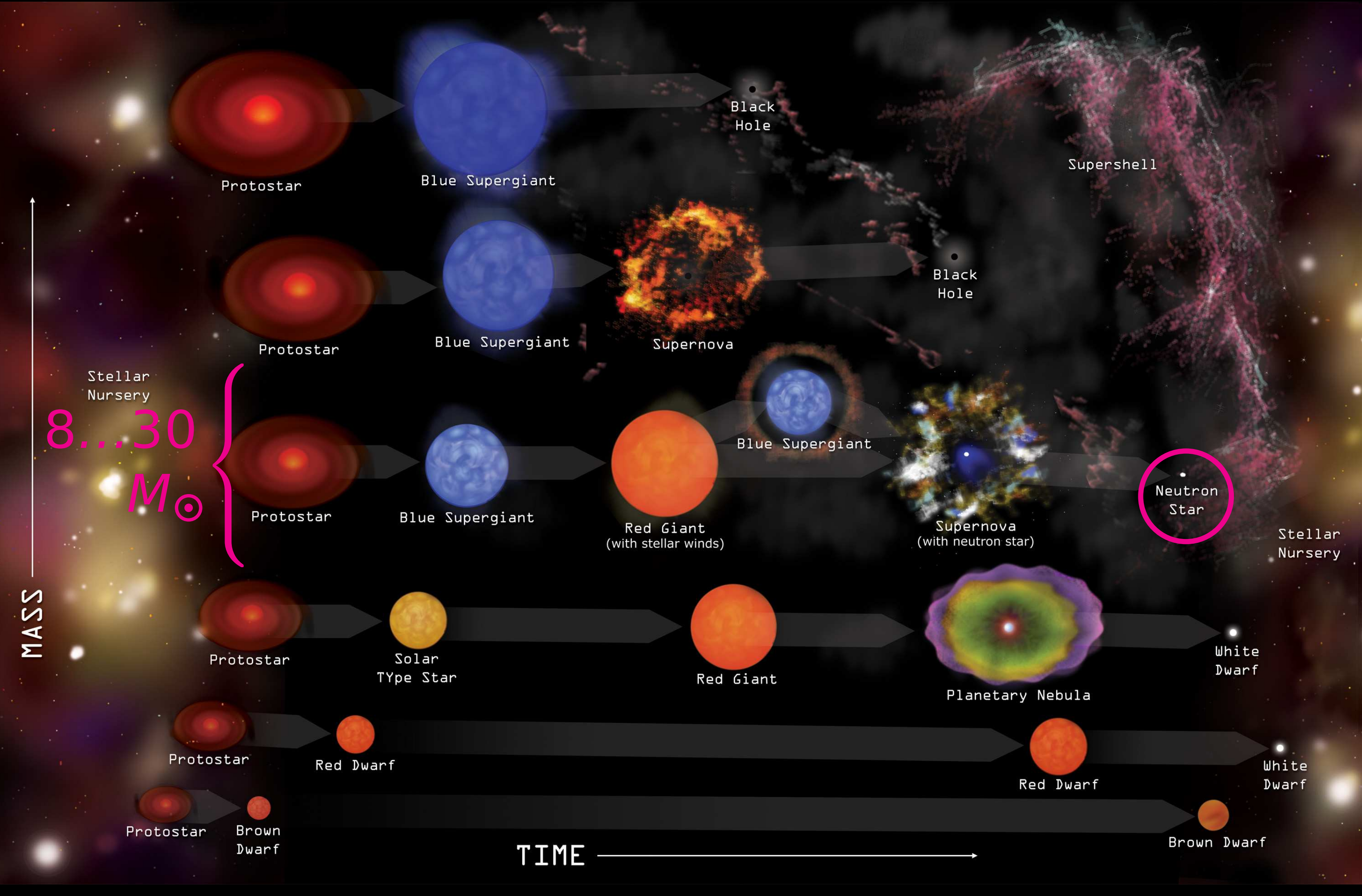
Strange Neutron Stars

M. Baldo & G.F. Burgio & H. Chen & U. Lombardo & H.-J. S. : Catania
T. Maruyama & S. Chiba & T. Tatsumi & N. Yasutake : Japan
A. Li & Z.H. Li & H.Q. Song & X.R. Zhou & W. Zuo : China
A. Polls & A. Ramos & I. Vidaña : Barcelona
M. Buballa & M. Oertel : Darmstadt
J. Cugnon & A. Lejeune : Liège
V. Ferrari & L. Gualtieri : Rome
F. Weber : San Diego
T. Rijken : Nijmegen

- BHF approach of hypernuclear matter
- Hypernuclei
- Neutron star properties
- Quark matter and hybrid stars

PRC 61, 055801 (2000)
PRC 64, 044301 (2001)
PRC 66, 025802 (2002)
PLB 562, 153 (2003)
A&A 408, 675 (2003)
PRC 69, 018801 (2004)
PRD 70, 043010 (2004)
A&A 451, 213 (2006)
PRC 73, 058801 (2006)
PRC 74, 047304 (2006)
PRD 74, 123001 (2006)
PRD 76, 123015 (2007)
PRC 77, 034316 (2008)
PRC 78, 028801 (2008)
A&A 518, A17 (2010)
PRC 83, 025804 (2011)
PRC 84, 035801 (2011)
PRD 84, 044017 (2011)
PRD 84, 105023 (2011)
PRD 86, 045006 (2012)
A&A 551, A13 (2013)
PRC 88, 024322 (2013)

http://chandra.harvard.edu



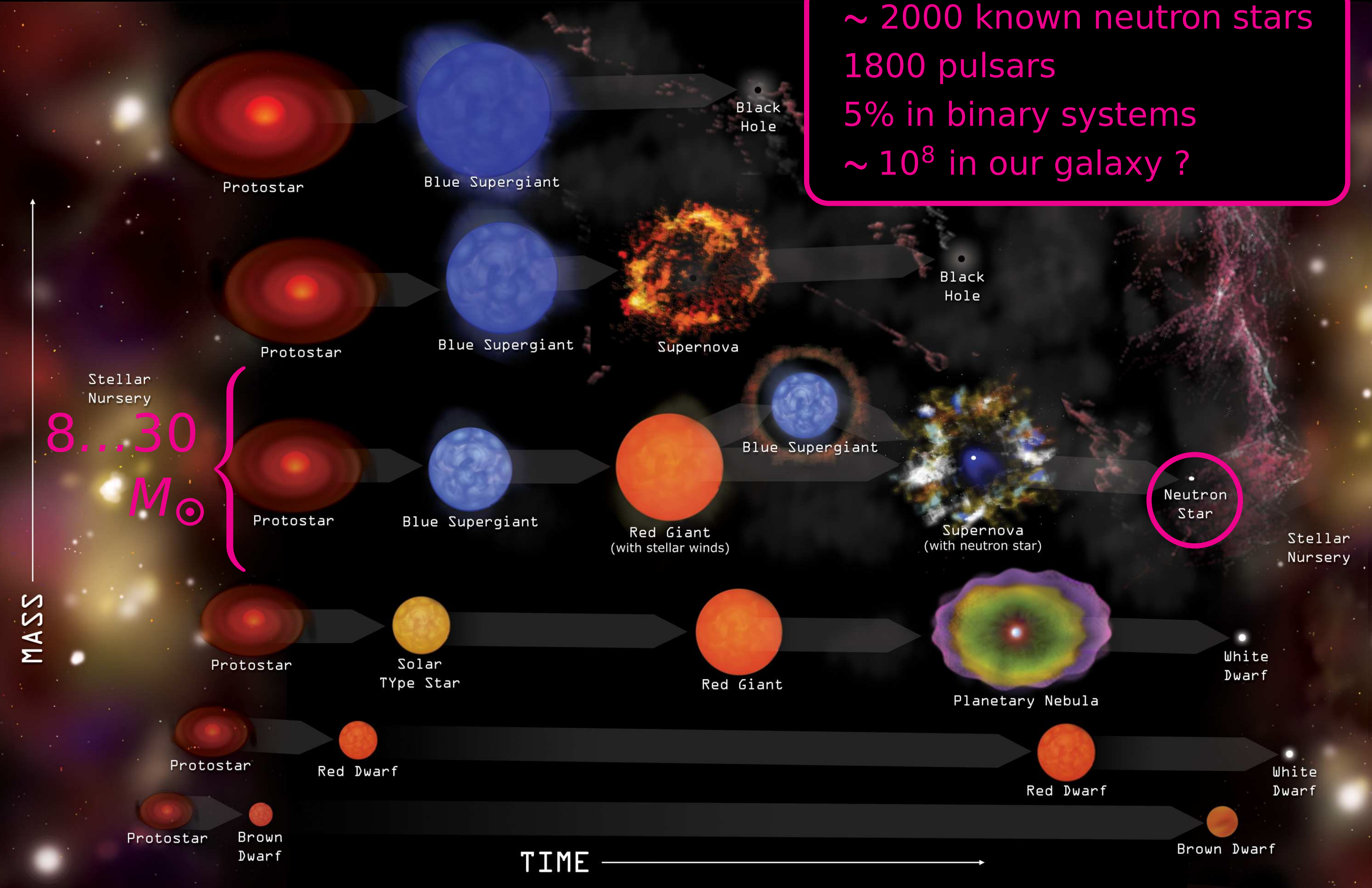
http://chandra.harvard.edu

~ 2000 known neutron stars

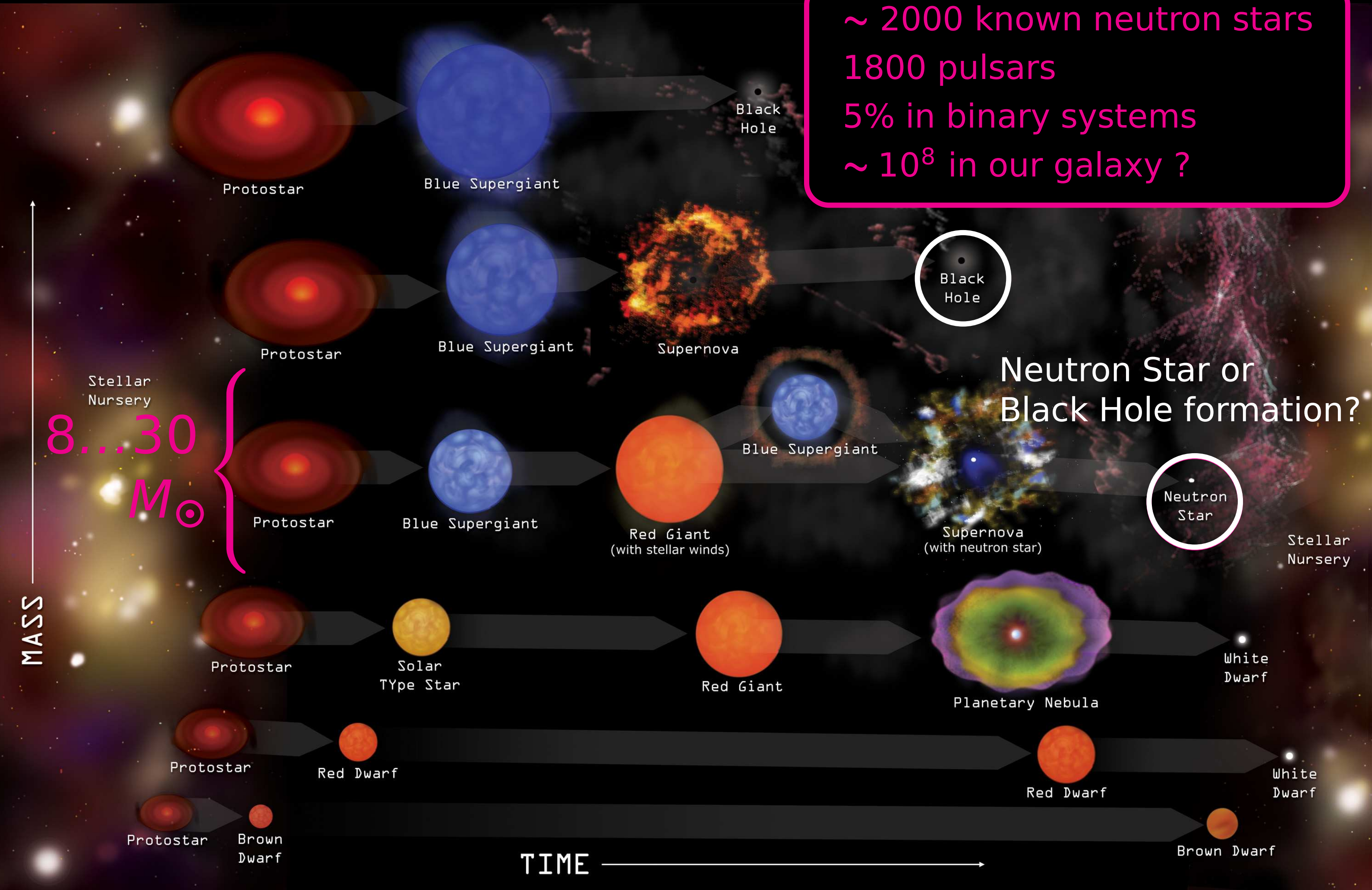
1800 pulsars

5% in binary systems

~ 10^8 in our galaxy ?



http://chandra.harvard.edu



- ~ 2000 known neutron stars
- 1800 pulsars
- 5% in binary systems
- ~ 10^8 in our galaxy ?

Neutron Star or Black Hole formation?

