高密度物質と中性子星の物理
Physics of Neutron Star Matter

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- 中性子星の基本的性質
- 状態方程式を記述する理論模型
- 対称エネルギーと非対称核物質の状態方程式
- ハイパー核物理と高密度核物質の状態方程式
- 中性子星におけるエキゾチック自由度

九州大学集中講義　7/8-10

高密度物質と中性子星の物理

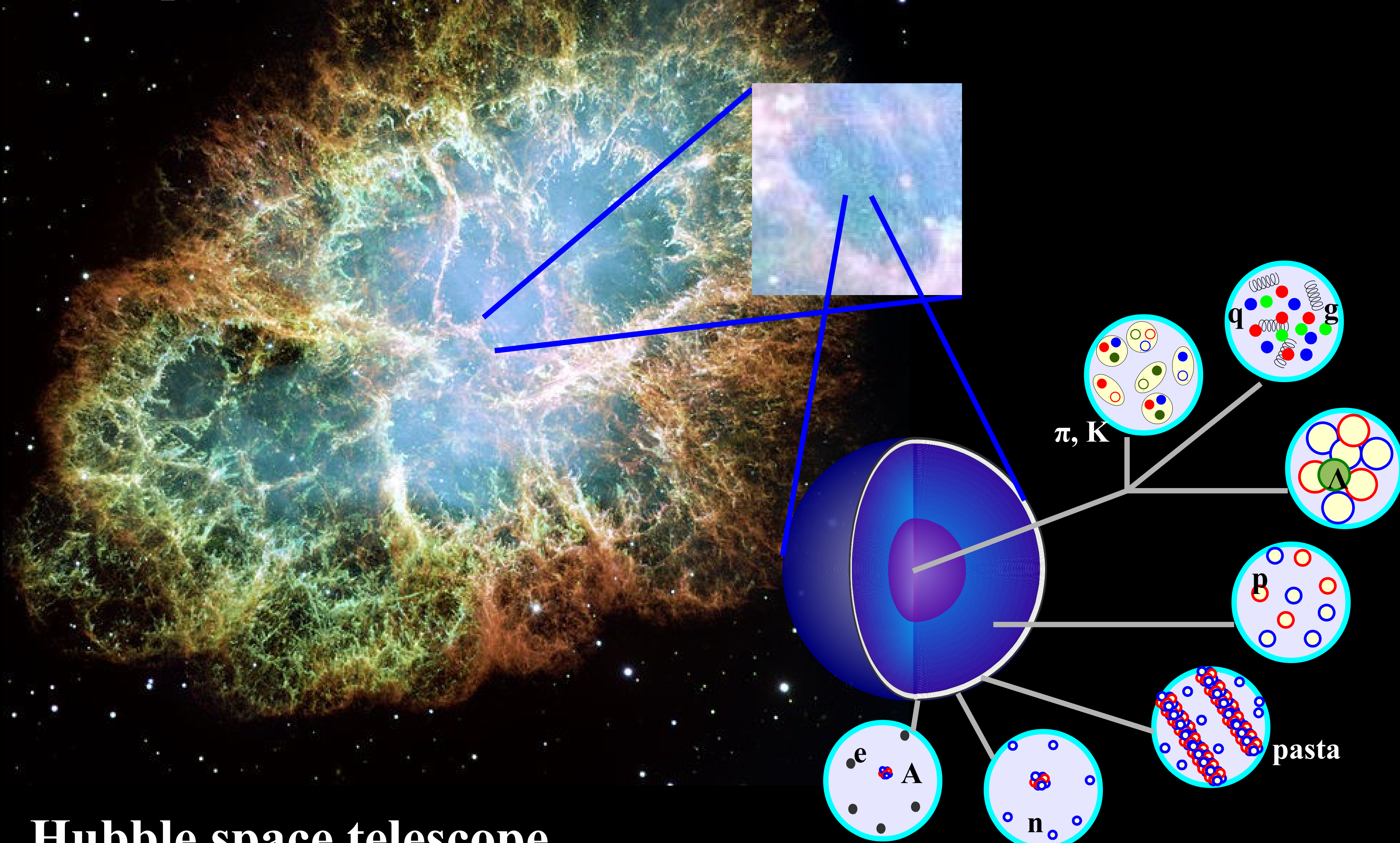
- 授業の目的
  　中性子星は密度、構成要素ともにバラエティに富む多体問題の宝庫である。近年の実験・観測の進展により、実験データから示唆される相互作用の性質と観測データをつき合わせて中性子星核物質状態方程式を定量的に議論できる時代を迎えつつある。一方、核子以外のハドロンを含む従来の状態方程式では支えられない重い中性子星が最近見つかり、大きなパズルとなっている。
  　本講義では中性子星の基本的性質について理解し、また中性子星物質などの高密度核物質の状態方程式を記述する理論形式について学ぶこと、また近年の中性子星をめぐる物理の進展を概観することを目的とする。
- キーワード
  中性子星、状態方程式、高密度物質、最大質量、ストレンジネス
- 授業概要
  中性子星についての大まかな性質を概観した後に、原子核物理学の立場から中性子星物質の状態方程式を理解する上で基本となる理論の枠組みについて、相対論的平均場理論を中心に解説する。また、中性子星物質の物理が深く関わる「対称エネルギー」、「ハイパー核物理」、および「エキゾチック自由度」における近年の研究の進展を紹介する。

高密度物質と中性子星の物理

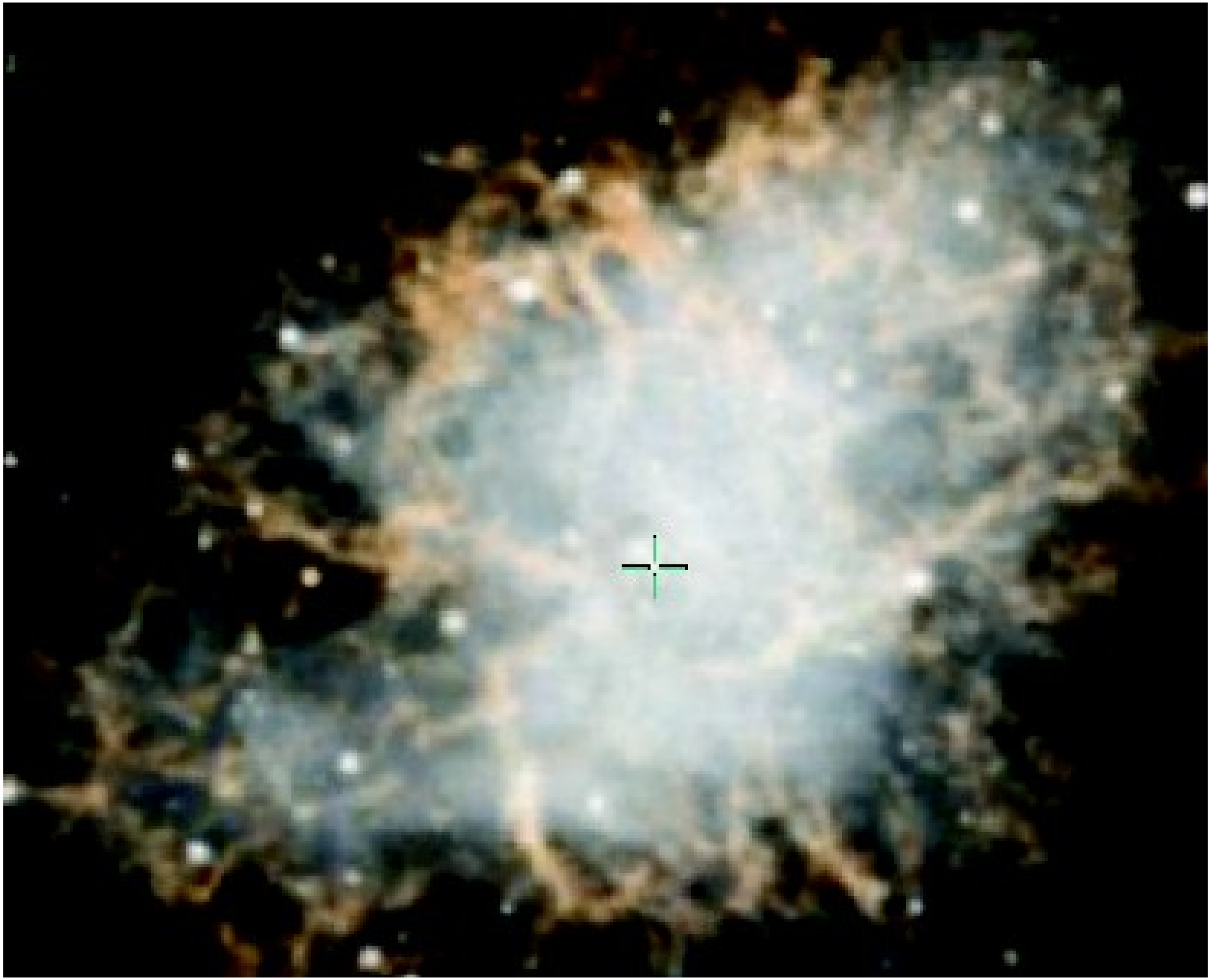
1. 中性子星の基本的性質 (1-2 コマ目)
2. 状態方程式を記述する理論模型 (3 コマ目)
3. 対称エネルギーと非対称核物質の状態方程式 (4 コマ目)
4. ハイパー核物理と高密度核物質の状態方程式 (5-6 コマ目)
5. 中性子星におけるエキゾチック自由度 (6 コマ目)

- 談話会
  「実験・観測・理論で解き明かす中性子星物質状態方程式」

Crab Nebula
SN1054 (e.g. Meigetsu-ki, Teika Fujiwara)
Crab pulsar (PSR J0534+2200), discovered in 1968.



Hubble space telescope



Pular position

http://simbad.u-strasbg.fr/simbad/sim-id?Ident=Crab+Pulsar

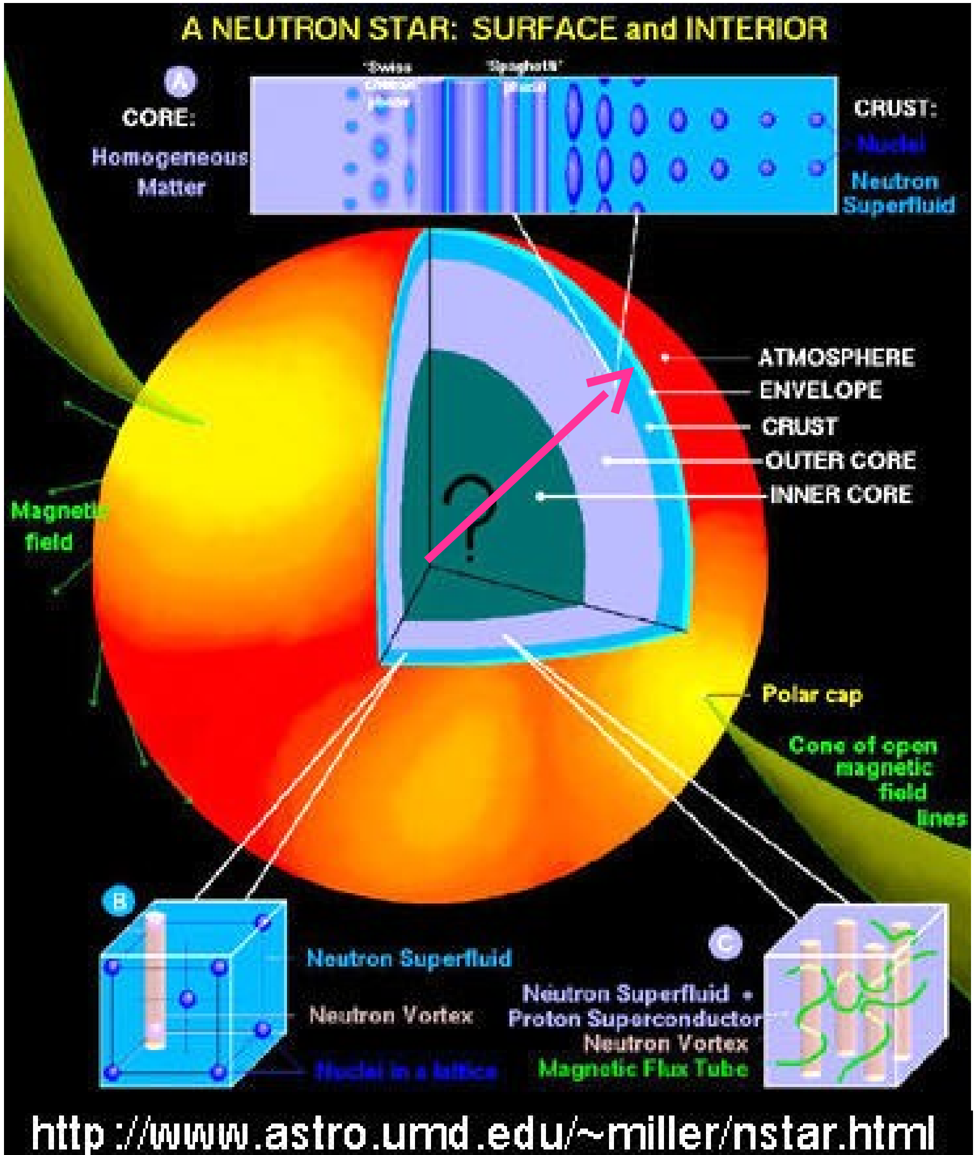
Basic properties of neutron stars

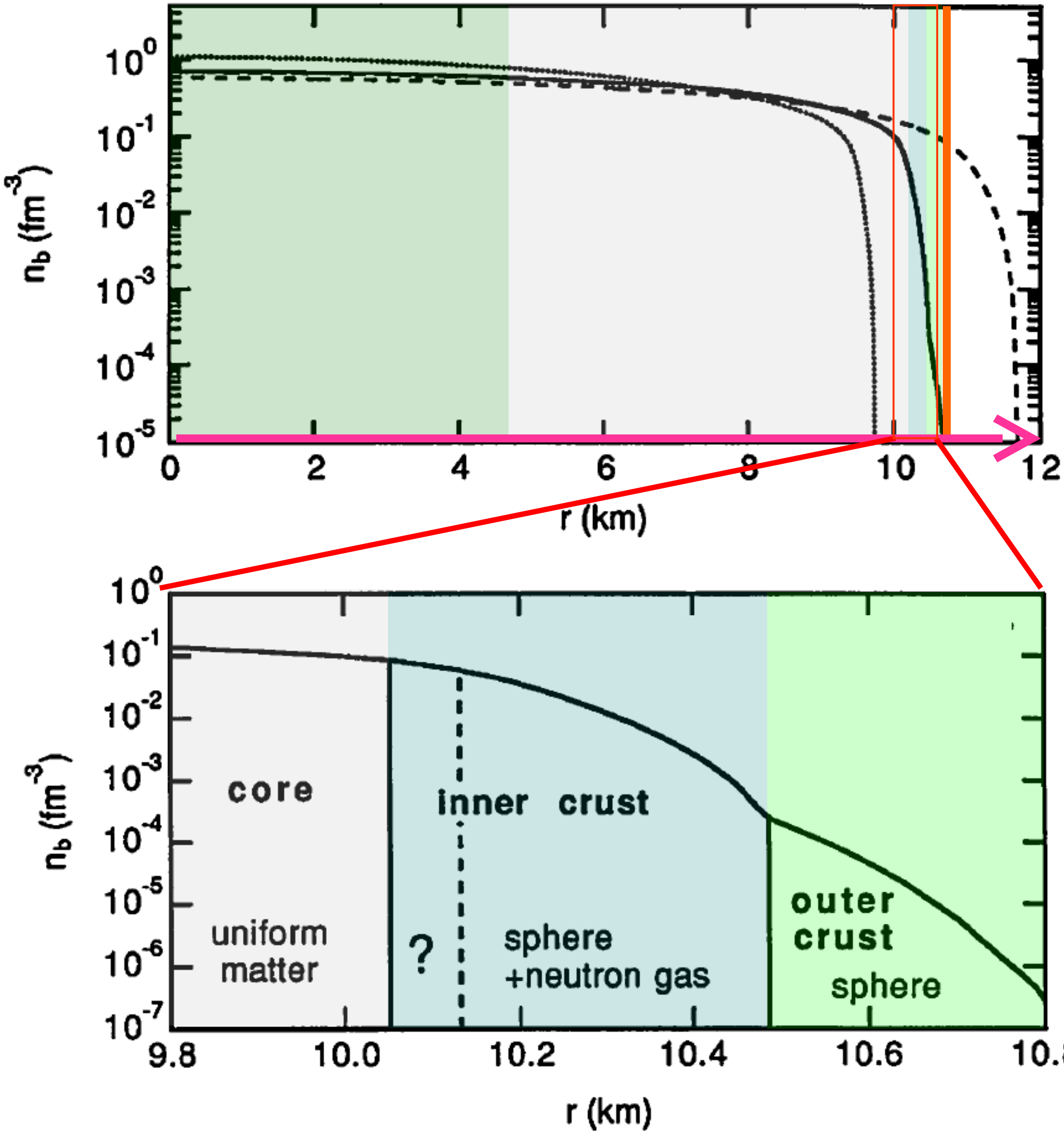
- **Mass: $M = (1\text{-}2)\ M_\odot$ $(M \sim 1.4\ M_\odot)$**
- **Radius: 5 km < R < 20 km (R ~ 10 km)**
- **Supported by Nuclear Pressure**
  c.f. Electron pressure for white dwarfs
- **Cold enough**
  ($T \sim 10^6$ K ~ 100 eV)
  compared with
  neutron Fermi energy.
- **Various constituents**
  (conjectured)
  n, p, e, μ, Y, $\bar{K}$, π,
  q, g, qq, ….

