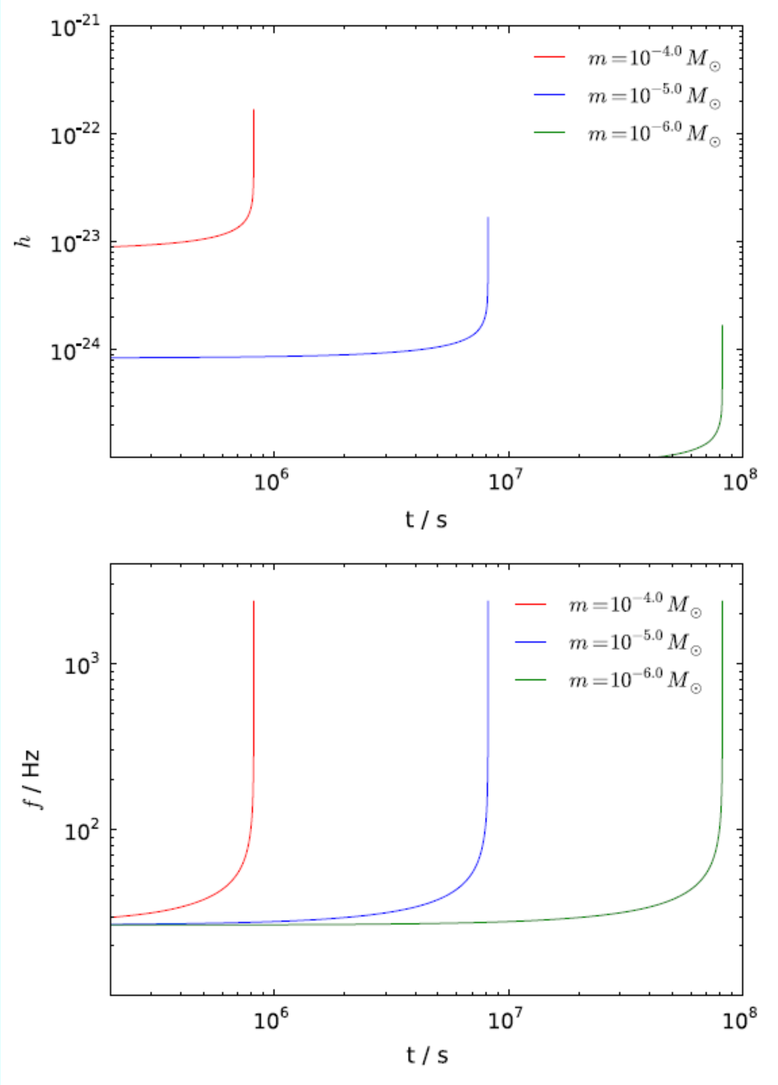
Extreme-mass-ratio inspirals
(Wen-Biao Han 2014; …)

GW radiation power:

$$P = \frac{32 G^4 M^2 m^2 (M + m)}{5 c^5 a^5},$$

GW amplitude:

$$h = 1.4 \times 10^{-24} \left(\frac{M}{1.4\, M_\odot} \right)^{2/3} \left(\frac{\rho_0}{4.0 \times 10^{14}\ \mathrm{g\ cm^{-3}}} \right)^{4/3} \times \left(\frac{R}{10^4\ \mathrm{cm}} \right)^3 \left(\frac{d}{10\ \mathrm{kpc}} \right)^{-1}.$$



Geng, Huang, Lu, 2015, ApJ, 804, 21

The GW bursts are detectable for adv-LIGO and ET.