$8 \ldots 30\ M_\odot$

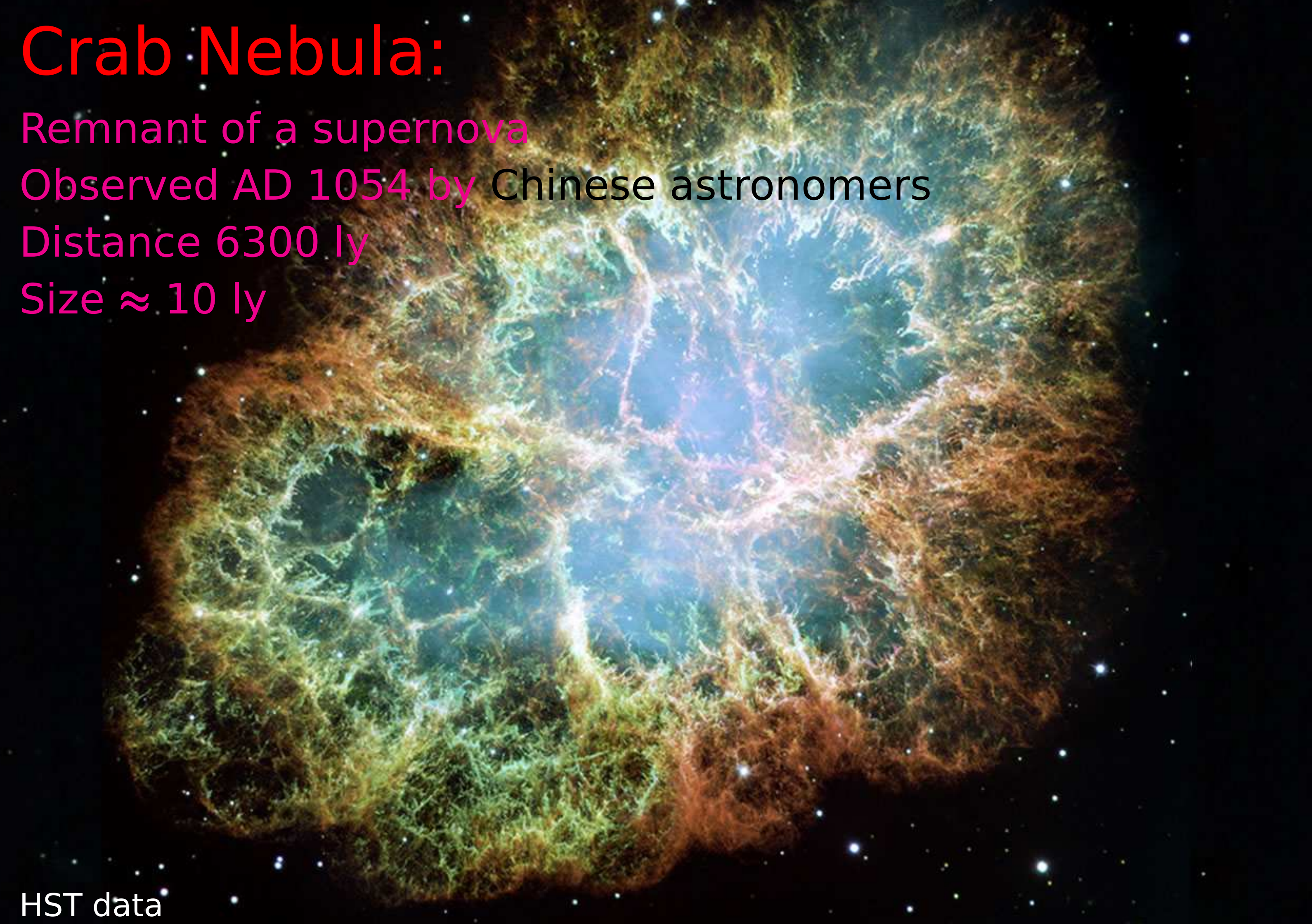
Crab Nebula:

Remnant of a supernova

Observed AD 1054 by Chinese astronomers

Distance 6300 ly

Size ≈ 10 ly



HST data

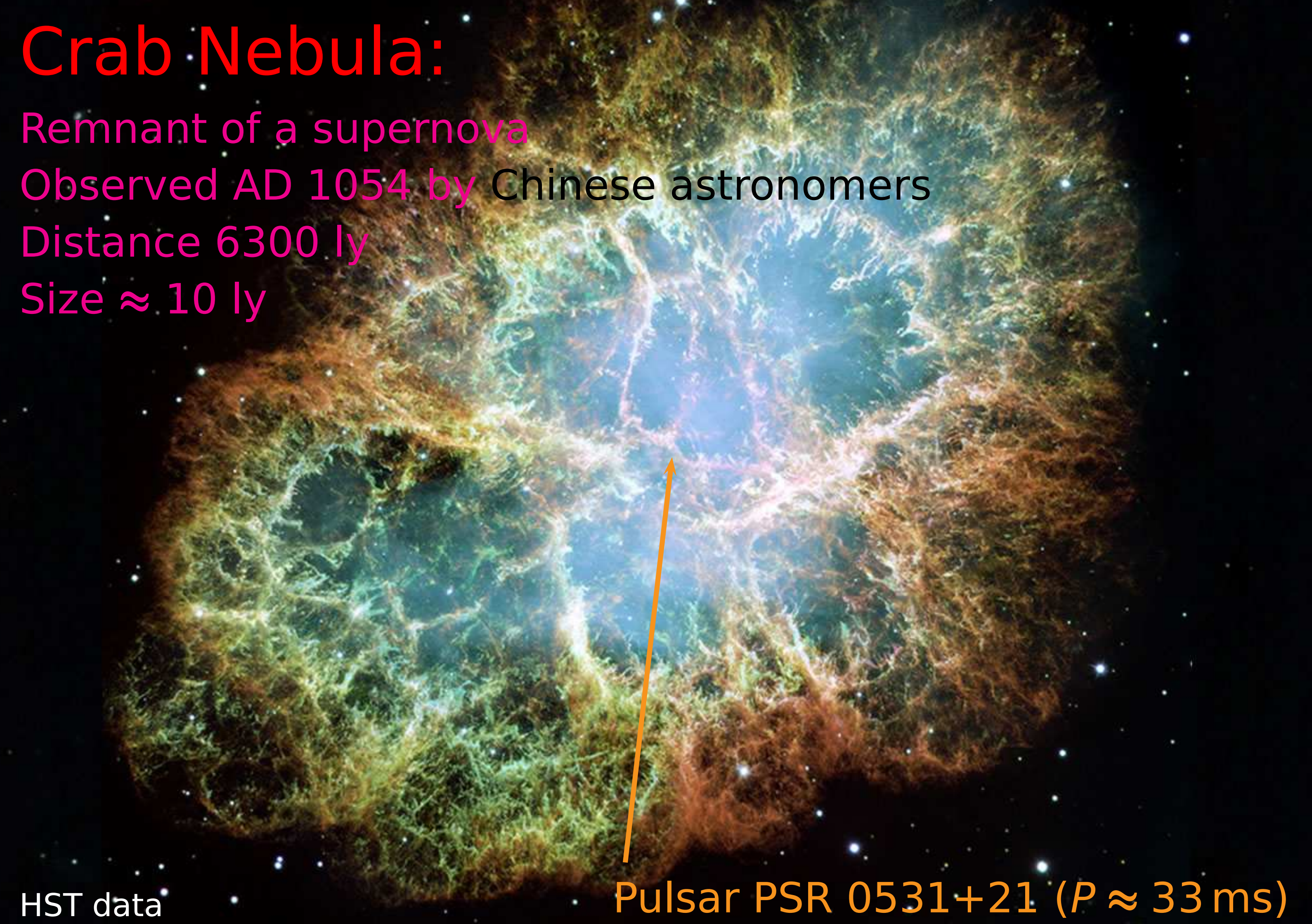
Crab Nebula:

Remnant of a supernova

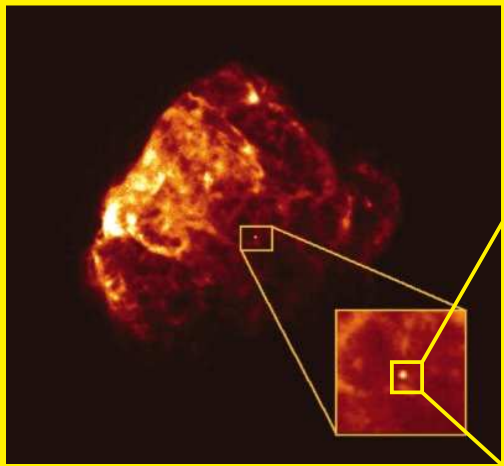
Observed AD 1054 by Chinese astronomers

Distance 6300 ly

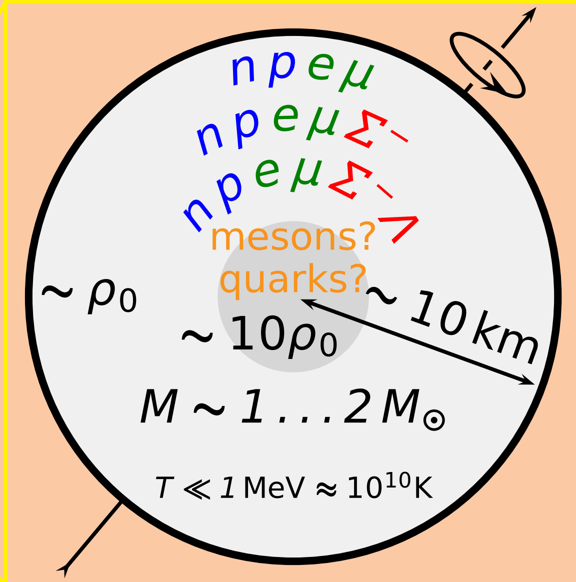
Size ≈ 10 ly



Neutron Star Structure from Brueckner Theory:



ROSAT image of *Puppis A*



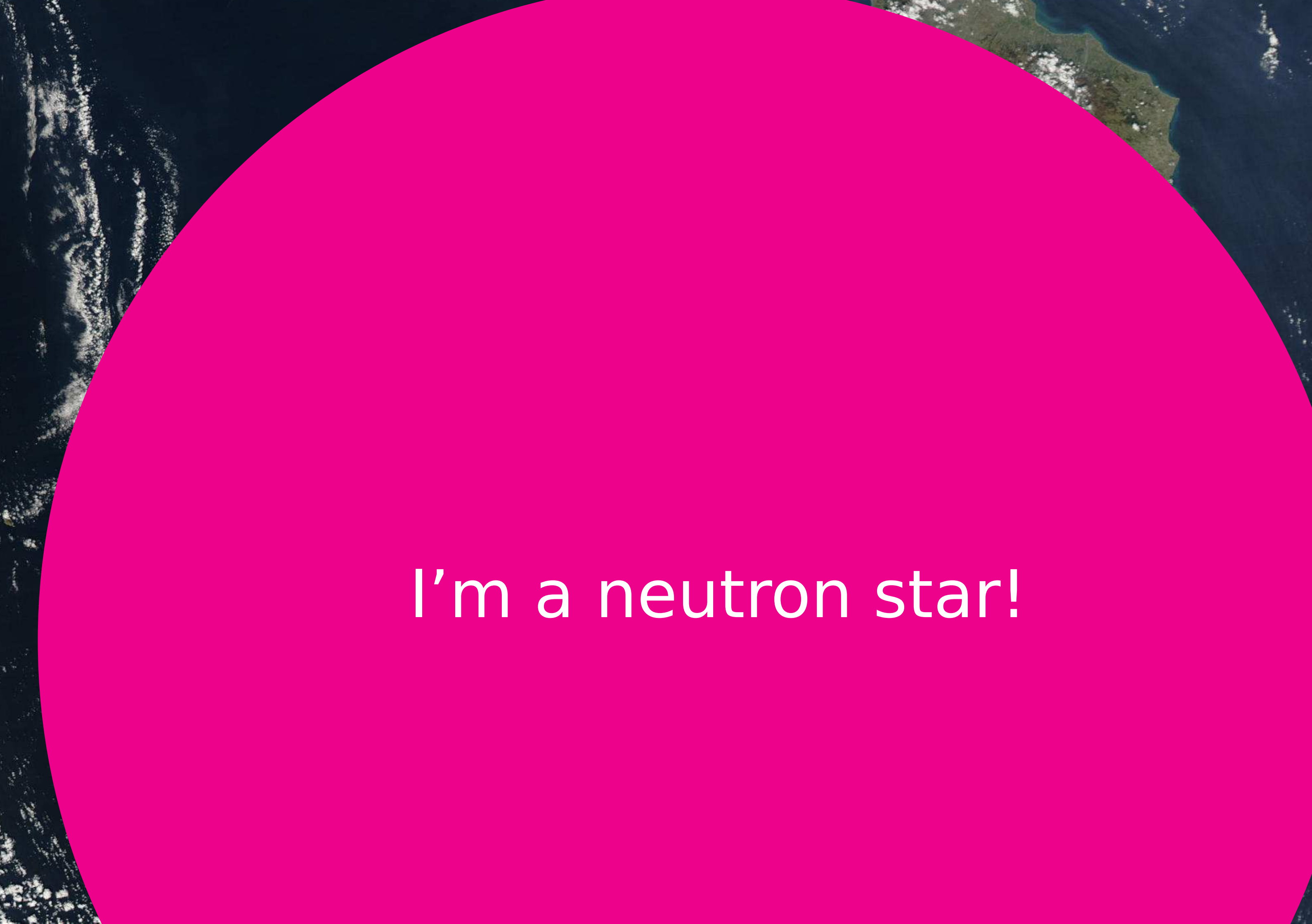
↪ The only "laboratory" for $\rho_B \sim 10\rho_0$ in the Universe !

Need EOS of nuclear matter including hyperons

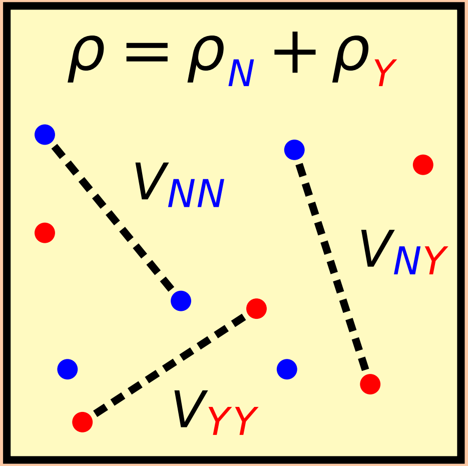

Catania


Catania


Etna Volcano
Catania


I’m a neutron star!