google & zenrin

Neutron Star Structure

- Dense core + Thin Crust



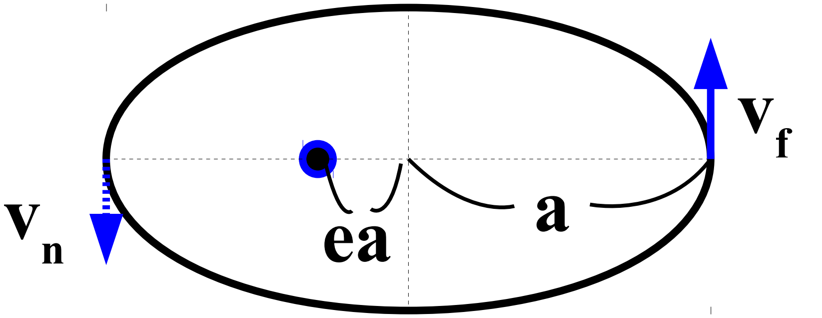


by Nakazato

Observables

Neutron Star Observables: Mass (1)

- **Please remember Kepler motion basics**
  - **major axis=a, eccentricity=e, reduced mass=m, total mass=M**



$$E/m=\frac{1}{2}v_f^2-\frac{GM}{a(1+e)}=\frac{1}{2}v_n^2-\frac{GM}{a(1-e)}$$

$$L=mv_f a(1+e)=mv_n a(1-e)$$

$$\rightarrow v_f^2=\frac{GM}{a}\frac{1-e}{1+e},\ L=2m\frac{dS}{dt}=m\sqrt{GMa(1-e^2)}$$

$$\rightarrow P=S/(dS/dt)=2\pi a^2\sqrt{1-e^2}/\sqrt{GMa(1-e^2)}=2\pi a^{3/2}/\sqrt{GM}$$

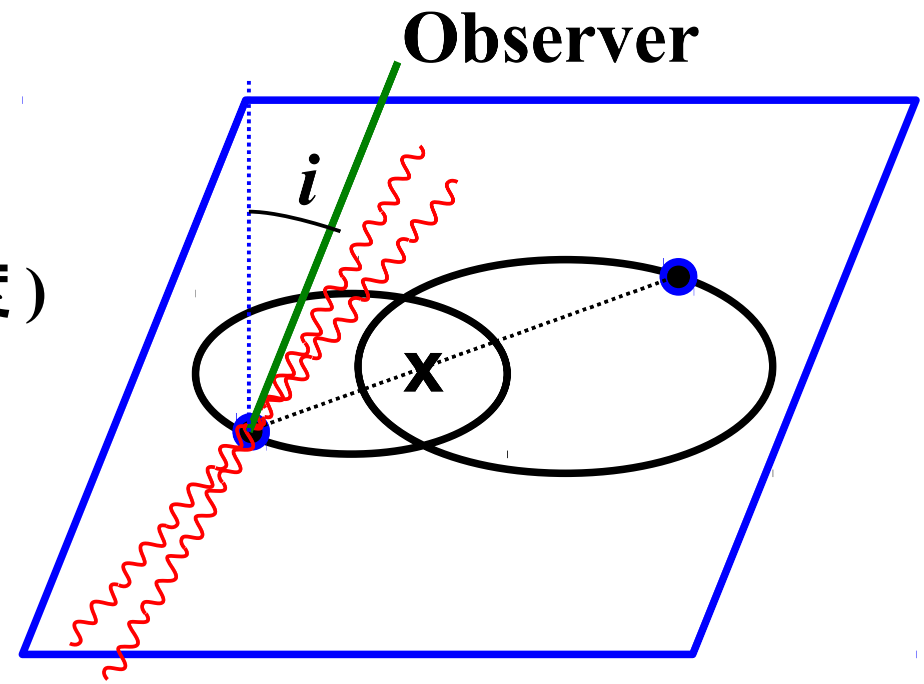
Neutron Star Observables: Mass (2)

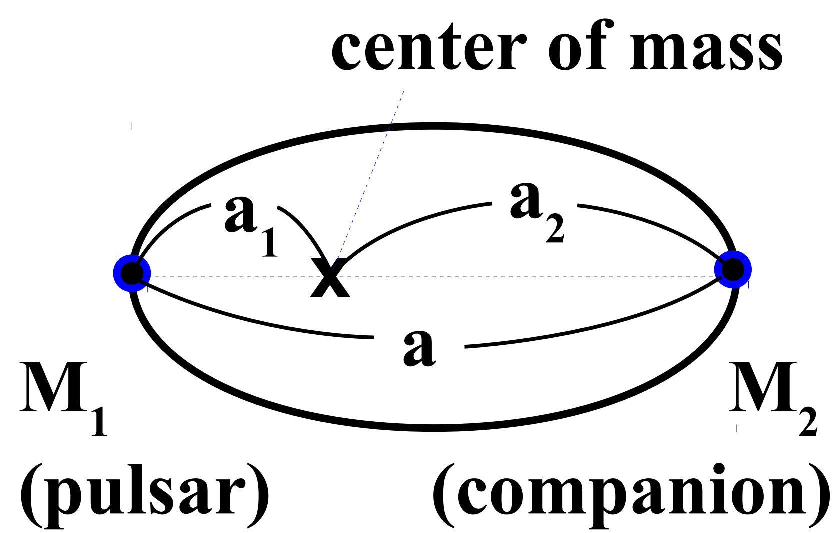
- **Binary stars**
  - **inclination angle = *i***
    → Doppler shift is given
    by the radial velocity (視線速度)
    $K = v \sin i$
  - **Mass function (observable)**

$$f \equiv \frac{(M_2 \sin i)^3}{M^2} = \frac{4\pi^2 (a_1 \sin i)^3}{G} P^2$$

$$= \frac{K^3 P (1-e^2)^{3/2}}{2\pi G} \quad (K = v \sin i)$$

  - **Doppler shift,**
    → radial velocity
    → orbit parameters





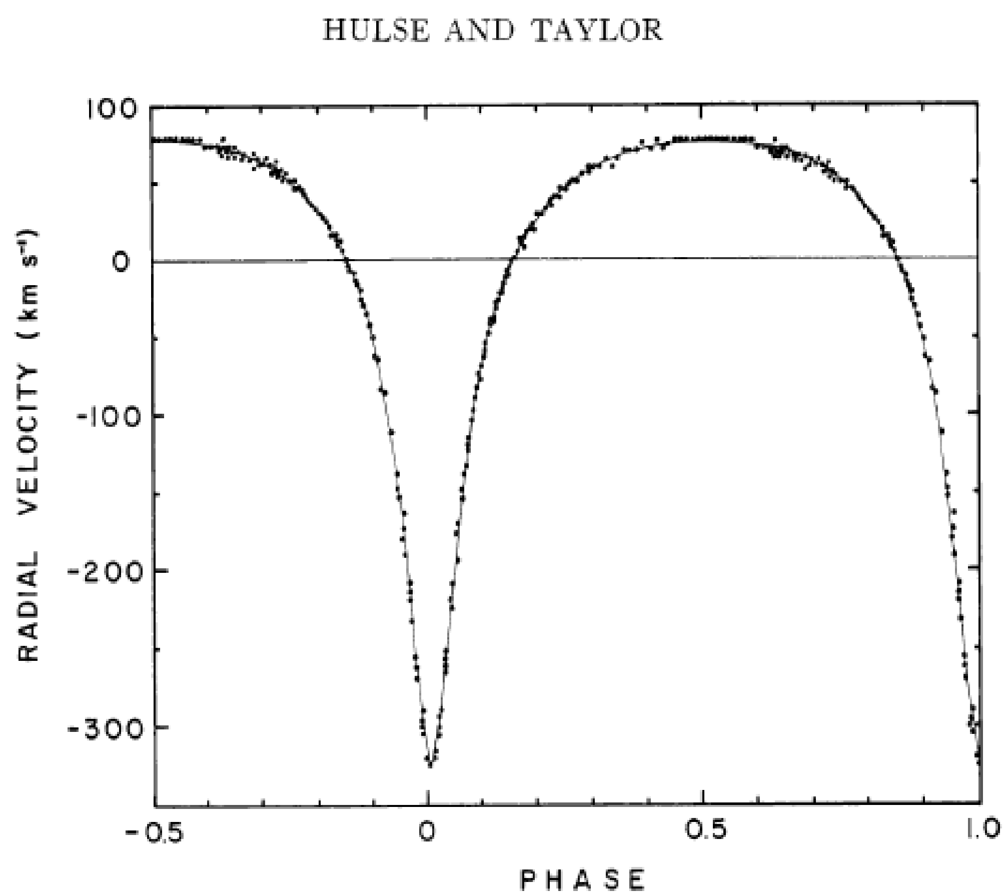
Hulse-Taylor Pulsar (PSR 1913+16)

- **Precisely (and firstly) measured neutron star binary (1993 Nobel prize)**
- **Radial velocity → P, e, a_1 sin *i* → Mass function**

TABLE 2

ELEMENTS OF THE ORBIT

K_1	=	199 ± 5 km s^{-1}
P_b	=	27908 ± 7 s
e	=	0.615 ± 0.010
ω	=	$179° \pm 1°$
T	=	JD $2{,}442{,}321.433 \pm 0.002$
$a_1 \sin i$	=	$1.00 \pm 0.02\ R_\odot$
$f(m)$	=	$0.13 \pm 0.01\ M_\odot$



Hulse-Taylor ('75)

More on Hulse-Taylor Pulsar (PSR 1913+16)

- **General Relativistic Effects**
  - **Perihelion shift (近日点移動)**

$$\dot{\omega}=3\left(\frac{2\pi}{P}\right)^{5/3}\frac{(GM)^{2/3}}{(1-e^2)c^2}$$

  - **Einstein delay**

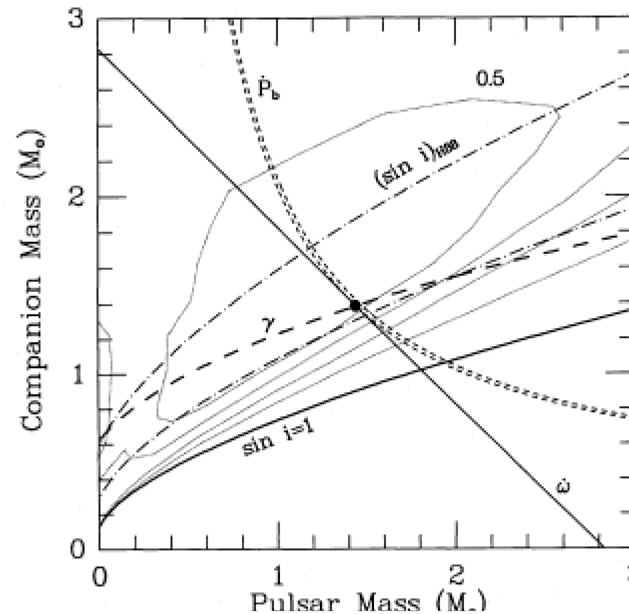
$$\Delta_E=\gamma\sin u$$
$$(u=\text{eccentric anomaly})$$

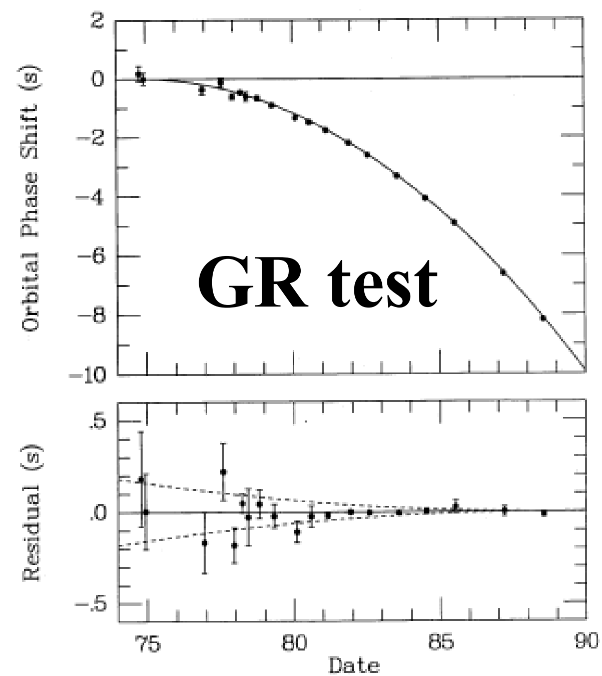
$$\gamma=\frac{eP_bGm_2(m_1+2m_2)}{2\pi c^2 a_R M} \qquad \frac{a_R^3}{P_b^2}=\frac{GM}{4\pi^2}\left[1+\left(\frac{m_1m_2}{M^2}-9\right)\frac{GM}{2a_Rc^2}\right]^2$$

  - **Two observable**

→ Precise measurement of m_1 and m_2.

$$m_1=1.442\pm0.003\,M_{\rm sun}$$
$$m_2=1.386\pm0.003\,M_{\rm sun}$$

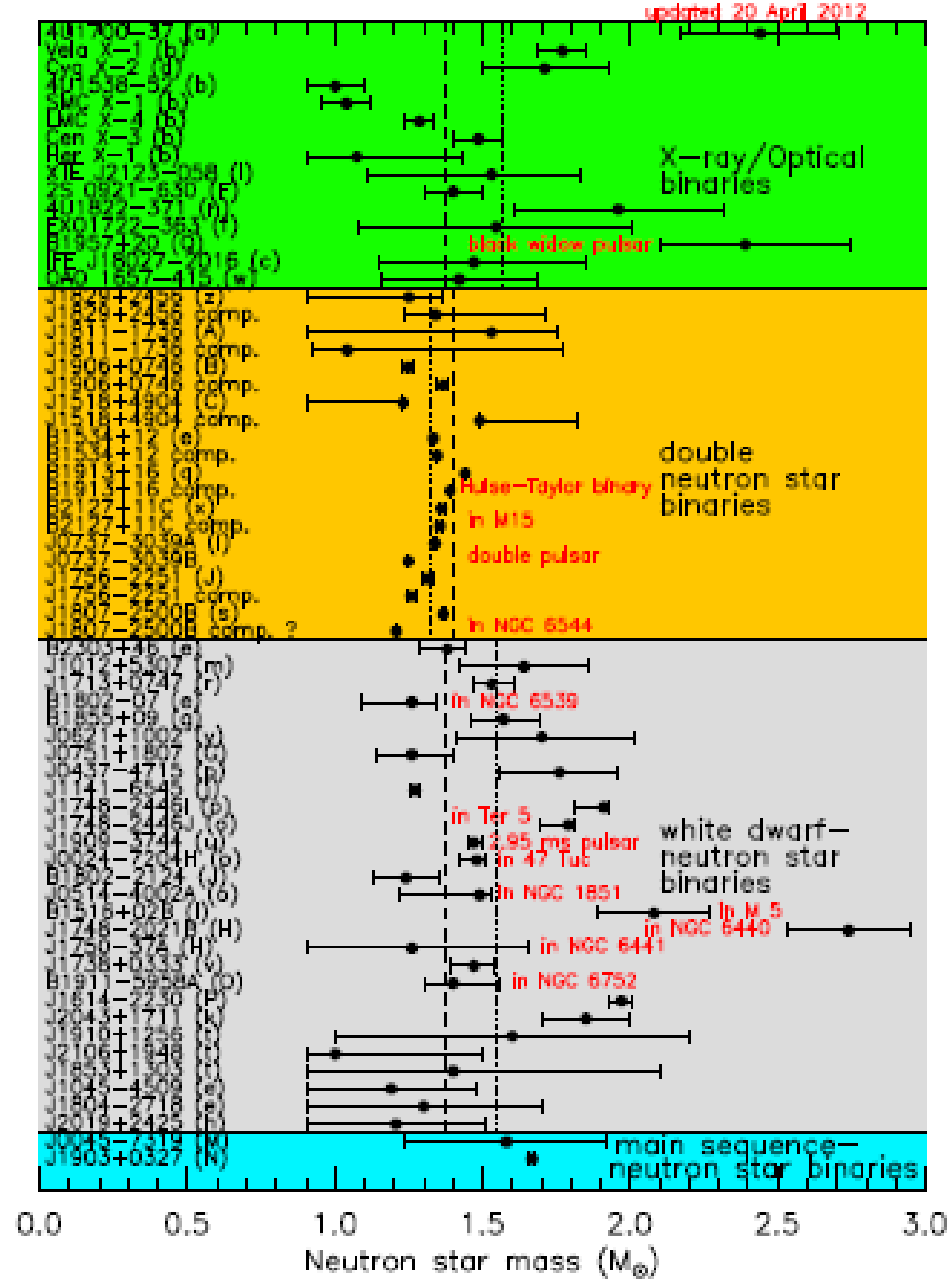




Taylor, Weisenberg ('89)

