Neutron Star Structure with Hyperons and Quarks

with
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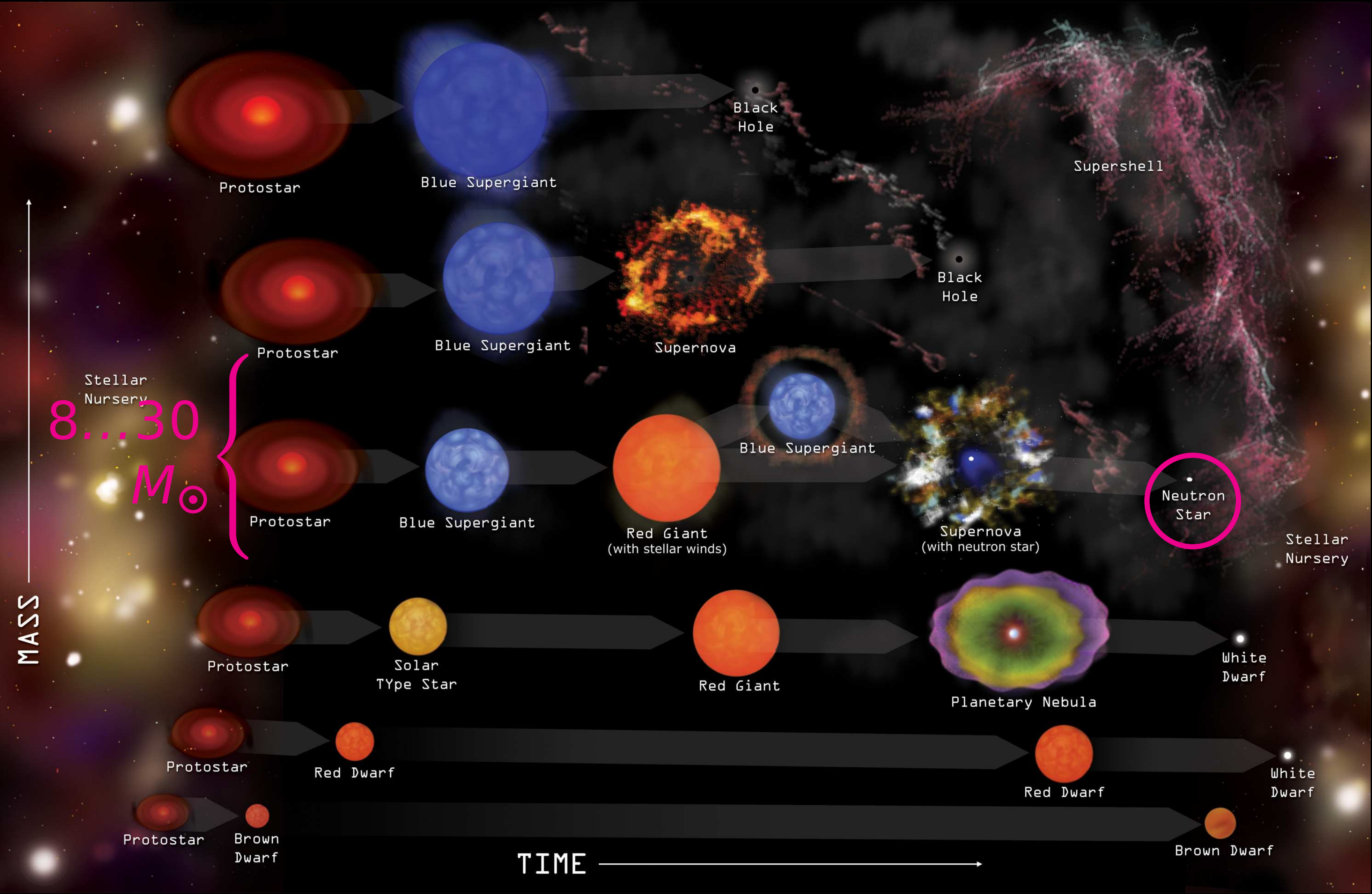
- BHF approach of hypernuclear matter
- Role of three-body forces
- Neutron star properties
- Protoneutron stars: finite temperature
- Inclusion of quark matter
- Hadron-quark phase transition

PRC 58, 3688 (1998)
PRC 61, 055801 (2000)
PRC 62, 064308 (2000)
PRC 64, 044301 (2001)
PLB 526, 19 (2002)
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)
PLB 659, 192 (2008)
PRC 77, 034316 (2008)
PRC 78, 028801 (2008)
PRC 81, 025806 (2010)
A&A 518, A17 (2010)
PRC 83, 025804 (2011)

http://chandra.harvard.edu



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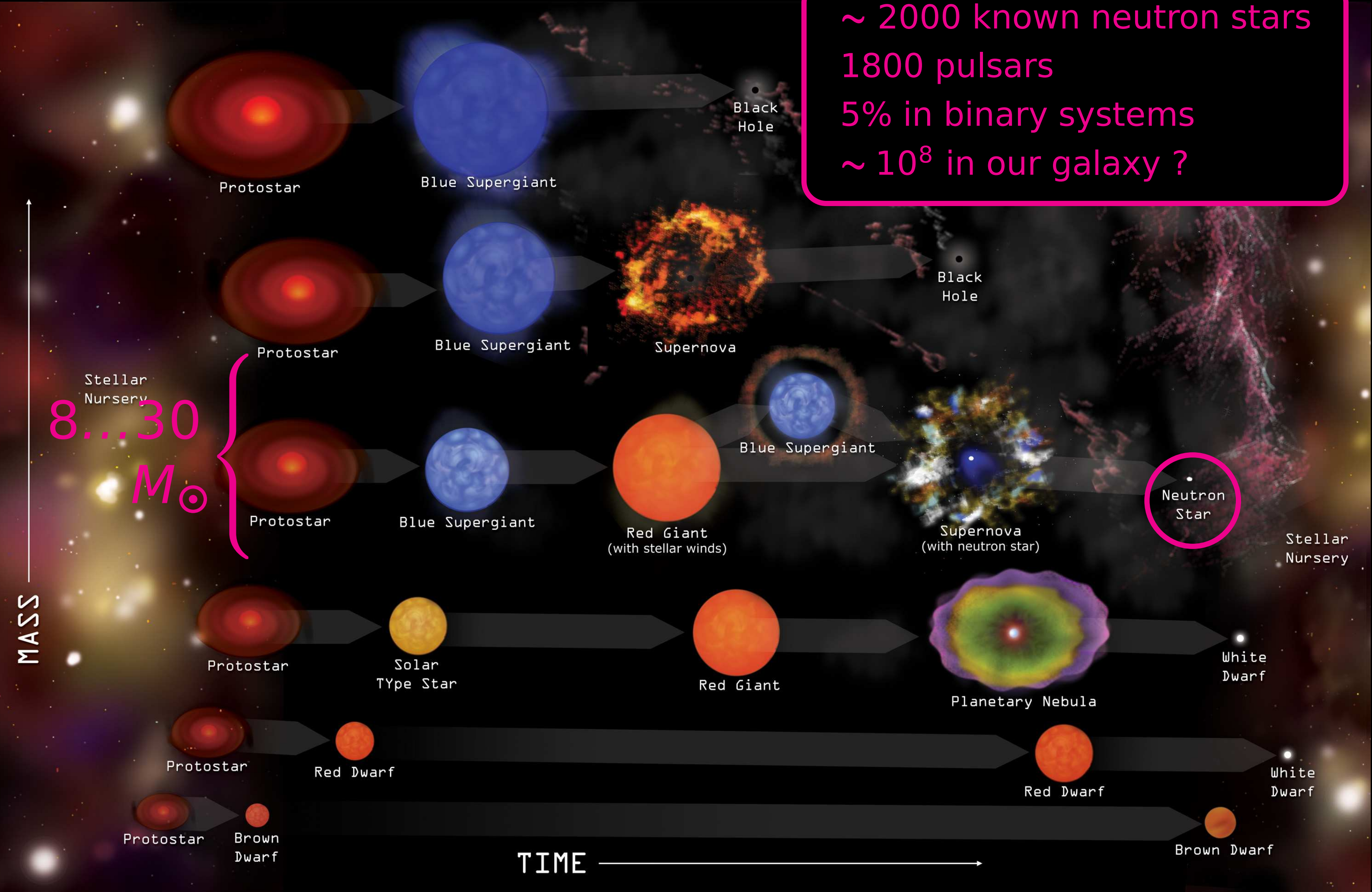

~ 2000 known neutron stars

1800 pulsars

5% in binary systems

~ 10^8 in our galaxy ?