Hypernuclear Matter:



$N = qqq$: n, p (939 MeV)

$Y = qqs$: Λ^0 (1116 MeV), Σ^{+0-} (1193 MeV)

V_{NN} : Argonne, Bonn, Paris, ...

V_{NY} : Nijmegen (NSC89, NSC97, ...)

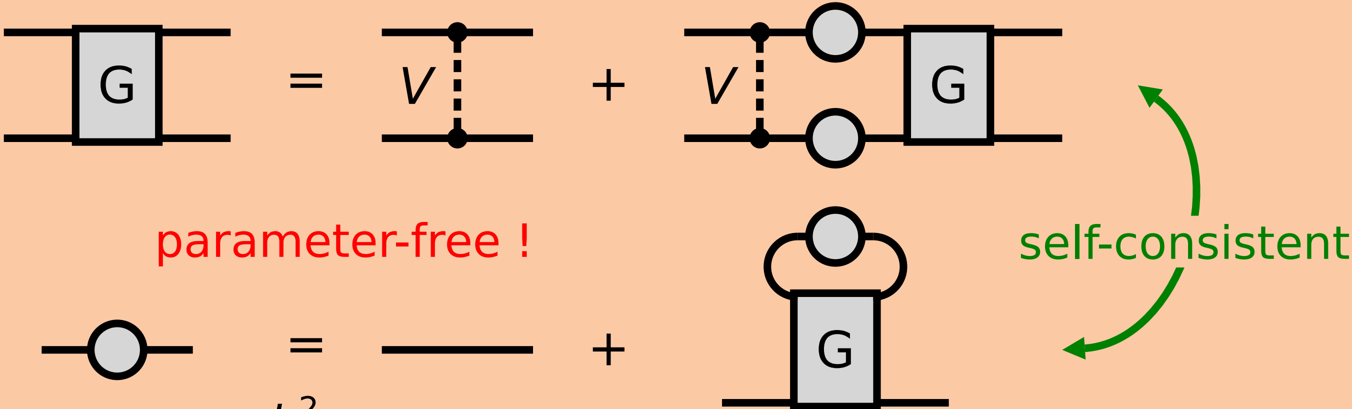
V_{YY} : ? (no scattering data)

In free space weak decay: $Y \to N + \pi$ etc. ($c\tau \approx 8$ cm)

In dense nucleonic medium the decay is Pauli-blocked !

Brueckner Theory of Nuclear Matter:

- Effective in-medium interaction G from potential V:



$$e_k = m + \frac{k^2}{2m} + U(k)$$

Results: binding energy $\epsilon(\rho_n, \rho_p, \rho_\Lambda, \rho_\Sigma) = \sum_i \sum_{k<k_F^{(i)}} \left[e_k^{(i)} - \frac{U_i(k)}{2} \right]$

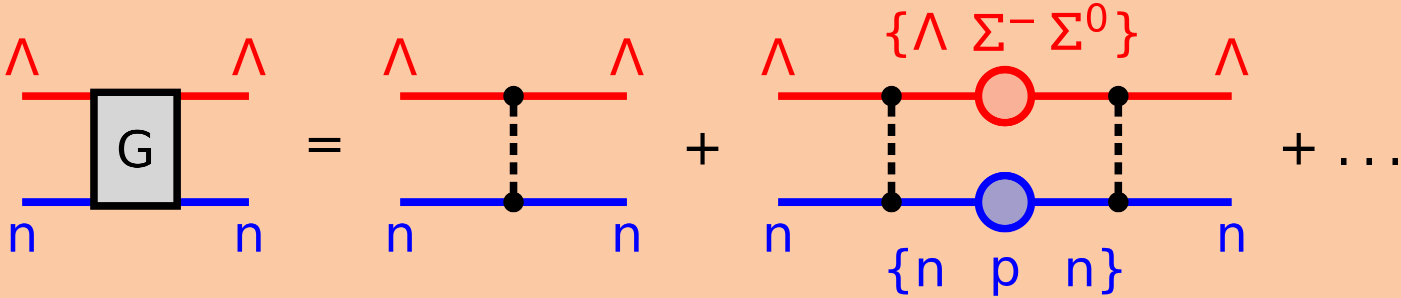
s.p. properties, cross sections, ...

K.A. Brueckner and J.L. Gammel; PR 109, 1023 (1958) for nuclear matter

Extension to hypernuclear matter ...

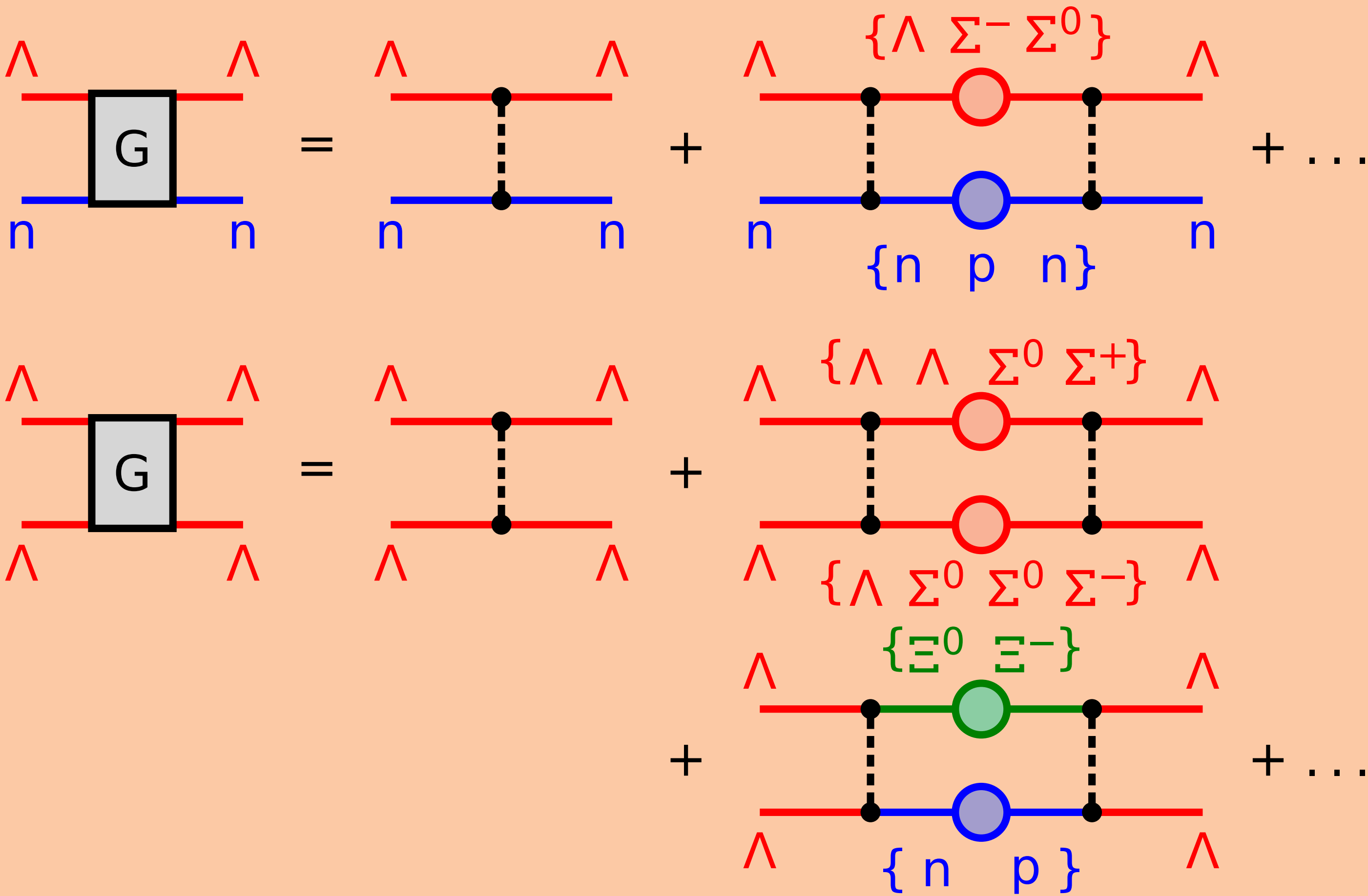
Include Hyperons:

- Technical difficulty: coupled channels:



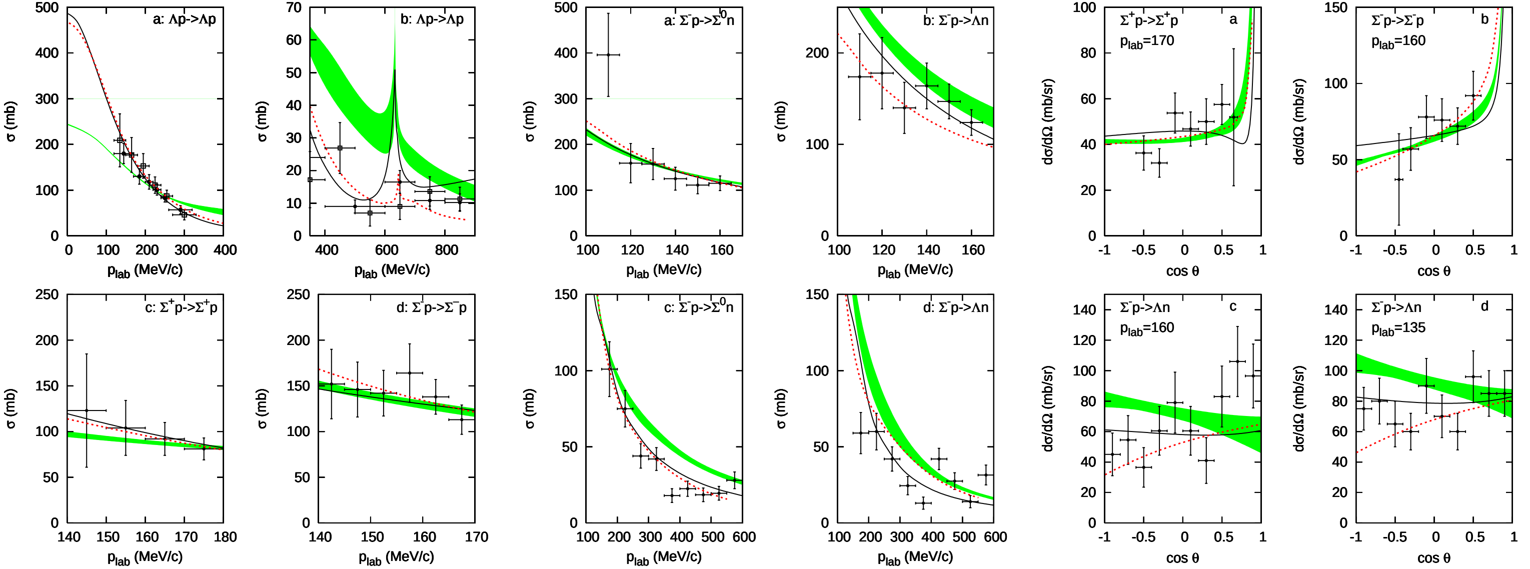
Include Hyperons:

- Technical difficulty: coupled channels:



NY Cross Section Data:

Polinder & Haidenbauer & Meissner, NPA 779, 244 (2006)



— NSC97f — Jülich04 — EFT LO

Data from the 1960's !

➥ Need more and better data

Lambda Hypernuclear Chart:

PTEP **2012**, 02B012 H. Tamura

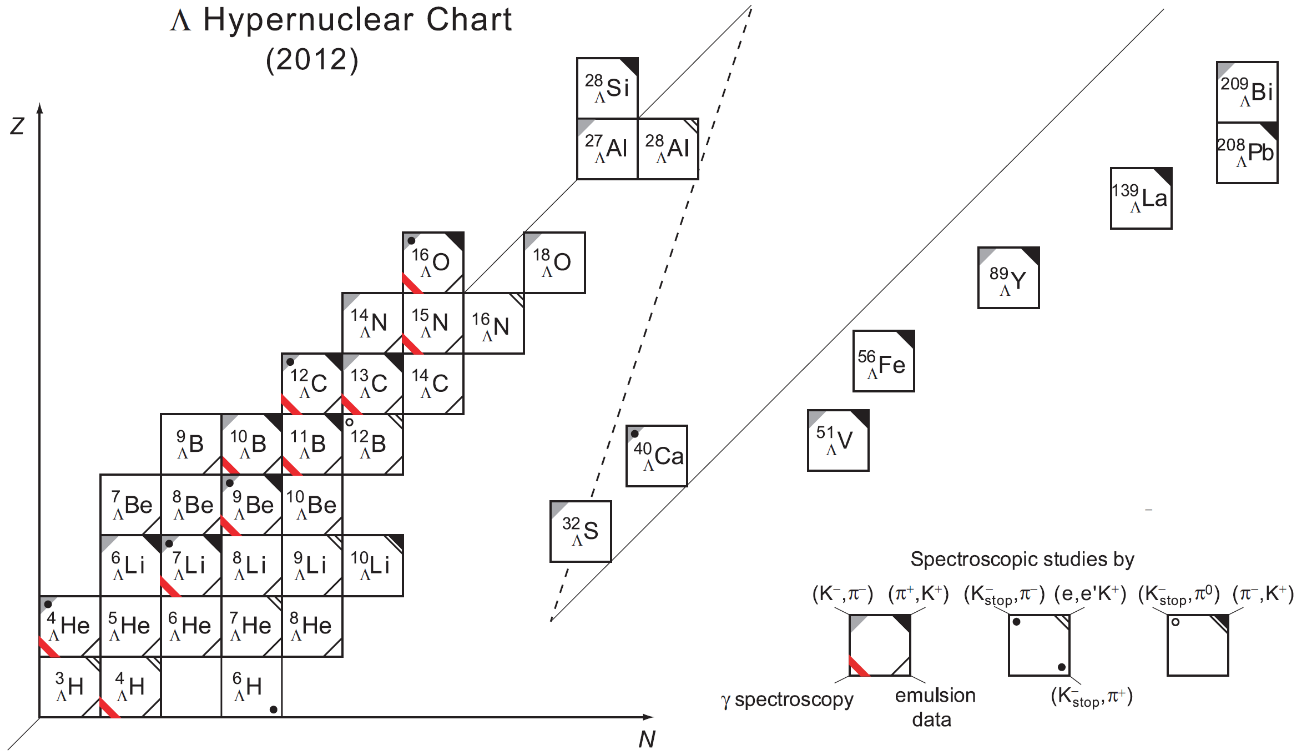


Fig. 2. Λ hypernuclear chart as of 2012.