Neutron Star Masses

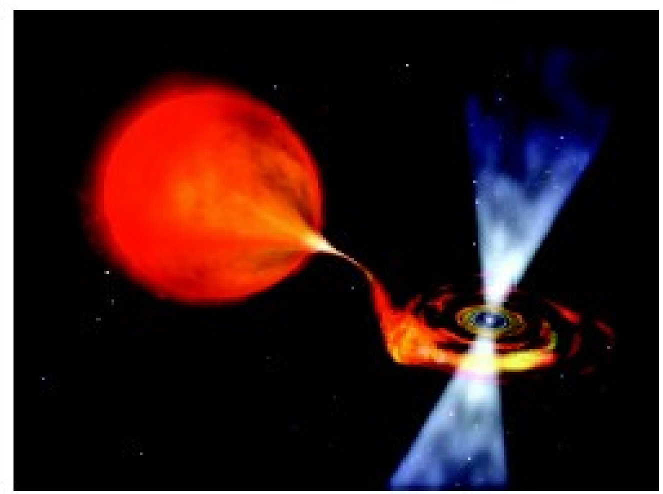
- **Many NSs have masses ~ 1.4 $M_\odot$.**
- **Massive NS masses had large error bars, and were considered not to be conclusive (before 2010).**



Lattimer (2013)

中性子星の半径観測

- 質量の測定よりも難しく、不定性大
- 中性子星は天球上の「点」でしかない
  - 中性子星半径 ~ 10 – 15 km
  - 銀河のサイズ ~ 3×10^{14} km （= 10 kpc）
- モデルを立てて検討する必要あり
- ここでは X 線バースターの場合について紹介



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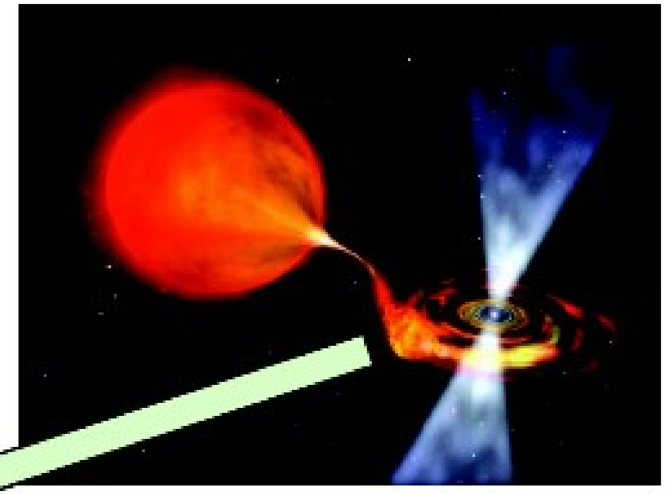
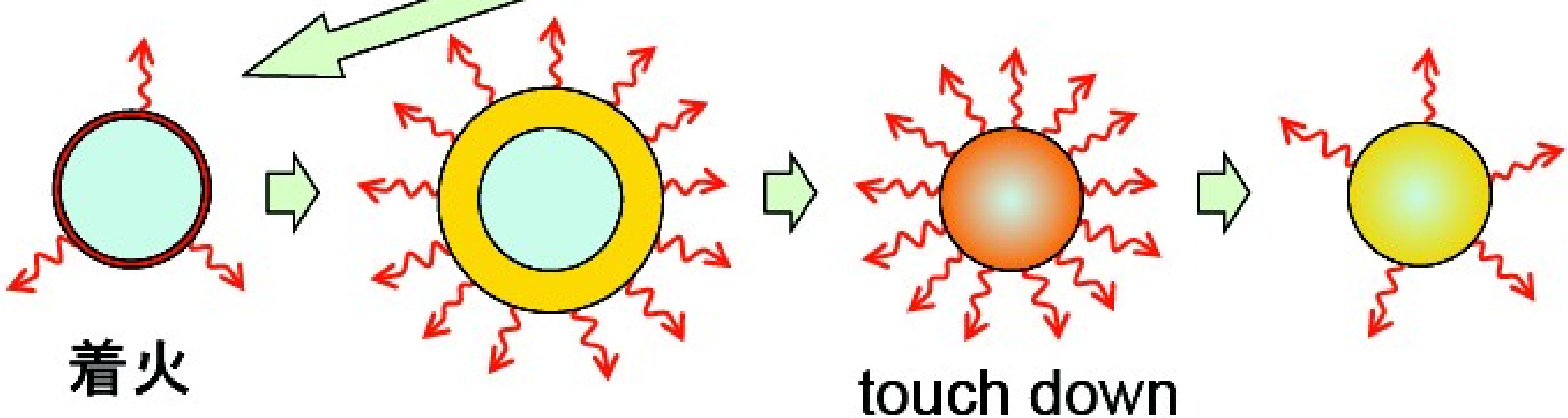
X 線バースターとは

- 伴星からの質量降着により中性子星表面に堆積したヘリウム（または水素）が、核燃焼を起こす（type I）。





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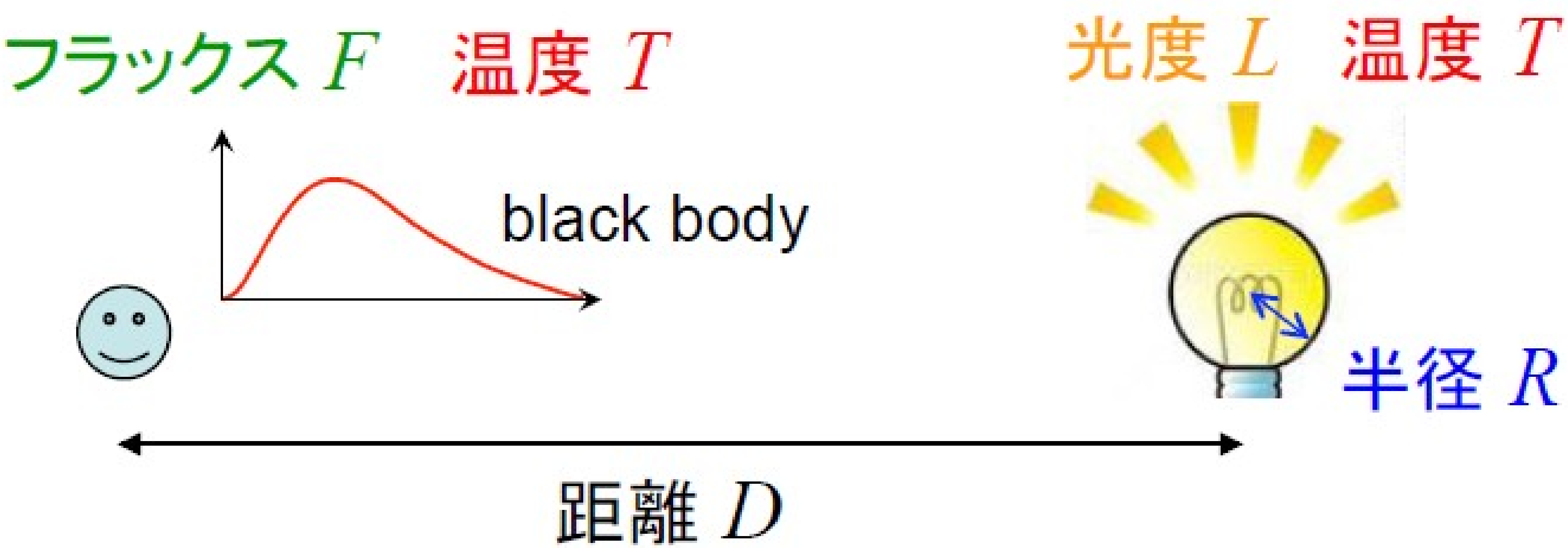
半径推定の原理

$$L = 4\pi R^2 \sigma_{\mathrm{SB}} T^4$$ （ステファン＝ボルツマンの法則）

$$F = \frac{L}{4\pi D^2} \quad \Rightarrow \quad R = D\sqrt{\frac{F}{\sigma_{\mathrm{SB}} T^4}}$$



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問題点

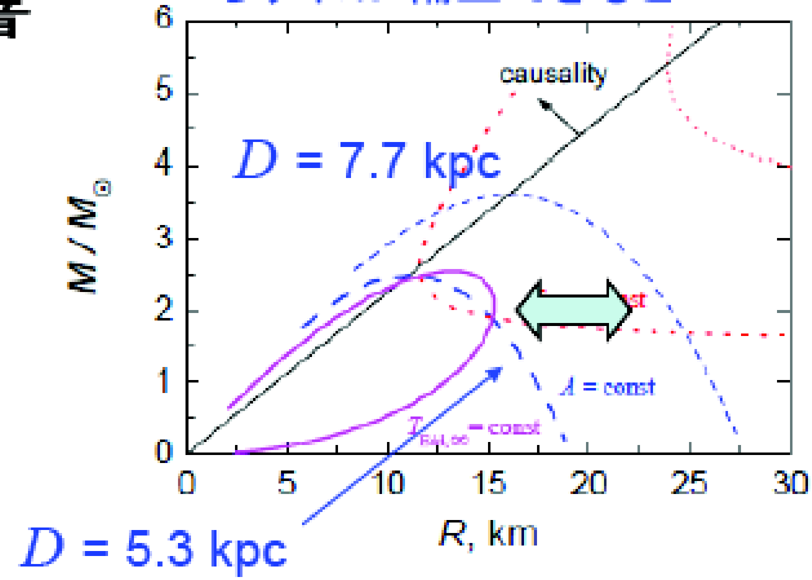
- 中性子星までの距離 D がわからない。
- 中性子星からの放射は黒体放射からずれる。
- 中性子星表面は強重力場
  → 重力赤方偏移の影響

$$E_{obs.} = E_{surf.}\sqrt{1-\frac{2GM}{Rc^2}}$$

$$\frac{2GM}{Rc^2} \sim 0.4$$

- 質量 M は？

D がわかって、黒体放射からずれが補正できると・・・



Suleimanov et al., A&A 527 (2011) A139

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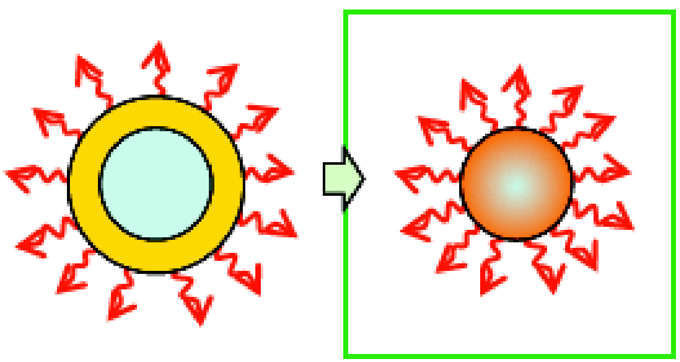
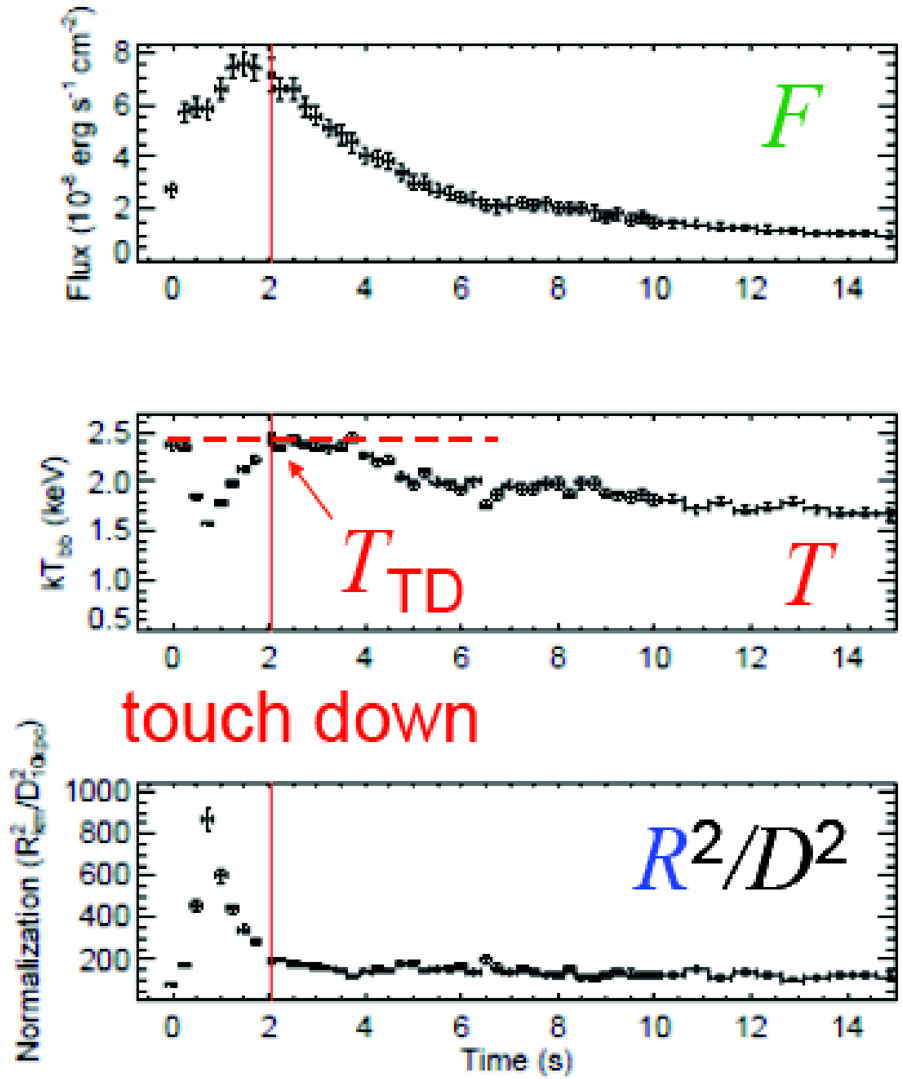
仮定