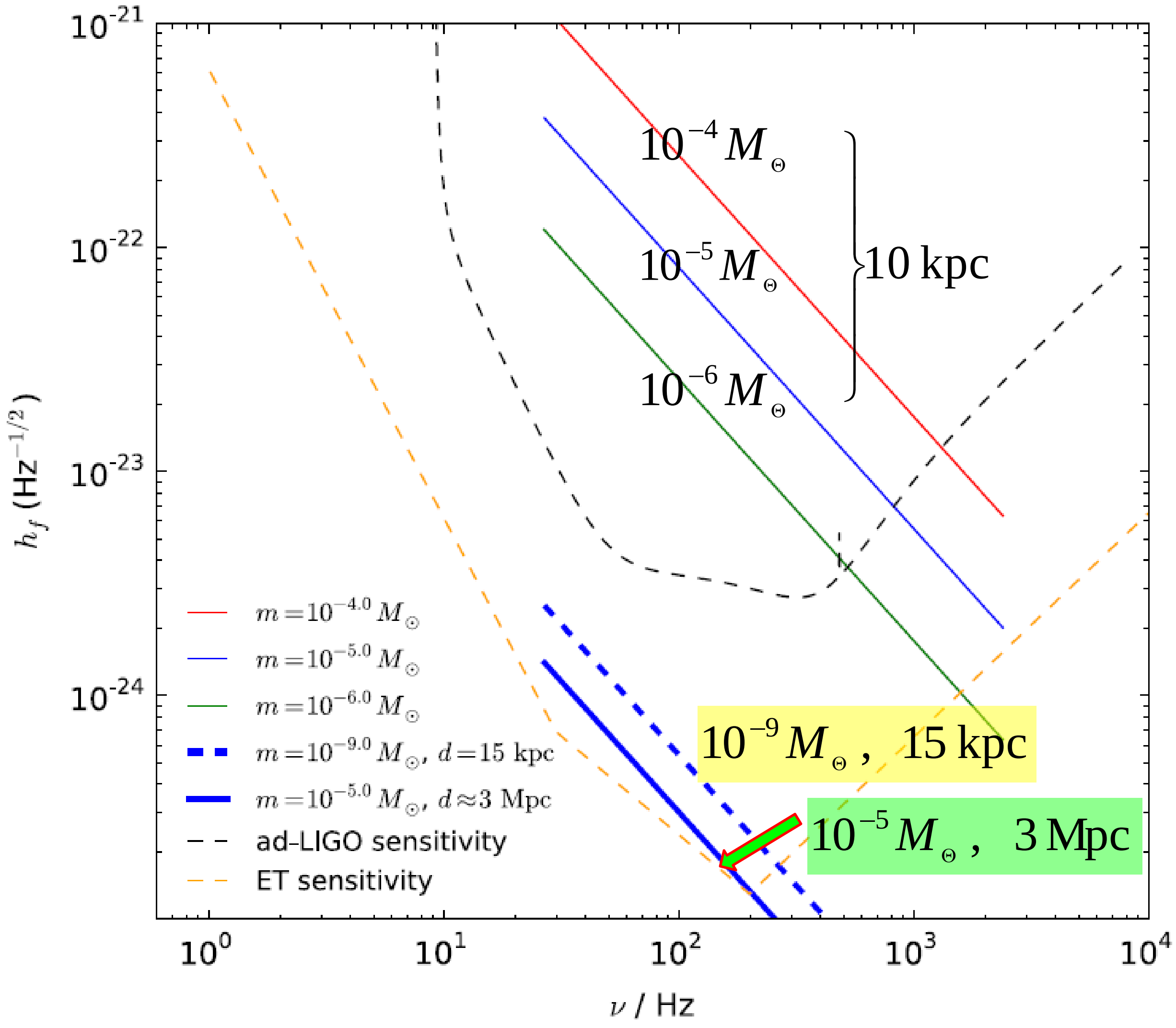
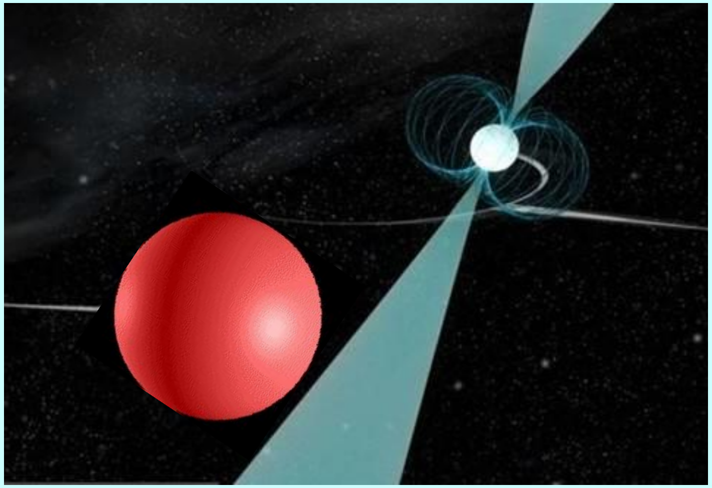


Figure 2. Strain spectral amplitude of the GWs against frequency for coalescing strange star–strange planet systems. The host strange star has a mass of 1.4 $M_\odot$. The straight red, blue, and green solid lines correspond to strange

Geng, Huang, Lu, 2015, ApJ, 804, 21

Event rate

- **Assuming: all neutron stars are actually strang stars: 10^9 SSs in our Galaxy**
- **0.1 percent have planets: 10^6 planetary SS systems.**
- **Timescale for a single planet system to undergo a large collision event(>10^{24}g/10^{-9} Msun) is ~10^5 yr (Katz et al. 1994).**
- **~ 10 GW bursts could be detected by ET.**
- **Still not including nearby galaxies, …**



- If you observed a “strange” GW burst event from:

a “neutron star” + a “planet”

- Then, do not hesitate, it must be a SQM planetary system.

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Conclusions

1. SQM could be the true ground state of hadronic matter.
2. Pulsars may actually be strange stars.
3. Strange planets may exist. Close-in planets are especially interesting.
4. Merging S-star/S-planet could produce GW bursts: a unique probe to test the SQM hypothesis.

Thank You!