Lambda Hypernuclear Chart:

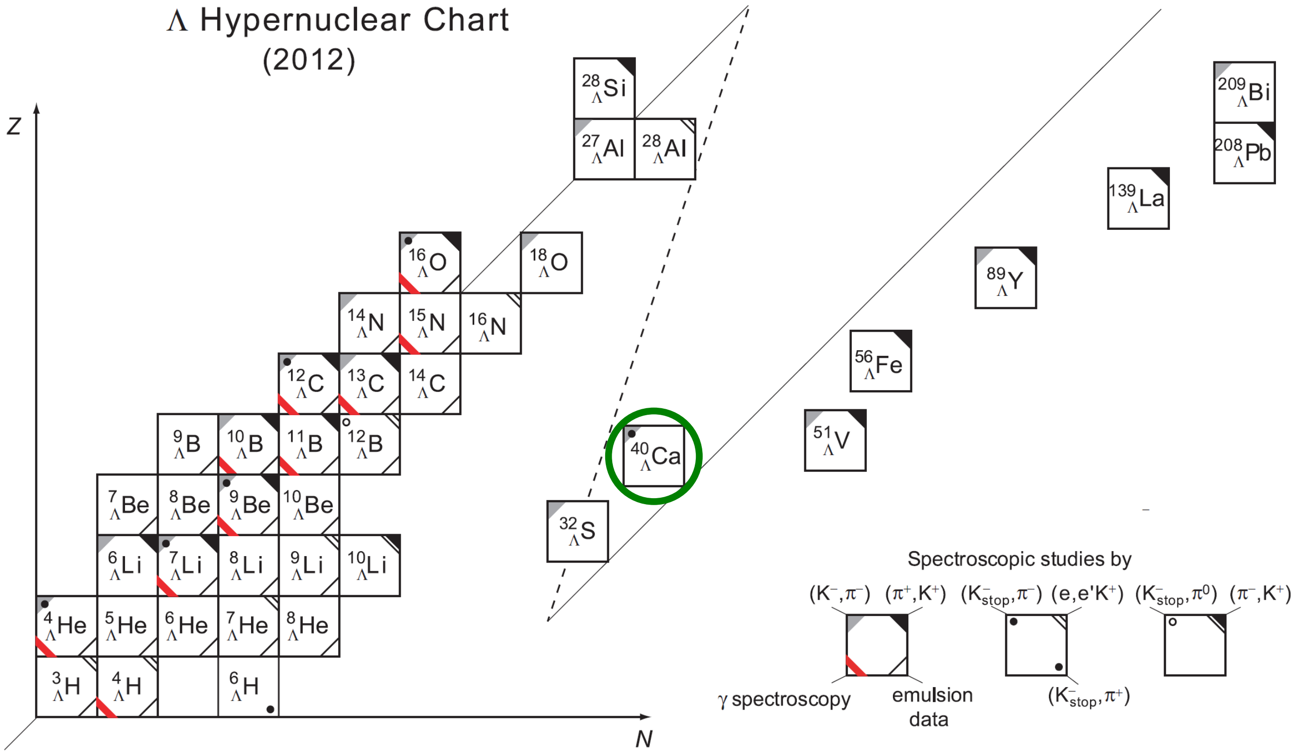
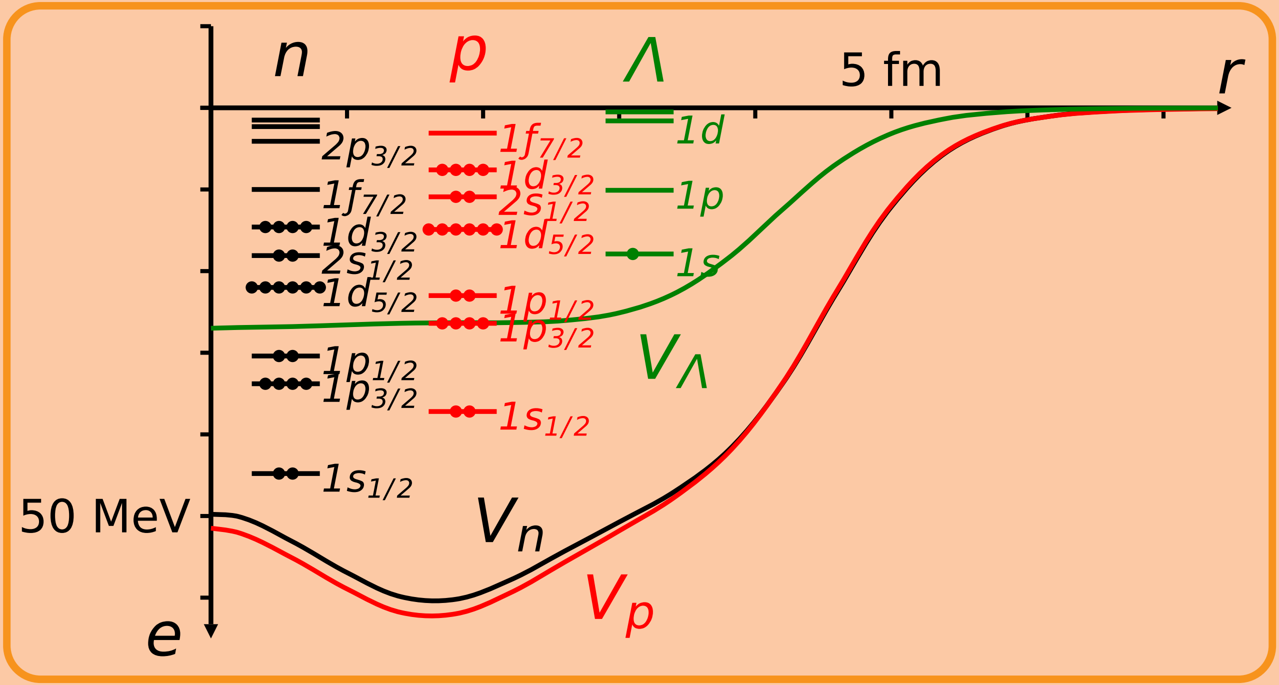


Fig. 2. Λ hypernuclear chart as of 2012.

Hypernuclei: Typical Example: ${}^{40}_{\Lambda}$Ca:



- Theoretical model:
  - Skyrme-Hartree-Fock (SHF) [Vautherin & Brink, PRC 5, 626 (1972)]
  - Standard *NN* force: SIII, SGII, SkI4, SLy4, . . .
  - Effective microscopic *N*Λ force from BHF results . . .

Extended SHF Model for Hypernuclei:

- Total energy of the hypernucleus:

$$E = \int d^3r\, \epsilon(r)$$

Energy density functional:

$$\epsilon = \epsilon_N[\tau_n, \tau_p, \rho_n, \rho_p, \boldsymbol{J}_n, \boldsymbol{J}_p] + \epsilon_\Lambda[\tau_\Lambda, \rho_\Lambda, \rho_N]$$

Local densities:

$$\rho_q = \sum_{i=1}^{N_q} |\phi_q^i|^2\,, \quad \tau_q = \sum_{i=1}^{N_q} |\nabla\phi_q^i|^2\,, \quad \boldsymbol{J}_q = \sum_{i=1}^{N_q} \phi_q^{i*}(\nabla\phi_q^i \times \boldsymbol{\sigma})/i$$

i: occupied states, N_q: number of particles $q = n, p, \Lambda$

- SHF Schrödinger equation:

$$\left[-\nabla\cdot\frac{1}{2m_q^*(r)}\nabla+V_q(r)-i\nabla W_q(r)\cdot(\nabla\times\boldsymbol{\sigma})\right]\phi_q^i(r) = -e_q^i\phi_q^i(r)$$

  - SHF mean fields:

$$V_N = V_N^{\rm SHF}+\frac{\partial\epsilon_{N\Lambda}}{\partial\rho_N} \quad , \quad V_\Lambda=\frac{\partial\epsilon_{N\Lambda}}{\partial\rho_\Lambda} \quad , \quad W_\Lambda=0$$

  - Effective mass $m_\Lambda^*(\rho_N,\rho_\Lambda)$ and
    Energy density due to $N\Lambda$ interaction: no free parameters

$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda)=$$

$$(\rho_N+\rho_\Lambda)\frac{B}{A}(\rho_N,\rho_\Lambda)-\rho_N\frac{B}{A}(\rho_N,0)-\frac{3}{5}\frac{(3\pi^2)^{2/3}}{2m_\Lambda}\rho_\Lambda^{5/3}$$

  - Coupled equations for eigenvalues e_q^i

- SHF Schrödinger equation:

$$\left[-\nabla\cdot\frac{1}{2m_q^*(r)}\nabla + V_q(r) - i\nabla W_q(r)\cdot(\nabla\times\boldsymbol{\sigma})\right]\phi_q^i(r) \;=\; -e_q^i\phi_q^i(r)$$

  - SHF mean fields:

$$V_N \;=\; V_N^{\rm SHF} + \frac{\partial\epsilon_{N\Lambda}}{\partial\rho_N} \quad , \quad V_\Lambda = \frac{\partial\epsilon_{N\Lambda}}{\partial\rho_\Lambda} \quad , \quad W_\Lambda = 0$$

  - Effective mass $m_\Lambda^*(\rho_N,\rho_\Lambda)$ and Energy density due to $N\Lambda$ interaction: from BHF no free parameters

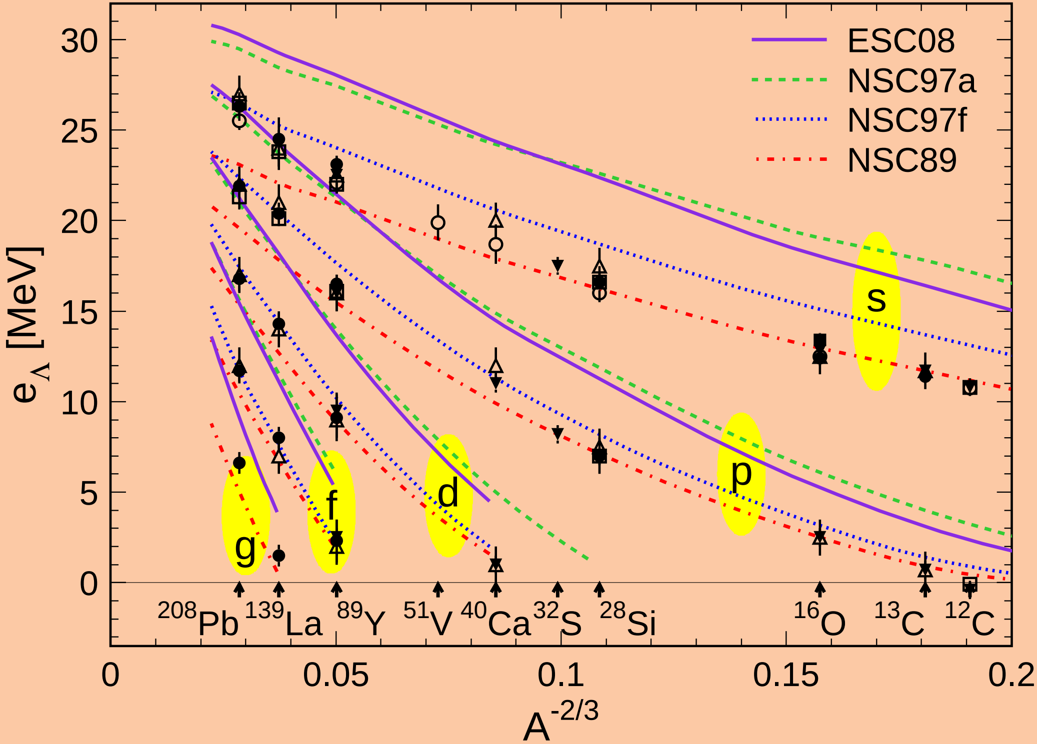
$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda) =$$

$$(\rho_N+\rho_\Lambda)\frac{B}{A}(\rho_N,\rho_\Lambda) - \rho_N\frac{B}{A}(\rho_N,0) - \frac{3}{5}\frac{(3\pi^2)^{2/3}}{2m_\Lambda}\rho_\Lambda^{5/3}$$

  - Coupled equations for eigenvalues e_q^i

Results: Single-Λ Hypernuclei:

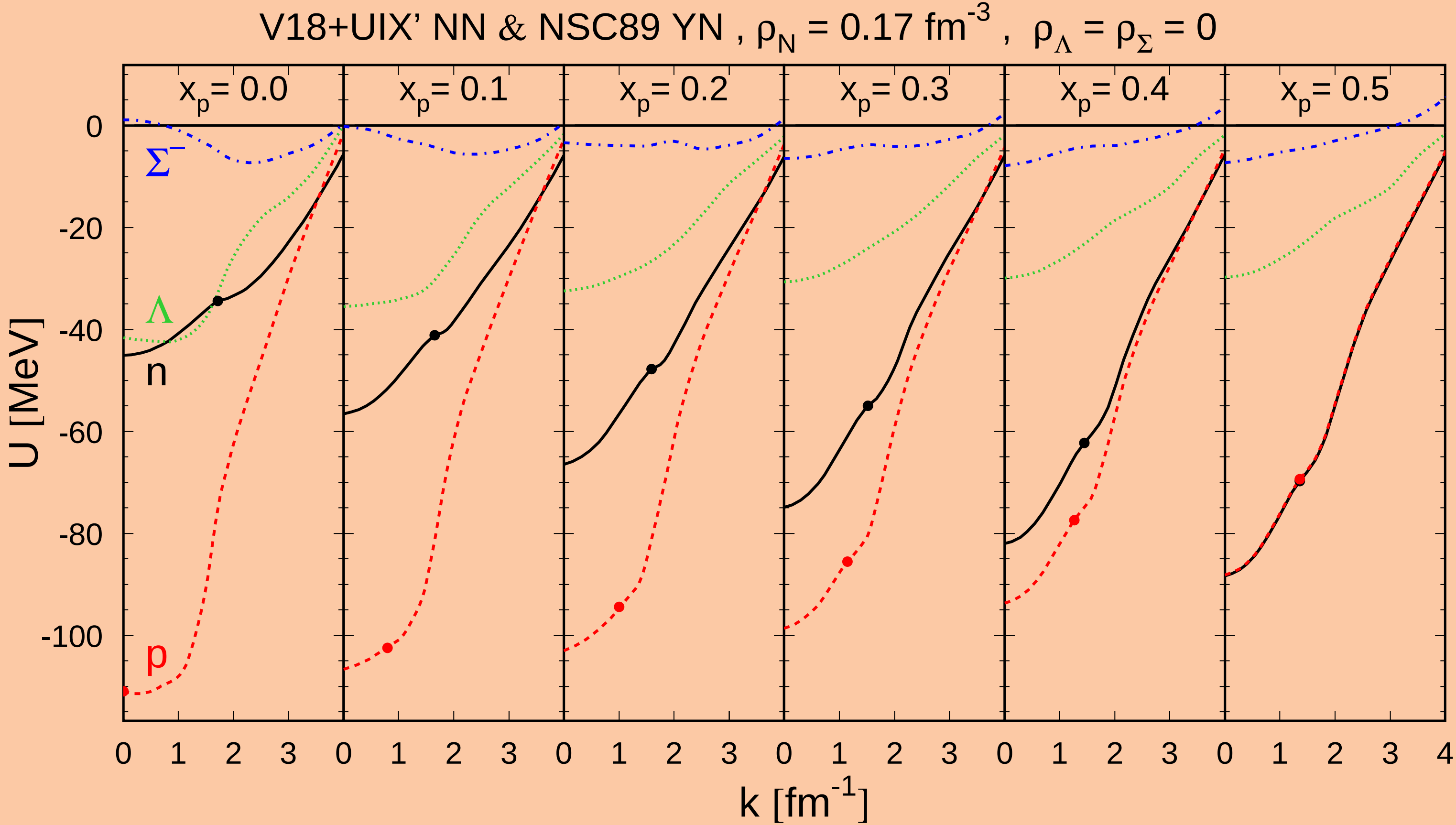
- Lambda single-particle levels:



↪ Best agreement with NSC89 and NSC97f potentials

No indication of strong hyperon TBF

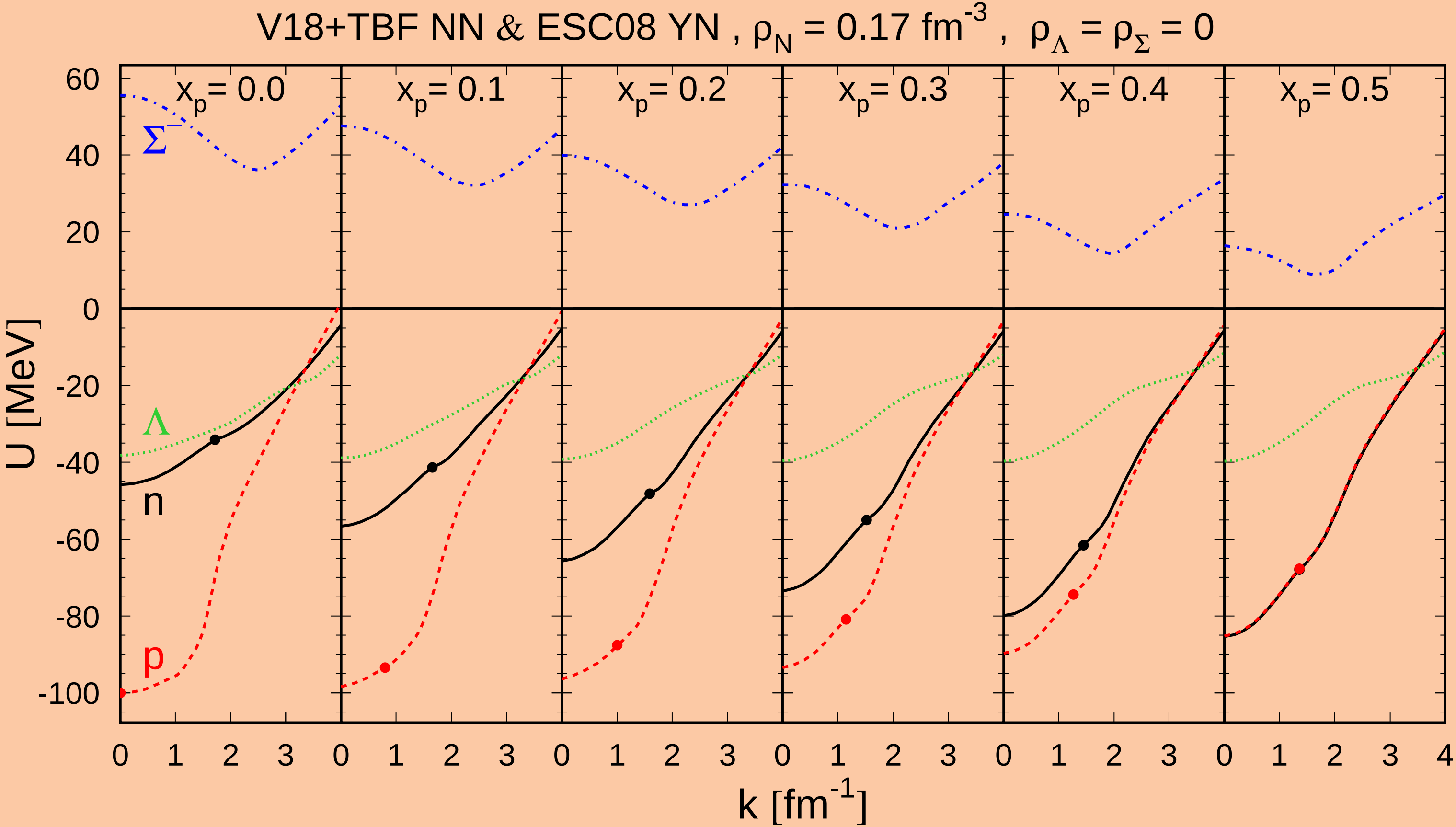
• Single-particle potentials in nuclear matter ($\rho_N = \rho_0$):



→ Hyperons are weaker bound than nucleons

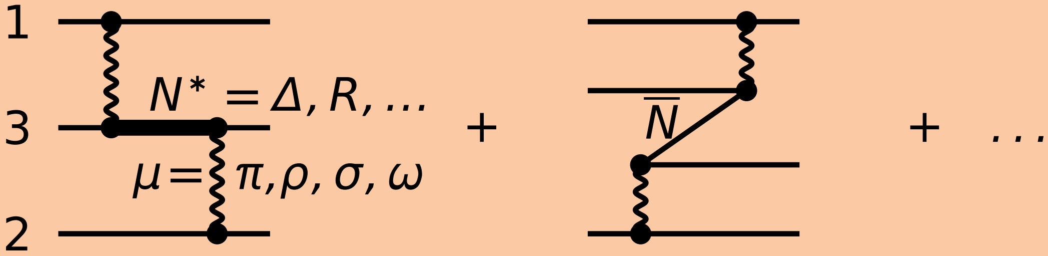
Only slight dependence on proton fraction $x_p = \rho_p/\rho_N$

• Results with ESC08b *NY* potential:



↪ $\Sigma^- N$ interaction is repulsive

Three-Nucleon Forces:



- Only small effect required [$\delta(B/A) \approx 1$ MeV at ρ_0]
- Model dependent, no final theory yet
- Use and compare microscopic and phenomenological TBF...
  - Microscopic TBF of P. Grangé et al., PRC 40, 1040 (1989):
    Exchange of $\pi, \rho, \sigma, \omega$ via Δ(1232), R(1440), $N\bar{N}$
    Parameters compatible with two-nucleon potential (Paris,V_{18},...)
  - Urbana IX phenomenological TBF:
    Only 2π-TBF + phenomenological repulsion
    Fit saturation point

«Recipe» for Neutron Star Structure Calculation:

Brueckner results: $\boldsymbol{\epsilon(\rho, x_e, x_p, x_\Lambda, x_\Sigma, \ldots)}$; $x_i = \frac{\rho_i}{\rho}$

Chemical potentials: $\mu_i = \frac{\partial \epsilon}{\partial \rho_i}$

Beta-equilibrium: $\mu_i = b_i \mu_n - q_i \mu_e$

Charge neutrality: $\sum_i x_i q_i = 0$

Composition: $x_i(\rho)$

Equation of state: $p(\rho) = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$

TOV equations:

$$\frac{dp}{dr} = -\frac{Gm}{r^2} \frac{(\epsilon + p)(1 + 4\pi r^3 p/m)}{1 - 2Gm/r}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

Structure of the star: $\rho(r)$, $\boldsymbol{M(R)}$ etc.

«Recipe» for Neutron Star Structure Calculation:

Brueckner results: $\boldsymbol{\epsilon(\rho, x_e, x_p, x_\Lambda, x_\Sigma, \ldots)}$; $x_i = \frac{\rho_i}{\rho}$

Chemical potentials: $\mu_i = \frac{\partial \epsilon}{\partial \rho_i}$

Beta-equilibrium: $\mu_i = b_i \mu_n - q_i \mu_e$

$\mu_e = \mu_\mu = \mu_n - \mu_p$

$\mu_{\Sigma^-} = 2\mu_n - \mu_p$

$\mu_{\Sigma^0} = \mu_\Lambda = \mu_n$

$\mu_{\Sigma^+} = \mu_p$

Charge neutrality: $\sum_i x_i q_i = 0$

Composition: $x_i(\rho)$

Equation of state: $p(\rho) = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$

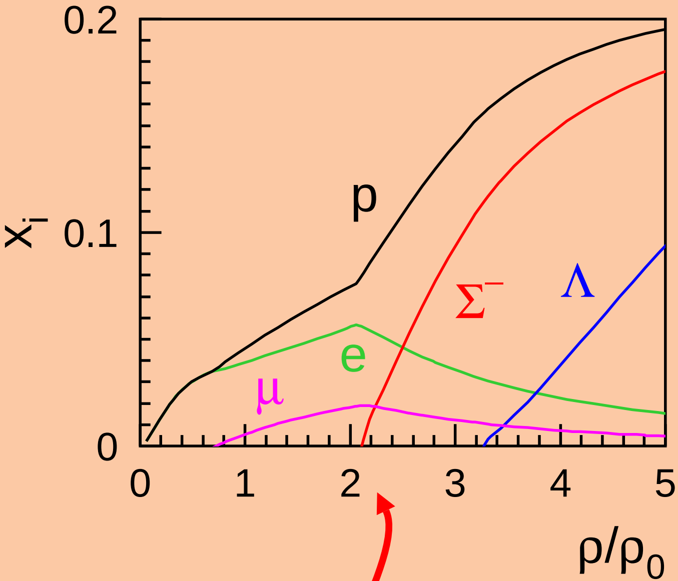
TOV equations:

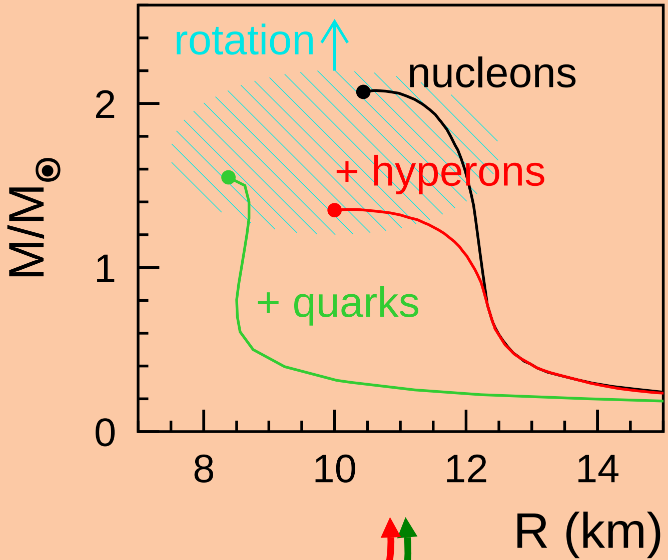
$$\frac{dp}{dr} = -\frac{Gm}{r^2}\frac{(\epsilon + p)(1 + 4\pi r^3 p/m)}{1 - 2Gm/r}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

Structure of the star: $\rho(r)$, $\boldsymbol{M(R)}$ etc.