- touch down のときの温度 T_{TD} が、エディントン限界のときの温度 $T_{\mathrm{Edd.}}$ に対応する。





Example from 4U 1636-536
Guver et al., ApJ 747 (2012) 47

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エディントン限界とは（1）

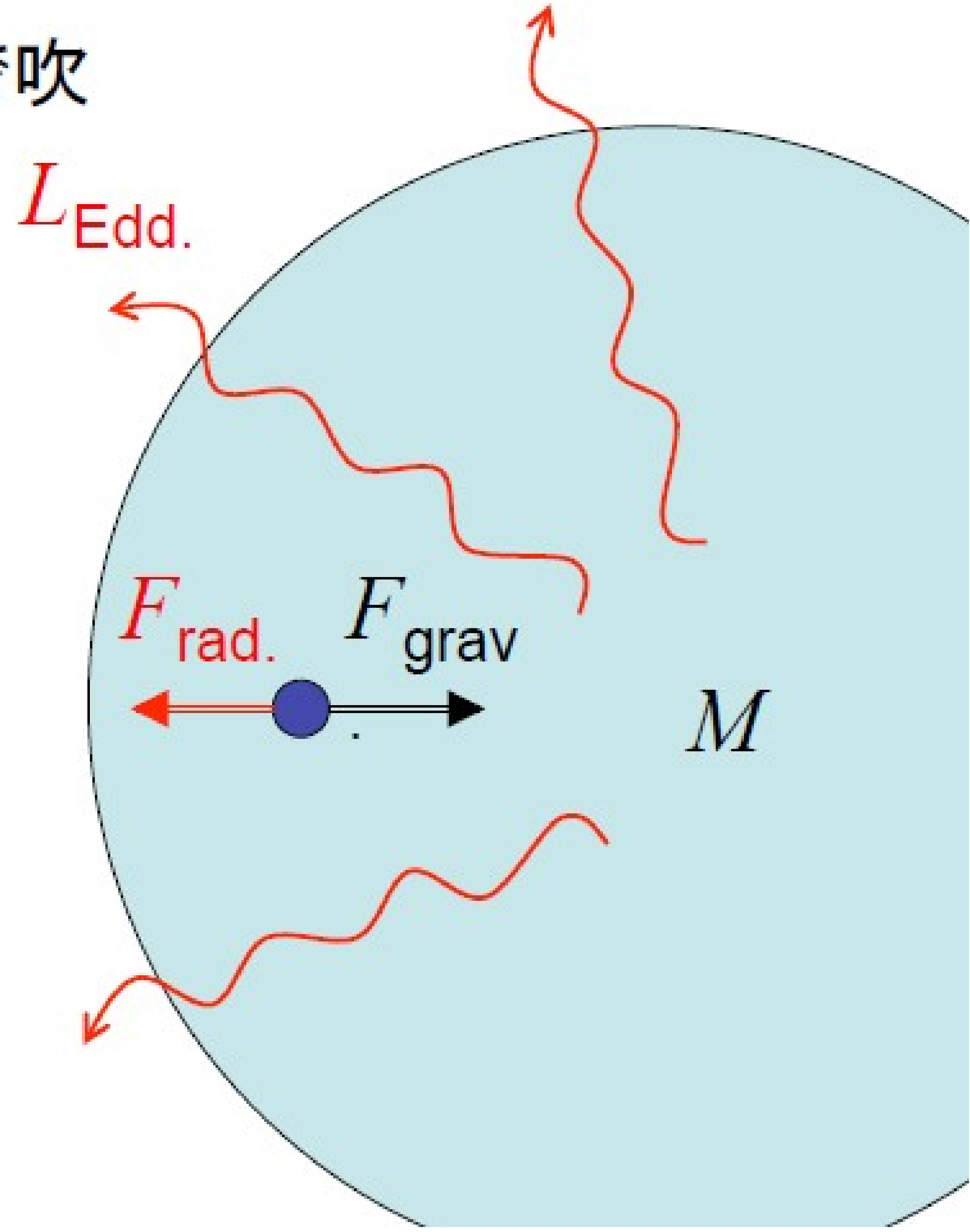
- 降着する物質が輻射圧で吹き飛ばされない限界。

$$F_{\mathrm{rad.}} = \underbrace{\frac{L_{\mathrm{Edd.}}}{4\pi r^2 c}}_{\text{輻射圧}} \cdot \underbrace{N_{\mathrm{e}}}_{\text{電子数}} \cdot \sigma_{\mathrm{T}}$$

輻射圧　電子数

$$F_{\mathrm{grav.}} = \frac{GM}{r^2} \cdot \underbrace{N_{\mathrm{N}}}_{\text{核子数}} \cdot m_{\mathrm{N}}$$

核子数



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エディントン限界とは(2)

- 釣り合いの式

$$F_{\mathrm{grav.}} = F_{\mathrm{rad.}} \quad \Rightarrow \quad L_{\mathrm{Edd.}} = \frac{4\pi\, Gcm_{\mathrm{N}}}{\sigma_{\mathrm{T}}} \cdot M \cdot \frac{N_{\mathrm{N}}}{N_{\mathrm{e}}}$$

- 核子数と電子数の比 $\frac{N_{\mathrm{e}}}{N_{\mathrm{N}}}$ は？
  - 水素の場合: $\frac{N_{\mathrm{e}}}{N_{\mathrm{N}}} = 1$
  - その他の元素の場合: $\frac{N_{\mathrm{e}}}{N_{\mathrm{N}}} = \frac{1}{2}$
- 水素の割合を X とおくと $\frac{N_{\mathrm{e}}}{N_{\mathrm{N}}} = \frac{1+X}{2}$

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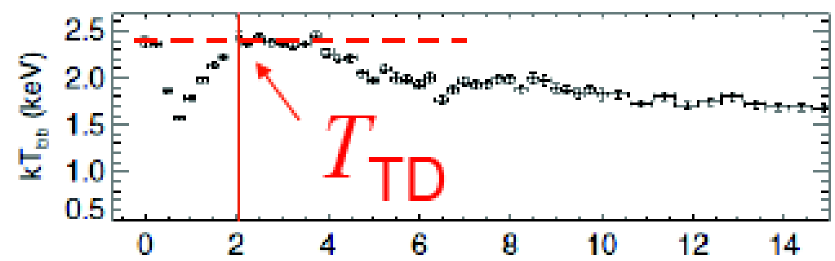
エディントン限界とは(3)

$$L_{\mathrm{Edd.}} = \frac{8\pi\, Gcm_{\mathrm{N}}}{\sigma_{\mathrm{T}}} \cdot \frac{M}{1+X}$$

- 温度に換算すると、



$$T_{\mathrm{Edd.}} = \left(\frac{L_{\mathrm{Edd.}}}{4\pi\, R^2 \sigma_{\mathrm{SB}}} \right)^{1/4}$$

距離 D に依存しない！

$$= \left(\frac{2Gcm_{\mathrm{N}}}{\sigma_{\mathrm{SB}} \sigma_{\mathrm{T}}} \right)^{1/4} (1+X)^{-\frac{1}{4}} M^{\frac{1}{4}} R^{-\frac{1}{2}}$$

でも、未知数が1個増えた気が・・・

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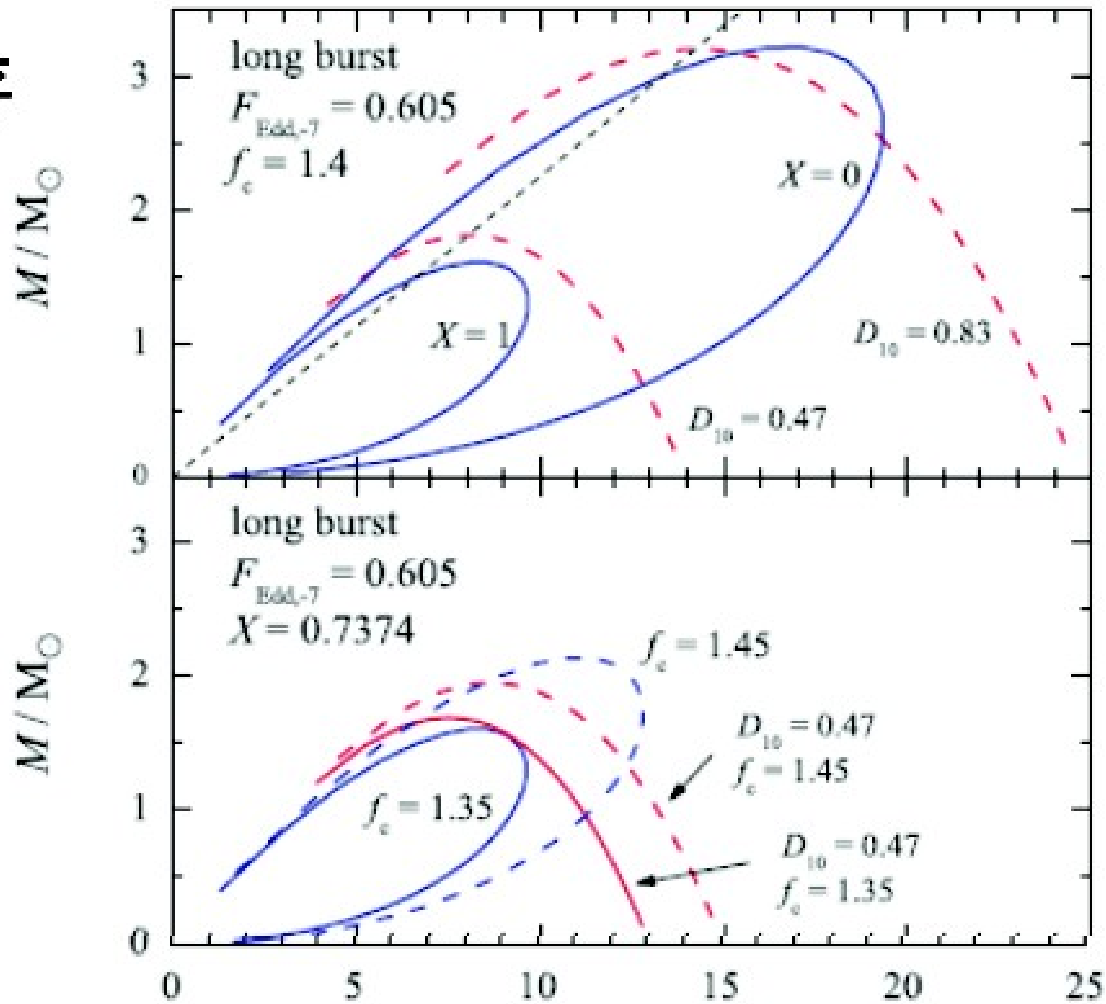
質量ー半径関係への制限の例

- 組成(X)に依存
- 黒体放射からの補正にも依存
- まだまだ不定性が大きい。

→ 新たな解析手法も提案される状況。

- そもそも観測数も少ない。



Example for 4U 1724-307
Suleimanov et al., ApJ 742 (2011) 122

Nakazato, NS school 2013

Astro-H 衛星

- 2014 年打ち上げ予定！
- 広帯域での高い検出感度
- 高精度のX 線分光

⇓

中性子星半径の精密決定

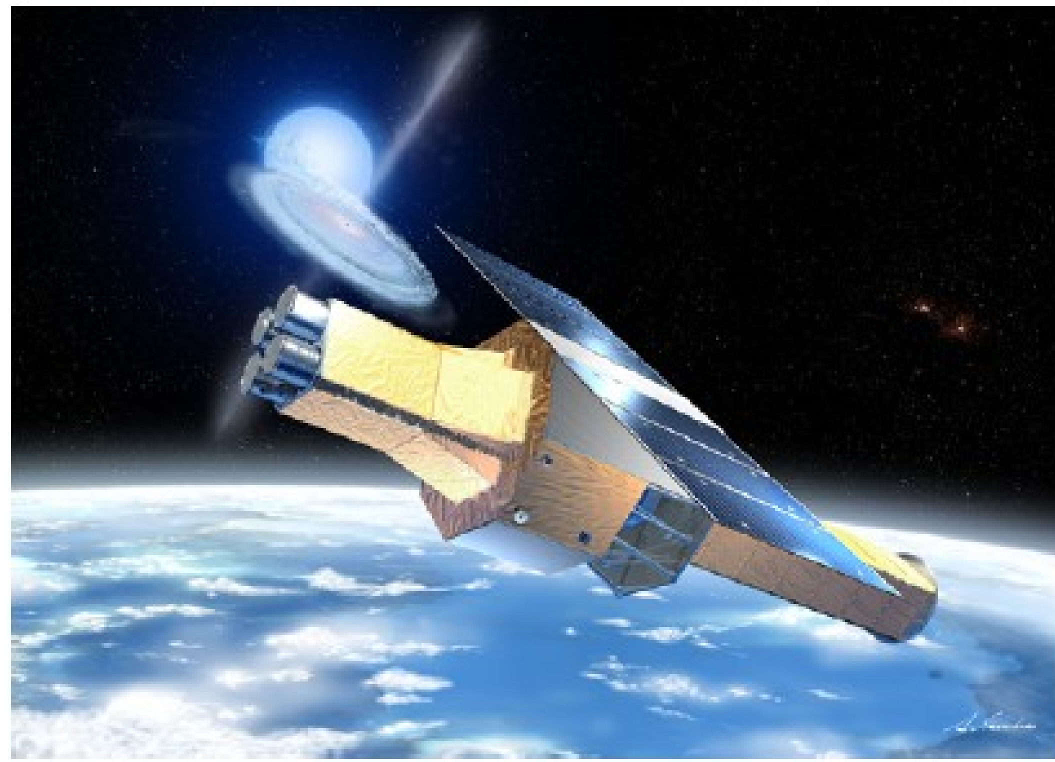


イラスト 池下章裕氏/提供 JAXA

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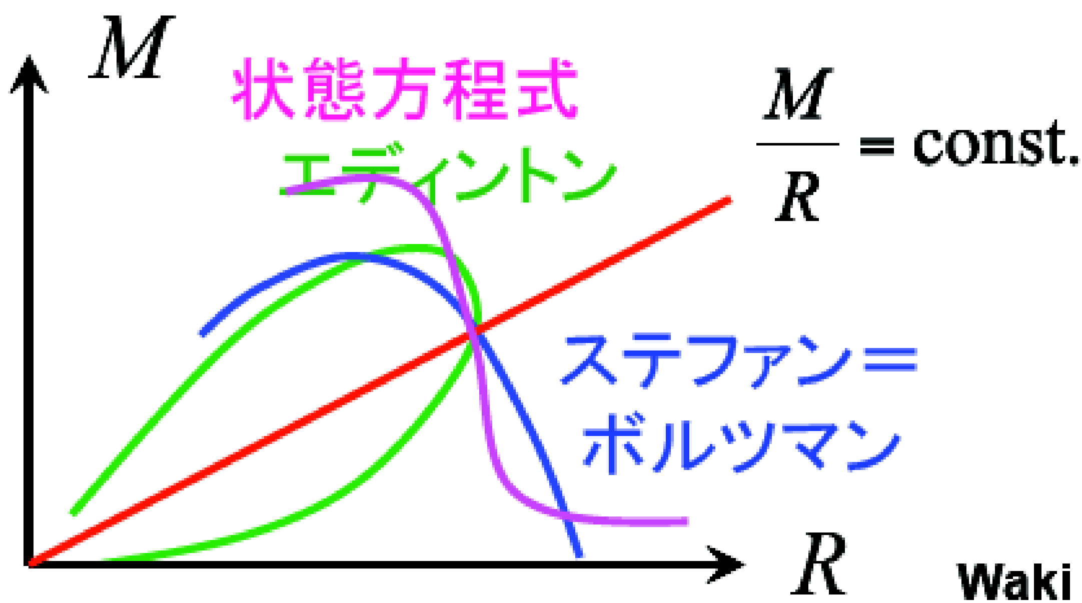
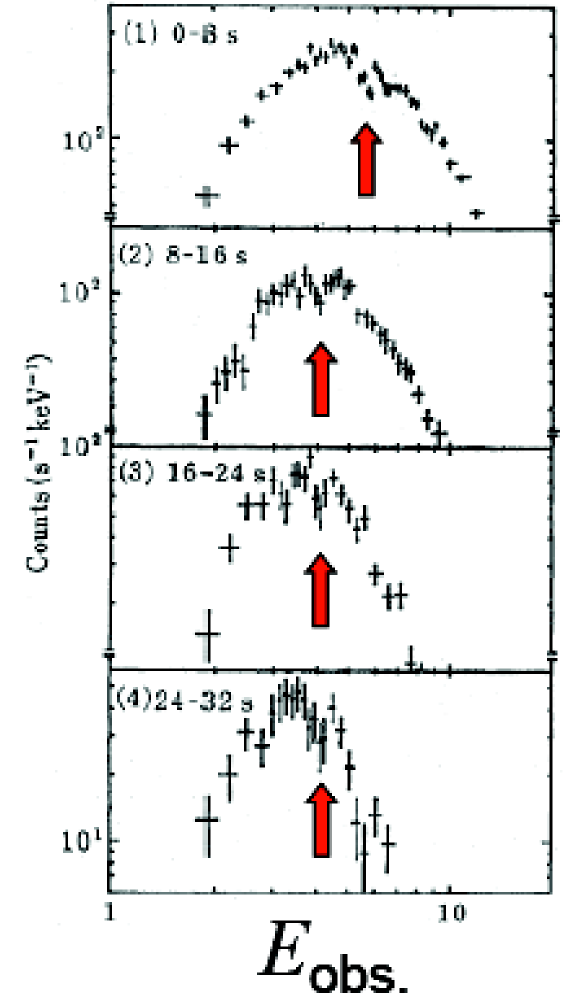
または：重力赤方偏移の直接測定

$$E_{\mathrm{obs.}} = E_{\mathrm{surf.}}\sqrt{1-\frac{2GM}{Rc^2}}$$

- 例えば、吸収線が見えると・・・

$E_{\mathrm{surf.}}$ = 6.7 keV（Fe XXV）





Example for X 1636-536
Waki et al., PASJ 36 (1984) 819

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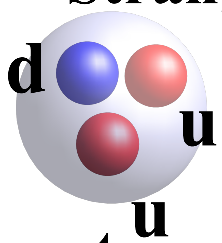
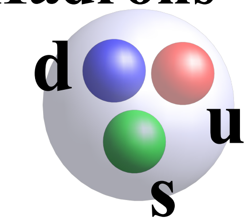
Structure & EOS

Neutron star – Is it made of neutrons ?