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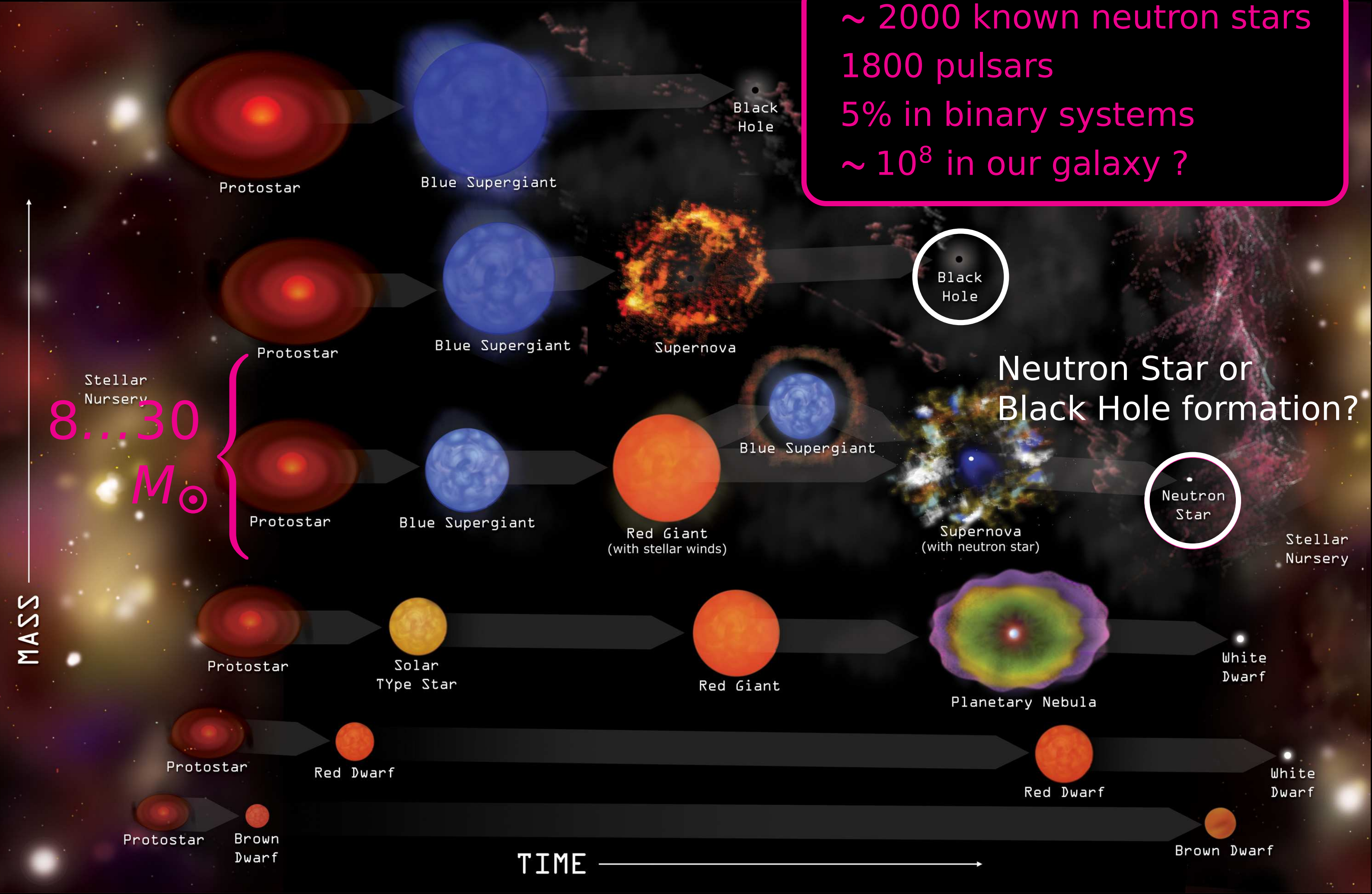


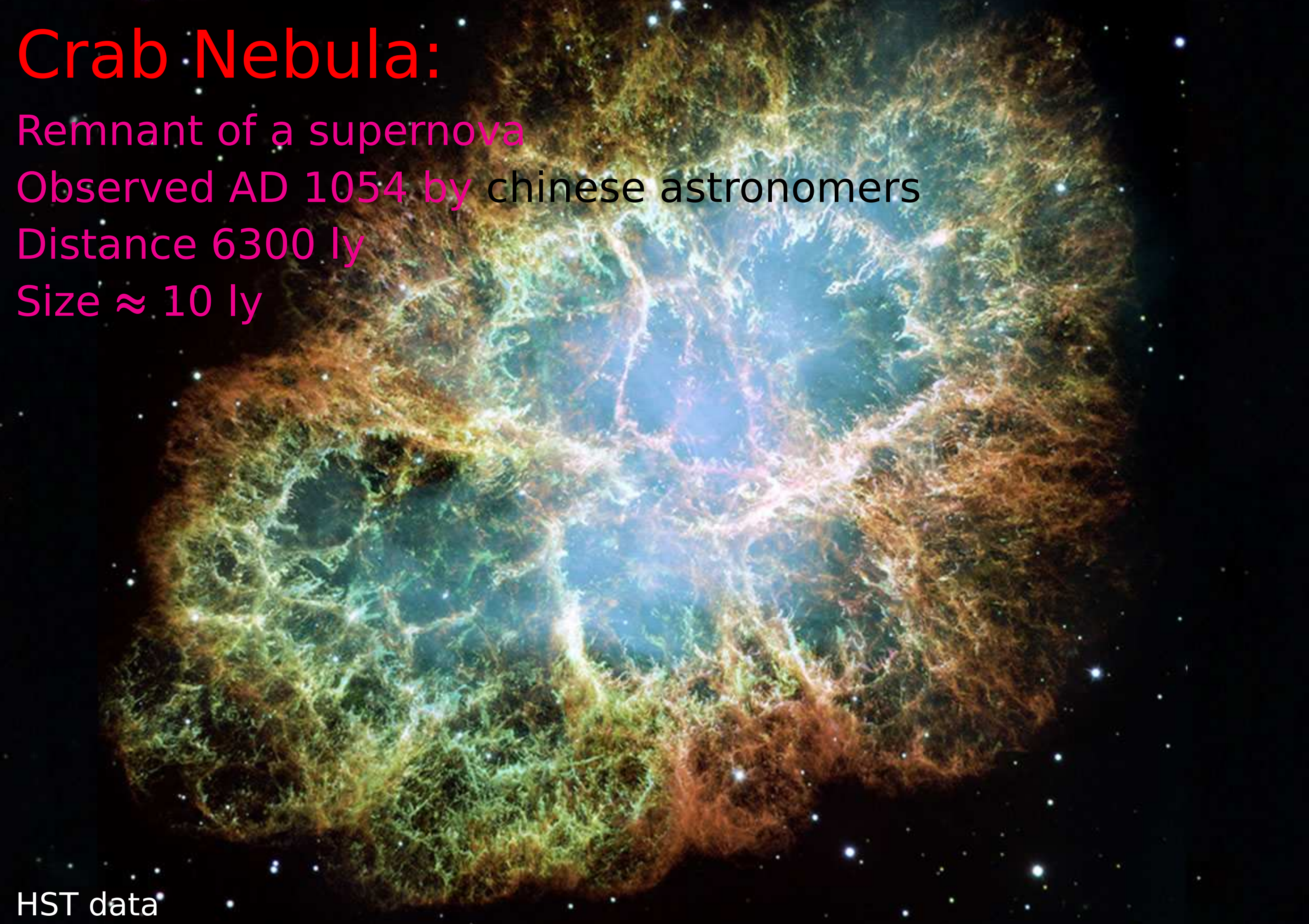
Crab Nebula:

Remnant of a supernova

Observed AD 1054 by chinese astronomers

Distance 6300 ly

Size ≈ 10 ly



HST data

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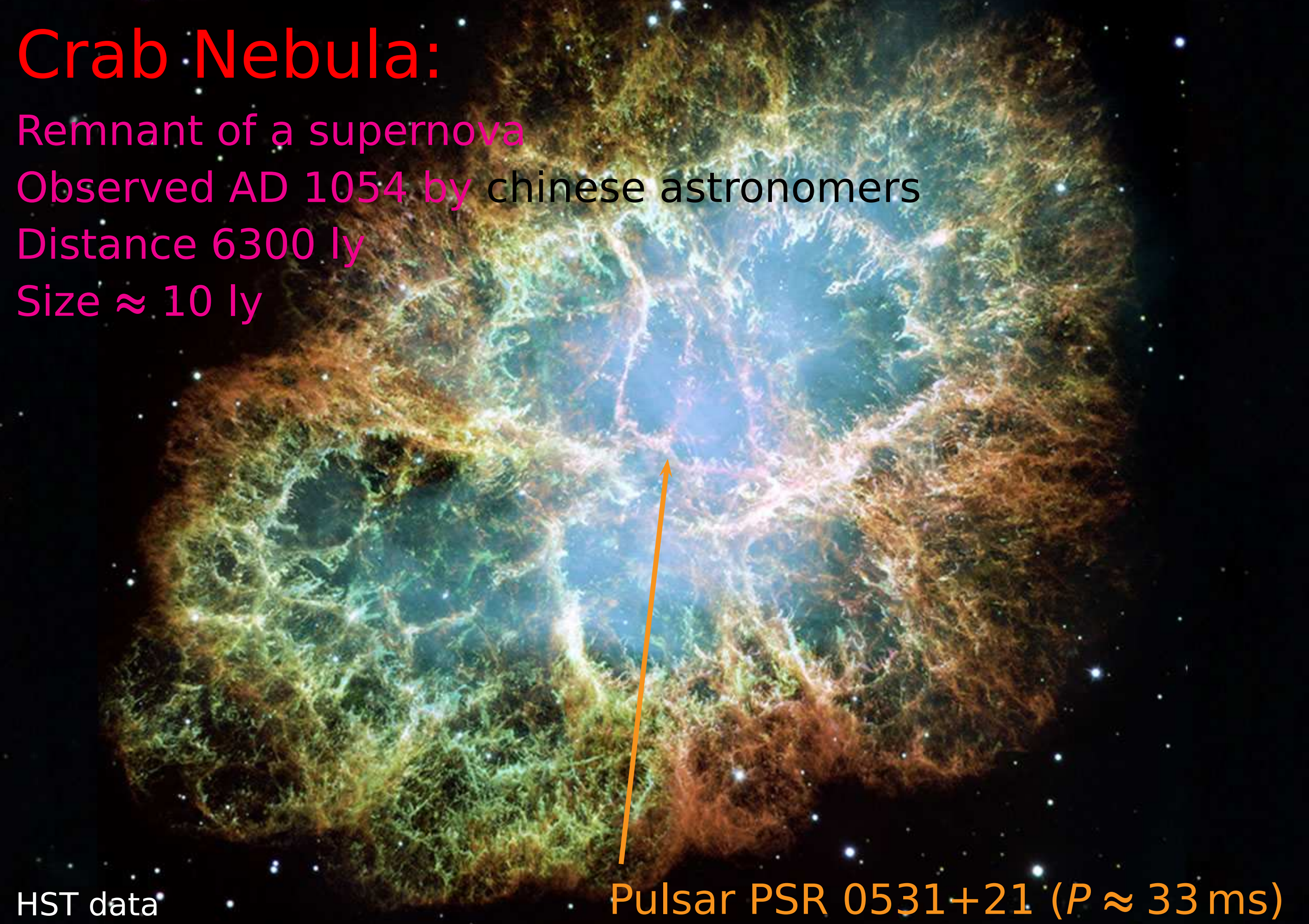
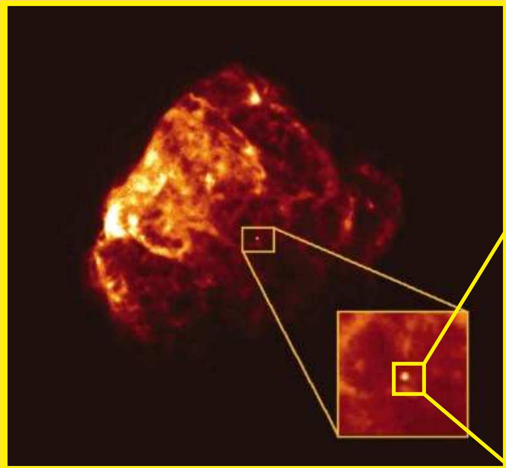
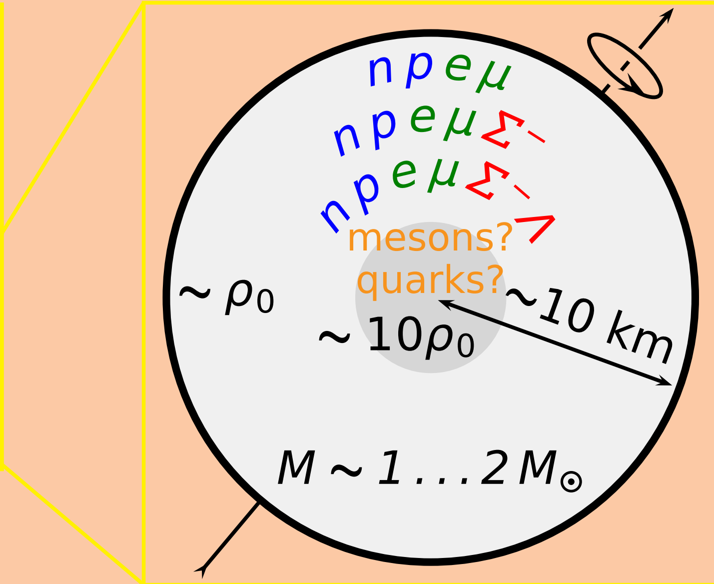


Neutron Star Structure from Brueckner Theory



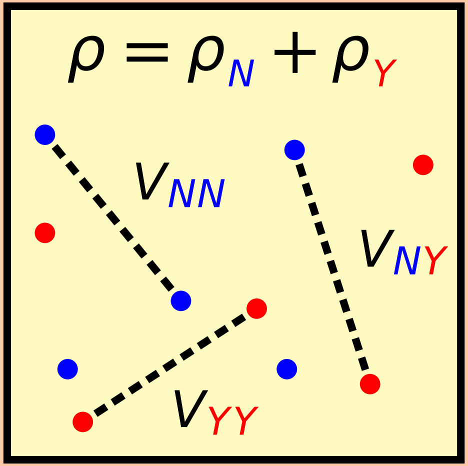
ROSAT image of *Puppis A*



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

Need EOS of nuclear matter including hyperons

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, . . .)

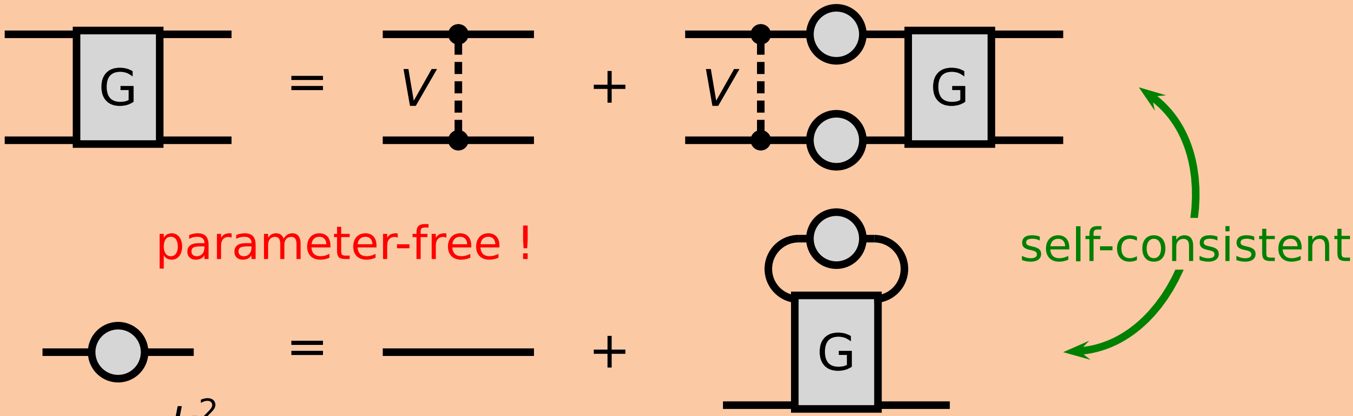
V_{YY} : ? (no scattering data)

In free space weak decay: $Y \rightarrow N + \pi$ etc.

In dense nucleonic medium the decay is Pauli-blocked !

Bruecknar Theory of Nuclear Matter:

- Effective in-medium interaction G from potential V:



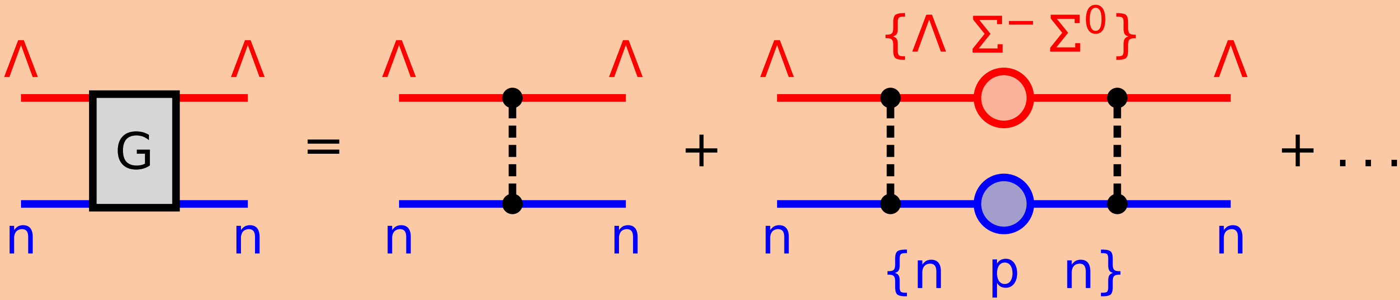
$$e_k = \frac{k^2}{2m} + U(k)$$

Compute: binding energy, s.p. properties, cross sections, ...

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

Include Hyperons:

- Technical difficulty: coupled channels:



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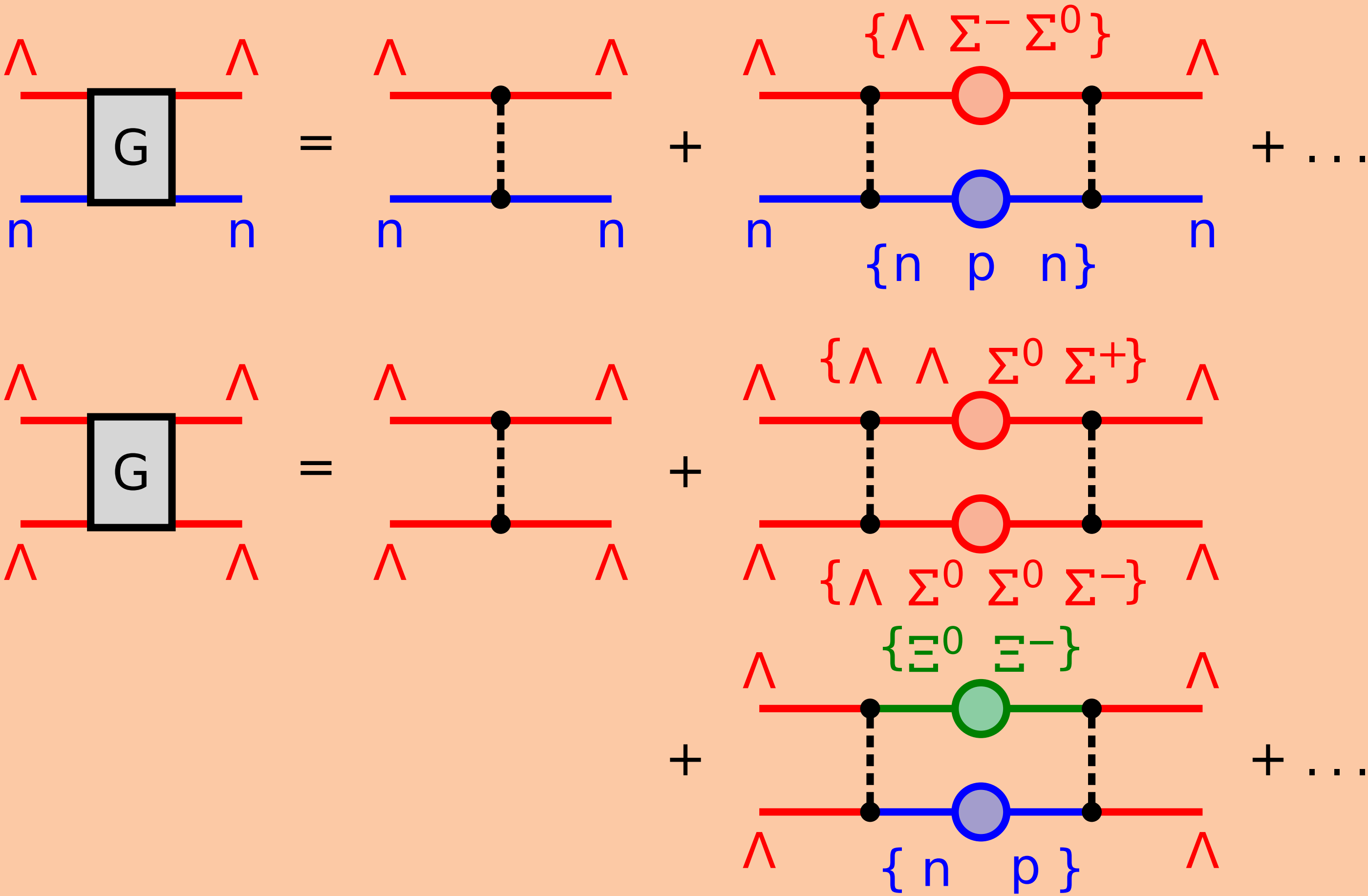
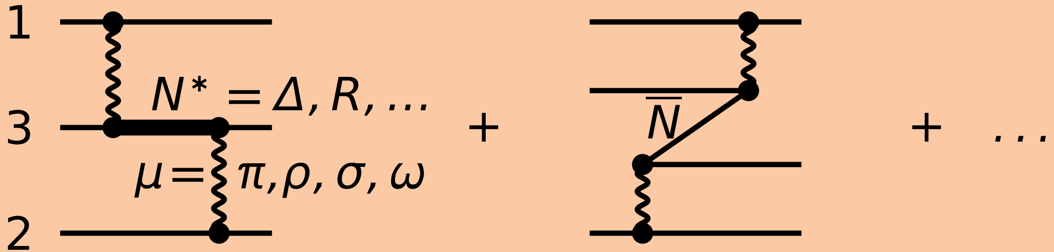
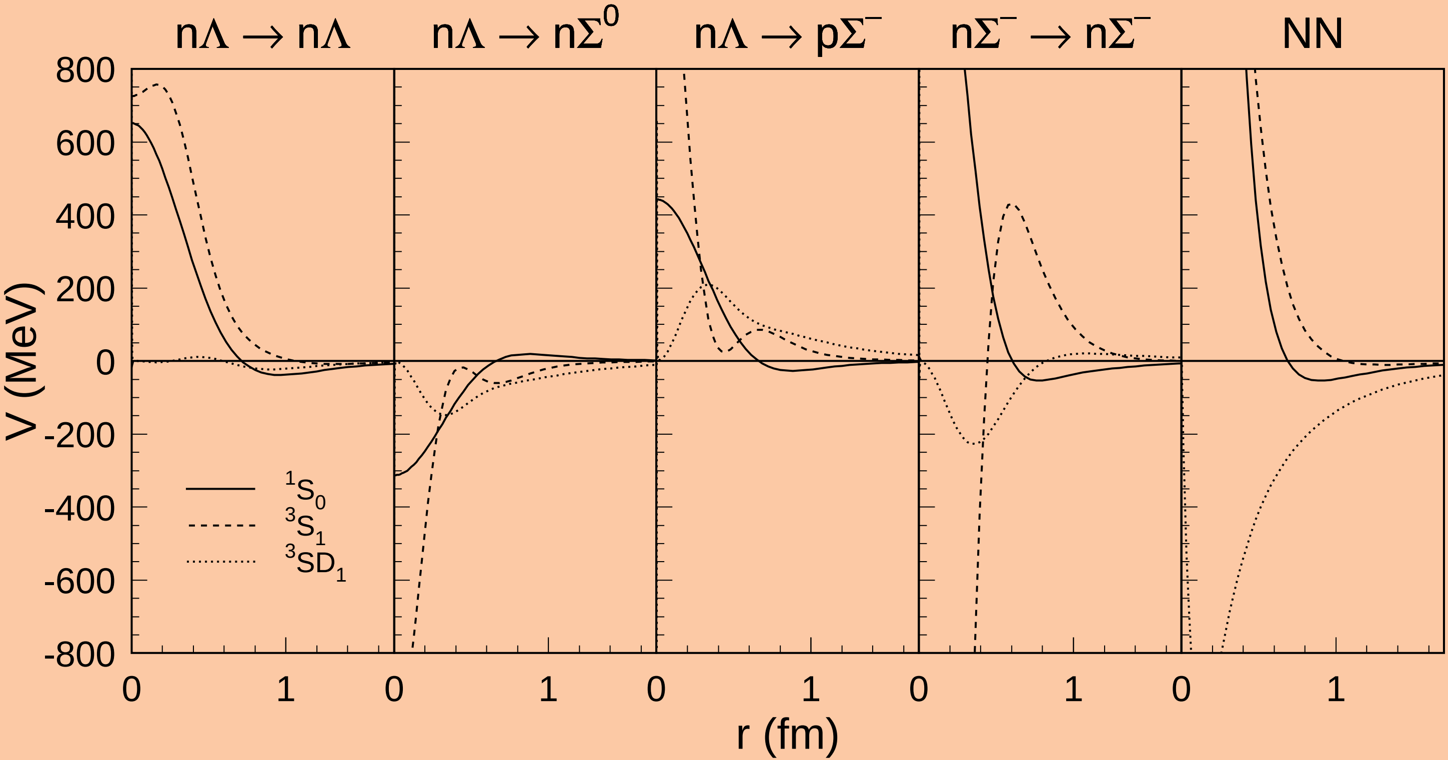


Three-Nucleon Forces:



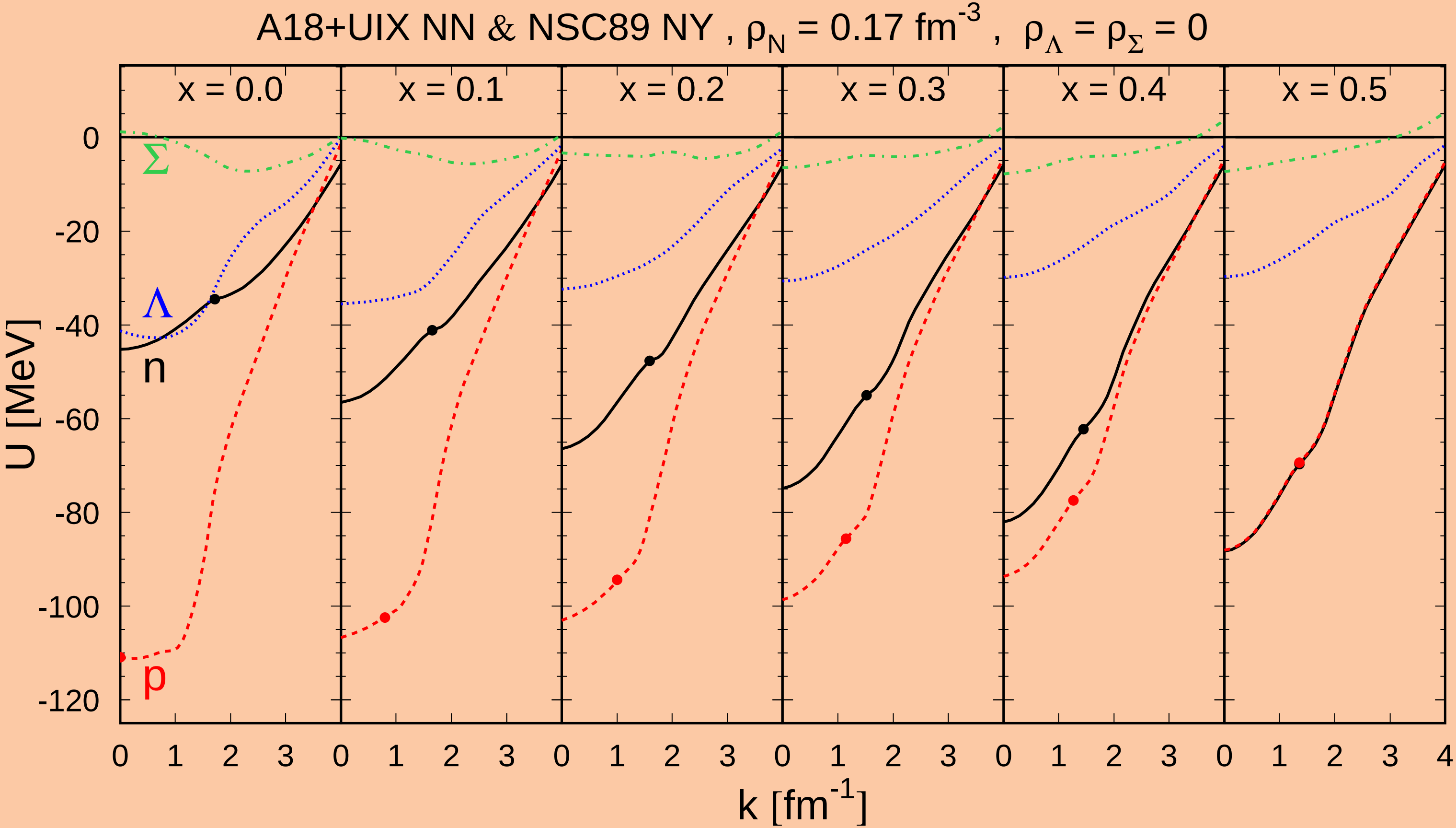
- Only small effect required [$\delta(B/A) \approx 1$ MeV at ρ_0]
- Model dependent, no final theory yet
- Use and compare microscopic and phenomenological TBF...
  - Microscopic TBF of P. Grangé et al., PRC 40, 1040 (1989):
    Exchange of $\pi, \rho, \sigma, \omega$ via $\Delta(1232)$, $R(1440)$, $N\bar{N}$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