- Typical results:



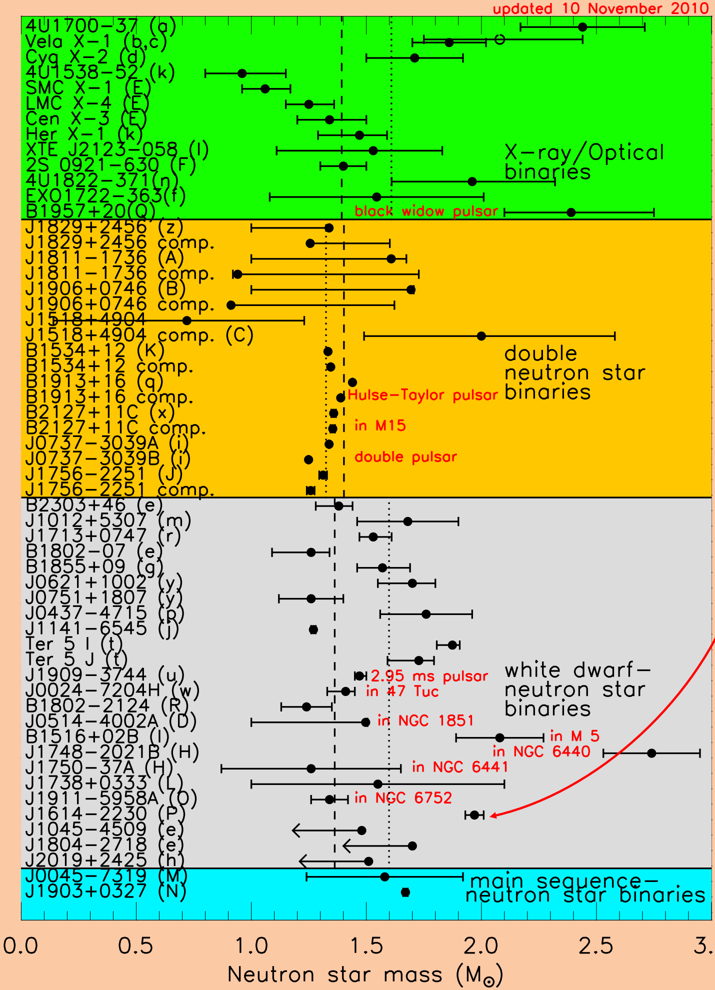


- Hyperon onset occurs at $\rho \sim 2\ldots3\,\rho_0$

- NS structure including hyperons
  . . . and including quark matter


Data ?
Vela pulsar
©2006

Observational Data: Masses



Courtesy of J. Lattimer

Two candidates for $\sim 1.7 M_\odot$

Recent: $\sim 1.97 M_\odot$ (Nature 09466) !?

Need accurate data of “high-mass” neutron stars !

No combined (M, R) measurements!
(Would practically fix the EOS)

Observational Data: Radii

The Best Measured Neutron Star Radii

Name	R_∞ (km/D)	D (kpc)	$kT_{eff,\infty}$ (eV)	N_H (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	5.36 ±6%	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen** (XMM)	13.6 ± 0.3	5.36 ±6%	67 ±2	9 ± 2.5	Gendre et al (2002)
M13** (XMM)	12.6 ± 0.4	7.80 ±2%	76 ±3	(1.1)	Gendre et al (2002)
47 Tuc X7 (Chandra)	34^{+22}_{-13}	5.13 ±4%	84^{+13}_{-12}	$0.13^{+0.06}_{-0.04}$	Heinke et al (2006)
M28** (Chandra)	$14.5^{+6.9}_{-3.8}$	5.5 ±10%	90^{+30}_{-10}	26 ± 4	Becker et al (2003)
M30 (Chandra)	$16.9^{+5.4}_{-4.3}$	--	94^{+17}_{-12}	$2.9^{+1.7}_{-1.2}$	Lugger et al (2006)
NGC 2808 (XMM)	??	9.6 (?)	103^{+18}_{-33}	18^{+11}_{-7}	Webb et al (2007)

$R_\infty < 5\%$

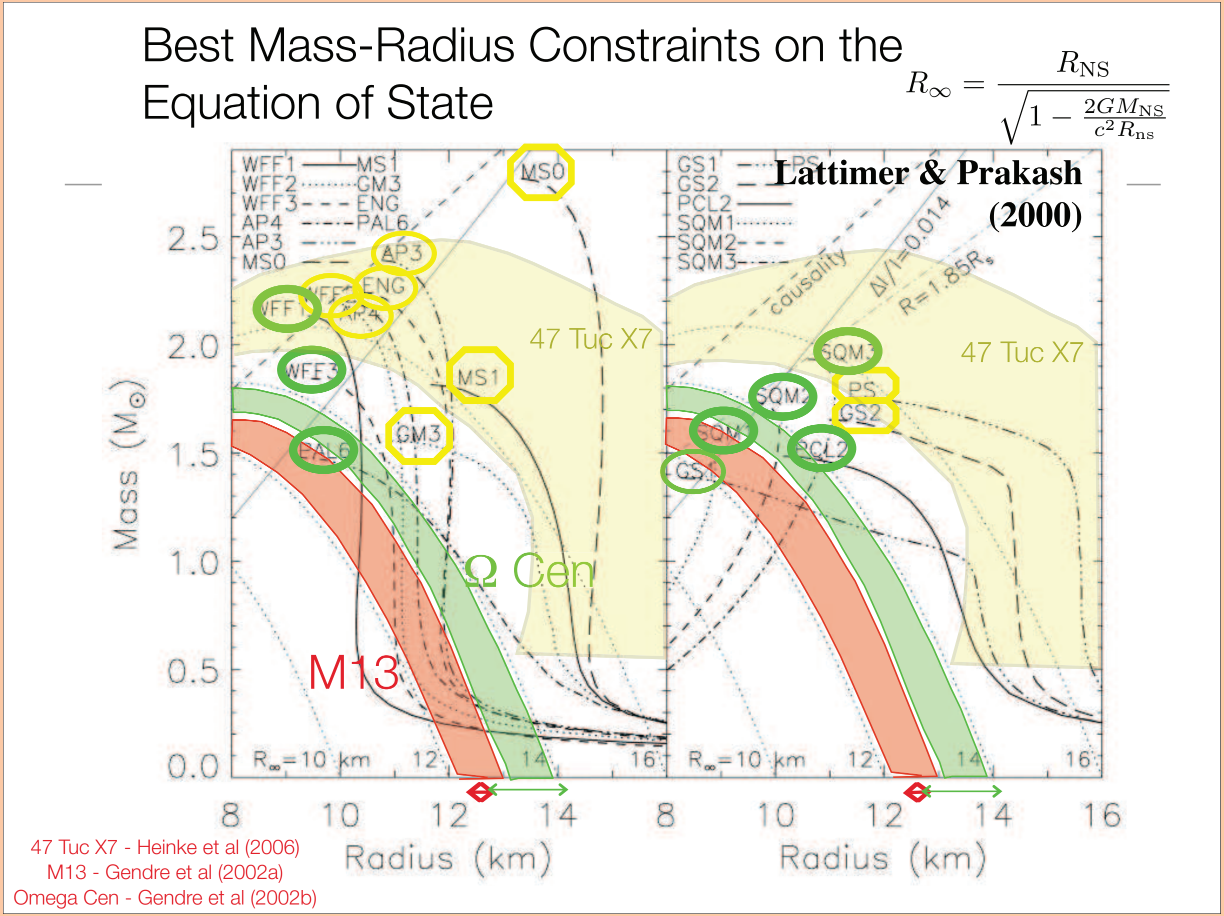
Caveats:

- All IDd by X-ray spectrum (47 Tuc, Omega Cen now have optical counterparts)
- calibration uncertainties

Distances: Carretta et al (2000), Thompson et al (2001)

Courtesy of R. Rutledge, NFQCD 2010 meeting

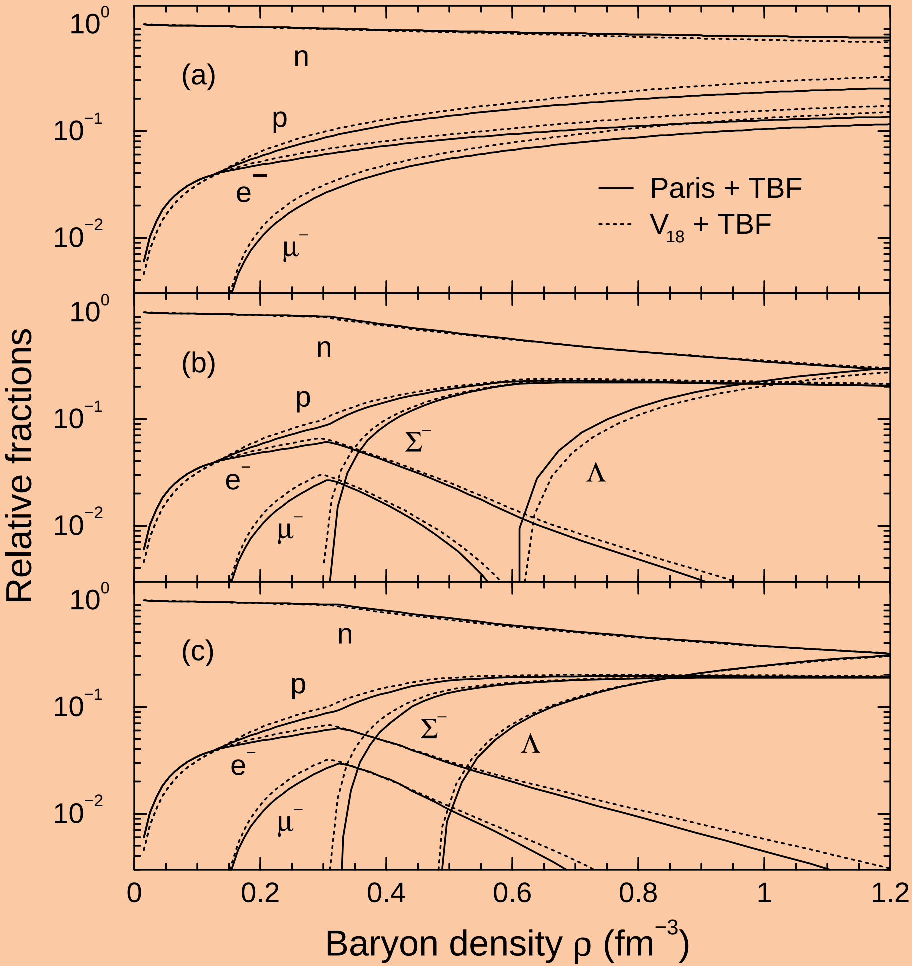
Mass-Radius Constraints:



Courtesy of R. Rutledge, NFQCD 2010 meeting


J0617 in IC 443
BHF Results ...

• Composition of neutron star matter:



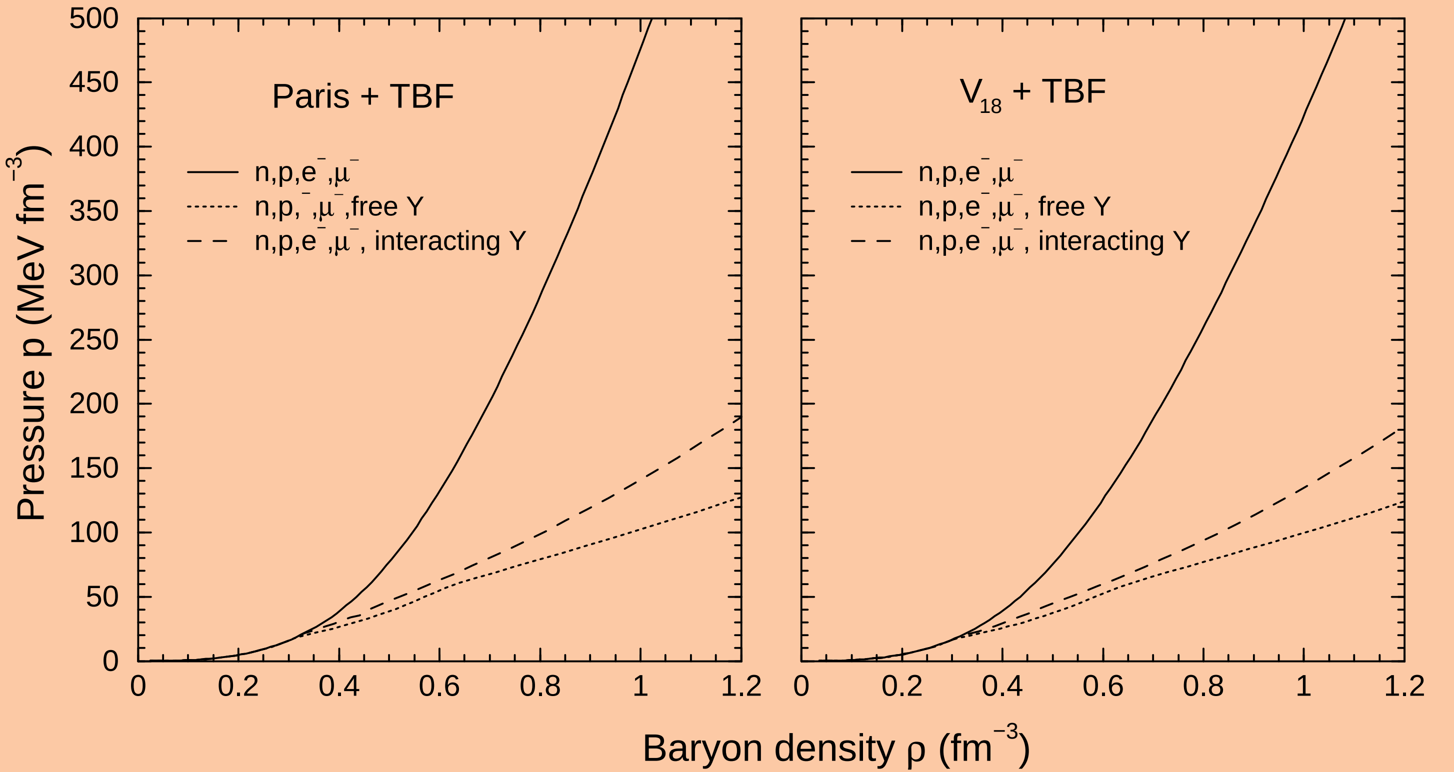
No hyperons

Free hyperons

Interacting hyperons
(Σ^- repulsive, Λ attractive)