- **Possibilities of various constituents in neutron star core**
  - **Strange Hadrons**

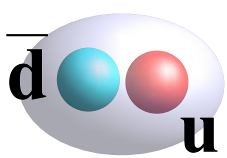


proton

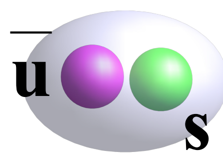


Λ hyperon

  - **Meson condensate (K, π)**

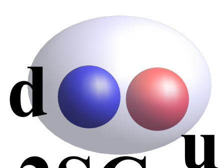


π

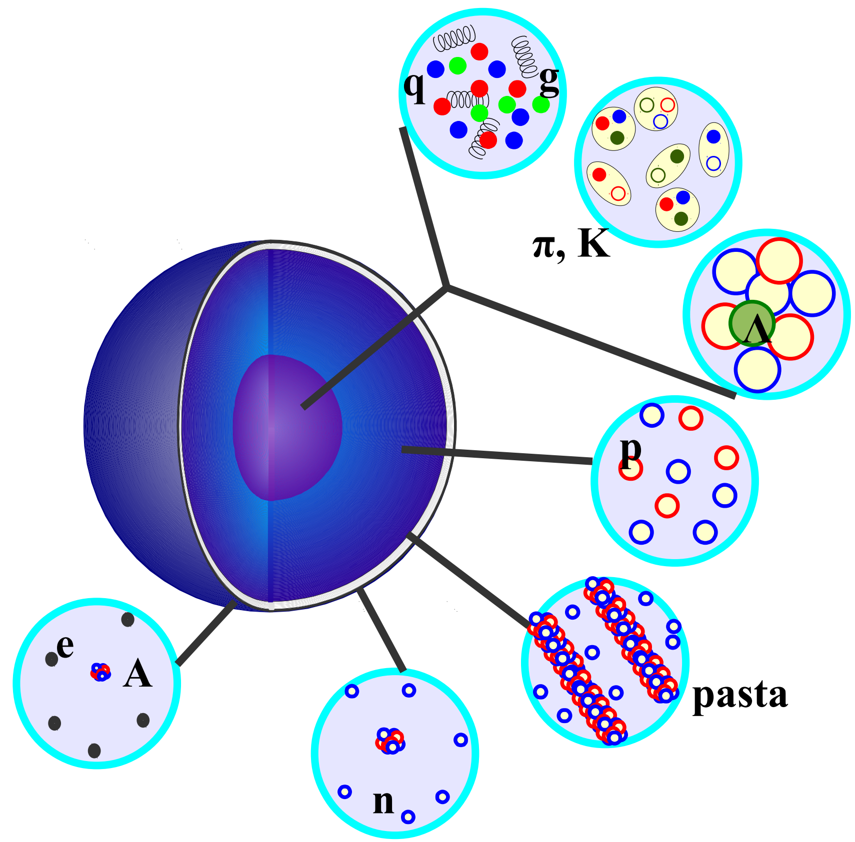


anti kaon

  - **Quark matter**
  - **Quark pair condensate (Color superconductor)**



2SC



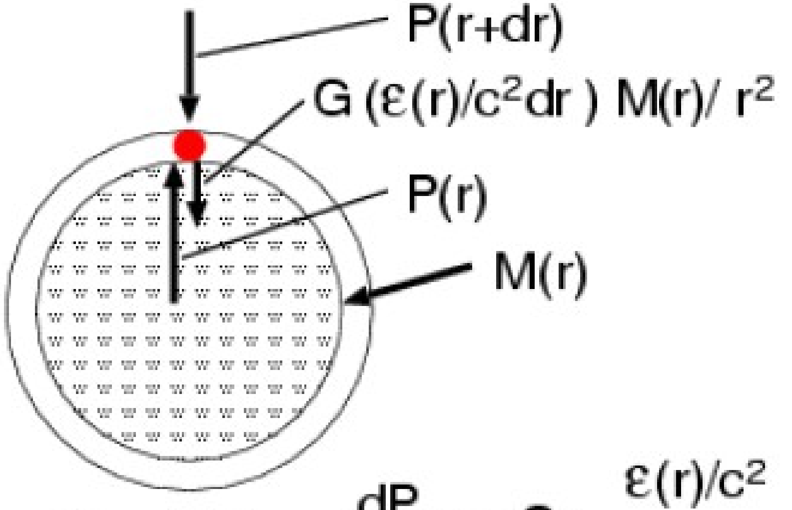
TOV equation

- **General Relativistic Hydrostatic Equation = TOV(Tolman-Oppenheimer-Volkoff) equation**

$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2, \quad P = P(\varepsilon) \quad (\text{EOS})$$

- **Spherical and non-rotating.**
- **3 Variables ($\varepsilon(r)$, P(r), M(r)), 3 Equations.**



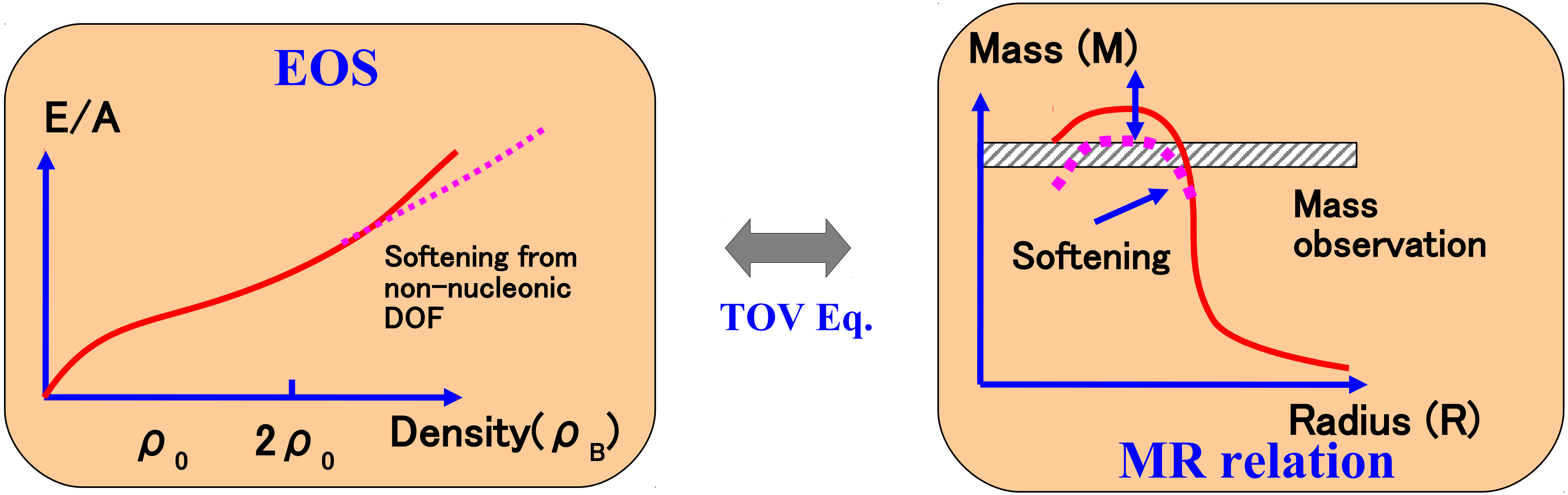
Non-Rela. $\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$

M-R Relation and EOS

- **Solving TOV eq.**
  starting from the "initial" condition, $\varepsilon(r=0) = \varepsilon_c$ = given
  until the "boundary" condition $P(r)=0$ is satisfied.
  → M and R are the functions of $\varepsilon(r=0)$ and functionals of EOS, $P=P(\varepsilon)$.

$$M = M(\varepsilon_c)[P(\varepsilon)] \quad , \quad R = R(\varepsilon_c)[P(\varepsilon)]$$

→ M-R curve and NS matter EOS : 1 to 1 correspondence



Nuclear Mass

- **Bethe-Weizsacker mass formula**
  Nuclear binding energy is roughly given by Liquid drop.
  Nuclear size measurement → $R = r_0 A^{1/3}$

$$B(A,Z) = a_v A - a_s A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} + a_p \frac{\delta_p}{A^\gamma}$$

Volume **Surface** **Coulomb** **Symmetry** **Paring**

$A \propto \frac{4\pi}{3} R^3$ $\quad A^{2/3} \propto 4\pi R^2$ $\quad \propto \frac{Q^2}{R}$

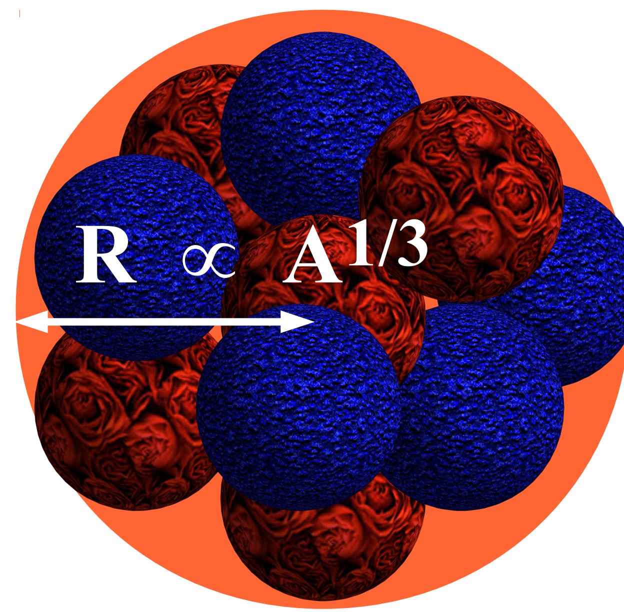
- **Ignore Coulomb, consider A → ∞,**

$$B/A = a_v(\rho) - a_a(\rho)\delta^2 \quad , \quad \delta = (N-Z)/A$$

$$a_v \simeq 16\,\mathrm{MeV}$$

$$a_a \simeq 23\,\mathrm{MeV}\,(a_a(\mathrm{vol}) \simeq 30\,\mathrm{MeV})$$

Coef. may depend on the number density ρ
→ Nuclear Matter EOS



Nuclear Matter EOS

- **Energy per nucleon in nuclear matter**

$$E(\rho,\delta)=E_{\mathrm{SNM}}(\rho)+E_{\mathrm{Sym}}(\rho)\delta^2\ ,\quad \delta=(N-Z)/A$$

- **Saturation point (ρ_0, E_0)**

  $\rho_0 \sim 0.15\ \mathrm{fm}^{-3}$

  $E_0 = -a_v \sim -16$ MeV

  (nuclear radius and mass)

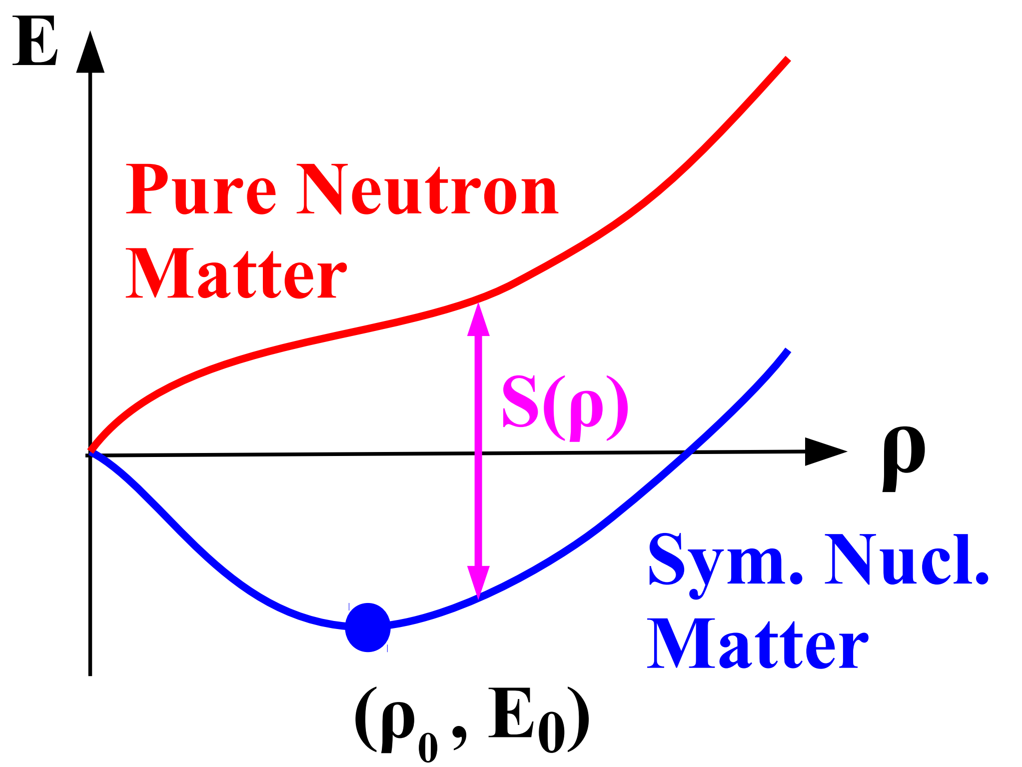
- **Symmetry energy**

  $S(\rho) = E_{\mathrm{PNM}}(\rho) - E_{\mathrm{SNM}}(\rho)$

  $= E(\rho, \delta=1) - E(\rho, \delta=0)$

  $S_0 = S(\rho_0) \sim 30$ MeV

  (mass formula)



Nuclear Matter EOS can be, in principle, determined by terrestrial (laboratory) nuclear physics experiments !

Nuclear Matter EOS

- **Additional two important parameters: K and L**
- **Pressure is given by the derivative of E via ρ**

$$P = \rho^2 (\partial E / \partial \rho)$$

At ρ_0, L determines P

$$P = \rho_0 L / 3 \;(\text{at} \;\; \rho = \rho_0)$$

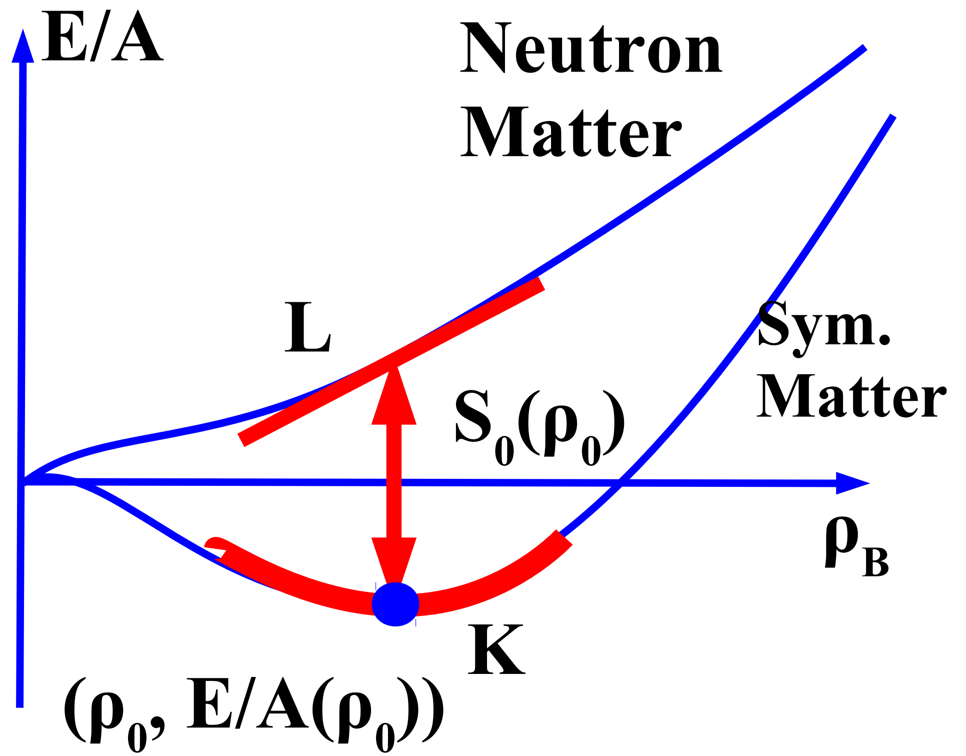
$$E/A(\rho, \delta) = \varepsilon(\rho) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

Symmetric Nuclear Matter

$$\varepsilon(\rho) = \varepsilon(\rho_0) + \frac{K(\rho - \rho_0)^2}{18\rho_0^2} + O((\rho - \rho_0)^3)$$

Symmetry Energy $(\delta = (N - Z)/A = 1 - 2Y_p)$

$$E_{sym}(\rho) = S_0 + \frac{L(\rho - \rho_0)}{3\rho_0} + \frac{K_{sym}(\rho - \rho_0)^2}{18\rho_0^2} + O((\rho - \rho_0)^3)$$



Neutron Star Matter EOS

- **What happens in low-density uniform neutron star matter ?**
  - **Constituents = proton, neutron and electron**
  - **Charge neutrality → # of electons= # of protons ($\rho_e = \rho_p = \rho(1-\delta)/2$)**

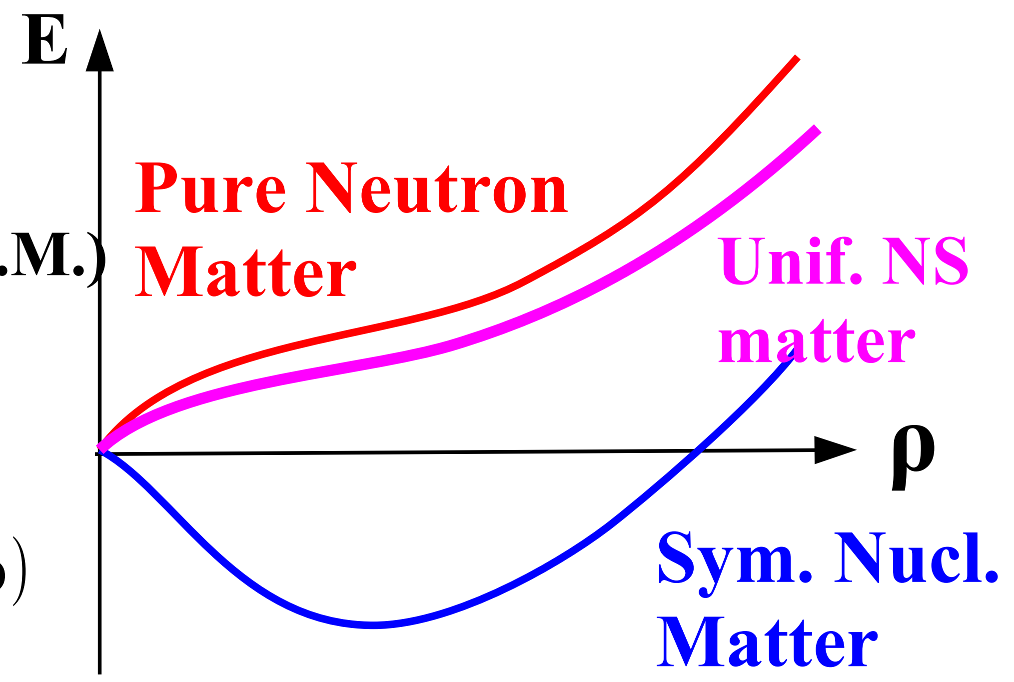
$$E_{\rm NSM}(\rho) = E_{\rm NM}(\rho, \delta) + E_e(\rho_e = \rho_p)$$

$$= E_{\rm SNM}(\rho) + S(\rho)\delta^2 + \frac{\Delta M}{2}\delta + \frac{3}{8}\hbar k_F (1-\delta)^{4/3}$$

(electron mass neglected,
neutron-proton mass diff. incl.
k_F= Fermi wave num. in Sym. N.M.)