- Hyperon-nucleon potentials (NSC89) vs. Paris NN:



↪ "Soft" cores, Strong coupling $N\Lambda \longleftrightarrow N\Sigma$

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



Hyperons are weaker bound than nucleons

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

- «Recipe» for neutron star structure calculation:

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

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: $\rho(r)$, $M(R)$ etc.

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Charge neutrality: $\sum_i x_i q_i = 0$

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

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

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

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

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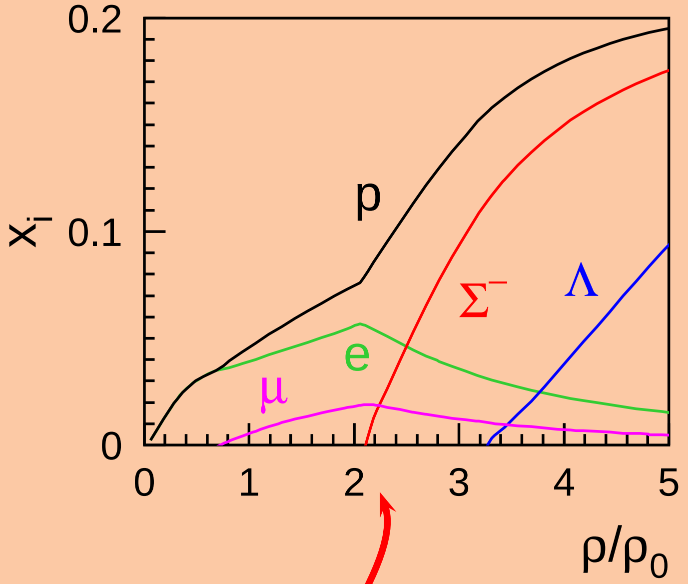
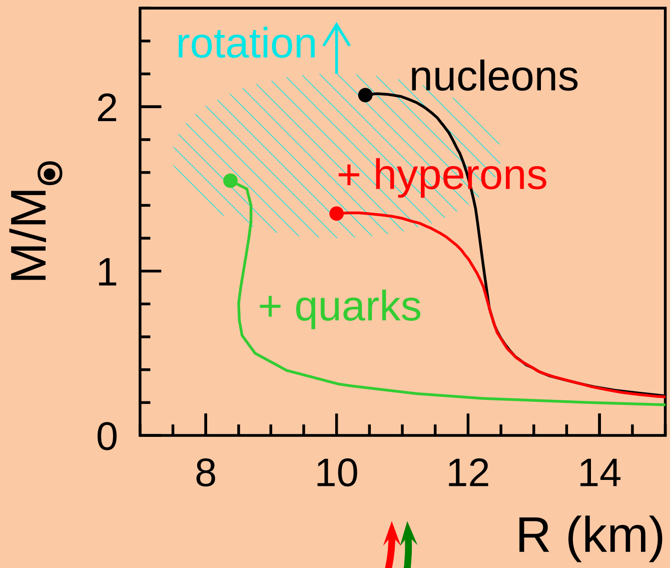
- Typical results:

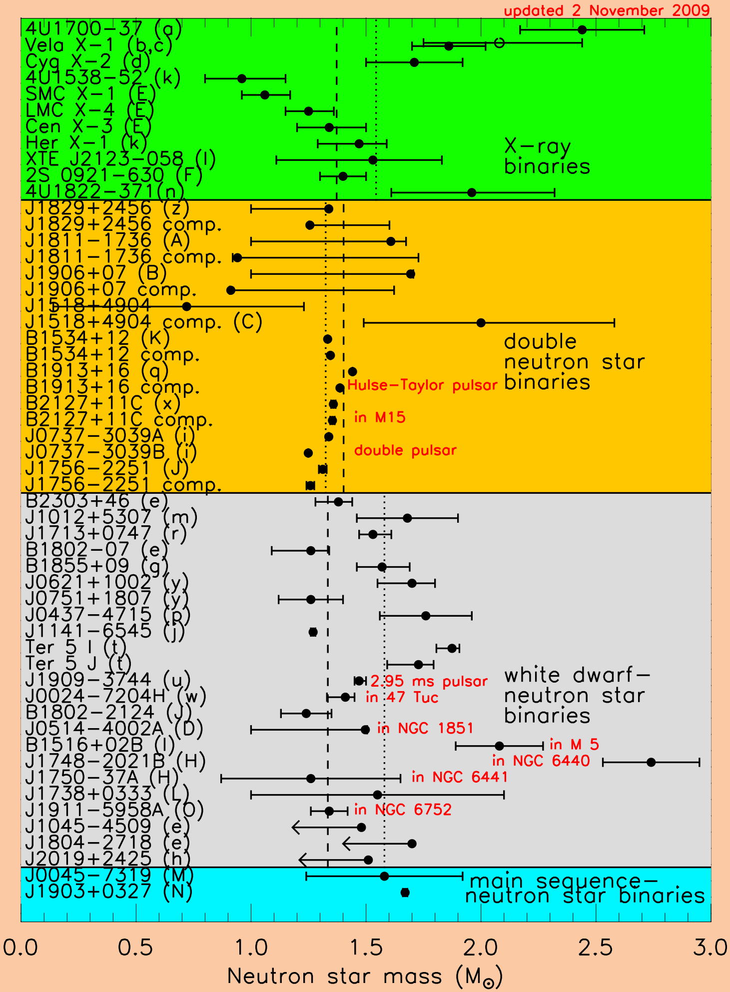




- Hyperon onset occurs at $\rho \sim 2 \ldots 3\, \rho_0$

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

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_{-13}^{+22}	5.13 ±4%	84^{+13}_{-12}	$0.13^{+0.06}_{-0.04}$	Heinke et al (2006)
M28** (Chandra)	$14.5_{-3.8}^{+6.9}$	5.5 ±10%	90_{-10}^{+30}	26 ± 4	Becker et al (2003)
M30 (Chandra)	$16.9_{-4.3}^{+5.4}$	--	94_{-12}^{+17}	$2.9^{+1.7}_{-1.2}$	Lugger et al (2006)
NGC 2808 (XMM)	??	9.6 (?)	103_{-33}^{+18}	18^{+11}_{-7}	Webb et al (2007)

$R_\infty < 5\%$

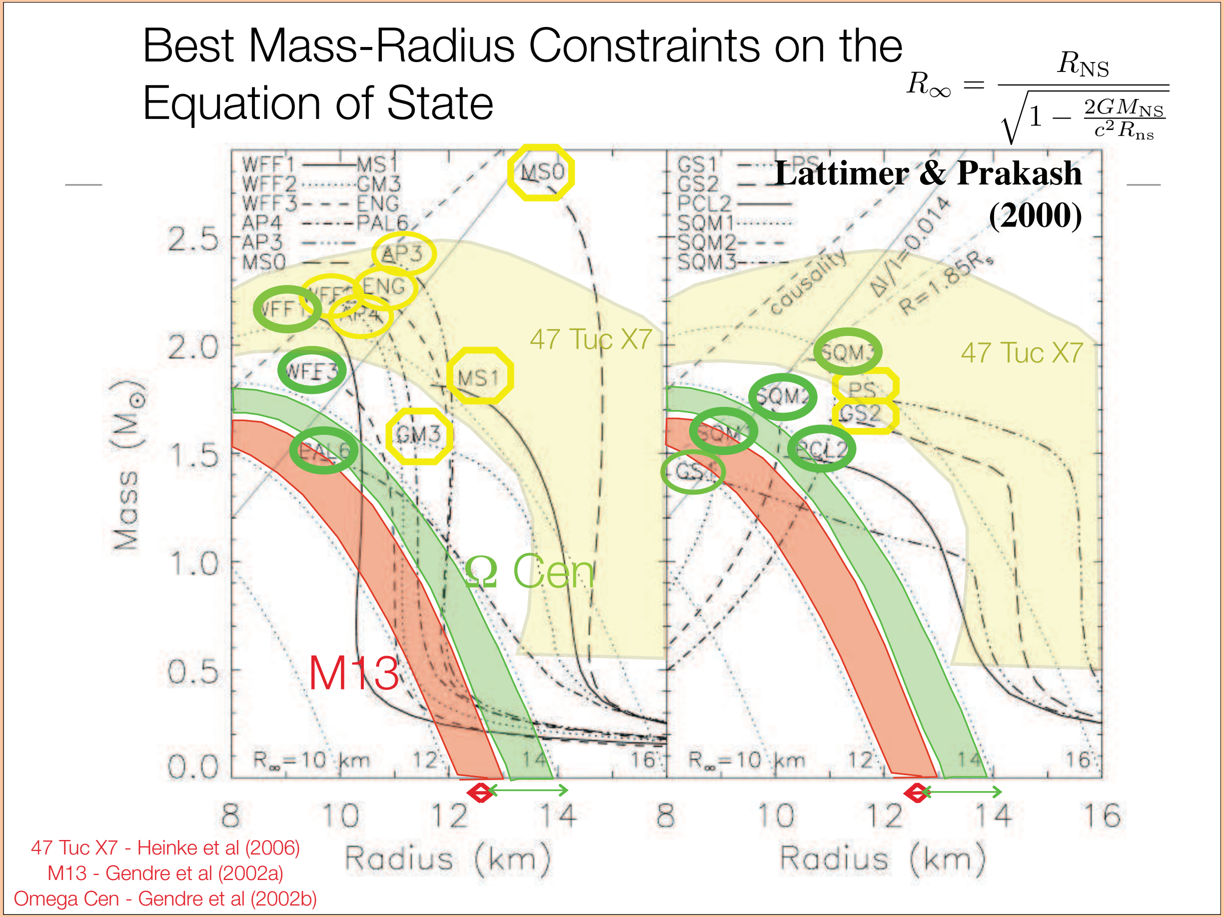
Caveats:

- 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

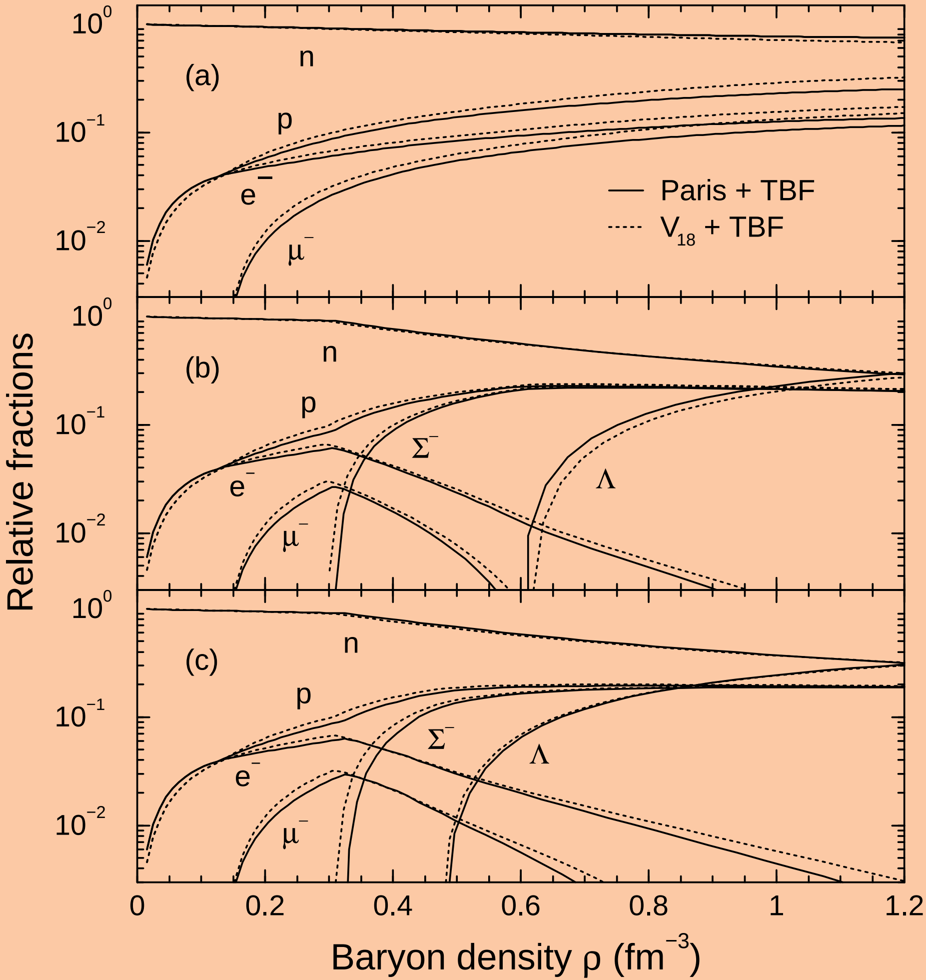
Mass-Radius Constraints:



Courtesy of R. Rutledge, NFQCD 2010 meeting


BHF Results ...

• Composition of neutron star matter:

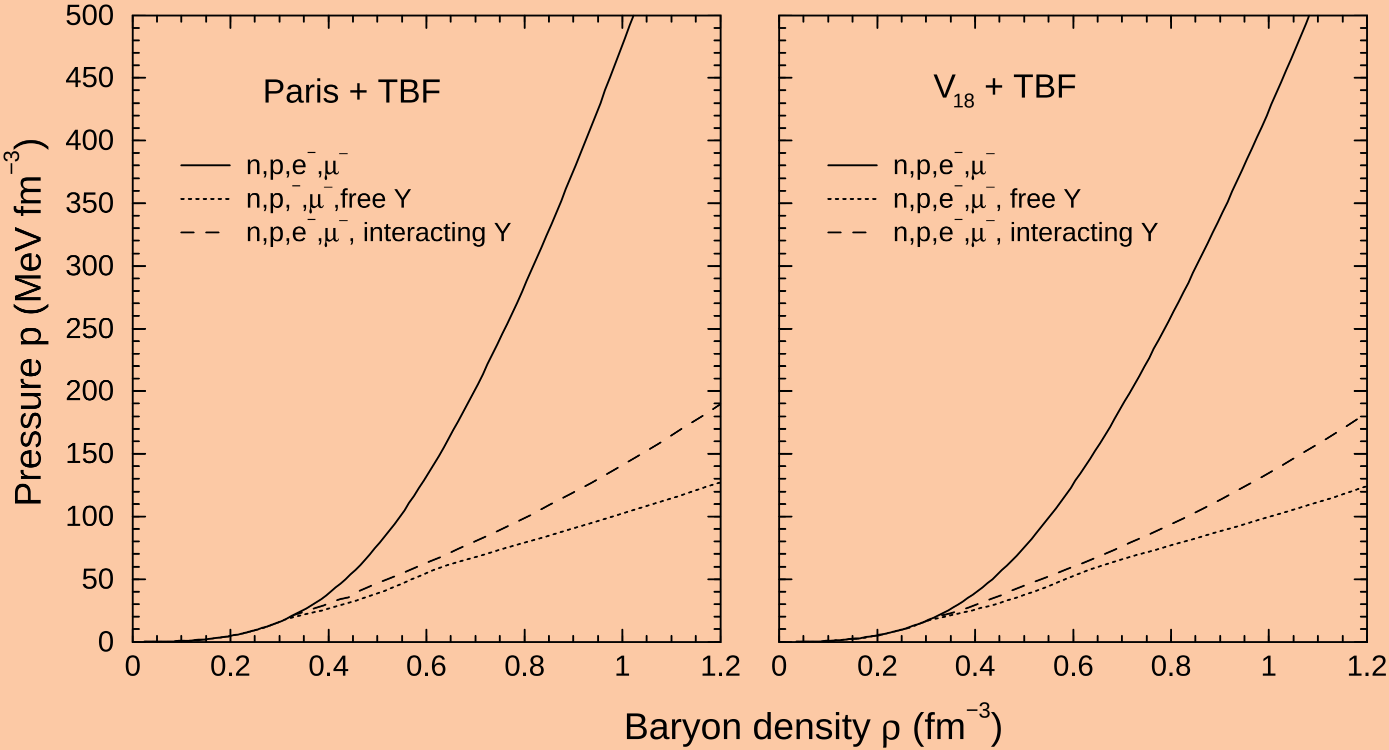


No hyperons

Free hyperons

Interacting hyperons
(Σ^- repulsive, Λ attractive)
YN interaction determines
Y onset

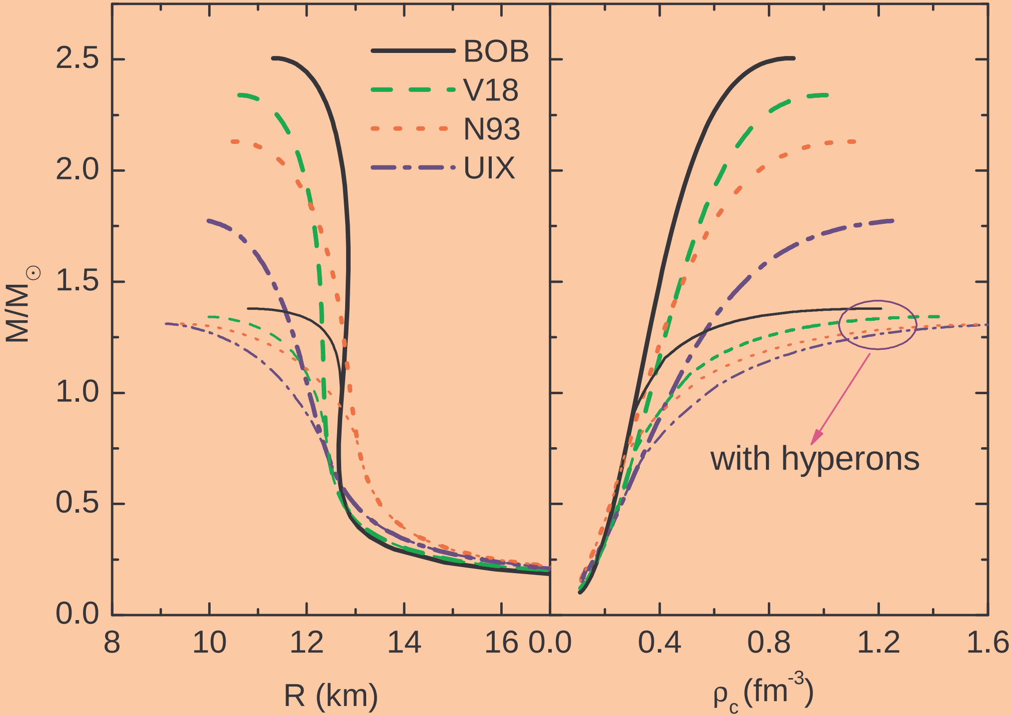
EOS of neutron star matter:



Strong softening due to hyperons !