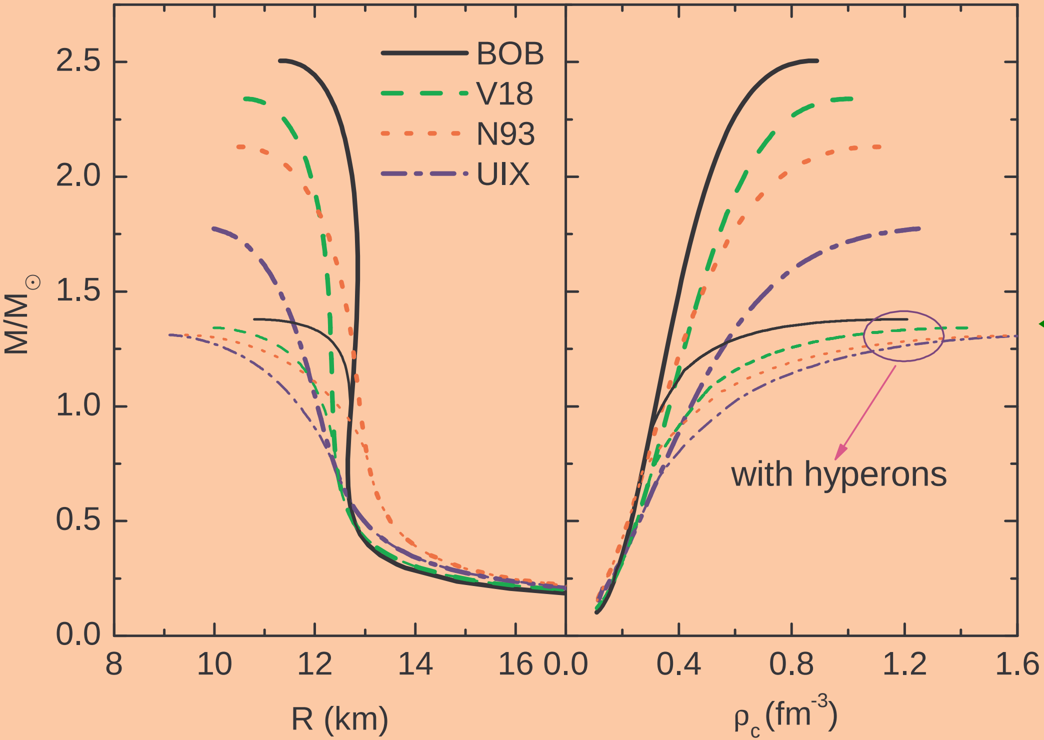
NY interaction determines
Y onset

- EOS of neutron star matter:



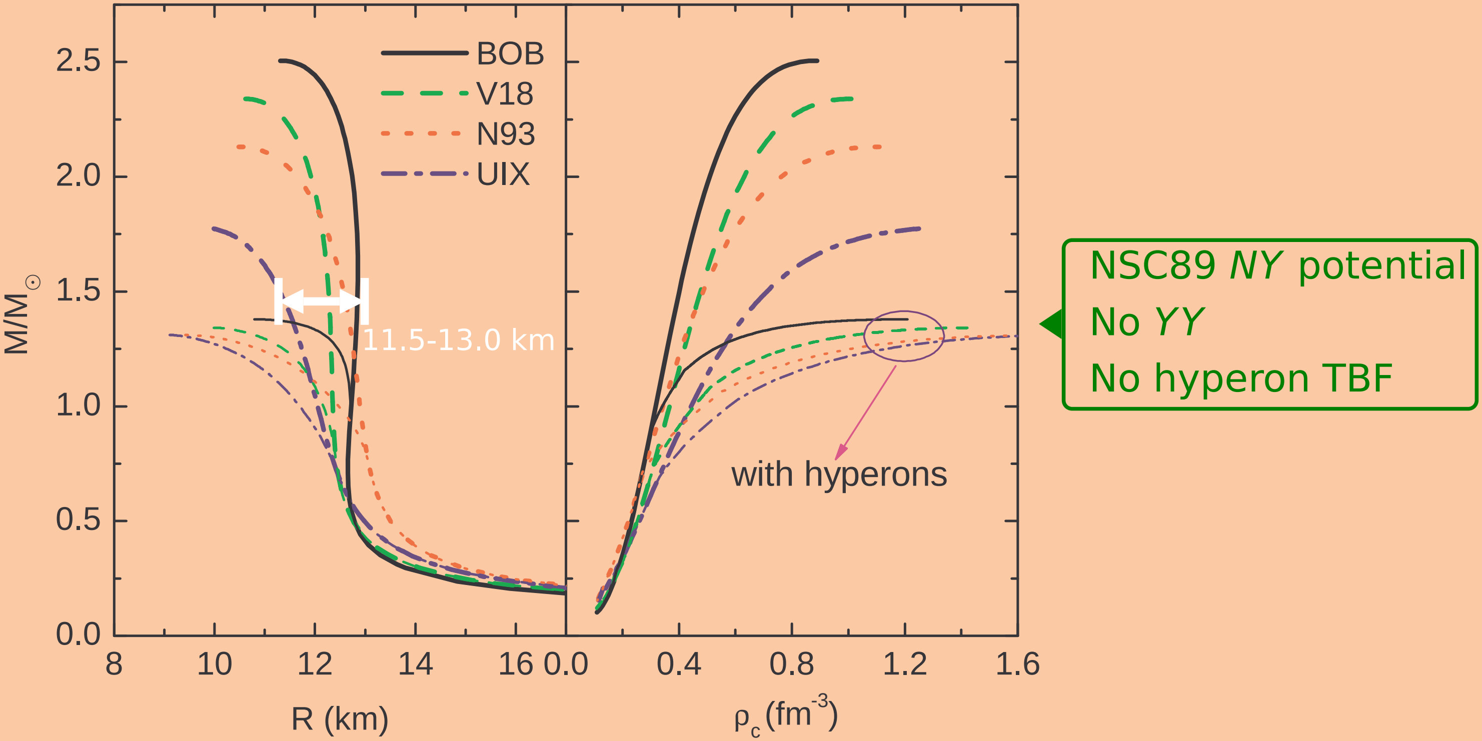
↪ Strong softening due to hyperons !
(More Fermi seas available)

- Mass-radius relations with different nucleonic TBF:



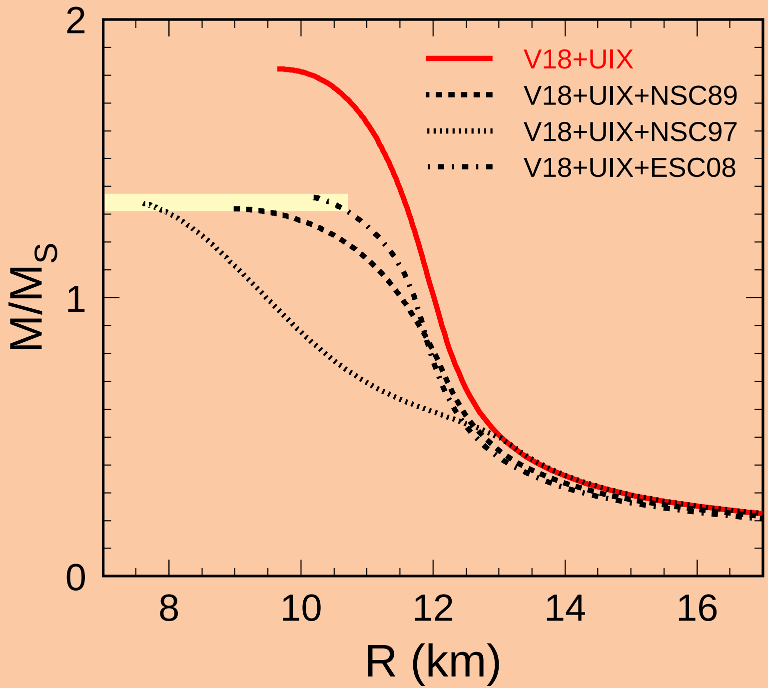
→ Large variation of M_{max} with nucleonic TBF
Self-regulating softening due to hyperon appearance
(stiffer nucleonic EOS → earlier hyperon onset)

- Mass-radius relations with different nucleonic TBF:



↪ Large variation of M_{max} with nucleonic TBF
Self-regulating softening due to hyperon appearance
(stiffer nucleonic EOS → earlier hyperon onset)

- Using different NY, YY potentials:

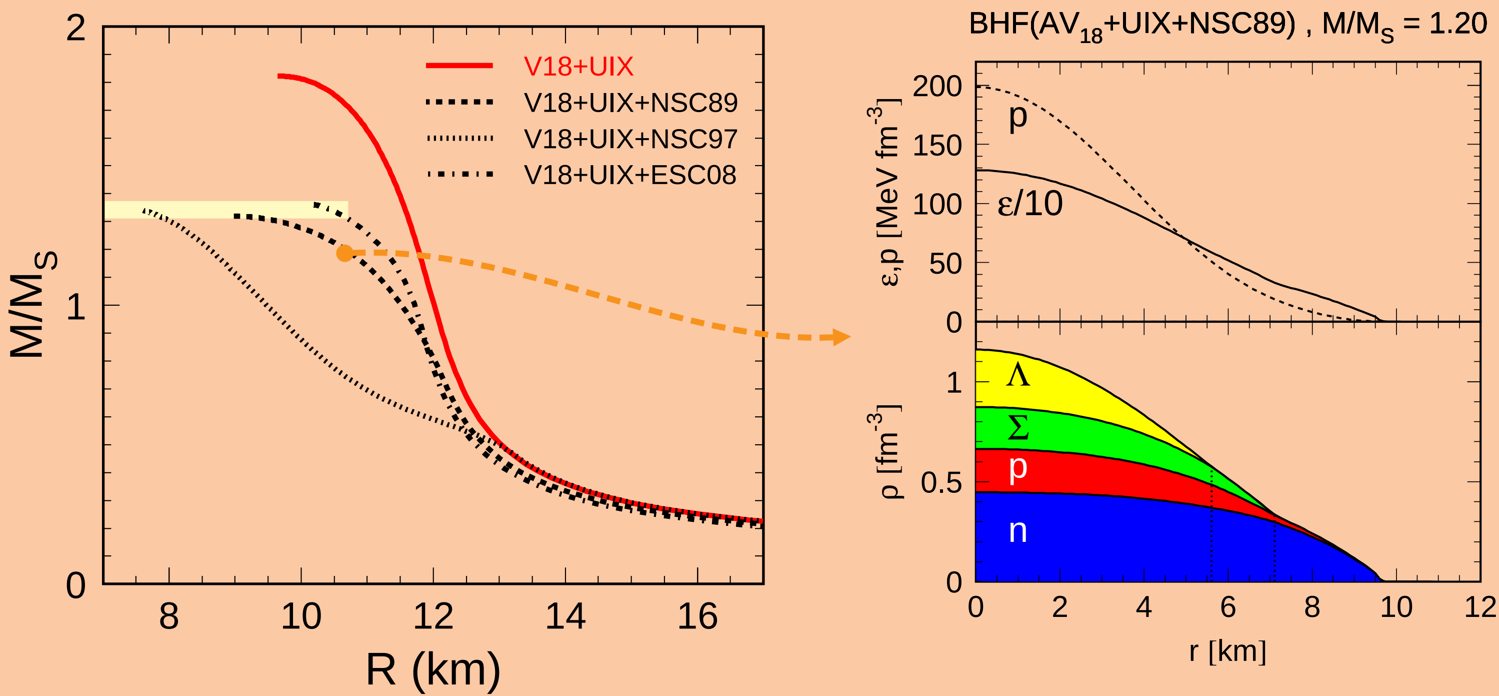


Maximum mass independent of potentials !

Maximum mass too low ($< 1.4\, M_\odot$) !

Proof for “quark” matter inside neutron stars ?!

• Using different NY, YY potentials:

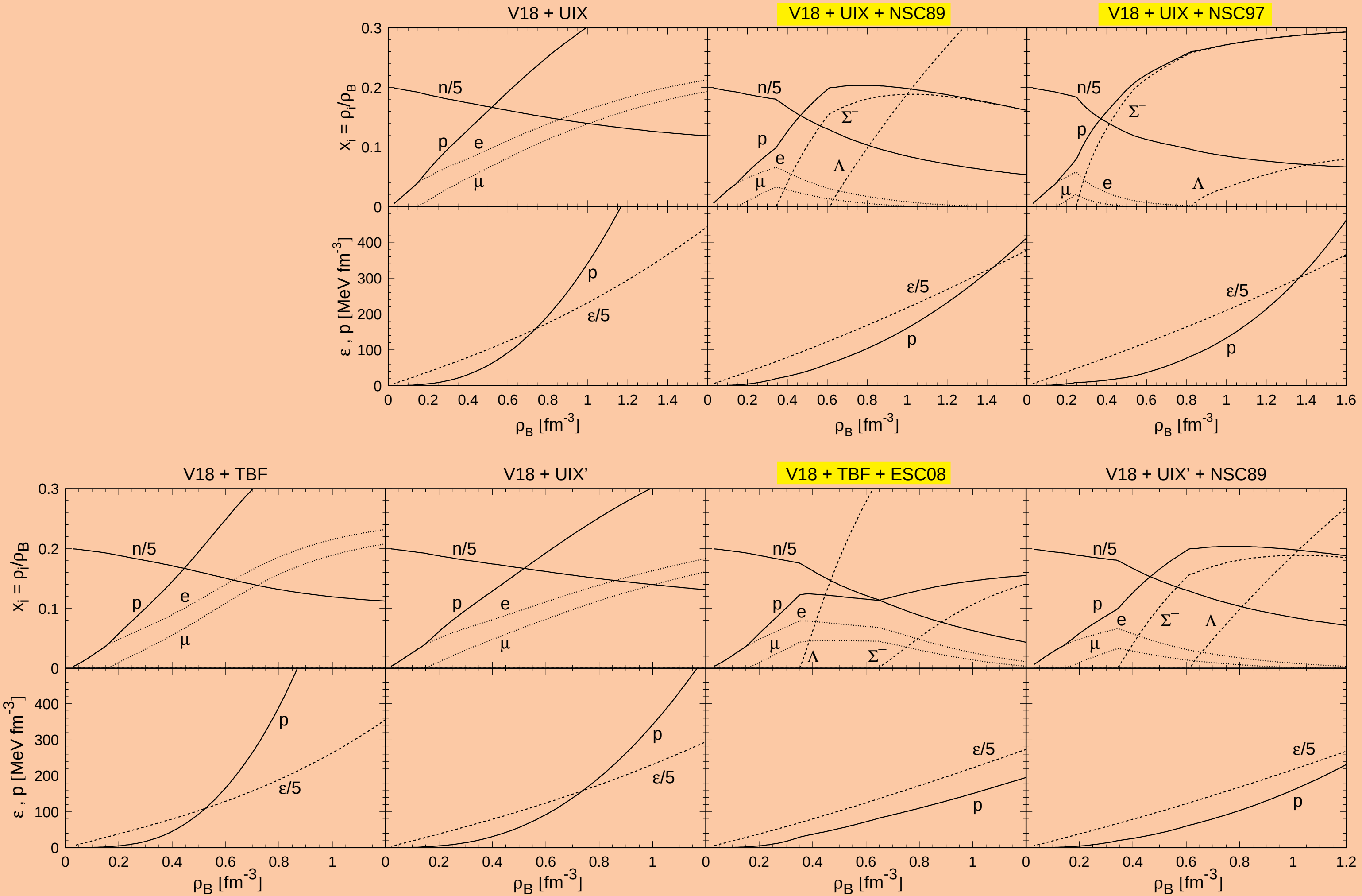


Maximum mass independent of potentials !