  - **δ is optimized to minimize energy per nucleon**

$$E_{\rm NSM}(\rho) \leq E_{\rm NM}(\rho, \delta = 1) = E_{\rm PNM}(\rho)$$



High Density Neutron Star Matter

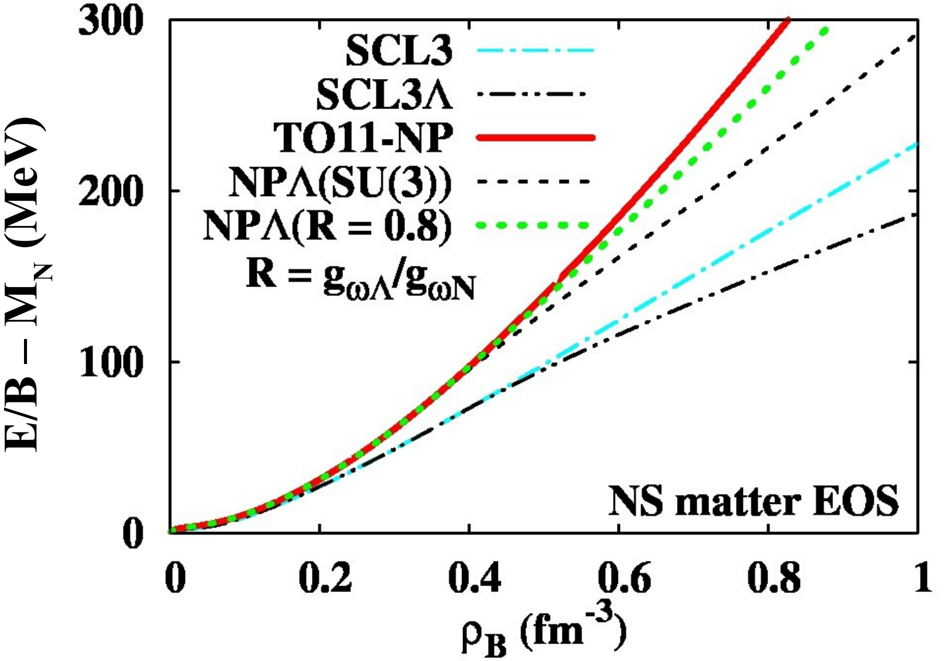
- **Hadrons other than nucleons can admix at high densities.**
  - **Proposed constituents = N, e, μ, π, Y, $\bar{K}$, q, qq**
  - **Conserved charge = Elec. Charge & Baryon number**

$$E_{\rm NSM}(\rho) = E_{\rm HM}(\rho_n, \rho_p, \rho_\Lambda, ...) + E_e(\rho_e) + E_\mu(\rho_\mu)$$

$$\rho = \rho_B = \sum_{i \in B} \rho_i \quad , \quad \rho_Q = \sum_i Q_i \rho_i$$

$$\rightarrow \mu_i = B_i \mu_B - Q_i \mu_e$$

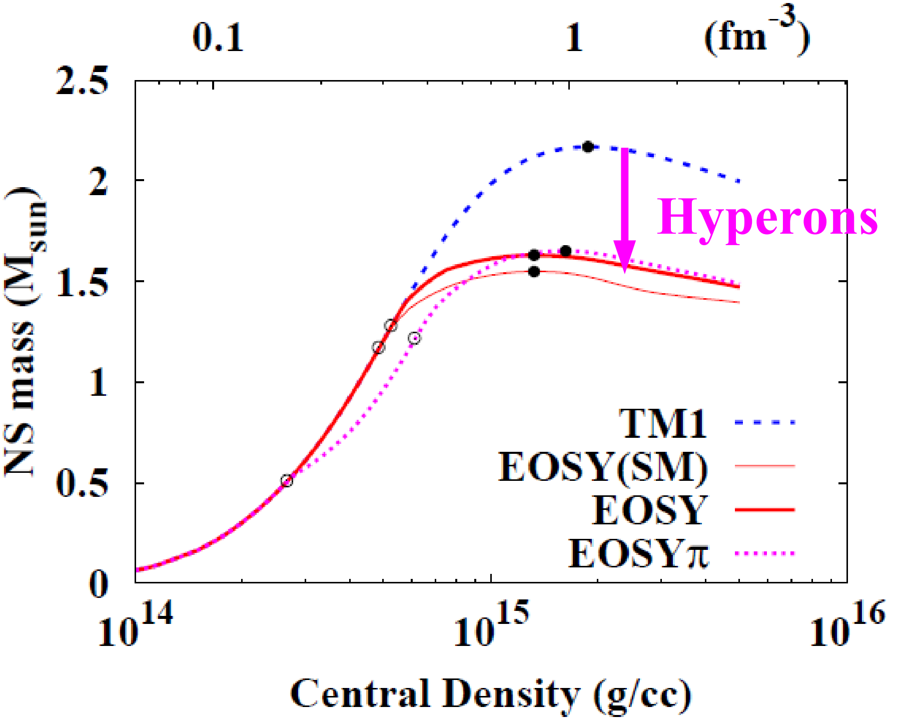
Negative charged baryons are favored.



  - **Each particle fraction is determined to minimize Energy per Baryon**
    → Softening of NS matter EOS

Common Understanding of Neutron Star Matter (<2010)

- **Neutron star crust ($\rho < \rho_0/2 \sim 10^{14}$ g/cc, 1-1.5 km)**
  - **Made of nuclei, free nucleons and electrons. We may have pasta nuclei in the inner crust.**
- **Outer core ($\rho_0/2 < \rho < 2\rho_0$)**
  - **Made of nucleons and leptons. Nucleons are in superfluid.**
- **Inner core ($\rho > 2\rho_0$)**
  - **Constituents are unknown.**
  - **Many calculations suggest hyperon admixture starting at $\rho = (2\text{-}4)\,\rho_0$, and EOS is softened.**
  - **$\overline{K}$ or quarks may appear at $\rho > 3\,\rho_0$.**

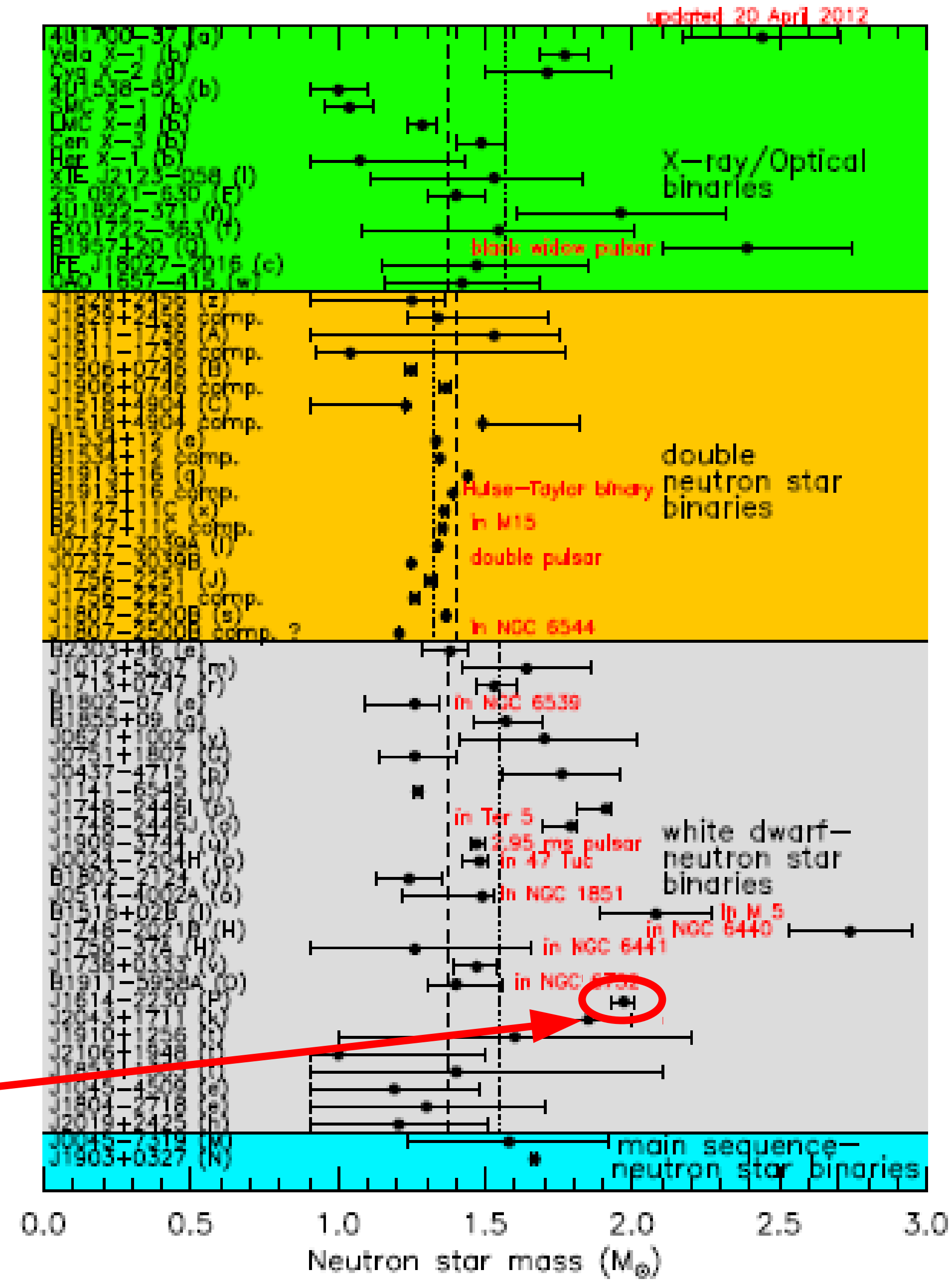


Ishizuka et al. (2008)

Neutron Star Masses

- Many NSs have masses $\sim 1.4\ M_\odot$.
- Massive NS masses had large error bars, and were considered not to be conclusive (before 2010).
- Discovery of massive neutron star, $M = 1.97\ M_\odot$.

This is it !

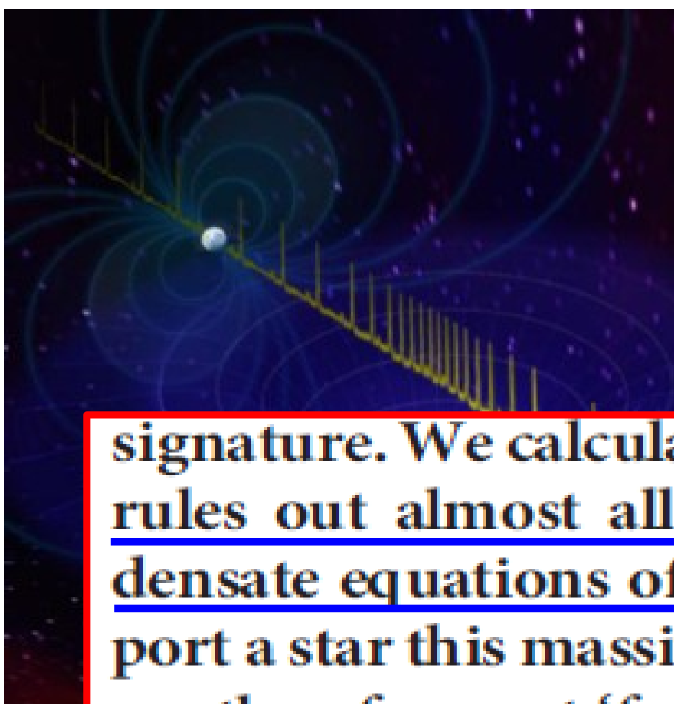


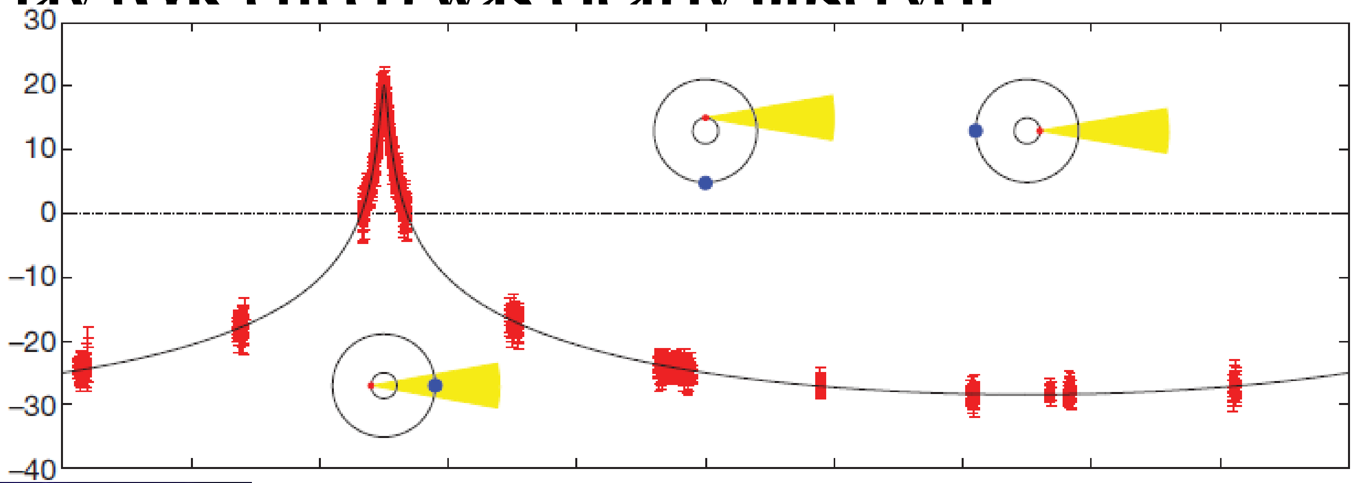
Lattimer (2013)

Neutron Stars Puzzles

Massive Neutron Star "Shock" (2010)

- **Big news in 2010 autumn**
  - **A neutron star is found to have the mass of 1.97 ± 0.04 $M_\odot$"**
    Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).
  - **Based on "kinetic" observable**
    - **Photon from the pulsar passes near the companion white dwarf, and Shapiro delay (GR effect) was clearly observed**