(More Fermi seas available)

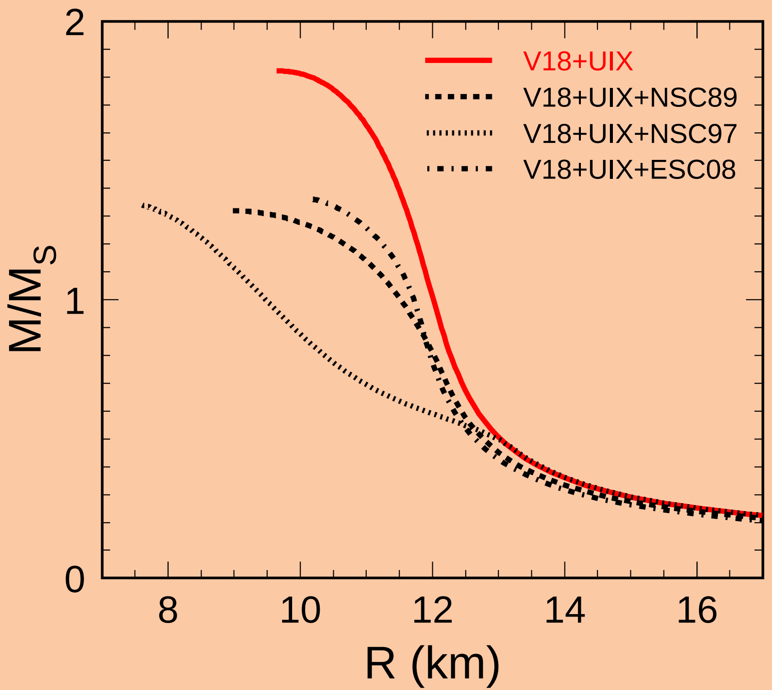
- Mass-radius relations with different nucleonic TBF:



NSC89 NY potential
No YY
No hyperon TBF

→ Large variation with nucleonic TBF
Self-regulating softening due to hyperon appearance

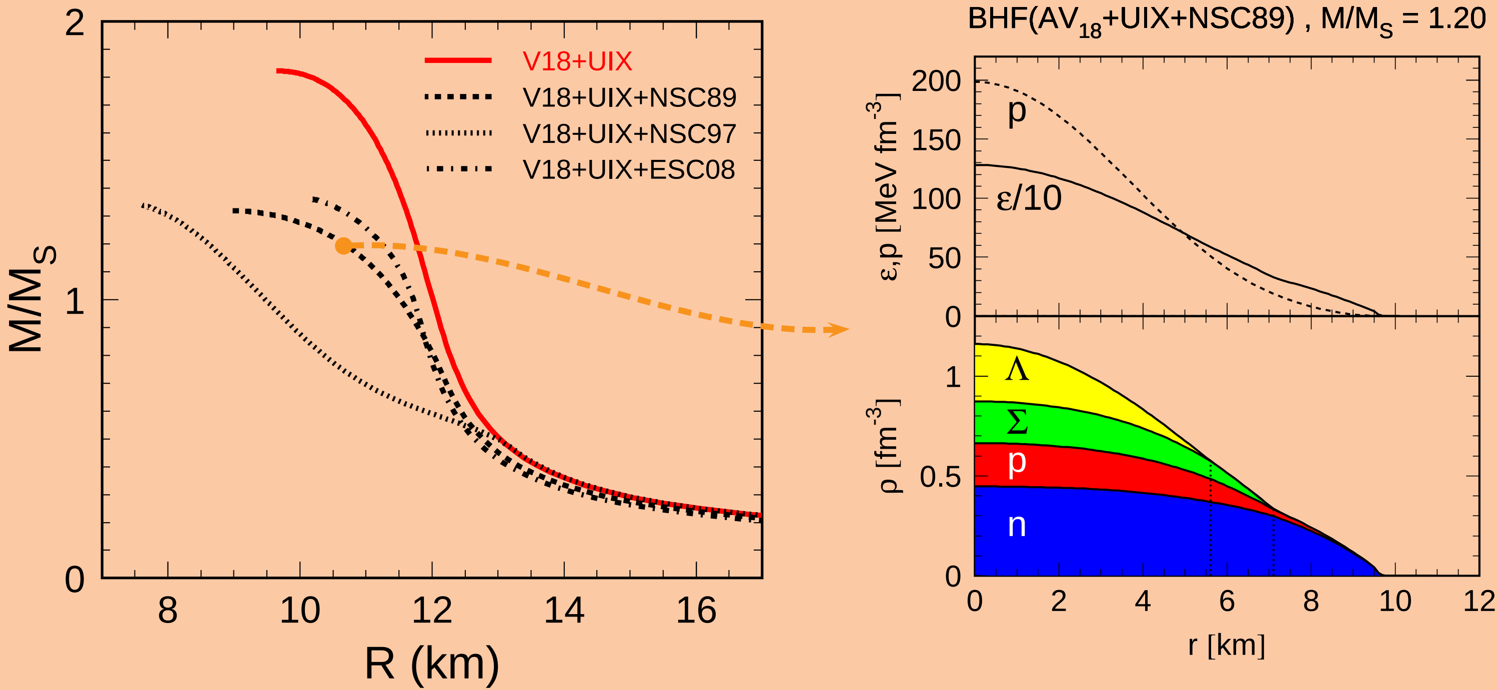
- Using different NY,YY potentials:



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

Proof for “quark” matter inside neutron stars ?!

- Using different NY,YY potentials:



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

Proof for “quark” matter inside neutron stars ?!

Inclusion of Quark Matter:

- Problem:

  Large theoretical uncertainties, limited predictive power

- Important constraint:

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

  We impose $\rho_c \approx 6\rho_0 \approx 1/\mathrm{fm}^3$ (CERN "result")

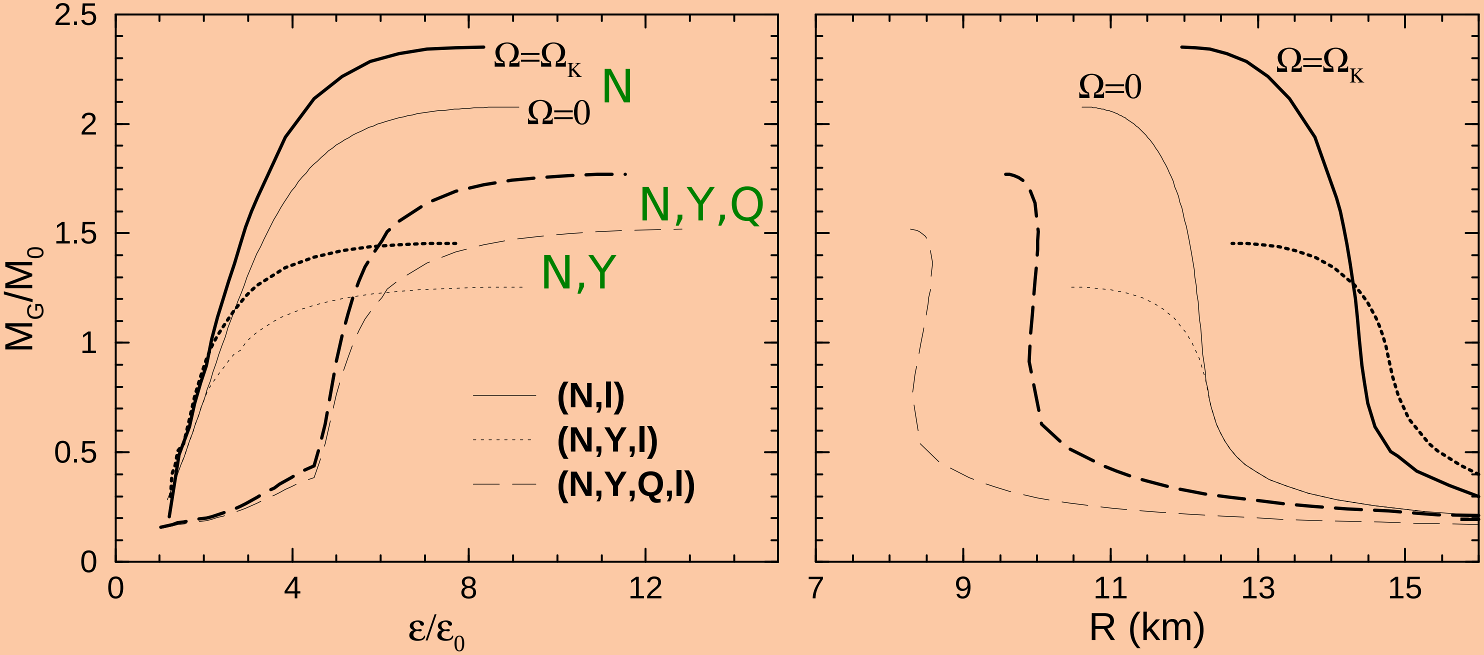
↪ MIT model requires density dependent bag "constant":