Maximum mass too low ($< 1.4\,M_\odot$) !

Proof for "quark" matter inside neutron stars ?!

• . . . in spite of different compositions:



Inclusion of Quark Matter:

- Problem:

  Large theoretical uncertainties, limited predictive power

- Strategy:

  Use available eff. quark models (MIT, NJL, CDM, DSM, ...) in combination with the hadronic EOS

- Important constraint:

  In symmetric matter phase transition not below $\approx 3\rho_0$

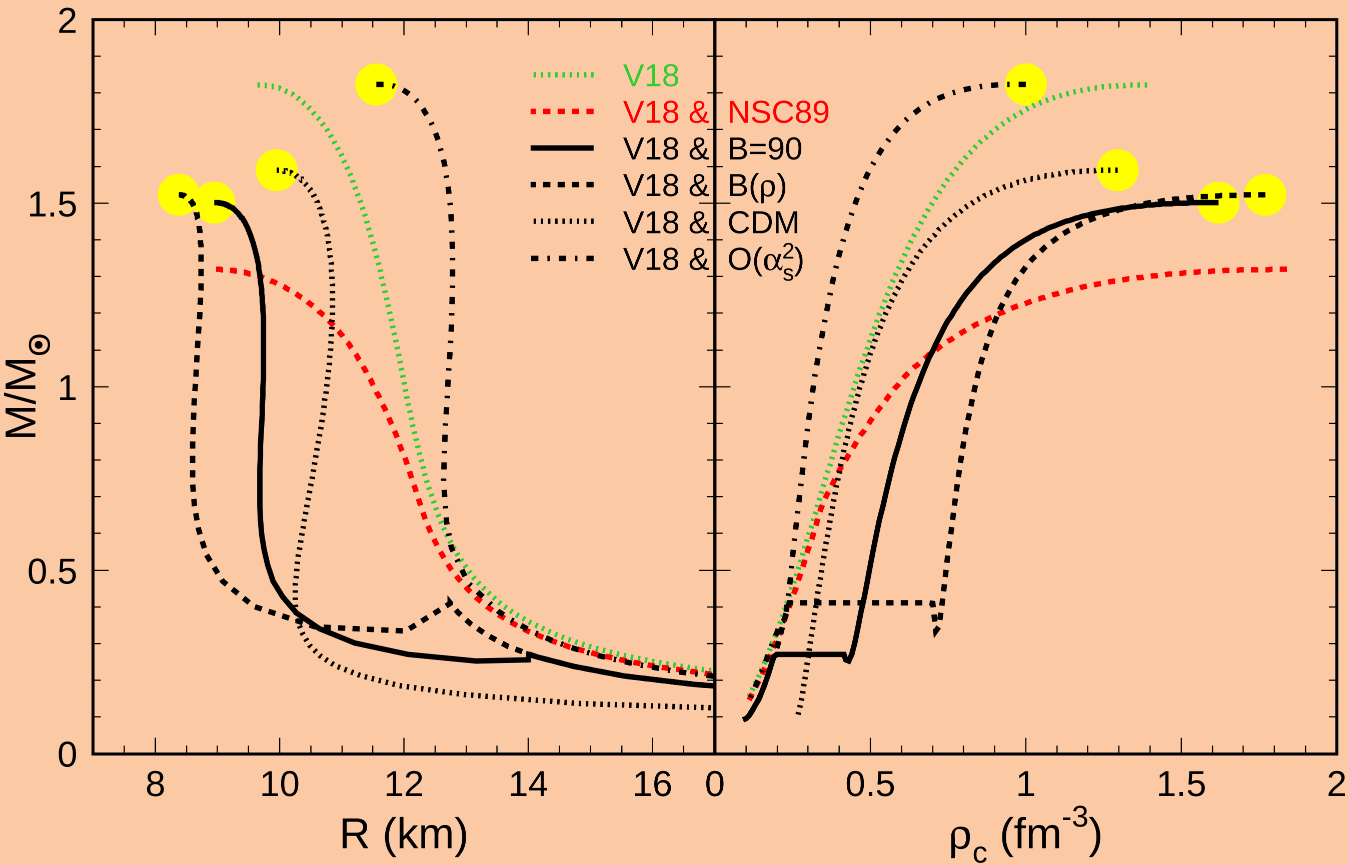
↪ MIT model requires density dependent bag “constant”:

$$\epsilon_Q = B + \sum_{f=u,d,s} \frac{3m_f^4}{8\pi^2}\left[\sqrt{x_f^2+1}\left(2x_f^3+x_f\right) - \operatorname{arsinh}(x_f)\right] + \alpha_s \times \ldots$$

$x_f = k_F^{(f)}/m_f$

$$B(\rho) = B_\infty + (B_0 - B_\infty)\exp\left[-\beta\left(\rho/\rho_0\right)^2\right]$$

- Different quark EOS: bag models, color dielectric model:

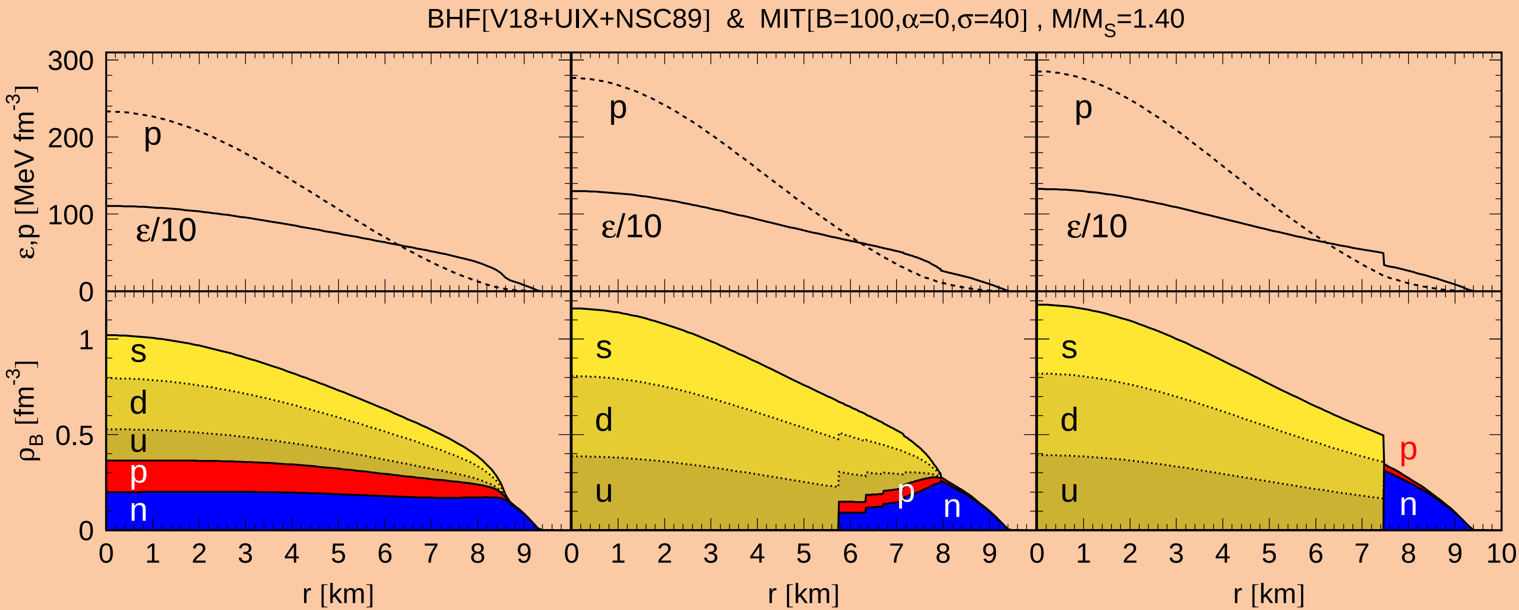


NJL, Dyson-Schwinger models: hyperons prevent phase transition

➥ Maximum masses: 1.5...1.9 $M_{\odot}$, Radii are different !

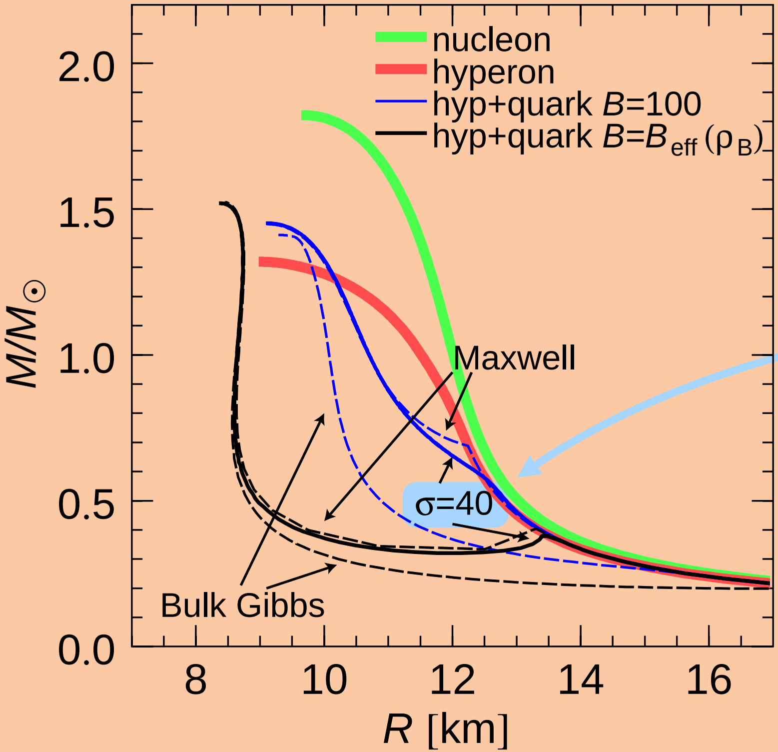
Neutron star profiles:

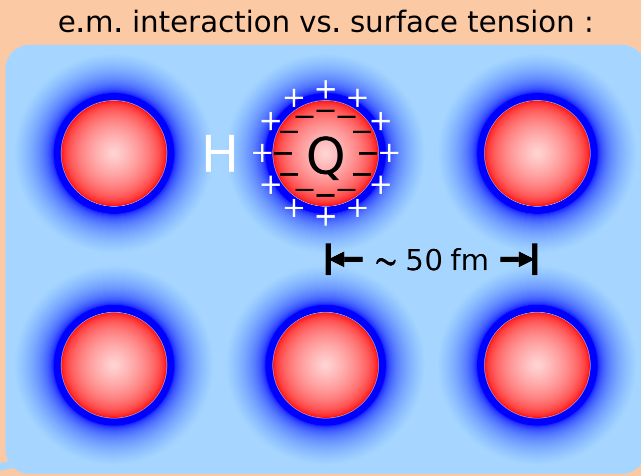
Bulk Gibbs   Screened Gibbs   Maxwell



- Hyperons replaced by strange quark matter
- Very different possible internal structures
- Surface tension + screening enforce ‘quasi’ Maxwell construction (exact for $\sigma \gtrsim 70$ MeV/fm^2)

- Mass-radius relations with different hadron-quark phase transition constructions:





- Screened Gibbs constr. very close to Maxwell construction
- Maximum mass independent of phase transition

Summary:

- Neutron star physics probes the 4 fundamental interactions:
  - Gravitation: Densest object in the Universe
  - Strong: Nuclear EOS
  - Weak: Beta-equilibrium of matter, Neutrino physics
  - EM: Charge-neutrality, Mixed-phase structures

Conclusions:

- Hyperons cannot be ignored !
- BHF EOS with hyperons predicts M_{max} not above $\sim 1.4\,M_\odot$
- Need "quark matter" to reach higher masses
- Currently $M_{\mathrm{max}} \approx 1.9\,M_\odot$ for hybrid stars in this approach

However:

However:

We do not know dark matter.

However:

We do not know dark matter.

We do not know dark energy.

However:

We do not know dark matter.

We do not know dark energy.

Do we know GR at 10 ρ_0?