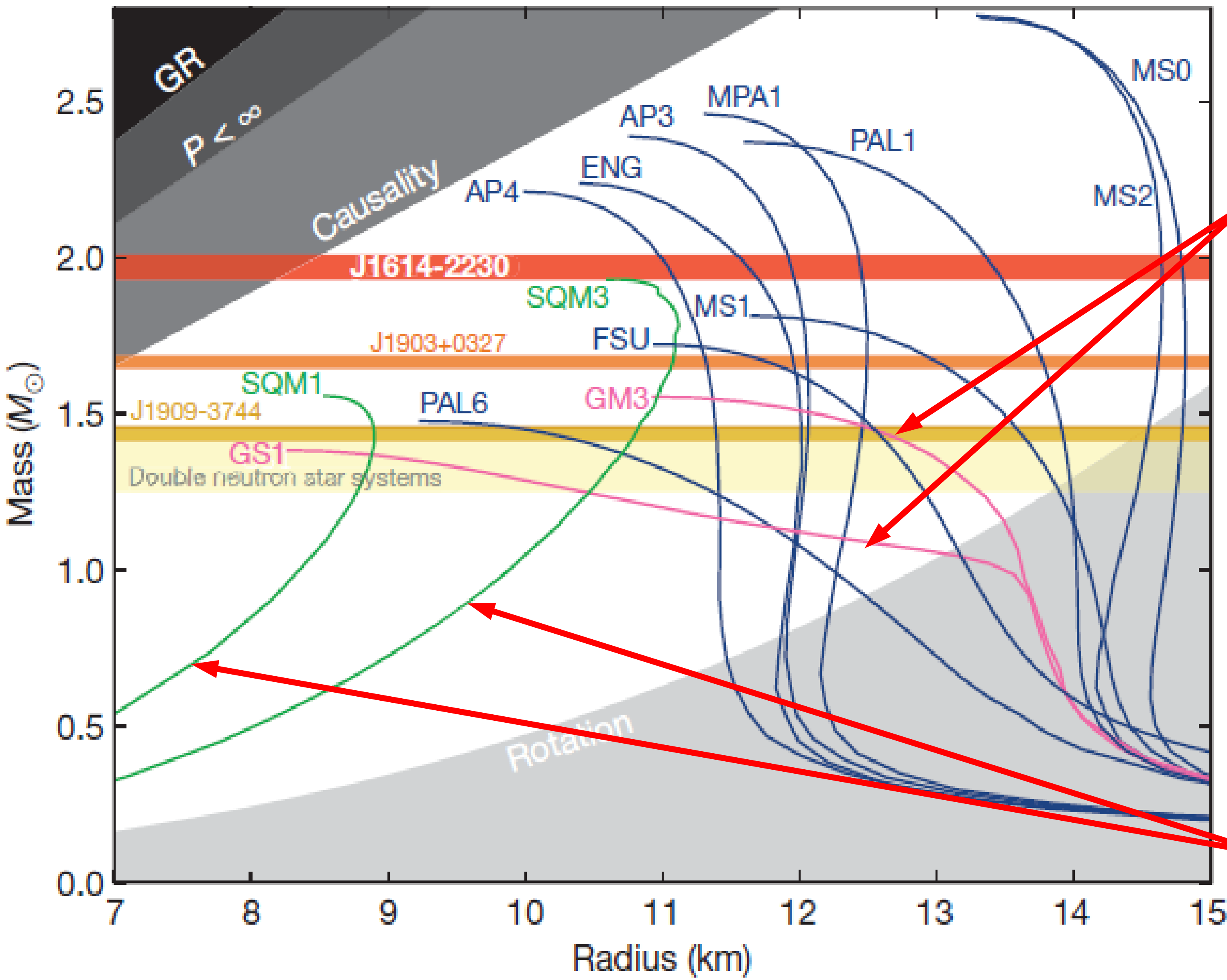




signature. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_\odot$, which rules out almost all currently proposed[2–5] hyperon or boson condensate equations of state ($M_\odot$, solar mass). Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not 'free' quarks[12].

$1.97 \pm 0.04\ M_{\odot}$ Neutron Star

Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).

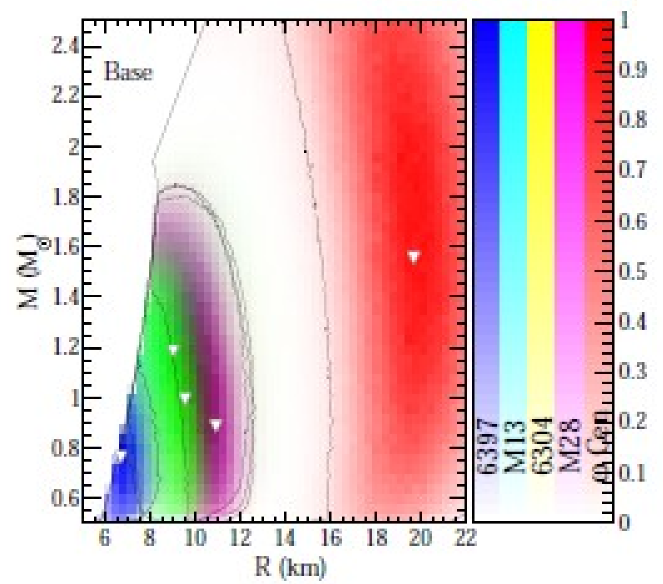


EOS with hyperons or Kaons

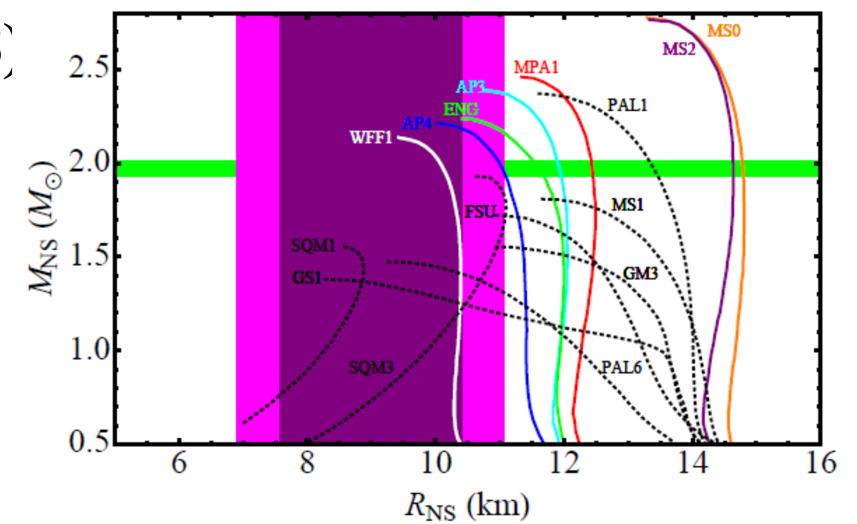
Quark matter EOS

Compact Neutron Star "Shock" (2013)

- **Compact NS "Puzzle"**
  Guillot et al. (2013); Lattimer, Steiner (2013).
  - **Markov-Chain MC fit of X-ray spectrum**
    Baysian analysis
    from quiescent Low Mass X-ray Binaries (qLMXB)
  - **Guillot+ (2013) results**
    $R_{NS} = 9.1^{+1.3}_{-1.4}$ **km**
    → Most of proposed EOSs are ruled out.
    WFF: Wiringa, Fiks, Fabrocini (1988)



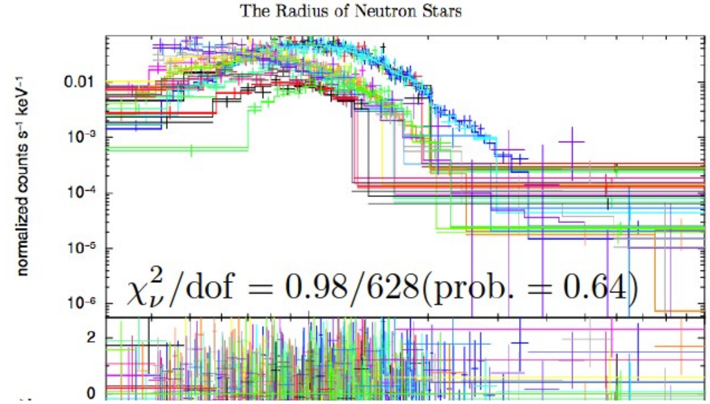
Lattimer, Steiner (2013).

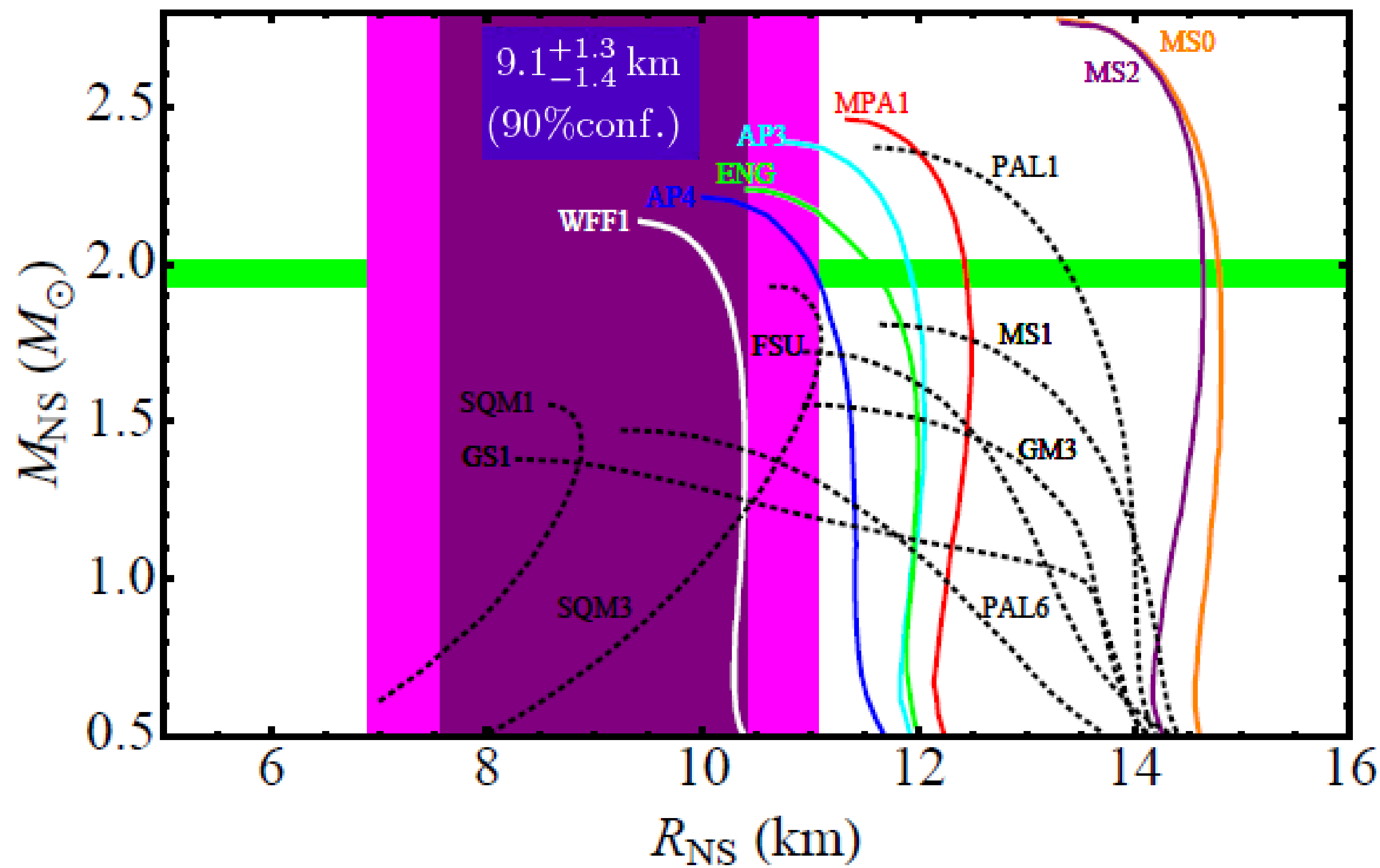


Guillot et al. (2013)

Guillot et al. (2013)

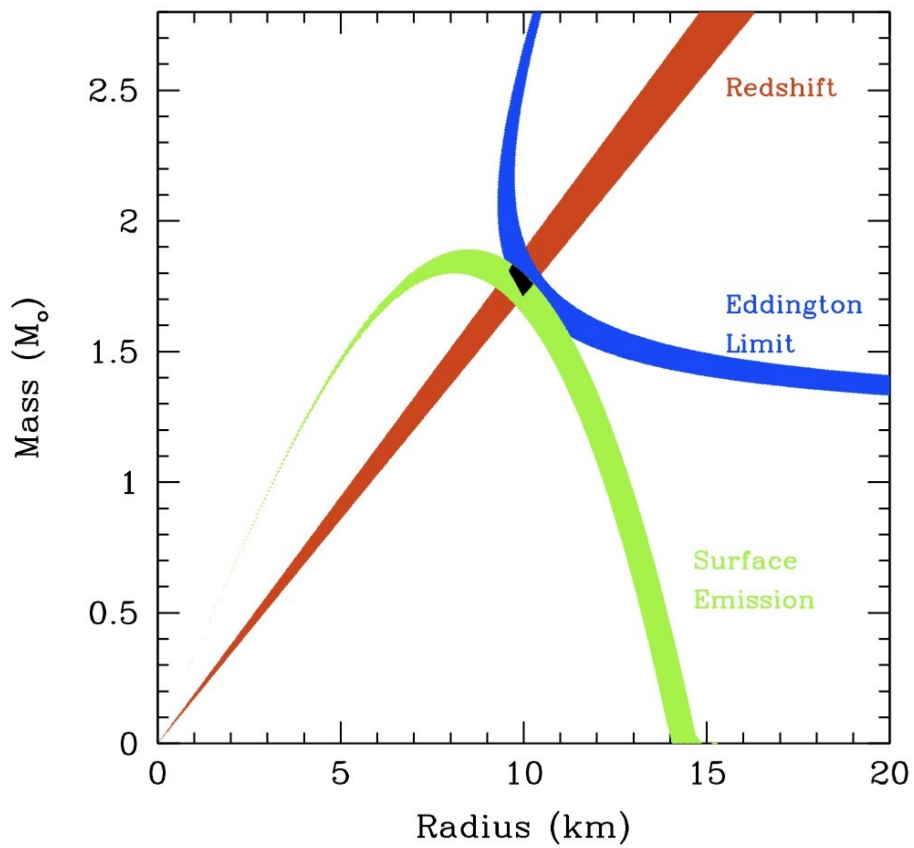
- **Assumptions**
  - **H atmosphere neutron stars.**
  - **Low B-field (<10^{10} G) neutron stars.**
  - **Emitting isotropically.**

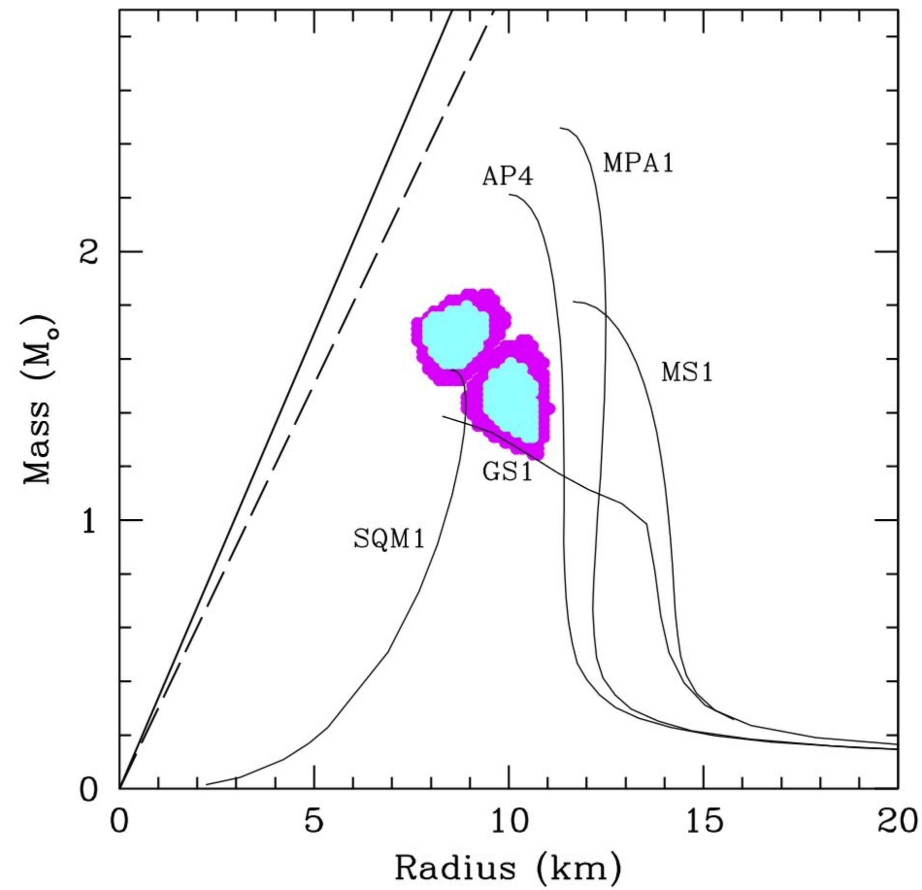




Özel et al. 2009

- **Photospheric radius expansion (PRE) burst (EXO 1745-248)**
  - $z_{ph} = z_{NS}$, **black-body radiation**
  - **(M, R)=(1.4 $M_\odot$, 11 km) or (1.7 $M_\odot$, 9 km)**