$k_F^{(f)}/m_f$

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

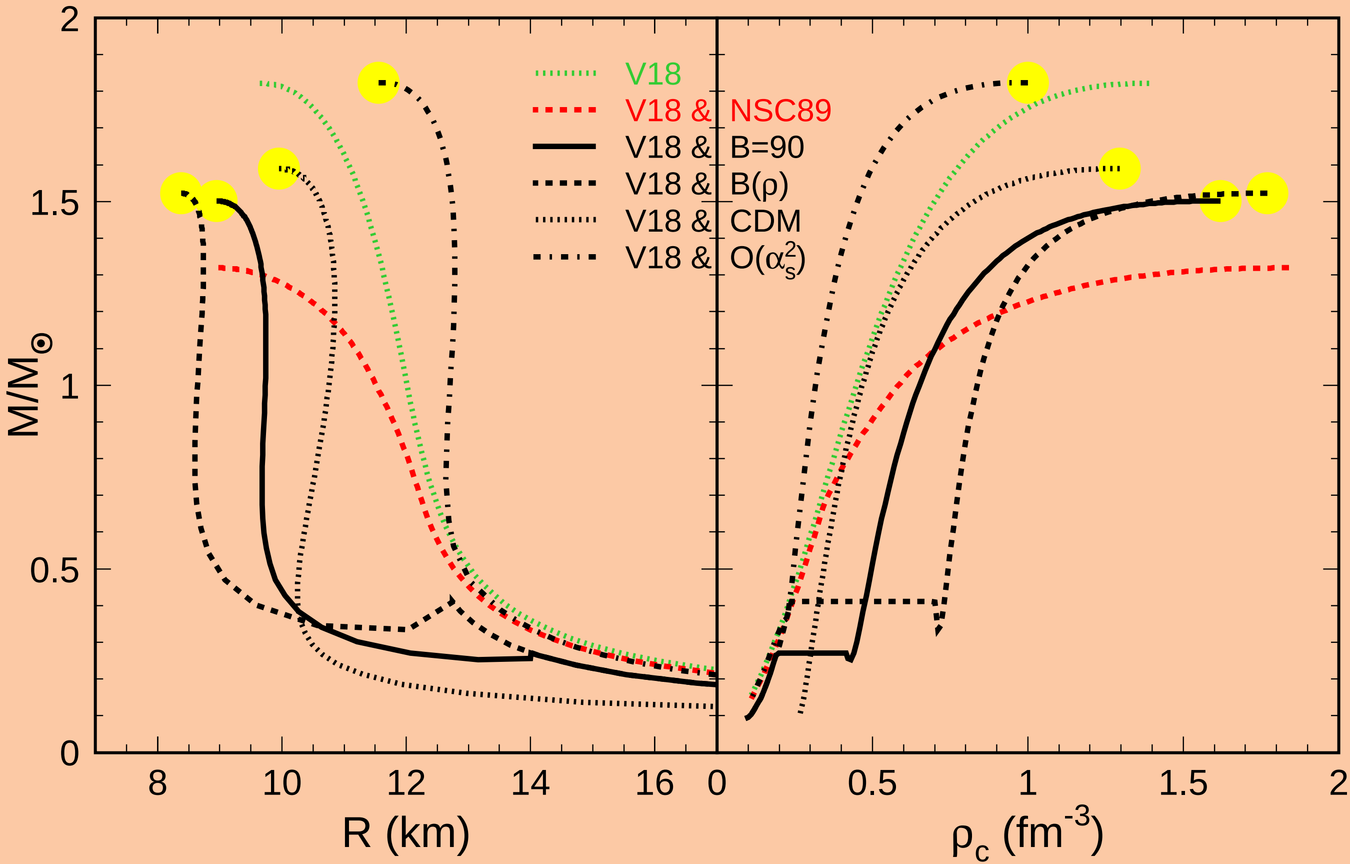
$$B(\rho) = B_\infty + (B_0 - B_\infty)\exp\left[-\beta\left(\frac{\rho}{\rho_0}\right)^2\right]$$

- Mass-radius relations (including rotation):



➥ Principal result: $M \lesssim 1.7 M_\odot$

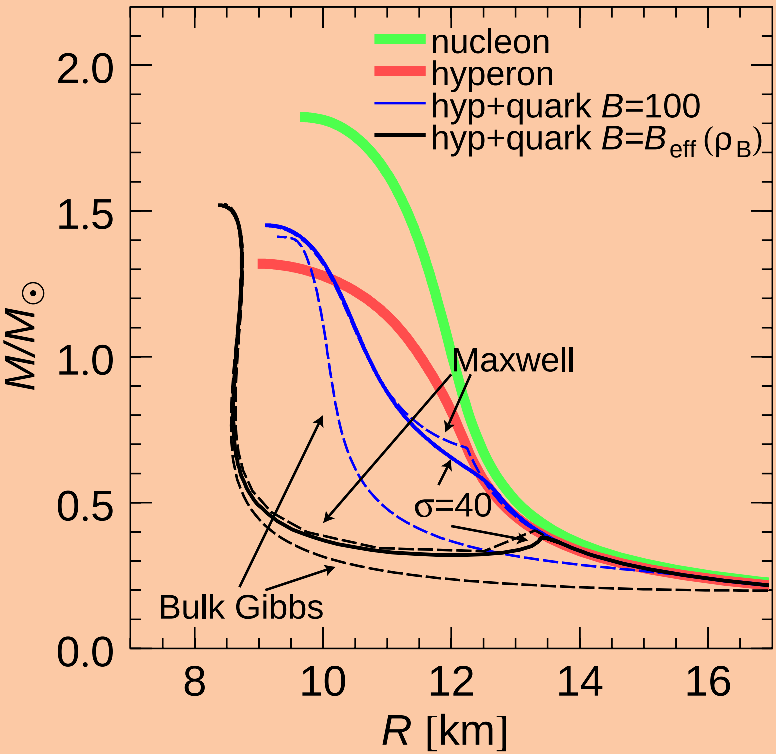
- Different quark EOS: bag models, color dielectric model:



NJL, Dyson-Schwinger models: hyperons prevent phase transition

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

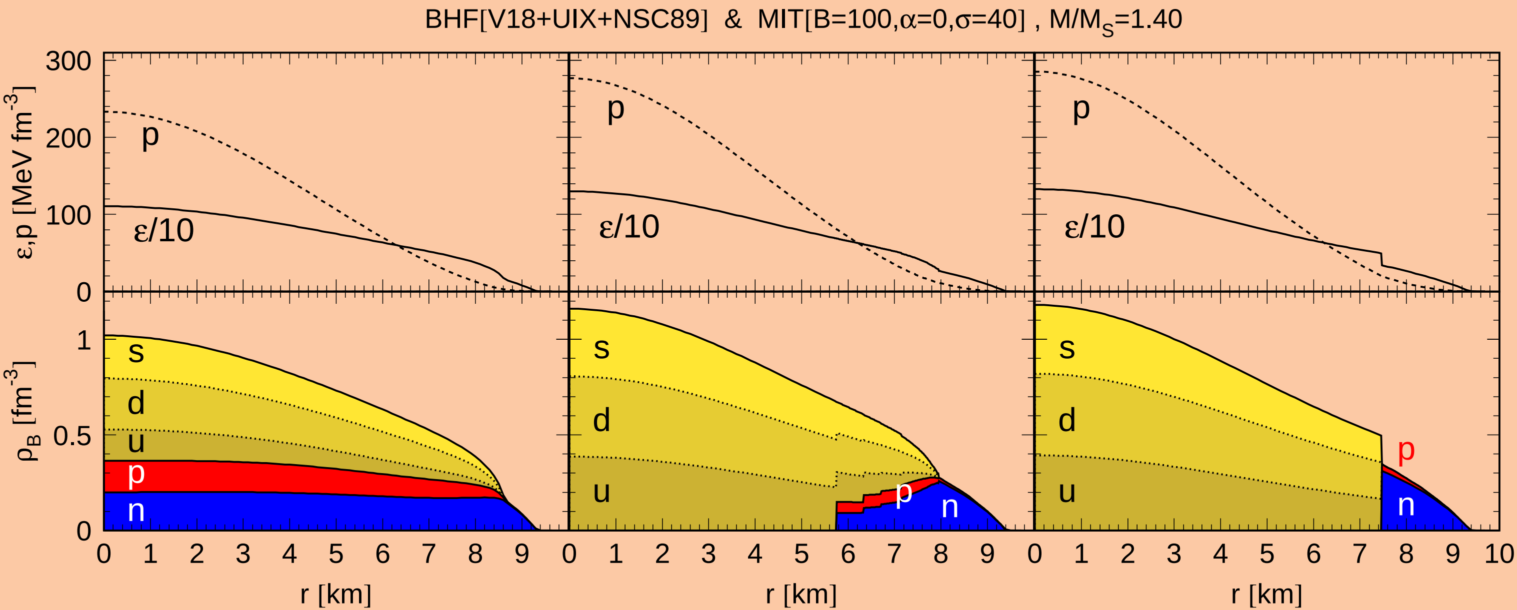
- Mass-radius relations with different hadron-quark phase transition constructions:



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

- Neutron star profiles:

Bulk Gibbs   Screened Gibbs   Maxwell



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

Summary:

- 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,
  but without phase transition in normal nuclear matter
- Currently $M_{max} \approx 1.9\, M_\odot$ for hybrid stars in this approach

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Current Activity:

- Other quark models, NY potentials, TBF, ...
- EOS at finite temperature: Proto neutron stars
- Gravitational wave emission