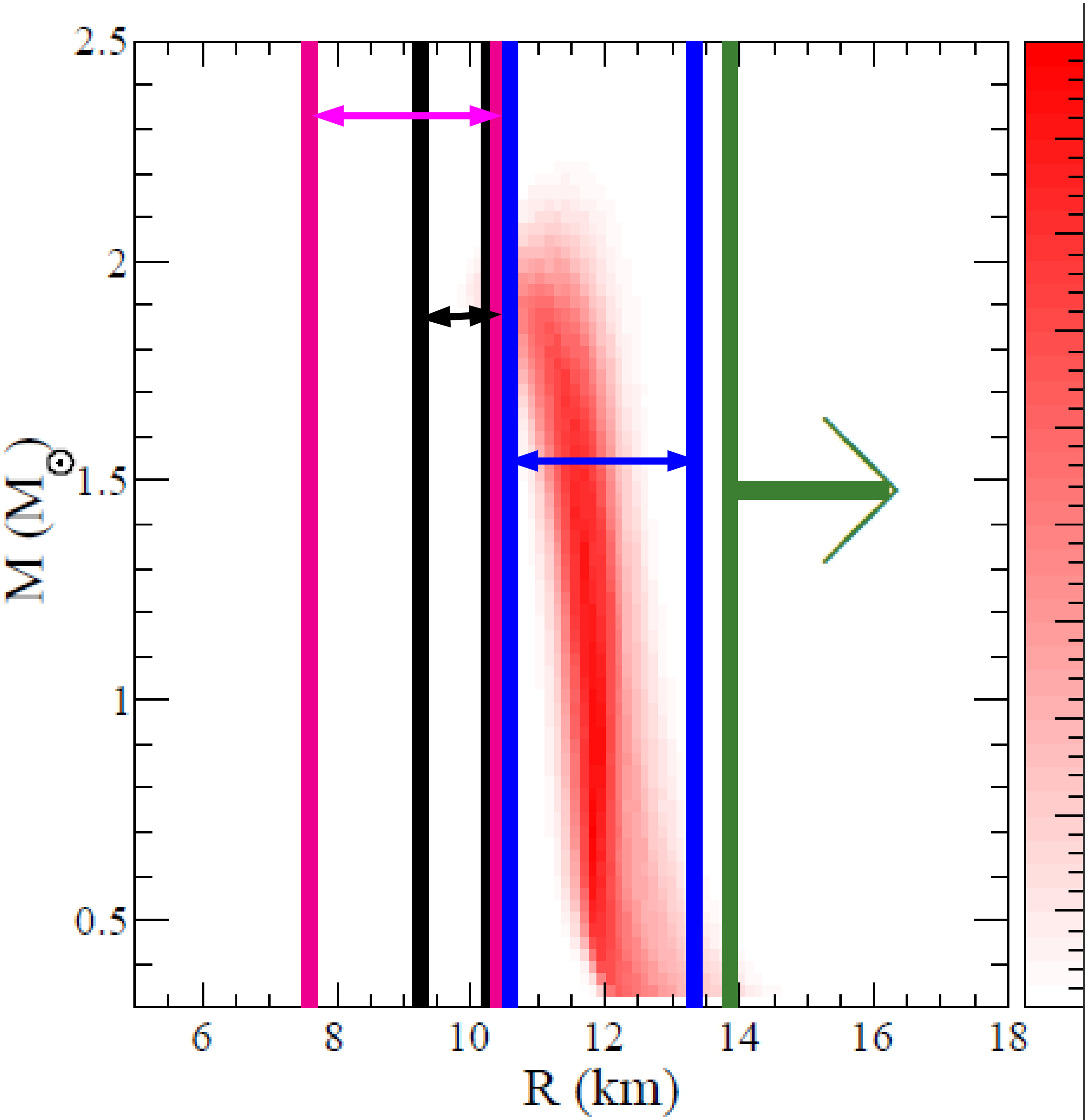




Özel et al. 2009, ApJ, 693, 1775

But the game is not over...

- Ozel et al., PRE bursts z_{ph} =z
  R = 9.74 ± 0.50 km.
- Suleimanov et al.,
  long PRE bursts
  $R_{1.4}$ > 13.9 km
- Guillot et al. (2013),
  the same radius for all NS,
  self NH
  R = 9.1+1.3-1.5 km.
- Lattimer & Steiner (2013),
  TOV, crust EOS, causality,
  maximum mass > 2M,
  z_{ph} = z, alt NH.
- Lattimer & Lim (2013),
  nuclear experiments
  29 MeV < Sv < 33 MeV,
  40 MeV < L < 65 MeV,
  $R_{1.4}$ = 12.0 ± 1.4 km.



R still depends on the analysis

Massive and Compact Neutron Star Puzzles

- **Puzzle 1:**
  Massive (~ 2 $M_\odot$) NS cannot be supported by "standard" EOS with hyperons or kaons, while theoretical model calculations based on laboratory hypernuclear physics experiments predict hyperon appearance.
  → Something is wrong !

- **Puzzle 2:**
  X-ray spectra from qLMXB may imply neutron star masses around 9 km, while most of theoretical model calculations based on laboratory normal and neutron-rich nuclear physics experiments predict neutron star radius above 11 km.
  → Something is wrong !

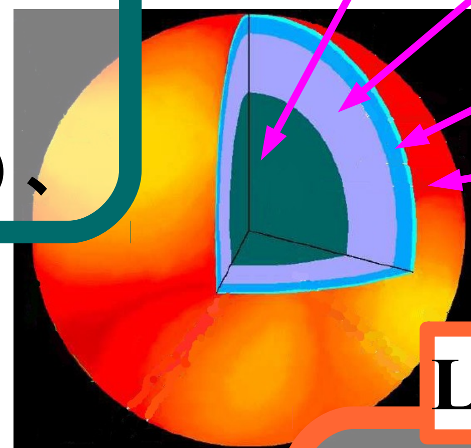
We need studies of neutron star matter EOS cooperated by Strangeness Nuclear Physics, Neutron-rich Nuclear Physics, Astronomical Observations, and Theories.

Grant-in-Aid Study on Neutron Star Matter

High ρ (Group A)

Hypernuclei, Kaonic nuclei
YN & YY int.,
Eff. Interaction
(Heavy-ion collisions)

J-PARC



Hyperons, mesons, quarks

Asym. nuclear matter +elec.+μ

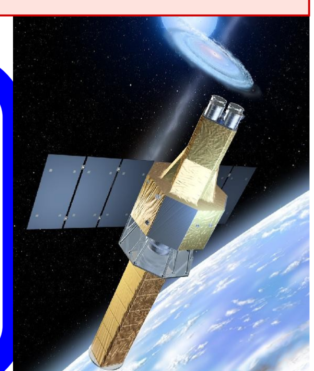
Nuclei+neutron gas+elec.

Nuclei + elec.

Low ρ (Group B)

Sym. E, Pairing gap,
BEC-BEC cross over,
Cold atom, Unitary gas

ASTRO-H



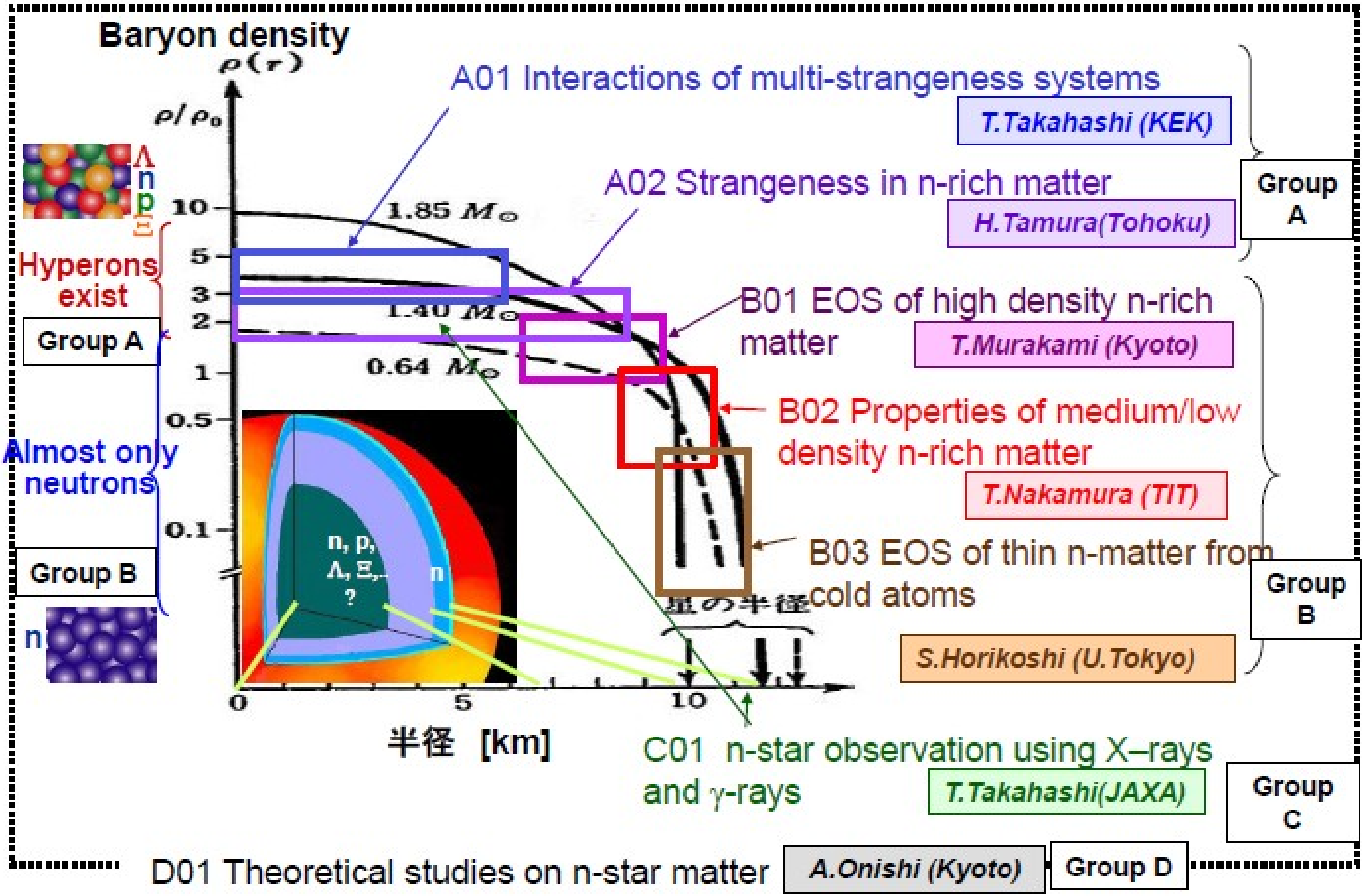
NS Obs. (Group C)

Radius, Mass,
Temp. (Cooling),
Star quake, Pasta

RIBF

Theory (Group D)

Groups and research subjects

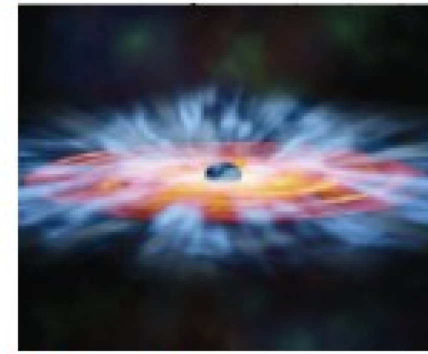


By Tadayuki Takahashi (C1)

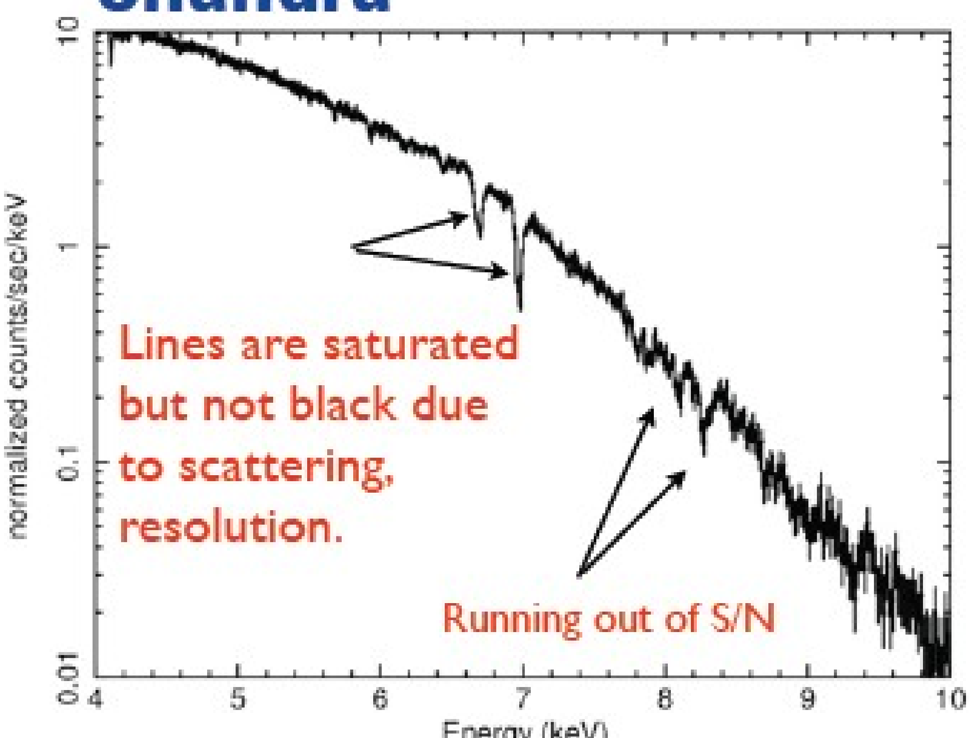
6. ASTRO-H Features --- High Resolution Spectroscopy ---

GRO J1655-40

The superior resolution of SXS in the Fe K band enables the unambiguous detection of weak and narrow lines from a wind.

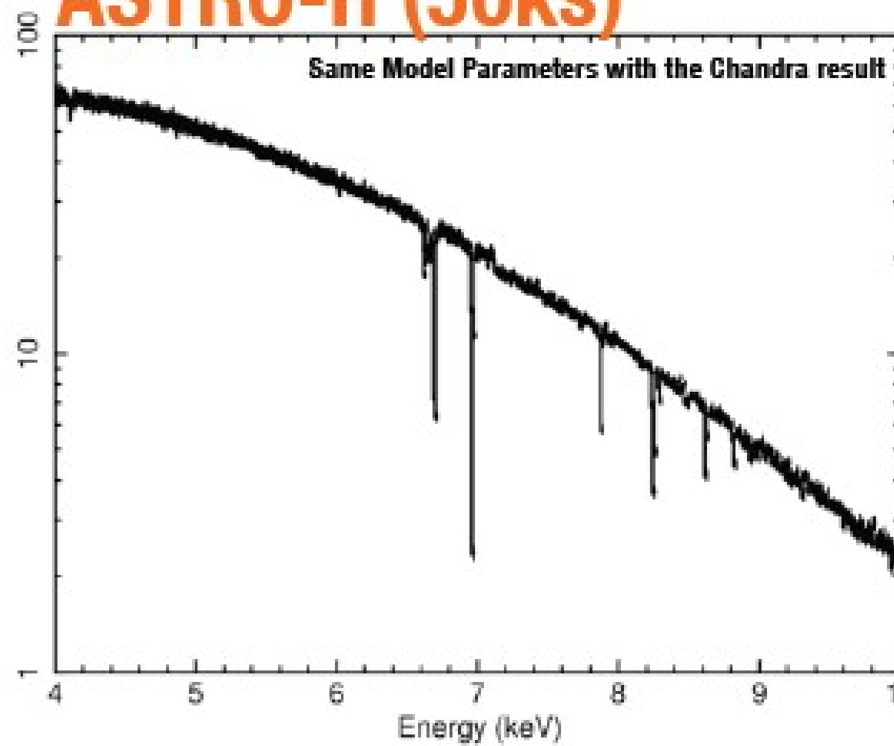


Chandra



(Simulation by J. Miller)

ASTRO-H (50ks)



ASTRO-H SXS can handle 250 cts/s

Summary of Lecture 1

- **Neutron Stars are**
  - **giant neutron-rich nuclei,**
  - **may have exotic constituents,**
  - **and have provided evidence of GR.**
- **We are in a stage where nuclear physics and astrophysics have to discuss seriously to understand neutron star matter EOS.**

Thank you !